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Methodology for the assessment of innovative nuclear reactors and fuel cycles

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

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METHODOLOGY FOR THE ASSESSMENT OF
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FOREWORD

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in the year 2000, based on resolutions of the IAEA General Conference (GC(44)/RES/21). INPRO intends to help to ensure that nuclear energy is available in the 21st century in a sustainable manner, and bring together all interested Member States, both technology holders and technology users, to jointly consider actions to achieve desired innovations.

INPRO is proceeding in steps. In its first step, referred to as Phase 1A, INPRO developed a set of basic principles, user requirements and criteria together with an assessment method, which taken together, comprise the INPRO methodology, for the evaluation of innovative nuclear energy systems. The results of Phase 1A were documented in IAEA-TECDOC-1362, published in 2003.

This report documents changes to the basic principles, user requirements, criteria and the method of assessment that resulted from the second step of INPRO (referred to as Phase 1B (first part)), which started in June 2003 and ended in December 2004. During this step, Member States and individual experts performed 14 case studies with the objective of testing and validating the INPRO methodology. Based on the feedback from these case studies and numerous consultancies mostly held at the IAEA, the INPRO methodology has been significantly updated and revised, as documented in this report.

The ongoing and future activities of INPRO will lead to further modifications to the INPRO methodology, based on the feedback received from Member States in light of their experience in applying the methodology. Thus, additional reports will be issued, as appropriate, to update the INPRO methodology.

The IAEA highly appreciates the contributions made by the INPRO cost-free experts and the participants listed at the end of this report, and the valuable guidance and advice provided by the Steering Committee at its 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.

Phase 1B (first part) of the project was implemented under the IAEA Project Manager Y.A. Sokolov, Deputy Director General, Department of Nuclear Energy, and the Project Coordinator J. Kupitz of the Department of Nuclear Energy. As of December 2004, INPRO has 22 members supporting the project.

EDITORIAL NOTE

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SUMMARY

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was initiated in the year 2000, based on resolution of the IAEA General Conference (GC(44)/RES/21). This followed an initiative of the Russian Federation supported by a group of IAEA Member States to join forces in a broad international effort to develop innovative nuclear reactor and fuel cycle technology, recognizing that:

- A sustainable energy supply for humanity in the 21st century will require the large-scale deployment of nuclear power as well as other energy sources;

- Nuclear power is an energy technology that offers practically unlimited energy resources whose deployment can reduce environmental pollution and the volumes of waste needing management, including greenhouse gas emissions.

As of December 2004, INPRO has 22 members: Argentina, Armenia, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, France, Germany, India, Indonesia, Morocco, Netherlands, Republic of Korea, Pakistan, Russian Federation, South Africa, Spain, Switzerland, 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;

- 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; and to

- Create a forum to involve 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.

To realize its objectives, INPRO has adopted a stepwise approach. In the first step, called Phase 1A, task groups established a hierarchy of Basic Principles, User Requirements and Criteria — in the areas of economics, safety, environment, waste management, proliferation resistance, and infrastructure – that must be fulfilled by an innovative nuclear energy system (INS) to meet the overall target of sustainable energy supply. As well, the initial development of the INPRO method for the assessment of nuclear energy systems was carried out. The Basic Principles, User Requirements, and Criteria and the INPRO method of assessment, taken together, comprise the INPRO methodology. The INPRO methodology provides the possibility to take into account local, regional and global boundary conditions of IAEA Member States, including those of both developing and developed countries.

Phase 1A was completed in June of 2003 with the publication of IAEA-TECDOC-1362, Guidance for the Evaluation of Innovative Nuclear Reactors and Fuel Cycles, which documented the results of the Phase 1A work. The next step of INPRO was immediately launched. In this step, referred to as Phase 1B (first part), INPRO arranged for some 14 case studies to be performed — by national teams or by individual experts from seven countries — to test and provide feedback on the applicability, consistency and completeness of the INPRO methodology. This feedback has lead to the present report which sets out the improved INPRO methodology and brings Phase 1B (first part) to a conclusion.

In this summary the content of the report is briefly described starting with a discussion of the concept of sustainable development and the importance of energy within this concept.

In 1987 the Brundtland Report, Our Common Future, alerted the world to the urgency of making progress toward economic development that could be sustained without depleting natural resources or harming the environment. Written by an international group of politicians, civil servants and experts on the environment and development, the report defined sustainable development, as:

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The Brundtland Report recognized that securing global equity would require economic growth and argued that such growth could only be sustained if it was accomplished simultaneously with protecting the environment and conserving non-renewable resources. The report also recognised that achieving global equity and sustainable growth would require technological and social change.

In follow up meetings and reports, the fundamental importance of energy in achieving sustainable human development has been emphasized. Energy plays an important role in each dimension of sustainable development: economic, social, environmental, and institutional. Energy services, for example, underpin economic activity. They enable basic needs, such as food and shelter, to be met, and they contribute to social development by improving education and public health. Access to modern energy services can also be environmentally beneficial, for example, by reducing deforestation and decreasing pollution caused by inefficient appliances and processes. But there can be conflicts. Sustainable development is about finding the right trade-offs.

The general concept of *sustainability* and considerations specific to the concept of sustainable energy have been incorporated in the INPRO Objectives and have been integrated into the INPRO methodology. As INPRO proceeds its activities will continue to benefit from and be guided by the general IAEA and UN activities related to sustainability and it is anticipated that the output from INPRO will represent an important contribution by the IAEA and its Member States in furthering the global development of sustainable energy.

Ensuring the availability of a secure supply of energy is one important aspect of governments' ultimate responsibility for national security and economic growth. National circumstances and policies will determine the mix of fuels necessary to contribute to the world's collective energy security and global economic growth, and to address the challenge of achieving sustainable development. To address the specific issues relevant to the development and deployment of innovative nuclear energy systems (INS) for sustainable energy supply, within the general framework of sustainability, INPRO established a number of task groups to develop a method for assessing INS in the following areas: economics, safety, environment, waste management, proliferation resistance and infrastructure. By focusing on each of these specific areas in turn, the INPRO methodology ensures that a given INS takes into account the four dimensions of sustainability and is assessed in sufficient detail to establish with confidence the potential of the INS to contribute to sustainable energy supply and hence to meeting the general objective of sustainable development. In addition, the results of such an assessment provide an important input for defining the strategy and the necessary short, medium and long term research, development and demonstration (RD&D) plans to support the development and deployment of a given system or component thereof.

By definition, an INS, in INPRO, encompasses all 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 of nuclear facilities. An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining design proveness to minimize technological risks. An innovative design is an advanced design, which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice to achieve a breakthrough in performance in selected areas.

The INPRO *method of assessment* provides a tool that can be used to:

- Screen an INS to evaluate whether it is compatible with the objective of ensuring that nuclear energy is available to contribute to meeting the energy needs in the 21st century in a sustainable manner;

- Compare different INS or components thereof to find a preferred or optimum INS consistent with the needs of a given IAEA Member State; and to

- Identify RD&D required to improve the performance of existing components of an INS or to develop new components.

An assessor of an INS may be interested in only one component of a complete INS, such as a reactor for electricity production or for desalination, or in several components of a complete system. Regardless of his specific interest, the assessor must include in the evaluation all components of the system to achieve a holistic view and so ensure that the component(s) of interest and the corresponding overall system are sustainable.

An assessment requires the participation of individuals with expertise in the INPRO areas and with adequate knowledge of the nuclear facilities comprising the INS to enable a holistic assessment. The results of such assessments should be available to all stakeholders, not only to nuclear experts. But, the format and language in which the results are communicated to non-nuclear experts has to meet the needs of the stakeholders and doing so represents a challenge that is yet to be addressed.

INPRO has defined a set of Basic Principles, User Requirements, and Criteria (consisting of an Indicator and an Acceptance Limit) for each area of interest. The highest level in the INPRO structure is a Basic Principle (BP), which is a statement of a general rule that provides broad guidance for the development of an INS (or design feature). All Basic Principles shall be taken into account in all areas considered within INPRO (economics, safety, environment, waste management, infrastructure, and proliferation resistance). User Requirements (UR) are the conditions that should be met to achieve Users' acceptance of a given INS. 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). By establishing User Requirements that encompass such a broad constituency INPRO seeks to ensure that an INPRO assessment takes into account the interests and views of all stakeholders. A Criterion (CR) (or more than one) is required to determine whether and how well a given User Requirement is being met. Indicators may be based on a single parameter, on an aggregate variable, or on a status statement.

BPs, URs, and Criteria are broadly based. They represent an idealization of what is desirable taking into account both national, regional and global trends and what is likely to be technologically achievable. It is difficult to factor in step changes in technology, so INPRO has extrapolated current trends. Member States are free to and, indeed, in a number of cases, e.g. economics and infrastructure, should specify country or region or technology specific Criteria and User Requirements. For some Acceptance Limits, INPRO has proposed values in this report, e.g., in the area of safety where the limits should be internationally accepted and applied. In the long term, it is expected that internationally agreed acceptance limits would be proposed also in the areas of proliferation resistance, environment, and waste management as well as safety. The INPRO manual under preparation will provide IAEA Member States more detailed information on the selection of Indicators and Acceptance Limits.

At the end of step 2 of INPRO, Phase 1B (first part), methods for performing screening and comparative assessments have been sufficiently developed for application by interested IAEA Member States. On the other hand it is anticipated that feedback from applying the INPRO methodology will result in further improvements. The method of performing RD&D assessments is still under development and the approaches set out in this report are expected to be developed further in the next step of INPRO, Phase 1B (second part).

The Basic Principles, User Requirements and Criteria are set out in detail in Chapters 4 to 9 of the report and are briefly summarized here.

In the area of *economics* one basic principle has been enunciated, namely that to contribute to sustainable development, energy and related products and services from INS must be affordable and available. If energy and related products and services are to be affordable the price to the consumer must be competitive with low cost/priced alternatives. If energy and related products and services are to be available, systems to supply the energy and related products need to be developed and deployed. To develop and deploy innovative energy systems requires investment and those making the investment, be they industry or governments, must be convinced that their choice of investment is wise. The alternatives for investment may be other energy technologies seeking investment for development or deployment or non-energy technology areas. So, to be developed and deployed, INS must compete successfully for investment. In different markets and regions and at different times and stages in the cycle of development and deployment the investor(s) may be different and different factors may assume more or less importance in determining attractiveness of investment. But in any case a sound business case must be made.

Given the nature of nuclear technology, it is recognized that government policies and actions (in some Member States, governments may participate in investment) will have a significant bearing and influence on investor decision making, both when deciding whether or not to invest in development and when deciding to invest in technology deployment/acquisition. For private sector investment profitability and return will be key factors in the business case. It follows that if the price to the consumer is to be competitive and at the same time investors are to receive an attractive return, the cost of production must also be competitive with that of alternatives. 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 competitive financial figures of merit, e.g., rate of return, which should be at least comparable to the values for competitive energy sources and preferably better. As well, a judgement must be made that the funds required to implement a project can be raised within a given expected investment climate, taking into account other investment options and other priorities requiring a share of available capital and the risk of investment must be acceptable, taking into account the risk of investment in other energy projects.

Given the uncertainty about the future, ideally, 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 and markets as possible. Thus, the ability to adapt specific components of an INS, as well as the overall adaptability of the INS, to accommodate different sized modules, to accommodate market changes and growth, to accommodate different fuels, to meet different energy applications, and to meet the needs of different countries/ regions is desirable. In assessing flexibility of a given component or set of components, possible synergisms with other components of the INS should be considered.

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 radio-nuclides, and confine radioactivity and shield radiation. To ensure that INS will fulfil these fundamental safety functions, INPRO has set out four 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 health and environmental 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 and prototype 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.

Protection of the *environment* is a major consideration in the processes for approving industrial activities in many countries and is a central theme within the concept of sustainable development. 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 the Environment, 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.

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.

Because *waste management* involves longer time scales and, in many cases, different source terms and pathways, compared with those considered in the safety of nuclear installations, this topic is dealt with in a separate chapter. The IAEA sets out nine fundamental principles for radioactive waste management in the document "Principles of Radioactive Waste Management Safety Fundamentals". Four INPRO Basic Principles for INS have been derived from these nine fundamental principles. Thus, the generation of waste shall be kept by design to the minimum practicable, waste shall be managed so as to secure an acceptable level of protection of human health and the environment regardless of the time or place at which impacts may occur, waste shall be managed in such a way that undue burdens are not imposed on future generations, and interdependencies among all waste generation and management steps shall be taken into account. These principles in turn lead to INPRO requirements to minimize the generation of waste with emphasis on waste containing long-lived toxic components that would be mobile in repository environment, to limit exposures to radiation and chemicals from waste, to specify a permanently safe end states for all wastes and to move wastes to this end state as early as practical, to classify wastes and to ensure that intermediate steps do not inhibit or complicate the achievement of the end state, and to accumulate assets for managing all wastes in the life cycle so that the accumulated liability at any stage of the life cycle is covered. 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 of long-lived fission products and minor actinides 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 to be 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 and at follow up meetings held in March 2004 in Cheju, Republic of Korea, and in September 2004 in Vienna, Austria, where the feedback from the case studies were taken into account. Proliferation resistance is a combination of intrinsic features and extrinsic measures. 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: a) commitments, obligations and policies of states, such as the Treaty on the Non-Proliferation of Nuclear Weapons and the IAEA safeguards agreements and protocols additional to such agreements; b) agreements between exporting and importing states on exclusive use of nuclear energy systems for agreed purposes; c) commercial, legal or institutional arrangements that control access to nuclear material and technology; d) verification measures by the IAEA or by regional, bilateral and national measures; and e) legal and institutional measures to address violations of measures defined above.

INPRO has produced Basic Principles that require that proliferation resistance features and measures be implemented throughout the full life cycle for INS and that both intrinsic features and extrinsic measures be utilized. To comply with these Basic Principles requires that: the commitment and obligations of States be adequate; the attractiveness of nuclear material with respect to its suitability for conversion into nuclear explosive devices be low; the diversion of nuclear material be difficult and be detectable; multiple features and measures be incorporated in INS covering plausible acquisition paths of fissile material for a nuclear weapons programme; and that the combination of intrinsic features and extrinsic measures be optimized during design and engineering to provide cost-effective proliferation resistance. RD&D is needed in a number of areas, in particular, in developing a process to assess the proliferation resistance of a defined INS, taking into account the respective maturity level of the INS and the level of detail available.

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 nuclear power *infrastructure*, both national infrastructure and that based on international arrangements. Nuclear power infrastructure comprises all features/ substructures that are necessary for the successful deployment and operation of nuclear power plants including legal, institutional, industrial, economic and social features/substructures. 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 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 dealing with safety, environment, waste management, and proliferation resistance 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, 'there is no need for relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility used for similar purpose,' 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.

Such considerations have lead INPRO to define a Basic Principle that regional and international arrangements shall provide options that enable any country to adopt INS without making an excessive investment in national infrastructure. The associated User Requirements recognize the need for establishing a national legal framework, that the industrial and economic infrastructure of a country planning to install an INS be adequate, that measure are taken to secure public acceptance, and that adequate human resources are available for safe operations. 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. It is recognized that in adopting nuclear technology for the supply of energy requires some investment in national capability – at the very least to position a country to be a knowledgeable purchaser – but the idea is that a country has options concerning the upfront investment required because of the wide range of services and products available internationally, including operating and even regulatory services.

In performing an INPRO assessment, the assessor must take into account a reference energy scenario or scenarios. For example, if the assessor were focussed on energy supply in his state he would take into account a national energy scenario (or perhaps a more localized scenario based on a region within his country). Such a national scenario would also be expected to take into account global and/or regional considerations such as the global demand for uranium, reprocessing capacity, etc., and so would also have to use some elements of a regional or global scenario. If the assessor were interested in global energy supply as a component of sustainable development, he would necessarily utilize a broadly based scenario that takes into account various regions and country groupings to arrive at a global scenario. Such scenarios will use modelling tools, including existing tools that have been developed by the IAEA and those under development by INPRO, in particular the DESAE code.

The DESAE code, as currently developed, calculates the resources, both financial and material, required for a given combination of reactors to meet a specified supply of nuclear energy as a function of time. Thus the user can study the practicality of a proposed system and material balances such as uranium demand as function of time, waste arisings, plutonium re-cycling, etc. The code is at an early stage of development. Future developments will extend its use to include other sources of energy supply and to couple it with IAEA codes such as MESSAGE.

In general the use of such modelling tools is seen to be an important part of energy planning and of INPRO and the use of such tools will be integrated into the INPRO methodology as it is further developed.

To conclude, this report presents a methodology, which has been tested and validated by Member States, for assessing innovative nuclear energy systems to ascertain whether a given nuclear energy system is sustainable. Thus, INPRO has taken a decisive step towards fulfilling its first objective "to help to ensure that nuclear energy is available in a sustainable manner within the 21st century". In the next step, Phase 1B (second part), it is anticipated that the methodology will be used to perform holistic assessments of complete INSs, beginning early in 2005. An important output of this step will be the creation of a Users Manual to assist Member States in applying the INPRO methodology. Feedback from the first few assessments will be invaluable in preparing such a manual. A data bank of INS assessments will be established.

As feedback is obtained from assessments, it is expected that the INPRO methodology and Manual will be further refined. It is also anticipated that the methodology will be used to identify complementarities and synergisms among systems of interest to different Member States, in both technology and in infrastructure, and so will assist in identifying possible paths to a globally sustainable nuclear energy system based on diverse national and regional components. Thus, such assessments will represent an important step towards fulfilling INPRO's second objective "to bring together all Member States to consider jointly the international and national actions to achieve desired innovations".

The work in the second part of Phase 1B and in the following Phase 2 (see Appendix) will include all stakeholders in nuclear energy. In this way INPRO will meet its third objective "to create a process that involves all relevant stakeholders" by providing a forum where experts and policy makers from industrialized and developing countries can discuss technical, economical, environmental, proliferation resistance and social aspects of nuclear energy planning as well as the development and deployment of Innovative Nuclear Energy Systems (INS) in the 21st century.

CHAPTER 1
INTRODUCTION

1.1. Mission of INPRO

The mission of INPRO is:

- To provide a forum where experts and policy makers from industrialized and developing countries can discuss technical, economical, environmental, proliferation resistance and social aspects of nuclear energy planning as well as the development and deployment of Innovative Nuclear Energy Systems (INS) in the 21st century;

- To develop the tools to analyse on a global, regional and national basis the role and structure of INS required to meet energy demands in a sustainable manner;

- To develop the methodology for assessing INS and to use it in establishing an internationally acknowledged IAEA set of recommendations for such assessments;

- To assist in coordinating international cooperation for INS development and deployment; and

- To pay particular attention to the needs of developing countries interested in INS.

The INPRO methodology will support the selection of a development path (or paths) for local, regional and global nuclear power infrastructures, allow the identification of its essential components, and facilitate the organization of the research, development and demonstration (RD&D) work needed to improve existing components and develop missing components of INS and the identification of approaches to local, regional, and global nuclear power infrastructures for sustainable nuclear energy systems. Of necessity, possible future changes in the requirements and conditions under which nuclear power will be developed and used need to be taken into account, including those of countries that currently do not have nuclear power. For such countries, the INPRO methodology will be of assistance in specifying their future energy demand and the means of meeting this demand.

To meet the energy demand in the 21st century in a sustainable manner (sustainable energy supply) will require the large-scale deployment of nuclear power as well as other energy sources. Nuclear power has the potential to provide cost-effective, reliable and safe energy supply in all regions of the world, either directly or indirectly. The developers of a given energy technology need to explore the real capabilities of that technology using appropriate modelling tools. Account must be taken of the potential for improving existing facilities, limitations on the permissible scale of their deployment, and the rate at which they are consuming the resources they use. It must also be borne in mind that a great deal of time may be needed to bring a new idea from the concept stage to its implementation on a scale capable of having a significant global, regional or even local impact on sustainable energy supply. In this regard it may be noted that nuclear power is an energy technology that offers practically unlimited energy resources whose deployment can reduce environmental pollution and the volumes of waste needing management, including greenhouse gas emissions.

The key feature of the INPRO methodology is that it provides a tool for the systematic presentation of information on: the potential of nuclear energy supply in general and that of different supply options, the consequences of the use of nuclear energy; energy development options for society; and on the associated development expenditures in terms of effort, resources and time. As it was noted at the International Conference on Innovative Fuel Cycles and Reactors [1-1] “the INPRO methodology is a navigator in a turbulent environment.” The INPRO methodology will greatly assist the effective development and deployment of nuclear energy systems on a local, regional, and global scale.

When looking to the future, it is well also to reflect on the past. For this reason, in the next section, some factors are discussed briefly that have affected the development and use of nuclear power to date.

1.2. Brief history of nuclear power

During its relatively short history, covering only fifty years, expectations and projections for the development and use of nuclear power have varied dramatically in a number of regions, varying with time from enthusiastic to pessimistic. Of note is the fact that this is so in a number of countries that were early adopters of nuclear power. In light of such changes it is worthwhile summarizing the scientific and technical advances that have been achieved and some basic restrictions of which one is now aware.

The volume of scientific and technological information related to nuclear power accumulated during the past fifty years is enormous. It includes basic nuclear, chemical, thermo-hydraulic and material science data and the information developed in designing, constructing, testing and operating several hundreds of nuclear facilities of many different types in dozens of countries. Based on this pool of knowledge it can be emphatically stated that:

- Known reserves of three naturally occurring isotopes of uranium and thorium ($^{235,238}U$ and ^{232}Th) have the potential to ensure global energy supplies sufficient to meet any reasonable projection of global energy needs for many hundreds of years; and

- This energy can be supplied using technologies that have already been tested and demonstrated at least at the pilot plant level.

This has been known for many years and so, projections made in the seventies for the global capacity of nuclear power as of the year 2000 were very high. But, the reality is that these projections were by an order of magnitude too high. Nevertheless they do reflect the real potential for the growth of nuclear power.

Nuclear power capacity grew fastest in the first half of the 1970s, averaging growth of 30% per year. But growth began to slow in the second half of the decade for several reasons. Increased challenges from a growing number of mainly environmentalist nuclear opponents began to stretch out licensing times and sometimes necessitated design changes. This increased costs, delayed cost recovery, and complicated financing. Another contributor to high costs was simply the inability in many cases of utilities, equipment suppliers, contractors and regulators to rise to the management challenges of such a new complex technology. The combination of inflation and rising energy costs in the 1970s both depressed growth in electricity demand (and thus utility revenues) at the same time that it increased utility costs.

In the USA, towards the end of the 1970s nuclear power orders dried up completely, and it has not revived. The most obvious cause was the Three Mile Island accident in 1979, the first major accident at a civilian nuclear power station. The psychological effect on the population in the neighbourhood, and eventually throughout the Western world, was immense. So was the damage to the plant itself and to the reputation of the nuclear power industry.

Globally, however, nuclear power's share of electricity continued to increase, even while the rate of nuclear expansion slowed. In 1981 the nuclear share was 9.1%. In 1987 it reached 16.2%. It then effectively stabilized as nuclear expansion slowed to the pace of overall electricity expansion. For the last 16 years nuclear growth has matched electricity growth and, in 2003, nuclear power's share of global electricity stood at 16.1%.

During this period there was modest growth in Japan, the Republic of Korea and a few developing countries. North America, western Europe, Russia and eastern Europe, however, saw almost no capacity growth. Two reasons were the 1986 Chernobyl accident and electricity market deregulation in many countries. Chernobyl broadened opposition to nuclear power, especially in Europe, and deregulation 'exposed' excess capacity that had accumulated in regulated markets, pushed electricity prices (and thus utility revenues) lower and made power plant investments more risky. Excess capacity reduced demand for new capacity — of any sort — and the emphasis on rapid reliable returns made nuclear power's 'front-loaded' cost structure, with high initial capital costs and low operating costs, an important disadvantage. These differences, coupled with low natural gas prices through most of the 1990s and natural gas' image as a clean burning fuel, steered new investments away from nuclear power and most often in the direction of natural gas.

Ironically, both the Chernobyl accident and deregulation, plus consolidation in the nuclear industry, led to rising availability factors so that global nuclear generation rose in the 1990s faster than global nuclear capacity. The Chernobyl accident prompted management and safety improvements around the world that resulted in higher availability factors. And in deregulated markets, higher availability factors translated directly into increased profits for operators, providing a powerful financial incentive for improvement.

1.3. Launching of INPRO

As documented in the report of the Brundtland Commission, the Rio declarations, and elsewhere, there exists, internationally, a strong interest in and support for the concept of sustainable development. This concept, described in more detail in this report in Chapter 2, INPRO and the concept of sustainability, includes the requirement for the development of energy supply that is sustainable. The Special Report on Emission Scenarios (SRES), commissioned by the Intergovernmental Panel on Climate Change (IPCC) in 1996 examines the energy needs of the 21st century based on 40 reference scenarios. The scenarios in the SRES report clearly predict an increase of demand for energy by a median factor of 2.5 and for electricity by a median factor of about 5. The report shows further that to ensure a sustainable development of supply of energy in the 21st century, nuclear energy is expected to expand, because the other energy sources such as fossil (because of GHG emissions) or renewables (because of discontinuous availability and land use) are unlikely to fulfil the predicted energy demand without nuclear. However, as indicated in the previous section, the sustainability of nuclear systems operating today, is questioned by the public and by some decision makers, because of issues related to safety, nuclear waste disposal, and proliferation of nuclear weapons.

To solve these issues and ensure a sustainable development of nuclear energy, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in the year 2000, based on resolutions of the IAEA General Conference (GC(44)/RES/21). This followed the Russian Federation's initiative supported by a group of IAEA Member States to join forces in a broad international effort to develop innovative nuclear reactor and fuel cycle technology with certain basic features. These features include:

- Effectively unlimited fuel resources;
- Exclusion of severe accidents;
- Environmentally benign energy production without disturbing the natural radiation balance;
- Blocking the nuclear weapons proliferation pathway associated with nuclear power; and
- Economic competitiveness.

The projected global energy demand and recent growing interest in the role of nuclear power in meeting this demand show the timeliness of these efforts. The IAEA, with its full spectrum of expertise, is in a unique position to assist its Member States in this undertaking.

Guidance to INPRO is provided by a Steering Committee. The first meeting of the Steering Committee was convened in May 2001. As of December 2004, INPRO has 22 members: Argentina, Armenia, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, France, Germany, India, Indonesia, Morocco, Netherlands, Pakistan, Republic of Korea, Russian Federation, South Africa, Spain, Switzerland, Turkey and the European Commission. Members contribute to the project by providing funds, experts and studies.

1.4. Overall objectives of INPRO

The overall objectives (see Ref. [1-2], Section 1.2.2) 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; and

- 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.

1.5. Realization of INPRO objectives

To realize its objectives, INPRO has adopted a stepwise approach (Ref. [1-2], Section 1.2.3.1).

In its first step, called Phase 1A, INPRO set up 8 task groups in the following areas:

- Prospects and potentials (Resources and demand) of nuclear power;
- Economics;
- Environment;
- Waste management;
- Safety of nuclear installations;
- Proliferation resistance;
- Infrastructure (Cross cutting issues); and
- Method for assessment.

The task groups set out a hierarchy of requirements, consisting of basic principles, user requirements and criteria that must be fulfilled by a nuclear energy system to meet the overall target of sustainability. Additionally, the initial development of the INPRO Method for the assessment of nuclear energy systems was carried out. The results of the Phase 1A work were documented in TECDOC-1362 [1-2].

In the second step, called Phase 1B (first part), INPRO arranged for several case studies to be performed — by national teams or by individual experts — to validate and test the applicability, consistency and completeness of the methodology. (The content of these case studies is briefly described in the following section.) The result of Phase 1B (first part) is an improved INPRO methodology, documented in this report.

The INPRO methodology provides the possibility to take into account, in the assessment, the local, regional and global boundary conditions of Member States, including those of developing and developed countries, and the time frame for the planned deployment of nuclear facilities in the 21st century. The term "nuclear facilities" encompasses all components of a nuclear system starting from the front end, e.g. mining, to the back end, e.g., end-state facilities for radioactive waste, and includes all applications of nuclear power such as electricity generation, desalination of sea water, co-generation, district heating, hydrogen production, etc. The assessment of a given nuclear energy system or systems can be performed by a single Member State, or by a group of Member States with common boundary conditions such as a geographic region, a comparable industrial capacity, or size of energy system needed, etc. Some aspects of nuclear energy systems can and perhaps are best evaluated on a global basis, e.g. international fuel cycle centres.

By creating a methodology to ascertain whether or not a nuclear energy system is sustainable, INPRO has realized its **first objective** "to help to ensure that NE is available in a sustainable manner" (full text in section above).

In the next step, called INPRO Phase 1B (2nd part), it is planned that a number of assessments of complete nuclear energy systems will be performed and, as an outcome of this step , the research, development and demonstration (RD&D) necessary for such systems, or parts of it, to be sustainable will be defined.

The performance of the assessment and the resulting definition of necessary short, medium and long-term RD&D goals (considering the planned schedule of deployment of nuclear energy systems) will involve all Member States interested in nuclear energy. In this way it is foreseen that INPRO will fulfil its **second objective** "to bring together all Member States to consider jointly the international and national actions to achieve desired innovations" (full text in section above).

In a subsequent step, called Phase 2, depending on the decision of the Member States, the IAEA via INPRO can coordinate the performance of selected RD&D tasks defined in Phase 1B (2nd part). This coordination of development efforts will include all stakeholders in nuclear energy. Thus the **third objective** of INPRO will be fulfilled "to create a process that involves all relevant stakeholders" (full text in section above).

1.6. National and individual case studies performed by INPRO

In the Phase 1B (1st part) several case studies have been performed to validate and test the INPRO methodology and to identify necessary improvements in the methodology. The national case studies used a variety of nuclear installations for the validation process as set out in Table 1.1.

Table 1.1. List of Member States that performed national case studies (NCS) and the nuclear installations considered

Member State (performing NCS)	**Nuclear installation** (used for validation of INPRO methodology)
Argentina	CAREM-X system (CAREM reactor and SIGMA fuel enrichment process).
China	High Temperature Gas-Cooled Test Reactor HTR-10.
Czech Republic	Evaluation and Comparison of Future Technologies with the special view to Molten Salt Reactors.
India	Advanced heavy water moderated reactor (AHWR) and its associated fuel cycle.
Republic of Korea	Direct Use of PWR Fuel In CANDU (DUPIC fuel cycle).
Russian Federation	Approach to an Innovative System with Sodium Fast Reactor of BN-800 Type.

It should be noted that while the national case studies were based on specific nuclear installations, they did not present an actual assessment of the installation but rather were used to test and validate the INPRO methodology.

The individual case studies covered several aspects of nuclear energy as described Table 1.2.

Table 1.2. List of individuals who performed individual case studies (ICS) and the topics considered in the case study

Author/ institution / country	**Topics** (covered by ICS)
SUBBOTIN, S. / RRC Kurchatov Institute/ Russian Federation.	Assessing and Defining the Direction of Enhancement of the Existing INPRO Methodology for its Applicability for Evaluation of Nuclear Power Systems with Small-Sized Reactor Units.
KOROVIN, Y. / Obninsk State University for Nuclear Power Engineering/ Russian Federation.	Assessing and Defining the Direction of Enhancement of the Existing INPRO Methodology for its Applicability in Future for Assessing Different Types of Non Carbon Energy Systems, including ADS, Fusion, and Renewables.
GAGARINSKY, A. Y. / RRC Kurchatov Institute/ Russian Federation.	Assessing and Defining the Direction of Enhancement of the Existing INPRO Methodology for its Applicability for Assessing Global and/or Regional Nuclear Power Systems that are Based on the Use of Innovative Technologies in Combination with International Fuel Cycle Centres.
TSURIKOV, D. / RRC Kurchatov Institute/ Russian Federation.	Applicability of the Existing INPRO Methodology for Assessing Multi-Product Nuclear Energy Systems.
TSIBULSKY, V. / RRC Kurchatov Institute/ Russian Federation.	The Interactive Model for Quantitative Assessment of Nuclear Energy System Key Indicators.
WIESENFELD, B. / BWM Conseil/ France.	Verification and Upgrading of the INPRO Methodology through Performing Assessment and Analysis for a Variety of Systems with Fast Neutron Spectrum.
RAJ, B. / Indira Ghandi Center for Atomic Research/ India.	International Fuel Cycle and the Option of Closed Fuel Cycle with Fast Breeder Reactors.
CIRIMELLO, R., BERGALLO, P., CNEA, Argentina.	Autonomous Nuclear fuel cycle.

The case studies used a common reporting structure (see details in Ref. [1-2], Section 5.5), namely:

- Brief description of the nuclear system assessed;
- General comments on the INPRO methodology; and
- Particular comments on each Basic Principle, User Requirement and Criterion.

The case studies provided many valuable recommendations to improve the INPRO methodology as it was described in TECDOC-1362. On request from Member States, the full text of the case studies can be provided by IAEA on a CD.

The main changes, in comparison to the TECDOC-1362, are summarized in the next section.

1.7. Main changes compared with IAEA-TECDOC-1362

Based on the case studies discussed above and the output from several consultancy meetings involving stakeholders in nuclear energy, such as regulators, industry, etc. this report has been written as a sequel to Ref. [1-2]. It differs from Ref. [1-2] as follows:

- A new chapter called INPRO and the concept of sustainability has been added, setting out the general concept of sustainability that provides the impetus and framework for INPRO;
- The chapter on method for assessment has been restructured and updated by introducing a separate treatment of uncertainties, defining three types of assessments and several possibilities for aggregation of judgements and options to handle near term, medium and long-term targets of RD&D;
- The basic principles (BP), in the chapters on economics, waste management, proliferation resistance, and safety of nuclear installations have been reformulated and reduced to eliminate redundancy, and to increase the coherence between the BP and the associated user requirements (UR);
- The explanations of terms used in and the background of BP, UR and criteria (CR) have been expanded;
- The capability of the methodology to assess fuel cycle facilities (other than the reactor) has been improved;
- BP, UR and CR dealing with infrastructure have been introduced into the chapter that was originally called Cross cutting issues, and the chapter has been re-titled National, Regional and International Infrastructure; and
- A chapter describing the available tools for modelling the future energy demand and supply on a national, regional and global basis has been added.

In the future, the revised set of BP, UR and Criteria should be used and not those set out in Ref. [1-2].

1.8. Outline of the report

In the following a short overview on the content of the following chapters is provided.

Chapter 2 describes the historic development of the concept of sustainable development. It elaborates the role of energy supply in this concept and links the INPRO methodology to the targets of sustainability.

Chapter 3 explains the main terms used by INPRO and the procedure for making a judgement on the capabilities of a single (or more than one) nuclear energy system. Additionally, the treatment of uncertainties in a qualitative form is presented and the stages in the nuclear development cycle are set out. Three types of assessments are discussed.

Chapter 4 defines the BP, UR and CR related to the cost of energy to the consumer and to the demands of possible investors in nuclear energy projects that have to be fulfilled by a nuclear energy system for it to be sustainable. A section extends the discussion of the development cycle introduced in the chapter on Method for Assessment.

Chapter 5 defines the requirements for a nuclear energy system to be sufficiently safe to achieve the corresponding sustainability target. The overall approach is an enhancement of the defence-in-depth concept, including, as appropriate, an increased use of inherent safety characteristics and passive systems.

Chapter 6 deals with environmental stressors and their impact on the environment using a holistic approach. Additionally, requirements for the sufficiency of resources and their efficient use are defined.

Chapter 7 defines the requirements for managing radioactive wastes in a holistic and sustainable manner.

Chapter 8 sets out the requirements to achieve a sufficient level of resistance against diversion of nuclear material, emphasizing the need for an optimised combination of intrinsic features and extrinsic measures.

Chapter 9 provides BP, UR and CR for the infrastructure necessary to deploy and operate nuclear facilities with an emphasis on the needs of developing countries. It further elaborates possibilities of changes in the international nuclear society that would facilitate the deployment of nuclear facilities in the future.

Chapter 10 describes the result of ongoing activities to develop suitable computer codes that can be used to explore scenarios relevant to the deployment of nuclear energy systems in the future taking into account the INPRO requirements for sustainable development.

Chapter 11 summarizes the main results of INPRO Phase 1B (1st part) and provides an outlook of what INPRO can be expected to achieve in the following phases.

References to Chapter 1

[1-1] VELIKHOV, E.P., "Development of nuclear power, 10 points", International Conference on Innovative Technologies for Nuclear Fuel Cycles and Nuclear Power, 23–26 June 2003, IAEA, Vienna (2003).

[1-2] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Evaluation of Innovative Nuclear Reactors and Fuel Cycles, Report of Phase 1A of INPRO, IAEA-TECDOC-1362, Vienna (2003).

CHAPTER 2
INPRO AND THE CONCEPT OF SUSTAINABILITY

2.1. Introduction

In 1987 the Brundtland Report [2-1], Our Common Future, alerted the world to the urgency of making progress toward economic development that could be sustained without depleting natural resources or harming the environment. Written by an international group of politicians, civil servants and experts on the environment and development, the report defined sustainable development, as:

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The Brundtland Report recognized that to secure global equity would require economic growth and argued that such growth could only be sustained if it was accomplished simultaneously with protecting the environment and conserving non-renewable resources. The report also recognised that achieving global equity and sustainable growth would require technological and social change. I.e. developing nations must be allowed to meet their basic needs of employment, food, energy, water and sanitation but the environment and the world's resource base should be conserved by gradually changing the ways in which one develops and uses technologies.

Agenda 21 [2-2], established at the 1992 United Nations Conference on Environment and Development, the "Earth Summit", in Rio de Janeiro, Brazil, provides the blueprint for achieving development in the 21st century that is socially, environmentally, and economically sustainable. It addresses social and environmental problems in a number of areas, including air pollution, deforestation, loss of biodiversity, health, overpopulation, poverty, energy consumption, waste production and transport issues. Governments, non-governmental organizations (NGOs), industry and the general public are all encouraged to participate in implementing Agenda 21. Nations that have pledged to participate are monitored by the International Commission on Sustainable Development, and are encouraged to promote Agenda 21 at the local and regional levels within their own countries.

The June 1997 Special Session of the UN General Assembly, convened to review progress on Agenda 21, emphasized that sustainable patterns of energy production, distribution, and use are crucial to continued improvements in the quality of life. It also declared that the ninth session of the United Nations Commission on Sustainable Development (CSD-9), in 2001, should focus on issues related to energy and the atmosphere and to energy and transport. To inform the discussion and debate, the United Nations Development Programme (UNDP), United Nations Department of Economic and Social Affairs (UNDESA), and World Energy Council (WEC) initiated the World Energy Assessment [2-3] in late 1998.

The report of the World Energy Assessment, subtitled "Energy and the challenge of sustainability", analyses the social, economic, environmental, and security issues linked to energy supply and use, and assesses options for sustainability in each area. It emphasizes the central role of energy in achieving the interrelated economic, social, and environmental aims of sustainable human development. The report affirms that it is possible to create energy systems that lead to a more equitable, environmentally sound, and economically viable world.

At the Ninth Session of the Commission on Sustainable Development (CSD-9) held in 2001 in New York, USA, energy was a major theme and the initial work on energy indicators, undertaken by the IAEA in co-operation with the IEA, UNDESA and other international and national organizations, was presented. The goal of this effort was to produce a core set of indicators for sustainable energy development (ISED) covering the three pillars of sustainability: social, environmental, and economic. The ISED handbook [2-4], currently being finalized as a multi-agency report, covers issues reflecting decisions taken at CSD-9 and includes the identification of key energy issues such as accessibility, energy efficiency, renewable energy, advanced fossil fuel technologies, nuclear energy technologies, rural energy and transport.

Energy, within the context of sustainable development, was revisited at the World Summit on Sustainable Development (WSSD) held in Johannesburg in 2002. The international community declared access to energy to be important in facilitating the Millennium Development Goal of halving the proportion of people in poverty by 2015. It was decided to assist and facilitate access to energy by the poor in developing countries taking into account the instrumental role of developing national policies on energy for sustainable development. The ISED handbook is expected to be useful in assessing current energy trends and policies and providing information in a format that facilitates decision-making efforts at the national level.

An important document related to the issue of sustainability is the Kyoto Protocol [2-5] to the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1997. It calls for greenhouse gas (GHG) emissions to be reduced by 2008-2012. A comprehensive analysis of GHG emissions from different electricity generation chains shows that nuclear power is one of the least carbon intensive generation technologies. Thus, the construction of new nuclear power plants will contribute to meeting the Kyoto targets of those countries that choose to continue with the nuclear option as a domestic energy supply source. While the Kyoto Protocol does not prohibit the benefit that nuclear energy brings in terms of reducing carbon dioxide emissions, it, none-the-less, incorporates conditions that effectively exclude nuclear energy as an option for implementation under two of the three "flexibility mechanisms" that can be used, in addition to domestic action, by parties to the UNFCCC to meet their commitments. (The three flexibility mechanisms are: projects implemented jointly, the clean development mechanism, and trading of emission reduction units. Restrictions on nuclear energy do not apply to emission trading.) The exclusion of nuclear energy from two of the three flexibility mechanisms appears to be driven by the opinion of some members of the UNFCCC that nuclear energy is unsustainable, because of issues related to safety, nuclear waste disposal, and proliferation of nuclear weapons [2-6]. INPRO specifically addresses these issues of concern, as well as other issues (economics, infrastructure and environment) relevant to sustainability.

2.2. Dimensions of sustainability

In a broad sense the aim of sustainable development is to achieve equity within and across countries as well as across generations, by integrating growth, environmental protection and social welfare [2-7]. Thus, sustainability can be considered from four related but different viewpoints or dimensions: economic, environment, social, and institutional. The key challenge for sustainable energy development is to address these four dimensions in a balanced way, taking advantage of their interactions and making relevant tradeoffs whenever needed.

The economic dimension encompasses the requirements for strong and durable economic growth, such as preserving financial stability and a low and stable inflation rate. The key issues for sustainable energy supply are: economic performance, energy consumption, energy intensities, and efficiency of energy distribution and use.

The environmental dimension requires eliminating/reducing negative externalities that are responsible for the depletion of natural resources and environmental degradation. The following topics can be considered within the environmental dimension: climate change, air pollution, water pollution, solid and radioactive waste, energy resources, land use and deforestation.

Social sustainability emphasizes the importance of equity among various groups of population, of adaptability to major demographic changes, of stability in social and cultural systems, of democratic participation in decision-making, etc. The main topics of interest within the social dimension are: energy affordability, accessibility and disparity, employment generation, public participation in decision making, energy security, proliferation threat and the safety of the energy system.

A fourth consideration or dimension in attaining sustainability is the development of an institutional infrastructure, since appropriate legal and policy instruments are required to encourage and implement sustainable development. The institutional dimension includes the following topics: national sustainable energy strategy, international cooperation on energy, energy legislation and regulatory framework, energy science and technology, and energy accident preparedness and response measures.

2.3. Role of energy supply in sustainability concept

Energy plays an important role in each dimension of sustainable development: economic, social, environmental and institutional. Energy services underpin economic activity. They enable basic needs, such as food and shelter, to be met, and they contribute to social development by improving education and public health. Access to modern energy services can also be environmentally beneficial, for example, by reducing deforestation and decreasing pollution caused by inefficient appliances and processes. But there can be conflicts: growing energy use can increase absolute levels of pollution and speed up resource depletion. Sustainable development is about finding the right trade-offs.

Energy remains a strategic commodity, and ensuring its availability and security of continuous and stable supply is one important aspect of governments' ultimate responsibility for national security and economic growth. National circumstances and policies will determine the mix of fuels necessary to contribute to the world's collective energy security and global economic growth, and to address the challenge of achieving sustainable development.

In Sections 2.3 and 4.1 of Ref. [2-8] scenarios for energy demand and supply in the 21st century were discussed. These discussions used the Special Report on Emission Scenarios (SRES), commissioned in 1996 by the Inter-governmental Panel on Climate Change (IPCC). Global primary energy use grows, between 2000 and 2050, in all SRES scenarios with a median increase by a factor of 2.5; electricity demand grows with a median increase by a factor of 4.7. Figures 2.1 and 2.2 illustrate the range of future primary energy demand and the range of nuclear power capacity as a function of time in the SRES scenarios.

Most of the scenarios include substantial increases in the use of nuclear power. Renewable energy sources (e.g. hydro, wind, solar, biomass) are also predicted, in the SRES scenarios, to increase considerably their share of global energy supply.

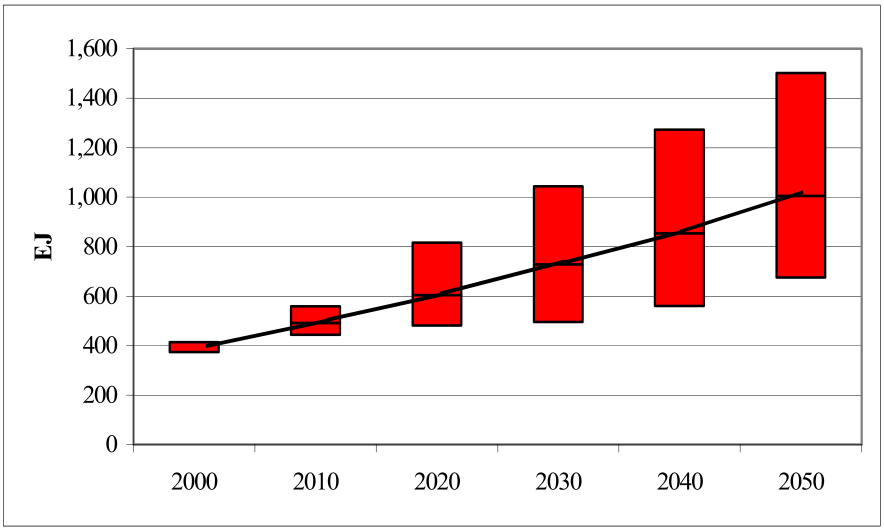

Figure 2.1. Range of future primary energy demand in SRES scenarios, 2000-2050. Solid line represents median. Source: IPCC, 2000.

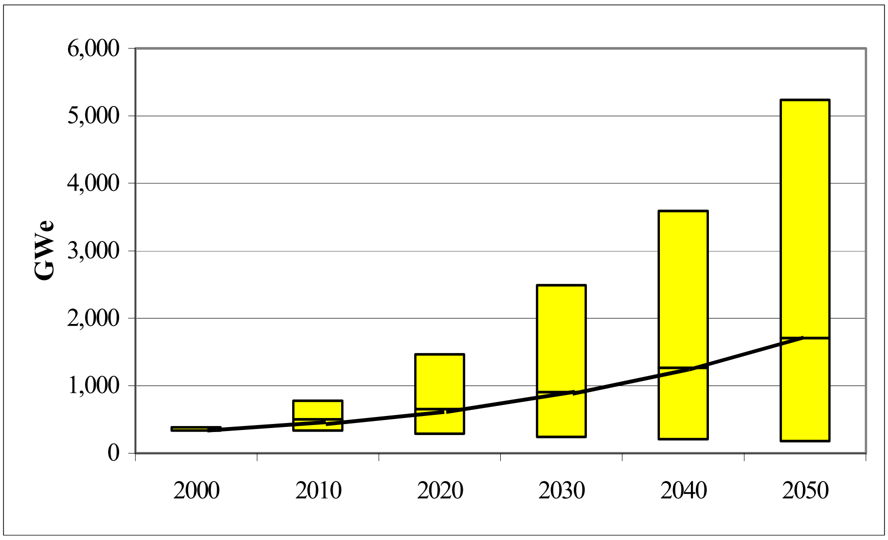

Figure 2.2. Range of nuclear power in SRES scenarios, 2000-2050. Solid line represents median. Source: IPCC, 2000.

On the other hand, a number of factors, such as land use requirements and discontinuous availability, may ultimately limit the potential of some renewables.

2.4. INPRO and the general concept of sustainability

As stated in the introductory section of this report, one of the main objectives of INPRO is to:

Help to ensure that nuclear energy is available to contribute in fulfilling, in a sustainable manner, energy needs in the 21st century.

Thus, INPRO is very much concerned with the contributing of INS to sustainable development and, in particular, to sustainable energy supply that, as discussed above, is a key aspect of sustainable development. To address the specific issues relevant to the development and deployment of INS for sustainable energy development, within the general framework of the four dimensions of sustainability, INPRO established a number of task groups to develop a method for assessing INS in the following areas: economics, environment, safety, waste management, proliferation resistance and infrastructure. As discussed in detail in the following section, Method of Assessment, INPRO defined, in Phase 1A of the project, a set of Basic Principles, User Requirements and related Criteria in each of these areas. By focusing on each of these specific areas in turn, the INPRO methodology ensures that a given INS is assessed in sufficient detail to establish with confidence the potential of the INS to contribute to sustainable energy development and hence to meeting the general objective of sustainability. In addition, the results of such an assessment provide an important input for defining the strategy and the necessary short, medium and long term RD&D plans to support the development and deployment of a given system or component thereof.

In this regard, INPRO recognizes that the development and deployment of INSs to reach the goals of sustainability will occur over time and indeed the time frame for INPRO extends to the end of the 21st century. The anticipated future demand for energy, as a function of time, the estimates of energy resources to meet this demand and proven and predicted capabilities of different energy sources can all be expected to change with time, on a national, regional and global basis. Thus, it needs to be recognized that the INPRO method of assessment for INS is not a static process to be carried out at single point in time but rather it is a dynamic process that needs to be updated as development proceeds and as boundary conditions change and the requirements for sustainable development evolve. Such assessments coupled with dynamic simulations of future scenarios (See Chapters 3 and 10) performed on a national and regional basis should identify and foster complementarity and synergism among different national approaches to INS and broader international cooperation.

The link between the general concept of sustainability with its four dimensions and the INPRO subject areas is illustrated in Figure 2.3 and is discussed in more detail in the following.

In this report the dimension of economics is addressed primarily in Chapter 4, Economics. The INPRO Economics Basic Principle (BP) requires that nuclear energy and related products and services be affordable and available. To fulfill this BP the related INPRO User Requirements (UR) ask for: Competitive costs of energy supplied by INS in comparison with alternative energy sources; availability of funds to develop and deploy INS; acceptable investment risk; and capability to adapt an INS to meet different market conditions. By requiring that these factors be analyzed, the INPRO methodology ensures that economics is considered when considering all other INPRO subject areas and implicitly requires that a cost benefit analysis is done for all measures that are needed to fulfill an INPRO requirement in any of the INPRO areas. As well, the question of energy security and employment generation, aspects that need to be addressed in the overall context of sustainability, need to be considered when comparing costs of alternate sources of energy. Some economic aspects are dealt with explicitly in other parts of the areas, e.g., resource utilization and efficiency of energy supply, are dealt with in Chapter 6, Environment.

The environmental dimension of sustainable energy development is treated in Chapter 6, Environment, and Chapter 7, Waste Management, of this report. The first INPRO Environmental BP deals with the acceptability of environmental effects. The corresponding URs require that stressors are controllable and that the impact of these stressors on the environment caused by an energy system, such as pollution of air and water, etc. are limited. The second INPRO Environmental BP addresses the issue of the efficient use and availability of resources needed for an energy system to be sustainable. The INPRO BPs regarding radioactive waste ask for protection of human health and the environment, avoidance of passing undue burdens to future generations, minimization of waste, and the optimization of waste management by taking all steps into account.

The social dimension is dealt with primarily in Chapter 5, Safety of Nuclear Installations, and Chapter 8, Proliferation Resistance, in this report. The INPRO BPs related to safety ask for enhanced application of the defence-in-depth concept, an increased emphasis on inherent and passive safety features in INS, limitation of risk from radiation exposures to a level comparable to risk from other comparable industries, and sufficient RD&D related to INS for assuring an appropriate confidence level. The INPRO BPs in the area of proliferation resistance require the minimization of the possibility of misuse of nuclear material and technology through a balanced application of intrinsic and extrinsic measures in INS.

Finally, the institutional dimension, including the topic of public participation in decision-making, is covered primarily in Chapter 9, National, Regional and International Infrastructure, but some specific aspects are addressed in some of the other chapters, e.g. the institutional measures (called extrinsic measures) for achieving proliferation resistance are covered in Chapter 8, Proliferation Resistance, of this report.

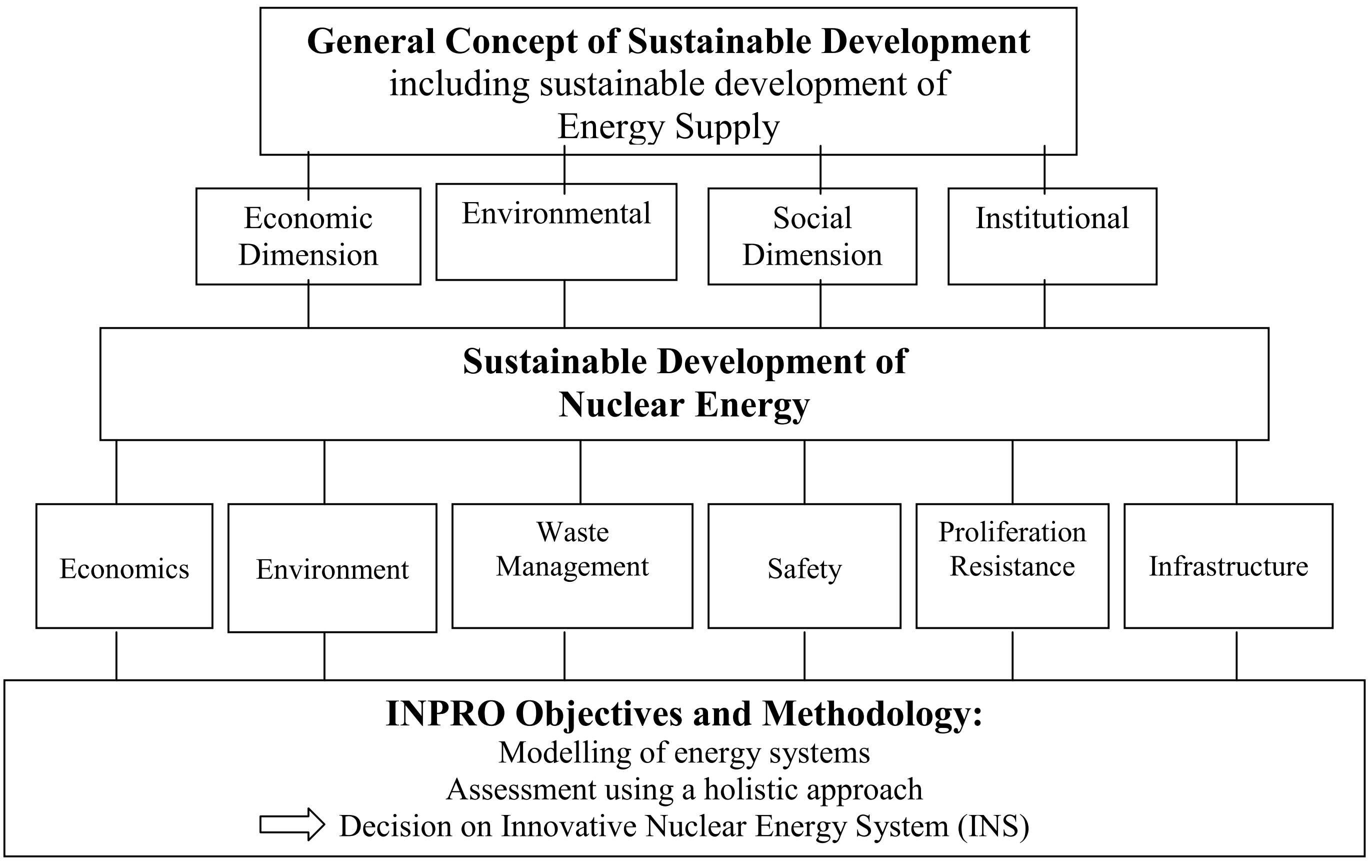

Figure 2.3. Interrelationship of UN concept of sustainability and INPRO.

2.5. Concluding remarks

Energy development is fundamental to sustainable development of the world. The overall objective of INPRO is to ensure that nuclear energy is available to make a substantial contribution to fulfilling, in a sustainable manner, the growing need for energy during the 21st century. The general concept of sustainability and considerations specific to the concept of sustainable energy have been incorporated in the INPRO Objectives and have been integrated into the INPRO methodology.

Nuclear technology has the potential to make a major contribution to sustainable energy supply. INPRO is focused on establishing specific requirements to be met by innovative nuclear energy systems if such systems are to make a major and sustainable contribution to world energy supply. While the INPRO subject areas are not aligned on a one-to-one basis with the four dimensions of sustainability set out in other UN initiatives, the structure chosen ensures that all relevant aspects of these dimensions are addressed.

As INPRO proceeds its activities will continue to benefit from and be guided by the general IAEA activities related to sustainability, e.g. ISED, and it is anticipated that the output from INPRO will represent an important contribution by the IAEA in furthering the global development of sustainable energy.

The basic principles, user requirements and criteria developed within INPRO and set out in the following chapters are designed to reflect sustainable development goals as described in the present chapter.

References to Chapter 2

[2-1] BRUNDTLAND COMMISSION, World Commission on Environment and Development, "Our Common Future", Oxford University Press, Oxford (1987).

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CHAPTER 3
METHOD FOR ASSESSMENT

3.1. Introduction

In elaborating national and international recommendations for the development of innovative nuclear energy systems (INS) there is a need for a structured and objective evaluation of options [3-1]. The INPRO method for assessment tries to answer this need by providing a tool to:

- Screen an INS (or more than one), selected by Member States on a national, regional and/or global basis, to evaluate whether it is compatible with the objective of sustainable energy development;

- Compare different INSs or components thereof, e.g., to find a preferred or optimum INS tailored to the needs of a given Member State; or to make a comparison of their capabilities on a global basis; and

- Identify research, development, and demonstration (RD&D) required to improve the performance of existing components of an INS and/or to develop new components.

The three types of assessment will be referred to as screening, comparative and RD&D assessments respectively. The INPRO methodology requires that any given INS be the subject of a screening assessment to arrive at a judgment of whether or not it is sustainable. Depending on the specific interest of the assessor, namely the individual or entity carrying out an assessment, a given INS may or may not be subject to a comparative and/or an RD&D assessment. For example, a Member State seeking to deploy a component of an INS, e.g., a reactor or a fuel fabrication facility would be expected to do a screening assessment followed by a comparative assessment of options. In the screening assessment one or more of the options may be judged not to be sustainable and be dropped from further consideration. The comparative assessment would then be carried out to assist the Member State in selecting a preferred option to meet its requirements and constraints. RD&D assessments are expected to be of most interest to developers and proponents/investors of INS components and systems. Again the starting point would be expected to be a screening assessment to ensure that the component is compatible with the objective of sustainable energy supply. If it were not, the screening assessment could be used to define RD&D targets to bring the component into compliance. If the component passed the screening assessment, the assessor might then proceed to an RD&D assessment to set RD&D targets or he might first do a comparative assessment to determine the position of his technology relative to other technologies, e.g., to assess whether technology development is warranted.

An assessor of an INS may be interested in only one component of a complete INS, such as a reactor for electricity production or for desalination, or in several components of a complete system or in a complete INS. Regardless of his specific interest, the assessor must include in the evaluation all components of the system, such as components for fuel production, waste management, etc., to achieve a holistic view and so ensure that the component(s) of interest and the corresponding overall system are sustainable (See Chapter 2, INPRO and the concept of sustainability). I.e., the INPRO method is to be applied always to a complete nuclear energy system.

It should be mentioned that an assessor — be it a MS, or a group of MS, or some other entity such as an investor in RD&D, or any other organization interested in the deployment of INS

— needs to take into account interests and views of all stakeholders in nuclear energy. The INPRO methodology has been specifically set up to facilitate doing so.

In performing an assessment, the assessor must take into account a reference energy scenario or scenarios. For example, if the assessor were focused on energy supply in his state he would take into account a national energy scenario (or perhaps a more localized scenario based on a region within his country). But a national scenario would also be expected to take into account global and/or regional considerations such as the global demand for uranium, reprocessing capacity, etc., and so would also have to use some elements of a regional or global scenario. If the assessor were interested in global energy supply as a component of sustainable development, he would necessarily utilize a broadly based scenario that takes into account various regions and country groupings to arrive at a global scenario. Such a scenario captures a best estimate evolution of energy demand in the future and depends on many factors that can be expected to change with time. As well, the development and deployment of INS will stretch out over time, during which the available mix of energy sources can be expected to change. Further, as conditions change the requirements that an INS is expected to fulfil may also change. Therefore, it is necessary to re-evaluate the role played by a given INS and/or components thereof in meeting national, regional and global energy demand on a periodic basis using dynamic (time-dependent) modelling and especially whenever circumstances and boundary conditions change significantly. Modelling tools to be used will include existing tools that have already been developed by the IAEA [3-2, 3-3, 3-4] and those under development by INPRO and others (see Chapter 10, Modelling).

The assessment method for screening assessments was tested and validated in the second INPRO step (first part of Phase 1B). The development of the method for comparative assessments is well advanced but not yet complete, while the development of the RD&D assessment method is at a relatively early stage.

3.2. Basic features and terminology

The INPRO method relies on an assessment of how well an INS complies with:

- Basic principles (BP);
- User requirements (UR); and
- Criteria, each consisting of an indicator and an acceptance limit (CR, IN and AL).

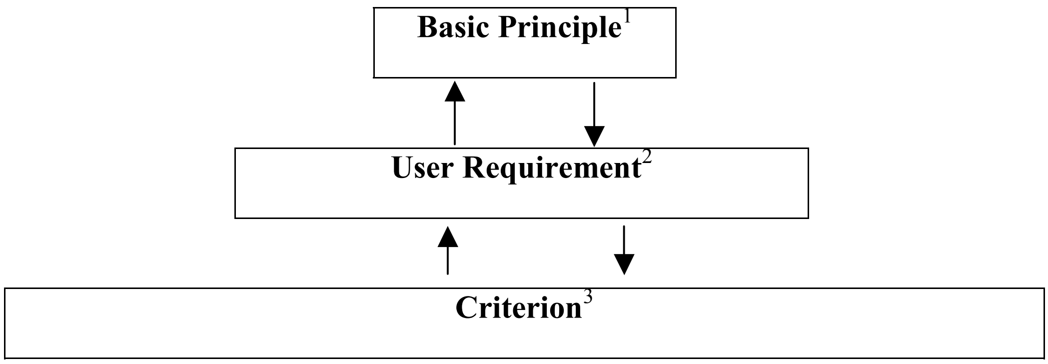
Because documents of interest to INPRO often use different terminology, even when discussing topics of a very general nature, e.g., goals, objectives, principles, fundamentals, rules, etc. using different orders of precedence, a common definition of these and other important terms is necessary. Therefore, the important terms used throughout this report and their relationship are described below.

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- related products, e.g., steam, hydrogen, desalination), reprocessing of nuclear fuel (if a closed nuclear fuel cycle is used), and facilities for related materials management activities, including storage, 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 actinides and fission products) and associated fuel cycles (e.g. U, U–Pu, Th, U–Pu–Th cycle) may 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) as part of the national and international infrastructure needed to deploy and 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, centralized fuel production and waste treatment facilities.

Innovative Nuclear Energy Systems (INS), in INPRO, encompasses all 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 of nuclear facilities. An evolutionary design [3-5] 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 [3-5] is an advanced design, which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. These systems may 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 [3-6] to [3-11].

Given the conservative nature of utilities and the desire of many Member States to use proven technology, the process by which a radical conceptual change is adopted is a topic of considerable importance. It is discussed, but only briefly, in the subsection below dealing with uncertainties and again in the section on Economics, also briefly.

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



Note: the arrows indicates the direction of derivation (downwards) and fulfilment (upwards)

Figure 3.1. INPRO hierarchy of demands on innovative designs of nuclear energy systems.

[1] Corresponds to the term Goal in Generation IV International Forum (GIF).
[2] Corresponds to the term Criterion in GIF.
[3] Corresponds to the term Metrics in GIF.

The highest level in the INPRO structure is a **Basic Principle (BP),** which is a statement of a general rule that provides broad guidance for the development of an INS (or design feature). All basic principles shall be taken into account in all areas considered within INPRO (economics, environment, safety, waste management, infrastructure, and proliferation resistance). An example of a basic principle, taken from the INPRO area of safety, is that an *INS shall incorporate enhanced defence-in-depth as a part of its fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations.* 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 and evolutionary 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, RD&D organizations, designers, power generators and utilities;
- Decision makers, such as national governments, legislative bodies, regulatory bodies, state local organizations and authorities, and their advisors and stakeholders including non-governmental organizations (NGO);
- The end users of energy (public, industry, etc.);
- Interested mass media; and
- Informed international organizations (e.g., IAEA, OECD-IEA, OECD-NEA, etc.).

By establishing user requirements that encompass such a broad constituency, INPRO seeks to ensure that an INPRO assessment takes into account the interests and views of all stakeholders. A number of the stakeholders listed above, or their advisors, would be expected to carry out INPRO assessments or require that the results of such assessments be made available to them, particularly those listed in the first and second bullets. These groups comprise the parties involved in energy planning, supply, and the siting and licensing of facilities. An assessment requires the participation of individuals with expertise in the INPRO areas and with adequate knowledge of the nuclear facilities comprising the INS to enable a holistic assessment. The results of such assessments should be available to all stakeholders, not only to nuclear experts. But, the format and language in which the results are communicated to non-nuclear experts has to meet the needs of the stakeholders and doing so represents a challenge that is yet to be addressed.

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 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 *a major release of radioactivity from an installation of an INS should be prevented for all practical* *purposes so that INS installations would not need relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility used for similar purpose.*

Finally, a **Criterion (CR)** (or more than one) is required to determine whether and how well a given user requirement is being met. A criterion consists of an **Indicator (IN)** and an **Acceptance Limit (AL)**. Indicators may be based on a single parameter, on an aggregate variable, or on a status statement.

One important aspect of the INPRO assessment method is the mathematical classification of the indicators. Three types of indicators are distinguished within the INPRO method:

1. **Real Indicator**: An experimentally verified or calculated value of one parameter varying continuously within the limits of a range. This indicator reflects a property of an INS to be assessed and may be used as the argument of an assessment function, either directly or after weighting, as discussed further in Section 3.4.
   Examples: The numerical economic, safety and environmental parameters, representing the bulk of quantitative information about the system.

2. **Integer Indicator**: An integer number assigned to each of the components of a ranked list of items.
   Examples: The number of safety barriers maintained after severe accident.

3. **Logical Indicator**: A variable with only two possible values, 0 and 1, which in the assessment procedure is interpreted as "yes" and "no" (acceptance or rejection). Logical indicators are usually associated with some necessary features of the INS and are only used for screening, not as metrics. Example: A question in a user requirement such as "*Is the safety concept defined?*".

In addition to the mathematical classification of indicators, another type of indicator, a so-called **Key Indicator** (KI), is discussed in Section 3.5, RD&D Assessments.

An **Acceptance Limit** (AL) 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.). As mentioned in the introduction to this chapter, the boundary conditions for an INS, as assumed in a particular scenario, are expected to change with time. Thus it is foreseeable that some ALs might also change with time.

An example of a criterion in the area of safety (related to the example of an user requirement in the preceding paragraph) could be the following: *The calculated frequency of major release of radioactive materials to the environment should be less than 10^{-6} per unit per year or be excluded by design.* In this case the indicator is a real value and represents the probability for a large release and the acceptance limit is the given value of the expected frequency of occurrence of 10^{-6} per unit per year. For the example (a question) of the logical indicator given above, the acceptance limit becomes the answer "yes" (an answer "no" would mean the INS is not acceptable).

The relationship between a basic principle, a user requirement and a criterion, indicated by the arrows in Figure 3.1, is as follows:

- The fulfilment of a criterion (criteria) for an INS is confirmed by the indicator(s) complying with the acceptance limit(s);

- The fulfilment of an user requirement(s) is confirmed by the fulfilment of the corresponding criterion (criteria) (bottoms up approach);

- The fulfilment of a basic principle is achieved by meeting the related user requirement(s);

- The logical sequence of the formulation of demands starts with the basic principles, followed by the derivation of user requirements and finally of the corresponding criteria (top down approach).

BPs, URs and CRs have been developed for the following areas of an INS:

- Economics (Chapter 4);
- Safety of Nuclear Installations (Chapter 5);
- Environment (Chapter 6);
- Waste Management (Chapter 7);
- Proliferation Resistance (Chapter 8); and
- National, regional and international Infrastructure (Chapter 9).

BPs, URs, and criteria are broadly based. They represent an idealization of what is desirable taking into account both national and regional trends and what is likely to be technologically achievable. It is difficult to factor in step changes in technology, so IPRO has extrapolated current trends. Member States are free to and, indeed, in a number of cases, e.g. economics and infrastructure, should specify country or region[4] or technology specific criteria and user requirements.

All INS shall meet the basic principles. 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 INS is so large and their characteristics are so varied; and
- Nuclear power will be a mix of existing, evolutionary, and innovative designs of components of an INS so it is not practical that all user requirements and criteria should apply to all types.

In a number of cases acceptance limits are based on a comparison of the value of an indicator for an INS with the value for an "existing design." The term "existing design " shall be understood to mean state-of-the-art designs as of 2004. As well, acceptance limits are sometimes defined in terms of compliance with "current regulations." The term, "current regulations" shall be understood to mean regulations in effect at the time that an assessment is performed.

The concept of **ALARP** (as low as reasonable practicable, economic and social factors taken into account) is used to define an acceptance limit for several indicators in different areas of INPRO, e.g., environment, waste management, etc. The concept is illustrated in the following Figure 3.2.

[4] In this publication the term region is used in two different ways. Region can mean a geographic region such as a region within a country, or a region comprising several countries located within a given geographical area. It can also mean a group of countries having similar interests and capabilities even though the countries may be located in different geographical regions of the world.

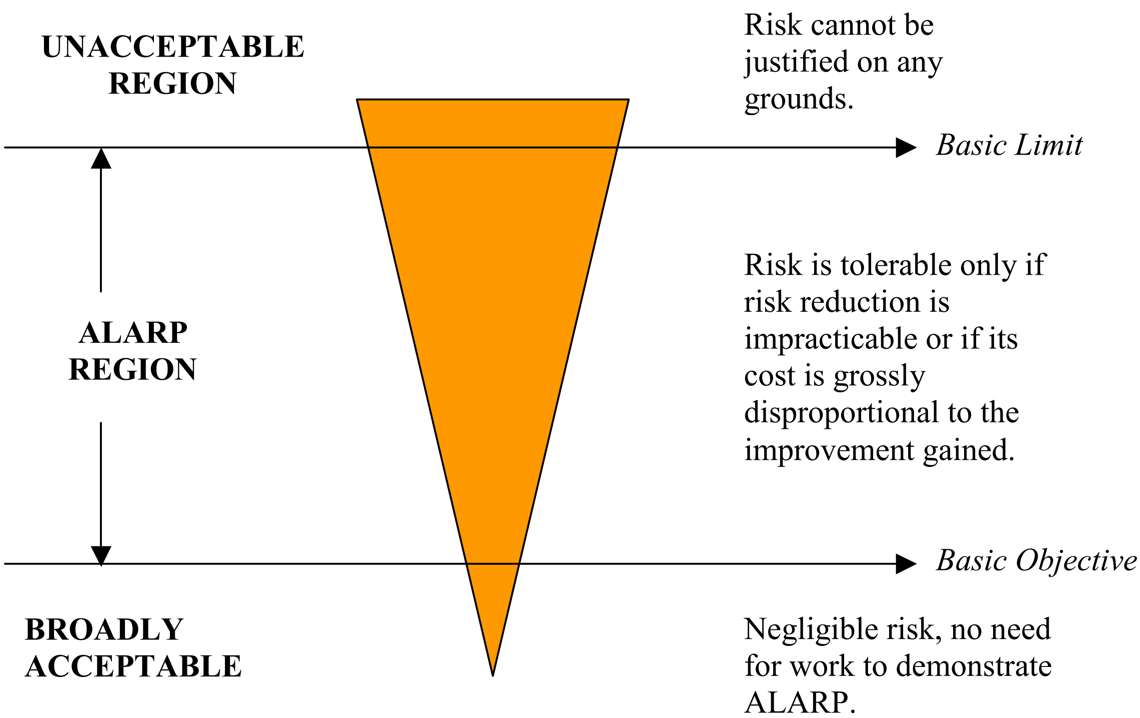


Figure 3.2. Illustration of the concept of ALARP.

As shown above, the risk (symbolized by the triangle) is divided into three regions: a broadly acceptable region, a tolerable region where a process for ALARP has to be used, and an unacceptably region.

As a first step of the ALARP concept to be applied within INPRO, the boundary values of these three regions have to be defined, such as the boundary between the tolerable and the unacceptable region, sometimes called a “basic limit”, and the boundary between the tolerable and broadly accepted region, sometimes called a “basic objective”. The next step is to confirm that the value of the indicator of an INS is within the ALARP region that is below the “basic limit”. The third step is to perform an optimization analysis to confirm that all measures to reduce the specific risk have been taken into account up to a level where the costs for these measures become “grossly disproportional” to the benefit gained. It is important to note that, in case the indicator of an INS has a value in the broadly accepted region below the boundary “basic objective”, no further work is necessary to be performed to fulfil the ALARP concept.

In the following, the three different types of INPRO assessments are described.

3.3. Screening assessment

The judgement procedure for assessing the capability of an INS to comply with the INPRO hierarchy of demands starts with the evaluation of the INPRO criteria (bottoms up approach). It is assumed that, if the criteria are fulfilled, the corresponding user requirements are fulfilled, as well as the basic principles. Or, in other words, the criteria are both necessary and sufficient to fulfil the corresponding UR, and similar for the UR and BP.

As a prerequisite for the performance of an assessment, the values of the indicators of the INS installation and, in general, of the corresponding acceptance limits have to be determined by the assessor. In the situation where a new concept of an INS is being assessed, the value to be used for a given indicator should be the best estimate value, (most likely) which will be achieved when the component of the INS is commercially deployed. It is recognized that, for new concepts, such estimates will be uncertain but such uncertainties are not taken into account in a screening assessment to avoid biasing a screening assessment against promising new concepts in favour of more mature systems. Uncertainties do need to be considered when performing comparative and RD&D assessments.

Uncertainties are expected to be reduced during the development process, (see Section 3.4, Comparative assessment, and Chapter 4, Economics) and as development proceeds the best estimate values of the indicators need to be tracked to ensure that they continue to meet acceptance limits. Should a value fail to do so, corrective action would be required. It is also recognized that after a system is commercially deployed, and the value of a given indicator is known, the design may be subsequently enhanced resulting in changes (improvements) in the values of selected indicators. Such enhancements are normally undertaken to maintain or improve the competitive position of a system or component and comparative and RD&D assessments would be expected to be used as a tool in identifying desirable enhancements and in setting development targets.

For some acceptance limits, INPRO has proposed values in this report, e.g., in the area of safety where the limits should be internationally accepted and applied. (In the long term, it is expected that internationally agreed acceptance limits would be proposed also in the areas of proliferation resistance, environment, and waste management as well as safety.) The INPRO manual [3-12], under preparation, will provide the assessor more detailed information on the selection of indicators and acceptance limits.

After determining the values of the indicator and the corresponding acceptance limit, the next task is to make a judgement on the capability, called potential in INPRO, of all components of an INS to fulfil a specific criterion. If the value of an indicator is acceptable, the judgment is that the INS has potential to fulfil the specific criterion. Otherwise the judgement becomes “No potential” for this criterion. This task is to be repeated for all criteria of a user requirement, then for all user requirements of a basic principle, then for an INPRO area (e.g. safety), and finally for all INPRO areas. The rationale for each judgement is to be documented during the assessment. As already indicated, it is recognized that in addition to the criteria developed by INPRO, an assessor may, indeed is expected to, specify and use additional criteria (or even user requirements, as illustrated in Table 3.1) in the course of an assessment to cover country or region specific issues or to take into account changing circumstances and boundary conditions. As assessors define and use such criteria it is expected that the INPRO criteria will be modified as a result of feedback.

Table 3.1 shows a format that could be used to assist in forming and summarizing a judgement of the potential, i.e., capability, of an INS to fulfil the INPRO criteria.

Table 3.1. Example for stepwise use of the INPRO method of assessment

Basic Principles BP	User Requirements UR		Criteria CR				INS value of Indicator	Judgement of Potential (capability)	Rationale for judgement
			Indicators IN		Acceptance Limits AL				
BP1	UR1.1		IN1.1		AL1.1	AL1.1 by MS	X1	P	X1<AL1.1
	UR1.n		IN1.n	IN1.n by MS	AL1.n	AL1.n by MS	Xn		
BP2	UR2.1		IN2.1		AL2.1		X2	NP	X2>AL2.1
	UR2.n		IN2.n		AL2.n				
BPn	URn.1		INn.1		ALn.1				
	URn.n	URn.n by MS	INn.n		ALn.n				

The ultimate goal of the application of the INPRO method is to confirm that the INS assessed fulfils all the INPRO criteria and therefore represents a sustainable system for a Member States (or group of MS). If only one criterion (for a single component) of an INS is not fulfilled, the complete system is defined to be non-sustainable. The consequence of such a negative result of an assessment is:

- The choice of an alternative INS (or alternative component) that is capable to fulfil all INPRO requirements; or

- The recognition that the INS (component), as currently specified, is not sustainable in the long term but that it might make a useful interim contribution provided that with further development it could become sustainable; or

- The formulation of necessary RD&D to overcome the deficiency of the INS (or component thereof), assuming that the INS (or component) is otherwise attractive. This is further discussed in step 3 of the assessment method.

The output of a screening assessment is a short list of INS (components) that are potentially capable to be sustainable and/or fulfil all the needs of a Member States (or group of MS) and additionally a list of INS (component) that need RD&D to become sustainable.

3.4. Comparative assessment

3.4.1. Introduction

The INPRO method offers the possibility to compare different INS (or different designs of a component thereof) to define, for instance, an optimized system or to identify areas of competitive weakness and strength and so establish development objectives. As well some assessors may be interested in comparing an INS with an alternate energy source. If different INSs, or different designs of a component of an INS, or different energy sources are to be compared, the judgement process has to be extended to distinguish the relative potential (capability) of the systems.

Normally a comparative assessment would only include an INS that had been subject to a screening assessment and had been found to be sustainable, at least in principle. Having determined that an INS is sustainable, an assessor may want to compare different systems/components in detail across the board — all areas, all basic principles, all user requirements, and all criteria — or the assessor may wish to focus on one or a few areas of particular interest such as economic competitiveness, environmental performance, recognizing that the screening assessment has confirmed that the INS meets expectations in the other areas. An assessor may even be interested primarily in a few specific indicators of prime importance to him, i.e. key indicators.

In making comparisons the level of detail employed and the sophistication used will depend on the circumstances and the needs of the assessor, which, in turn, depend on the rationale for carrying out the assessment, i.e. the objectives. In what follows, some examples of approaches that may be used are outlined. The examples assume that comparisons are comprehensive but of course they may be more restrictive as discussed above. The simplest approaches can be said to be broadly available, the more complex approaches represent approaches that might be developed further depending on the needs and interests of INPRO members.

3.4.2. Judgement on the capability of INS

When performing a comparative assessment, rather than simply deciding whether a given indicator meets the acceptance limit (as done in a screening assessment) and so satisfies the criterion (has potential) or it does not meet the criteria (no potential), the value of the indicator relative to the acceptance limit has to be taken into account. The better the actual value of the indicator relative to the acceptance limit, the greater the “Relative potential” or capability of the INS (or components thereof) for the given criterion (and for the associated UR and BP).

This extended judgement is primarily applicable for criteria with numerical values of the indicator and acceptance limit. By performing such comparative assessments for several INSs (or different designs of a component thereof), a comparison of the relative capability (or potential) of different INSs to fulfil each criterion can be established. Figure 3.3 illustrates one method of presenting such a comparative assessment of two INS.

In Figure 3.3 it may be noted that since, in the example, INS No. 1 does not meet the acceptance limit for the nth indicator, the judgement is that it is not sustainable in the long term. But, if, for a given assessor, indicators IN-1 and IN-2 were particularly important, the outcome of such a comparison could be a decision to look for ways/developments that would enable IN-n to meet the acceptance limit. These three indicators might then become “Key Indicators” to be tracked during development to ensure that the relative advantage of INS No.1 in indicators IN-1 and IN-2 is maintained or even improved while the performance of INS No.1 for indicator IN-n is improved to meet the acceptance limit.

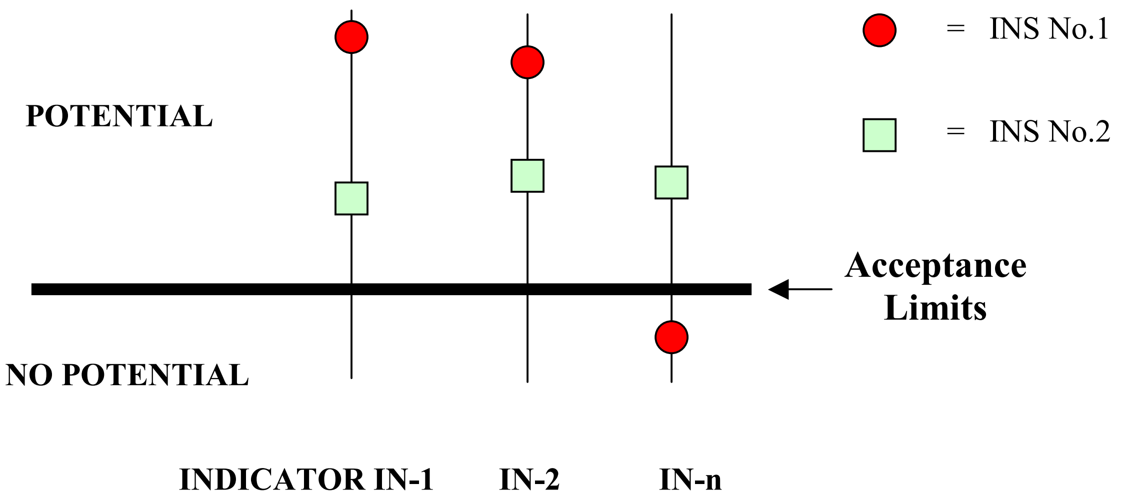


Figure 3.3. Illustration of a comparative assessment of two INS (vertical axes have different scales for each indicator).

3.4.3. Judgement on the maturity of INS

In addition to the assessment of the capability of an INS to fulfil criteria, (and then user requirements and basic principles) the uncertainty of the judgement arrived at in the assessment should also be specified when making a comparative assessment. The overall level of uncertainty of the judgement is directly related to the level of maturity of the INS or a component thereof (as defined in Table 3.2). Further, as noted in Section 4.5, the higher the uncertainty, the greater are the risks that development goals will not be fully met and that the costs of development will exceed estimated costs.

Table 3.3 indicates in more detail the effort required to advance an innovation from the pre-conceptual stage to a commercially proven stage. This table should be used to determine the level of uncertainty of an INS (or component thereof) but would not usually be applicable to an individual criterion. Nevertheless, where the judgement of a criterion is close to an acceptance limit it may be worthwhile to look at the associated uncertainty.

Table 3.2. Classification of maturity and corresponding uncertainty of a judgement on the capabilities of a complete INS (or a component thereof)

Stage of development of an INS (or a component thereof)	**Level of maturity of an INS (or component)**	**Level of Uncertainty of Judgement**
No theoretical or experimental evidence exists that any of the Criteria cannot be met by the INS, due to some physical, technological or other limitation, which cannot be overcome by later technology developments.	Pre-Conceptual	Very High
Most important (Not all) components of the INS have been theoretically demonstrated or experimentally verified, and there is theoretical evidence that this INS could meet all the Criteria.	Conceptual Feasibility Established	High
All components of the INS have been theoretically demonstrated and, where necessary, experimentally verified and meet the Criteria.	Feasibility Demonstrated	Moderate
All components of the INS have been designed in enough detail to prepare a bid. If needed, a Pilot Plant (reduced size) was built and is operating successfully.	Developed and Demonstrated	Low
First of a kind plant (full size) built and operating.	Commercially Proven	Lower
Series of plants built and operated.	Full Commercial Exploitation	Lowest

Table 3.3. Definition of maturity level of an INS (or component thereof) based on factors

Maturity Level	Factors (Minimum requirements necessary for a given Maturity Level)			
	R&D scale	**Verification & Testing performed**	**Available Technical Documentation**	**Status of Regulator's Approval**
Pre-Conceptual	Theoretical considerations or evaluations and numerical calculations done by an individual or a small team of professionals.	None or very little. Previously published data on the properties of the materials and components have been used to a large extent.	Publications in refereed journals and presentations at national and international conferences.	No formal regulatory approval but discussions with the regulator may have been started.
Conceptual Feasibility Established	Detailed theoretical and numerical analyses of new features supported by experiments have been done by dedicated team of experts at a National Laboratory or Technical University level in cooperation with designers.	Physical soundness and feasibility of new principal technical solutions verified in laboratory experiments including preliminary (out- reactor) endurance tests.	Conceptual design completed sufficient to documenting all the principal innovative elements of the design and specify design requirements for the system.	Experimental program approved by regulating body, and the requirements to validate all the numerical codes to be used for detailed design calculations have been agreed. for the purpose.
Feasibility Demonstrated	Complete set of design parameters calculated. Comprehensive experimental programs on neutronics, thermo hydraulics and material science underway.	Testing of major new equipment elements underway in full scale rigs and where necessary in in-pile runs including long term endurance tests and initial test results are available.	Detailed design sufficient to specify major components completed and component suppliers have accepted the specifications.	Preliminary experimental and test programs results presented to the regulating body and accepted.
Developed and Demonstrated	Post reactor examination of irradiated samples and evaluation of test results of new construction elements completed. Pilot plant operation analyzed to make final improvements in the design of commercial unit.	If needed, Pilot plant (reduced size) built and operated long enough to verify new basic technical, economic, safety and environmental parameters.	Detailed design sufficient to prepare commercial bid and to start manufacturing and construction.	Pre-licensing discussions well advanced and regulatory issues sufficiently resolved to permit a commercial bid to be made.
Commercially Proven	Pre-conceptual work on next generation design underway.	First-of-a-kind commercial unit constructed and operated.	Lessons learned document prepared and design improvements to be incorporated in subsequent units as part of continuous improvements identified.	FOAK licensed.

An INS usually consists of components with different levels of maturity. A graph showing the maturity level of each component (e.g. in bars) of an INS may be helpful to visualize the maturity of a complete INS for comparison with a different INS.

A maturity level of pre-conceptual is included in Tables 3.2 and 3.3 but it is recommended that the INPRO method not be applied at such an early stage of development other than to carry out a preliminary screening to identify at an early stage any clear showstopper.

3.4.4. Aggregating the results of a comparative assessment

Approach 1

The final outcome of a comparison of different INS regarding their relative capability or potential to fulfil the INPRO requirements could be summarized or aggregated in a variety of ways. A simple method would be to compare the fraction of the total indicators in a given area for which one INS was better than another. The results could be displayed graphically, as in Figure 3.4, or in tabular form. Thus, for example, from Figure 3.4 one sees that in the area of safety, INS No.1 outperformed INS No.2 in 60% of the safety indicators while INS No.2 outperformed INS No.1 in 40% of the indicators. Such a comparison effectively assigns an equal weight to all indicators in a given area.

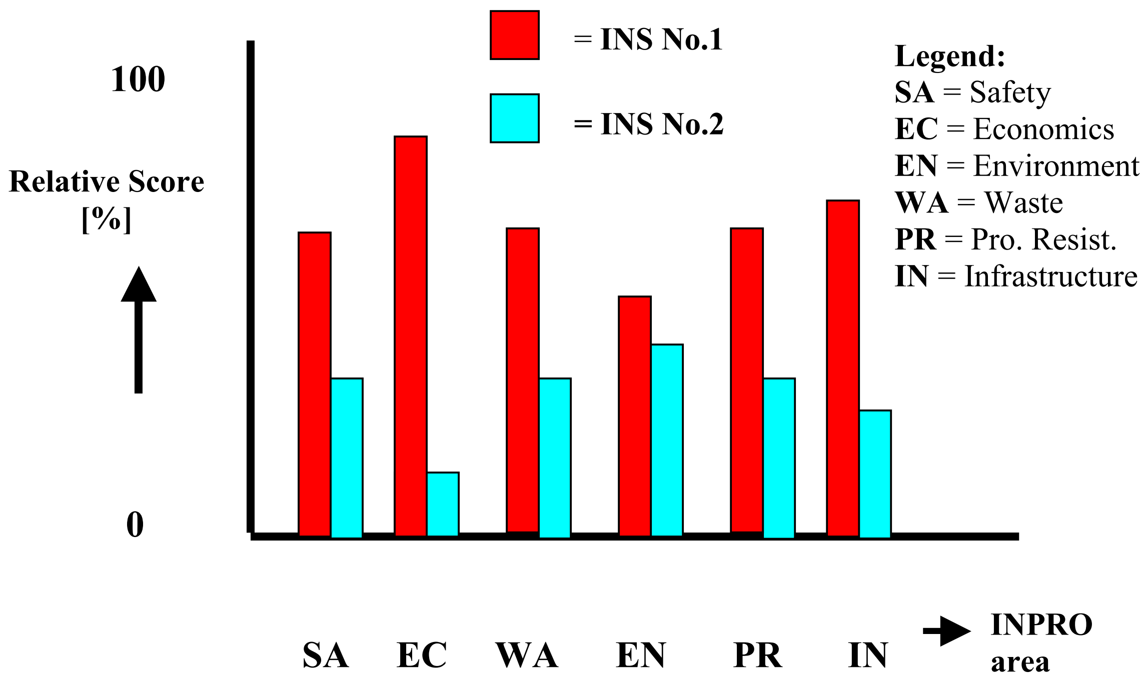


Figure 3.4. Outcome of comparison of capability of two INS.

In the example illustrated in Figure 3.4, INS No.1 is superior (has higher capability or potential) to INS No.2 in all areas and so is clearly superior overall. In reality it is expected that the scores in each INPRO area of two INS would in many cases be much closer. In such circumstances, a more detailed evaluation of the individual characteristics of the INS would be necessary. An aggregated judgment as displayed in Figure 3.4 does not reflect the detail that can be seen in Figure 3.3 but such an aggregation may be useful for summarizing information for decision makers.

A comparison of two INS should not be considered complete without presenting information concerning the uncertainty of the judgements made on the capability of the two INS. Such information could also be displayed using a block diagram as shown in Figure 3.5.

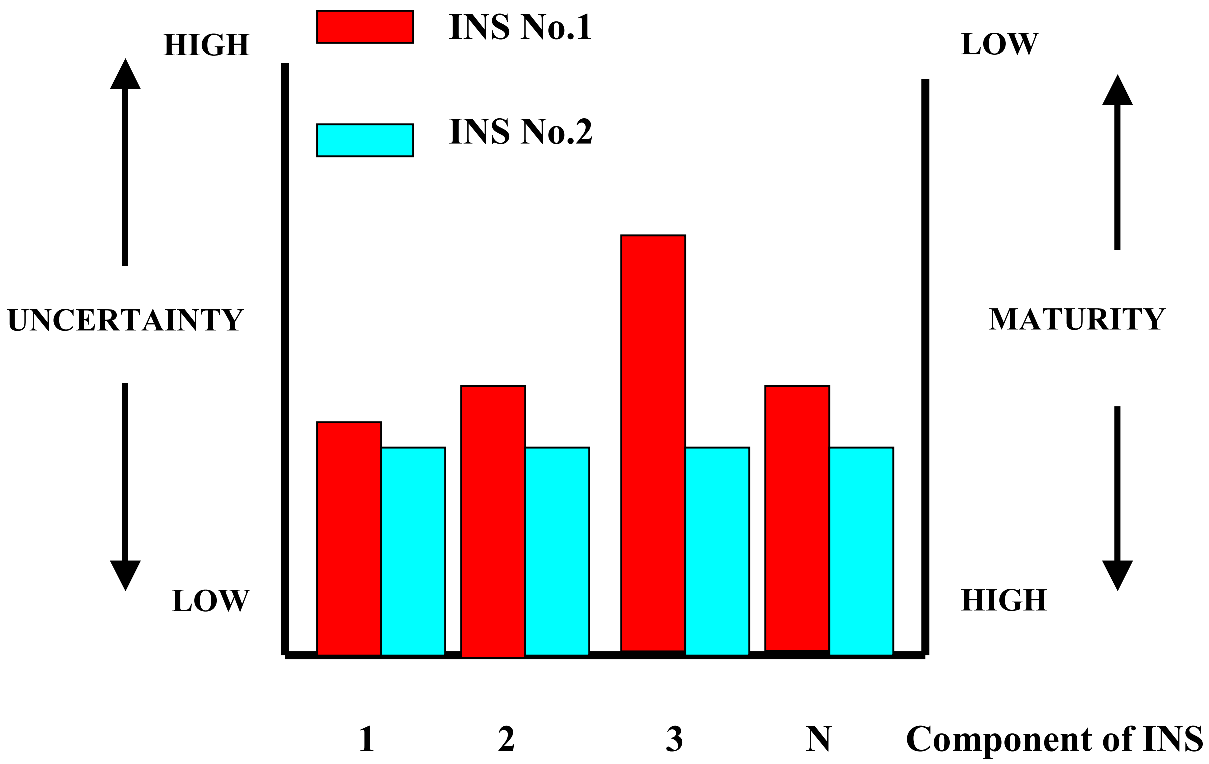


Figure 3.5. Maturity chart comparing components[5] of two INS.

The example given above shows that INS No.1 compared to INS No.2 has a lower level of maturity (Figure 3.5) and therefore a higher uncertainty of the judgements made, however it has also in general higher capabilities (Figure 3.4).

Additional approaches for comparing INS and aggregating judgements.

Defining different ranges of relative potential of capability of an INS to fulfil a criterion can refine the judgement process. Doing so will also enhance the capabilities of the assessment method for aggregation of the results. Ranges might be designated “Moderate Potential” (MP), for the range of values close to the acceptance limit, “High Potential” (HP), for the next (better) range of values, and then “Very High Potential” (VHP). To do so, of course, requires that the boundaries of each of the ranges of potential (capability) need to be determined, at least approximately. Figure 3.6 illustrates schematically the different levels of capability or potential for one possible economic indicator, overnight construction cost, assuming for the purposes of illustration that the acceptance limit is $1800/kW$_{installed}$.

[5] Components of an INS are nuclear installations such as an enrichment facility, the reactor, a reprocessing facility, etc.

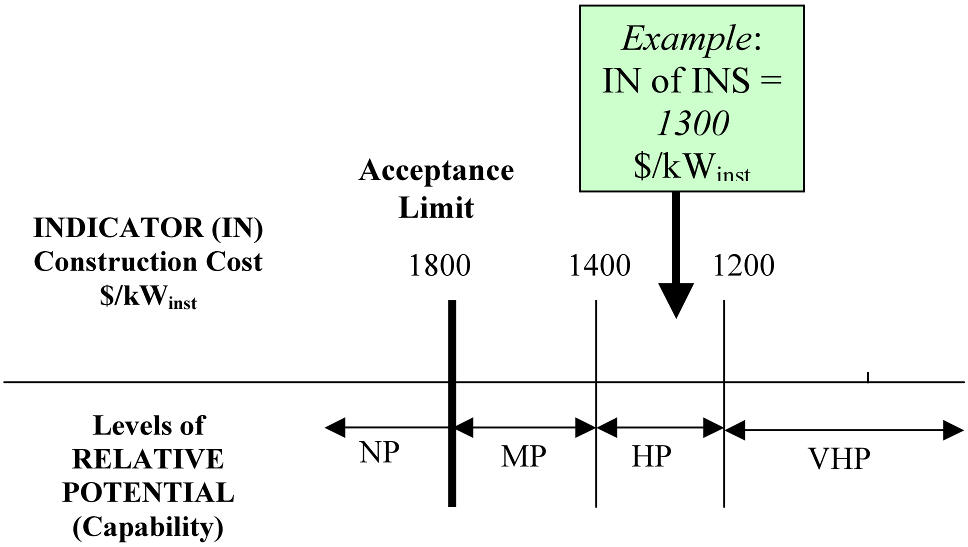


Figure 3.6. Illustration of the judgement procedure with different levels of capability or potential defined.

The example in Figure 3.6 above demonstrates that, if for an INS the value of the indicator construction cost is 1300 $\$/kW_{inst}$, the judgement will be High Potential (HP) to fulfil the corresponding criterion. With different ranges of potential established, for each indicator and acceptance limit taken into account in the assessment, an assessment leads to judgements of the different levels of potential for each criterion, depending on the value of the indicator with respect to the ranges for that indicator. The individual judgements of criteria could now be aggregated in several ways as discussed below.

A simple method of doing so would be to simply add up the relative number[6] (percentage) of judgements of "Moderate Potential", "High Potential", etc., for each user requirement, basic principle, INPRO area and finally for an INS (or different designs of a component thereof). Figure 3.7 illustrates the possible result of such an aggregation process for two different INS.

In the example illustrated in Figure 3.7, INS No.1 is clearly superior to INS No.2, because of the higher frequency of higher relative potentials for INS No.1.

A more sophisticated approach would be to assign a numerical value to the judgement of an individual criterion by introducing scores (e.g. non-linear) for the individual judgements, either in a discrete fashion, e.g., 10 for "Moderate Potential", 20 for "High Potential", 40 for "Very High Potential", or by using a scoring function. Figure 3.8 illustrates this approach for the indicator "Specific Capital Cost".

[6] The relative number is understood as the number of actual judgements with a certain level of potential divided by the total number of judgements to be made.

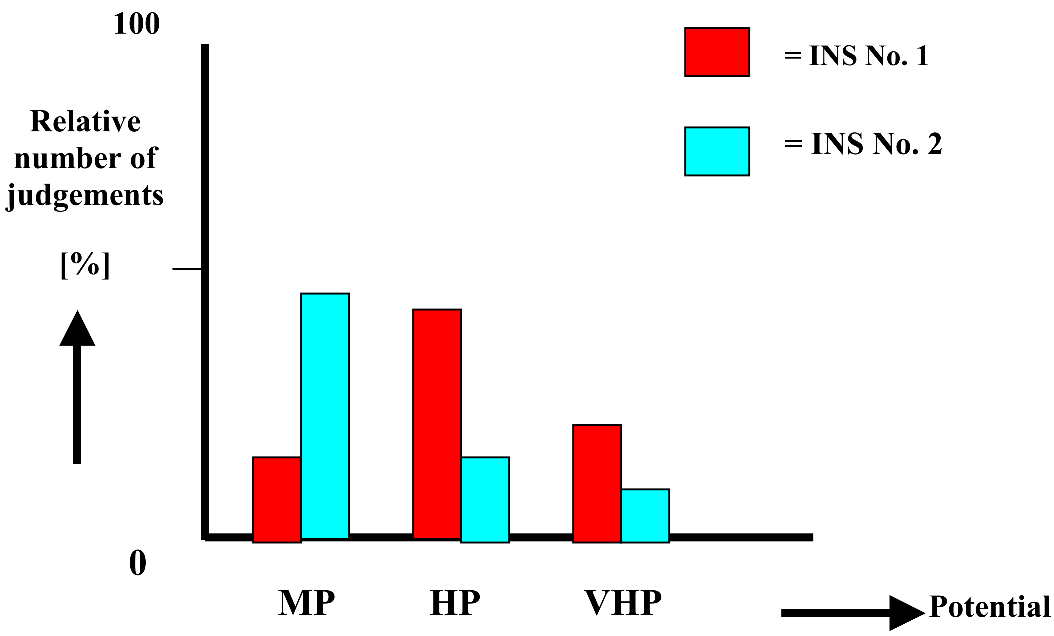


Figure 3.7. Aggregation of judgements on potential for a UR, BP, INPRO area or INS.

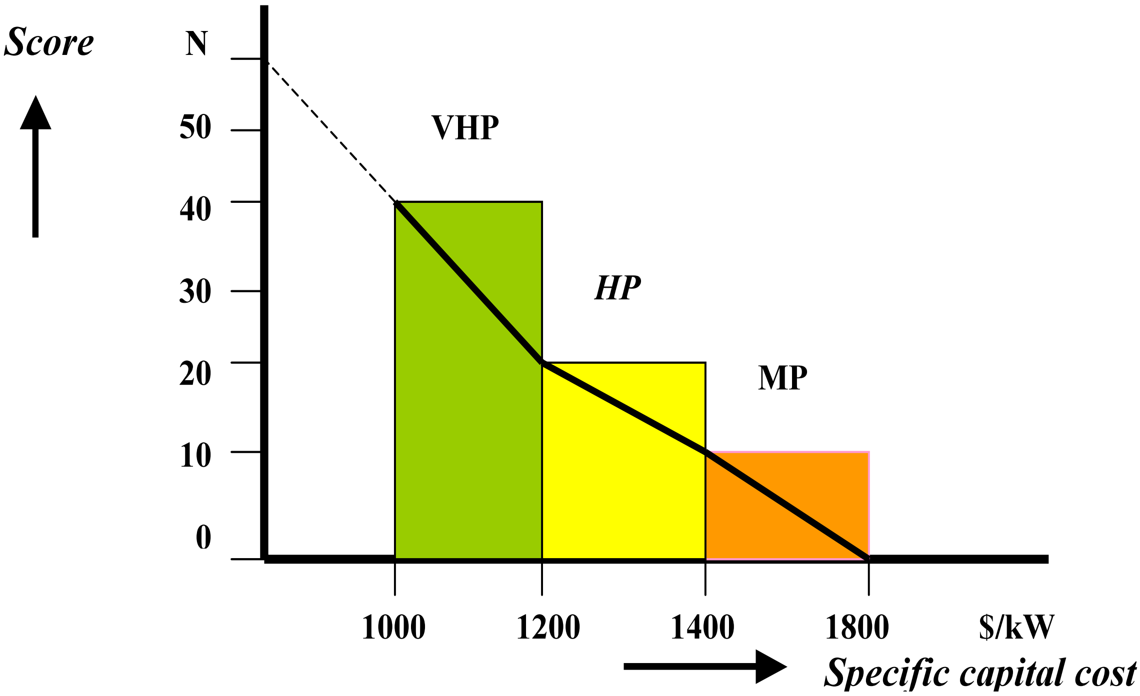


Figure 3.8. Example for the introduction of ranges of potential and scores into the process of judgement.

One could then add the judgement score for each criterion, user requirement, basic principle, and INPRO area to arrive at an aggregated value for each and for the INS itself (or for different designs of a component thereof). The result of such a refined aggregation process of the judgements could look as follows.

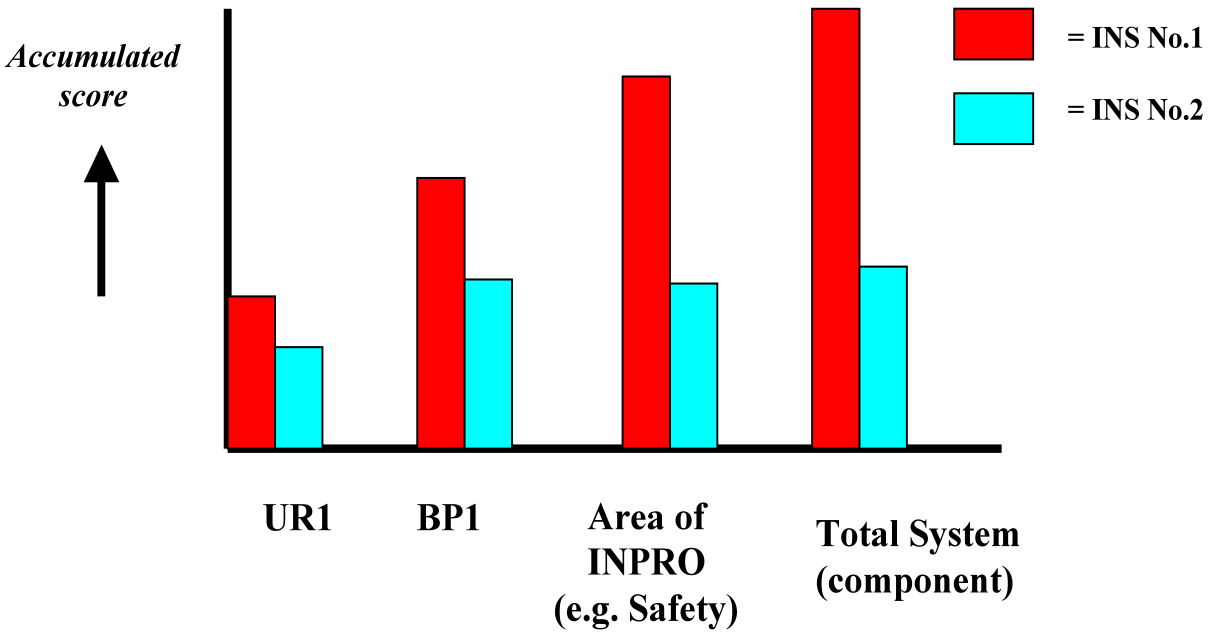


Figure 3.9. Aggregation of judgements using scores.

The example in Figure 3.9 above would again confirm the superiority of INS No.1 in comparison to INS No.2, however assigning non-linear scores to the judgement levels now enhances the actual differences in capability of both systems. Instead of absolute values of the accumulated scores, relative scores could be used.

At this stage of INPRO (Phase 1B, 1st part) international consensus on neither the boundaries for the various ranges for different criteria nor on the scoring to be applied has been established. Examples for selected criteria and scoring functions will be presented in the INPRO manual [3-12]. But, just as it is the case for the criteria, themselves, it is expected that assessors will, if they so desire, specify ranges for different ranges of potential and assign scores.

In aggregating results, weights might be assigned to different areas or to different basic principles or to different user requirements or even different criteria. As has already been discussed above, a given assessor may effectively apply weights by focusing on only one or two key areas of interest once he had determined that a given INS had been screened and met criteria, user requirements, and basic principles. The use of scoring functions and weighting of criteria or user requirements would be expected to be more useful in such circumstances.

In aggregating results, it should be emphasized that the detailed information obtained in assessing an individual criterion is seen to be of greatest value when defining development goals and plans. But, the aggregation of such assessments represents a potentially useful technique for summarizing information for decision makers.

3.5. RD&D assessment

INPRO assessments can be used to identify target values of specific indicators to be reached via RD&D. The basic features of this concept are discussed in this section.

3.5.1. Key indicators and desirable target values

As mentioned previously (see Section 3.2, Basic features and terminology), in identifying the need for and the potential benefit that would result from RD&D a selected list of indicators, so-called Key Indicators (KI) may be defined in specific or in all INPRO areas, depending on the preferences of Member States. The idea is that a KI would have a distinctive capability for capturing the essence of a given user requirement, basic principle, or INPRO area and that they would provide a means to establish targets in a specific area to be reached via RD&D and to track progress towards the targets during the execution of the RD&D programme. KIs may be formulated, e.g., by selecting a specific indicator or user requirement used for screening and comparative assessments, by grouping a few existing indicators or, in some cases, even by specifying a new indicator. For a given INS, the KI would be chosen taking into account relevant/salient design features, technological and/or institutional approaches, and boundary conditions, such as alternative sources of energy supply, industrial capability.

In addition a desired target value (DTV) would also be defined for a given KI. The DTV would be chosen to represent the ultimate value of a KI that could practically be achieved through RD&D. The value of the DTV could be selected by a Member State or technology developer but, in due course, might be chosen to reflect an international consensus. The DTV cannot exceed the ultimate value that the laws of physics impose. But it is recognized that at a given point in time a more conservative value may be chosen for the DTV taking into account what is seen to be achievable within a time frame of interest, which for INPRO is ~50-100 years. Thus, the DTV represents a stretch target for a KI that is judged to be eventually or ultimately achievable by appropriate RD&D.

Some general features or attributes of desirable target values (DTV) and KIs can be suggested:

- Attainment of the DTV should substantially improve the performance of the INS in one or more of the INPRO subject areas (Economics, Safety, etc.), as compared to the best available performance in current generation of nuclear facilities already in operation;
- Attainment of DTV should be prima-facie feasible;
- A KI should have a good capability to discriminate between two or more concepts of INS;
- Each KI should be distinct, and should not have any overlap with any other KI;
- KI may be chosen from among existing INPRO indicators with good discriminating capabilities.

In performing the RD&D, one would track the value of the KI to see that the gap between the current value of the indicator and the DTV was closing. As well as tracking the KIs, the developer would also need to make periodic screening assessments using the complete set of criteria, URs and BPs to ensure that the component or INS of interest was assessed holistically and that it was sustainable.

3.5.2. Relative benefit and risk indices

The concept of DTV can be linked to the concept of relative potentials introduced in Section 3.4.4 dealing with comparative assessments. In that discussion, the concept of differentiating different values of potential for a given indicator was introduced and the idea of assigning to an indicator different values, such as moderate potential, high potential, and a very high potential value, was presented. The idea of assigning scoring values to a given value of potential or utilizing a scoring function was also discussed. When considering KIs and DTVs, one can extend this concept by defining a so-called Relative Benefit Index (RBI). The DTV for a KI would, by definition, be assigned a RBI of 100, the acceptance limit for the KI would be assigned a RBI of 0, and a function would be defined for assigning a RBI to a KI for values between the DTV and the acceptance limit. The relationship between "relative potential" with respect to the acceptance limit for an indicator and the "relative benefit index" is summarized in Table 3.4.

Table 3.4. Correspondence between Relative Potential (RP) and Relative Benefit Index (RBI)

R P **of Indicator (IN)**	**RBI**	**Comment**
IN < AL, No potential (NP).	RBI < 0	The RBI of a KI is assigned a value of 0 when the value of the KI equals the AL for the indicator.
IN ≈ AL, moderate potential (MP).	0 < RBI < 100	A suitable function (e.g. linear, non-linear, etc.) for RBI is to be defined.
IN > AL, HP		
IN >> AL, VHP		
IN = DTV	RBI = 100	The DTV for the KI is assigned a value of 100.

The RBI would be used in tracking the improvement obtained from RD&D. A value of RBI ~0 would represent little progress while a value close to 100 would represent very substantial progress.

In deciding on whether or not to undertake a proposed RD&D programme, not only would the benefit to be achieved need to be taken into account but also the risk. Thus, a relative risk index (RRI) should also be defined for each key indicator. The risk may include the uncertainty in the DTV value of the Key Indicator (KI) determined to be achievable for a specific INS, but would also reflect the development effort required and the maturity level of the concept. Thus, a concept may be advanced that has a good possibility of achieving a very substantial improvement in the value of a KI but at the same time the concept may require the development of specific technical features that are at an early stage of development, and may require significant investment of funds, personnel, etc. The RRI would be chosen accordingly.

In order to aggregate the values of RBI and RRI obtained for different Key Indicators the assessor may apply different values of weighting factors corresponding to each Key Indicator. Ideally, weighting factor for each Key Indicator should relate to the impact of a change in the value of that indicator (using sensitivity analysis) to the change in competitiveness as measured, e.g., by the change in rate of deployment of the INS. This requires the use of more rigorous computational models and tools than currently available.

In the future, INPRO activities could include development of models and computational tools to determine weighting factors for each indicator and the associated method for arriving at aggregated RBI of an INS. A similar approach could also be developed for aggregation of uncertainties associated with each indicator value to determine RRI. One approach for determining a RRI would be to base it on the cost of RD&D to achieve a given benefit.

To guide the further development of RRI one could consider comparing RBI and RRI using a two dimensional diagram as illustrated in Figure 3.10, which shows an example of the outcome of a theoretical RD&D assessment performed for three INS.

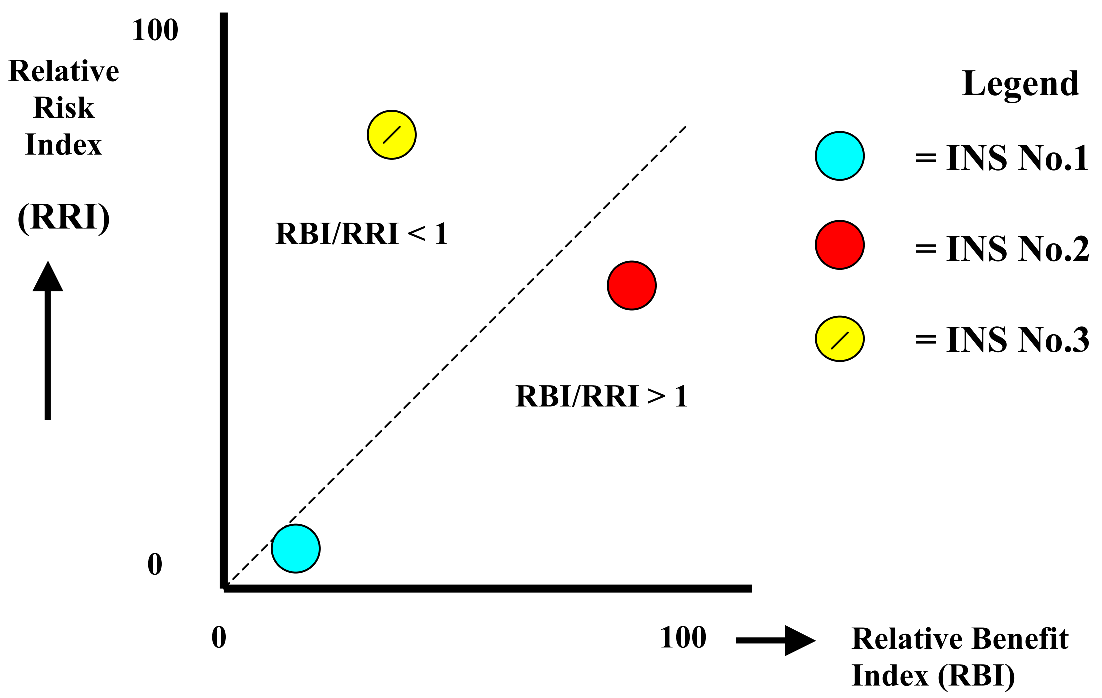


Figure 3.10. Illustration of the concept of relative indexes for benefit and risk.

As shown in Figure 3.10, the origin of the plot (0,0) represents a highly mature and commercially proven technology that could generally provide the best achievable performance of the current generation Nuclear Energy Systems. A 'Relative Risk Index' of 100 would apply to an INS concept with low level of maturity for several key design features, or institutional measures contemplated in the concept. A 'Relative Benefit Index' of 100 reflects the desirable target performance levels which can be credibly assumed for a future INS. The line separates the risk-benefit plane into two zones: in the lower zone the benefit, as measured by the RBI, exceeds the risk, as measured by RRI, and in the upper zone the risk exceeds the benefit. Thus, concepts in the upper zone, such as concept INS No. 3 would not likely be considered for development while concepts falling within the lower zone, concepts INS No.1 and No.2, would be considered for development. A concept located close to the origin such as Concept INS No.1 would represent an evolutionary design of an INS. It meets the criteria for sustainability and represents a low risk and could, if developed, be available within a relatively short time frame. INS Concept INS No.2 is potentially superior to INS No.1, i.e. when developed it is expected to outperform INS No.1, so it is a candidate for RD&D investment.

A more sophisticated approach would factor in three aspects – relative benefit, relative risk based on the maturity of the technology, and the estimated cost of RD&D. It has to be emphasized that in Phase 1B (first part), the RD&D assessment method represents only the outline of an approach that could be developed further in subsequent steps of INPRO, including in Phase 1B (second part) to be started at the beginning of 2005. The extent to which this is done will depend on feedback from the users of the INPRO methodology.

3.6. General rules for the application of the INPRO method for assessment

In the context of an assessment to be carried out for a Member State, it is important to note that several acceptance limits are flexible enough to let the acceptable numerical value be decided by the Member State on the basis of its needs and priorities. But it should be recognized that the URs and criteria pertaining to safety, proliferation resistance, waste management, and environment, are considered to be global in nature. While recognizing this, when performing an assessment, the terms user requirements and criteria, as used in this report refer, unless otherwise stated, to the user requirements and criteria accepted by the Member State as being necessary and sufficient for meeting its needs.

Experience, gained during the performance of case studies [3-13] in assessing a given INS, has shown the need to modify criteria to adapt them to the specific circumstances of Member States and even to introduce new criteria. As stated above, adding (see for instance [3-14]) or modifying criteria, taking country or regional boundary conditions (e.g. priorities, constraints) into account, is a distinctive option in the INPRO method. In this case, the following considerations should be taken into account:

- To the extent possible, a criterion should be applicable to all kinds of INS and not design specific;
- A criterion should be clear (not ambiguous);
- A criterion should not include prejudgments;
- Wherever possible, indicators should be measurable and quantifiable;
- Indicators should be logically independent; and
- A criterion should be established in such a way that the fulfilment of all criteria should ensure that users are convinced that the user requirement is met.

Typical examples for such country or region specific criteria (and especially its acceptance limits) are the economical criteria in Chapter 4, Economics.

In any comparison of existing nuclear energy systems with innovative systems that include radical changes in design compared with existing designs, the maturity of the system — a priori higher for existing technologies — should not influence negatively the judgment of the assessment of a future technology with respect to its capability/potential for meeting the INPRO basic principles, user requirements and criteria. Correctly formulated and used, the INPRO method for assessment 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. Having said this it needs to be acknowledged that the maturity of a given technological innovation is an important factor in determining when and whether to adopt the innovation in a commercial application (see Chapter 4, Economics). Thus, the INPRO method for assessment can be helpful in selecting the technologies, to which to apply RD&D funds, to bring them to the level of maturity where they can be applied commercially.

Another aspect for innovative facilities with radical changes of design compared to existing designs is the likelihood of a lack of an extended experience base. Therefore, expert opinion will be very important in forming the judgment for those facilities. 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.

It can be expected that for a future global nuclear energy system a number of different INS (including nuclear technology concepts and institutional measures) might be needed to meet the differing preferences of various Member States and regions.

In principle, it is desirable to have a common (internationally agreed) set of criteria for the confirmation of the necessary capability of all INS. Nevertheless, for some INS different criteria may be needed.

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 method 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.

3.7. Concluding remarks

The basic terminology and technique for implementing the INPRO Method for the assessment of INS have been developed in Phase 1A of INPRO and tested in the first part of Phase 1B via several case studies.

Substantial effort will be needed to develop the method further for widespread use and to ensure consistency and credibility of the results.

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CHAPTER 4
ECONOMICS

4.1. Introduction

As set out in Chapter 2, INPRO and the concept of sustainability, energy plays an important role in each dimension of sustainable development — economic, social and environmental — and ensuring its availability is one important aspect of governments' ultimate responsibility for national security and economic growth. Not only must energy be available but as discussed briefly in Chapter 2, INPRO and the concept of sustainability, it also needs to be affordable. These considerations lead to the following basic principle.

4.2. Economic basic principle

Economic Basic Principle BP1: ***Energy and related products and services from innovative nuclear energy systems shall be affordable and available.***

The best way of ensuring that nuclear energy and related services are affordable is for the price to the consumer to be competitive with low cost/priced alternatives. If energy and related products and services are to be available, systems to supply the energy and related products need to be developed and deployed. To develop and deploy innovative energy systems requires investment and those making the investment, be they industry or governments, must be convinced that their choice of investment is wise. The alternatives for investment may be other energy technologies seeking investment for development or deployment or non-energy technology areas. So, to be developed and deployed, INS must compete successfully for investment.

As discussed below (Section 4.5), in different markets and regions and at different times and stages in the cycle of development and deployment the investor(s) may be different and different factors may assume more or less importance in determining attractiveness of investment. But in any case a sound business case must be made.

Given the nature of nuclear technology, it is recognized that government policies and actions (in some Member States governments may participate in investment) will have a significant bearing and influence on investor decision making, both when deciding whether or not to invest in development and when deciding to invest in technology deployment/acquisition. For private sector investment profitability and return will be key factors in the business case. It follows that if the price to the consumer is to be competitive and at the same time investors are to receive an attractive return, the cost of production must also be competitive with that of alternatives.

4.3. Economic user requirements and criteria related to economic BP1

User requirements and related criteria required to satisfy the basic principle are set out in Table 4.1.

Table 4.1. User requirements and criteria related to economic basic principle BP1

Economic Basic Principle BP1: ***Energy and related products and services from Innovative Nuclear Energy Systems shall be affordable and available.***		
User Requirements	Criteria	
	Indicators	Acceptance Limits
UR1.1 *The cost of energy from innovative nuclear energy systems, taking all relevant costs and credits into account, C_N, should be competitive with that of alternative energy sources, C_A. that are available for a given application in the same time frame and geographic region.*	1.1.1 Cost of nuclear energy, C_N. 1.1.2 Cost of energy from alternative source, C_A.	For item 1.1.1 and.1.1.2: $C_N < k*C_A$
UR1.2 *The total investment required to design, construct, and commission innovative nuclear energy systems, including interest during construction, should be such that the necessary investment funds can be raised.*	1.2.1 Financial figures of merit. 1.2.2 Total investment.	1.2.1 Figures of merit are comparable with or better than those for competing energy technologies of comparable size. 1.2.2 The total investment required should be compatible with the ability to raise capital in a given market climate.
UR1.3 *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.*	1.3.1 Licensing status. 1.3.2 Project construction and commissioning times. 1.3.3 Relevant indicators of the political environment show long-term support for nuclear power.	1.3.1 Pre-licensing possible in country of origin. 1.3.2 Schedule analysed to demonstrate that scheduled times are realistic. Times comparable with those for other energy supply alternatives. 1.3.3 yes.
UR1.4 *Innovative energy systems should be compatible with meeting the requirements of different markets.*	1.4.1 Flexibility of INS.	1.4.1 Ability to demonstrate design flexibility to accommodate different postulated sets of circumstances.

The user requirements set out in Table 4.1 are discussed in more detail below.

Economic User Requirement UR1.1: *The cost of energy from innovative nuclear energy systems, taking all relevant costs and credits into account, C_N, must be competitive with that of alternative energy sources, C_A, that are available for a given application in the same time frame and geographic region.*

The first user requirement relates to cost competitiveness which, as discussed in the Introduction, is a requirement for the INS is to be both available and affordable. In determining the cost of energy (or other products) from INS and competing alternatives all relevant costs must be included. Depending on the jurisdiction, one energy source may be burdened with costs, e.g. for waste management, while another may not. In a number of Member States, the external costs of nuclear power[7] that are not accounted for are small since producers are required by law to make provisions for the costs of waste management, including disposal, and decommissioning whereas the external costs of competing energy sources that are not accounted for may be significant. Ideally all external costs should be considered and, where possible, internalised, when comparing INS with competing energy systems.

As discussed in Chapter 3, Method for Assessment, Member States may well develop their own specific criteria for each user requirement. One criterion would be based on a comparison of C_N and C_A with an acceptance limit that $C_N/C_A<k$, where k is a factor that can be less than or greater than one in a given Member State or region depending on whether or not nuclear costs are offset by credits relative to the alternative energy source or vice versa. Thus, Member States and investors will determine the value of k depending on their particular circumstances. Such a determination could well be made in the decision making process as part of taking into account factors to which it is hard to assign definitive costs, such as the cost of externalities. Thus the argument in favour of a given choice may well be phrased more or less as follows: 'Option N is slightly more costly that option A but the following benefits of option N compared with option A more than outweigh the cost disadvantage and hence option N is preferred.' But, as well as being cost competitive, if the energy product is to be profitable, the cost must still be smaller than the selling price in a given market to provide investors with a profitable return.

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, i.e. the energy mix, of both the market as a whole and of the a given producer/supplier; 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; utilization of domestic resources, such as mineral and labour resources and industrial capacity; public and hence political acceptance (see also Chapter 9, National, Regional and International Infrastructure), etc. Such considerations may lead decision makers and investors, particularly governments, to accept a somewhat higher cost for one energy option compared with an alternative. See, e.g., Refs [4-1, 4-2], which discuss the credit that could be assigned to security of energy supply in Japan. As circumstances change so may the value of k that will apply in a given country/region. In the longer term, market forces would be expected to constrain the value of k to be close to unity.

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[7] By definition an external cost is a cost imposed on society and the environment that is not accounted for by the producers and consumers of energy.

C_N and C_A should be calculated using a levelized discounted cost (LDC) model (see, e.g., ref. [4-3]) taking into account all relevant cost determinants for both the INS and the competing energy technology. In making such cost comparisons sensitivity analyses should be employed to assess the impact of possible changes in costs such as O&M costs and fuel costs. Further, the cost comparison should be based on costs for the relevant region/market and the time frame for the deployment of the INS, using energy planning tools (see, e.g., Refs [4-4, 4-5]) to arrive at the best quantitative estimates of the various cost components.

Costs should be based on the costs for repeat units or N^{th} of a kind (NOAK), rather than for a first of a kind unit (FOAK). The model should be transparent and complete. Cost determinants include the following: specific capital costs for overnight construction, financing costs, including interest during construction (IDC), operating and maintenance costs, regulatory 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, credits/penalties applied, e.g., credits for avoided emissions or industrial benefits, etc. Further, at the time that investment is being made in developing INS, the cost estimate (for the product of the INS) should include a component to recover the development costs with a suitable return.

For an INS, many of these costs, particularly at early stages of development (see Section 4.5), may have uncertain values, and hence may encompass or require ranges of estimates. Thus, sensitivity analysis should be used in assessing the impact of potential variability in costs. Such sensitivity analysis can be used to identify the relative importance of the various cost determinants and also to identify opportunities for cost reduction. The completeness and the ranges of the cost determinants 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 an INS as it evolves is an important and necessary discipline to ensure that is will be cost competitive.

Additional considerations concerning possible specific cost criteria are discussed at the end of this section.

Economic User Requirement UR1.2: *The total investment required to deploy an innovative nuclear energy system, including interest during construction, should be such that the necessary investment funds can be raised.*

Investors look at a variety of financial indicators when evaluating investments including internal rate of return (IRR), the closely related indicator, net present value (NPV), payback period, return on investment (ROI), etc. The financial indicators used in a given region will reflect the investment climate and requirements of a given country/region, including the source(s) of investment funds. In some countries/regions INS will require private sector investment while in other countries/regions INS may 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. As noted NPV and IRR are closely related but net present value analysis may facilitate taking into account other benefits such as security of energy supply and technology development that may be of more interest to government investors than private sector investors. Return on investment (ROI) may be attractive as an indicator complimentary to IRR, since it is more independent of IRR than NPV. In the end, the acceptance limit is that the values of the financial indicators chosen, for a given INS, be attractive compared with investments in competing energy technologies. Thus, they must be at least comparable to the values for competitive energy sources and preferably better.

The total investment required to deploy a given INS, or component thereof, comprises the costs to adapt a given design to a given site, and then to construct and commission the plant, including the interest during construction. The latter depends on construction time and the time to commission. A universally applicable criterion for what constitutes an acceptable 'size' 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. But a judgment must be made that the funds required to implement a project can be raised within a given expected investment climate. Factors influencing this ability may include the overall state of the economy of a given region/country, the size of the investment relative to a utility's annual cash flow (and hence the size of the unit relative to the size of the grid), and the size of the investment compared with that needed for alternative sources of supply. When comparing investments required for alternative sources of supply the cash flows during construction and commissioning for the different options are important. One way of comparing these is to use the discounted capital costs of the options. It may be noted in setting specific development criteria, that a judgment concerning the capacity to raise investments of a given amount for investment in a given region can be obtained from a review of the historical investments in that region, particularly those in energy supply. In the end the investment in an INS must be affordable and attractive in a given investment climate taking into account other investment options and other priorities requiring a share of available capital.

Economic User Requirement UR1.3: *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.*

Investor risk comprises several factors, including among others, uncertainties in basic project cost, the cost of project delays, and shortfalls in plant operation. Regulatory uncertainties can impact on all three as would failure to meet basic requirements, such as those related to safety, environment etc. Thus, the demonstration of compliance with requirements, e.g. INPRO BPs, and URs, is important in minimizing plant performance risks and, also, regulatory risk. 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. Thus, there is an expectation that the technology has been adequately demonstrated as part of the innovation and technology adoption process.

Uncertainties in project basic cost estimates has been discussed above, under economic UR 1.1, and as noted there sensitivity analysis should be used in estimating the potential variability in costs and the results of such analyses should be taken into account in assessing risk. Such sensitivity analyses can be extended to assess the sensitivity of the financial indicators, e.g., IRR, to changes in a variety of cost parameters, including overnight construction costs, project execution times, discount rate, etc. The results of such analyses would be expected to affect the hurdle rates employed in the financial analyses called for in economic UR 1.2. Hence, a separate criterion related to project cost estimates has not been specified.

Project delays lead to cost overruns, particularly in project management and engineering support costs and in IDC. The greatest impact of project delays, particularly on IDC, arises during construction and commissioning. Thus, 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 and specific targets can and should be set as development objectives for INS.

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.

Different plant designs may have different project execution times. 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 might be achievable.

Another factor that needs to be considered is whether or not the political climate is supportive of the use of nuclear power and whether such support is likely to be sustained over time scales of interest. A variety of indicators can be considered in determining whether the climate is supportive. For example, does a country have an energy strategy that recognizes that nuclear power is an essential component of its energy supply mix? Do both the governing party and the leading opposition party support nuclear power? Has progress been made in addressing controversial issues such as the siting of end-state waste management facilities?

Economic User Requirement UR1.4: *Innovative energy systems should be compatible with meeting the requirements of different markets.*

Given the uncertainty about the future, as reflected for example in the wide range of possible future scenarios considered in the SRES (see Ref. [4-6] and Section 4.1 of Ref. [4-8]), 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 and markets as possible. Thus, the ability to adapt specific components of an INS, as well as the overall adaptability of the INS, to accommodate different sized modules, to accommodate market changes and growth, to accommodate different fuels, to meet different energy applications, and to meet the needs of different countries/ regions is desirable. In assessing flexibility of a given component or set of components, possible synergisms with other components of the INS should be considered.

4.4. Additional considerations concerning cost criteria and targets

Costs are not static but vary with time. In principle, such variations can be taken into account in the cash flow analyses required to calculate a LDC for C_N and C_A. But, one Member State has noted that in the case where the LDC of the competing energy source is sensitive to the fuel cost, e.g. combined cycle gas turbines, and where there is an expectation that the fuel cost is expected to increase dramatically in the future, it is useful to compare the LDC of the INS with the expected annual cost for the competing energy source to determine how the competitive position of the system changes with time. In such a situation, a significant benefit would result from up front licensing and site selection work for an INS, particularly if the INS had a short construction and commissioning time. Then, a utility could track the increasing operating cost for the high fuel cost option against the LDC for the nuclear system and so be more confident that the competitive advantage had shifted to the INS when committing to its construction. The shorter the time between making such a decision and the time to bring the nuclear plant on line the smaller would be the risk to the utility in making such a commitment.

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, acceptance limits may be defined for specific cost determinants, e.g. specific capital cost. Here it may be noted that the high capital cost of nuclear makes the LDC for it sensitive to the discount rate while the LDC for fossil fuel plants are sensitive to fuel costs [4-7].

In the near to intermediate term (over the next 20 to 50 years) in many Member States, 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 (see Section 4.1.1 of Ref. [4-8]). Thus, reductions in the specific capital costs of nuclear power plants while maintaining low fuel and O&M costs, as well as waste management and decommissioning costs, would improve the competitive position of INS.

As noted in Chapter 2, INPRO and the concept of sustainability, renewable energy sources (e.g. hydro, wind, solar, biomass) are predicted, in the SRES scenarios, to increase considerably their share of global energy supply, especially in the latter half of the 21st century. Thus, in the longer term, renewable energy sources such as photovoltaics and wind power may 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, including the capital cost for back-up storage and/or alternate sources of energy and the 'cost' of land use. Because of their inherent nature, renewable energy sources such as wind and solar do not generate power continuously. So, as they gain market share, it becomes increasingly important to provide back-up sources and the cost of doing so must be taken into account. The higher capacity factors expected from nuclear technologies compared with those from renewables represents a competitive advantage for nuclear. In recent years average availability factors >90% have been achieved. With INS even higher availability factors, ~95% should be achievable.

In some jurisdictions, land use can be an important factor, in which case it might be adopted as an indicator. 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. 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. [4-9]).

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

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 cost of the energy 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.

4.5. Economics and the cycle of development

The INPRO BP, UR and C can be used as a tool to assist investors, be they governments or industry, to assess whether or not to invest in research, development, design, and deployment of INS. Thus, e.g., the decisions makers involved in deciding whether to invest in the RD&D to develop a given system or component, would be expected to require information to show that, once the INS is developed, the cost of the product provided by the INS, e.g., energy, will be competitive with that of alternatives at the future time when the INS is deployed. Once an INS is sufficiently developed, a decision needs to be made whether or not to commit to its deployment. In most, if not all Member States, this will involve another set of investors since, simplistically, deployment can be thought of a two-step process – the offering of the INS in a given market by the developers and the acquisition of the technology by users. Technology users need confidence, at the time a decision is being made to commit a given INS, that once the INS has been constructed, commissioned, and brought into service (a process that will take several years) the INS will deliver its product at a competitive price and so enable the user to earn an adequate return.

In this context, it is well to consider briefly the various stages of development in bringing an INS to the point of large-scale deployment (See Chapter 3, Method for assessment). Firstly, preliminary work is carried out to define a concept for an INS. Such work is often funded by national governments in Member States having significant nuclear power programs, e.g. in national laboratories and/or in universities. One output of such work needs to be an assessment of the potential of the proposed INS to meet national and international requirements, as set out e.g. in the INPRO BP, UR, and CR, augmented by specific additional requirements that the Member States may have or may develop. Such an assessment also needs to identify uncertainties and the potential impact of such uncertainties using, e.g., sensitivity analysis. So, the INPRO BP, UR, and C can be used to assist decisions makers at a very preliminary stage in deciding whether or not to commit funds to invest in RD&D to advance the development of an INS beyond the preliminary stage. The proponent of an INS may seek funding and assistance to advance the development of the INS from a number of possible sources – government and/or industrial. In the early stages development may well be funded internally, but at later stages internal funds may be supplemented or replaced by external funds.

While development times vary from sector to sector, in general, the more innovative the development, the longer will be the development time and the greater will be the uncertainty concerning a successful outcome, i.e. the higher the risk of a successful development, including, in the early stages, the uncertainty in the actual cost of development. (See Table 3.3 in Chapter 3, Method for assessment, which summarizes the different levels of technology maturity for the development and deployment).

Development times for nuclear technology can extend to tens of years. Thus, the more innovative the development is, the greater the likelihood that government support, in one form or another, will be sought. Since, the development decision is a decision to invest in RD&D, the cost of the RD&D must be estimated and an argument must be made that there will be a suitable return on the RD&D investment. For investment by industry, financial analyses will be required to demonstrate that there is expected to be a financial pay back. The justification for government investment may be partly financial but could be largely based on the strategic benefits expected to be realized, e.g. maintenance and development of industrial capacity, security and diversity of energy supply.

As development proceeds, periodic re-assessments need to be carried out to confirm, with the improved knowledge base resulting from RD&D, that targets are still expected to be met and that future investments are justified. Throughout this process, close contact between the developer and potential users, i.e. the market(s), will impose a useful discipline to ensure that the needs of the users are understood and are being addressed. At some stage, a commitment will be required to proceed with a first-of-a-kind (FOAK) plant. Prior to making such a decision significant resources will have been committed to demonstrating key aspects/components of the INS, including possibly a prototype plant, and as these aspects/components are evaluated and demonstrated, the decision whether or not to commit funds for further development and demonstration would be based, in whole or in part, on a re-assessment of the whether the development targets, e.g. the INPRO BP, UR, and CR, can still be achieved.

Where government funds have been used in development, the source of investment funds may well shift as a given INS advances towards a FOAK plant, with an expectation that industry will accept a greater share of investment as uncertainty is reduced by RD&D. Thus, as the development process proceeds, the make up of decision makers may well change. At the time of the commitment to a FOAK plant the decision makers will almost certainly change since by definition the FOAK plant will be "commercial" plant and so will involve investment by the user, i.e., a customer, e.g., a utility. But, depending on the perceived risk, some form of government assistance or risk sharing between the developer and the customer may still be required to convince the user to commit to the FOAK plant.

For the sake of illustration, one can assume that committing a FOAK plant would require a sharing of costs (for adaptation/completion of design, construction, commissioning, and operation etc.) and/or risk among the developer, the customer/utility and government. Each would need to be assured that its investment would provide a payback. Each would look at the issue from its own perspective. In all cases, the different decision makers/investors should have an expectation that once the plant is operating it will meet requirements such as the INPRO BP, UR and C. But each may evaluate the BP, UR and CR, particularly those related to economics, somewhat differently. Thus, for example the government may take into account spin off benefits whereas a utility would be expected to consider the return on its investment, and the developer would need assurance that he will recover any additional investment required to complete the FOAK plant (and ideally any sunk costs for RD&D already performed) from the sale and servicing of additional units.

Once a FOAK plant has been constructed, the decision makers/investors for future plants could well change again with the decision being much more a commercial decision between a customer and supplier resulting from a commercial negotiation. Governments may still be involved to a greater of lesser extent, e.g. in providing loan guarantees or, in the case of international sales, in assisting with financing. Again, the customers will want assurance that requirements will be met but, given the experience gained with the first plant risks should be lower and so customer confidence should be higher. But the situation would be expected to be different depending on the customer's nuclear experience and knowledge.

If the customer is already an established user of nuclear technology, he may be willing to accept an INS provided that he judges that the potential risk in doing so is offset by the benefits. On the other hand, if the customer for the INS is a first time user of nuclear technology the decision whether or not to acquire a given INS may well be more complex and in this case the nature of the offer may be very different than for a customer with relevant nuclear experience. Such a first time customer will probably be a late adopter of a given technology and would not be prepared to acquire an INS (or component) until it has arrived at the stage of full commercial exploitation. Even then, he may well want the supplier to provide substantial support and technology transfer, even going so far as to want to contract for the operation and maintenance of the plant (see also Chapter 9, National, regional and international infrastructure). But in the end, this customer must also be convinced that what he acquires will deliver a product that is competitive in his market, existing or anticipated, and that given the price structure in that market he will realize an appropriate return.

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CHAPTER 5
SAFETY OF NUCLEAR INSTALLATIONS

5.1. Introduction and background

Basic Principles, User Requirements and Criteria for the safety of Innovative Nuclear Energy Systems (INS) have been established in INPRO taking into account the large body of work that already exists dealing with the safety of reactors and fuel cycle facilities operating today, and previous work on establishing requirements for next generation reactors.

One of the basic assumptions of INPRO is the expectation that to fulfil the needs of sustainable energy supply within the next 50 years and beyond, the number of nuclear energy systems (NES) in operation will have to be increased considerably compared to the situation today. Keeping the safety level of the newly deployed NES at the same level as the operating systems today, would lead to an overall increase in the numerical risk of nuclear accidents. It is expected however that this increase in calculated risk would be compensated by the increased safety level of the innovative nuclear energy systems, based, in part, on lessons learned from systems in operation.

5.1.1. Existing requirements

The IAEA has updated documents that define the elements necessary to ensure the safety of nuclear power plants [5-1, 5-2]. 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).

Such documents have been prepared for evolutionary and innovative designs by organizations such as EPRI (Advanced Light Water Reactor Utility Requirements Document - ALWR-URD), Japanese Utilities (JURD), Korean Utilities (KURD), Chinese Utilities (CURD) and the European Utilities (European Utility Requirements - EUR). They were authored largely by electricity-generating utilities and arose from well-characterized reactor designs, reflected operating experience and formed the basis for the development of modern designs.

In 2004 the IAEA [5-3] presented an overview of these utility documents. A summary of the essence of these requirements is presented below.

- A design life of 60 years;
- Reliable and flexible operation, with high overall plant availability, low levels 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 more restrictive release targets for EUR as follows:

- To limit emergency protection actions beyond 800 m from the reactor to a minimum, during early releases from the containment;
- 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.

5.1.2. Future requirements

The scope of the INPRO project covers nuclear reactors expected to come into service in the next 50 years and beyond, together with the associated fuel cycles. It is recognized that a mixture of existing[8], evolutionary, and innovative designs will be brought into service and co-exist within this period. The recently published 'Three Agency Study' [5-4] 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 widespread and long-term use of nuclear power to be sustainable, a nuclear fuel strategy is required which utilizes, at least as a component, breeding, reprocessing and recycling of fissile material. In some countries or regions and for intermediate time scales, innovative once-through fuel cycle 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 include closed fuel cycles that make better use of uranium and thorium resources.

User requirements are well established for existing nuclear power reactors. 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, as of today there are no widely accepted user requirements for them. This section applies user requirements for INS to both reactors and fuel cycle facilities. The requirements are intended to be as generic as possible; where they cannot be made fully generic, it is so noted.

The scope of this section includes the safety of reactors and of both front-end and back-end fuel cycle activities, including fuel fabrication and reprocessing; it extends to primary spent fuel storage at reactor sites but excludes extended fuel storage and waste management, addressed in Chapter 7, Waste Management.

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[8]The term "existing" will be used in this section consistently to refer to the most modern commercially available designs and operating plants as of 2004.

5.2. General approach to safety

5.2.1. General safety objective

There is a worldwide consensus on the **General Nuclear Safety Objective** [5-5], 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 as 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 practicable, economic and social factors taken into account (ALARP); 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.

5.2.2. 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 in pools at reactor sites), the fundamental safety functions 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. For INS, defence-in-depth should include, as appropriate, an increased use of inherent safety characteristics and passive systems in nuclear designs.

5.2.3. Defence-in-depth

Defence-in-depth (DID) provides an overall strategy for safety measures and features of nuclear installations [5-6], [5-7]. 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, because 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 departures – 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 designs and installations.

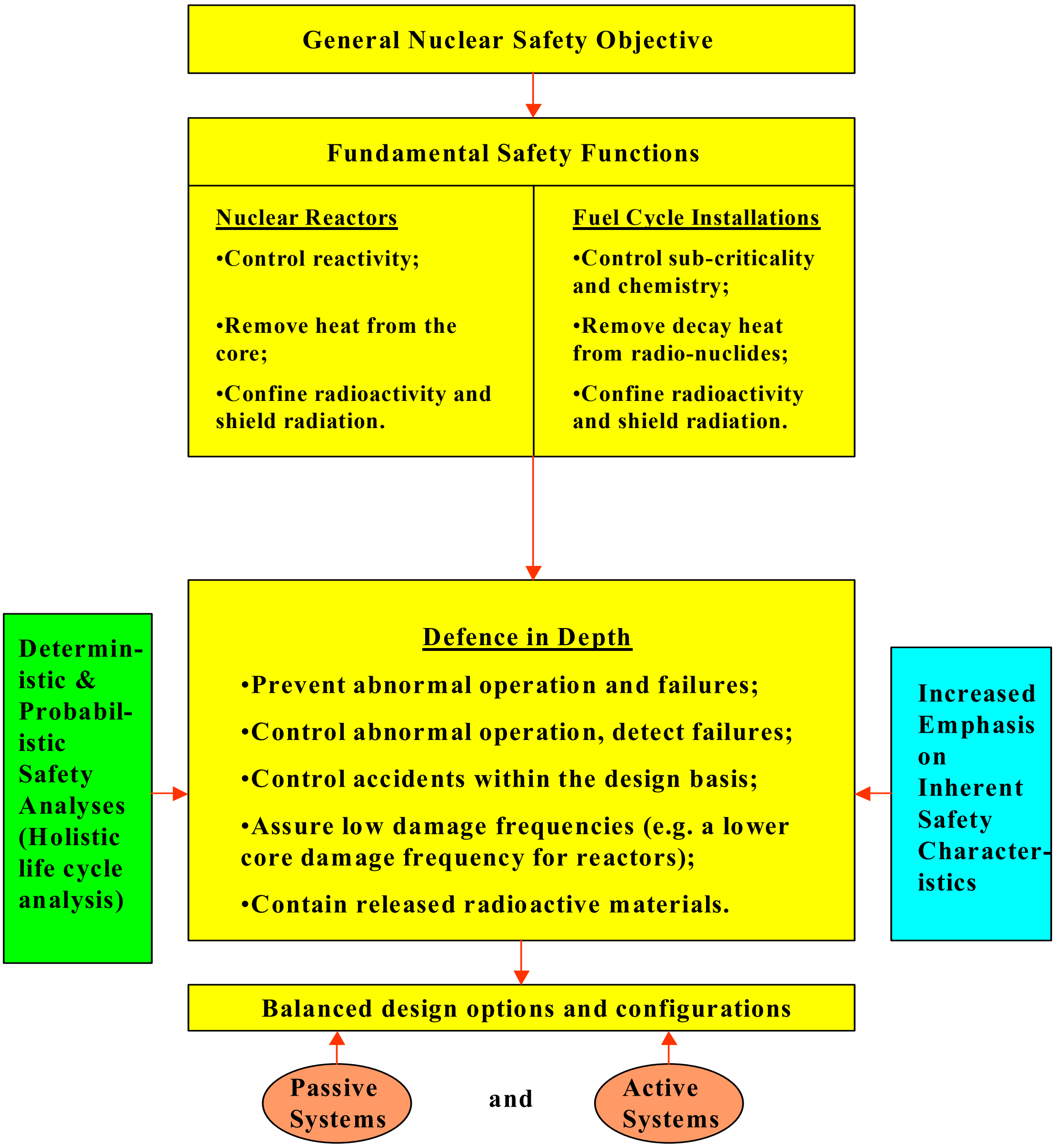

Figure 5.1. Framework for development of user requirements for safety of INS.

Typically defence-in-depth is characterized by five levels of protection, shown in Figure 5.1 and discussed below, with the top level being prevention, and the remaining four levels representing the response to increasing challenges to the plant and to public safety.

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 existing reactors, an accident could challenge several levels of defence-in-depth simultaneously. In INS, 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, through more use of passive systems and through greater separation of redundant systems, all of which has the effect of pushing the accident defence to the top levels.

An increased use of inherent safety characteristics will strengthen accident prevention in innovative 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 nuclear physics, and the physical and chemical properties of nuclear fuel, coolant and other components. The term inherent safety is normally used with respect to a particular 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 in one place a critical configuration of material, etc.

In assessing safety, the scope of the safety assessment should be holistic, covering the effects on people and on the environment (considered in Chapter 6, Environment) of the entire integrated fuel cycle. This ensures that an improvement in safety in one area or component of the fuel cycle is not negated by a decrease in safety in another area.

The resulting approach to safety of INS is outlined in the Figure 5.1.

INPRO has developed general directions for innovation to enhance defence-in-depth relative to existing plants and designs. These are presented in Table 5.1. The end point should be the prevention, reduction and containment of radioactive releases to make the health and environmental 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.

5.2.4. Application of basic safety approach to fuel cycle facilities (other than a reactor)

Typical safety hazards in fuel cycle facilities (FCF) include the release of radioactivity, contamination and exposures of workers, criticality, and releases of chemical and stored energy (e.g., from radioactive decay heating, chemical reactions including fires, and failure of pressurized systems) [5-8]. Techniques and methods similar to those used in existing facilities should be used in innovative fuel cycle installations to limit hazards, as innovative facilities should benefit from proven technical design solutions. Advantage should be taken of inherent characteristics, and passive safety systems should be used to the extent possible. A much higher degree of automation of fuel reprocessing and fabrication facilities is desirable in the 50-year time frame. In the interim, manual operations cannot be completely avoided, so that much emphasis will still need to be placed on administrative procedures, including a clear definition of responsibilities and appropriate training for the control of operation.

Table 5.1. INPRO innovations in application of Defence-in-Depth

<table>
<tr><th>Level of defence -in-depth</th><th>INSAG Objectives (see Ref. [5-6])</th><th colspan="2">Innovation Direction (INPRO)</th></tr>
<tr><td>1</td><td>Prevention of abnormal operation and failures.</td><td>Enhance prevention by increased emphasis on inherently safe design characteristics and passive safety features, and by further reducing human actions in the routine operation of the plant.</td><td rowspan="5">More independence of levels from each other</td></tr>
<tr><td>2</td><td>Control of abnormal operation and detection of failures.</td><td>Give priority to advanced control and monitoring systems with enhanced reliability, intelligence and the ability to anticipate and compensate abnormal transients.</td></tr>
<tr><td>3</td><td>Control of accidents within the design basis.</td><td>Achieve fundamental safety functions by optimised combination of active & passive design features; limit consequences such as fuel failures; minimize reliance on human intervention by increasing grace period, e.g. between several hours and several days.</td></tr>
<tr><td>4</td><td>Control of severe plant conditions, including prevention and mitigation of the consequences of severe accidents.</td><td>Increase reliability and capability of systems to control and monitor complex accident sequences; decrease expected frequency of severe plant conditions; e.g. for reactors, reduce severe core damage frequency by at least one order of magnitude relative to existing plants and designs, and even more for urban-sited facilities[9].</td></tr>
<tr><td>5</td><td>Mitigation of radiological consequences of significant releases of radioactive materials</td><td>Avoid the necessity for evacuation or relocation measures outside the plant site.</td></tr>
</table>

[9] Similarly, an appropriate target should be chosen for fuel cycle facilities.

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

- The power density in a FCF is orders of magnitude smaller than in a reactor core;
- The integral stored energy of the solid structures and the enthalpy of the fluids or gases during operation of a FCF is low compared to a reactor;
- The radioactive material in FCF is often in a more easily dispersed state, the flow (volume and mass) of radioactive material into and out of the FCF is much higher, and there are fewer barriers to the environment, although the concentration of radioactive material is much less, especially at the front end of the fuel cycle, compared to a reactor;
- Some FCFs use more reactive or flammable chemicals such as hydrazine and nitric acid.

These differences result in the following consequences:

- Occupational risk in a FCF needs particular care because of the proximity of the operator to the material being processed;
- The routine releases of hazardous material from a FCF such as a uranium mine may be larger due to mechanical or chemical processes;
- The likelihood of release of chemical energy (e.g. fire, explosion) in a FCF is higher;
- The potential consequences of a criticality accident in a FCF are much less than for a criticality accident in a reactor because the energy released would be much smaller.

These differences lead to a modified safety approach. As stated above, for existing FCFs the emphasis is on the control of operations using administrative and operator controls to ensure safety, as opposed to engineered safety features used in reactors. There is also more emphasis on criticality prevention in view of the greater mobility (distribution and transfer) of fissile materials.

Because of the intimate contact with nuclear material in the process, which may include open handling and transfer of nuclear material in routine processing, special attention is warranted to ensure worker safety. Potential intakes of radioactive material require control to prevent and minimize contamination and so ensure adherence to operational dose limits. In addition, releases of radioactive material into the facilities and through monitored and unmonitored pathways can result in significant exposures, particularly from long-lived radiotoxic isotopes.

The number of physical barriers in a nuclear facility that are necessary to protect the environment and people depends on the potential internal and external hazards, and the potential consequences of failures; therefore the barriers are different in number and strength for different kinds of nuclear reactors (e.g. with high or very low power cores)[10] and for FCFs. For example, in the front end of a natural uranium fuel cycle, safety is focused on preventing

[10] For existing light water reactors, the multi-barrier concept comprises four components which are: the fuel matrix, the fuel rod cladding, the primary coolant boundary and the containment.

the spread of contamination via low-level radioactive material. In mining, an important focus is preventing contamination of ground or surface water with releases from uranium mining tails. Chemicals and uranium by-products are the potential hazards of the conversion stage. In a fuel fabrication facility, safety is again focused on preventing contamination with waste from fuel fabrication. One method of mitigating these hazards that might be employed in an INS facility is co-location of front end (e.g. enrichment and mining facilities) and back end (e.g. reprocessing and waste handling) facilities. This would have benefits e.g., through handling depleted uranium together with mine tailings.

In summary, the five levels of defence-in-depth might not have the same relative importance in the fuel cycle installations as in reactor installations. The basic strategy, however, remains the same, namely: all levels of protection should be implemented. In addition, reliance on human action in assuring the independence of the different levels of defence-in-depth should be reduced.

5.3. Basic principles, user requirements and criteria for the safety of innovative nuclear installations

5.3.1. Introduction

In the area of safety for innovative reactors and fuel cycle facilities a set of basic principles, user requirements, and criteria has been defined, the focus of which is directed to those requirements that would most likely change for INS, reflecting the expected changes in nuclear technology. The concept of 'Safety culture' and associated requirements are assumed to be 'taken over' from existing practice [5-9, 5-10, 5-11]. It is also assumed that requirements and practices set out in IAEA Safety Standards and Guides will be followed where applicable, e.g., Refs [5-1], [5-12], [5-13]. These provide detailed guidance, e.g., for allowable fuel failure rates and capabilities for resuming operation following a transient. This set of basic principles, user requirements and criteria 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 (see also Section 3.2).

For INS, it is expected that INPRO requirements and criteria will eventually become formalized in IAEA Safety Standards and Guides for innovative reactors and FCFs; and conversely as the INPRO methodology evolves, it will benefit from and reflect advances in the IAEA Standards and Guides.

5.3.2. Safety basic principles

Installations of an Innovative Nuclear Energy System shall:

1. Incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations.

2. Excel in safety and reliability by incorporating into their designs, when appropriate, increased emphasis on inherently safe characteristics and passive systems as a part of their fundamental safety approach.

3. Ensure that the risk from radiation exposures to workers, the public and the environment during construction/commissioning, operation, and decommissioning, shall be comparable to that of other industrial facilities used for similar purposes.

Further, the development of Innovative Nuclear Energy System shall:

4. Include associated RD&D work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing plants.

5.3.3. Safety user requirements and criteria for each basic principle

In the following, for each basic principle defined above, the corresponding user requirements and criteria are set out in Tables 5.2 to 5.5 and are then briefly discussed.

Table 5.2. User requirements and criteria related to safety basic principle BP1

Safety Basic Principle **BP1**: ***Installations of an Innovative Nuclear Energy System shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations***.		
User Requirements	Criteria	
	Indicators	Acceptance Limits
UR1.1[11] *Installations of an INS should be more robust relative to existing designs regarding system and component failures as well as operation.*	1.1.1 Robustness of design (simplicity, margins). 1.1.2 High quality of operation. 1.1.3 Capability to inspect. 1.1.4 Expected frequency of failures and disturbances. 1.1.5 Grace period until human actions are required. 1.1.6 Inertia to cope with transients.	1.1.1. to 1.1.6: Superior to existing designs in at least some of the aspects discussed in the text.
UR1.2[12] *Installations of an INS should detect and intercept deviations from normal operational states in order to prevent anticipated operational occurrences from escalating to accident conditions*	1.2.1 Capability of control and instrumentation system and/or inherent characteristics to detect and intercept and/or compensate such deviations.	1.2.1 Key system variables relevant to safety (e.g. flow, pressure, temperature, radiation levels) do not exceed limits acceptable for continued operation (no event reporting necessary).

[11] Related to: DID Level 1: Prevention of Abnormal Operation and Failures, Table 5.1.

[12] Related to: DID Level 2: Control of Abnormal Operation and Detection of Failures, Table 5.1.

Table 5.2. User requirements and criteria related to safety basic principle BP1 (continued)

Safety Basic Principle **BP1***: **Installations of an Innovative Nuclear Energy System shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations***.		
User Requirements	Criteria	
	Indicators	Acceptance Limits
UR1.3[13] *The frequency of occurrence of accidents should be reduced, consistent with the overall safety objectives. If an accident occurs, engineered safety features should be able to restore an installation of an INS to a controlled state, and subsequently (where relevant) to a safe shutdown state, and ensure the confinement of radioactive material. Reliance on human intervention should be minimal, and should only be required after some grace period.*	1.3.1 Calculated frequency of occurrence of design basis accidents. 1.3.2 Grace period until human intervention is necessary. 1.3.3 Reliability of engineered safety features. 1.3.4 Number of confinement barriers maintained. 1.3.5 Capability of the engineered safety features to restore the INS to a controlled state (without operator actions). 1.3.6 Sub-criticality margins.	1.3.1 Reduced frequency of accidents that can cause plant damage relative to existing facilities. 1.3.2 Increased relative to existing facilities. 1.3.3 Equal or superior to existing designs. 1.3.4 At least one. 1.3.5 Sufficient to reach a controlled state. 1.3.6 Sufficient to cover uncertainties and to allow adequate grace period.
UR1.4[14] *The frequency of a major release of radioactivity into the containment / confinement of an INS due to internal events should be reduced. Should a release occur, the consequences should be mitigated.*	1.4.1 Calculated frequency of major release of radioactive materials into the containment / confinement. 1.4.2 Natural or engineered processes sufficient for controlling relevant system parameters and activity levels in containment / confinement 1.4.3 In-plant severe accident management	1.4.1 At least an order of magnitude less than for existing designs; even lower for installations at urban sites. 1.4.2 Existence of such processes. 1.4.3 Procedures, equipment and training sufficient to prevent large release outside containment / confinement and regain control of the facility.

[13] Related to: DID Level 3: Control of Accidents, Table 5.1.

[14] Related to: DID Level 4: Prevention of Major Radioactivity Release, Table 5.1.

Table 5.2. User requirements and criteria related to safety basic principle BP1 (continued)

Safety Basic Principle **BP1**: ***Installations of an Innovative Nuclear Energy System shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations***.		
User Requirements	Criteria	
	Indicators	Acceptance Limits
UR1.5[15] *A major release of radioactivity from an installation of an INS should be prevented for all practical purposes, so that INS installations would not need relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility used for similar purpose.*	1.5.1 Calculated frequency of a major release of radioactive materials to the environment. 1.5.2 Calculated consequences of releases (e.g. dose). 1.5.3 Calculated individual and collective risk.	1.5.1 Calculated frequency $<10^{-6}$ per unit-year, or practically excluded by design. 1.5.2 Consequences sufficiently low to avoid necessity for evacuation. Appropriate off-site mitigation measures (e.g. temporary food restrictions) are available. 1.5 3 Comparable to facilities used for a similar purpose.[16]
UR1.6 *An assessment should be performed for an INS to demonstrate that the different levels of defence-in-depth are met and are more independent from each other than for existing systems.*	1.6.1 Independence of different levels of DID	1.6.1 Adequate independence is demonstrated, e.g. through deterministic and probabilistic means, hazards analysis etc.

[15] Related to DID Level 5: Prevention of Containment Failure and Mitigation of Radiological Consequences, Table 5.1

[16] e.g. an oil refinery would be analogous to an enrichment facility; a chemical plant would be analogous to a fuel reprocessing facility; a coal-fired power plant would be analogous to a nuclear power plant.

Table 5.2. User requirements and criteria related to safety basic principle BP1 (continued)

Safety Basic Principle **BP1**: ***Installations of an Innovative Nuclear Energy System shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations***.		
User Requirements	Criteria	
	Indicators	Acceptance Limits
UR1.7 *Safe operation of installations of an INS should be supported by an improved Human Machine Interface resulting from systematic application of human factors requirements to the design, construction, operation and decommissioning.*	1.7.1. Evidence that human factors (HF) are addressed systematically in the plant life cycle. 1.7.2. Application of formal human response models from other industries or development of nuclear-specific models	For item 1.7.1: - Satisfactory results from assessment. For item 1.7.2: - Reduced likelihood of human error relative to existing plants, as predicted by HF models. - Use of artificial intelligence for early diagnosis and real-time operator aids - Less dependence on operator for normal operation and short-term accident management relative to existing plants

In the following, the first safety basic principle, its user requirements and criteria are briefly discussed.

Safety Basic Principle BP1: ***Installations of an Innovative Nuclear Energy System shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations.***

To compensate for potential human or mechanical failures, a defence-in-depth concept shall be implemented, utilizing several levels of protection and successive physical barriers to prevent the release of radioactive material to the environment. Means should also be provided to protect the barriers themselves. Further accident management measures should be available to protect the public and the environment from undue harm in case a severe accident occurs.

Optimization of the balance among different levels of defence is important – the user requirements for this basic principle place more emphasis on preventative than on corrective measures or mitigative barriers.

Thus 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 User Requirement UR1.1: *Installations of an INS should be more robust relative to existing designs regarding system and component failures as well as operation.*

The major means to achieve an increase in robustness are to ensure a high quality of design, construction and operation, including human performance. For innovative designs the expected frequencies of initiating failures or disturbances should be reduced relative to existing designs. This reduction could be achieved by use of e.g.: improved materials, simplified designs to minimize failures and errors, improved design margins to overstressing and fatigue, increased operating margins, increased redundancies of systems, less impact from incorrect human intervention (the machine should be tolerant to mistakes), more effective and efficient inspections, a continuous monitoring of the plant health, etc. Examples of reactor concepts with increased robustness against certain potential hazards are designs with all cooling loops inside the pressure vessel (avoidance of loop breaks), use of liquid metals or molten salts (avoidance of high system pressures), use of small excess reactivity (avoidance of large power excursions), low power density cores (limiting the temperature in reactivity transients), extensive use of passive systems (potentially higher reliability, e.g. natural convection), higher reliability self-checking control systems (avoidance of deviations from normal operation), use of non-flammable materials (avoidance of fires), etc. The use of inherent safety characteristics is a useful means of achieving robustness and has been highlighted as a separate basic safety principle – see Table 5.3.

"Capability to inspect" means that the system should require and permit more efficient and intelligent inspection, not just more inspection – i.e. an inspection programme driven by a sound understanding of failure mechanisms so that the right locations are inspected at the right times. It is recognized that in the early stages of an INS, before the technology base is fully established, more inspection might be required.

The indicator "Grace period" is the time available, in case of a failure or the beginning of abnormal operation, before human action is required. The appropriate value of this "grace period" could depend on the type of nuclear facility, the ease of diagnosis of the failure, and the complexity of the human action to be taken, simple failures and straightforward actions requiring less grace period. As an example, for an innovative nuclear power plant after a loss of main feed water and successful automatic switch to a redundant system, a grace period of about a day is appropriate.

The indicator "inertia" means the capability of a nuclear system to cope with anticipated operational occurrences, avoiding consequences that could delay restart and return to normal operation. A typical example of an acceptance limit in a PWR related to inertia would be that after a loss of load transient, no material flow out of the primary system should occur; the corresponding design measure is sufficient size of the pressurizer. Another example for a nuclear reactor would be the thermal inertia of the fuel (slow increase of temperature) after a transient such as the loss of flow (main coolant pump failure) in the primary system. An example for a reprocessing facility would be the slow increase of uranium and plutonium concentrations in the raffinate solution in the co-decontamination step, in the event of a loss of flow (solvent feed pump failure) in the first solvent extraction cycle

Safety User Requirement UR1.2: *Installations of an INS should detect and intercept deviations from normal operational states in order to prevent anticipated operational occurrences from escalating to accident conditions*

Priority should be given to advanced control systems, and improving the reliability of systems, so as to reduce the need for costly equipment redundancy and diversity requirements.

Optimization of passive and active systems will be important. In the longer term, priority should be given to design-specific inherent limiting characteristics (sometimes called "self controlling properties") and to robust and simple (possibly passive) control and advanced monitoring systems.

For a nuclear power station, an analysis of the plant dynamics is required to show how the different events causing a deviation from normal operation are detected and mitigated. The plant model has to simulate the control and reactor protection system variables, trip parameters and the safety and auxiliary systems operational behavior. For fuel cycle facilities (FCF), similar activities are recommended, taking into account the differences between reactors and FCFs.

The ideal is a rapid return to normal operation with no need for inspections or regulatory event reports.

Safety User Requirement UR1.3: *The frequency of occurrence of accidents should be reduced, consistent with the overall safety objectives. If an accident occurs, engineered safety features should be able to restore an installation of an INS to a controlled state, and subsequently (where relevant) to a safe shutdown state, and ensure the confinement of radioactive material. Reliance on human intervention should be minimal, and should only be required after some grace period.*

As an example of the expected frequency of occurrence of accidents for LWRs, the Acceptance Limit for small break LOCAs could be $<10^{-2}$ per unit-year, and for large break LOCAs, $<10^{-4}$ per unit-year.

The term "controlled state" used in the UR1.3 is characterized by a situation in which the engineered safety features are able to compensate for the loss of functionality resulting from the accident. An optimized combination of active and passive engineered safety features should be used. For INS, it might be possible that passive design features could achieve almost all of the fundamental safety functions. For a nuclear reactor these features could include passive shutdown, passive decay heat removal systems and passively operated coolant injection systems.

The indicator "grace period until human action is necessary" is the same concept as introduced under control of abnormal operation. Here it implies that the action of automatic or passive safety systems provide the grace period.

Enhanced "reliability of engineered safety features" may be achieved by passive design, although other methods can also be effective.

The indicator "number of barriers maintained" and the corresponding acceptance limit "at least one" means that the design of engineered safety features should deterministically provide for continued integrity at least of one barrier (containing the radioactive material) following any design accident. Alternatively the probability of losing all barriers could be used as an Indicator.

The indicator "sub-criticality margins" applies (after an accident) both to nuclear reactors (shutdown depth), and to a fuel cycle facility, interpreted as preventing accumulation of fissile material or critical geometries.

Safety User Requirement UR1.4: *The frequency of a major release of radioactivity into the containment / confinement of an INS due to internal events should be reduced. Should a release occur, the consequences should be mitigated.*

For innovative nuclear reactors and fuel cycle installations the reliability of systems in controlling complex accident sequences should be increased, including instrumentation, control and diagnostic systems. Thus the frequency of a major radioactivity release into the containment may be reduced.

Releases into containment can be controlled or mitigated by e.g. spray systems, thereby reducing the potential for a large release outside containment.

In-plant severe accident management measures give the operator tools to prevent further release into the containment / confinement and/or to reduce the concentration of radio-nuclides already there.

Safety User Requirement UR1.5: *A major release of radioactivity from an installation of an INS should be prevented for all practical purposes, so that INS installations would not need relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility used for similar purpose.*

The requirement addresses the issue that if nuclear energy is to play a major role in the future, there will be many more plants, and they must be able to be easily sited. Some countries have the good fortune to have numerous large remote sites, but many do not; hence the safety of an innovative plant should not rely heavily on distance from population.

Engineered safety features of innovative reactors and fuel cycle installations should be able to control severe accident (beyond design basis) scenarios and mitigate their consequences, so as to prevent containment failure. Control and mitigation should address all threats (internal and external).

Thus innovative designs should show that:

- The likelihood of a large release is so small that off-site emergency measures, while they may reduce the consequences thereof, do not lead to a significant reduction in risk[17]; or

- A large release could be excluded by design for all practical purposes, e.g. through use of inherent safety characteristics.

Consequently, for an INS there should be no need for an offsite emergency plan, which is different in kind from the plan for *any* industrial facility used for a similar purpose.

Safety User Requirement UR1.6: *An assessment should be performed for an INS to demonstrate that the different levels of defence-in-depth are met and are more independent from each other than for existing systems.*

[17] Defined as the product of a calculated frequency multiplied by the potential consequences of this scenario.

A safety assessment should be performed using a suitable combination of deterministic and probabilistic approaches, or hazards analysis. Further requirements on the method of assessment are outlined under Basic Principle BP4.

Safety User Requirement UR1.7: *Safe operation of installations of an INS should be supported by an improved Human Machine Interface resulting from systematic application of human factors requirements to the design, construction, operation and decommissioning..*

The designer of an INS should place increased emphasis on human factors to minimize the possibilities for human (e.g. operator or maintainer) error. The experience available from operating nuclear plants and the best practices from other industries such as aircraft and chemical plants should be taken into account in this process. It is expected that the ability to predict human response to both normal and abnormal situations will improve dramatically over the next 50 years and will have a major impact on plant design and operation. Simulator technology will likewise improve allowing more realistic event mimicking, including severe accidents, and resulting (via training) in improved operator response. — cf. the existing situation with aircraft.

Table 5.3. User requirements and criteria related to safety basic principle BP2

Safety Basic Principle BP2: ***Installations of an INS shall excel in safety and reliability by incorporating into their designs, when appropriate, increased emphasis on inherently safe characteristics and passive systems as a part of their fundamental safety approach.***		
User Requirements	Criteria	
	Indicators	Acceptance Limits
UR2.1 *INS should strive for elimination or minimization of some hazards relative to existing plants by incorporating inherently safe characteristics and/or passive systems, when appropriate.*	2.1.1. Sample indicators: stored energy, flammability, criticality, inventory of radioactive materials, available excess reactivity, reactivity feedback. 2.1.2. Expected frequency of abnormal operation and accidents. 2.1.3. Consequences of abnormal operation and accidents. 2.1.4. Confidence in innovative components and approaches.	2.1.1. Superior to existing designs. 2.1.2. Lower frequencies compared to existing facilities. 2.1.3. Lower consequences compared to existing facilities. 2.1.4. Validity established.

In the following, the second safety basic principle, its user requirement and criteria are briefly discussed.

Safety Basic Principle BP2: ***Installations of an Innovative Nuclear Energy System shall excel in safety and reliability by incorporating into their designs, when appropriate, increased emphasis on inherently safe characteristics and passive systems as a part of their fundamental safety approach.***

Basic principle BP2 is focused on the role of inherent safety and passive safety features in future nuclear designs. The meaning of an inherent safety characteristic was explained previously, (Subsection 5.2.3). If incorporated into a design correctly, an inherent safety characteristic eliminates the cause of the hazard. Passive systems can provide additional safety margins; in such cases, deterministic design requirements such as the single active failure criterion may not be necessary (since safety will not depend as much on active components), assuming that reliability models are developed for passive systems. Nevertheless, failures in passive systems due to human error in design or maintenance, the presence of unexpected phenomena, and potential adverse system interactions, should be analysed and may need to be compensated by other design measures.

Safety User Requirement UR2.1: *INS should strive for elimination or minimization of some hazards relative to existing plants by incorporating inherently safe characteristics and/or passive systems, when appropriate.*

The analysis of an inherent safety characteristic is difficult but should be possible given adequate mathematical models and, in some cases, experimental testing. Most inherent safety characteristics for power reactors are expected to be partial – i.e., they limit a hazard but do not eliminate it.

The user requirement is one of degree: there are likely fundamental limitations in power reactor type or power range, which prevent absolute inherent safety characteristics (e.g. for many power reactors, one needs to have available enough positive reactivity to compensate for xenon poison).

The demonstration of the acceptance limit is via deterministic and probabilistic safety analysis.

Table 5.4. User requirements and criteria related to safety basic principle BP3

Safety Basic Principle BP3: ***Installations of an INS shall ensure that the risk from radiation exposures to workers, the public and the environment during construction/commissioning, operation, and decommissioning, are comparable to the risk from other industrial facilities used for similar purposes.***		
User Requirements	**Criteria**	
	Indicators	**Acceptance Limits**
UR3.1. *INS installations should ensure an efficient implementation of the concept of optimization of radiation protection through the use of automation, remote maintenance and operational experience from existing designs.*	3.1.1 Occupational dose values.	3.1.1 Less than limits defined by national laws or international standards and so that the health hazard to workers is comparable to that from an industry used for a similar purpose.
UR3.2 *Dose to an individual member of the public from an individual INS installation during normal operation should reflect an efficient implementation of the concept of optimization, and for increased flexibility in siting may be reduced below levels from existing facilities.*	3.2.1 Public dose values.	3.2.1 Less than the limits defined by national laws or international standards and so that the health hazard to the public is comparable to that from an industry used for a similar purpose

Safety Basic Principle BP3: ***Installations of an INS shall ensure that the risk from radiation exposures to workers, the public and the environment during construction/commissioning, operation, and decommissioning are comparable to the risk from other industrial facilities used for similar purposes.***

The basic principle reflects two concepts:

- It is life-cycle based. This principle asks for the optimization of radiation exposure to people inside and outside of a nuclear facility during the lifetime of a nuclear facility that is during construction, commissioning, operation and decommissioning.

- It is risk-based — i.e. the appropriate figure-of-merit for judging INS is the risk from other industries used for similar purposes.

Note that the basic principle does not apply to accidents, for which optimization is not a useful tool. The requirement to avoid undue burden from radiation doses to the public during accidents is met via User Requirement UR1.5, which states that there should be no need for evacuation.

Safety User Requirement UR3.1: *INS installations should ensure an efficient implementation of the concept of optimization of radiation protection through the use of automation, remote maintenance and operational experience from existing designs.*

For normal operation, this user requirement repeats the internationally accepted principle of dose optimization for nuclear energy workers. However doses from operating facilities are already low, so it does not go beyond the optimization principle by asking for further *ad hoc* reductions in dose. The experience in existing reactors is that in-service inspection, periodic tests and repairs (including replacement) are the source of most occupational doses. The user requirement anticipates that INS can take advantage of innovative design concepts to achieve occupational dose reduction as a zero-cost side-effect of aspects such as automated inspection and maintenance. Innovative designs should be maintenance-friendly through careful layout, reliable equipment, and availability of maintenance procedures electronically at the work-face to guide the maintainer.

Safety User Requirement UR3.2: *Dose to an individual member of the public from an individual INS installation during normal operation should reflect an efficient implementation of the concept of optimization, and for increased flexibility in siting may be reduced below levels from existing facilities.*

This user requirement applies the same principles to public dose optimization but no *ad hoc* reduction. Existing generation plants have a very low risk (compared to other industries) due to radiation exposure in normal operation and no dramatic changes are needed in innovative installations. It notes however that where an INS is located very close to densely populated areas (e.g. local district heating plants), further dose reduction may be required, e.g. by recycling waste streams, consistent with the practice that will be expected of other industries.

In comparing INS of radically different sizes, a more precise indicator than dose for these user requirements would be “Person-Sv per Unit energy”. Also some INS concepts have many units or different facilities co-located at one large site. For such scenarios a reduction in dose per unit or facility relative to existing facilities may be necessary to ensure that the dose from the entire site is acceptable.

In Table 5.5 the user requirements related to the research, development and demonstration (RD&D) that needs to be performed prior to the commercial deployment of INS are set out.

Table 5.5. User requirements and criteria related to safety basic principle BP4

Safety Basic Principle BP4: ***The development of INS shall include associated Research, Development and Demonstration work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing plants*.**		
User Requirements	Criteria	
	Indicators	Acceptance Limits
UR4.1 *The safety basis of INS installations should be confidently established prior to commercial deployment.*	4.1.1 Safety concept defined. 4.1.2. Design-related safety requirements specified. 4.1.3. Clear process for addressing safety issues.	Yes for all.
UR4.2 *Research, Development and Demonstration on the reliability of components and systems, including passive systems and inherent safety characteristics, should be performed to achieve a thorough understanding of all relevant physical and engineering phenomena required to support the safety assessment.*	4.2.1. RD&D defined and performed and database developed. 4.2.2. Computer codes or analytical methods developed and validated. 4.2.3. Scaling understood and/or full scale tests performed.	Yes for all.
UR4.3 *A reduced-scale pilot plant or large-scale demonstration facility should be built for reactors and/or fuel cycle processes, which represent a major departure from existing operating experience.*	4.3.1. Degree of novelty of the process. 4.3.2. Level of adequacy of the pilot facility.	4.3.1a. *High degree of novelty:* Facility specified, built, operated, and lessons learned documented. 4.3.1b. *Low degree of novelty*: Rationale provided for bypassing pilot plant. 4.3.2. Results sufficient to be extrapolated.

Table 5.5. User requirements and criteria related to safety basic principle BP4 (continued)

Safety Basic Principle BP4: ***The development of INS shall include associated Research, Development and Demonstration work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing plants*.**		
User Requirements	Criteria	
	Indicators	Acceptance Limits
UR4.4 *For the safety analysis, 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.*	4.4.1. Use of a risk informed approach. 4.4.2. Uncertainties and sensitivities identified and appropriately dealt with.	Yes to all.

The overall approach to deployment of a new technology is described in Chapter 3, Method for assessment.

In the following the basic principle and the corresponding user requirements and criteria are set out.

Safety Basic Principle BP4: ***The development of INS shall include associated Research, Development and Demonstration work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing plants*.**

Rationale for RD&D

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 (see also Chapter 4, Economics, and Chapter 3, Method for assessment, where the development cycle is discussed.). A recent OECD/NEA workshop on Advanced Nuclear Reactor Safety Issues and Research Needs [5-14] is of particular interest for planning and designing next generation reactors.

A sound knowledge of the phenomena, component, and system behaviour is required to develop computer models for accident analysis. Hence, the more the plant differs from existing designs, the more RD&D is required. RD&D provides the basis for understanding events that threaten the integrity of the barriers of the defence-in-depth structure. RD&D can also reduce allowances for uncertainties in design, operating envelopes, and in estimates for accident frequencies and consequences.

Integration of RD&D and Development of Safety Codes/Analytical Methods

As the development of an INS proceeds, RD&D is carried out to identify phenomena important to plant safety and operation and to develop and demonstrate an understanding of such phenomena. At any given point in the development process (see Tables 3.1 and 3.2 of Chapter 3, Method for assessment) the current understanding is incorporated into models that form the basis for design and for safety assessments. Such assessments are then used as a tool for sensitivity analyses (using both deterministic and probabilistic techniques) to identify important variables and to estimate safety margins. Phenomena Identification and Ranking Tables (PIRT assessments) can also be used to find and determine the importance of key phenomena. Such analyses are also used to identify coupled effects and interactions among systems that are important to safety. It is not unusual to obtain unexpected results, particularly in the early stages of development. The results, whether expected or not, are used to guide the RD&D program to e.g., improve conceptual understanding, obtain more accurate data, to confirm the extent of system interactions/independence, and characterize the design. The RD&D, in turn, leads to improvements in understanding and in the analytical tools used in design and in safety analyses. The process is iterative. At the pre-conceptual stage of development, physical understanding, analytical models, supporting data bases, and codes may be simplistic and involve significant uncertainties; but as development proceeds, understanding increases and uncertainties (both in conceptual understanding and in data) are reduced, and the validation of analytical models and codes improves. At the time of commercialization, all safety relevant phenomena and system interactions need to be identified and understood and the associated codes and models need to be adequately qualified and validated for use in the safety analyses, which in turn demonstrates that the plant design is safe.

The user requirements related to technical confidence (and set out in Table 5.5) are discussed in more detail below. Areas of RD&D that can already be anticipated are discussed in Section 5.4, below.

Safety User Requirement UR4.1: *The safety basis of INS installations should be confidently established prior to commercial deployment.*

The term "safety basis" is understood to be the documentation of the safety requirements and safety assessment of the plant design before it is being constructed and operated. The safety basis includes a well-defined concept for achieving safety with a logical and auditable process to determine and document all the design and safety requirements for the facility. Iteration among design, RD&D and safety analysis is a necessary part of this process. Once the requirements have been set, it must be demonstrated and documented that they are met.

Safety User Requirement UR4.2: *Research, Development and Demonstration on the reliability of components and systems, including passive systems and inherent safety characteristics, should be performed to achieve a thorough understanding of all relevant physical and engineering phenomena required to support the safety assessment.*

It is common practice to assess the system or component behaviour on the basis of code calculations, operating experience and commonly accepted engineering practice. The development of innovative designs may use new core materials, employ fluids in new thermo-hydraulic regimes, and use radically different fuels and coolants. Development of computer codes to model such designs should proceed in parallel. Such computer codes should be formally verified[18] and validated in their regions of applicability, using state-of-the-art techniques established in the international standards (validation matrices, uncertainty quantification, proof of scalability, automated verification tools, code qualification reports, etc.) and should be well described (software requirements specifications, theory manuals, user manuals, flow charts, etc.).

Uncertainties are taken into account by applying safety margins. For innovative installations, there is limited or zero operating experience. Computer codes and analytical methods 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. Where such tests are conducted in small-scale facilities, it is necessary to adopt appropriate scaling philosophies.

At least the following requirements 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 (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.

Safety User Requirement UR4.3: *A reduced-scale pilot plant or large-scale demonstration facility should be built for reactors and/or fuel cycle processes, which represent a major departure from existing operating experience.*

Demonstration of a new technology typically progresses from bench-scale experiments, to small-scale industrial tests, to large-scale tests, to (possibly) small pilot plants, to large-scale demonstration plants, to full commercialization. The need for a pilot plant or a demonstration plant will depend on the degree of novelty of the processes and the associated potential risk to the owner and the public.

It is recognized that a small pilot plant can to be used only to demonstrate adequate safety features for occurrences (abnormal operation and failures) corresponding to level 1 and 2 of the defence-in-depth concept. The safe behaviour of an INS during accidents (with a potential of radioactive release) cannot be studied in a pilot plant and has to be demonstrated as defined in the user requirement UR4.2 above, using codes or analyses validated against e.g. integrated multiple-effects tests. These methods are covered in user requirement UR4.4. Nonetheless, pilot plants should be able to demonstrate the ability to cope with potential accident initiators.

It is important that the pilot plant facility is of adequate scale, such that the results and experience gained from the facility could be extrapolated with a reasonable degree of

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[18] *Validation* is the comparison of a code prediction against experiment, to demonstrate its accuracy (bias) and uncertainty. *Verification* is the demonstration that the chosen physical models have been correctly incorporated into the code and that the internal code logic and numerical solution are correct.

accuracy to the full-scale plant, e.g. for a reprocessing plant to be constructed to process 100 tonnes of spent fuel per year, it may be appropriate to have a pilot plant that could process 1-10 tonnes per year, rather than a facility where only a few kg are processed.

Safety User Requirement UR4.4: *For the safety analysis, 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*

The safety analysis should be performed using a suitable combination of deterministic and probabilistic evaluations[19]. The analyses should cover all modes of operation of the installation to obtain a complete assessment of the compliance with defence-in-depth. In the case of simple installations, mainly related to the fuel cycle, only a deterministic analysis may be needed, as long as the scenarios are selected to demonstrate coverage of all levels of defence-in-depth.

The extent to which each method is used should be consistent with the confidence in the method for the particular application, in terms of reliability data, failure modes and physical phenomena. In some innovative systems, the application of probabilistic methods could be more restricted in comparison with those accepted for existing reactor types, as a result of changes in technology and the resulting limited availability of data.

The degree of conservatism in a deterministic safety analysis should be commensurate with the uncertainties in the technology evaluated; when the phenomena are well known and the codes are validated, a realistic hypothesis (best estimate) could be considered in the analysis. A best estimate analysis should be accompanied by a calculation of the experimental, model and plant uncertainties affecting the result. Where the technology itself is uncertain, a more traditional approach should be taken: for example, when other liquid metals than those used today are foreseen in a reactor, the existing codes are not sufficiently developed to simulate all phenomena. Until these tools are available and proven accurate enough, safety margins and conservatism should be implemented in the sequence simulations.

In addition to the assessment of the vulnerability of the installation to severe accidents and large releases, a probabilistic safety analysis should be used starting at the design stage to:

- Determine more realistic loads and conditions for mitigation systems, including containment;
- Assess the balance of the design and possible weakness;
- Integrate human factors into the safety analysis;

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[19] Deterministic Safety Analysis uses a pre-defined set of accidents to define the design of the safety systems. Normally pessimistic assumptions on accident initiation and evolution, plant state, and plant response are used; often computer codes with known conservatisms in their physical models are used. Safety analysis can also be done using realistic assumptions in these four areas, and is then called "Best Estimate" Analysis. Usually Best Estimate Analysis is coupled with a calculation of the uncertainty in the result, giving rise to "Best Estimate + Uncertainty Analysis" (BE+UA). Probabilistic Safety Analysis calculates the frequency and consequences of all accidents down to a very low probability level, in order: to determine the risk from the plant; to aid in design optimization; to aid in accident management, etc. Best Estimate Analysis is commonly used to calculate the consequences of the event sequences in a Probabilistic Safety Analysis, since a realistic answer is desired (so as not to distort the risk); and to estimate the margins in predicted plant behaviour between conservative deterministic safety analysis and 'reality'.

- Identify safety margins;
- Help to define operational safety requirements; and
- Identify sensitivities and uncertainties.

5.3.4. Specific aspects for fuel cycle facilities

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 of impacts from wastes are relatively more important, for example by recycling of low-level active liquid wastes within the plant after appropriate treatment, rather than discharge to the environment. 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, 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 [5-15, 5-16].

Dose apportionment is dependant on siting of the INS. The number and mix of facilities at a plant site should be consistent with a future vision for utilization of the site.

Mining and milling, conversion and enrichment for innovative fuel cycles should not bring a disproportionate additional risk to occupational and public health and the environment. Better utilization of thorium and uranium, implying less mining and milling per unit energy production, reduces the risk to occupational and public health in absolute terms. In effect, any approach which reduces mining and milling operations, or reduces the volume of fuel to be processed, is an innovative approach that influences not only risk factors, but also exposure to the public and the environmental impact of the fuel cycle operations. Thus, choice of fuel material and improvements in fuel design and operational philosophy, which would enable a fuel to reach higher levels of burn-up, meet the above innovation requirements, because the quantity of fuel to be processed (from milling to reprocessing) per unit energy production is reduced. This aspect is brought out under Chapter 7, Waste management, also.

The fuel type should be selected with a high priority given to safety for all portions of the fuel cycle, including, but not limited to, reactors. Specific safety requirements for the fuel will depend on the innovative reactor and fuel cycle installation concept. The selection of fuel types affects the safety of all steps of the integrated fuel cycle, from mining to disposal, in both normal operation and accident conditions. While the advanced fuels adopted for innovative reactors might achieve superior core performance to existing water reactors, some of their physical and chemical features may be weaker in terms of safety, compared with existing water-reactor fuel, requiring compensating design or operational procedures. The safety of fuel types should be evaluated for each step in the whole fuel cycle, including reactors, with emphasis (and compensation or mitigation) applied to any step where the safety is weaker.

The safety level for the fabrication of advanced fuel should be similar to the safety level for the fabrication of conventional water reactor fuels. However, other fuel fabrication methods would be required for advanced fuels of innovative reactors, such as vibro-packed, casting, coated particles, and molten salts. Criticality control should be addressed using established methods. Another aspect is that the raw material supplied for fabrication from reprocessing will include some actinides and long-lived fission products. Advanced fuels may have higher radioactivity and higher heat generation, causing technical challenges to fuel fabrication. Fuel fabrication installations should make much greater use of advanced instrumentation and automatic monitoring of material quantities and composition, and use the information to drive artificial-intelligence-based control — so as to compensate for the higher radio-toxicity of advanced fuels.

In developing innovative fuel, proper and safe handling of the fuel in interim storage, as well as waste management requirements (see Chapter 7, Waste Management), have to be kept in mind from the beginning. Spent fuel should be handled and stored with appropriate inspection, and qualification of fuel characteristics should be conducted in a timely manner. Expected higher burnup levels will result in higher concentration of Pu and other transuranic elements and increased decay heat generation in the spent fuel. The shielding of fuel handling equipment and spent fuel storage pools, as well as the systems for heat removal, have to be adjusted accordingly. Spent fuel should be stored without systematic fuel failure and release of radioactive material. Fuel in storage, storage containers as well as the facility itself should all be monitored to confirm their integrity.

The safety of advanced reprocessing/recycling should be at least comparable to the safety of conventional water reactor UO_2 reprocessing and U/Pu recycling in thermal reactors. In this context, it is recognized that some aspects of safety of Th/^{233}U reprocessing will be more challenging than those for conventional U/Pu recycling. Safety aspects of Reprocessing and Recycling include criticality, shielding, fire and explosion, and control and monitoring.

Transportation of innovative fuel cycle materials must consider aspects such as shielding, increased heat generation, dispersion, criticality, pilferage, etc. Transportation risks could be reduced if most or all fuel cycle activities are carried out on the same site, as envisioned for certain closed fuel cycle concepts.

The decommissioning strategy for innovative reactor and fuel cycle installations should include technical and administrative means to minimize public and worker radiation exposure. Ideally, a decommissioning plan should be available at the time of deployment of the installation. As a minimum, an outline decommissioning plan should normally be completed during the initial design phase of the nuclear power plant. The plan should be modified during operation to facilitate the completion of the final decommissioning plan at the end of operations and before the beginning of the decommissioning.

5.4. Areas of safety RD&D

The following RD&D areas can be anticipated:

Advanced nuclear power plant designs envisioned today 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. Further work is needed to better understand 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[20].

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

Innovative fuel designs will require tests on fuel performance including dimensional and mechanical stability, possible chemical interaction between fuel element and coolant, and mechanical-chemical interaction between fuel material and fuel element cladding.

INS may include *accelerator driven systems* (ADS), which transmute minor actinides and long-lived fission products. The spectrum of unresolved problems for which RD&D is required extends from proton/neutron physics (database) 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.

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.

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, which use 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;
- Accounting for ageing effects; and
- Quantifying the effects of random, data and modelling uncertainties.

Finally, the implementation of *defence-in-depth* (DID) for advanced reactors 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 would play an important role in the development of future reactors and fuel cycle facilities [5-17]. 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.

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;

- Obtain reliability data; and
- Develop tools for risk-informed decision-making.

5.5. Concluding remarks

For innovative nuclear reactors and fuel cycle installations, four basic principles have been formulated along with fourteen 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 defence-in-depth is considered a key element to avoid failure propagation from one level to the subsequent one. The number of physical barriers in a nuclear facility that are necessary to protect the environment and people depends on the potential internal and external hazards and the potential consequences of failures; therefore the barriers will vary in number and strength depending on the type of nuclear reactor (e.g. with high or very low power cores) or FCF.

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.

It is recognized 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 (e.g. dose) of the whole reactor and fuel cycle (including the associated waste treatment installations) should be evaluated at the concept definition stage for innovative nuclear reactors and fuel cycle installations. A balancing of risks, impacts, and economics should be sought to optimize global energy production.

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CHAPTER 6
ENVIRONMENT

6.1. Introduction

6.1.1. INPRO and the environment

As was previously mentioned in Chapter 2, INPRO and the concept of sustainability, the concept of sustainability can be considered from several related but different points of view: social, economic, environmental, and institutional. The present chapter deals with the environmental dimension of sustainability, by considering issues related to depletion of natural resources and environmental degradation.

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 Brundtland Commission [6-1], the Rio declarations on sustainable development [6-2], a Joint Convention of the IAEA [6-3] and others as discussed in Chapter 2, INPRO and the concept of sustainability.

The present generation should not compromise the ability of future generations to fulfil 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.

The purpose of INPRO is to support the development of nuclear technology that should be able to meet the global energy needs of the 21st century in a sustainable manner. To be sustainable, an INS must, among other things, be safe. Separate tasks of INPRO deal specifically with safety (Chapter 5, Safety of nuclear installations) 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.

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 considered. These costs are accounted for in Chapter 4, Economics.

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" [6-4]. 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.

Although INPRO deals with innovative systems that may be implemented in the next 50 years and beyond, 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.

6.1.2. Objectives

The objectives of this chapter 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 innovative nuclear energy systems are discussed in detail in Sections 6.2, 6.3, and summarized in Tables 6.1 and 6.2. Requirements for the method of assessment are outlined in Sections 6.4.

6.1.3. 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.

Figure 6.1 illustrates the factors involved in an assessment of environmental effects of a nuclear energy system. In particular the causal chain from source to effects is shown.

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.

An INS potentially will have adverse environmental effects that must be recognized in evaluating the system. At the same time, it must be recognized that the INS will have environmental benefits (e.g. nuclear power is acknowledged as a key technology in meeting global emission targets of Kyoto Protocol and UN Framework convention on climate change) that are very important. Although it is adverse effects and their minimization that are emphasized in assessing environmental performance, it is important that the existence of the benefits be always kept in mind.

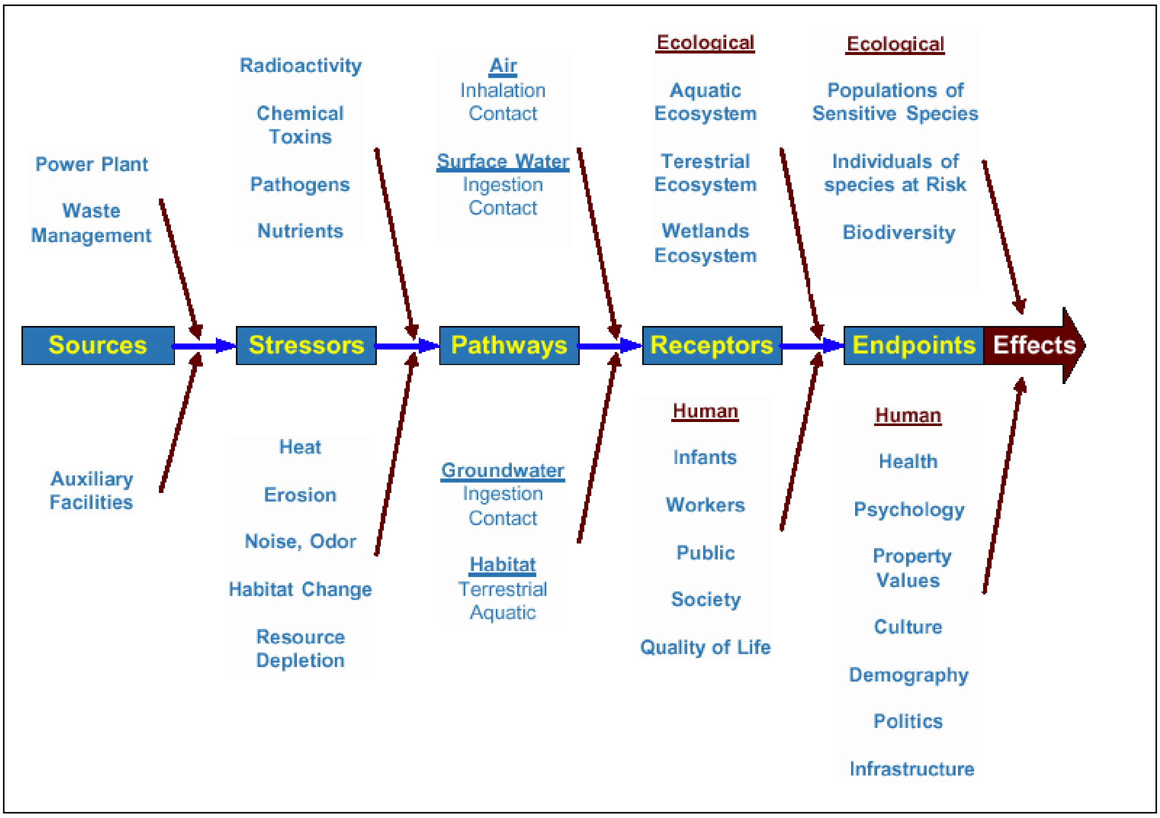

Figure 6.1. Factors in environmental assessment.

Both radiological and non-radiological effects are relevant. 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 nuclear energy systems as a whole and components within them with respect to their technical environmental performance as part of an overall INPRO technical evaluation.

6.2. Environmental basic principles

The following two basic principles have been defined for the area of environment:

Basic Principle BP1 (Acceptability of Expected Adverse Environmental Effects):

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

Basic Principle BP2 (Fitness for Purpose):

The innovative nuclear energy system shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources.

6.3. Environmental 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 6.1 and 6.2.

Table 6.1. User requirements and criteria related to environmental basic principle BP1

Environmental Basic Principle BP1: (Acceptability of Expected Adverse Environmental Effects) ***The expected (best estimate) adverse environmental effects of the innovative nuclear energy system shall be well within the performance envelope of current nuclear energy systems delivering similar energy products.***		
User Requirements	**Criteria**	
	Indicators	**Acceptance Limits**
UR1.1 *The environmental stressors from each part of the INS over the complete life cycle should be controllable to levels meeting or superior to current standards*.	1.1.1: L_{St-i} , level of stressor *i.*	1.1.1: $L_{St-i} \leq S_{i,}$ where S_i is the standard for stressor i .
UR1.2 *The likely adverse environmental effects attributable to the INS should be as low as reasonably practicable, social and economic factors taken into account*.	1.2 1: Does the INS reflect application of ALARP to limit environmental effects?	1.2.1: Yes.

In the following, the first environmental basic principle and its user requirements and criteria are briefly discussed.

Environmental Basic Principle BP1: (Acceptability of Expected Adverse Environmental Effects)

The expected (best estimate) adverse environmental effects of the innovative nuclear energy system shall 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 should 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 [6-5], which has examined the impacts of alternative energy production systems and has shown that the existing nuclear generation has a low relative impact. In some circumstances, it may be appropriate to use a standard that is expected to apply when the system is implemented. There is an expectation that the environmental performance of the innovative nuclear energy system will be better than that of an existing system.

For an INS, the most readily accessible measures of potential environmental effects are the stressors that result from the facilities and processes of the INS. The stressors include radioactive and non-radioactive chemical emissions, heat discharges and mechanical energy. The actual effects attributable to the stressors may differ significantly with geographical location and other site-specific and project-specific factors. However, all things being equal, the lower the level (magnitude) of a stressor, the lower will be the resultant environmental effect. Moreover, the stressors, as opposed to environmental pathways and receptors, are relatively more under the control of designers. For this reason, the primary measure of environmental effect used for INPRO is the set of environmental stressors associated with the INS.

Figure 6.2 helps to provide some clarification of the basic principle. Each stressor in either the INS, or a current nuclear system (CNS) chosen for comparison, is represented by a vector whose length is proportional to the level of the stressor. The radius of the circle passing along the vector represents the standard for that stressor. In this way each stressor can be represented relative to its standard, and all standards will lie on the circumference. The number of stressors illustrated is arbitrary and the relative magnitude of vectors representing different stressors is not meaningful. Stressors arising from the CNS are shown as blue arrows, and their magnitude is denoted as $L_{CNS\text{-}i}$. The green arrows represent the stressors arising from an INS and their magnitude is denoted by $L_{INS\text{-}i}$. Each environmental stressor from an INS must be located inside the red circle (i.e., must meet its standard). A current system may or may not be entirely inside the circle, depending on whether the current standards are different from those that applied when the CNS was implemented, as illustrated by $L_{CNS\text{-}4}$. As shown in the figure, some stressors arising from an INS may have a lower magnitude ($L_{INS\text{-}2}$, $L_{INS\text{-}4}$, $L_{INS\text{-}5}$) than the current energy system while some of them may be higher ($L_{INS\text{-}1}$) or the same ($L_{INS\text{-}6}$, $L_{INS\text{-}7}$). Some stressors from the current energy system may be eliminated by INS (one is illustrated by $L_{INS\text{-}3}$) while the INS may bring some new stressors (one is illustrated by $L_{INS\text{-}8}$). Note neither the magnitude of the blue or green area nor the angles at which the vectors are drawn represent any quantity. They are for visualization only.

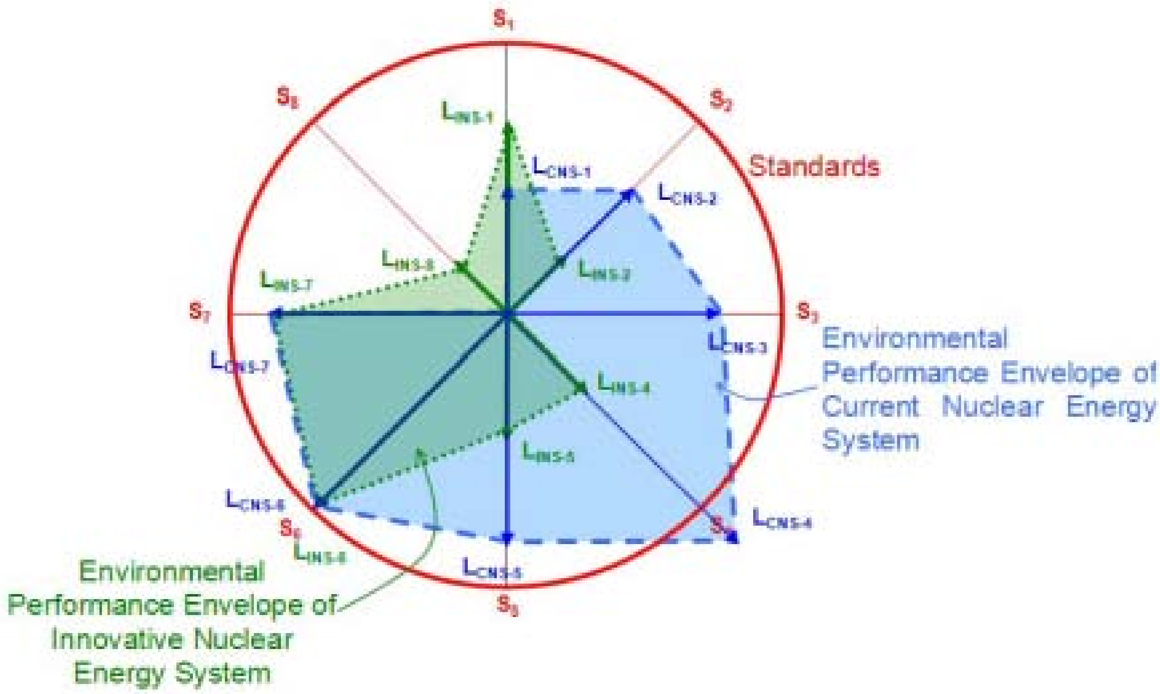

Figure 6.2. Environmental performance envelopes.

When all the stressors are considered, the performance envelope of an INS (green) should be well within the performance envelope of CNS (blue). This does not mean that the magnitude of all stressors of the INS must be smaller than that of the stressor in the current energy system. Rather, that, on balance, any stressor that is greater in the INS should be more than compensated by other stressors being lower. In case one or more of the stressors of the INS compares unfavourably with the corresponding stressor of the CNS, the use of multivariate analysis is suggested as one tool to assist with making the determination of the degree to which the INS is within the CNS environmental performance envelope. An alternative approach would be to express the level of all stressors commensurately so that they may be accumulated into a single "figure of merit". Both methods would introduce subjective judgments and both methods would also be useful for comparisons of one INS to another.

When stressor levels are used as part of a comparison between INSs it is important to normalize the stressor levels to per-unit-energy values.

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

The holistic approach recommended for the environmental analysis within INPRO is illustrated in Figure 6.3. The various components and flows included in the picture are described in following sections.

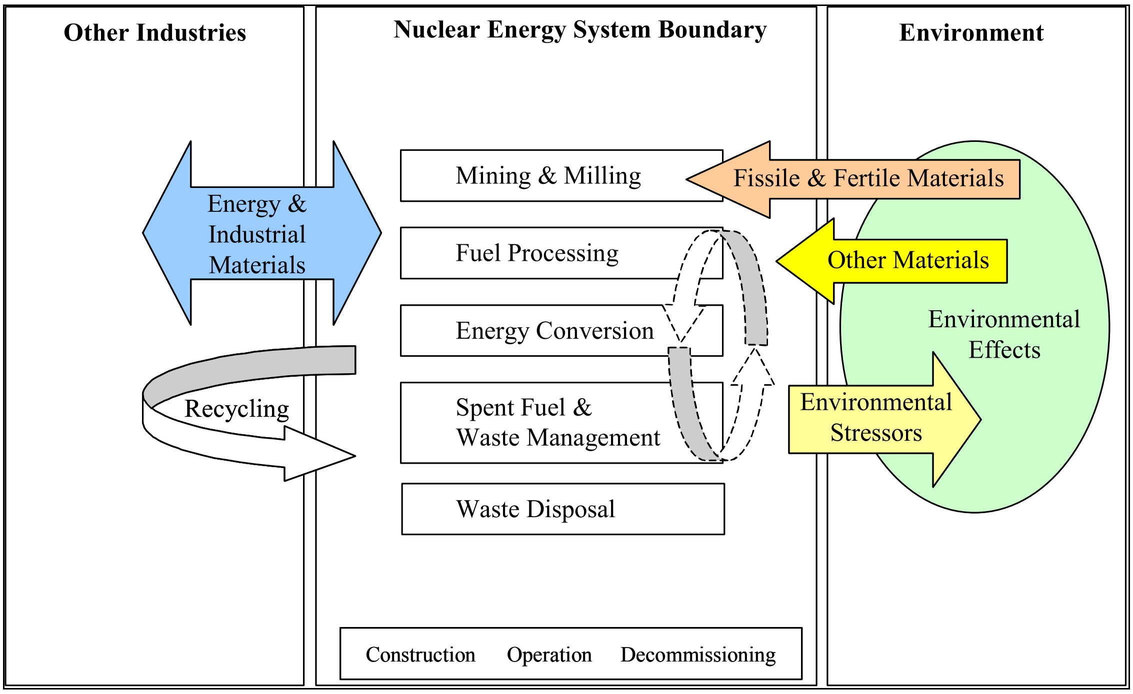

Figure 6.3. Holistic approach.

Environmental User Requirement UR1.1: (Controllability of Environmental Stressors)

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

Any energy system will inevitably introduce stressors to the environment, such as radio-nuclides or non-radioactive chemicals, and use of resources, with potentially adverse environmental effects on a local, regional or even global scale. The operators of the nuclear facilities and processes will be responsible for controlling the stressors. The 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 should 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.

Environmental User Requirement UR1.2: (Adverse Effects as Low as Reasonably Practicable)

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

An innovative nuclear energy system 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 (i) applies the philosophy of achieving the best performance reasonably practicable to the entire innovative nuclear energy system, (ii) extends it to all adverse environmental effects, not only radiological effects on humans, and (iii) 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). The ALARP analysis includes an evaluation of both the cost and benefit of reducing the level of significant environmental stressors. The evaluation would lead to either the implementation of a reduction method or rejection of a reduction on the grounds that the cost of the reduction would significantly outweigh the benefit.

In the following Table 6.2 the second environmental basic principle BP2 and its user requirements and criteria are presented.

Table 6.2. User requirements and criteria related to environmental basic principle BP2

Environmental Basic Principle BP2: (Fitness for Purpose) ***The INS shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources***		
UR2.1 (Consistency with Resource Availability) *The INS should be able to contribute to 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 INS. In addition, the INS should make efficient use of non-renewable resources.*	2.1.1: F_j (t) : quantity of fissile/fertile material j available for use in the INS at time t.	2.1.1: $F_j (t) > 0 \ \forall t <$ 100 years[21].
	2.1.2. Qi (t) : quantity of material i available for use in the INS at time t.	2.1.2. $Qi(t) > 0 \ \forall t <$ 100 years.
	2.1.3. P (t): power available (from both internal and external sources) for use in the INS at time t.	2.1.3. $P(t) \geq P_{INS}(t) \ \forall t$ < 100 years, where $P_{INS}(t)$ is the power required by the INS at time t.
	2.1.4. U : end use (net) energy delivered by the INS per Mg of uranium mined.	2.1.4. U > U0 U0 : maximum achievable for a once-through PWR.
	2.1.5. T : end use (net) energy delivered by the INS per Mg of thorium mined.	2.1.5. T > T0 T0 : maximum T achievable with a current operating thorium cycle.
	2.1.6. Ci : end use (net) energy delivered per Mg of limited non-renewable resource consumed.	2.1.6. Ci > C0 C0 to be determined on a case specific basis.
UR2.2 (Adequate Net Energy Output) *The energy output of the INS should exceed the energy required to implement and operate the INS within an acceptably short period.*	2.2.1. T_{EQ} : time required to match the total energy input with energy output (yrs).	2.2.1. $T_{EQ} \leq k \cdot T_L$ T_L : intended life of INS k < 1

21 "$F_j (t) > 0 \ \forall t < 100$ years" reads like : F_j (t) must be greater than zero for any time t less than 100 years.

In the following, the second basic principle and the corresponding user requirements and criteria are outlined.

Environmental Basic Principle BP2: (Fitness for Purpose)

The INS shall be capable of contributing to the energy needs in the 21st century 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.

Environmental User Requirement UR2.1: (Consistency with Resource Availability)

The INS should be able to contribute to 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 INS. In addition, the INS should make efficient use of non-renewable resources.

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 6.3).

The availability of resources when considering an INS should be considered on a global scale rather than on an individual nation basis. Also, the resources should include estimated additional resources beyond those currently proven. Whether or not non-conventional sources (e.g., extraction of uranium from seawater) are considered is at the discretion of the evaluators of the INS, and should be consistent with the economic evaluation of the INS. Such use of non-conventional resources would have implications not only for the environment, dealt with here, but also for cost, which must be dealt with in the economic analysis.

Assumptions regarding technologies for extraction of fissile and fertile material, breeding rates, etc., should be carefully reviewed for practicality. Requirements for other non-renewable resources must also be considered.

The INS will at any time require power (electrical or other) for facility operations, facility construction, etc. The indicator P(t) is the power available at time t for use by the INS from all sources, both internal and external to the INS. At any time throughout the life cycle, this power should equal or exceed $P_{INS}(t)$, the power requirement of the INS at time t. At the beginning of the INS life cycle, all of the power would need to be available from external sources, while at later times the source of much or all of the power for the operation of the system and/or its growth, may be internal to the INS.

Depletion of resources by other industries and their importance for these industries should also be taken into account.

Environmental User Requirement UR2.2: (Adequate Net Energy Output)

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

The net energy output of the INS 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. Obviously, the shorter the better. 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) [6-6] 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.

In the following, requirements on the methods used to assess the environmental performance of the nuclear energy system are outlined.

6.4. Requirements for assessment methods

6.4.1. Factors to be considered

All relevant factors (sources, stressors, pathways, receptors and endpoints) should be accounted for in the analysis of the environmental effects of a proposed energy system.

Figure 6.1 illustrates the factors involved in an assessment of environmental effects of a project. 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.

The first factors to be identified are the sources of stressors: power plants, auxiliary facilities, etc. Each source has associated stressors: releases of radio-nuclides, 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: e.g. human beings can be affected in their health, their property values, etc.

A complete overview of all the relevant factors that should be taken into account can be found in IAEA publications such as Refs [6-7 and 6-8].

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.

6.4.2. Complete system approach

The environmental performance of a proposed technology should 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 6.5.

6.4.3. Complete material flow

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

The material and energy flows can be categorized as follows (Figure 6.3):

- 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: (i) evaluating the potential impact of environmental stressors associated with the material flows, and (ii) 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 should 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.

6.4.4. 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.

6.5. Methods of assessment

6.5.1. Material and energy accounting

Life Cycle Assessment

Life Cycle Assessment (LCA) [6-9] 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 [6-10], 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) [6-11, 6-12].

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.

The evaluation of the environmental performance of an INS using INPRO environmental indicators may require use of specific expertise and engineering judgement for each of the INS components or at least for those components which are identified as the key contributors to the indicators. For innovative systems, extrapolation from existing studies may provide a useful basis for analysis.

Addressing effects due to (low-probability) accidents is more difficult, however these effects 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 Subsection 6.4.4.

Material Flow Assessment

Material Flow Assessment (MFA) [6-11, 6-13] 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 analyse 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: (i) 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, (ii) 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.

Radiation equivalence of radioactive waste and feed materials

Another useful method to synthesize all the environmental effects of radioactive waste on an equivalent basis is the so-called radiation equivalence. This method is based on a comparison of different properties of the radioactive waste and feed materials (uranium and thorium ore), as well as their respective impact on human health, plant and animal life (biota).

The parameters used for the comparison are deduced from the permissible concentration (Ci/t) and the dose factor (Sv/Bq), which are universally accepted parameters for comparing the radiation characteristics of materials.

Some other properties to be compared are: total decay time, specific energy release, radiation-equivalent activity, potential biological hazard (product of the nuclide's activity by the dose factor), etc.

A detailed description of the method can be found in Chapter 13 of the White Book of Nuclear Power [6-14].

6.5.2. Environmental effects

Figure 6.4 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.

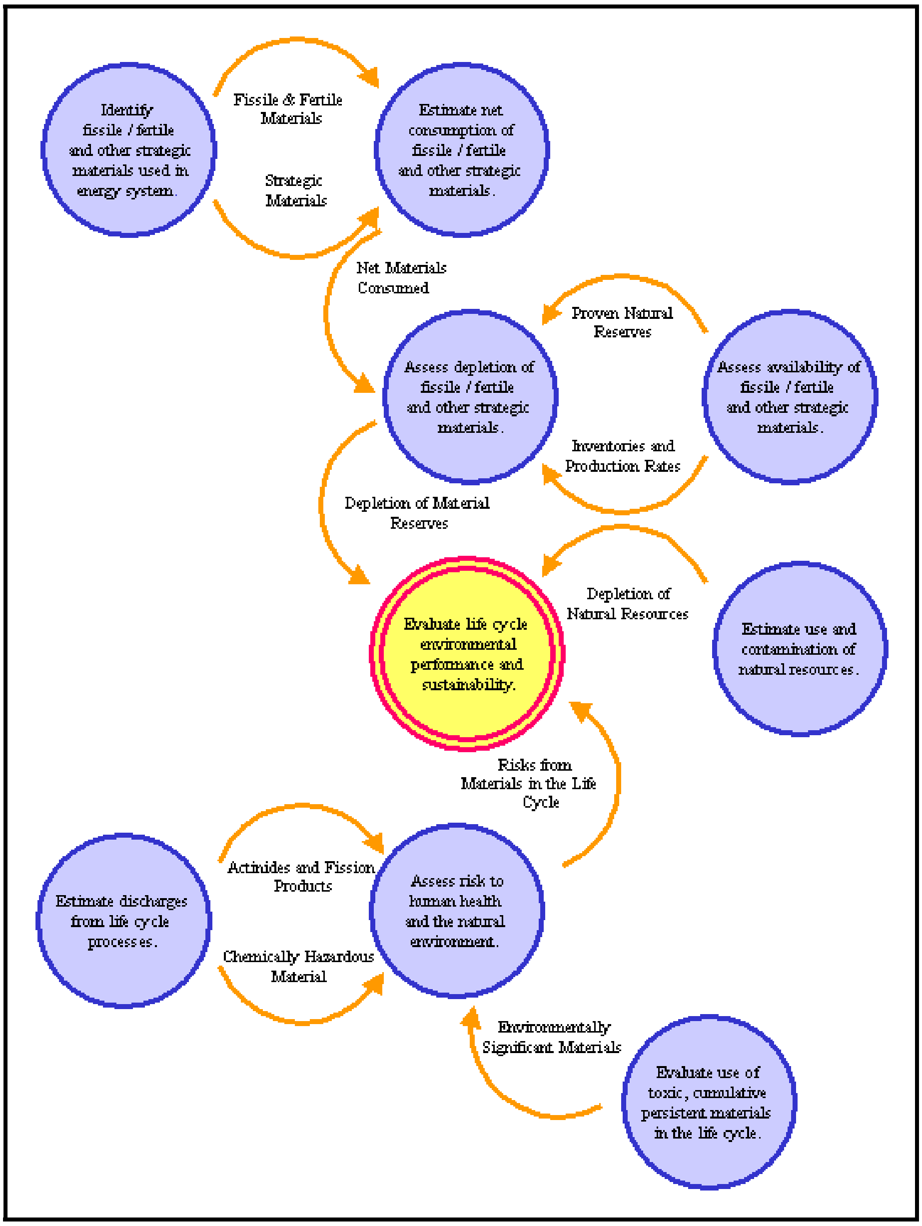

Figure 6.4. Information diagram for application of MFA/LCA to evaluation of environmental performance.

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.

- Evaluation of the use and depletion of natural resources (e.g. water and land) and of energy use by all parts of the system.

6.6. Further development of assessment methods

Development work should be focused on adapting LCA and MFA techniques to the specific requirements of INPRO. Preliminary suggestions follow.

6.6.1. Material accounting methods

Achievement of sufficiently detailed LCA and MFA may require the development of time-dependent material accounting in order to reflect time dependence of important parameters, such as system efficiency (which may improve over time) or energy mix. Tools for this purpose may be developed, and may need to be coupled with energy-economy models or waste management models. A code like DESAE, which among other things defines the amount of isotopes needed to calculate the activities of waste, further described in Chapter 10, Modeling, may be useful and applicable.

The major materials and energy forms should be identified and methods specified for estimating all their flows. Figure 6.3 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: (i) the flow of material through all stages of the life cycle; (ii) the inventories of the material at each stage; (iii) the time over which the materials remain accessible to the environment in both transient and steady state conditions; (iv) 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.

6.6.2. 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. A clear scientific basis is preferable to conservative analysis for determining the environmental detriment associated with various stressors. The measures of detriment should be practical for the uses in INPRO as well as sufficiently indicative of the environmental effects. Alternative approaches are: (i) use of commensurate values for all stressors with weighting factors or (ii) multivariate analysis. In both cases, the evaluation 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. Tools will need to be developed to effectively incorporate these judgments into a "figure of merit" analysis or a multivariate analysis.

One method of associating a commensurate value with each stressor would be to evaluate the associated external environmental cost (see Subsection 6.1.1). This would require development of a method to connect the stressors to the environmental effects that they cause. The location-dependency of the stressor-effect relationship may be dealt with by use of generic site characteristics or specific examples from different regions in which the facilities of the INS would be deployed. The method for calculating the external costs would need to be adapted to future economic conditions.

6.7. Concluding remarks

Environmental aspects are related to all characteristics of innovative reactors and fuel cycles: safety, economy, proliferation resistance, and the ability to meet the global energy needs of the 21st century in a sustainable manner. 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 INS shall be well within the performance envelope of current nuclear energy systems delivering similar energy products.

2) The INS shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources.

Arising from these basic principles are user requirements divided into two classes: requirements imposed on an innovative nuclear energy system, and requirements imposed on the methods used to assess its environmental performance.

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 6.3 and 6.4).

The techniques of Life Cycle Assessment and Materials Flow Analysis 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.

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CHAPTER 7
WASTE MANAGEMENT

7.1. Introduction

7.1.1. Purpose and objectives

According to the IAEA "...radioactive waste may be defined as material that contains, or is contaminated with, radio-nuclides at concentrations or activities greater than clearance levels as established by the regulatory body, and for which no use is foreseen" [7-1].

This chapter:

- Specifies and discusses basic principles and user requirements for safe management of radioactive waste in an innovative nuclear energy system (INS); and
- Recommends research, development and demonstration in the area of radioactive waste management to improve existing practices and investigate innovative approaches for INSs.

The radioactive waste arises from the following components of an INS:

- Mining, milling and extraction
- Uranium conversion
- Uranium enrichment
- Fuel fabrication
- Reactor operation
- Fuel reprocessing
- Management of spent fuel
- Waste management
- Decommissioning

The discussions in this chapter apply to all these components. The primary storage of spent fuel (e.g. in the fuel pool inside the plant) is dealt with in Chapter 5 "Safety of Nuclear Installations". This chapter deals with the management of spent fuel once it is moved from primary storage[22].

7.1.2. 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

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[22] By definition storage at the reactor site can be considered primary storage as long as the reactor remains in operation under an operating license. Once the reactor enters decommissioning, the spent fuel would either be removed to a waste management facility or, if it were to remain in the site storage facility, the storage facility would cease to be considered primary storage but rather a waste management facility that would therefore need to comply with the BPs, URs and CRs set out in this chapter.

innovative nuclear energy systems should include improvements in the safe management of radioactive waste. In fact, to be successful any innovative technology must emphasize long-term waste management to a degree consistent with its importance to society.

7.2. Basic principles in the area of waste management

An INS requires measures that will protect human health and the environment from adverse effects of radioactive waste now and in the future. The measures should not impose undue burdens on future generations.

The IAEA has issued a set of nine fundamental principles for radioactive waste management [7-1]. Four basic principles governing all innovative nuclear energy systems for INPRO are derived from these nine fundamental principles. The relationship of the INPRO basic principles and the IAEA fundamental principles is shown in Table 7.1.

Table 7.1. Relationship between the INPRO basic principles and the IAEA fundamental principles

<table>
<tr><th>No.</th><th>Safety Series Principles</th><th>INPRO Basic Principles</th></tr>
<tr><td>7.</td><td>Generation of radioactive waste shall be kept to a minimum practicable.</td><td>Basic Principle BP1: Minimization
Generation of radioactive waste in an INS shall be kept to the minimum practicable.</td></tr>
<tr><td>1.</td><td>Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.</td><td rowspan="5">Basic Principle BP2: Protection of human health and environment
Radioactive waste in an INS shall be managed in such a way as to secure an acceptable level of protection for human health and the environment, regardless of the time or place at which impacts may occur.</td></tr>
<tr><td>2.</td><td>Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.</td></tr>
<tr><td>3.</td><td>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.</td></tr>
<tr><td>4.</td><td>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.</td></tr>
<tr><td>9.</td><td>The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.</td></tr>
<tr><td>5.</td><td>Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.</td><td>Basic Principle BP3: Burden on future generations
Radioactive waste in an INS shall be managed in such a way that it will not impose undue burdens on future generations.</td></tr>
<tr><td>8.</td><td>Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.</td><td>Basic Principle BP4: Waste optimization
Interactions and relationships among all waste generation and management steps shall be accounted for in the design of the INS, such that overall operational and long-term safety is optimized.</td></tr>
<tr><td>6.</td><td>Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.</td><td>(This principle falls outside the scope of the chapter on waste management. It is treated in the chapter on Infrastructure.)</td></tr>
</table>

7.3. User requirements and criteria in the area of waste management

Criteria associated with the user requirements are listed in Tables 7.2 to 7.5. In addition to the INPRO requirements, guidance is also provided in the IAEA Safety Standards Series and other documents applicable today [7-2 to 7-25].

After each of the Tables 7.2 to 7.5, a short discussion of the BP, UR and CR is provided.

Table 7.2. User requirement and criteria arising from waste management basic principle BP1

Waste management Basic Principle BP1: (Waste minimization) ***Generation of radioactive waste in an INS shall be kept to the minimum practicable.***		
User Requirement	**Criteria**	
	Indicators	**Acceptance Limits**
UR1.1 (Reduction of waste at the source): *The INS should be designed to minimize the generation of waste at all stages, with emphasis on waste containing long-lived toxic components that would be mobile in a repository environment.*	Alpha-emitters and other long-lived radio-nuclides per GWa.	ALARP
	Total activity per GWa.	ALARP
	Mass per GWa.	ALARP
	Volume per GWa.	ALARP
	Chemically toxic elements that would become part of the radioactive waste per GWa.	ALARP

In the following the first waste management basic principle and its user requirement and criteria are briefly discussed.

Waste management Basic Principle BP1: (Waste minimization)

Generation of radioactive waste in an INS shall be kept to the minimum practicable.

In keeping with the globally accepted principle of pollution prevention, the INS should be designed such that the generation of radioactive waste is the minimum practicable, in terms of its activity and volume.

Waste management User Requirement UR1.1: (Reduction of Waste at the Source)

The INS should be designed to minimize the generation of waste at all stages, with emphasis on waste containing long-lived toxic components that would be mobile in a repository environment.

The first basic principle states that the generation of radioactive waste shall be kept to a minimum practicable. Reduction of waste 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 inherently safer than depending upon operational practices. It is particularly important to reduce components of the waste that are toxic for a long time and that are mobile in the repository environment.

Methods for reducing the radioactive waste include:

- Segregation of waste streams to avoid cross contamination, 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 dismantling of facilities; and
- Extraction of long-lived decay products in mining and milling operations; and
- Reduction of secondary waste from waste management systems.

Technologies worthy of consideration for further development include:

- Improvement of both aqueous and non-aqueous methods of processing spent fuel;
- Partition and transmutation (P&T) of long-lived radio-nuclides 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.

Table 7.3. User requirements and criteria arising from waste management basic principle BP2

Waste management Basic Principle BP2: (Protection of human health and the environment) ***Radioactive waste in an INS shall be managed in such a way as to secure an acceptable level of protection for human health and the environment, regardless of the time or place at which impacts may occur.***		
User Requirements	**Criteria**	
	Indicators	**Acceptance Limits**
UR2.1: (Protection of Human Health) *Exposure of humans to radiation and chemicals from INS waste management systems should be below currently accepted levels and protection of human health from exposure to radiation and chemically toxic substances should be optimised.*	2.1.1 Estimated dose rate to an individual of the critical group 2.1.2 Radiological exposure of workers 2.1.3 Estimated concentrations of chemical toxins in working areas	2.1.1 Meets regulatory standards of specific Member State[23]. 2.1.2 Meets regulatory standards of specific Member State. 2.1.3 Meet regulatory standards of specific Member State.
Waste management Basic Principle BP2: (Protection of human health and the environment) ***Radioactive waste in an INS shall be managed in such a way as to secure an acceptable level of protection for human health and the environment, regardless of the time or place at which impacts may occur.***		
User Requirements	**Criteria**	
	Indicators	**Acceptance Limits**
UR2.2: (Protection of the Environment) *The cumulative releases of radio-nuclides and chemical toxins from waste management components of the INS should be optimised.*	Estimated releases of radio-nuclides and chemical toxins from waste management facilities	Meet regulatory standards of specific Member State.

[23] In all cases when the regulatory requirement of a Member State is indicated, any available international guidance should be taken into account as well.

In the following the second waste management basic principle and its user requirements and criteria are briefly discussed.

Waste management Basic Principle BP2: (Protection of human health and the environment)

***Radioactive waste in an INS shall be managed in such a way as to secure an acceptable level of protection for human health and the environment, regardless of the time or place at which impacts may occur*.**

Humans must be protected from both the radio-toxicity and chemical toxicity of radioactive waste that arises from an INS. Particular attention needs to be paid to controlling the various ways by which humans might be exposed to radiation, and to ensuring that such exposure is within established requirements. Such requirements typically take account of the recommendations of the International Commission on Radiological Protection (ICRP) and the IAEA for protection of human health from the effects of ionizing radiation, which include the concepts of justification, optimization, and dose limitation. Thus, any waste generating component of an INS would need to be justifiable, be part of a suitably optimized system, and be associated with an appropriate management system to limit the dose received by humans.

The activities associated with the INS and their consequences may be separated by long time intervals. An evaluation of the safety of radioactive waste management for an INS should take into account the facts that the benefits and the exposures might affect populations separated by many generations, that long time periods lead to increased uncertainties in the results of safety assessments, and that radio-nuclides decay.

When radio-nuclides are released into the environment, species other than humans can be exposed to ionizing radiation, and the impacts of such exposures should be taken into consideration. Moreover, any adverse effects on the future availability or utilization of natural resources over extended periods of time should be considered.

As a matter of ethics, the consideration of the effects of radio-active waste on human health and the environment should not be limited by national boundaries. Similarly, the consideration of effects should not be limited by time, but should recognize the ethical principle that the health of future generations and their environment are to be protected to at least to the level of current standards. While it is not possible to ensure total isolation of radioactive waste over extended time-scales, the intent is to achieve reasonable assurance that there will be no unacceptable impacts on human health. In considering the effects of radioactive waste from the INS, uncertainties in long-term safety assessment due to the inherent difficulty in predicting impacts far into the future should be taken into account.

Waste management User Requirement UR2.1: (Protection of Human Health)

Exposure of humans to radiation and chemicals from INS waste management systems should be below currently accepted levels and protection of human health from exposure to radiation and chemically toxic substances should be optimized.

The requirement arises from the second basic principle. 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 assessing an INS holistically. Thus, the optimization of any single component is secondary. The factors to be considered include:

- Radio-toxicity, as a function of time, of the waste generated;
- Ability of the waste form to retain radio-nuclides under normal and accident conditions;
- Mobility of the toxic elements through environmental pathways;
- The length of time that wastes containing long-lived radio-nuclides remain in interim storage;
- The degree to which the waste 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 radio-toxicity of spent fuel decreases as the result of radioactive decay. The long-term radio-toxicity is due primarily to actinides and a small number of fission products with very long half-lives. Transmutation of these long-lived nuclides into shorter-lived nuclides would reduce the long-term radio-toxicity 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 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. 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 fuel would be necessary. Such reprocessing would mobilize the actinides as well, whether or not they are subjected to transmutation processes. Thus, the evaluation of whether or not to transmute actinides 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.

Waste management User Requirement UR2.2: (Protection of the Environment)

The cumulative releases of radio-nuclides and chemical toxins from waste management components of the INS should be optimized.

Like the previous requirement, this one arises from the second basic principle. All parts of the energy system should be considered in an integrated manner to be consistent with the requirements set out in (Chapter 6, Environment), and the complete life cycle of each component of each facility should be considered (cradle to grave). Cumulative releases over time and space, without regard to national boundaries, should be considered. Non-radioactive releases from the management of the radioactive waste should also be taken into account. The first priority is to minimize, by design, the generation of the waste. The next priority is to incorporate improvements in processing into the waste management system.

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, chemically the important long-lived nuclides, e.g., ^{230}Th, ^{226}Ra, should be considered in designing mining and milling processes for an INS.

Fuel types

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

- ThO2 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 radio-nuclides, 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 waste. Burning actinides in the PHWR can reduce fuel radio-toxicity.
- 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 radio-nuclides.

Reactors

All aspects of reactor design and operation should be reviewed to identify possibilities for reducing the volumes of waste. 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 FP. If so, the long-lived radio-nuclides 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 waste 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; 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); and
- 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.

Table 7.4. User requirements and criteria arising from waste management basic principle BP3

Waste Management Basic Principle BP3*:* (Burden on future generations) ***Radioactive waste in an INS shall be managed in such a way that it will not impose undue burdens on future generations.***		
User Requirements	**Criteria**	
	Indicators	**Acceptance Limits**
UR3.1 (End State): *An achievable end state should be specified for each class of waste, which provides permanent safety without further modification. 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 any release of hazardous materials to the environment will be below that which is acceptable today.*	3.1.1 Availability of technology. 3.1.2.Time required. 3.1.3 Availability of resources. 3.1.4 Safety of the end state (long-term expected dose to an individual of the critical group). 3.1.5 Time to reach the end state.	3.1.1 All required technology is currently available[24] or reasonably expected to be available on a schedule compatible with the schedule for introducing the proposed innovative fuel cycle. 3.1.2 Any time required to bring the technology to the industrial scale must be less than the time specified to achieve the end state. 3.1.3 Resources (funding, space, capacity, etc.) available for achieving the end state compatible with the size and growth rate of the energy system. 3.1.4 Meet regulatory standards of specific Member State. 3.1.5 As short as reasonably practicable.
UR3.2 (Attribution of Waste Management Costs): *The costs of managing all waste in the life cycle should be included in the estimated cost of energy from the INS, 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.

In the following the third waste management basic principle and its user requirements and criteria are briefly discussed.

[24] 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.

Waste Management Basic Principle BP3: (Burden on future generations)

Radioactive waste in an INS shall be managed in such a way that it will not impose undue burdens on future generations.

This principle is based on the ethical consideration that the generations that receive the benefits of a practice should bear the responsibility to manage the resulting waste. Limited actions, however, may be passed to succeeding generations, for example, the continuation of institutional control over a disposal facility, if and as needed.

The INS plan should include provision for construction and operation of facilities, and provision of funding for safe management of the waste in the future, and the disposal of the waste at an appropriate time. The plans for management of the radioactive waste should, to the extent possible, not rely on long-term institutional arrangements or actions as a necessary safety feature, recognizing that the reliability of such arrangements is expected to decrease with time.

Waste Management User requirement UR3.1: (End State)

An achievable end state should be specified for each class of waste, which provides permanent safety without further modification. 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 any release of hazardous materials to the environment will be below that which is acceptable today.

This requirement arises from the third basic principle, which states that radioactive waste shall be managed in such a way that it will not impose undue burdens on future generations. 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.

By definition, the state of the waste that provides permanent safety without further modification is 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, 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 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. 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. It is recognized that, during the INPRO evaluation, demonstration of safety would in general be impractical. The safety case would need to rely on generally accepted theoretical analysis combined with evidence of component performance to the extent possible from present day operations of relevant facilities. For example, a waste form satisfying waste acceptance criteria of current disposal facilities would be acceptable.

Waste management User Requirement UR3.2: (Attribution of Waste Management Costs)

The costs of managing all waste in the life cycle should be included in the estimated cost of energy from the INS, in such a way as to cover the accumulated liability at any stage of the life cycle.

The third basic principle states that radioactive waste shall be managed so as not to impose undue burdens on future generations. Thus, people in the future 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 internalization of all costs is a fundamental requirement of sound environmental management.

In principle, the assets accumulated to manage the waste 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 internalize 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 associated with waste management should be included in the estimated cost of the INS.

Table 7.5. User requirements and criteria arising from waste management basic principle BP4

<table>
<tr><td colspan="3">Waste Management Basic Principle BP4: (Waste optimization)

Interactions and relationships among all waste generation and management steps shall be accounted for in the design of the INS, such that overall operational and long-term safety is optimized.</td></tr>
<tr><td rowspan="2">User Requirements</td><td colspan="2">Criteria</td></tr>
<tr><td>Indicators</td><td>Acceptance Limits</td></tr>
<tr><td>UR4.1 (Waste Classification):
The radioactive waste arising from the INS should be classified to facilitate waste management in all parts of the INS.</td><td>Classification scheme.</td><td>The scheme permits unambiguous, practical segregation and measurement of waste arisings.</td></tr>
<tr><td rowspan="3">UR4.2 (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.</td><td>Time to produce the waste form specified for the end state.</td><td>As short as reasonably practicable.</td></tr>
<tr><td>Technical indicators: e.g., Criticality compliance;

Heat removal provisions;

Radioactive emission control measures;

Radiation protection; measures (shielding etc.);

Volume / activity reduction measures; and

Waste forms.</td><td>Criteria as prescribed by regulatory bodies of specific Member States.</td></tr>
<tr><td>Process descriptions that encompass the entire waste life cycle.</td><td>Complete chain of processes from generation to final end state and sufficiently detailed to make evident the feasibility of all steps.</td></tr>
</table>

In the following the fourth waste management basic principle and its user requirements and criteria are briefly discussed.

Waste Management Basic Principle BP4: (Waste optimization)

Interactions and relationships among all waste generation and management steps shall be accounted for in the design of the INS, such that overall operational and long-term safety is optimized.

The basic steps in radioactive waste management: pre-treatment, treatment, conditioning, storage, transportation, and disposal should be considered in the plan for an INS. There are interdependencies among the steps in waste management. Decisions on radioactive waste management made at one step may foreclose alternatives for, or otherwise affect, a subsequent step. Furthermore, there are relationships between waste management steps and other operations in the INS. These interactions should be recognized so that, overall, safety and effectiveness of radioactive waste management are balanced. Conflicting requirements that could compromise operational and long-term safety should be avoided. The effects of all waste management activities up to and including disposal should be taken into account in the design and planning of the INS.

Since the steps of radioactive waste management occur at different times, there are, in practice, many situations where decisions must be made before all radioactive waste management activities are established. As far as reasonably practicable, the effects of future radioactive waste management activities, particularly disposal, should be taken into account when any one radioactive waste management activity is being considered.

Waste Management User Requirement UR4.1: (Waste Classification)

The radioactive waste arising from the INS should be classified to facilitate waste management in all parts of the INS.

The fourth basic principle refers to optimization of the waste management process with respect to overall operational and long-term safety. This will require a waste classification scheme that facilitates optimal management of various waste types within the INS.

Classification of radioactive waste provides a link between the waste characteristics and the requirements for waste management safety in the INS [7-9]. All waste in each category of the classification scheme should have a common end state, and the scheme should be applicable to the entire fuel cycle. (See discussion of UR4.2 for a detailed description of the end state).

Waste Management User Requirement UR4.2: (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

The fourth basic principle deals with the steps in pre-disposal waste management. By definition, the state of the waste that provides permanent safety without further modification 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 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. 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, which is not appropriate in the long term, has led to a legacy of large amounts of such waste. This waste must now be subject to remediation at great cost to the present generation, and 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 an industrial scale should be evident, either through demonstration or confirmed conceptual design, before the energy system is implemented. This will give confidence 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.

Factors important to achieving safety and other pre-disposal waste management requirements include:

- Quantities and potential hazards of the waste;
- Necessary degree of isolation of the waste;

- Dispersibility and mobility of the waste forms involved;
- Experience with, and maturity of the technology, and potential for future advances;
- Reliability of equipment and its safety-related function;
- Complexity and degree of standardization of the activities;
- Novelty and maturity of the activity; and
- Organization size, number and complexity of interfaces and safety culture.

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.

7.4. Recommended research and development

The adverse effects of radioactive waste in innovative nuclear energy systems can potentially be reduced by RD&D on relevant technologies. Table 7.6 summarizes recommended areas that offer particularly good potential for reducing these adverse effects. Detailed information is available in IAEA Working Materials prepared during INPRO Phase 1A.

Table 7.6. Recommended research

Waste Management Element	**RD&D Targets**	**Expected time for results**
Methods of characterizing waste in the nuclear fuel cycle	Reduce occupational exposure and improve efficiency. Facilitate showing compliance with waste acceptance criteria.	Short (<5a)
Waste treatment and conditioning methods	Reduce radiological impact from storage and disposal of waste. Decrease the amount of hazardous material requiring disposal. Improve the waste forms (chemical durability, mechanical stability, etc.).	Medium (5 – 10 a)
Reprocessing of spent fuel (inc. partitioning)	Improve waste stream characteristics. Reduce secondary waste. Improve separation of recyclable nuclides.	Medium to Long
Interim Storage Methods	Increase safety of interim storage.	Short to Medium
Transmutation	Reduce long-lived radioactive components in HLW. Demonstrate transmutation technology.	Medium to Long

Table 7.6. Recommended research (continued)

Waste Management Element	RD&D Targets	Expected time for results
Geological Disposal	Demonstrate disposal technologies. Improve geological characterization. Enhance understanding of hydro-geo-chemical transport processes. Improve long-term monitoring technologies. Facilitate the detailed design of geological repositories. Continue the development of performance assessment methods.	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

7.5. Concluding remarks

Nine fundamental principles for safety of radioactive waste management have been developed by the IAEA. From these fundamental principles, four basic principles relating to waste management safety for an INS are derived. Based on these four basic principles, seven user requirements have been developed. For each of these user requirements, criteria have been specified.

All aspects of radioactive waste management for innovative systems can benefit from RD&D in areas such as methods of waste characterization, waste treatment and conditioning methods, spent fuel interim storage, reprocessing, transmutation, geological disposal, long term human factors, and design-based comparisons of waste arising from proposed innovative reactors and fuel cycles.

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CHAPTER 8
PROLIFERATION RESISTANCE

8.1. 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 IAEA 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. With sufficient cooperation and resources, any INS can be adequately safeguarded, but it is important to bear in mind that the cost of providing safeguards assurances depends, *inter alia*, 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.

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 alia, on site inspections. This term has different meanings 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 [8-1]. "**National safeguards**" will be used to refer to a State System of Accounting and Control, along with physical protection.

8.2. 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.

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.

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.

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.

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.

Examples of intrinsic features are [8-5, 8-6]: 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.

For future INS, development and implementation of intrinsic features compatible with other design considerations should be encouraged.

8.2.1. Some further considerations on intrinsic features

A number of high-level intrinsic features have been raised in recent discussions regarding proliferation resistance for an INS. These include, *inter alia*, multi-national fuel cycle facilities[25], co-location of fuel cycle facilities, closure of fuel cycles, stockpiling, and the potential significance of source material. While all of these could be significant to portions of the fuel cycle, the overall proliferation resistance of an INS (full fuel cycle, full life cycle) is paramount and requires comprehensive assessment using widely accepted methods.

Centralization and co-location of fuel cycle facilities have both been proposed to address proliferation. Centralization can provide stronger international control of proliferation-

[25] Multi-national fuel cycle facilities require extrinsic measures to implement, but provide intrinsic features because States do not acquire their own fuel cycle facilities and need to transport nuclear material to and from the multi-national fuel cycle facilities.

sensitive enrichment and reprocessing technology. Co-location can limit transportation and storage of potentially proliferation-sensitive materials.

Closure of the fuel cycle is an important consideration in the assessment of proliferation resistance for an INS. Effective closure of the fuel cycle is an intrinsic feature that could provide benefit by addressing the growing inventories of spent fuel. Similarly, fuel cycles that minimize the quantity of nuclear material in the fuel cycle, and minimize the production of proliferation sensitive materials that cannot be burned in a closed fuel cycle could provide benefits for proliferation resistance. It is important to recognize however, that closure and the quantity of material do not generally provide proliferation resistance, and that an overall assessment is required to examine the many intrinsic features and extrinsic measures that would contribute to the proliferation resistance of a specific closed fuel cycle.

One consideration that is often raised in discussions about closed fuel cycles is “stockpiling”, or maintaining excessive inventories of nuclear material. Minimizing inventories of sensitive nuclear material that could be readily utilized in a nuclear weapons program provides benefits for proliferation resistance, but a comprehensive assessment is required to verify that a fuel cycle with small inventories does not provide other avenues for proliferation such as undeclared production.

Natural uranium, depleted uranium, and thorium provide input material for many fuel cycles. Although not directly useable in a nuclear weapon, these materials require due consideration in a proliferation resistance assessment because they can be used as source material to generate weapons useable materials.

8.3. Extrinsic measures

Regardless of the level of effectiveness of the intrinsic features, extrinsic measures will always be required.

Extrinsic proliferation resistance measures result from States’ decisions and undertakings related to nuclear energy systems and can be divided into five categories [8-4]. The first are States’ commitments, obligations and policies with regard to nuclear non-proliferation. These include the Treaty on the Non-Proliferation of Nuclear Weapons (the NPT) and nuclear-weapons-free zone treaties, comprehensive IAEA safeguards agreements[26] and protocols additional to such agreements.[27]

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.

The third category consists of commercial, legal or institutional arrangements that control access to nuclear material and nuclear energy systems. This can include use of multi-national fuel cycle facilities, and arrangements for spent fuel take-back.

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[26] Comprehensive IAEA safeguards agreements are based upon INFCIRC/153, [8-2].

[27] Additional Protocols are based upon INFCIRC/540, [8-3].

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.

8.4. Background

Proliferation resistance differs from most other considerations for an INS for a number of reasons. First, proliferation is a malevolent human activity. In contrast, other areas are primarily concerned with technical aspects such as equipment/system failures, radioactive releases, costs, human health, etc. Whereas in most areas it is assumed that agreements are respected and followed, with proliferation it is assumed that non-proliferation agreements are broken.

Because proliferation involves the interaction between two sides (the proliferator and the safeguarder/defender), it is sometimes examined using gaming theory. The choices that each side makes depend to some extent on what choices they expect the other side to make. This human element must be considered in making a comprehensive assessment of proliferation resistance, and is further complicated because many analysts believe that proliferators would disregard common safety and environmental norms.

Another complication with assessment of proliferation resistance is that it requires a means to handle sensitive information without disclosing the sensitive details. For example, detailed understanding of how the nuclear material characteristics (e.g. isotopic composition, chemical composition, etc.) affect a nuclear explosive is generally classified information. This makes assessment of the proliferation resistance provided by material characteristics difficult when considered in more than a coarse sense (e.g. HEU versus LEU or WG Pu versus RG Pu).

Many of the elements considered in making an assessment of proliferation resistance are inherently qualitative and difficult to quantify. Some elements, such as treaties, agreements, and policies are difficult to quantify because of variations in strength, quality and degree of compliance (a political judgement). Others are difficult to quantify because they involve human choices and activities that are outside of the range of normal experience. For example, the technique for extracting Pu from irradiated targets can vary considerably depending on what the potential proliferator is prepared to do. If human health is not a significant consideration, then extraction can be performed with minimal shielding and protective equipment.

8.5. Basic principles in the area of proliferation resistance

Two basic principles provide high-level guidance regarding innovative nuclear energy systems.

Basic Principle BP1: ***Proliferation resistance features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.***

Basic Principle BP2: ***Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.***

These BPs emphasize the importance of both intrinsic features and extrinsic measures. The development and implementation of intrinsic features that enhance proliferation resistance and are compatible with other design considerations should be encouraged. At the same time, regardless of the effectiveness of the intrinsic features, extrinsic measures will always be required. Even with the most proliferation resistance INS, extrinsic measures would be required to verify that the INS had not been modified so as to reduce the strength of the barriers provided by the intrinsic features.

8.6. User requirements and criteria in the area of proliferation resistance

Five top-level user requirements provide guidance regarding innovative nuclear energy systems. As noted before, this list of user requirements is not intended to be complete or exhaustive, but to provide high-level guidance. Clear and transparent tools to perform proliferation resistance assessments will be required to evaluate INSs against the criteria.

The following Tables 8.1 and 8.2 set out the user requirements and criteria for the basic principles defined above.

Table 8.1. User requirements and criteria for proliferation resistance basic principle BP1

Basic Principle BP1: ***Proliferation resistance features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.***		
Requirements	**Criteria**	
	Indicator	**Acceptance Limits**
UR1.1 *States' commitments, obligations and policies regarding non-proliferation should be adequate.*	1.1.1 States' commitments, obligations and policies regarding non-proliferation.	1.1.1 A set of commitments, obligations and policies regarded as acceptable by the international community.
UR1.2 *The attractiveness of nuclear material in an INS for a nuclear weapons programme should be low. This includes the attractiveness of undeclared nuclear material that could credibly be produced or processed in the INS.*	1.2.1. Material Attractiveness.	1.2.1 ALARP[28].
UR1.3 *The diversion of nuclear material should be reasonably difficult and detectable. Diversion includes the use of an INS facility for the introduction, production or processing of undeclared nuclear material.*	1.3.1 Difficulty and detectability of diversion.	1.3.1. Difficulty and detectability sufficient to make the implementation of an independent nuclear weapons program more attractive than use of the INS. (Methods to evaluate this indicator do not currently exist.)

[28]The attractiveness of NM reflects its suitability for conversion into nuclear explosive devices. A coarse basis for measuring attractiveness could be the IAEA safeguards categories of irradiated DU, un-irradiated DU and Indirect Use materials. Further work would be required to refine this scale to provide finer gradation between different materials. Other categorization schemes and approaches to evaluating the attractiveness of NM exist e.g. US DOE material attractiveness categories I to IV for nuclear materials (ref. US DOE Order 5633.3A); and Russian General Rules for Accounting and Control of Nuclear Material (OPUK).

In the following the rationale of the first basic principle and its related user requirements is presented.

Proliferation Resistance Basic Principle BP1: ***Proliferation resistance features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.***

The first basic principle is that intrinsic features and extrinsic measures for PR be implemented throughout the full life cycle of an INS. This requires that consideration is given to proliferations resistance in all major decisions made by the responsible bodies regarding a INS, including design concepts, R&D, demonstration facilities etc. The BP goes on to explain that the reason for such implementation is to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.

The term *implemented* is used in this BP to refer to the range of activities that occur over the life cycle of an INS. Early in the conceptual design the term *implemented* refers to consideration of PR in making basic design choices such as the fuel cycle. These design choices can provide intrinsic PR features (e.g. isotopic content, chemical form, physical form, radiation fields, nuclear material flows and inventories) that affect the attractiveness of the nuclear material in production, use, transport, storage and disposal.

As design progresses, the term *implemented* refers to making design choices that create other intrinsic PR features in the INS facilities, and policy choices that result in extrinsic measures that strengthen the PR of the INS. During construction, key intrinsic features must be verified (verification is an extrinsic measure), as the facilities are built. During operation of an INS, safeguards (extrinsic measure) are implemented. In some cases other extrinsic measures such as fuel arrangements may be implemented to enhance proliferation resistance. Operators must consider the impact of facility changes on the PR.

Some examples of intrinsic features that affect PR during the shutdown and decommissioning phases for an INS are the inventories of nuclear material in the facilities, and the ease with which portions of the facilities could be restarted for use in a weapons program.

In the explanation of the reason for requiring that PR features and measures be implemented, the BP includes the phrase “will continue to be”, implying that current nuclear technology provides a baseline standard for PR in a qualitative sense. The term fissile is used in this BP to refer to the fissile material that is ultimately required to make a nuclear explosive. This does not detract from the role that fertile nuclear material can serve in a nuclear weapons program, but recognizes that fertile material is used to generate fissile material to manufacture the explosive.

Proliferation Resistance User Requirement UR1.1:

States’ commitments, obligations and policies regarding non-proliferation should be adequate.

State commitments, obligations and policies regarding non-proliferation have considerable impact on the proliferation resistance of an INS. Consequently the first UR is that these should be adequate. The indicator is the commitments, obligations and policies themselves. Because the impact of extrinsic measures on PR depends on characteristics of the specific state involved, the acceptance limit for this indicator is necessarily that the set of commitments, obligations and policies be regarded as acceptable by the international community. The availability of indigenous uranium is one example of a state-specific characteristic that might affect how important extrinsic fuel supply arrangements are to PR for an INS.

Proliferation Resistance User Requirement UR1.2:

The attractiveness of nuclear material in an INS for a nuclear weapons programme should be low. This includes the attractiveness of undeclared nuclear material that could credibly be produced or processed in the INS.

Nuclear material can vary considerably in how useful it is for use in a nuclear weapons program. This utility is commonly referred to as material attractiveness or quality. An INS would have a range of declared nuclear material, as well as nuclear material that could be acquired through misuse of INS services, equipment or facilities, that could be targets for a proliferator to use in weapons programme. There is currently no defined metric for material attractiveness, and the term generally refers to key material characteristics such as isotopic content, chemical form, etc. Several categorization schemes for nuclear materials can be used as a coarse basis for assessing material attractiveness. One example would be to use the IAEA safeguards categories described in the Safeguards Glossary, taking into account the necessary additional processing steps required to get weapons useable material. The US DOE material attractiveness categories I to IV for nuclear materials (USDOE Order 5633.3A) and the Russian General Rules for Accounting and Control of Nuclear Material (OPUK) provide similar categorization schemes.

The second user requirement is that the attractiveness of the nuclear materials in an INS be low. The indicator is the material attractiveness itself and the acceptance limit is that the attractiveness be as low as reasonably achievable. In assessing this indicator, it must be recognized that an INS may contain a wide range of nuclear materials and that the quality of each material will differ. Care is required in determining how to present or aggregate the quality values for the different materials. Some aggregation methods could obscure a weak link. For example averaging the values might hide the fact that an INS contains a large quantity of high quality material. Other aggregation methods could place unwarranted emphasis on insignificant material. For example, a fuel cycle might involve a small quantity of good quality material for a short period in the life cycle of the INS. Aggregating by selecting the highest material quality might highlight this material, without recognizing that the opportunity for diversion is limited.

Proliferation Resistance User Requirement UR1.3:

The diversion of nuclear material should be reasonably difficult and detectable. Diversion includes the use of an INS facility for the introduction, production or processing of undeclared nuclear material.

A key barrier to proliferation is the difficulty of diversion and the risk of detection. The latter provides both a deterrent and an opportunity to detect and react to the proliferation activity. UR1.3 requires that diversion be reasonably difficult and detectable. The indicator is the difficulty and detectability, and the acceptance limit is that these be sufficient to make the implementation of an independent nuclear weapons program more attractive than using the INS.

The level of difficulty and detectability required to make a potential proliferator prefer to implement an independent nuclear weapons program depends on the proliferator; in particular his goals, strategy, and preferences. Past proliferation attempts have not involved nuclear energy systems constructed for peaceful use, suggesting that the difficulty and detectability of current nuclear energy systems is sufficient to make an independent nuclear weapons program more attractive. This could provide a qualitative benchmark acceptance limit for this indicator and is consistent with the implication in BP1 that current nuclear technology provides a baseline standard for PR in a qualitative sense.

Methods to evaluate this indicator do not currently exist. The term detectability might be quantified as detection probability, a concept used in designing safeguards and security systems, but accepted metrics for difficulty do not currently exist. Development of methods for the assessment of proliferation resistance, including this indicator, is discussed further in Section 8.7.

In the following the user requirements and criteria for the second basic principle in the area of proliferation resistance are set out.

Table 8.2 User requirements and criteria for proliferation resistance basic principle BP2

Basic Principle BP2: ***Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.***

User Requirements	Criteria	
	Indicators	**Acceptance Limits**
UR2.1 *Innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures.*	2.1.1 The extent by which the INS is covered by multiple intrinsic features. "Extent" is the fraction of plausible acquisition paths. It is understood that each acquisition path is covered by appropriate verification measures.	2.1.1 Some % TBD, recognizing that this % might best be a flexible target because some intrinsic features adversely affect verification. Variables: Multiple refers to any combination of variable attributes listed under UR1.1.
	2.1.2 Robustness of barriers covering an acquisition path.	2.1.2 Robustness is an inherently qualitative concept. Defeating a robust barrier requires significant effort and time and hence is detectable.
UR2.2 *The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized (in the design/engineering phase) to provide cost-efficient proliferation resistance.*	2.2.1 Cost to incorporate those intrinsic features and extrinsic measures, which are required to provide proliferation resistance.	2.2.1 Minimal Cost (understanding that an acceptable level of proliferation resistance is required by User Requirement UR1.1).
	2.2.2 Verification approach with a level of extrinsic measures agreed to between the verification authority (e.g. IAEA, Regional safeguards organizations, etc.) and the State.	2.2.2 Yes.

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In the following the rationale of the second basic principle and its related user requirements are discussed.

Proliferation Resistance Basic Principle BP2: ***Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.***

The second basic principle recognizes that both intrinsic features and extrinsic measures are essential for achieving proliferation resistance and that neither should be considered sufficient by itself. Even a system with extremely robust intrinsic PR features requires safeguards (an extrinsic measure) for periodic re-verification that the facilities have not been changed in a way that facilitates bypassing of the intrinsic features.

Proliferation Resistance User Requirement UR2.1:

Innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures.

The second indicator for this UR is the robustness (strength) of the barriers covering each acquisition path. Robustness is inherently a qualitative concept. Defeating a robust barrier requires significant time and effort, and hence increases the likelihood of detection. While some arbitrary scales for robustness have been proposed in the context of PR, none has been widely adopted. Evaluation of robustness and adoption of a scale are required before an acceptance limit for this indicator can be established.

In evaluating the overall robustness provided by a set of barriers covering an acquisition path, it is important to account for interdependencies among the barriers provided by intrinsic features. In some cases, the actions required to overcome one barrier will overcome multiple barriers. For example, high radiation field, chemical form, mass and bulk might all appear to provide barriers that impede separation of Pu from spent fuel, but successful dissolution of the spent fuel might simultaneously overcome or reduces all of these barriers. Hence, evaluation of this indicator requires a comprehensive examination of barriers in the context of acquisition pathways. Development of methods for the assessment of proliferation resistance, including this indicator, is discussed further in Section 8.7.

Proliferation Resistance User Requirement UR2.2:

The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized (in the design/engineering phase) to provide cost-efficient proliferation resistance.

Subject to international cooperation and sufficient resource, every INS can be adequately safeguarded but the effort required to implement the verification measures varies. UR2.2 recognizes that there are cost trade-offs between intrinsic features and extrinsic measures, and encourages their optimization for cost effectiveness. The UR further recognizes that the features and measures must be compatible with other design considerations such as safety and economics, and that the verification costs must be reasonable.

In this UR, the term "optimized" refers to the result of an optimization process as opposed to a mathematically optimal result. During development of an INS, intrinsic design features that would reduce the cost of extrinsic measures, notably verification, should be considered. Intrinsic features specifically to enhance the PR of the INS should be included in the design where they are compatible with other design considerations, and where the anticipated saving in the cost of applying extrinsic measures over the life of the INS outweigh the cost to incorporate the intrinsic feature.

The first indicator for this UR is the cost to incorporate intrinsic features and extrinsic measures, which are required to provide proliferation resistance. Some technical features that provide PR may be incorporated in the design of an INS primarily for other reasons such as safety or functionality. In evaluating this indicator it is important to only include the incremental cost of making technical choices to provide PR. Where two choices exist, and the more costly one is selected because it provides enhanced proliferation resistance, then the difference between the cost of the two choices should be recognized as a cost to incorporate an intrinsic feature.

The acceptance limit for this indicator is minimal total cost for all of the intrinsic features and extrinsic measures over the life cycle of the INS, recognizing that an INS must have an acceptable level of PR, as required by other URs. The term "minimal" should be understood to be the result of the optimization process specified in the UR, as opposed to a true mathematically minimal result. Evaluation of this indicator can be performed through an assessment of the INS. The acceptance limit is met if the conclusion of the assessment is that there are no potential design changes consistent with other design considerations, that would significantly reduce the total cost of the intrinsic features and extrinsic measures (primarily verification). This is similar to performing an analysis of the sensitivity of the cost for extrinsic measures relative to INS design changes.

The second indicator for this UR is that an INS must have a verification approach with a level of extrinsic measures agreed to between the verification authorities and the State. This indicator establishes a flexible limit on the maximum verification effort for an INS, that limit being set by the verification authorities during their development of a verification approach in consultation with the State.

8.7. Variables for evaluation of indicators

Further work is required to establish a set of variables for evaluation of the indicators.

Indicator IN1.1.1 (related to User Requirement UR1.1) would be evaluated through review of a States' commitments, obligations and policies regarding non-proliferation. This is necessarily a state-specific indicator. Examples of relevant commitments, obligations and policies include:

- 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; and
- An effective international response mechanism for violations.

Evaluation of Indicator IN1.2.1, material attractiveness, requires examination of material characteristics such as the following:

- Isotopic content;
- Chemical form;
- Radiation field;
- Heat generated; and
- Spontaneous neutron generation rate.

Evaluation of Indicators IN1.3.1, IN2.1.1, IN2.1.2 requires examination of a wide range of material, facility, and process characteristics such as the following:

- Isotopic content of each nuclear material target;
- Chemical form of each nuclear material target;
- Radiation field from each nuclear material target;
- Heat generated from each nuclear material target;
- Spontaneous neutron generation rate from each nuclear material target;
- Complexity of, and time required for modifications necessary to use a civilian INS for a weapons production facility;
- Mass and bulk of each nuclear material target;
- 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; and
- Material stocks and flows.

Evaluation of Indicator IN2.2.1 require examination of extrinsic measures and intrinsic features including all potentially applicable features and measures, along with their anticipated cost. As discussed in Section 8.6, evaluation is expected to be done through an assessment similar to sensitivity analysis and is not expected to require exhaustive examination of all features and measures.

The one variable for indicator IN2.2.2 is agreement between the State and the verification authorities on a verification approach.

8.8. Assessment of proliferation resistance

Application of the requirements presented in Section 8.6 requires an accepted means to assess the proliferation resistance of a nuclear energy system, using clear and transparent tools. 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 used 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 similar to those used in safety and physical security analysis to examine material and facility targets within the INS [8-7].

It is important to recognize that while assessment methodologies can be developed to assess the proliferation resistance of an INS, care is required when making comparison between different INSs. Different INSs will have different strengths and weaknesses with regard to PR. Assessments can identify the strengths and weaknesses to aid with decision-making, but assessments cannot generally render a judgement as to which system is stronger with regard to PR. Aggregation methods to generate a single score for PR based on the strengths and weaknesses identified in an assessment can be misleading, possibly hiding weak links.

Proliferation resistance includes both purely technical and state-specific considerations. The strength of the proliferation resistance provided by some intrinsic features can depend on state-specific information such as, *inter alia*, the presence of indigenous uranium resources or the presence of other nuclear facilities. Similarly, state-specific extrinsic measures such as fuel supply agreements for procurement of fresh fuel and return of spent fuel (e.g. commitment to multilateral fuel cycle facilities) can affect the proliferation resistance of an INS. On the other hand, intrinsic features that facilitate verification generally provide proliferation resistance independent of the State in which the INS is deployed. Proliferation resistance assessments must address both aspects. Where required, credible stylized state descriptions can provide a means to address the state-specific aspects early in the design process.

Because assessment of proliferation resistance is a difficult and complex task, it is likely that initial assessment methods 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.

8.9. Research and development

Concentrated efforts are required to develop a widely accepted method for conducting assessments of proliferation resistance as discussed in Section 8.7. Such a method will support efforts 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 coordinating such research and development remains to be established.

8.10. Glossary for proliferation resistance[29]

The glossary summarizes definitions for key terms used in this section. Additional clarification on terms can be obtained from the IAEA Safeguards Glossary.

Acquisition path	A (hypothetical) scheme, which a State could consider, based on its existing (declared) nuclear fuel cycle-related capabilities, to acquire nuclear material useable for manufacturing a nuclear explosive device. An acquisition strategy could include a diversion strategy and could involve the use of an undeclared facility or undeclared nuclear material.
Barrier	Impediment to proliferation.
Complementary	In the context of features and measures, a feature or measure that, taken in combination with other applicable features and measures, provides a complete set.
Continuity of knowledge	Uninterrupted knowledge of essential information relevant to verification.
Diversion	The undeclared removal of declared nuclear material from a safeguarded facility; or the use of a safeguarded facility for the introduction, production, or processing of undeclared nuclear material.
Extrinsic proliferation resistance measures	Measures that result from States' decisions and undertakings related to nuclear energy systems.
Intrinsic proliferation resistance features	Features that result from the technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures.
Material attractiveness	A measure of the degree to which a material is desirable for use in a nuclear weapons programme. The term generally refers to key material characteristics such as isotopic content, chemical form, etc., and a defined metric does not exist.
Misuse	The use of non-nuclear material, services, equipment, facilities or information placed under safeguards to further any proscribed use. An INS facility can be misused for the purpose of producing nuclear weapons by such undeclared actions as, *inter alia,* irradiation of fertile targets, separation of fissile material, or isotopic enrichment.
National safeguards	State System of Accounting and Control, along with physical protection and export control.

[29] These definitions are for discussions of proliferation resistance within INPRO.

Proliferation Resistance	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*.
Redundant	Provision of alternative (identical or diverse) *structures, systems or components*, so that any one can perform the required function regardless of the state of operation or *failure* of any other.
Regional safeguards	A regime of independent international verification of commitments made by States within Regional Agreements such as the Euratom Treaty or the Guadalajara Declaration.
Robust	Strong enough to resist defeat
Safeguards	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.
Target	Nuclear material or a facility that could be used by a potential proliferator in an acquisition path.
Undeclared	Clandestine activities, facilities or material not disclosed to verification authorities as required by binding agreements.

References to Chapter 8

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[8-4] INTERNATIONAL ATOMIC ENERGY AGENCY DEPARTMENT OF SAFEGUARDS, Proliferation Resistance Fundamentals for Future Nuclear Energy Systems, STR-332, IAEA, Vienna (2002).

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[8-6] 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).

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CHAPTER 9
NATIONAL, REGIONAL AND INTERNATIONAL INFRASTRUCTURE

9.1. 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, defines a Basic Principle and corresponding User Requirements and Criteria, and indicates potential 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 so safe that they could be 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, global standardization of requirements and regulations could facilitate cost reductions by enabling assembly line type production for large series of plants. 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 [9-1] and [9-2]. In addition to presenting basic principles and corresponding user requirements based on the information provided in the referenced documents, 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.

9.2. Basic principle for infrastructure

The following basic principle regarding infrastructure was defined:

Regional and international arrangements shall provide options that enable any country that so wishes to adopt INS for the supply of energy and related products without making an excessive investment in national infrastructure.

9.3. User requirements and criteria for infrastructure

In the following Table 9.1 the user requirements and criteria are defined for the basic principle above.

Table 9.1 User requirements and criteria related to infrastructure

Infrastructure Basic Principle **BP1**: ***Regional and international arrangements shall provide options that enable any country that so wishes to adopt INS for the supply of energy and related products without making an excessive investment in national infrastructure.***		
User Requirements	**Criteria**	
	Indicators	**Acceptance Limits**
UR1.1 (Legal and institutional infrastructure): *Prior to deployment of an INS installation, a national legal framework should be established covering the issues of nuclear liability, safety and radiation protection, control of operation and security, and proliferation resistance.*	1.1.1 Legal framework established. 1.1.2 Safety and radiation protection arrangements established.	1.1.1 and 1.1.2: In accordance with international standards.
UR1.2 (Economical and industrial infrastructure): *The industrial and economic infrastructure of a country planning to install an INS installation should be adequate to support the project during construction and operation.*	1.2.1 Availability of credit lines. 1.2.2 Demand for and price of energy products. 1.2.3 Size of installation. 1.2.4 Support infrastructure. 1.2.5 Value of proposed nuclear installation (VNI).	1.2.1 Sufficient to cover project. 1.2.2 Adequate to enable ROI[30]. 1.2.3 Matches local needs. 1.2.4.Internally or externally available. 1.2.5 VNI > NII NII = national infrastructure investment necessary to support nuclear installation.
UR1.3 (Socio-political infrastructure): *Adequate measures should be taken to achieve public acceptance of a planned INS installation.*	1.3.1 Information to public. 1.3.2 Participation of public in decision-making process (to foster public acceptance). 1.3.3 Long-term commitment. 1.3.4 Public acceptance of nuclear power.	1.3.1 and 1.3.2 Sufficient according to best international practice. 1.3.3 Sufficient to enable ROI[30]. 1.3.4 Sufficient to ensure there is negligible political or policy risk to the investment.
UR1.4 (Socio-political infrastructure): *The necessary human resources should be available to enable an operating organization to maintain a safety culture to achieve safe operation of the INS installation. The operating organization should have enough knowledge of the plant to be an intelligent customer and should keep a stable cadre of trained staff.*	1.4.1 Availability of human resources. 1.4.2 Evidence that safety culture prevails. 1.4.3 Benefit to society (BTS) of the INS.	1.4.1 Sufficient according to international experience. 1.4.2 Presence of periodic safety review mechanism, covering technical infrastructure and management areas. 1.4.3 BTS > costs necessary to establish and maintain the required expertise.

[30] To be evaluated as part of the economic assessment, see Section 4.3.

In the following the basic principle and related user requirements for infrastructure together with their trends and expected developments are discussed in more detail.

Infrastructure Basic Principle BP1: ***Regional and international arrangements shall provide options that enable any country that so wishes to adopt INS for the supply of energy and related products without making an excessive investment in national infrastructure.***

The nuclear power infrastructure may be defined to be all features or substructures that are necessary in a given country for the successful deployment and operation of an INS including legal, institutional, industrial, economic and socio-political features and substructures. In this chapter some of the main features that comprise current nuclear power infrastructures are highlighted. As indicated in the introduction, additionally the infrastructure needs for deployment of INS in the future are examined in the light of possible changing world circumstances.

It is recognized that in adopting nuclear technology for the supply of energy requires some investment in national capability – at the very least to position a country to be a knowledgeable purchaser – but the idea is that a country has options concerning the upfront investment required because of the wide range of services and products available internationally, including even regulatory services.

Different countries may have different aspirations and capacities concerning nuclear energy. For example countries might be characterized as follows:

1) Countries who develop and use nuclear energy technology and have a well developed national nuclear infrastructure and who have an interest in developing INS components.

2) Countries who do not use nuclear energy technology but have a well developed national nuclear infrastructure for non energy uses and have a limited interest in developing INS components but who are interested in acquiring INS, e.g., for electricity production.

3) Countries who have a significant industrial capacity but little or no national nuclear infrastructure and who have a need and interest in acquiring INS and building their national capabilities but not in developing an INS.

4) Countries with limited industrial capacity and little or no national nuclear infrastructure but who have a need for energy and who could benefit if energy or energy products from INS were available to them without significant infrastructure investment.

Other types of countries could be specified reflecting other factors such as domestic energy resources, including uranium, geographic regions, populations, etc., and groups of countries that may benefit from sharing resources.

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 the government decreases. However as noted in Chapter 2, INPRO and the concept of sustainability, ensuring the availability of affordable energy should be one of a government's basic responsibilities. In some countries this responsibility includes providing the necessary funding of appropriate RD&D to assure sustainable energy development.

The SRES scenarios created by IIASA (see Chapter 2 and Section 4.1 of Ref. [9-8]) indicate that the growth of nuclear power will be facilitated by globalization and internationalization of the world economy, and that the growth of demand for energy 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.

Infrastructure User Requirements UR1.1: (Legal and institutional infrastructure)

Prior to deployment of an INS installation, the legal framework should be established covering the issues of nuclear liability, safety and radiation protection, control of operation and security, and non-proliferation.

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. The implementation of the legal framework involves organizations and institutions (e.g. nuclear safety and radiation protection authorities), which could be national, regional or even international, in particular in the areas of policy, regulation and RD&D. National standards for safety should comply with internationally agreed standards and guidelines and international conventions on the safety of nuclear installations and waste management (see Refs cited in [9-1] and [9-2] and page 7 of Ref. [9-3]) have been ratified by a majority of countries that are using nuclear power. Current guidance can be found in Ref. [9-9], but this may need to be developed in the future to improve the possibility of introducing INS.

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. [9-1]). Currently, 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. [9-1]).

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 [9-1] 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. Currently, 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. Even without this international certification, bilateral arrangements may achieve improvements, simplification and reduced infrastructure and licensing costs.

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.

Two main developments could affect the existing legal structures with beneficial effects. In the first place, the development of INS to comply with the Basic Principles, Requirements and Criteria set out in earlier chapters of this report could make it possible to change the way the use 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 nuclear 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 Member States in which the system would be used. Conditions for the realization 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.

Infrastructure Requirement UR1.2: (Economical and industrial infrastructure)

The industrial and economic infrastructure of a country planning to install an INS installation should be adequate to support the project during construction and operation.

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 [9-1] and [9-2] and the references cited therein.

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 (e.g. engineering and manufacturing companies) 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 fabrication capabilities. Using the international market for fuel supply has proven to be reliable and it is normally cheaper. For the final disposal of the spent fuel or waste (after reprocessing of spent fuel), however, it is common that countries have to put in place their own disposal facilities within their national boundaries. The availability of disposal facilities that can accept spent fuel or waste from a variety of countries [9-4], particularly from those countries that operate a small nuclear energy system, or the return of spent fuel to the country of manufacture of new fuel 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 or necessary 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. 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 [9-5, 9-6].

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, e.g. enabling the return of spent fuel and high level waste to country of origin of the new fuel. 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;

- Development of commercial arrangements may simplify infrastructure requirements. Commercial contracts for BOO/BOT may reduce local needs to create additional infrastructure;

- 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.

Infrastructure User Requirement UR1.3 : (Socio-political infrastructure)

Adequate measures should be taken to achieve public acceptance of a planned INS installation.

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. In a minority of countries public opposition has stopped the building of new nuclear plants and led, in these 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, 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. INPRO has developed Basic Principles, User Requirements and Criteria for innovative reactors and fuel cycles in each of these areas. 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 internationally acceptable 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 internationally acceptable 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. Comparative risk assessment methods should further be developed to enable risks from INS to be compared accurately with risks from other energy sources and the results of such assessments also need to be clearly communicated. 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 [9-3].

Infrastructure User Requirement UR1.4 : (Socio-political infrastructure)

The necessary human resources should be available to enable an operating organization to maintain a safety culture to achieve safe operation of the INS installation. The operating organization should have enough knowledge of the plant to be an intelligent customer and should keep a stable cadre of trained staff.

The development and use of nuclear power technology requires adequate human resources and knowledge. There is already concern in some countries 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 (via Universities and research centres) 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.

The necessary regulatory capability needs to be established to ensure appropriate checking of nuclear facilities. This capability should be adequate either through direct capability or by the funding of adequate supporting expertise to perform regulatory duties.

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 [9-7].

9.4. 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.

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CHAPTER 10
NUCLEAR POWER DEVELOPMENT MODELLING (NPDM)

10.1. Introduction

In performing an INPRO assessment, the assessor must take into account a reference energy scenario or scenarios. For example, if the assessor were focused on energy supply in his state he would take into account a national energy scenario (or perhaps a more localized scenario based on a region within his country). Such a national scenario would also be expected to take into account global and/or regional considerations such as the global demand for uranium, reprocessing capacity, etc., and so would also have to use some elements of a regional or global scenario. If the assessor were interested in global energy supply as a component of sustainable development, he would necessarily utilize a broadly based scenario that takes into account various regions and country groupings to arrive at a global scenario. Modelling and codes are also needed for a variety of other purposes. For example for material flow analyses for use in environmental assessments (see Chapter 6), for macro-economic analysis as one input when considering the relative benefits of different energy supply options to arrive at a value for the factor ‘k’ introduced in the discussion on cost competitiveness (see Chapter 4), and for estimating resource requirements for different mixes of energy supply to arrive at a judgment of overall sustainability. Such analyses are basic inputs required to form a judgement of the overall sustainability of a given scenario with a given mix of different kinds of INS and other energy sources.

Modelling tools include existing tools that have been developed by the IAEA Planning & Economic Studies Section (PESS) (see, e.g., Refs [10-1, 10-2, 10-3, and 10-4]) and those under development within INPRO and by national activities. The latter are discussed below in Sections 10.8 and 10.9.

10.2. MESSAGE code: Model of energy supply systems and their general environmental impacts

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 [10-1]. 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 industrial 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.

10.3. MAED: Model for analysis of energy demand

MAED [10-2] evaluates future energy demands based on medium- to long-term scenarios of socio-economic, technological and demographic development. Energy demand is disaggregated into a large number of end-use categories corresponding to different goods and services. The influences of social, economic and technological driving factors from a given scenario are estimated. These are combined for an overall picture of future energy demand growth.

10.4. WASP: Wien automatic system planning package

WASP [10-3] is the most widely used model in developing countries for power system planning (over 100 countries). Within constraints defined by the user, WASP determines the optimal long-term expansion plan for a power generating system. Constraints may include limited fuel availability, emission restrictions, system reliability requirements and other factors. Optimal expansion is determined by minimizing discounted total costs.

10.5. ENPEP: Energy and power evaluation program

ENPEP [10-4], now used in approximately 60 developing countries, provides comprehensive evaluation of energy system development strategies. It includes modules:

- To assess energy demand (MAED);
- To compute market clearing prices and balance energy demand and supply under market conditions;
- To optimize expansion of the electric sector (WASP); and
- To estimate environmental burdens from the energy system.

10.6. FINPLAN: Model for financial analysis of electric sector expansion plans

In developing countries, financial constraints are often the most important obstacle to implementing optimal electricity expansion plans. FINPLAN [10-4] helps assess the financial viability of plans and projects. It takes into account different financial sources — including export credits, commercial loans, bonds, equity and modern instruments like swaps — and calculates projected cash flows, balance sheet, financial ratios and other financial indicators. It is currently used in more than 20 developing countries.

10.7. SIMPACTS: Simplified approach for estimating impacts of electricity generation

SIMPACTS [10-4] is a user-friendly, simplified approach for estimating the environmental impacts and external costs of different electricity generation chains. Designed for use in developing countries, it requires much less data, but produces comparable results, relative to more sophisticated data-hungry models. The SIMPACTS package covers:

- Health, agricultural, forest and materials damage;
- Airborne and water pollution as well as solid waste; and,
- Different generating technologies.

10.8. The DESAE code

The DESAE (Dynamic of Energy System – Atomic Energy) code, as currently developed for use in INPRO [10-5], calculates the resources, both financial and material, required for a given combination of reactors to meet a specified supply of nuclear energy as a function of time (See Figure 10.1). Thus, the user can study the practicality of a proposed system and material balances such as uranium demand as function of time, waste arising, plutonium recycling, etc. The code is at an early stage of development. Future developments, discussed in Section 10.8.1, are planned to extend its use to include other sources of energy supply and to couple it with IAEA codes such as MESSAGE [10-1].

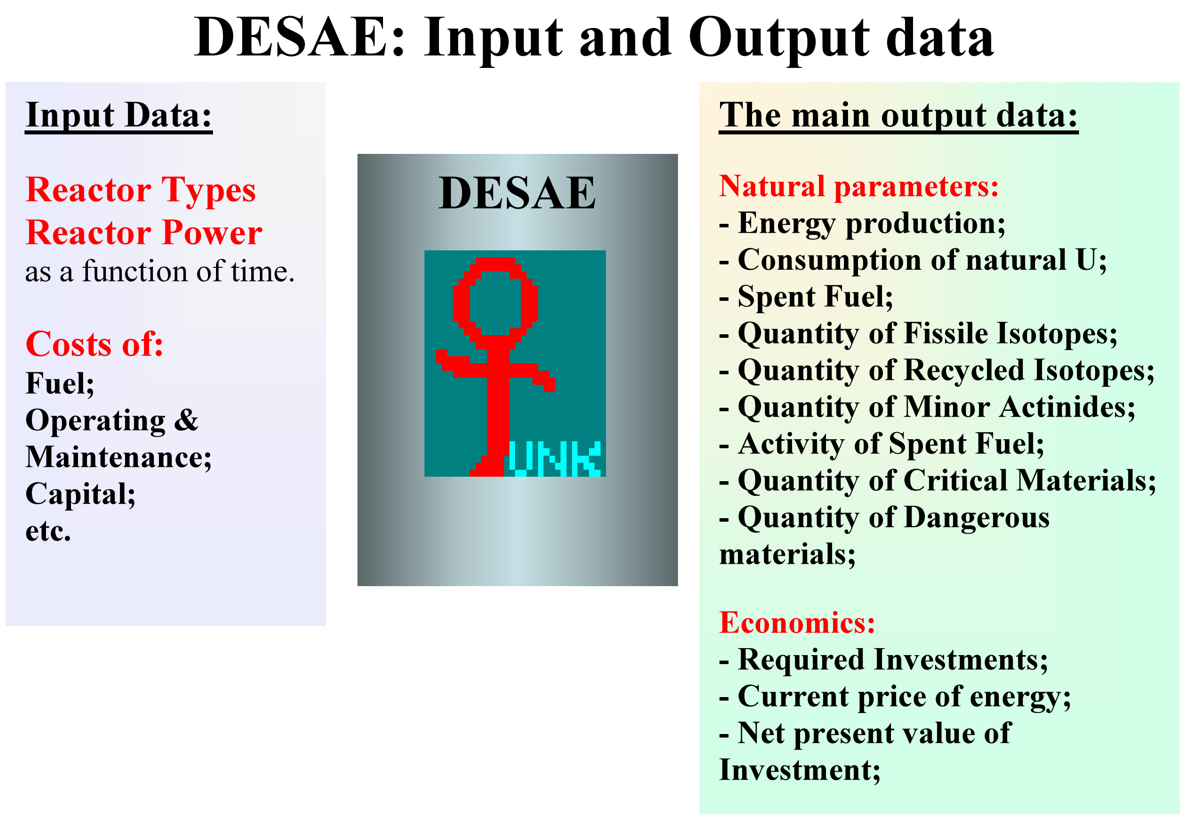

Figure10.1. Main input and output data of DESAE code.

DESAE is an interactive code, as illustrated in Figure 10.2. The user specifies a given demand for nuclear energy — at present only nuclear electricity can be modelled — and the combination of reactor types that will be used to supply this energy, the fuel cycles to be used and the costs (overnight construction cost, fuel cost, operating costs, etc.) for each. The code then calculates a variety of parameters such as the consumption of natural uranium as a function of time, quantities of spent fuel and other materials such as actinides and recycled materials; the consumption of critical materials such as zirconium, the investment required, the cost of energy etc, in near real time. The user can then seek to optimize the nuclear energy system by varying the mix of reactor types and fuel cycles. The code does not utilize an optimization function but does provide information to the user to assist the user in the choice of alternatives.

The user can choose from a variety of reactors that are in use and that are under consideration for development, including LWRs, PHWRs, fast reactor, HTGRs, etc. Users can also specify a new reactor type by supplying information on its relevant characteristics.

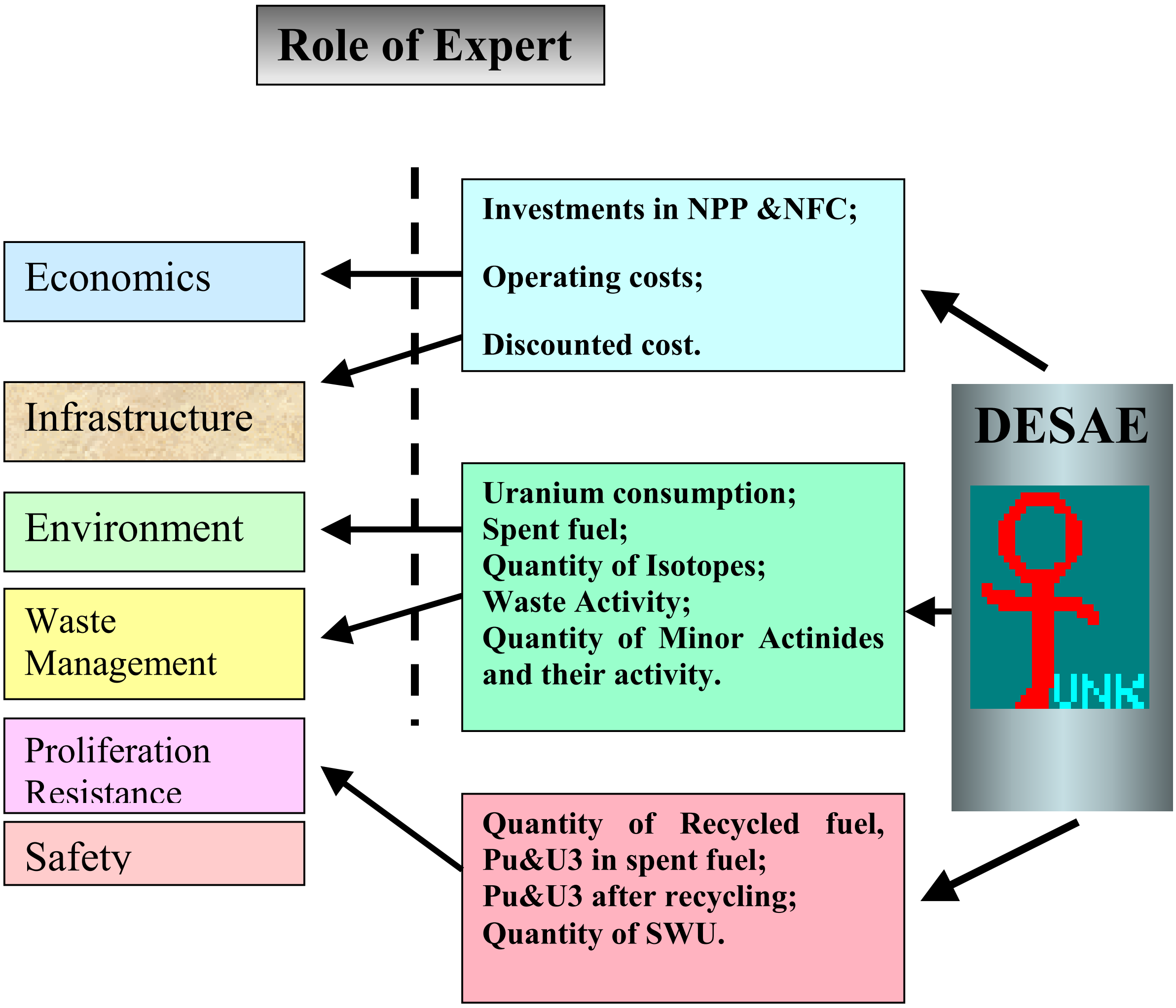

Figure10.2. Interactive role of expert in using the DESAE code.

It is foreseen that DESAE will be used in national, regional, and global energy studies for the following:

- Calculating material and financial resources required for different nuclear energy deployment strategies, which is of interest in itself and which can be used in INS assessments, e.g. in environmental material flow analyses;

- Inter-comparing different nuclear energy systems and components thereof, including the evaluation and demonstration of the benefits of various option for closed fuel cycles and the identification of the reactor characteristics that are most important for a given system;

- Comparing different INS structures on a regional and global basis to identify complementarities and synergisms among systems of interest to different Member States, in both technology and in infrastructure.

In this way DESAE will assist in identifying possible paths to a globally sustainable nuclear energy system based on diverse national and regional components.

10.8.1. Future developments – DESAE

As has been noted DESAE as currently developed treats only nuclear electricity (Figure 10.3). In the future it is foreseen that DESAE will be expanded to include, for example:

- Non-electrical NE applications such as the supply of heat and hydrogen, desalination, and transmutation of minor actinides;
- Modules for other source of energy supply, namely, gas, oil, coal, hydro, and renewables;
- Modelling of interregional transportation of fuels and other raw materials, nuclear waste, reactor systems, etc.;
- Modules to correlate outputs with the values of INPRO Key Indicators; and to include
- Feedback from learning into the costs used in DESAE.

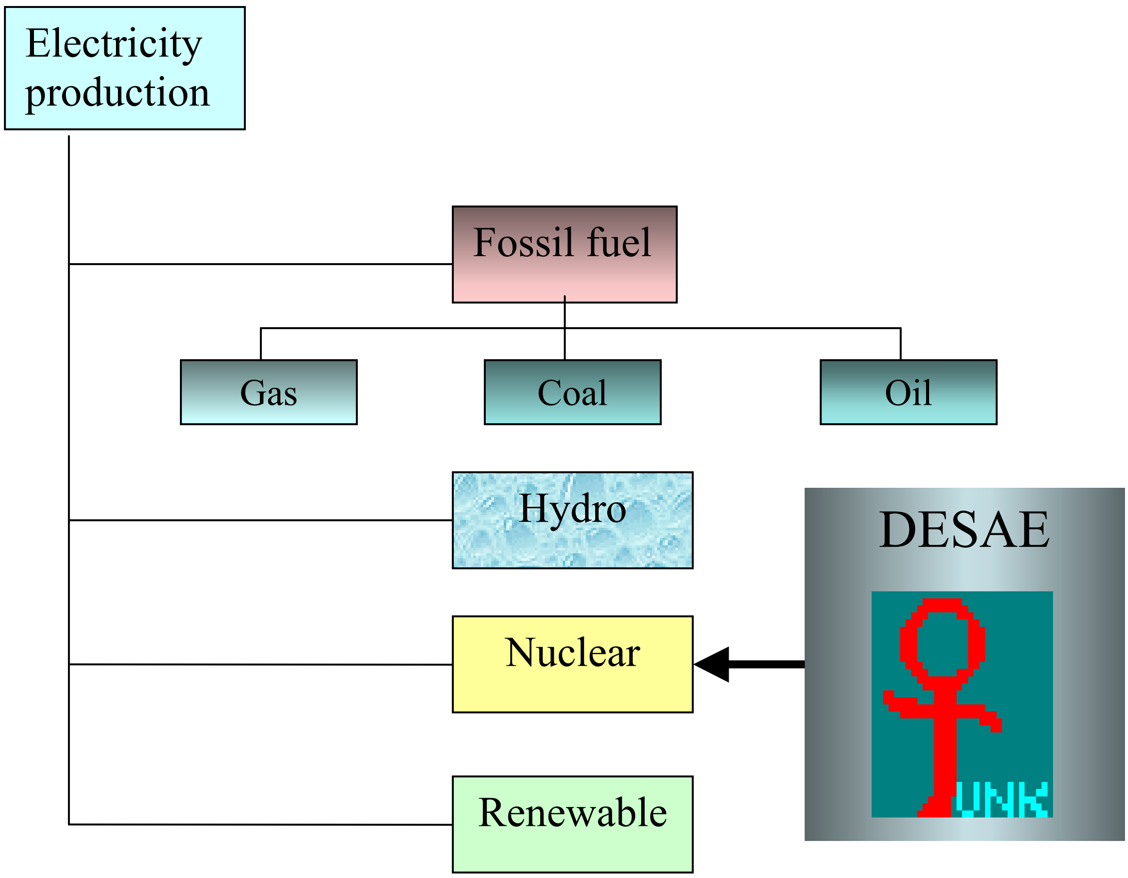

Figure10.3. Current status of DESAE code and its future development.

A User Manual needs to be developed and arrangements need to be established to provide potential users of the code with training.

10.9. The SYRTEX code

The SYRTEX (System Rate of Technology Expansion) is under development now, and has been used for assessing the competitiveness of different INS for different market conditions [10-6, 10-7]. The deployment rates for different systems are calculated, starting from an initial market structure, assuming a given demand for electricity, and key characteristics of a given INS, including its specific capital cost, capacity factor, construction time, fuel cost, etc., for a given discount rate. The results can be used to determine the sensitivity of the deployment rate for variations in individual parameters such as cost of externalities, capital cost, construction period etc. and hence is appears to be a useful tool for identifying indicators that are important for INS competitiveness and hence for prioritising RD&D. An important concept utilized in the code is that of a dynamic equilibrium price.

10.10. Concluding remarks

The use of modelling tools is seen to be an important part of energy planning and of INPRO and the use of such tools will be integrated into the INPRO methodology as it is further developed. A number of modelling tools are currently available including IAEA codes such as MESSAGE [10-1] and SIMPACT [10-4] and DESAE [10-5]. In the future INPRO will investigate the advisability and of integrating such codes and the potential utility of other codes such as SYRTEX [10-6] and those used in other Member States.

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CHAPTER 11
CONCLUSION, OUTLOOK AND RECOMMENDATIONS

This report represents the conclusion of the first part of Phase 1B of INPRO. It incorporates improvements into the INPRO methodology that were identified by applying the methodology, on a test basis, in fourteen different case studies, six of which were carried out by national teams and eight of which were performed by individuals. The results from these case studies were augmented by feedback from a number of consultancy meetings at which representatives from diverse areas, e.g. regulators and vendors/developers, contributed.

This report presents a tested and validated methodology for assessing innovative nuclear energy systems. By creating such a methodology to ascertain whether a given nuclear energy system is sustainable, INPRO has performed a decisive step towards fulfilling its first objective "to help to ensure that NE is available in a sustainable manner within the 21st century".

The case studies carried out in the first part of Phase 1B were based on a large variety of nuclear systems, including small LWRs, fast breeders, molten salt reactors, gas cooled reactors, HWRs, ADS, etc. The primary aim of the studies was to test the INPRO methodology and not to actually assess the systems considered.

The feedback from the first part of Phase 1B has lead to significant changes in the INPRO methodology, as documented in the Phase 1A report. These changes are set out in this report. The most significant changes can be summarized as follows:

- The INPRO methodology has been more clearly linked with and integrated into the general concept of sustainable development.
- A basic principle, and associated user requirements and criteria have been defined to address the needs for innovation in infrastructure arrangements, thus extending the application of the method of assessment to include this important topic.
- The number of basic principles, user requirements and criteria has been reduced to eliminate redundancy/overlap, and improve the coherence of the basic principles and user requirements in the areas of economics, safety, environment, waste management, and proliferation resistance.
- The applicability of the methodology to fuel cycle facilities other than the reactor has been improved.
- The description of the assessment method has been improved by introducing a separate treatment of uncertainties, defining several possibilities for aggregating judgements and by clarifying how the method provides a tool for handling near term, medium and long-term RD&D strategies.
- A description of some tools for modelling the future energy demand and supply on a national, regional and global basis is included.

The Phase 1B report is a significant step forward in establishing the INPRO methodology as a tool for the assessment of INS. In the second part of Phase 1B (see Appendix) it is anticipated that the methodology will be used to perform holistic assessments of complete INSs ("cradle to grave"). Such assessments are expected to start early in 2005. They will represent an important step towards fulfilling INPRO's second objective "to bring together all MS to consider jointly the international and national actions to achieve desired innovations". Another important output of the second part of Phase 1B will be the creation of a users manual to assist Member States in applying the INPRO methodology. Feedback from the first few assessments will be invaluable in preparing such a manual. A data bank of all INSs to be assessed will be established.

As feedback is obtained from such assessments, it is expected that the INPRO methodology and manual will be further refined. It is anticipated that Member States may wish to form an INPRO Users Club to manage the process of updating the methodology and enhancing the tools to be used. It is also anticipated that the methodology will be used to identify complementarities and synergisms among systems of interest to different Member States, in both technology and in infrastructure, and so will assist in identifying possible paths to a globally sustainable nuclear energy system based on diverse national and regional components.

The work in the second part of Phase 1B and in the following Phase 2 (see Appendix) will include all stakeholders in nuclear energy. In this way INPRO will meet its third objective "to create a process that involves all relevant stakeholders" by providing a forum where experts and policy makers from industrialized and developing countries can discuss technical, economical, environmental, proliferation resistance and social aspects of nuclear energy planning as well as the development and deployment of Innovative Nuclear Energy Systems in the 21st century.

APPENDIX

Terms of Reference

for

PHASE-1B (second part) and PHASE 2

of the

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

International Atomic Energy Agency

1. Introduction

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is addressing the identification of full spectrum of user requirements for innovative technologies as well as the development of methodologies and guidelines for the comparison of different innovative approaches taking into account variations in potential demands across countries. INPRO can make major contributions by focussing on economic aspects and societal acceptability issues, and those areas where IAEA can make unique contributions, such as proliferation resistance, nuclear safety, waste management and sustainability issues, and by providing assistance to the user community. To enhance the potential for the deployment of innovative technologies, some changes in the infrastructure under which nuclear energy is developed and used should be envisaged.

Phase 1 of INPRO was initiated in May 2001. During Phase 1, work was subdivided in two sub phases:

- Phase-1A (completed in May 2003): Selection of basic principles, user requirements, criteria and development of a methodology and guidelines for the evaluation of different INS and recommendations for changes in the infrastructure.

- Phase-1B (started in June 2003):

- 1st Part: (June 2003–December 2004):

Validation and improvement of the Methodology through national and individual case studies; preparation of a User Manual to perform INS assessments;

- 2nd Part (January 2005–mid 2006):

Assessments of INS using the updated INPRO methodology.

2. Phase-1B (second part)

The Second Part of Phase-1B (*2005– middle 2006*) will contain the following activities and objectives, bearing in mind that the Project should also integrate IAEA activities on INS development and deployment:

- Facilitate assessments of INS by MS (nationally or jointly) using the updated INPRO methodology as stated in the IAEA General Conference Resolution GC(48)/RES/13(F), which invites all Member States to perform "innovative nuclear energy systems assessments";
- Continuous improvement of methodology with a focus on a more quantitative approach;
- Finalizing and publication of a Users' Manual, and identification and possible development of essential models, codes and techniques;
- Identification of possible frameworks and implementation options for collaborative R&D for INS development, which could be performed during Phase 2;
- Enhance collaboration, on a complementary and synergetic basis, with other national and international INS initiatives (e.g. GIF);
- Determination of national, regional and global balances of demands and resources and of infrastructure needs, and establishment of a databank and further development of codes (e.g. DESAE);
- Defining and modelling of INS deployment scenarios taking into account strategies considered by MS;
- Review of technological and infrastructure options of Multilateral Nuclear Fuel Cycles (MNFC) as components of different INSs; and
- Enhance communication among INPRO members by regular updating the website and publishing electronic newsletters.

3. Phase 2 (starting in mid 2006)

While some Member States may still require IAEA assistance in assessment of various INS options, the main objective of Phase 2 is to encourage and support IAEA Member States in facilitating the development, demonstration and deployment of safe, competitive, environmentally clean, and proliferation resistant INSs for sustainable development.

This will/could be achieved by R&D, institutional/infrastructure and methodology oriented activities:

R&D oriented activities:

- Facilitate analysis of INSs in INPRO Member States as required;

- Provide a forum to enable identification and prioritization of R&D needed under the framework defined in Phase-1;

- Assist in assessing R&D progress against targets and in reorienting as necessary;

- Identify and enable specific R&D to be performed under IAEA / INPRO auspices (e.g. under CRP framework, TC projects);

- Encourage, provide guidance and assistance to interested IAEA Member States to perform joint research and implement projects for INS development; and

- Preparation of country profiles on R&D programmes for innovative nuclear technologies;

Institutional/infrastructure oriented activities:

- Undertake relevant studies and analysis to evaluate the potential role of INS for sustainable development;

- Make efforts to promote the use of INS for electricity production and non-electrical applications;

- Facilitate the application of INPRO methodology to provide guidance for INS deployment strategies on a national, regional, or global scale, with emphasis on the needs of developing countries;

- Identify MNFC institutional and infrastructure options and other innovative approaches, which would facilitate the introduction and further deployment of nuclear energy;

- Identify approaches to the communication process of all aspects of INS to the public, policy advisors, decision makers and other stakeholders and encourage their use;

- Assistance for and facilitation of harmonization of licensing and industrial codes and standards, subcontracting by licensing authorities and international design certification; maintenance or development of necessary competences and experience, research facilities, etc. for INS; and

- Facilitate the analysis of fuel cycle strategies and options on national and regional basis in order to determine best-suited solutions, which meet anticipated local and global constraints, within the INPRO context.

Methodology oriented activities:

- Further development of INPRO methodology and refinement of the assessment method in all INPRO areas to support the above mentioned activities.

Within Phase 2, INPRO activities will address the needs of both technology users and technology holders with special emphasis on the needs of developing countries. INPRO will seek continued cooperation with other national and international initiatives, such as the Generation-IV International Forum.

IAEA/INPRO Secretariat will be available to coordinate and support implementation in Member States of activities in Phase 1B (second part) and Phase 2.

4. Resources

The project will be implemented using extra budgetary contributions offered by interested IAEA Member States and the IAEA Regular budget. The ICG Members and INPRO Task Managers will continue their basic functions as defined in the Terms of Reference of Phase 1 taking into account the progress achieved.

Rules and procedures for Task Managers will be established by the IAEA.

5. INPRO members

Members of INPRO are all IAEA Member States and International Organizations, which contributed to INPRO during Phase 1 A and Phase-1B (first part) of the project according to the established rules (via sending CFEs to the ICG, performing work packages, case studies or providing direct financial support). In Phase-1B, second part, and Phase 2 all interested Member States and International Organizations who participate in and contribute to an assessment of an INS will also qualify to become Members of INPRO.

6. Steering Committee

The Steering Committee formed by the representatives of INPRO members will continue its role in Phase-1B (second part) and Phase 2.

7. Schedule

Phase-1B (second part) is planned to present first results in the middle of 2006 and may continue in parallel with Phase 2. Phase 2 of the project is proposed to start in the middle of 2006.

ABBREVIATIONS

ADS	accelerator driven system
AGR	advanced gas reactor
AL	acceptance limit (INPRO)
ALARP	as low as reasonably practical, social and economic factors taken into account
BOO	build, own and operate
BOT	build, own and transfer
BP	basic principle (INPRO)
BWR	boiling water reactor
CFE	cost free expert (INPRO)
CNS	current nuclear system
CR	criterion (INPRO)
CRP	coordinated research project
DTV	desired target value (INPRO)
DU	depleted uranium
EUR	European utility requirements
FCF	fuel cycle facility
FOAK	first-of-a-kind
FP	fission products
FR	fast reactor
GC	IAEA General Conference
GHG	green house gas
GIF	Generation IV International Forum
HEU	highly enriched uranium
HF	human factor
HLW	high level waste
HTGR	high temperature gas reactor

HWR	heavy water reactor
I&C	instrumentation and control
IEA	International Energy Agency (OECD)
ICG	international coordinating group in INPRO
ICS	individual case study (INPRO)
ICRP	International Commission on Radiological Protection
IDC	interest during construction
IGCC	integrated gasification combined cycle (coal power plant)
IIASA	International Institute for Applied System Analysis
IN	indicator (INPRO)
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles (IAEA)
INS	innovative nuclear energy system (INPRO)
INSAG	International Nuclear Safety Advisory Group (IAEA)
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
ISED	indicator for sustainable energy development (IAEA)
KI	key indicator (INPRO)
LCA	life cycle assessment
LCI	life cycle inventory
LDC	levelized discounted cost
LEU	low enriched uranium
LOCA	loss of coolant accident
LWR	light water reactor
MFA	material flow assessment
MNFC	multilateral fuel cycle (INPRO)
MS	Member State (IAEA)
NCS	national case study (INPRO)

NEA	Nuclear Energy Agency (OECD)
NGO	non-governmental organization
NII	investment needed for national infrastructure (INPRO)
NM	nuclear material
NPP	nuclear power plant
NPV	net present value
NPT	Non-Proliferation Treaty
NOAK	N^{th} of a kind
NRC	Nuclear Regulatory Commission (USA)
OECD	Organization 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
PIRT	phenomena identification and ranking table
PR	proliferation resistance (INPRO)
PRIS	Power Reactor Information System (IAEA)
PSA	probabilistic safety analysis
PWR	pressurized water reactor
RBI	relative benefit index (INPRO)
RBMK	graphite moderated fuel channel reactor
RD&D	research, development and demonstration
REF	SRES region of countries with economic reform (formerly Eastern Europe and the Soviet Union)
RES	resolution (of the IAEA General Conference)
RG	reactor grade
ROI	return on investment
ROW	SRES region of rest of the world (beside OECD-90, Asia and REF)

RRI	relative risk index (INPRO)
SRES	Special report on emission scenarios (IIASA)
TBD	to be determined
TOR	terms of reference
UNDP	United Nations Development Programme
UNDESA	United Nations Department of Economics and Social Affairs
UNFCCC	United Nation Framework Convention on Climate Change
UR	user requirement (INPRO)
VNI	value of nuclear installation (INPRO)
WANO	World Association of Nuclear Operators
WEC	World Energy Council
WG	weapon grade
WNA	World Nuclear Association
WIPP	Waste Isolation Pilot Plant (US)
WSSD	World Summit on Sustainable Development
WWER	water cooled, water moderated power reactor

LIST OF PARTICIPANTS

In addition to the participants in INPRO Phase 1A (documented in TECDOC1362) the following experts contributed to the INPRO methodology during Phase 1B (1st part):

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