IAEA-TECDOC-1575 Rev. 1

# *Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems*

## *INPRO Manual — Overview of the Methodology*

*Volume 1 of 9 of the*
*Final Report of Phase 1 of the International Project on*
*Innovative Nuclear Reactors and Fuel Cycles (INPRO)*
*including a CD-ROM comprising all volumes*

IAEA
International Atomic Energy Agency

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FOR INNOVATIVE NUCLEAR ENERGY SYSTEMS
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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 seeks to bring together all interested Member States, both technology holders and technology users, to consider, jointly, 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 June 2003.

In its second step, referred to as Phase 1B (first part), 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 the INPRO methodology was revised, as documented in IAEA-TECDOC-1434, published in December 2004.

In its third step, referred to as Phase 1B (second part), INPRO was requested to provide additional guidance in using the INPRO methodology to assess the sustainability of an innovative nuclear energy system (INS) in the form of an INPRO assessment manual. The resulting INPRO manual is comprised of an overview volume (laid out in this report), and eight additional volumes (available on a CD-ROM attached to the inside back cover of this report) covering the areas of economics (Volume 2), infrastructure (Volume 3), waste management (Volume 4), proliferation resistance (Volume 5), physical protection (Volume 6), environment (Volume 7), safety of reactors (Volume 8), and safety of nuclear fuel cycle facilities (Volume 9).

This volume of the INPRO manual has been developed by C. Allan (Canada) under a special service agreement with the IAEA. The report is based, largely, on material documented in IAEA-TECDOC-1434.

The IAEA highly appreciates the contributions made by the INPRO international coordinating group (ICG) members and the participants of the consultancies, and the valuable guidance and advice provided by the Steering Committee. The IAEA would also like to express its thanks to F. Depisch (Germany) for editing the publication.

Phase 1B (second part) of the INPRO project was implemented under the IAEA Project Manager Y. A. Sokolov and the Project Coordinators, A. Omoto, A. Rao, J. Kupitz, I. Facer, and T. Ganguly of the Department of Nuclear Energy. As of December 2006, INPRO has 27 Member States (and the EC) supporting the project.

Based on a decision of the 9th INPRO steering committee in July 2006, INPRO has entered into Phase 2. This phase has three main directions of activity: methodology improvement, infrastructure/ institutional aspects and collaborative projects. The ongoing and future activities of INPRO are expected to lead to further improvements in the INPRO methodology, based on the feedback received from Member States in light of their experience in applying the methodology.

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INPRO Manual – Economics, Volume 2 of the final report of Phase 1 of INPRO

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INPRO Manual – Environment, Volume 7 of the final report of Phase 1 of INPRO

INPRO Manual – Safety of Nuclear Reactors, Volume 8 of the final report of Phase 1 of INPRO

INPRO Manual – Safety of Nuclear Fuel Cycle Facilities, Volume 9 of the final report of Phase 1 of INPRO

# CHAPTER 1
# INTRODUCTION

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 naturally occurring isotopes of uranium and thorium ($^{235}$U,$^{238}$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.

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 cost, 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, which, however, had no significant release of radioactivity to the environment, but 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, Russian Federation 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.

## 1.1. 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, includes the requirement for sustainable energy supply. 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 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 of limitations associated with other energy sources such as fossil fuels (GHG emissions) and renewables (discontinuous availability and land use limitations). However, as discussed above, the sustainability of nuclear systems that are operating today is questioned by the public and by some decision makers, because of concerns related to safety, nuclear waste disposal, and the proliferation of nuclear weapons.

To address these concerns and ensure a sustainable development of nuclear energy, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was initiated in the year 2000, based on a 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.

### 1.2. Main objectives of INPRO

The main objectives of INPRO are to [1]:

- 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
- 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.

### 1.3. Mission of INPRO

The mission of INPRO reads as follows:

- To provide a forum for discussion of experts and policy makers from industrialized and developing countries on all aspects of nuclear energy planning as well as on the development and deployment of innovative nuclear energy systems (INS) in the 21st century;
- To develop the methodology to assess INS on a global, regional and national basis and to establish it as an Agency recommendation;
- To facilitate coordination and cooperation among Member States for planning of INS development and deployment; and
- To pay particular attention to the needs of developing countries interested in INS.

### 1.4. Development of INPRO

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 [1], 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 different countries — to test and provide feedback on the applicability, consistency and completeness of the INPRO methodology. This feedback lead to the publication of IAEA-TECDOC-1434, Methodology for the Assessment of Innovative Nuclear Reactors and Fuel Cycles [2], which sets out the improved INPRO methodology and brought Phase 1B (first part) to a conclusion.

In the following step, referred to as Phase 1B (second part), INPRO was requested to provide additional guidance in using the INPRO methodology to assess the sustainability of an INS in the form of an assessment manual. Additionally, based on a decision of the INPRO steering committee, the area of physical protection was included in the INPRO methodology. By use of external contractors and input from IAEA experts including the INPRO international coordinating group (ICG), the INPRO manual was created. It incorporates material from TECDOC-1434 [2] and expands on that material. It is intended to be a stand-alone document. The INPRO manual sets out general background information on the INPRO requirements for each INPRO area, and sets out procedures for determining the values of indicators and acceptance limits of the INPRO criteria to enable a judgement to be made on the potential of an INS to meet the INPRO requirements.

### 1.5. INPRO and the UN concept of sustainability

The general UN concept of *sustainability* and considerations specific to the concept of sustainable energy[3] have been incorporated in the INPRO objectives. The INPRO methodology has been developed specifically to determine whether or not a given innovative nuclear energy system (INS) is sustainable.

To address the specific issues relevant to the development and deployment of INS for sustainable energy supply, within the general framework of sustainability, INPRO established a number of task groups that established requirements in all areas mentioned above. By considering each of these areas, 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, by identifying areas where improvements are needed, 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.

### 1.6. Holistic approach of INPRO methodology

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 and, thus, INPRO, include evolutionary as well as innovative designs of nuclear facilities. An evolutionary design [3] 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] 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.

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[3] Discussed further in this report in Chapter 2, INPRO and the concept of sustainability.

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 research, development and demonstration (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. As well, the assessor may be primarily interested in only one area, e.g., economics, but all areas must ultimately be included in the evaluation to achieve a holistic view. The INPRO methodology thus requires that a comprehensive and holistic assessment be carried out to arrive at a judgment of the sustainability of an INS. Such a comprehensive and holistic assessment requires the participation of a number of individuals with expertise in the different INPRO areas and knowledge of the nuclear facilities comprising the INS, i.e. an assessment team.

INPRO requires that the whole life time of the INS has to be evaluated, starting from the design to construction, operation and finally decommissioning (cradle to grave). In addition to all facilities of a nuclear energy system the associated legislative and institutional measures, e.g. the legal framework and the regulatory bodies, are to be considered in an INPRO assessment.

INPRO has established a set of requirements, organized in a hierarchy of basic principles, user requirements and criteria, comprising an indicator and an acceptance limit in all areas that must be fulfilled by an innovative nuclear energy system (INS) to meet the overall target of sustainable energy supply. These were set out and discussed in Ref. [2], IAEA-TECDOC-1434, Methodology for the Assessment of Innovative Reactors and Fuel Cycles. This volume of the INPRO manual provides additional background information and advice to that presented in Ref. [2] to assist Member States in carrying out an INPRO assessment of an INS.

It is expected that for each area of INPRO one expert (i.e. a person knowledgeable in that INPRO area) would need about 8 weeks to perform a specific INPRO assessment, assuming he had made himself familiar with the INPRO methodology and received all the needed input before starting his assessment. Familiarization with the INPRO methodology in a specific area should take not significantly more than about two weeks. Collecting the input[4] could be done iteratively during the assessment work, but might cause significant delay of the overall schedule. Thus, a complete INPRO assessment of an INS should require a team of about eight people, each of whom would work about 10 weeks in his subject area, plus a

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[4] The INPRO portal , described in Section 4.7.1 should help an INPRO assessor in gathering the necessary information.

project manager to bring together a comprehensive report (~ 2 – 4 weeks). Thus, optimistically, the accumulated effort by the team of experts should be about 80 persons weeks plus the time needed for the project manager.

### 1.7. Users of the INPRO manual

It is expected that the INPRO manual will be employed by two broad classes of users – *technology users* and *technology developers/holders*.

A technology user, such as a national or a local (state or provincial) government or a utility considering the purchase of a nuclear power plant (NPP) would find an INPRO assessment useful as a means of assessing the relative merits of deploying a NPP in comparison with alternative sources of energy supply. Such an applicant would expect to be provided with much of the information needed to perform the assessment by NPP vendors and fuel suppliers and where necessary, for example, in the area of economics, by vendors of alternative technologies. In such cases the manual will be of assistance to the technology user in determining what information to request from the vendor(s). Detailed guidance is provided in each subject area within Volumes 2 to 9 of the INPRO manual. Such an applicant may seek additional information from the vendors of alternative technologies to enable a more comprehensive comparison of the alternatives with the NPP option in a number of areas, in addition to economics, in particular environmental impact and the health impact of emissions. In such a situation the INPRO method of assessment could be used as a starting point for making such a comprehensive and holistic assessment of competing energy technologies.

In a number of instances, e.g. when considering emissions the INPRO requirement is that regulatory requirements are met. For Member States where NPPs are already deployed such regulatory requirements will already exist and can be used in the INPRO assessment. For Member States considering the acquisition of a first NPP, such regulations may not yet exist. In such a case the INPRO assessment would identify this as a shortcoming that would need to be addressed prior to acquisition of the NPP, as discussed, for example in Volume 3, dealing with the INPRO area of infrastructure [4].

The other broad class of user is the technology developer. The developer (and those investing in the development) will need to consider whether and to what extent the component product that is being developed (or is proposed to be developed) as part of an INS will comply with the INPRO requirements, since such compliance would be expected to affect the competitive position of the product when developed and offered for commercial use. Thus, the developer must project ahead and estimate whether the INPRO acceptance limits will be met once the product is developed. In this situation it is the developer who will need to develop the information needed to complete the INPRO assessment at a given time in the future when his product is to be offered to the market place. Roughly speaking, the INPRO criteria should be met, with a sufficient margin to accommodate uncertainties commensurate with the state of development, (see Section 4.4.3) to justify the investment needed.

At the national level, a given country may be a technology user or it may be both a technology developer and a technology user. In only rare instances, most notably uranium mining, would a country be a developer of nuclear energy technology without also being a user of nuclear energy technology. Technology developing countries usually have a well established nuclear infrastructure including staff with competence in all the INPRO subject areas. For such countries this manual is primarily intended to ensure that a standard approach is followed in performing an INPRO assessment.

For prospective technology user countries without nuclear energy development programmes, particularly those considering whether or not to acquire a first nuclear energy system, this manual provides detailed guidance for performing an INPRO assessment, the results of which can provide one input to their decision making process.

### 1.8. General structure of the INPRO manual

The INPRO manual comprises this overview volume and eight additional volumes covering all areas of INPRO. The overview volume sets out the philosophy of INPRO and a general discussion of the INPRO methodology. Each of the other volumes of the INPRO manual, dealing with a given INPRO subject area (see Table 1.1), provides general background information in the subject area to guide an assessor, and, as well, identifies the information an assessor needs to be able to assemble or have available to perform an INPRO assessment in the subject area.

Table 1.1. List of volumes of the INPRO manual

| Number of volume | Content of volume |
|---|---|
| 1 | INPRO Manual Overview of the INPRO methodology |
| 2 | INPRO Manual for the area of economics |
| 3 | INPRO Manual for the area of infrastructure |
| 4 | INPRO Manual for the area of waste management |
| 5 | INPRO Manual for the area of proliferation resistance |
| 6 | INPRO Manual for the area of physical protection |
| 7 | INPRO Manual for the area of environment |
| 8 | INPRO Manual for the area of safety of nuclear reactors |
| 9 | INPRO Manual for the area of safety of nuclear fuel cycle facilities |

In the volumes 2 to 9, special attention is paid to the definition of and means for evaluating the indicators and the selection of the acceptance limits for these indicators. Finally, in several volumes an example is presented to illustrate the application of the INPRO method of assessment to a given INS, selected for the illustration, to assess whether or not the INS complies with the INPRO requirements in the INPRO area of interest.

### 1.9. Outline of this volume

This overview volume:

- discusses the relationship of INPRO with the UN concept of sustainability to demonstrate how the INPRO requirements reflect the goals of sustainable development in Chapter 2;
- provides an overview or summary of the INPRO requirements in all subject areas in Chapter 3;

- presents an overview of the INPRO method of assessment in Chapter 4, including basic features and terminology, and a description of screening and comparative assessment;
- describes, in Chapter 5, the use of energy scenarios and modelling in defining an INS that would become the subject of an INPRO assessment;
- provides in Annex A tables with INPRO basic principles, user requirements and criteria in all areas;
- discusses in Annex B additional examples of approaches to aggregate INPRO results; and
- lays out, in Annex C, the objectives of the INPRO portal.

As noted above, an INPRO assessment of an INS is intended to be a comprehensive and holistic assessment, and hence will require the participation of a team of experts (i.e. persons with a general background in the INPRO areas). An INPRO assessor[4] responsible for a given INPRO area should be familiar with the information presented in this overview volume and with the detailed information presented in the volume dealing with his/her area of interest.

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[4] The term assessor is used in this publication in two different ways to mean either an INPRO assessment team comprising several experts who collectively are responsible for performing a comprehensive INPRO assessment or a member of such an assessment team who is responsible for work in a given area of interest. The meaning of the term in a given situation will be clear from the context in which it is used.

# CHAPTER 2
# INPRO AND THE CONCEPT OF SUSTAINABILITY

## 2.1. Introduction

In 1987 the Brundtland Report [5], 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 [6], 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 [7] 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 covering the three pillars of sustainability: social, environmental, and economic. The publication [8], 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 [9] 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 [10]. INPRO specifically addresses these issues of concern, as well as other issues (economics, infrastructure, environment and physical protection) 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. 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.

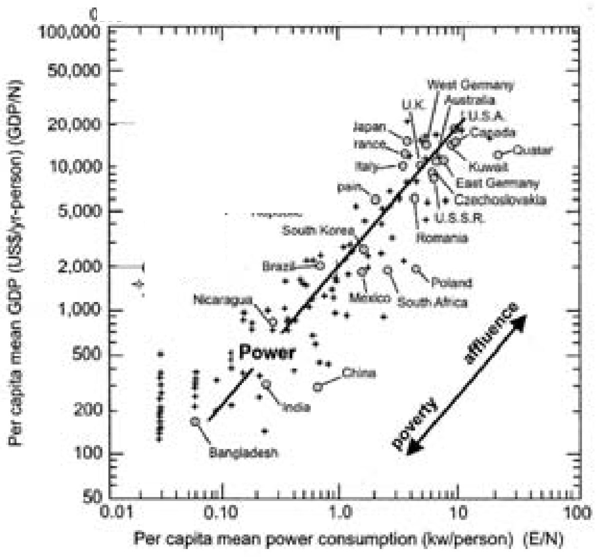
The *environmental dimension* requires eliminating/reducing negative externalities that are responsible for the depletion of natural resources and environmental degradation. The following topics can be considered within the environmental dimension: climate change, air pollution, water pollution, solid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



Power: +, ⊙ data derived from Hammond (1990, Tables 15.1 and 20.1)

*Figure 2.1. Link between GDP per capita-year and energy use per capita-year.*

A nation's GDP/capita/year and energy use/capita/year are linked as shown by the data displayed in Figure 2.1 above. Industrialized and post-industrial western nations use from 4 to 9 tonnes of oil equivalent (toe) primary energy per capita per year (~ 5 to 12 kW/person) and derive a GDP/capita/year in the range of 20 to 30 thousand US-$/capita/year. By contrast, many developing countries utilize a tenth or less the energy and produce economic activity that is also a tenth or less of that of western nations.

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. [1] 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 2.2 and 2.3 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. On the other hand, a number of factors, such as land use requirements and discontinuous availability, may ultimately limit the potential of some renewables.

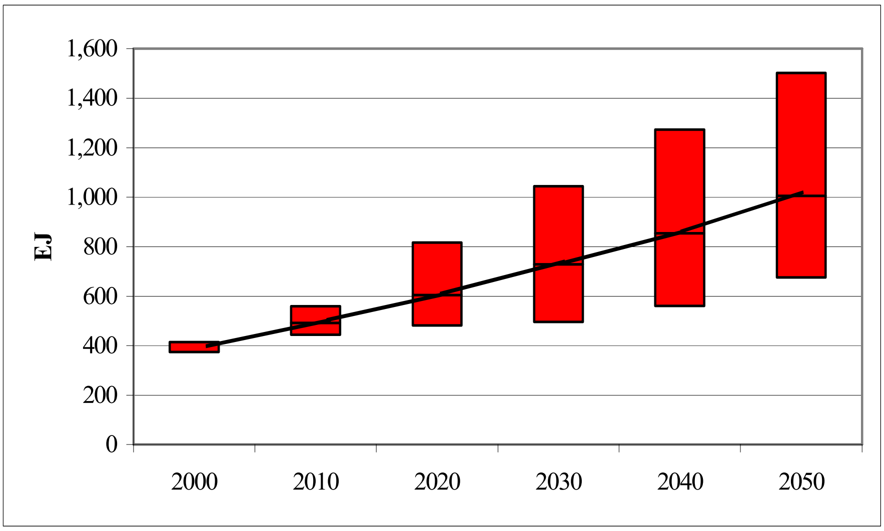


*Figure 2.2. Range of future primary energy demand in SRES scenarios, 2000-2050. Solid line represents median. Source: IPCC, 2000.*

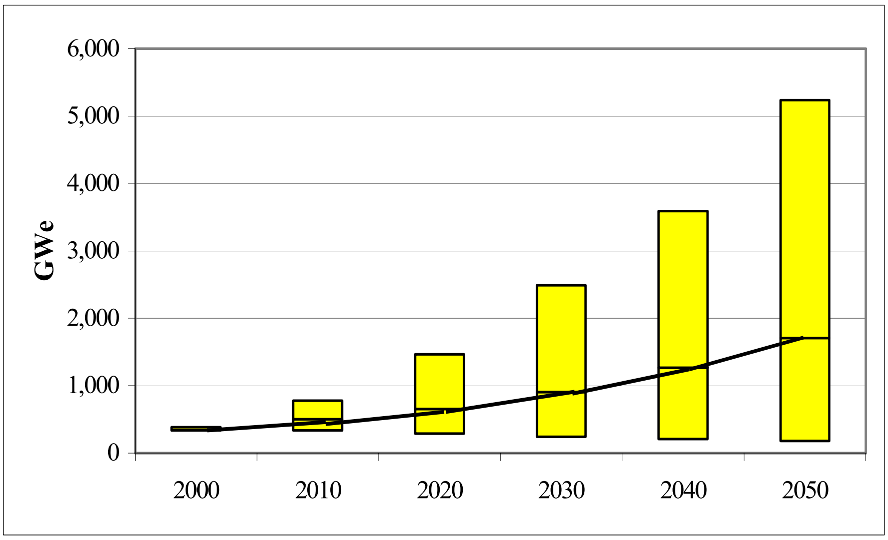


*Figure 2.3. Range of nuclear power in SRES scenarios, 2000-2050. Solid line represents median. Source: IPCC, 2000.*

## 2.4. INPRO and the general concept of sustainability

As stated in the introduction 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 21<sup>st</sup> 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 all areas. As discussed in detail in Chapter 4, 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 Chapter 5) 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 2.4.

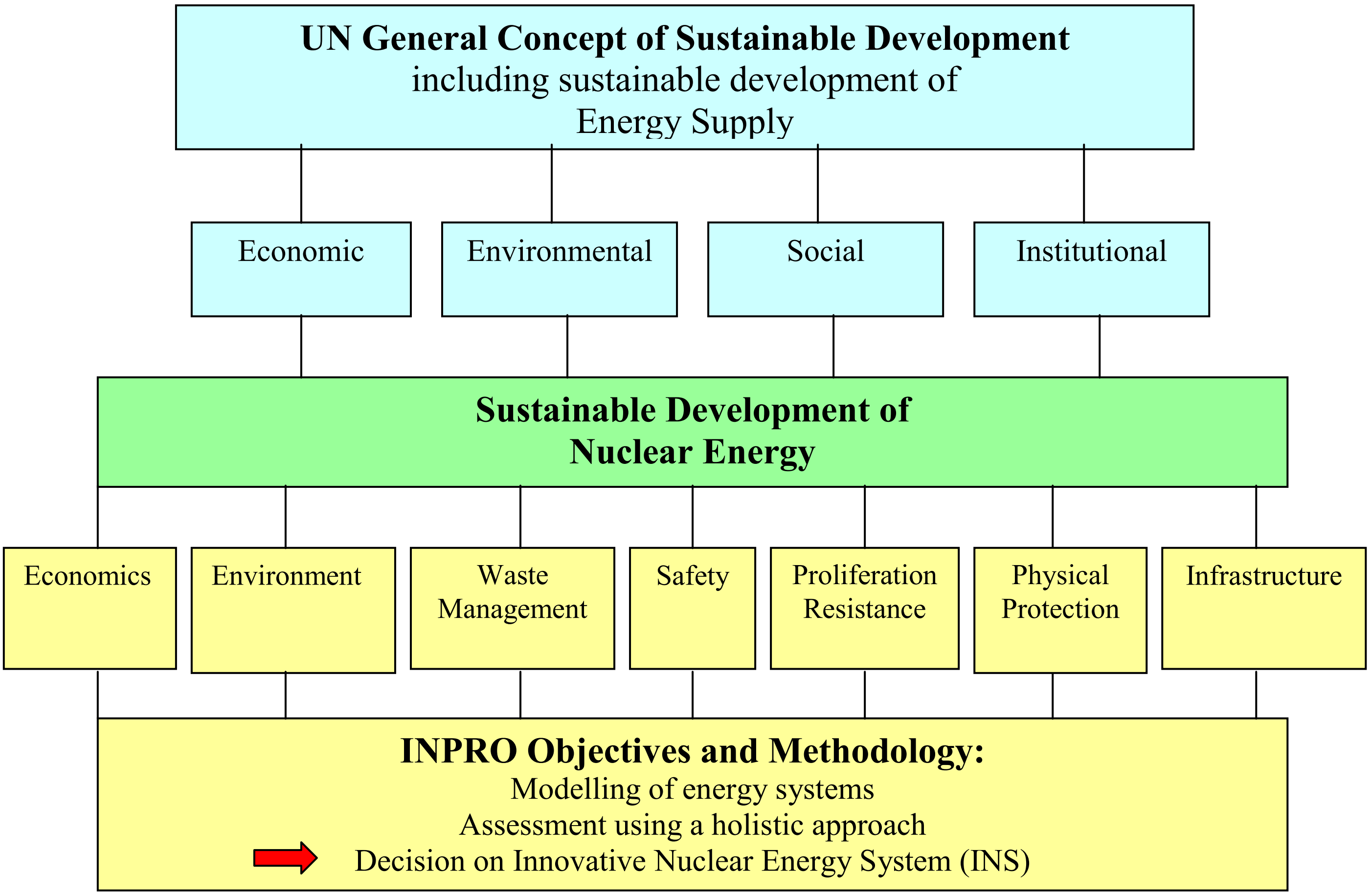


*Figure 2.4. Interrelationship of UN concept of sustainability and INPRO.*

## 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 [8], 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 by

- creating a standardized methodology for assessing the potential of INS for making a sustainable contribution to future energy needs and fostering its application,
- bringing 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 by
- creating 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.

# CHAPTER 3
# OVERVIEW OF THE INPRO REQUIREMENTS

## 3.1. Introduction

As has been noted in Chapter 1, the INPRO methodology comprises the set of INPRO requirements for eight different areas of interest, which taken as a whole encompass the four dimensions of sustainable development and the INPRO method of assessment that is presented in summary form, in Chapter 4. The INPRO requirements in each area of interest are discussed in detail in Volumes 2 to 9. In this chapter, a summary of the content of these requirements is presented for each area. Additionally, in Annex A, tables with all INPRO basic principles, user requirements and criteria are provided.

While a given member of an assessment team may only be interested in a single area, such team members should, none-the-less read the information presented here to assist him/her in understanding the context in which the requirements in his/her area of interest have been developed. The detailed requirements for the safety of reactors and for the safety of nuclear fuel cycle facilities are addressed in two separate volumes but they are considered together in the present summary.

## 3.2. Economics

In the area of *economics* [11] 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.

An example is given the economics manual [11] illustrating the INPRO assessment in this area. The INPRO assessor, presumably a private utility, is investigating the possibility of adding a medium sized nuclear power station (PWR or HWR) to his electricity grid. The alternative energy sources considered are a gas turbine and a combined cycle gas turbine. The example shows that under the given boundary conditions, nuclear power could compete on price for electricity, but the necessary investment is too high for the utility. The consequence is therefore that the technology developer has to look for means (RD&D) that would decrease the capital cost. Alternatively, different ways of financing could be considered.

### 3.3. Infrastructure

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* [4], both national infrastructure and that based on international arrangements. Nuclear power infrastructure comprises all features and substructures that are necessary for the successful deployment and operation of nuclear power plants including legal, institutional, industrial, economic and social features and 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 manual 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 which also addresses international obligations, that the industrial and economic infrastructure of a country planning to install an INS is adequate, that appropriate measures are taken to secure public acceptance, and that adequate human resources are available for nuclear deployment and 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.

### 3.4. Waste management

Because *waste management* [12] 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 volume of the INPRO manual. The IAEA sets out nine fundamental principles for radioactive waste management in the publication "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 state 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.

An example of an INPRO assessment is provided in the INPRO manual for waste management [12]. The example assumes that the assessment is performed as part of a study carried out under the leadership of a professor in Canada. The professor is leading a team of graduate students who are examining the possibility of establishing a uranium enrichment facility, a LWR fuel manufacturing plant, and a DUPIC fuel manufacturing facility using the INPRO methodology. The result of the INPRO assessment confirms the feasibility of the planned project, but also indicates the need for specific RD&D to be performed for some processes in the DUPIC fuel manufacturing facility.

### 3.5. Proliferation resistance

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 [13] into INS. The INPRO results in this area are largely based on the international consensus reached in several meetings. 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 one basic principle that requires 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 this basic principle requires that the attractiveness of nuclear technology with respect to its suitability for conversion into nuclear explosive devices be low; the diversion of nuclear material be difficult and be detectable; the commitment and obligations of States be adequate; multiple features and measures be incorporated in the 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. A detailed acquisition pathways analysis is required for each component of the INS as an input for the INPRO assessment. Effective use of intrinsic features can assist with minimizing the impact of safeguards implementation. Country profiles would be prepared to evaluate the commitments, obligations and policies of states, both technology developer states and technology user states, regarding non-proliferation. 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.

### 3.6. Physical protection

The IAEA has provided training courses on physical protection of nuclear material and facilities since the 1970's. The overall objective of the IAEA activities in the area of nuclear security can be expressed as follows: To achieve improved worldwide security of nuclear and other radioactive material in use, storage, and transport, and of associated facilities, by supporting Member States in their efforts to establish, maintain, and sustain effective national nuclear security regimes (from the IAEA Nuclear Security Plan 2006-2009).

One basic principle has been defined by INPRO in this area [14], asking for an effective and efficient implementation of a physical protection regime for the full life cycle of an INS by the State. The user requirements were developed with due consideration of the Fundamental

Principles of Physical Protection contained in the amended Convention on the Physical Protection of Nuclear Material and Facilities.

### 3.7. Environment

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 [15], one dealing with the acceptability of environmental effects caused by nuclear energy and the second dealing with the capability of INS to deliver energy while making efficient use of non-renewable resources.

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.

The INPRO assessment will utilize the results obtained from an environmental analysis which should account for all relevant factors (sources, stressors, pathways, receptors and endpoints) for the proposed energy system. The INPRO assessment itself considers the stressors identified in the analysis. The performance of a proposed technology needs to be evaluated as an integrated whole by considering the likely environmental effects of the entire collection of processes, activities and facilities in the energy system at all stages of its life cycle.

In the manual [15] several examples are provided for the assessment of specific criteria.

### 3.8. Safety

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 publications 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 reports. 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 with innovative designs, 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.

There are two INPRO reports available for nuclear safety, Volume 8 deals with the safety of nuclear reactors [16], and Volume 9 with the safety of nuclear fuel cycle facilities [17]. In Volume 8 an example of an INPRO assessment in this area is presented comparing an operating BWR with an innovative BWR. In Volume 9 an INPRO assessment of an innovative fuel fabrication facility is provided as an example.

# CHAPTER 4
# OVERVIEW OF THE INPRO METHOD OF ASSESSMENT

## 4.1. 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 [18]. 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* where *improvements* in an INS are necessary which, in turn, will lead to research, development, and demonstration (RD&D) to improve the performance of existing components of an INS and/or to develop new components.

Thus, two types of assessments, *screening* and *comparative*, can be identified, either of which may lead to the specification of development goals.

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 assessment. For example, a Member State seeking to deploy a component of an INS, e.g., a reactor, i.e., a technology user, would be expected to do a screening assessment, possibly followed by a comparative assessment of options. In the screening assessment, one or more of the options may be judged not to be sufficiently attractive and be dropped from further consideration. A comparative assessment could then be carried out to assist the technology user in selecting a preferred option to meet its requirements and constraints.

The use of an INRO assessment to identify RD&D is expected to be of most interest to developers and proponents of INS components and systems, i.e. to technology holders. 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 a comparative assessment to determine the position of his technology relative to other technologies, e.g., to identify areas of weakness that need to be bolstered by RD&D, or, in the case of an investor, to help in determining 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 be able to judge whether the component(s) of interest and the corresponding overall system are sustainable. I.e., the INPRO method is to be applied to a complete nuclear energy system.

It should be mentioned that an assessor — be it a Member State, or a group of Member States, 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 an estimate of the evolution of energy demand in the future and depends on many factors including the objectives of the assessor as well as many external factors that can be expected to change with time. The development of the energy scenario(s) is discussed in more detail in Chapter 5.

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 (Refs [19], [20], and [21]) and those under development by INPRO and others (see Chapter 5).

The assessment method for screening assessments was tested and validated in the second step of the INPRO project (first part of Phase 1B).

## 4.2. Basic features and terminology

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 all volumes of the INPRO manual, and their relationship are described below.

### 4.2.1. Innovative nuclear energy system

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), 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 transmutation of actinides and fission products) and associated fuel cycles (e.g. U, U–Pu, Th, U–Pu–Th cycle) may be considered. 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.

All phases in the life cycle of such facilities need to be considered, including site acquisition, design, construction, equipment manufacture and installation, commissioning, operation, decommissioning and site release/closure. In practice, the INPRO Requirements do not, in all areas, always address each of these life-cycle phases explicitly. But, in performing an assessment, a variety of IAEA Safety documents (guides, standards, etc.) are expected to be used and such documents address the life-cycle phases. So, taken as a whole, the INPRO Requirements do take them into account.

An example of a Nuclear Energy System could be a combination of thermal reactors and fast reactors, a closed fuel cycle based on plutonium/uranium, reprocessing facilities, centralized fuel production and waste management 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 and thus, INPRO, may include evolutionary as well as innovative designs of nuclear facilities[6].

An *evolutionary design* [3] 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] 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 [22] to [27]).

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 Section 4.4.3 below dealing with uncertainties and again in Volume 2 of the INPRO manual [11], also briefly.

For some considerable period of time nuclear energy systems will consist of a mix of existing, evolutionary, and innovative designs of components. In assessing an INS which includes such an admixture of components, it is likely that some INPRO requirements will need to be modified or not used for some components. As further discussed in Section 4.3.3, failure to meet all INPRO requirements does not necessarily mean that an INS should not be deployed, since it may well be able to make a significant and useful contribution to meeting the energy needs of a given Member State (or region or globally) on an interim basis. An

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[6] It is to be mentioned that in some INPRO areas, e.g. waste management, also existing nuclear facilities have to be included into the INPRO assessment, i.e. they are treated as part of the INS.

INPRO assessment of such a system is a valid and useful exercise since it will identify the gaps that will need to be addressed to bring the INS into full compliance with the INPRO requirements and hence with the objective of sustainability.

### 4.2.2. Hierarchy of INPRO requirements

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

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

which comprise, by definition, the INPRO Requirements.

These requirements are structured in a hierarchical order (see Figure 4.1).

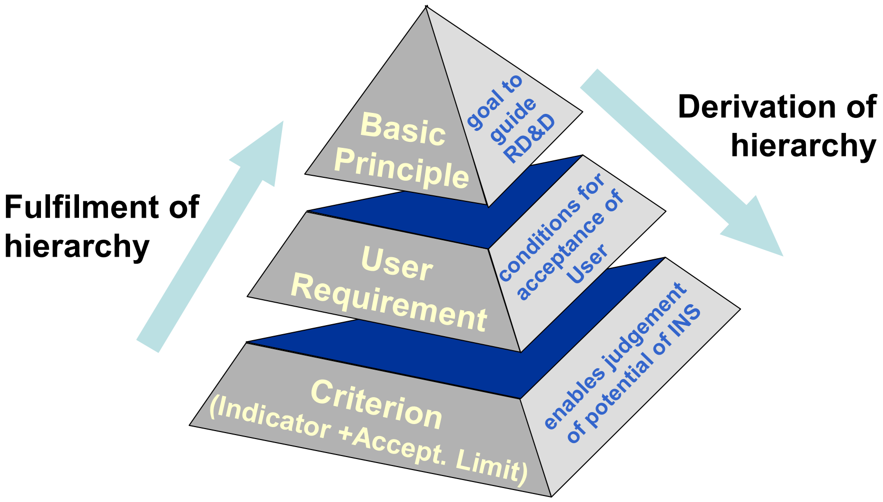

*Figure 4.1. INPRO hierarchy of demands on innovative designs of nuclear energy systems.*

The highest level in the INPRO structure is a **Basic Principle (BP),** which is a statement of a general goal that is to be achieved in an INS and provides broad guidance for the development of an INS (or a design feature thereof). The wording of an INPRO basic principle always utilizes the verb “shall” or “must”.

To achieve a sustainable INS, as discussed in Chapter 2, all BPs shall be taken into account in all areas considered within INPRO (economics, infrastructure, waste management, proliferation resistance, physical protection, environment, and safety). 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 an INPRO 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. They have been taken into account during the development of the INPRO basic principles.

The second level in the INPRO hierarchy is called a **User Requirement (UR)**. URs are the conditions that should be met to achieve users' acceptance of a given Innovative Nuclear Energy System (INS). I.e., the user requirements define the means of achieving the goal set out in the basic principle. All user requirements of a basic principle should be fulfilled to achieve a sustainable INS. The wording of a user requirement utilizes the verb "should".

In the context of the definition of user requirement, in INPRO, a **user** is an entity that has a stake or interest in potential applications of nuclear technologies and who, therefore, has an interest in applying the INPRO method of assessment or in reviewing the results of such an assessment. Users, in this context, 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.).

A number of the stakeholders listed above, or their advisors, would be expected to carry out INPRO assessments, i.e. become an assessor, 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. While performing an assessment requires the participation of individuals with expertise in the INPRO areas and with an adequate knowledge of the nuclear facilities comprising the INS, 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 significant challenge. This issue is discussed in more detail in Volume 3 of the INPRO manual that deals with the area of infrastructure [4].

The INPRO URs set out measures to be taken by technology developers or designers, by owners/operators of nuclear facilities, and by the State to ensure fulfilment of the basic principle(s) to which they relate. User requirements are applicable to components comprising a Nuclear Energy System. An example of 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 enable the INPRO assessor to determine whether and how well a given user requirement is being met by a given INS. An INPRO 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.

Two types of *indicators* of INPRO criteria are distinguished, numerical and logical. A *numerical indicator* may be based on a measured or a calculated value that reflects a property of an INS. Examples might be the estimated probability of a major release of radio nuclides to the containment obtained from a PSA or the number of intact safety barriers maintained after a severe accident. A *logical indicator* is usually associated with some necessary feature of an INS and usually is presented in form of a question. In the INPRO areas (economics, safety, waste management, etc.) some indicators may be applicable to the total INS, 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.

In addition, some indicators utilize **Evaluation Parameters (EP).** These parameters were introduced to assist the INPRO assessor in determining whether the acceptance limit for an indicator has been met. In some specific cases these evaluation parameters have their own acceptance limits, in which case they could be called sub-indicators. An example of evaluation parameters could be the use of parameters, such as some combination of design simplification, improved materials, increased operating margins, increased use of passive safety, increased redundancy, as an indicator for increasing the robustness of an INS component relative to an existing design as a means of enhancing defence in depth.

In addition to the mathematical classification of indicators, another type of indicator, a so-called **Key Indicator** (KI), is discussed in Section 4.5.

The **Acceptance Limit** (AL) of an INPRO criterion is a target, either qualitative or quantitative, against which the value of an indicator can be compared by the INPRO assessor leading to a judgement of acceptability (pass/fail, good /bad, better/poorer.). In correspondence to the two types of indicators there are also two types of acceptance limits, numerical (for quantitative targets) and logical (for qualitative targets). Typically, a logical AL is a positive (yes) or negative (no) answer to a question raised by the indicator.

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 (numerical and logical) in the area of safety (related to the example of the user requirement regarding a major release of radioactivity discussed above) could be the following:

Indicator: *Calculated frequency F of major release of radioactive materials to the environment*

Acceptance limit: *F should be less than* $10^{-6}$ *per unit per year or a major release should be excluded by design.*

If the calculated frequency is used, the indicator is a numerical indicator that 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. If “exclusion by design” is used, the indicator is a logical indicator for which the acceptance limit is the answer “yes”. For some components of the INS the assessor, e.g., technology developer, might use the calculated frequency while for other components the assessor might use “exclusion by design.”

The relationship between a basic principle, a user requirement and a criterion, indicated by the arrows in Figure 4.1, 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); and

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

While, the sequence of an INPRO assessment is bottoms up, the logical sequence in presenting and discussing the INPRO requirements starts with the basic principles (BP), followed by the user requirements (UR) and finally the corresponding criteria (CR), i.e. a top down approach. The process followed in developing and modifying the requirements is an iterative one, involving a mixture of top-down and bottoms-up approaches.

BPs, URs and CRs have been developed during Phase 1 of INPRO [2] for all areas of an INS.

They are discussed in detail in the separate volumes (see Table 1.1). A brief summary of the content of the set of BPs and URs was presented in Chapter 3 of this report. For completeness and ease of access, the BPs, URs and CR are set out in Annex A.

In preparing the various volumes of the INPRO manual it became apparent that the statements of basic principles (BP) and user requirements (UR) set out in TECDOC–1434 [2] were not in all cases fully consistent with the definitions given above. Where this problem could be addressed by a small modification in wording and/or minor changes in structure of the BPs and URs, the change was made. Thus, in the INPRO manual the statements of basic principles and user requirement in several INPRO areas, e.g., infrastructure, deviate somewhat from those in TECDOC-1434. Where a significant modification was required, the statements presented in TECDOC-1434 were retained but a statement has been added to indicate the nature of the change contemplated. One of the main goals of the INPRO manual has been to provide more detailed advice on the specification of criteria. The clarification of the criteria provided in the INPRO manuals has also led to some deviation from the information provided in TECDOC-1434.

INPRO 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 INPRO has extrapolated current trends. Member States are free to and, indeed, in a number of INPRO areas, particularly economics and infrastructure, should specify country or region[7] or technology specific criteria and user requirements.

## 4.3. Screening assessment

### 4.3.1. Evaluation of criteria

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. I.e., the criteria are considered both necessary and sufficient to fulfil the corresponding UR, and similarly for the URs and BPs.

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[7] In this publication the term region is used in several 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. The meaning should be clear from the context in which the term is used.

As a prerequisite for the performance of an assessment, the values of the indicators of the INS installation have to be determined by the assessor. In general, the corresponding acceptance limits also have to be specified. Detailed guidance on indicators and acceptance limits are provided in Volumes 2 to 9. This guidance is directed to both technology developers and technology users.

In the situation where an INS employing a new concept (innovative design) for one or more of its components 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 new component(s) 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 by a technology developer 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 assessments, in setting RD&D goals, and in deciding whether or not to initiate or continue a development program. Uncertainties also need to be taken into account by technology users should they be considering whether to base their plans for nuclear energy on deploying an INS system or component that is still under development.

During the early stages of development of an innovative design (with radical design changes compared to operating facilities today) of a nuclear facility, it will not be possible to obtain much of the information needed for an INPRO assessment because of the lack of test data and the preliminary state of design. In such a situation the assessment would need to utilize available generic information for similar or comparable facilities already fully designed. As development proceeds such generic information would be gradually replaced by facility specific information.

Thus, uncertainties are expected to be reduced during the development process, (see Section 4.4.3 of this volume and Volume 2 of the INPRO manual [11]) 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 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 the respective volumes of the INPRO manual, 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 physical protection, proliferation resistance, environment, and waste management as well as safety.) Volumes 2 to 9 provide the assessor more detailed information on the selection of acceptance limits.

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 with at least one plant in commercial operation 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 INPRO assessment is performed.

### 4.3.2. Concept of ALARP

The concept of ALARP[8] (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 Figure 4.2. As shown, 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.

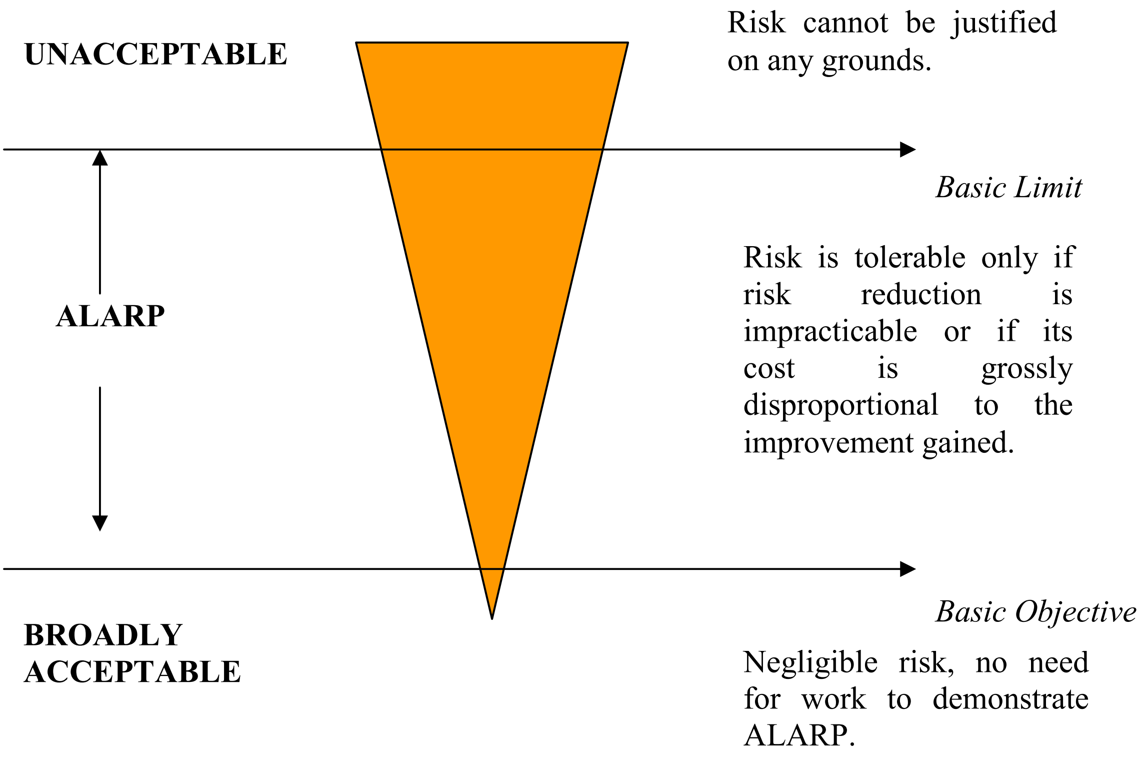

*Figure 4.2. The concept of ALARP.*

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[8] The concept of ALARP is used mainly in the UK for the reduction of all kinds of risks including radiation. The well known concept of ALARA (as low as reasonably achievable) is used primarily in the area of radiological protection to ensure the reduction of radiation doses. .

Basic limit values and basic objective values may be specified for specific indicators in national regulations or as an outcome of an environmental assessment, or it may be necessary to infer such values from other evidence such as licence conditions, actions planned, underway or completed to remediate an existing situation or improve a given practice, presentations at national or international conferences, publications in referred journals, the IAEA Safety Standards and other IAEA publications, the work of other organizations such as the International Commission on Radiological Protection (ICRP), the Nuclear Energy Agency (NEA) of the OECD, and the European Commission. When a Basic Limit or a Basic Objective is deduced from such evidence, the rationale for doing so needs to be clearly stated to ensure transparency. While national and international consensus may not exist and may be slow to emerge, by suggesting a value for a given Basic Objective and the associated rationale, a given INPRO assessment would be expected to make a valuable contribution to the process of national and international consensus building.

In this connection it may be noted that releases of radioactive substances from operating facilities are considered in a number of INPRO areas – safety, waste management, and environment. Releases from facilities will be subject to regulatory oversight and control, by the competent authority in a given Member State and should comply with the guidance provided by the IAEA in Ref. [28].

In general, release limits are established so that members of the critical group are not exposed to an annual dose greater than the dose limit recommended by the ICRP, 1 mSv per annum. In practice, facilities are designed, licensed and operated to ensure that estimated doses arising from actual releases are a fraction of the dose limit, consistent with the concept of a dose constraint. The concept of a dose constraint is that the critical group dose is unlikely to exceed the dose limit, taking into account all contributions to dose from all other practices or sources to which the critical group can be expected to be exposed. As set out in the appendix of Ref. [28] dose constraints tend to lie in the range of 0.1 mSv/a to 0.3 mSv/a. Actual releases are often significantly lower (see Ref. [29]), corresponding to doses that are close to or less than the value of 0.01 mSv/a that is considered to be an exemption limit. (See, e.g. the appendix of Ref. [28], and Ref. [30]).

Data on releases and calculated doses are publicly available in many countries and the assessor should consider such information to ensure that releases from each of the facilities that comprise a given INS are small. If releases from each of the facilities are low (say ~ 10 % of release authorizations based on the dose constraint, i.e. releases that correspond to a critical group dose of ~ 0.01 mSv/a), it can be assumed that the releases for the INS have been optimized, to the extent necessary. If licensed releases from a given facility are significantly above 10 % of licensed limits, then the assessor should seek a justification for this situation, including a rationale that overall the releases for the INS are optimized.

### 4.3.3. Judgement on potential of INS

After determining the values of the indicator and the corresponding acceptance limit, the next task for the assessor is to make a judgement on whether or not the INS complies with the criteria, or for INS under development, is expected to comply, i.e. has potential to comply. If the value of an indicator is acceptable, the judgment is that the INS "complies" with or has "potential" to fulfil the specific criterion. Otherwise the judgement becomes "non-compliant" or "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) in the course of an assessment to cover country or region specific issues or to take into account changing circumstances and boundary conditions (see Table 4.1). As assessors define and use such criteria it is expected that the INPRO criteria will be modified as a result of feedback.

Table 4.1. Example for stepwise use of the INPRO method of assessment

| **Basic Principles (BP)** | **User Requirements (UR)** | | **Criteria CR** | | | | **INS value of IN or EP** | **Judgement on potential of INS to meet AL** | **Rationale for judgement** |
|---|---|---|---|---|---|---|---|---|---|
| | | | **Indicators (IN) or Evaluation Parameter (EP)** | | **Acceptance Limits (AL)** | | | | |
| BP1 | UR1.1 | | IN1.1 | | AL1.1 | AL1.1 by MS* | X1 | compliant | X1<br><<br>AL1.1 |
| | UR1.n | | IN1.n | IN1.n by MS* | AL1.n | AL1.n by MS* | Xn | Potential | See text for rationale |
| BP2 | UR2.1 | | IN2.1 | | AL2.1 | | X2 | No Potential | X2<br>><br>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 | | | | |

* this means the UR, IN or AL has been defined by the INPRO assessor of a Member State.

Table 4.1 shows a format[9] that could also be used to assist in forming and summarizing a judgement of the potential, i.e., capability, of an INS to fulfil the INPRO criteria. In the case of a numerical indicator the rationale for the judgment would seem to be self-evident, the numerical value of the indicator either meets the acceptance limit or it does not. But, in some situations, for example, in cases where development has not yet been completed and so results from an analysis of the INS that may be needed for the assessment are not available, or for logical indicators, or where the evaluation of an indicator involves evaluation parameters, judgement of compliance/potential may depend on a logical argument. In such circumstances, the assessor needs to present the logical argument that has been used to arrive at the judgement.

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[9] A table with a similar format like the Table 4.1 is added as an appendix to each of the other volumes of the INPRO manual.

The reader will note that in some instances an INPRO assessment will use results of an analysis. An example of such a situation was presented in Section 4.2.2 above where an example of a criterion in the area of safety (related to the example of the user requirement regarding a major release of radioactivity discussed above) 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.* In this example an analysis would need to be performed to calculate the frequency. Depending on whether the assessor is a technology developer or a technology user the analysis may or may not be the responsibility of the assessor. As a general guide,

- technology developers will need to perform such analyses as part of their development and so, where a technology developer is performing an INPRO assessment, the developer would also be responsible for the analysis; and
- technology users would not be expected to perform such analyses but would expect to obtain such information directly from technology developers or from other sources.

In both cases the scope of the INPRO assessment is the same. It does not include the analysis per se but the results of such an analysis are needed to carryout the INPRO assessment. This issue is discussed further in Chapter 5.

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 State (or group of Member States). But, it may be noted that since INPRO:

- considers both evolutionary and innovative designs, and
- requires a comprehensive and holistic assessment,

it can be expected that some, perhaps many, INS assessed using INPRO, will not meet all INPRO requirements. Failure to meet all INPRO requirements implies that such an INS is not a sustainable source of energy, at least in the long term. The consequence of such a negative result is:

- The choice of an alternative INS (or alternative component) that is capable to fulfil all INPRO requirements; 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 Section 4. 5.

But, it is also important to note that failure to meet all INPRO requirements does not necessarily mean that such an INS should not be deployed in the interim. Rather, it may well be that the INS as defined can make a significant and useful contribution to meeting the energy needs of a given Member State (or region or globally) on an interim basis, but that, in due course, some components may need to be supplemented with additional components or be phased out in favour of other components.

A possible example could be an INS based on thermal reactors operating on either a once through fuel cycle or employing a limited amount of re-cycling of spent fuel in the form of MOX fuel. While many such systems exist today and can be expected to continue to be deployed in the future, in due course, particularly as uranium becomes scarce, it can be expected that a closed fuel cycle based, e.g., on fast reactors, will need to be introduced to augment the thermal reactors and eventually to displace some or all of them. Thus, to properly assess the sustainability of an INS it is necessary to consider how the INS and its components might evolve with time. In the example just discussed, restricting the definition of the INS to thermal reactors employing a once through fuel cycle and a limited amount of MOX fuel, may mean that the INS is not sustainable in the long term. But, if it is recognized that if, in due course, the INS could be modified to incorporate fast breeder reactors and closed fuel cycle, the modified INS might then become sustainable. So, the evolution of the INS with time is an important factor to be taken into account in an INPRO assessment.

A number of INPRO Member States are already performing INPRO screening assessments for example, to evaluate INS component systems that they are developing or to assist them in determining whether or not to adopt nuclear power. The output from assessments already underway and of additional such assessments would be expected to be a list of INS (components) that are (potentially) capable to be sustainable and/or fulfil all the needs of a Member States (or group of Member States) and additionally a list of INS (component) that need innovation to become sustainable.

## 4.4. Comparative assessment

### 4.4.1. Introduction

The INPRO method offers the possibility to compare different INS (or different designs of a component thereof). For technology developers the objective could be to define an optimized system or to identify areas of competitive weakness and strength and so establish development objectives. For technology users, the assessor 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. Having carried out such an assessment, 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 already been applied 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 (to be discussed further in Section 4.5.2).

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 whether the assessor is a technology user or a technology developer and his/her rationale for carrying out the assessment, i.e. the objectives. A simple example of a comparative assessment is presented below.

### 4.4.2. 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 is 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 4.3 illustrates one method of presenting such a comparative assessment of two INS.

In Figure 4.3 it may be noted that since, in this 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 No 1 to meet the acceptance limit for IN-n, while maintaining the capability of the INS for IN-1 and In-2. 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.

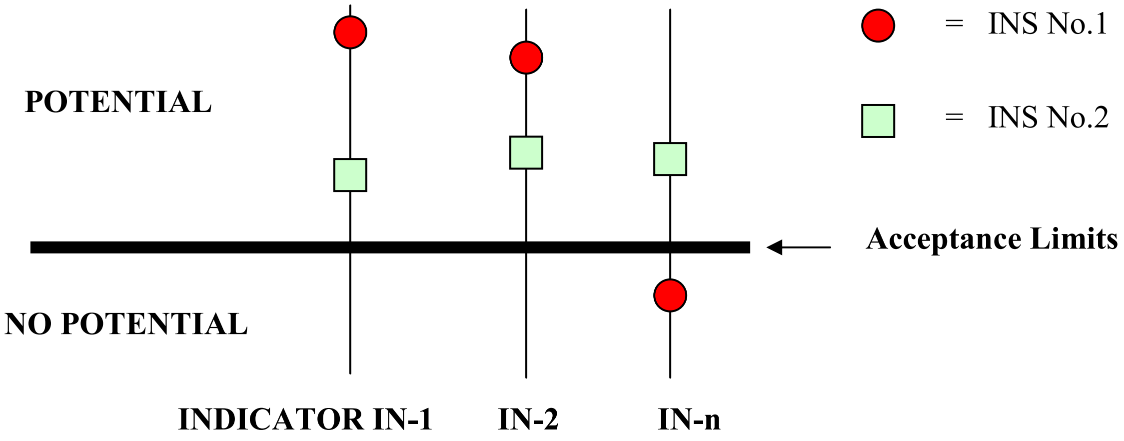

*Figure 4.3. Illustration of a comparative assessment of two INS (vertical axes have different scales for each indicator).*

### 4.4.3. 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 4.2). Further, as noted in Section 2.4 of Volume 2 [11], 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 4.3 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.

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 4.2 and 4.3 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 and information gaps that will need to be addressed in due course.

Table 4.2. 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 4.3. 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.<br>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 identified. | FOAK licensed. |

### 4.4.4. Aggregating and consolidating the results of an INPRO assessment

The outcome of an INPRO assessment, particularly an assessment used to compare the relative capabilities of different INS can be summarized or aggregated in a variety of ways depending on the needs of the assessor. Some approaches to aggregating the results of a comparative assessment are presented in Annex B. Other approaches could include a summary report noting the overall conclusions of an assessment. For example the results of a screening assessment carried out by a technology user, might conclude that a given INS would meet all requirements in the areas of safety, environment, proliferation resistance, physical protection, and waste management and so was attractive as an energy source but that in the area of economics some indicators were not met, as discussed, e.g., in the example presented in Volume 2 [11]. The consequences of failing to comply with all economic requirements are discussed and recommendations could then be presented for future action.

Interim results from an INPRO assessment being performed by France compare, graphically, the performance of an INS based on Generation IV fast reactors (year 2100) and a closed fuel cycle with an INS based on LWRs (year 2010), as illustrated in Figure 4.4.

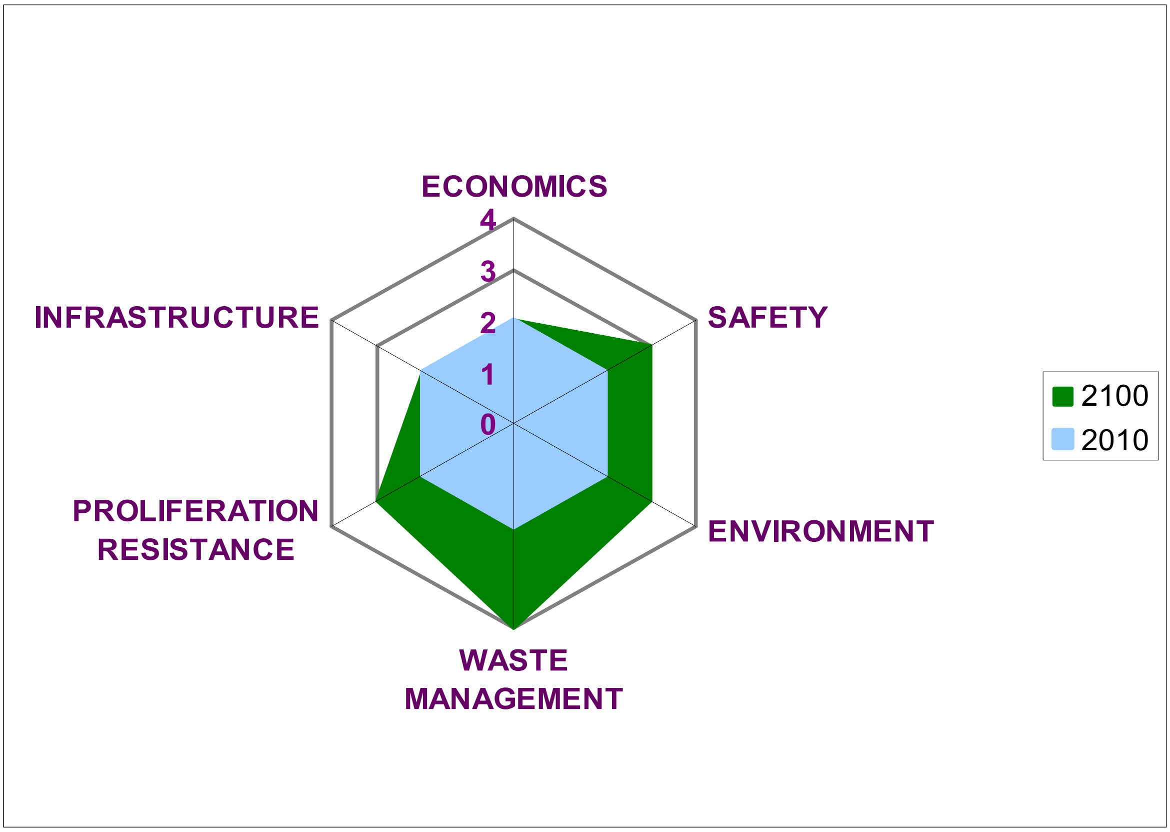

*Figure 4.4. Comparison of the capability of two INS operating in France in 2010 (blue) and 2100 (green ) in the areas of economics, safety, environment, proliferation resistance, waste management, and infrastructure (The higher the number on the diagram, the better the performance).*

As can be seen the INS based on fast reactors and a closed fuel cycle is superior to the INS based on LWRs in the areas of safety, environment, waste management and proliferation resistance and, the two different INSs are comparable in the area of economics and infrastructure.

The approach to be followed by a given assessor in summarizing the results obtained by an assessor who has performed an INPRO assessment will depend on many factors including the intended audience and its needs, the key messages that the user wishes to convey, and objectives of the assessment.

## 4.5. The use of INPRO as a development tool –some considerations

### 4.5.1. Introduction

As has been previously discussed one possible output from an INS assessment is the identification of areas where a given INS needs to be improved. Given the comprehensive nature on an INPRO assessment it would not be surprising to identify such needs. At the same time, given its comprehensive nature an INS assessment would also be expected to indicate clearly the specific attributes of an INS that need to be improved. It would then be the responsibility of technology developers to determine whether to undertake development initiatives aimed at improving the INS to address identified shortcomings/weaknesses. The developer would normally identify target values for specific indicators to be reached via RD&D and would establish the strategy to be followed in doing so. The issues involved in establishing RD&D goals and strategies are expected to be of most interest to prospective technology developers. But they are also expected to be of some interest to technology users for a variety of reasons. For example, in the area of infrastructure, shortcomings in the infrastructure of a given Member State that is considering whether or not to adopt a nuclear energy system, i.e. a prospective technology user, will need to be addressed by that state, probably with the assistance of the IAEA and possibly Member States who are technology developers. As well, the development cycle for INS should also be of interest to technology users, since an understanding of the cycle and, in particular, of the time scale involved, will assist them in judging whether or not a proposed innovation will be developed on a time scale commensurate with their needs.

Some of the issues involved in establishing RD&D goals and strategies are discussed below.

### 4.5.2. Key indicators and desirable target values

As mentioned previously (see Section 4.2, 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 technology developers and 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. An individual technology holder might identify KIs of particular interest to it or a group of technology holders might identify KIs to be addressed through a collaborative project. As well, a group of technology users/adopters might also wish to enter into a collaborative project, e.g. to develop a regional capacity in some area of infrastructure such as training, possibly also involving one or more technology holders, and they, too, might be interested in identifying KIs to track the progress of their collaboration.

In addition, a desired target value (DTV) would usually 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 development. The value of the DTV could be selected by a Member State or technology developer or in the case of a collaborative project by the project members, but, in due course, an international consensus might emerge. The DTV cannot exceed the ultimate value that the laws of physics impose or that Member States are prepared to accept. 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 to 100 years. Thus, the DTV represents a stretch target for a KI that is judged to be eventually or ultimately achievable by appropriate development and 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 of nuclear facilities already in operation;

- Attainment of DTV should be prima-facie feasible;

- Each KI should be distinct, and should not have any overlap with any other KI;

- A KI should have a good capability to discriminate between different concepts of INS; and

- KI may be chosen from among existing INPRO indicators with good discriminating capabilities.

In performing the RD&D and development, 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.

### 4.5.3. Relative benefit and risk indices

The concept of DTV can be extended by defining a so-called Relative Benefit Index (RBI). The DTV for a KI would, by definition, be assigned a RBI of 100, while 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 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. One approach for determining a RRI would be to base it on the estimated cost of RD&D required 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 4.5, which shows an example of the outcome of a theoretical RD&D assessment performed for three INS.

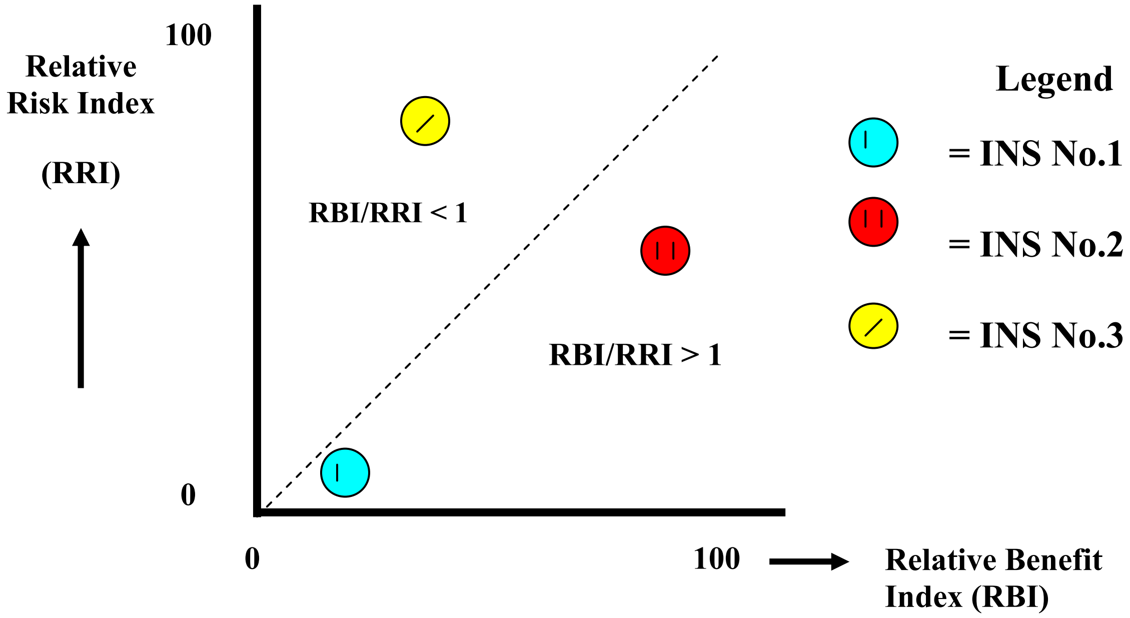

*Figure 4.5. Illustration of the concept of relative indexes for benefit and risk.*

As shown in Figure 4.5, 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 existing generation of 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 more likely to 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 INPRO Phase 1, only the outline of an approach was developed. This approach could be developed further in subsequent work to improve the INPRO

Methodology. The extent to which this is done will depend on feedback from the users of the methodology and the needs of INPRO Members.

### 4.6. 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, physical protection, 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 INPRO case studies (performed in 2004, Section 1.6 of Ref. [2]) 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 Ref. [31]) 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 (indicators and, especially, acceptance limits) are the economical criteria discussed in Volume 2 of the INPRO manual [11].

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 Volume 2 of the INPRO manual [11]). 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.

## 4.7. Sources of data for INPRO assessment

The necessary input for and steps of an INPRO assessment will be described in the following. A prerequisite for an INPRO assessment is the existence of an energy planning study that defines the role of nuclear in a mix of energy supply, either national, regional or global, depending on the goal of such an assessment. In case such a study is not available, some simplistic approaches that can be used to generate the necessary information are laid out in Section 5.2.

To perform an INPRO assessment, the assessment team will require access to a variety of data for the different INPRO areas of interest (economics, safety, etc.) and for the different components (reactors and fuel cycle facilities) that comprise an INS. The details of the data required for a given INPRO area are presented in Volumes 2 to 9. In this section some general guidance is presented for acquiring/assembling the necessary data.

In providing this guidance it is acknowledged that different countries and, hence, assessment teams, may have different aspirations and capacities concerning nuclear energy. For example countries might be characterized as follows:

- Type-1 countries that develop and use nuclear energy technology and have a well developed national nuclear infrastructure and who have an interest in developing INS components.
- Type-2 countries that do not use nuclear energy technology but have a significant industrial capacity, a well developed national nuclear infrastructure for non energy uses, a limited interest in developing INS components, and who are interested in acquiring INS, e.g., for electricity production.

- Type-3 countries that 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.
- Type-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 but for this manual the discussion concerning data sources will be limited to the types defined above.

It is assumed that *technology developers within type-1 countries* have the knowledge and capacity to develop the information needed to perform an INPRO assessment. Thus, the principal reason for a technology developer to use this manual is to ensure consistency in interpreting the INPRO requirements, selecting indicators and acceptance limits, and in presenting the results of an assessment and not with developing basic input data.

*Technology users, within type-1 countries* (e.g., utilities), may not have the capacity to develop all the information needed to perform an assessment but it is expected that they would be able to obtain the necessary information from technology developers within their country and other domestic sources.

Most *technology users in type-2 and -3 countries* who have significant industrial capacity would also have the capacity to develop much or all of the data needed for an INPRO assessment other than INS specific data, e.g., data needed for developing an energy scenario, data related to economics and infrastructure.

Thus, in the current volume we deal primarily with the information needs of an assessor in a type-4 country.

Technical data on reactors, the INS component which is assumed to be of principal interest to an INPRO assessor in a type-4 country, are available from reactors vendors, and/or from the IAEA, specifically from the Department of Nuclear Energy.

It is recommended that the scope of the initial assessment deal with a limited number of areas to begin with but that as experience is gained that it be expanded in a systematic fashion to cover all areas. It is recommended that the initial work focus on infrastructure and economics, infrastructure to identify whether gaps exist that need to be addressed before acquiring a nuclear power plant and economics because of its overall importance. Waste management will also need to be addressed early in the assessment as discussed below. Physical protection, safety, environment and proliferation resistance will also need to be addressed in due course to provide a holistic assessment of the complete INS. It can be noted that when assessing the INPRO area of infrastructure some aspects such as legal requirements of nuclear safety, environment, physical protection and proliferation resistance will have been addressed.

INS specific data needed for an economic INPRO assessment are best obtained from reactor vendors/developers who can provide information on overnight capital costs, O&M costs, fuel costs, construction times etc all of which is needed to calculate the levelized unit energy cost (LUEC)and total capital investment. Suppliers of competing energy systems should be contacted to obtain data for their technology. It is important that the assessor be supplied with all data that affects the cost of the energy provided by the system. In this respect it would be useful for the economic assessor to talk with users of such systems to develop an understanding of the costs that an actual user encounters and not rely only on vendors to identify significant cost items. For example some fossil plants may need major refurbishments and replacement of parts on a relatively short cycle time – say once every 4 to 5 years. If that were the case, it could represent a significant cost that should be included in calculating levelized unit energy costs (LUEC).

Data needed for an INPRO assessment in the area of infrastructure [4] is discussed in detail in Volume 3. Here we note, by way of example, that the INPRO assessor is supposed to collect information about the existing national legal framework for comparison with the related INPRO requirements, and that the assessor should have access to the results of a variety of planning studies carried out to determine, e.g., the capacity of national industry to contribute to a nuclear power program, and the investment needed to upgrade the national industrial capacity etc.

A waste management strategy needs to be defined for the operational waste arising from the operation of the plant and for the spent fuel. So, it is recommended that the assessment includes the impact of establishing a domestic disposal facility for the spent fuel from the reactor. It is expected that the cost of doing so to accommodate waste from only a single reactor may have a significant impact on the economics of nuclear power. In such a situation, the assessment should take into account an estimate of whether, how many, and when additional reactors might be brought into service. The economic improvement that would result from adopting a “take back” option might also be considered but it needs to be recognized that such an option, while potentially desirable, is not generally available today.

To perform an assessment it is recommended that the assessment team establish contacts with other groups to secure information needed in the assessment – with the IAEA, for example and also, possibly, with prospective supplier countries. The IAEA can provide assistance in a number of areas, including for example, energy planning, infrastructure assessment, economic analysis, waste management, etc. Reactor vendors will often also provide some assistance as part of their marketing effort, provided they judge that there is a good prospect that the country in question will adopt nuclear power. In such situations, the vendors may also assist with performing an assessment.

INPRO assessors are not expected to carry out a safety analysis of a reactor or of a related fuel cycle facility themselves. Rather, technology developer and /or operators from other countries who already operate the type of the facility under consideration should be consulted to obtain the results of safety analyses to be used in performing the INPRO assessment in the area of safety. Similarly, the technology developer or supplier should be consulted to secure the results of analyses that have been carried out in other areas of INPRO including proliferation resistance, physical protection, environment and waste management. Details on the assistance that can be obtained from IAEA are presented in Volumes 2 to 9 of the INPRO manual.

### 4.7.1. INPRO information portal for INS assessment

At the time this report was written, INPRO has started a process of creating a web site where the information needed, as discussed above, for an INPRO assessment should be accessible. The intention of the INPRO portal, once established, is to enable assessors to provide data on INS components to:

- Facilitate new assessment of Innovative Nuclear Systems (INS) by having access to existing studies that have been done before;
- Compare results of different INS assessment studies to find commonalities and/or contrasts; and to
- Establish common needs for R&D, etc.

Once established the 'INPRO Portal' will become a valuable aid in performing an INPRO assessment by providing an assessor easy access to up-to-date and referable information on all aspects of the INPRO Assessment Methodology. The information portal is discussed in more detail in Annex C.

### 4.8. Summary of the INPRO method of assessment

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 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 a team comprising 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 not specifically addressed in detail in the INPRO manual. Some aspects of such communication are, however, discussed in Volume 3 of the INPRO manual [4]. Here it is noted that there is a wide range of possible audiences that may have an interest in the results of an INPRO assessment and that it is unlikely that a single document will be suitable for communicating with all audiences. Thus, different documents will be needed for different target audiences. But, the information contained is such documents needs to be consistent.

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 goal and 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, infrastructure, waste management, proliferation resistance, physical protection, environment, and safety). 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 CRs 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 the respective volumes of the INPRO manual, 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 waste management, proliferation resistance, physical protection, and environment as well as safety.

# CHAPTER 5
# ENERGY SCENARIOS AND MODELLING

## 5.1. Introduction

In performing an INPRO assessment, the assessor must take into account a reference energy scenario or scenarios. For example, if the INPRO 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, uranium enrichment capacity, etc., and so would also have to use some elements of a regional or global scenario. If the INPRO 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. A variety of energy planning codes or tools are available that may be used by an energy planning expert in defining energy scenarios.

Codes are also needed for a variety of other purposes. For example for material flow analyses for use in environmental analyses (see Volume 7 of the INPRO manual [15]), for macro-economic analysis as one input when considering the relative benefits of different energy supply options (see Volume 2 of the INPRO manual [11]), 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.

Existing tools for energy planning include codes that have been developed by the IAEA Planning & Economic Studies Section (PESS). These codes and their use are discussed in Section 5.5.

Regardless of the specific tools used, an energy scenario (or scenarios) is needed that sets out the projected (total) demand for energy as a function of time. Within that scenario the role of nuclear in meeting the projected energy demand must be identified as an input for the INPRO assessment. The INPRO assessor must then choose the INS and its components that will supply the nuclear energy in accordance with the projected role of nuclear power. To illustrate some of the issues involved in defining an energy scenario and defining the role of nuclear power, a simple example is discussed below in Sections 5.2 and 5.3 for a national energy scenario. Since a regional energy scenario would normally be built up from a number of national scenarios, the example discussed also applies more or less to a regional scenario. The case of a global scenario is considered in Section 5.4.

Figure 5.1 shows the steps that comprise an INPRO assessment and the related energy planning. The activities listed in the first three boxes are identified as *energy planning* and provide an essential input to start an INPRO assessment. The first box at the top of Figure 5.1 called “Construction of energy demand scenarios, National, regional, global” is discussed in Section 5.2 and 5.4. The second box called “Evaluation of energy supply options” and the third one called “Specification of the potential role of nuclear power to contribute to mix of energy supply” is addressed in Section 5.3. The outcome of such an energy planning activity should be the definition of the demand for installed nuclear capacity (MW) as a function of time.

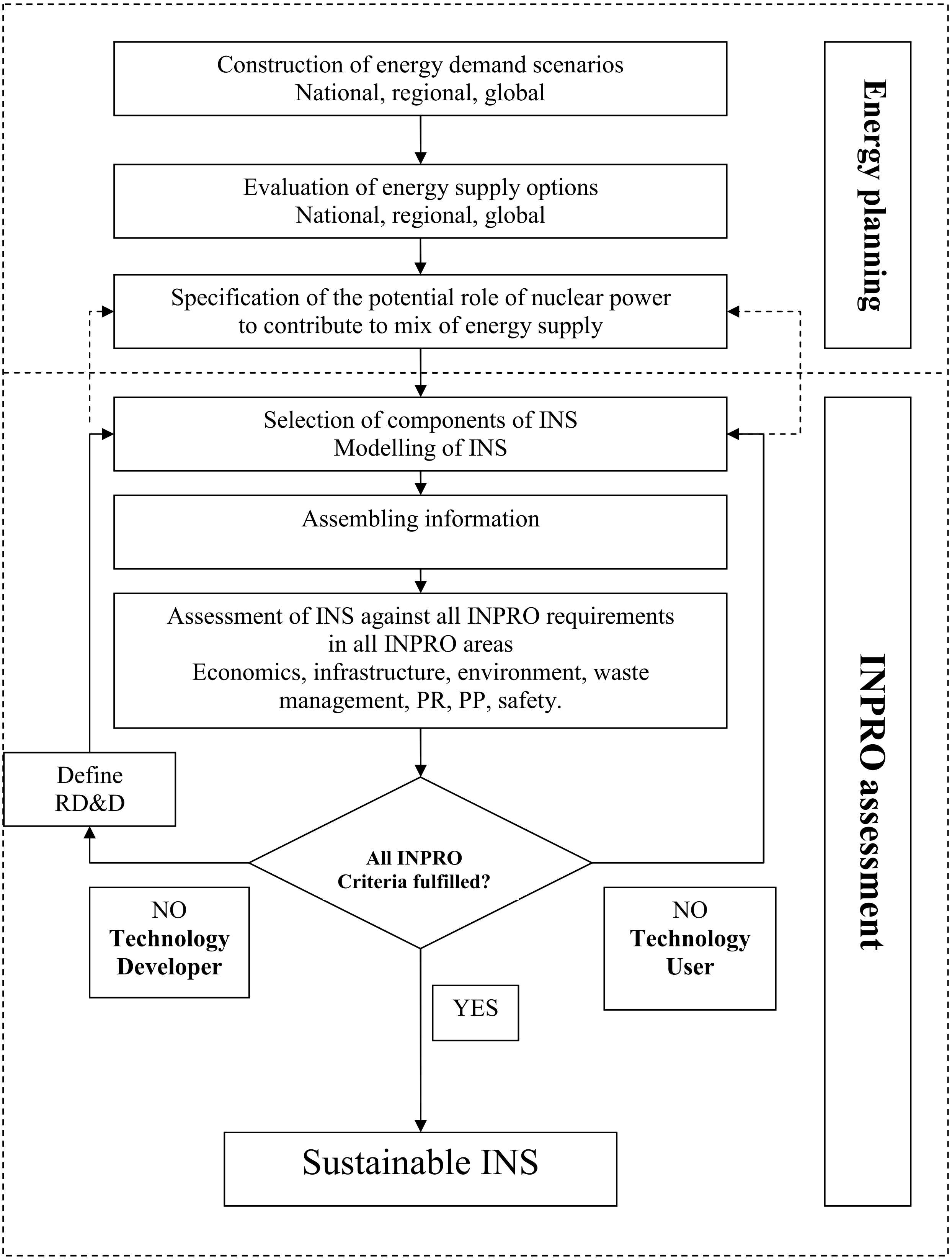

*Figure 5.1. Necessary steps of an INPRO assessment.*

The following boxes describe activities carried out as part of an INPRO assessment. The box called "Selection of components of INS" refers to the definition of an INS that meets the nuclear energy demand determined in the energy planning activity. INPRO recommends modelling the chosen INS using the tools described in Section 5.5.2 to support the comparison of different options of INS components.

"Assembling of Information" refers to gathering of information that is needed to carry out an assessment. As discussed in Section 4.7 of this volume and also in more detail in Volumes 2 to 9 of the INPRO manual, much of the information needed for an assessment, e.g., the results of safety and environmental analyses, the status of waste management planning and implementation, is to be supplied to the INPRO assessor by others. It is the task of the assessor to request and assemble this information, as input for the assessment.

The output of an assessment is a determination that either all criteria have been met, in which case the INS is sustainable, or all criteria have not been met in which case the INS, as proposed, is not sustainable. In the latter case, and depending on whether or not the assessor is a technology developer or a technology user/adopter, there are several possible courses of action, as was discussed briefly in Section 4.3.3.

In the case of a technology user these could include the following:

- Choosing an alternative INS (or alternative component) that is capable of meeting all INPRO requirements, for example a smaller unit with better economics; or
- Adjusting the nuclear energy plan, for example, to delay the introduction of the first or next NPP to ensure that the necessary infrastructure is in place, or reducing the role of nuclear energy technology as a supply option; or
- Accepting the INS as a satisfactory interim source of energy supply while advocating innovation on the part of technology developers to improve the performance of components that would be added to or substituted in the INS in the future.

The dotted line on the right side of Figure 5.1 relates to the second bullet above, i.e. adjusting the nuclear energy plan.

In the case of a technology developer, actions could include:

- 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.

The dotted line on the left side of Figure 5.1 (between the boxes "Define RD&D" and "Specification of the potential role of nuclear") indicates that as the result of successful RD&D the role of nuclear in an energy mix might be redefined, e.g., resulting in a larger contribution by nuclear energy. It further illustrates that, based on the results of an INPRO assessment, the schedule for introducing nuclear power into a country defined in an energy planning study might need modifications, e.g. for encompassing the instalment of an adequate infrastructure.

If the INS meets all criteria and, therefore, is sustainable, a technology developer may still wish to formulate RD&D to improve the performance of the INS. As well, in the case of a sustainable INS, there may be interest in considering an expanded role for the INS as an energy supply option. Thus, INPRO can be used as one component within the energy planning process, when that process identifies nuclear energy as an energy supply option.

## 5.2. Constructing a national electricity demand scenario

A prerequisite for performing a national INPRO assessment is the definition of reference energy demand projections over a reference time frame. Since nuclear energy plants are, today, expected to operate over a time scale of 50 years or longer, the energy demand projections should extend over a time frame of at least 50years and preferably longer. It is recognized that projections over such long time frames are inherently uncertain so that it would usually be the case that a range of future energy demand projections would be considered, for example by considering a best estimate or median energy demand projection, a low energy growth demand scenario , and a high energy growth demand scenario. These projections would coincide at time zero but deviate as time progressed (as an example, see Figure 3.12 of Ref. [32]).

At present, nuclear energy systems are primarily used for the supply of electricity and so, to simplify the discussion, we consider, to begin with, only this application of nuclear energy. The impact of this is to simplify the demands on an energy planning team to estimating not total energy demand as a function of time but only electricity demand as a function of time. Usually, it is expected that a INPRO assessment team would have access to projections of electricity demand.

In what follows, a simplistic approach for deriving such a projection is presented to assist INPRO assessors in making their own projections. It is recognized that this simplistic approach represents only a starting point and that more sophisticated energy planning tools, discussed in Section 5.5, will ultimately need to be employed (by energy planners).

The simplistic approach is based on considering three factors, expected population growth, per capita gross domestic product (GDP), and electricity intensity as a function of GDP. This assumes that the demand for energy is driven by two factors – population growth and improvement in the standard of living. The per capita GDP is a measure of the latter. The demand for electricity is coupled to the GDP and will be expected to increase as the GDP increases. As well, the availability of electricity, and other energy supply options, will lead to increased prosperity as measured by the per capita GDP.

Starting from the current national population the INPRO assessor needs an estimate of future population growth rate. As a first approximation, the population growth rate can be estimated from the recent historical growth rate obtained from national statistics. National authorities such as those responsible for national statistics would need to be consulted to determine whether growth rates are expected to deviate from historical rates and how. Based on the most recently available national data for population and GDP a per capita GDP can be determined at a given point in time. The per capita GDP is needed since it is this quantity that serves as a measure of the national (average) standard of living. A projection is then needed of the rate at which the per capita GDP is expected to change – to increase if the standard of living is increasing or to decrease if it is falling. Historical data can be used to provide one estimate. In developed countries rates of increase in the per capita GDP may be ~ a per cent per year or so. In a rapidly expanding economy the rate may be ~ 5 to 10 % per year. The change in the GDP can then be estimated as a function of time.

The change in national GDP as a function of time can be used to estimate the national demand for electricity as a function of time. As a first approximation the most recent data on electricity consumption and GDP can be used to determine the relationship between electricity demand and GDP. As the GDP grows the demand for electricity will also grow, initially in the same ratio as the current ratio. But the ratio of annual electricity consumption (demand) to GDP may change with time. In some developed countries the ratio is increasing slowly even though total energy intensity is decreasing, reflecting a preference for and the versatility of electricity as an energy carrier and end use energy form.

A recent report of the IEA-OECD [33] notes that between 1971 and 2002 the global economy grew by 3.3 % on average, and electricity demand grew by 3.6 % and over the period 2002 to 2030 the IEA projects an annual average growth rate of 2.5 % as the global economy increases at 3.22 % per year and the share of electricity in total final energy consumption will rise from 16 % in 2002 to 20 % in 2030.

An even simpler approach is to use electricity consumption per capita as a measure of national prosperity. Thus, the INPRO assessor would then make an assumption about annual growth in per capita electricity consumption to reflect his assumption about improvements in standard of living, starting from the historical relationship between growth in electricity consumption and growth in GDP. Thus, for example, if country were to seek to increase its per capita GDP by say a factor of 2 over a period of say 20 years (a doubling of its average GDP per capita) and if, based on past experience, changes in GDP were reflected by similar changes in electricity consumption, it could be assumed that the its per capita consumption of electricity would also double (to a first approximation) for an average annual growth rate in per capita electricity consumption over the twenty year period of 5 %. (Note that such an assumption may not be justified if, as discussed below, economic re-structuring results in a significant disruption of historical trends.)

If, for the same example, population growth over the same period were projected to be, say, 50 % then total electricity demand would then be projected to increase, over the twenty year period, by a factor of 3 - a factor of 1.5 for population growth multiplied by a factor of 2 for the increase in per capita electricity consumption. A factor of 3 increase in demand over a period of 20 years corresponds to an annual growth rate (year over year, compounded over a period of 20 years) of 5.65 % per year.

Recall that changes in per capita and total electricity consumption are assumed to correspond to changes in per capita GDP and total GDP. Hence, an annual growth rate in electricity consumption of 5.65 % corresponds to an annual growth rate in GDP of 5.65 %. If actual growth rates over the past few years are not too different from the targeted growth rate that underlie the projection, then the projected growth rate can be taken to be a reasonable estimate for the purposes of initial planning and as starting point for an INPRO assessment. The question then arises as to what is a growth rate that is “not too different?” The INPRO assessment team will ultimately have to arrive at such a judgment. For example, if the actual growth rate in recent years were substantially greater the assessor might want to use a higher growth rate in his assessment but he would also have to ask himself if such a growth rate could be sustained over the time period of 20 years used for the projection. Similarly, if the actual growth rate were substantially smaller, the assessor would have to make a judgment as to the feasibility/expectation that the growth rate could be expanded to meet the 20 year target of a doubling of the per capita GDP within the next 20 years.

Several studies based on using IAEA planning tools discussed in Section 5.5 have been published (Refs [32], [34], [35], [36], and [37]) In an energy planning study for Armenia [34], covering the period 1999 to 2020, per capita GDP was expected to grow from $ 462 (1999 USD) in 1999 to $ 1552 in 2020, in the reference growth scenario and to $ 1019 in a low growth scenario. At the same time the population was expected to grow from 3.2 million in 1999 to 3.26 million in 2020. The electricity demand in 1999 was 0.41 GW.yr. Using the simplistic reasoning set out above electricity demand in 2020 would be projected to be:

$(0.41/3.2)\text{x}3.26\text{x}(1552/462) = 1.40$ GW.yr for the reference scenario, and

$(0.41/32.)\text{x}3.26\text{x}(1019/462) = 0.92$ GW.yr, for the low growth scenario.

The detailed analysis yields values of 1.30 GW.yr and 01.03 GW.yr for the two scenarios respectively.

Thus, the simplistic analysis provides a reasonable first approximation to projected growth in electrical demand but it underestimates demand in the one scenario and overestimates it in the other scenario. The difference in the projections based on simplistic modelling and detailed modelling can be largely accounted for by an increase of fossil fuels' share in total energy supply due to economic restructuring and an anticipated increase in the use of natural gas to meet energy demand, e.g., for heat applications. Such changes cannot be accounted for using the simplistic analysis.

In a study of energy supply options for Lithuania, total GDP was projected to increase by a factor of 2.468 between 2000 and 2025 in the base scenario (see Table 3.3 of Ref. [32]). Thus, to a first approximation electricity demand would be expected to increase by the same factor. Detailed analysis projects an increase of a factor of 2.238 (see Table 3.13 of Ref. [32].) The difference between the two values appears to arise in large part from a decrease in the electrical intensity in industrial branches of the economy, which is not accounted for in the simple approach (See Table 3.6 of Ref. [32]).

A third example is provided by a study of energy supply options for Poland [35]. Over the period 1997 to 2020 population was projected to increase from 38.66 million to 40.34 million while population income growth (i.e. per capita income) was projected to increase by 5.1 % per year between 1997 and 2005, by 3.7 % per year between 2006 and 2010, by 3.4 % per year between 2011 and 2015 and by 3.2 % per year between 2016 and 2020, in the reference scenario, for a total increase over the period by a factor of 2.47. Thus using the simplistic approach the demand for electricity would be projected to increase by a factor of (40.34/38.660x2.47) = 2.58. But electrical intensity of GDP was also expected to decrease by an average factor of about 25 % over this period, thus reducing the increase in the demand for electrical energy by a similar amount to a factor of 1.93. Detailed modelling gives essentially the same result, showing the importance of factoring into the analysis anticipated changes in electrical intensity.

While, the back-of-the-envelop approach discussed above may be helpful in getting started, ultimately more sophisticated energy and electricity planning tools and procedures will be needed. As noted in a recent conference paper [38]:

"Planning for and assessing energy system developments are becoming increasingly complex with the recognition that social, economic and environmental aspects of energy are intrinsically linked. Each energy option or technology, besides direct costs, has varying degree of social and environmental costs and benefits. Energy planners and decision makers are confronted with the need to strike a balance among all these while choosing any option or technology. The complexity of their task is compounded by energy market restructuring which has become necessary almost everywhere as high demand for energy investment funds squeezes public sector budgets.

To facilitate the analysis of energy issues in making sound policy decisions, the International Atomic Energy Agency (IAEA) has developed a set of energy and environmental impact modelling tools. These tools (models) cover the entire spectrum of energy issues and provide a consistent framework for developing and evaluating alternative development paths for the energy sector in a country, taking into account expected changes in demography and life-styles, technological development and innovations, economic competitiveness, environmental regulations, market restructuring, and global and regional developments."

These energy planning tools are discussed in Section 5.5.1 below.

### 5.3. Specifying the national role of nuclear energy and the selection of an INS

Given an electricity demand projection the next task for an energy planning team is to specify what fraction of the demand is to be met with nuclear power and what fraction is to be met with alternative sources, i.e. to specify an optimized mix of energy sources.

This kind of energy planning study (examples are in Refs [32], [34], [35], and [36]) has to consider many aspects such as the availability of fuels (fossil fuels, uranium, etc.) and the reliability of their supply, sufficiency of domestic supply to meet the projected demand, the possibility for energy imports, potential for energy exports, industrial capacity and the ability to supply components of a proposed energy system, the technical characteristics of the supply options such as unit sizes, times between maintenance outages, characteristic capacity factors, grid size, peak to base load demand, and the current development of the energy infrastructure.

In general the selection of energy supply options will be based on *driving forces* such as economic considerations (e.g., availability of capital, cost of energy services, etc.), taking into account *constraints* such as the availability of fuels, the need to limit environmental emissions , and the desire to limit imports and diversify fuel types for strategic reasons, etc. Detailed modelling, based for example on the suite of IAEA energy planning tools (Section 5.5), can be used to arrive at such an optimized energy supply mix. In using such codes it is important that the user is knowledgeable about the specific models and assumptions used in the codes or works jointly with a code expert. The Planning and Economics Studies Section (PESS), Department of Nuclear Energy, IAEA, is experienced in providing assistance to Member States with energy planning and so can assist defining the energy demand and supply scenario(s) and the role of nuclear power therein as input for an INPRO assessment and in providing generic information needed in an INPRO economic assessment.

Since the focus of the INPRO assessment team is on the assessment of an INS, the team would be expected to be primarily concerned with the fraction of total demand that should or could be met with nuclear. This demand for nuclear power might be available from detailed energy planning studies that have already been carried out. As discussed above, if such studies have not been carried out the INPRO assessment team might adopt a more simplistic approach as discussed below.

In general, the energy demand and supply scenario, to be used as input for an INPRO assessment, represents an evolution from an existing grid supplied by a mix of different generating sources powered by different fuels. To combine existing energy systems with energy supply options is relatively straight forward. The assessor has the possibility of adding new energy sources (i.e. sources that are not present in the existing system) recognizing that energy sources selected in the past are not necessarily the only options that might be deployed in the future.

If a given country already employs nuclear power, the team might make a variety of assumptions depending on the aims of the assessment. For example, if the aim were to explore the potential for, and implications of, an expanding role for nuclear power, the team could assume that nuclear power would expand its share of the market so that the demand for nuclear power would, initially, increase faster than total demand and then later would continue to expand at the same rate as total demand. Or the assessment might take a more conservative view and examine the implications of assuming that nuclear power retained its traditional share of the market so that nuclear power would expand at the same rate as the increase in total demand. Or the assessor might wish to consider both options.

For a country that already employs nuclear power and has an existing nuclear power infrastructure, it is assumed that the assessment team would have the necessary experience or would have access to such experience to be able to specify the INS and its components chosen to match the capabilities and needs of the country. Such a country would, in all likelihood, not need to make use of this manual in selecting its INS. So, the following discussion is aimed at providing advice to an assessment team from a country that does not already employ nuclear power. For such an assessor, it is recommended that the assessment team keep its task as simple as possible – at least to begin with, recognizing that the scope of the assessment will probably change with time as experience is gained.

As a first step, the team should make a reasonable assumption that a first nuclear power plant will be brought into service at some specified time in the future. That time has to be selected taking into account a number of factors. One is the time that it will take to establish the necessary national infrastructure and capability that is needed to plan for and to utilize nuclear power, perhaps a decade or more (See Volume 3 of the INPRO manual [4]). Another factor relates to the demand for electricity and the need to match the size of the plant to the demand for electricity. Commercially available nuclear power plants range in output from ~ 300 MWe to > 1500 MWe. Such plants can and would, for economic reasons, be expected to be operated at a high capacity factor and so would supply from ~ 2 TWh to ~ 10 TWh of electrical energy per year, depending on the plant size[10]. A related factor is the size of the electrical grid. As a rule, it is desirable to limit the size of a generating unit to a small fraction (say ~ 10 % or less) of the peak demand serviced by the grid. Thus, to accommodate a 300 MWe unit the peak demand serviced by the electrical supply system should be ~ 3000 MWe. A final factor is the time taken to plan for and acquire a nuclear plant. Such planning can proceed in parallel with establishing a national capability and is also ~ 10 years or longer. So, it is recommended that the assessment team assume that the first nuclear power plant will be brought into operation no sooner than 10 years after the start of the assessment and later if one of the factors discussed above indicates a longer time will be needed.

The next task is for the assessment team to specify the INS. Again the advice is to keep the selected INS as simple as possible to begin with and to focus the first stages of the assessment on a limited number of INPRO areas. So, it is recommended that, to begin, the assessment team assume that only the nuclear power plant and related waste management facilities will be located in its country and that most other components of the INS will be located elsewhere. This recognizes that a healthy market exist at the front end of the fuel cycle. As noted in Ref. [39], in the course of only "two years a nuclear power plant operating in Finland has bought uranium originating from mines in seven different countries" and "conversion has been carried out in three different countries, and enrichment services have been bought from three different companies." If, however, the country already has a uranium mining industry, or has uranium resources and wishes to develop them as part of acquiring nuclear power, it would also assume that uranium mining and refining would be located in its country. But for the rest of the discussion let us assume that only the nuclear

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[10] In this context it can be noted that in some Member States nuclear plants are used primarily to meet base load demand and other technologies are used primarily for power peaking. In other Member States where nuclear plants dominate the installed capacity, the load factor for (at least) some of the nuclear plants could be considerably smaller than for plants operated to meet exclusively base load demand.

power plant and associated waste management facilities are to be located in the assessor's country.

The assessment would initially be restricted to two components – the nuclear power plant and related waste management facilities. The issue of waste management can be expected to arise in any discussion of nuclear power and so it needs to be considered early in the process of adopting a nuclear power plant. A waste management strategy needs to be defined for the operational waste arising from the operation of the plant and for the spent fuel and responsibilities for implementing waste disposal end state systems need to be assigned. To keep the INS simple, it is recommended that, in a first assessment, reprocessing of spent fuel not be included. Thus, spent fuel would be considered a waste for which a safe end state would need to be defined. If, in subsequent assessments, reprocessing is considered, the work on the end state for spent fuel would be the starting point for discussing the end state for the high level waste (HLW) arsing from reprocessing and much of what had been done for spent fuel would be applicable to HLW. So, the early work that assumed the direct disposal of spent fuel would not represent wasted effort.

An end state disposal facility for operational wastes (sometimes called low level wastes, see Volume 4 of the INPRO manual [12]) would be expected to be developed coincident with acquiring the NPP or shortly thereafter. Thus, the INS would include such a disposal facility located in the country. Most countries operating nuclear power plants are planning to establish domestic end-state facilities for their spent fuel and/or HLW, since to day most supplier countries are not prepared to accept spent fuel from other countries. The Russian Federation is a notable exception [40]. As well, the United States is promoting the concept of a Global Nuclear Energy Partnership [41] a part of which could involve the "take back" of spent fuel from reactor user countries by supplier countries. This initiative is, however, at an early stage. As well as waste disposal facilities, waste storage facilities will also be needed. These can be considered to be part of the nuclear power plant – at least in an initial assessment – but, none-the-less, they would need to be identified and their costs estimated.

Once some experience has been obtained from looking at a first reactor a more complex assessment might be warranted in which, for example, a fleet of reactors is planned to be brought into service over some defined time frame, commensurate with the expected growth of electricity demand. As well, additional domestic facilities might be added as components of the INS, such as fuel manufacturing (but not necessarily enrichment, since establishing enrichment facilities in more and more countries has implications for proliferation resistance). Also, the use of nuclear technology for other applications such as for desalination might be considered.

### 5.4. Global assessment of the role of nuclear power

An INPRO assessment based on a global energy scenario is expected to be of interest to strategic planners interested in global issues such as sustainable development, long term energy supply, climate change, etc and the potential for INS to address such issues. So, the assessment team considering a global energy scenario would, it can reasonably be assumed, consist of experts with international experience, knowledgeable in global energy issues, as well as the INPRO subject areas.

An INPRO assessment, for example, could be carried out to identify the potential that nuclear energy could play in expanding energy supply globally to meet the energy needs of a much more prosperous world, whose prosperity would depend on and be attributed to the availability of affordable energy. One such scenario, derived from the work of the IPCC Special Report on Emissions Scenarios (SRES) was discussed in Ref. [1], the so-called A1T scenario which depicts a world of high economic growth and rapid increase of energy demand. As noted there, in the original SRES A1T scenario, nuclear contributes more than 100 EJ to global hydrogen and electricity production in 2050 and the additional market potential for nuclear energy is vast and could increase to 400 EJ of hydrogen and 200 EJ of electricity by 2100. Figure 2.3 (in Chapter 2) shows the range of demand for nuclear electricity to the year 2050 arising from the SRES scenarios. The high demand shows nuclear installed capacity increasing from ~ 400 GWe in 2006 to more than 5000 MWe in 2050. Thus, this demand curve might be chosen for an INPRO assessment aimed at demonstrating the potential for INS to make a major contribution to meeting the energy needs of the 21st century in a sustainable manner.

If such a demand projection were used, the next step would be to define the INS. It is beyond the scope of this manual to do so. Rather it would be up to the team of international experts to do so [42]. But we can note some of the components of such a system. These would include, most likely, the following:

- A range of reactor types, LWRS and HWRs as well as fast reactors operating on a range of fuels, such as uranium based fuels, MOX fuel, Pu based fuels and Th based fuels. The mix of reactors types and fuel cycles used would evolve with time as uranium resources were assumed to be depleted and plants operating today and expected to be brought into operation over the near term (say between now and 2020) reached the end of their operating lives. The INS descriptions would show this evolution of reactor mix.

- A range of NFC facilities, such as re-processing facilities, waste management facilities including disposal facilities for both spent fuel, ILW and for HLW from reprocessing , and multi national fuel cycle facilities (MNFCF). The mix of facilities would change with time to mach the changing mix of reactor types.

The sustainability of this global INS would be assessed using the INPRO method of assessment. This assessment would probably need to be done iteratively to arrive at a preferred set of INSs that best met the INPRO Requirements.

It was noted in Section 5.1 that in developing a national energy scenario and specifying the INS to be used in the INPRO assessment, a national INPRO assessment team needs to take into account constraints that may be imposed by the global demand for energy. The most significant constraints that might affect a national nuclear energy program are often considered to be the availability of uranium and the availability of enrichment capacity. As was noted in Section 5.3, a nuclear power plant operating in Finland had, in the course of two years, purchased enrichment from three different companies. Thus, a healthy commercial market exists for enrichment and so, it can be assumed that as the demand for enrichment increases the market place will respond by developing additional supply capacity. In other words, the lack of enrichment capacity should not be considered to be a limiting constraint.

Information on the availability of uranium can be obtained from the so-called “Red Book” jointly published by the IAEA and the OECD Nuclear Energy Agency [43]. In discussing the long term perspective, this document notes the following:

- Known conventional resources (of uranium) are sufficient for several decades at current usage rates. Exploitation of undiscovered conventional resources could increase this to several hundred years, though significant exploration and development effort would be required to move these resources to more definitive categories (of resources).

- Sufficient nuclear fuel resources exist to meet energy demands at current and increased demand levels well into the future.

The World Nuclear Association, in an information brief on the supply of uranium [44], states the following:

"The world's present measured resources of uranium in the lower cost category (3.5 Mt) and used only in conventional reactors, are enough to last for some 50 years. This represents a higher level of assured resources than is normal for most minerals. Further exploration and higher prices will certainly, on the basis of present geological knowledge, yield further resources as present ones are used up. There was very little uranium exploration between 1985 and 2005, so a significant increase in exploration effort could readily double the known economic resources, and a doubling of price from present levels could be expected to create about a tenfold increase in measured resources, over time."

The brief contains a discussion of the sustainability of mineral resources with reference to uranium which notes, among its many observations the following:

"Uranium supply news is usually framed within a short-term perspective. It concerns who is producing with what resources, who might produce or sell, and how does this balance with demand? However, long-term supply analysis enters the realm of resource economics. This discipline has as a central concern the understanding of not just supply/demand/price dynamics for known resources, but also the mechanisms for replacing resources with new ones presently unknown. Such a focus on sustainability of supply is unique to the long view. Normally-functioning metals markets and technology changes provide the drivers to ensure that supply at costs affordable to consumers is continuously replenished, both through the discovery of new resources and the re-definition (in economic terms) of known ones."

"Another way to understand resource sustainability is in terms of economics and capital conservation. Under this perspective, mineral resources are not so much rare or scarce as they are simply too expensive to discover if you cannot realise the profits from your discovery fairly soon. Simple economic considerations therefore discourage companies from discovering much more than society needs through messages of reduced commodity prices during times of oversupply. Economically rational players will only invest in finding these new reserves when they are most confident of gaining a return from them, which usually requires positive price messages caused by undersupply trends. If the economic system is working correctly and maximizing capital efficiency, there should never be more than a few decades of any resource commodity in reserves at any point in time."

Thus, there is a strong argument that, for many decades the availability of uranium will not be a limiting constraint[11].

This conclusion should not be taken as an argument for not proceeding to develop INS based on advanced fuel cycle**s** since the time taken to develop and deploy them on a commercial basis can also be expected to take several decades. Rather the argument is that a nation considering whether or not to adopt nuclear energy as a component of its supply mix should not focus unduly on concern about the availability of uranium. Also, such general

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[11] If closed fuel cycles with fast breeder reactors (with use of Pu) are taken into account the availability of nuclear fuel will be thousands of years.

conclusions about the future availability of uranium and of enrichment should not preclude users of nuclear energy from developing their own strategies for ensuring the long term availability of fuel. For nuclear users such strategies could include securing long term guarantees from suppliers and/or entering into long term contracts with suppliers for uranium, for enrichment, and/or for fuel. For technology developers it should include the continued development of innovative reactors and fuel cycles.

## 5.5. Codes for energy planning and INS modelling tools

A number of codes that can be used in modelling energy scenarios and systems are described briefly below beginning with the IAEA codes, then presenting the INPRO code DESAE as a model for INS and concluding with some other additional useful tools.

### 5.5.1. Codes for energy planning activities

The following codes are IAEA codes that are used to define energy scenarios considering all energy supply options. The information on these IAEA codes has been reproduced from Ref. [38].

#### Model for energy supply systems and their general environmental impacts (MESSAGE)

This code is the most versatile and most sophisticated of all codes available at the IAEA, and in principle could fulfil all the objectives of the rest of the IAEA code family of energy planning tools described below.

MESSAGE [19] is designed to formulate and evaluate alternative energy supply strategies consonant with user-defined constraints on new investment limits, market penetration rates for new technologies, fuel availability and trade, environmental emissions, etc. It was originally developed at the International Institute for Applied Systems Analysis (IIASA). The IAEA acquired the latest version of the model and added a user-interface to facilitate its applications. The underlying principle of the model is the optimisation of an objective function under a set of constraints.

The backbone of MESSAGE is the technical description of the modelled system. This includes the definition of the categories of energy forms considered (e.g., primary energy, final energy, useful energy), the energy forms (commodities) actually used (e.g., coal or district heat), as well as energy services (e.g., useful space heat provided by energy). Technologies are defined by their inputs and outputs, their efficiency, and the degree of variability if more than one input or output exists, e.g., the possible production patterns of a refinery or a pass-out-turbine.

These energy carriers and technologies are combined to construct so-called energy chains, where the energy flows from supply to demand. The definitional limitations on supplying energy carriers are that they can belong to any category except useful energy, they have to be chosen in light of the actual problem, and limits on availability inside the region/area and on import possibilities have to be specified. The technical system provides the basic set of constraints to the model, together with demand, that is exogenous to the model. Demand must be met by the energy flowing from domestic resources and from imports through the modelled energy chain(s) (see Figure 5.2).

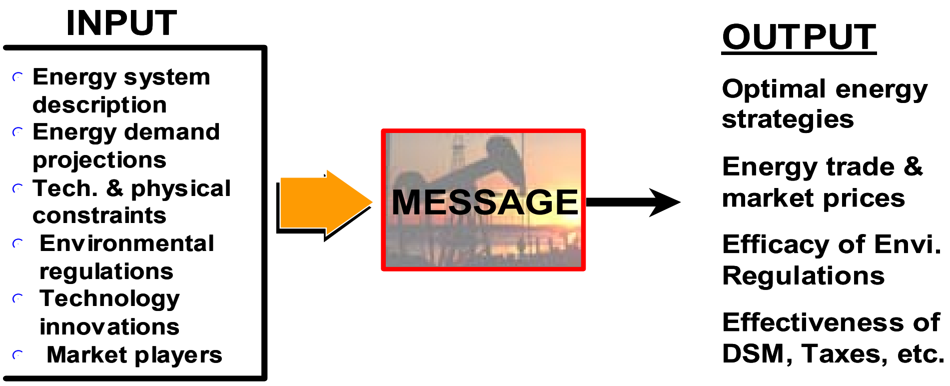

*Figure 5.2 Selected MESSAGE applications.*

The model takes into account existing installations, their vintage and their retirement at the end of their useful life. During the optimisation process, this determines the need to construct new capacity of various technologies. Knowing new capacity requirements permits the user to assess the effects of system growth on the economy.

The investment requirements can be distributed over the construction time of the plant and can be subdivided into different categories to reflect more accurately the requirements from significant industrial and commercial sectors. The requirements for basic materials and for non-energy inputs during construction and operation of a plant can also be accounted for, by tracing their flow from the relevant originating industries either in monetary terms or in physical units.

For some energy carriers assuring timely availability entails considerable cost and management effort. Electricity has to be provided by the utility at exactly the same time it is consumed. MESSAGE simulates this situation by subdividing each year into an optional number of so-called “load regions.” The parts of the year can be aggregated into one load region according to different criteria, for example, sorted according to power requirements or aggregation of typical consumption patterns (summer/winter, day/night). The latter (semi-ordered) load representation creates the opportunity to model energy storage as the transfer of energy (e.g., from night to day, or from summer to winter). Including a load curve further improves the representation of power requirements and the utilization of different types of power plants.

Environmental aspects can be analysed by keeping track of, and if necessary limiting, the amounts of pollutants emitted by various technologies at each step of the energy chains. This helps to evaluate the impact of environmental regulations on energy system development.

The most powerful feature of MESSAGE is that it provides the opportunity to define constraints between all types of technology-related variables. The user could, among others, limit one technology in relation to some other technologies (e.g., a maximum share of wind energy that can be handled in an electricity network), give exogenous limits on sets of technologies (e.g., a common limit on all technologies emitting $SO_2$, that would be defined in millions tons of $SO_2$), or define additional constraints between production and installed capacity (e.g., ensure take-or-pay clauses in international gas contracts forcing customers to consume or pay for a minimum share of their contracted level during summer months). The model is extremely flexible and can also be used to analyse energy/electricity markets and climate change issues.

The following IAEA codes have special objectives, which in principle could be fulfilled, as said above, by the MESSAGE code.

### Model for assessment of energy demand (MAED)

MAED [21] evaluates future energy demand based on medium- to long-term scenarios of socio-economic, technological and demographic developments. The model relates systematically the specific energy demand for producing various goods and services identified in the model, to the corresponding social, economic and technological factors that affect this demand. Energy demand is disaggregated into a large number of end-use categories; each one corresponding to a given service or to the production of a certain good. The nature and level of the demand for goods and services are a function of several determining factors; including population growth, number of inhabitants per dwelling, number of electrical appliances used in households, peoples' mobility and preferences for transportation modes, national priorities for the development of certain industries or economic sectors, the evolution of the efficiency of certain types of equipment, market penetration of new technologies or energy forms, etc. The expected future trends for these determining factors, which constitute "scenarios", are exogenously introduced.

An understanding of these determining factors permits the evaluation of the various categories of energy demand for each economic sector considered. The total energy demand for each end-use category is aggregated into three main "energy consumer" sectors: Household/Service; Industry, including agriculture, mining, construction and manufacturing; and the Transportation Sector. The model provides a systematic accounting framework for evaluating the effect on energy demand of a change in economics or in the standard of living of the population.

The starting point for using MAED is the reconstruction of base year energy consumption patterns within the model. This requires compiling and reconciling necessary data from different sources, deriving and calculating various input parameters and adjusting them to establish a base year energy balance. This helps to calibrate the model to the specific situation of the country.

The next step is developing future scenarios, specific to a country's situation and objectives. The scenarios can be sub-divided into two sub-scenarios:

- one related to the socio-economic system describing the fundamental characteristics of the social and economic evolution of the country; and
- the second related to the technological factors affecting the calculation of energy demand, for example, the efficiency and market penetration potential of each alternative energy form.

The key to plausible and useful scenarios is internal consistency of assumptions, especially for social, economic and technological evolution. A good understanding of the dynamic interplay among various driving forces or determining factors is necessary. The model output, i.e. future energy demand, is just a reflection of these scenario assumptions. The evaluation of output and the modification of initial assumptions is the basic process by which reasonable results are derived.

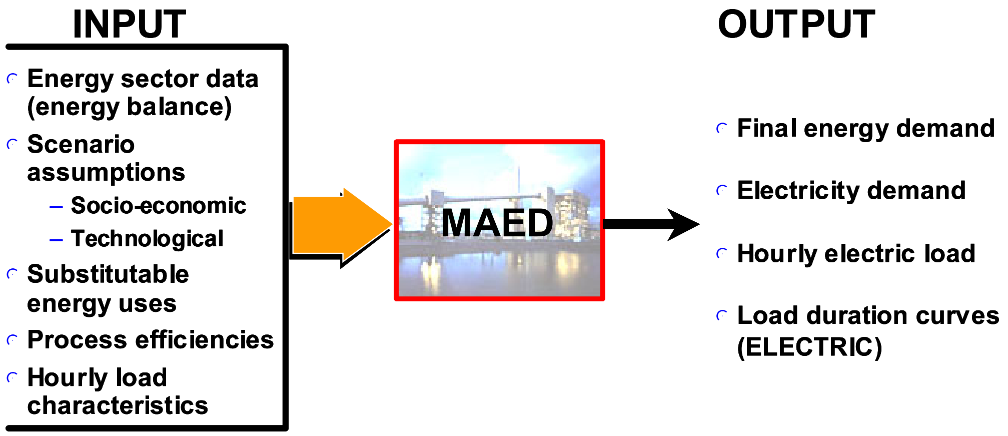

*Figure 5.3. Main inputs and outputs of MAED.*

The model focuses exclusively on energy demand, and even more specifically on demand for specified energy services. When various energy forms, i.e. electricity, fossil fuels, etc., are competing for a given end-use category of energy demand, this demand is calculated first in terms of useful energy and then converted into final energy, taking into account market penetration and the efficiency of each alternative energy source, both specified as scenario parameters. Non-substitutable energy uses such as motor fuels for cars, electricity for specific uses (electrolysis, lighting, etc.) are calculated directly in terms of final energy.

Demand for fossil fuels is therefore not broken down in terms of coal, gas or oil, because this energy supply mix largely depends on the technological possibilities of supply and relative prices of these fuels, aspects that are outside the scope of the MAED analysis. The substitution of fossil fuels by alternative "new" energy forms (i.e. solar, district heat, etc.) is nevertheless estimated, due to the importance of the structural changes in energy demand that these energy forms may introduce in the future. Since these substitutions will be essentially determined by policy decisions, they are to be taken into account at the stage of formulating and writing the scenarios of development.

Special attention is given to the calculation of electricity demand, which is performed not only annually as for all other energy forms, but also on an hourly basis. These calculations in turn, can serve as input data for further analysis of the generating system using the WASP model. These calculations specifically determine the electric load imposed on the generating system, which will then permit WASP to select suitable generation technologies that match the variation in demand within a year or season.

The hourly load calculations are performed using various "modulation factors" which correlate changes in hourly electricity consumption with respect to average consumption. In determining hourly, daily and weekly electric load from the total annual electricity demand of the sector, the model takes into account:

a) The trend of the average annual growth rate of electricity demand;
b) The seasonal changes in electricity consumption (this variation may be reflected on a monthly or weekly basis, depending on available information);
c) The changes in electricity consumption owing to the type of day being considered (i.e. working days, weekends, special holidays, etc.);
d) The hourly variation in electricity consumption during the given type of day considered.

### Wien automatic system planning package (WASP)

WASP [20] is the IAEA's long-standing model for analysing electricity generation system expansion plans. Initially developed in the 1970s, it has been enhanced and upgraded over time to match emerging needs and to allow analysis of contemporary issues like environmental regulations, market restructuring, etc.

WASP permits the user to find an optimal expansion plan for a power generating system over a long period and within the constraints defined by the planner. The optimum is defined in terms of minimum discounted total costs. Each possible sequence of power plants that could be added to the system (expansion plan or expansion policy) and that meets the selected constraints, is evaluated by means of a cost function composed of: capital investment costs, fuel costs, operation and maintenance costs, fuel inventory costs, salvage value of investments and cost of energy demand not served.

As a starting point, WASP requires representation of the existing system defining the technical, economic and environmental characteristics of all existing power plants. These characteristics include: plant capacities, minimum and maximum operating levels, heat rates, maintenance requirements, outage rates, fuel and operation costs, emission rates, etc. For the given yearly future demand for electricity, it explores all possible sequences of capacity additions that will match this demand and at the same time satisfy all the constraints. The constraints can be based on achieving a certain level of system reliability, availability of certain fuels, build-up of various technologies, or environmental emissions. The sequences of capacity additions are first screened and those that satisfy the constraints, called feasible configurations for expansion of the system, are selected. The operation of a system for all these configurations is then simulated using a probabilistic simulation technique, which takes into account the failure probabilities of the plants and produces unit dispatch schedules to meet the given load. Available units are dispatched according to their marginal production costs. The generation, fuel requirement and environmental emissions of each unit are calculated and checked against any limitations imposed externally. Finally, a dynamic programming algorithm traces the optimal sequencing of capacity additions.

Electricity demand, which is an input to the model, is specified in terms of annual peak load and variations in this load during the year. Each year can be sub-divided into 12 periods. For each period, load duration curves are used to represent load variations. All of this information can be prepared with and transferred from the MAED model.

Treatment of hydroelectric plants is designed to accommodate the stochastic nature of hydrology by permitting the user to choose from a range of hydrological conditions (up to five), each one defined by its probability of occurrence and the corresponding available capacity and energy. This information is again an input to the model and can be prepared with the help of hydro simulation models. Pumped storage hydro plants are handled in a similar way. However, their operation is determined based on the cost of electricity available for pumping and the cost of peaking units.

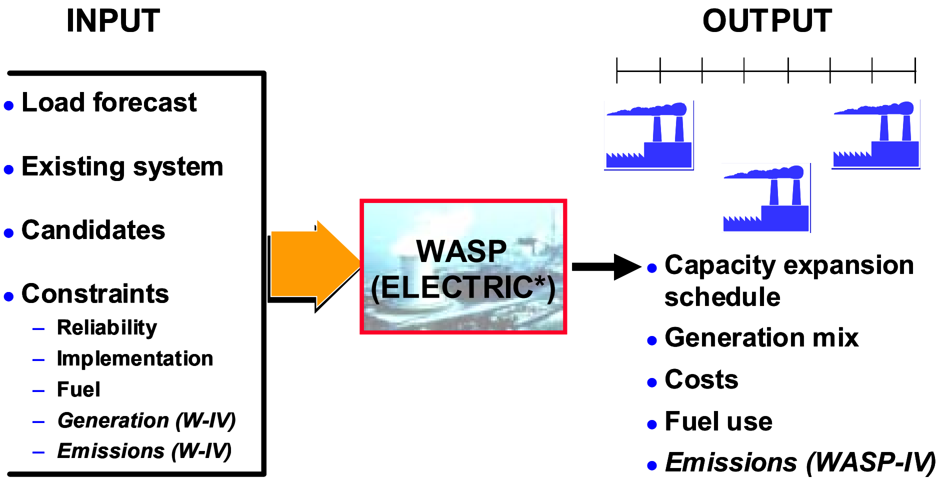

*Figure5.4. Main inputs and outputs of WASP.*

System reliability is a major concern in power system planning. WASP evaluates the reliability of a system in terms of the loss-of-load-probability (LOLP). This index is calculated by the model for each period of the year and for each hydro-condition. The expected value of LOLP is calculated as the sum of LOLP for all hydro-conditions weighted by their respective probabilities. The user can specify a desired level of LOLP as a constraint.

For hydro dominant electric systems, another reliability index, energy-not-served (ENS) is more relevant. This index is also used in WASP to guide the system to build sufficient reserve capacity. ENS is assigned a cost which is minimised along with other costs related to system build-up and operation. This cost will reflect the expected damage to the economy when a certain amount of demand for electricity is not satisfied.

For systematic handling of information, the WASP model is sub-divided into seven modules: LOADSY (load system description), FIXSYS (fixed system description), VARSYS (variable system description), CONGEN (configuration generator), MERSIM (merge and simulate), DYNPRO (dynamic programming optimisation), and REPROBAT (report writer). This modular structure ensures a systematic flow of information and permits input validation at each stage.

### Energy and power evaluation program (ENPEP)

The ENPEP model (see Chapter 10 of Ref. [2]) is designed to simulate energy markets by determining the long-term energy supply and demand balance for a given country. To achieve this goal, the model takes into account all energy production, conversion, transport, distribution, and utilization activities in the country as well as the flows of energy and fuels among those activities. The model uses a non-linear, equilibrium approach to determine the energy supply and demand balance. This equilibrium modelling approach is based on the concept that the energy sector consists of autonomous energy producers and consumers that carry out production and consumption activities, each making decisions on available choices and maximizing their benefits. However, these decisions are made within system boundaries determined by government policies, regulations, existing capital stock, new technological opportunities, personal preferences, etc.

For its simulation, the model uses an energy network that is designed to trace the flow of energy from primary resource (e.g., crude oil, coal) through to final energy demand (e.g., diesel, fuel oil) and/or useful energy demand (e.g., residential hot water, industrial process steam). The model solves simultaneously for the intersection of all energy supply forms and all energy uses in the energy network. The equilibrium is reached when the model finds a set of prices and quantities that satisfies all relevant equations and inequalities.

The energy network represents all energy production, conversion, transport, distribution, and utilization activities in a country or region, as well as the flows of energy and fuels among those activities. It is constructed with a set of sub-models or building blocks, called “nodes” that represent energy activities or processes, such as petroleum refining. The user connects the nodes with a set of “links” that represent energy and fuel flows and associated costs among specific energy activities. Links convey price and quantity information from one node to another. The energy network is developed by defining energy flows among the different nodes for a given base year. All sectors of the energy supply and demand system are included in a typical analysis.

The market shares of competing fuels are estimated by a logarithmic function where the market share of a commodity is a function of the commodity’s price relative to the price of alternative commodities. Demand is sensitive to the prices of alternatives. Supply price is sensitive to the quantity demanded. As market shares of energy are dependent on energy prices and energy prices are dependent on the quantity of fuel demands, the model uses an iterative process to bring network prices and quantities into equilibrium.

Since energy purchase decisions are not always solely based on price, premium multipliers are used in the model to simulate the preference that consumers may have for some commodities over others. In addition, the model uses a lag parameter to simulate the time that is required for prices and demands to reach an equilibrium or balance. In general, capital-intensive industries have longer lag times than those that require relatively smaller capital investments.

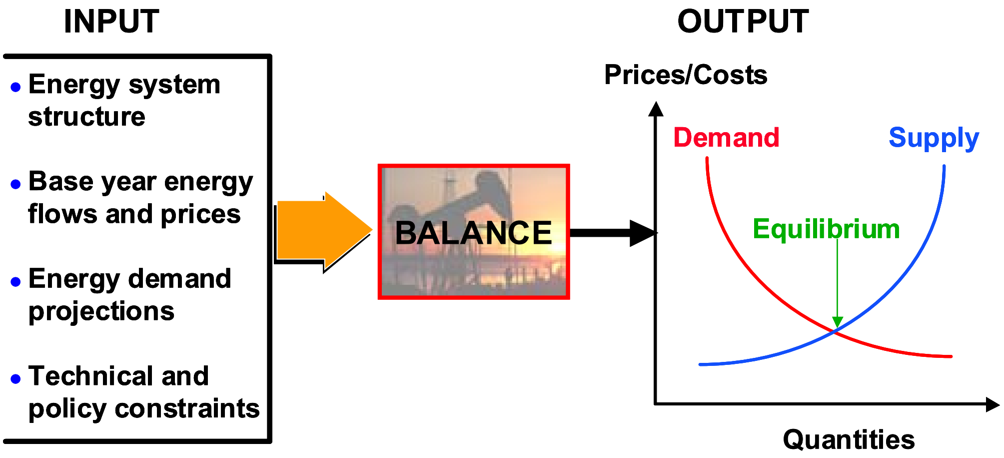

*Figure 5.5. Equilibrium approach of ENPEP.*

Environmental considerations are also taken into account, by calculating the emissions of various pollutants arising from a given fuel mix at each stage. The model then calculates the environmental costs associated with these emissions and adds these to energy costs.

Environmental costs can thus be used to affect the solution found by the market equilibrium algorithm.

### Model for financial analysis of electric sector expansion plans (FINPLAN)

FINPLAN (see Chapter 10 of Ref. [2]) is designed to evaluate the financial implications of an expansion plan for a power generating system. When an optimal or desired investment programme for system expansion has been determined, for example with the help of the WASP model, it should be subjected to various reality checks. If the expansion plan is too ambitious for available resources, even the most efficient configuration may not be realisable. Such financial constraints may require a revision of the economically optimum expansion plan. FINPLAN helps to analyse alternative expansion plans by evaluating their financial consequences.

Given the difficulty of isolating a specific power plant from the rest of system, both physically and financially, the FINPLAN model is designed to consider all power plants in a system or owned by a company. It can, however, also be used for financial analysis of a single power plant. In case of a system level analysis, the model evaluates the consequences of adding a set of power plants, over a given time period, on the overall financial performance of the company. For a single plant analysis, it evaluates financial viability of the plant under assumed market conditions.

The information used by the model as inputs can be grouped into three types: (1) data specific to the expansion plan, i.e. types, sizes and timing of power plant additions; expected electricity generation by each plant; and investment, fuel and operating costs; (2) economic and fiscal parameters, describing assumptions on inflation, price escalation, exchange rates, prices, taxes, etc.; (3) financial parameters, defining financing possibilities such as fixed-rate credits/loans, variable rate loans, bonds and equity.

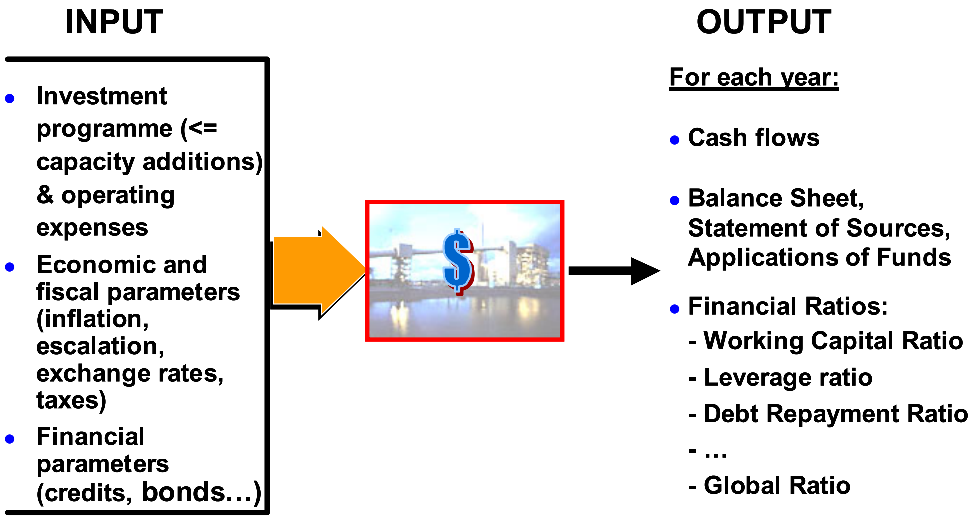

*Figure 5.6. Main inputs and outputs of FINPLAN.*

For developing countries, arranging funds in foreign exchange is an added difficulty. The model treats all expenditures in two currencies, one foreign and the other local. The cash flows for all expenditures in the respective currencies are maintained and the impact of future exchange rate changes is analysed accordingly.

The model has five built-in sub-modules: (1) investment, (2) debt, (3) revenue and expenditure, (4) tax and royalty, and (5) foreign exchange. The investment module calculates cash flows associated with on-going and new investments in the generation, transmission and distribution systems. (The transmission and distribution investments can be ignored if the model is applied to a generation company.) The debt module computes cash flows related to borrowing, interest payments and loan repayments. The revenues and expenditure module handles accounts of revenues from the sale of electricity and any other income, and all expenditures including operating expenses and dividend payments. It also calculates depreciation charge on fixed assets. The tax and royalty module computes income tax and royalties as well as equity repayments. The foreign exchange module calculates foreign currency requirements for investments, purchase of imported fuels and debt service for foreign currency loans.

In addition to calculating discounted cash flows, the model also generates various standard financial statements such as sources and applications of funds, current accounts of revenues and expenditures, income statements and balance sheets. It also computes a number of financial ratios, which can be used as indicators for the financial condition and creditworthiness of the company. The ratios included are: working capital, equipment renewal, leverage, gross-profit rate, debt repayment time, exchange rate risk, break even point, interest charge weight.

The model does not optimise the financing package. The user achieves financial equilibrium, through an iterative process, analysing the output and revising the inputs. While this is more time consuming it also permits leeway for creative financial proposals. The model is very useful as it helps to analyse the impact of assumed future conditions that affect the financial health of a company.

### Simplified approach for estimating impacts of electricity generation (SIMPACTS)

SIMPACTS (see Chapter 10 of Ref. [2]) consists of separate modules for estimating the impacts on human health, agricultural crops and buildings resulting from routine atmospheric emissions of pollutants from energy facilities. It covers fossil and nuclear as well as hydro installations. It estimates physical damages, and provides as well for a monetary estimate of these external costs. A decision aiding module permits comparison of the relative advantages of different technologies according to different selected criteria. The most significant aspect of SIMPACTS is its simplicity. It is designed for use on a PC with a minimum of input data, in contrast to other external cost models that are complex and data hungry.

For airborne pollution, whether from fossil or nuclear plants, the model follows the impact-pathway approach. In this approach, the emission source is characterised and an inventory of airborne releases is prepared. The changes in ambient concentrations of various pollutants are estimated using atmospheric dispersion models and, in the case of radioactive emissions, deposition. Then, exposure response functions are used to relate the change in pollutant concentration to a physical impact on the relevant receptors. For hydropower, the model offers a simplified approach to estimate the loss of land, population displacement, and emissions during construction from hydro dams as well as the impacts from dam failures. Finally, all the impacts and burdens are monetised and aggregated.

The model allows a user to make a range of external cost estimates ranging from crude to quite accurate, depending upon availability of data. An approximate estimate can be obtained with input on average population, plant characteristics and emissions, even if no data are available on local weather conditions. In a typical application, the user may start the analysis with minimum data to get a rough estimate and then gradually add more information, as it becomes available, to obtain more reliable results. Given the high uncertainties involved in any estimation of external costs, SIMPACTS produces results well within the range of more complex models.

The nuclear assessment includes two sub-modules, one for routine emissions and the other for accidental emissions. In the routine emissions case, four pathways for radio-nuclides are included, viz. direct inhalation of radio-nuclides in the air; external irradiation from radio-nuclides immersed in clouds; external irradiation from deposited radio-nuclides; and ingestion of radio-nuclides in agricultural products. The key stages for these pathways are: releases, transport, contamination, human exposure and health effects. The accidental emissions component uses expert judgement about the probability and magnitude of a consequence and utilises an expected risk aversion approach. Monetization of expected consequences gives the external cost of an accident.

The hydro module (Figure 5.7) considers displaced population, loss of agricultural and forest land, impacts of dam failures, emissions during construction, etc. Though the impacts of hydropower projects are generally considered to be extremely site specific, and the project specific information should be used wherever possible for estimating impacts, the model nonetheless provides a first-order estimate, if site specific information is not available, for future hydro projects. In such cases, it uses different reservoir models based on terrain characterisation to estimate inundated area and potential impacts. It also calculates expected loss of life and economic damage due to dam failure.

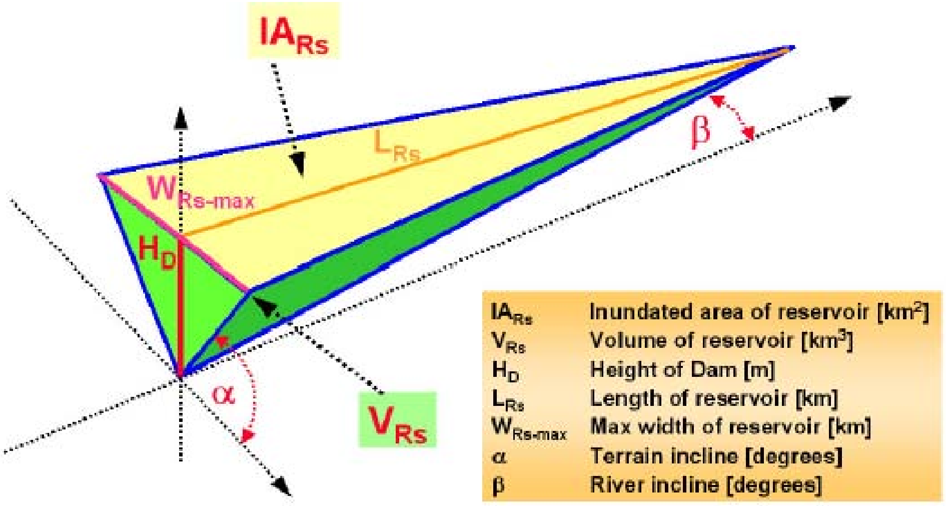

*Figure 5.7. SIMPACTS, Simple 3D reservoir model of triangular shape.*

With these modules, SIMPACTS covers the major energy sources and most of the associated impacts on human health and the environment. Most important, it makes available to any user, instead of just to a select few, a simple but accurate tool for estimating external costs associated with electricity generation. The model can be used for comparing and ranking various options in terms of these external costs.

### 5.5.2. Selected tools for modelling INS

Modelling tools are computer codes that calculate specific data of defined nuclear energy systems such as waste produced, fuel needed, cost of electricity, etc.

**The dynamics of energy systems – atomic energy (DESAE)**

The DESAE-code, i.e. Dynamic of Energy System – Atomic Energy, is being developed by the UNK (United Knowledge) Group in the Russia Federation as an INPRO task (see Chapter 10 of Ref. [2]). DESAE 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 5.8). 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.

DESAE is an interactive code. 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.

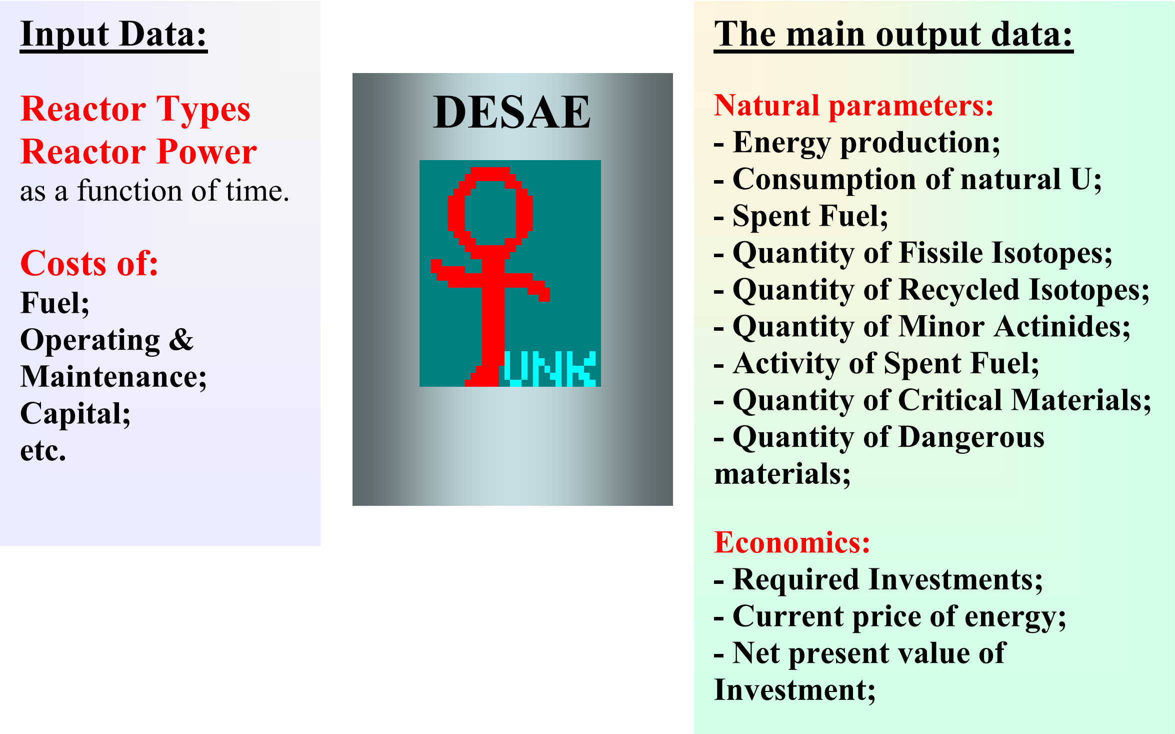

*Figure 5.8. Main input and output data of DESAE code.*

The code performs material flow analysis based on a user-defined deployment scenario of reactors and fuel cycle facilities. The code does not perform burn-up or core management calculations but bases the calculations on tabled fresh and spent fuel compositions provided by the user (databases with this characteristics are available). The tabled fuel characteristics include data for equilibrium and start-up core compositions for various reactor types. The fuel composition is followed for 17 isotopes, i.e. $^{232}$Th, $^{232}$U, $^{233}$U, $^{234}$U, $^{235}$U, $^{236}$U, $^{238}$U, $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{242}$Pu, $^{237}$Np, $^{242}$mAm, $^{244}$Cm, $^{129}$I, $^{99}$Tc, with one additional group for the other fission products. The code also calculates integral and differential consumption of different materials in an INS, e.g. Fe, Cu, Al, Zr.

DESAE allows modelling seven reactor types in parallel in one simulation with all of them having any chain of fuel exchange with each of the other reactors. These fuel exchange paths need to be defined by the user. However, the fuel cycle representation in DESAE is done with only 4 fuel cycle facilities, without yet tracing losses in these facilities. The activity and radio-toxicity of spent fuel is calculated but repository needs are currently (as of September 2005) only defined by the volume of materials to be stored. Proliferation risk is assumed to be dependent on the volume of so-called relevant materials, i.e. fissile Pu.

The economic analysis within DESAE calculates levelized cost of energy calculation based on the capital costs for reactors and nuclear fuel cycle facilities, the operation and maintenance costs and the calculated fuel cycle costs as well as total investment needs to deploy a certain nuclear energy system scenario.

DESAE is under continuous development and is subject of some testing programme within the INPRO community. Benchmark validation with other codes has been proposed, as well as links with the macro-economic energy market analysis code MESSAGE. The DESAE code has been developed using the MATHLAB-software. The code is available to all Members of INPRO.

In the following some additional codes are shortly described that could be used for specific tasks.

### The nuclear fuel cycle simulation system VISTA

The nuclear fuel cycle simulation system (VISTA) was developed in the context of the IAEA’s “Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities” (1997) [45]. It has since then been further developed by, for instance, inclusion of a simplified isotopic composition calculation program (CAIN).

VISTA calculates, by year over a long period, nuclear fuel cycle requirements for several types of reactors. Calculations could be performed for a reactor, a reactor park in a country or worldwide nuclear reactor park. Natural uranium, conversion, enrichment and fuel fabrication quantities are estimated. Furthermore, the quantities and qualities (isotopic composition) of spent fuels can be evaluated to let the user apply a recycling strategy if desired. The main assumption in the model is that it is possible to simulate the nuclear fuel cycle by taking into account the evolution of different types of reactors with time, without the precision of using a reactor by reactor database. The reactor types taken into consideration in VISTA are PWR, BWR, PHWR, AGR, GCR, RBMK and WWER.

The CAIN model in VISTA allows to track a set of isotopes detailed enough to grasp the main decay chains of fuel isotopes but not overly detailing the calculation by exclusion of nuclides with very short half-lives (< 8 days) or that may be considered stable (> 400 years half-life) for the scenario period of interest. In total, 14 fuel isotopes are considered, i.e. $^{235}$U, $^{236}$U, $^{238}$U, $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{242}$Pu, $^{237}$Np, $^{241}$Am, $^{242m}$Am, $^{242}$Cm, and $^{244}$Cm.

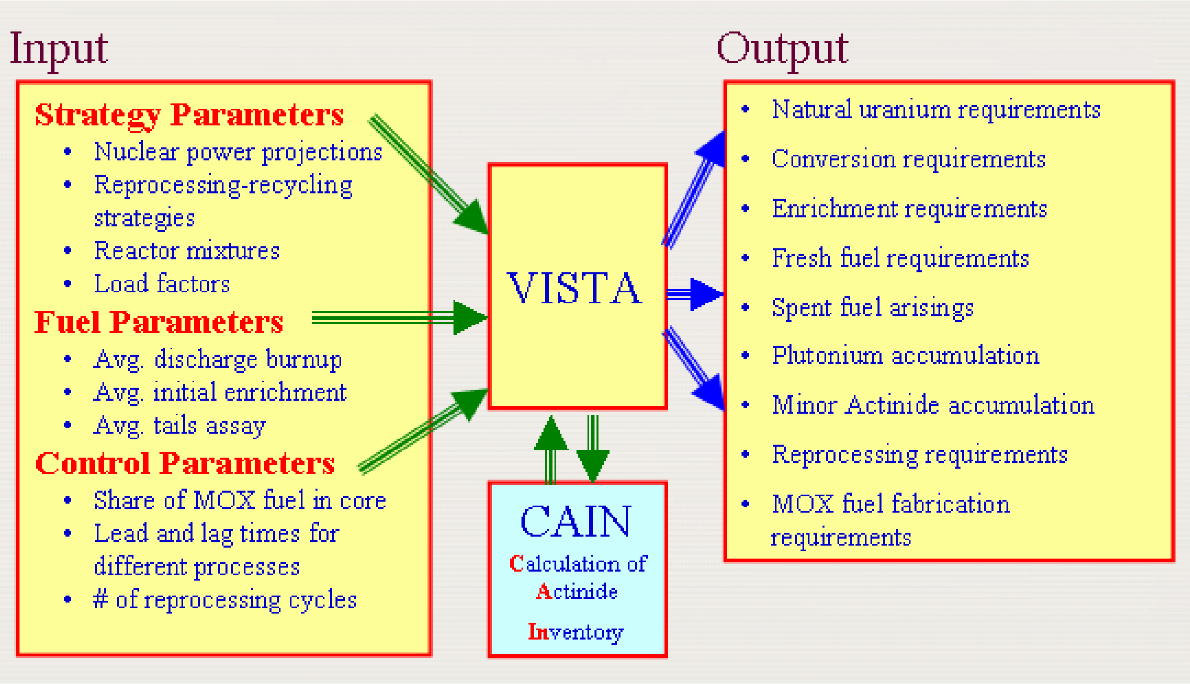

*Figure 5.9. Main features of VISTA.*

The seven different reactor types are also treated in CAIN allowing isotopic burn-up calculations based on the Bateman equations. Benchmarking with other codes and experiments has been undertaken and provided very good results, i.e. 1 to 3 % error margin for the main U and Pu isotopes.

VISTA may be used to simulate various aspects of evolving nuclear energy systems, i.e. varying reactor park compositions, changing fuel cycle options, changing reactor load factors, enrichment tails assay, and others, i.e. all typical reactor and fuel cycle facility characteristics may be set to change during a simulation which allows to run rather realistic scenarios.

VISTA is currently MS-EXCEL based. Data input is reduced to a few basic data in order to let non-nuclear fuel specialists develop different energy scenarios. The calculation speed of the system is quick enough to enable making comparisons of different options in a considerably short time.

One of the purposes of VISTA is to evaluate the radio-toxicity of different nuclear fuel cycle options. Currently, radio-toxicity can be calculated using isotopic contents from the VISTA calculations and their individual radiotoxic contribution. Direct calculation of radio-toxicity of fuel is currently not available in VISTA but an improvement planned for the nearby future. Economical and further environmental analysis is out of scope for VISTA for now.

VISTA is available to Member States via IAEA.

### SYRTEX

The SYRTEX (System Rate of Technology Expansion) code is under development, and has been used for assessing the competitiveness of different INS for different market conditions (see Chapter 10 of Ref. [2]). 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.

### COSI (CEA, France)

COSI, developed by CEA (France), is a code simulating a pool of nuclear electricity generating plants with their associated fuel cycle facilities [48]. The code has been designed to study various short, medium and long-term options for the introduction of various types of nuclear reactors and for the use of associated nuclear materials. COSI calculates the mass and the isotopic composition of all the materials, in each part of the nuclear park, at any time of the simulation period.

The main particularities of the COSI code are a detailed material flow accounting analysis of the nuclear fuel cycle with the possibility to take into account the conversion, enrichment of natural and/or recovered uranium from reprocessing, and the fuel fabrication, as well as the irradiated stockpiles, reprocessing throughput and associated separated fissile/fertile material flows, wastes in the back-end of the fuel cycle.

All the reactor plants and fuel cycle facilities are characterized by their unit and/or annual capacity, operating time, losses, date of commissioning, load factor, lifetime, and other parameters allowing to represent these INS components in sufficient detail for the an MFA. COSI currently considers various reactor types (PWRs, SFRs, GFRs, HTRs) where the core management is user-defined according to time history, reload fuel management, and type of fuel, i.e. UOX, MOX, MOX with enriched U (MOX Ue), U-free fuel, MOX including MA, HTR Fuel, and FR fuel with each time the characteristics of reloads (mass, cycle path).

Very accurate physical models, benefiting of an extensive French benchmarking with experimental data, allows to trace the material flows in great detail and accuracy as well as to detail the isotopic composition for each batch of fuel. The isotopic composition follows in total 28 isotopes, i.e. $^{232}$U, $^{234}$U, $^{236}$U, $^{238}$U, $^{237}$Np, $^{239}$Np, $^{236}$Pu, $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{242}$Pu, $^{241}$Am, $^{242m}$Am, $^{243}$Am, $^{242}$Cm, $^{243}$Cm, $^{244}$Cm, $^{245}$Cm, $^{246}$Cm, $^{231}$Pa, $^{230}$Th, $^{99}$Tc, $^{129}$I, $^{133}$Cs, $^{134}$Cs, $^{135}$Cs, $^{137}$Cs.

COSI allows the user to define boundaries or constraints in the operation of fuel cycle facilities, e.g., $^{241}$Am maximum acceptable concentration in MOX fuel fabrication, processing plant capacity in heavy metal and in Pu, minimum cooling down period prior to spent fuel processing, and the user may still define more details on fuel cycle facility operation practices such as ‘first in’/‘first out’ management of spent fuel, various types of dilution in reprocessing, and others.

COSI gives a detailed computation of the material balances including the computation of the Pu-content or $^{235}$U enrichment entering fuel fabrication based on the composition of the various batches of Pu used, the origin of the uranium, the core management, and the burn-up. The computation of the fuel isotopic content in and out of the reactor at any time is given for each step in the fuel cycle.

COSI can also assess an economic balance of reactors and fuel facilities so as to obtain a levelized cost per kWhe. The economical model in COSI can take account of the investment, exploitation and decommissioning costs for each of the reactors and fuel cycle facilities and their associated planning, the cost of natural materials and the actualization rate.

COSI is only available through license agreements with CEA.

**DANESS (ANL, USA)**

DANESS, i.e. Dynamic Analysis of Nuclear Energy System Strategies, is an integrated dynamic nuclear process model for the analysis of today's and future nuclear energy systems on a fuel batch, reactor, and country, regional or even worldwide level [49]. The model allows simulating up to 10 different reactor types and up to 10 different fuel types in one simulation. Starting from today's nuclear reactor park and fuel cycle situation DANESS analyzes energy-demand driven nuclear energy system scenarios over time and allows the simulation of changing nuclear reactor parks and fuel cycle options. The nuclear energy systems may not only generate electricity but may as well result in other energy vectors such as hydrogen and district heat. The energy demand is hereby given as an exogenously defined energy-demand scenario. New reactors are introduced based on the energy demand and the economic and technological ability to build new reactors. The technological development of reactors and fuel cycle facilities is modelled to simulate delays in availability of technology. Levelized fuel cycle costs are calculated for each nuclear fuel batch for each type of reactor over time and are combined with capital cost models to arrive at energy generation costs per reactor and, by aggregation, into a cost of energy for the whole nuclear energy system. A utility sector and government-policy model are implemented to simulate the decision-making process for new generating assets and new fuel cycle options. The government-policy model allows simulating different actions that government may exert through, for instance, tax rates, regulation, R&D-funding and others. Learning curve effects may be applied on different parameters in the simulation and may experience different learning rates. A (current) simple life-cycle inventory model traces all losses in the nuclear fuel cycle and traces also all main secondary material flows, such as water, energy, metals, needed during the deployment, operation and decommissioning of the nuclear energy system.

The MFA-part is based on tabled fresh and spent fuel compositions where the isotopic composition of the fuel or high-level waste is traced according to 71 isotopes, i.e. $^{232}$U, $^{233}$U, $^{234}$U, $^{235}$U, $^{236}$U, $^{237}$U, $^{238}$U, $^{236}$Pu, $^{237}$Pu, $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{242}$Pu, $^{244}$Pu, $^{246}$Pu, $^{235}$Np, $^{236}$Np, $^{237}$Np, $^{241}$Am, $^{242}$Am, $^{243}$Am, $^{242}$Cm, $^{243}$Cm, $^{244}$Cm, $^{245}$Cm, $^{246}$Cm, $^{247}$Cm, $^{248}$Cm, $^{250}$Cm, $^{227}$Th, $^{228}$Th, $^{229}$Th, $^{230}$Th, $^{232}$Th $^{234}$Th, $^{231}$Pa, $^{233}$Pa, $^{247}$Bk, $^{249}$Cf, $^{250}$Cf, $^{251}$Cf, $^{252}$Cf, $^{253}$Cf, $^{254}$Cf, $^{253}$Es, $^{254}$Es, $^{255}$Es, $^{223}$Ra, $^{224}$Ra, $^{225}$Ra, $^{226}$Ra, $^{228}$Ra, $^{225}$Ac, $^{227}$Ac, $^{222}$Rn, $^{60}$Co, $^{90}$Sr, $^{125}$Sb, $^{134}$Cs, $^{137}$Cs, $^{144}$Ce, $^{147}$Pm, $^{154}$Eu, $^{155}$Eu, $^{129}$I, $^{99}$Tc, a short-lived and a long-lived fission product group. This decomposition allows to calculate correctly the isotopic evolution from discharge of irradiated fuel until geological disposal, whatever the fuel cycle option taken, and to calculate the decay heat to be evacuated from repository and thus defining the repository space needs.

DANESS has been developed according a flexible architecture which remains the same independent of the size of INS being assessed, i.e. from single reactor up to multi-regional nuclear energy systems.

A graphical user interface allows easy input and output of INS-information and results while a typical 100-year simulation only takes a few minutes on PCs.

DANESS is available via license agreements with ANL in run-time and in developer's version. Further developments are ongoing to include more detailed life-cycle inventory models as well as to further the benchmarking of the code for various INS assessment cases.

# ANNEX A
# BASIC PRINCIPLES, USER REQUIREMENTS AND CRITERIA

In the following for each area of INPRO tables are provided with the basic principles (BP), user requirements (UR) and criteria (CR).

Table A.1. BP, UR, and CR for the INPRO area of economics [11].

| **Economic basic principle BP**: *Energy and related products and services from Innovative Nuclear Energy Systems shall be affordable and available.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1 (Cost of energy):** *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.* | **CR1.1** cost competitiveness | |
| | **IN1.1**: Cost of nuclear energy, $C_N$.<br>**IN1.2:** Cost of energy from alternative source, $C_A$. | **AL1:** $C_N \leq k*C_A$ |
| **UR2 (Ability to finance):** *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.* | **CR2.1** figures of merit | |
| | **IN2.1:** Financial figures of merit. | **AL2.1:** Figures of merit are comparable with or better than those for competing energy technologies of comparable size. |
| | **CR2.2** total investment | |
| | **IN2.2:** Total investment. | **AL2.2:** The total investment required should be compatible with the ability to raise capital in a given market climate. |

Table A.1. BP, UR, and CR for the INPRO area of economics [11] (continued).

| **Economic basic principle BP**: *Energy and related products and services from Innovative Nuclear Energy Systems shall be affordable and available.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR3 (Investment risk):** *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.* | **CR3.1** maturity of design[12] | |
| | **IN3.1:** Licensing status. | **AL3.1.1:** *For deployment of first few NPPs in a country:* Plants of same basic design have been constructed and operated.<br>**AL3.1.2:** *For deployment of a FOAK plant in a country with experience operating NPPs:* Design is licensable in country of origin.<br>**AL3.1.3:** *For development*: Plan to address regulatory issues available and costs included in development proposal. |
| | **CR3.2**[13] construction schedule | |
| | **IN3.2:** Evidence that project construction and commissioning times used in financial analyses are realistic. | **AL3.2.1**: *For deployment of first few NPPs in a country*: Construction schedule times used in financial analyses have been met in previous constructions projects for plants of the same basic design.<br>**AL3.2.2**: *For deployment of a FOAK plant:* A convincing argument exists that the construction schedule is realistic and consistent with experience with previous NPP construction projects carried out by the supplier and includes adequate contingency.<br>**AL3.2.3**: *For technology development:* Schedules analyzed to demonstrate that scheduled times are realistic taking into account experience with previous NPP construction projects. |

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[12] The acceptance limit of criterion CR3.1 has been extended in comparison to Ref. [2] to cover 3 situations (first NPP, FOAK, and development).

[13] The acceptance limit of criterion CR3.2 has been extended in comparison to Ref. [2] to cover 3 situations (first NPP, FOAK, and development).

Table A.1. BP, UR, and CR for the INPRO area of economics [11] (continued).

| **Economic basic principle BP**: *Energy and related products and services from Innovative Nuclear Energy Systems shall be affordable and available.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR3 (Investment risk) (continued):**<br>*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.* | **CR3.3** robustness[14] | |
| | **IN3.3:** Financial robustness index of INS, RI. | **AL3.3:** RI $\geq$ 1 |
| | **CR3.4** political environment | |
| | **IN3.4:** Long term commitment to nuclear option. | **AL3.4:** Commitment sufficient to enable a return on investment. |
| **UR4 (Flexibility):**<br>*Innovative energy systems should be compatible with meeting the requirements of different markets.* | **CR4.1** flexibility | |
| | **IN4.1**: Are the INS components adaptable to different markets? | **AL4.1:** Yes. |

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[14] In comparison to Ref. [2] criterion CR3.3 was added to UR3 in this report.

Table A.2. BP, UR and CR for the INPRO area of infrastructure [4].

<table>
<tr><td colspan="3"><b>Infrastructure basic principle BP:</b> <i>Regional and international arrangements shall provide options that enable any country that so wishes to adopt, maintain or enlarge an INS for the supply of energy and related products without making an excessive investment in national infrastructure</i>[15].</td></tr>
<tr><th rowspan="2">User Requirement (UR)</th><th colspan="2">Criterion (CR)</th></tr>
<tr><th>Indicator (IN)</th><th>Acceptance Limit (AL)</th></tr>
<tr><td rowspan="4"><b>UR1 Legal and institutional infrastructure:</b> <i>Prior to deployment of an INS installation, the legal framework should be established to cover the issues of nuclear liability, safety and radiation protection, environmental protection, control of operation, waste management and decommissioning, security, and non-proliferation</i>[16].</td><td colspan="2"><b>CR1.1</b> legal aspects</td></tr>
<tr><td><b>IN1.1:</b> Status of legal framework.</td><td><b>AL1.1</b>: Legal framework has been established in accordance with international standards.</td></tr>
<tr><td colspan="2"><b>CR1.2</b> institutions</td></tr>
<tr><td><b>IN1.2:</b> Status of State organizations with responsibilities for safety and radiation protection, environmental protection, control of operation, waste management and decommissioning, security and non-proliferation.</td><td><b>AL1.2</b>: State organizations have been established, in accordance with international standards.</td></tr>
</table>

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[15] In comparison to Ref. [2], in the BP the words “maintain or enlarge” have been added. BP1 was changed to BP.

[16] In comparison to Ref. [2], in UR1 the words “proliferation resistance” was replaced by “non-proliferation”.

Table A.2. BP, UR and CR for the INPRO area of infrastructure [4] (continued).

| **Infrastructure basic principle BP:** *Regional and international arrangements shall provide options that enable any country that so wishes to adopt, maintain or enlarge an INS for the supply of energy and related products without making an excessive investment in national infrastructure*[17]*.* | | |
|---|---|---|
| **User Requirement (UR)** | **Criterion (CR)** | |
| | **Indicator (IN)** | **Acceptance Limit (AL)** |
| **UR2 Industrial and economic infrastructure:** *The industrial and economic infrastructure of a country planning to install an INS installation should be adequate to support the project throughout the complete lifetime of the nuclear power program, including planning, construction, operation, decommissioning and related waste management activities*[18]*.* | **CR2.1** financing | |
| | **IN2.1:** Availability of credit lines. | **AL2.1:** Sufficient to cover the program. |
| | **CR2.2** energy market | |
| | **IN2.2:** Demand for and price of energy products. | **AL2.2:** Adequate to enable a satisfactory financial return. |
| | **CR2.3** size | |
| | **IN2.3:** Size of installation. | **AL2.3:** Matches local needs. Assumed to have been defined in energy planning study. |
| | **CR2.4** support structure | |
| | **IN2.4:** Availability of infrastructure to support owner/ operator. | **AL2.4:** Internally or externally available. |
| | **CR2.5** added value | |
| | **IN2.5:** Overall added value of proposed nuclear installation (AVNI). | **AL2.5:** AVNI > national infrastructure investment necessary to support nuclear installation. |

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[17] In comparison to Ref. [2], wording of BP was extended to include the words "*maintain or enlarge*".

[18] In comparison to Ref. [2], wording of UR2 was extended to include the words "*throughout the complete lifetime of the nuclear power program, including planning, construction, operation, decommissioning and related waste management activities*".

Table A.2. BP, UR and CR for the INPRO area of infrastructure [4] (continued).

| **Infrastructure basic principle BP:** *Regional and international arrangements shall provide options that enable any country that so wishes to adopt, maintain or enlarge an INS for the supply of energy and related products without making an excessive investment in national infrastructure***.** | | |
|---|---|---|
| **User Requirement (UR)** | **Criterion (CR)** | |
| | **Indicator (IN)** | **Acceptance Limit (AL)** |
| **UR3 Political support and public acceptance:**<br>*Adequate measures should be taken to achieve public*[19] *acceptance of a planned INS installation to enable a government policy commitment to support the deployment of INS to be made and then sustained*[20]. | **CR3.1** public information | |
| | **IN3.1:** Information provided to public | **AL3.1:** Sufficient according to best international practice. |
| | **CR3.2** public participation | |
| | **IN3.2:** Participation of public in decision making process (to foster public acceptance). | **AL3.2:** Sufficient according to national requirements. |
| | **CR3.3** public acceptance | |
| | **IN3.3:** Public acceptance of nuclear power. | **AL3.3:** Sufficient to ensure there is negligible political risk to policy support for nuclear power. |
| | **CR3.4** political commitment | |
| | **IN3.4:**.Government policy. | **AL3.4:** Policy is supportive of nuclear power. |

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[19] Public is meant here to be all stakeholders in a nuclear power program, i.e. society.

[20] In comparison to Ref. [2], wording of UR3 has been extended to include "*to enable a government policy commitment to support the deployment of INS to be made and then sustained"*.

Table A.2. BP, UR and CR for the INPRO area of infrastructure [4] (continued).

| **Infrastructure basic principle BP:** *Regional and international arrangements shall provide options that enable any country that so wishes to adopt, maintain or enlarge an INS for the supply of energy and related products without making an excessive investment in national infrastructure.* | | |
|---|---|---|
| **User Requirement (UR)** | **Criterion (CR)** | |
| | **Indicator (IN)** | **Acceptance Limit (AL)** |
| **UR4 Human resources[21]:** *The necessary human resources should be available to enable all responsible parties involved in a nuclear power program to achieve safe, secure and economical operation of the INS installations during their lifetime. The owners/operators should have enough knowledge of the INS to be intelligent customers and should keep a stable cadre of competent and trained staff.* | **CR4.1** availability of human resources | |
| | **IN4.1:** Availability of human resources. | **AL4.1:** Sufficient according to international experience. |
| | **CR4.2** safety and security culture | |
| | **IN4.2:** Attitude to safety and security. | **AL4.2**: Evidence that a safety and security culture prevails provided by periodic safety and security reviews. |

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[21] In comparison to Ref. [2], wording of UR4 was extended to include "*all responsible parties*", "*secure and economical operation of the INS*", and the criterion CR4.3 (dealing also with added value) in Ref. [2] was combined with CR2.5.

Table A.3. BP, UR and CR for the INPRO area of waste management [12]

| **Waste management basic principle BP1 (Waste minimization):** *Generation of radioactive waste in an INS shall be kept to the minimum practicable.* | | |
|---|---|---|
| **User requirement (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1.1 Reduction of waste at the source:**<br>*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.* | **CR1.1.1** waste characteristics | |
| | **IN1.1.1:** Technical indicators:<br>- Alpha-emitters and other long-lived radio-nuclides per GWa.<br>- Total activity per GWa.<br>- Mass per GWa.<br>- Volume per GWa.<br>- Chemically toxic elements that would become part of the radioactive waste per GWa. | **AL1.1.1:** ALARP |
| | **CR1.1.2** minimization study[22] | |
| | **IN1.1.2:** A waste minimization study has been preformed, leading to a waste minimization strategy and plan for each component of the INS. | **AL1.1.2:** The study, strategies and plans are available. |

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[22] In comparison to Ref. [2] criterion CR1.1.2 has been added.

Table A.3. BP, UR and CR for the INPRO area of waste management [12] (continued)

| **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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR2.1 Protection of human health**:<br>*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.* | **CR2.1.1** public dose | |
| | **IN2.1.1:** Estimated dose rate to an individual of the critical group. | **AL2.1.1:** Meets regulatory standards of specific Member State[23]. |
| | **CR2.1.2** occupational dose | |
| | **IN2.1.2:** Radiological exposure of workers. | **AL2.1.2**: Meets regulatory standards of specific Member State. |
| | **CR2.1.3** chemical toxins | |
| | **IN2.1.3:** Estimated concentrations of chemical toxins in working areas. | **AL2.1.3:** Meet regulatory standards of specific Member State. |
| **UR2.2 Protection of the environment:**<br>*The cumulative releases of radio-nuclides and chemical toxins from waste management components of the INS should be optimized.* | **CR2.2.1** release from WM facilities | |
| | **IN2.2.1:** Estimated releases of radio-nuclides and chemical toxins from waste management facilities. | **AL2.2.1:** Meet regulatory standards of specific Member State. |
| | **CR2.2.2**[24] release from all other INS facilities | |
| | **IN2.2.2:** Estimated releases of radio-nuclides and chemical toxins from all other INS facilities. | **AL2.2.2:** Meet regulatory standards of specific Member State. |

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[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.

[24] In comparison to Ref. [2] this criterion CR2.2.2 has been added.

Table A.3. BP, UR and CR for the INPRO area of waste management [12] (continued)

| | | |
|---|---|---|
| **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 (UR)** | **Criteria (CR)** | |
| | **Indicators IN)** | **Acceptance Limits (AL)** |
| **UR3.1 End state**:<br>*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.* | **CR3.1.1** technology | |
| | **IN3.1.1:** Availability of technology. | **AL3.1.1:** All required technology is currently available or reasonably expected to be available on a schedule compatible with the schedule for introducing the proposed innovative fuel cycle. |
| | **CR3.1.2** time for technology development | |
| | **IN3.1.2:** Time required. | **AL3.1.2:** Any time required to bring the technology to the industrial scale must be less than the time specified to achieve the end state. |
| | **CR3.1.3** resources | |
| | **IN3.1.3:** Availability of resources. | **AL3.1.3:** Resources (funding, space, capacity, etc.) available for achieving the end state compatible with the size and growth rate of the energy system. |
| | **CR3.1.4** safety | |
| | **IN3.1.4:** Safety of the end state (long-term expected dose to an individual of the critical group). | **AL3.1.4:** Meet regulatory standards of specific Member State. |
| | **CR3.1.5** time for end state | |
| | **IN3.1.5:** Time to reach the end state. | **AL3.1.5:** As short as reasonably practicable. |

Table A.3. BP, UR and CR for the INPRO area of waste management [12] (continued)

<table>
<tr><td colspan="3"><b>Waste management basic principle BP3 (Burden on future generations):</b><i>Radioactive waste in an INS shall be managed in such a way that it will not impose undue burdens on future generations.(continued)</i></td></tr>
<tr><th rowspan="2">User Requirements (UR)</th><th colspan="2">Criteria (CR)</th></tr>
<tr><th>Indicators (IN)</th><th>Acceptance Limits (AL)</th></tr>
<tr><td rowspan="2"><b>UR3.2 Attribution of waste management costs</b>:<br><i>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<b>.</b></i></td><td colspan="2"><b>CR3.2.1</b> cost</td></tr>
<tr><td><b>IN3.2.1:</b> Specific line item in the cost estimate.</td><td><b>AL3.2.1:</b> Included.</td></tr>
</table>

Table A.3. BP, UR and CR for the INPRO area of waste management [12] (continued)

| **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.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR4.1 Waste Classification**:<br>*The radioactive waste arising from the INS should be classified to facilitate waste management in all parts of the INS.* | **CR4.1.1** classification | |
| | **IN4.1.1:** Classification scheme. | **AL4.1.1:** The scheme permits unambiguous, practical segregation and measurement of waste arisings. |
| **UR4.2 Pre-disposal Waste Management:**<br>*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.* | **CR4.2.1** time for waste form production | |
| | **IN4.2.1:** Time to produce the waste form specified for the end state. | **AL4.2.1:** As short as reasonably practicable. |
| | **CR4.2.2** technical measures | |
| | **IN4.2.2:** Technical indicators, e.g.,<br>- Criticality compliance.<br>- Heat removal provisions.<br>- Radioactive emission control measures.<br>- Radiation protection; measures (shielding etc.).<br>- Volume / activity reduction measures.<br>- Waste forms. | **AL4.2.2:** Criteria as prescribed by regulatory bodies of specific Member States. |
| | **CR4.2.3** process descriptions | |
| | **IN4.2.3:** Process descriptions that encompass the entire waste life cycle. | **AL4.2.3:** Complete chain of processes from generation to final end state and sufficiently detailed to make evident the feasibility of all steps. |

Table A.4. BP, UR and CR for the INPRO area of proliferation resistance [13]

<table>
<tr><td colspan="3"><b>Proliferation resistance basic principle BP[25]:</b> <i>Proliferation resistance intrinsic features and extrinsic 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 program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.</i></td></tr>
<tr><th rowspan="2">User Requirements (UR)</th><th colspan="2">Criteria (CR)</th></tr>
<tr><th>Indicator(IN)</th><th>Acceptance Limits (AL)</th></tr>
<tr><td rowspan="2"><b>UR1 State commitments:</b> <i>States' commitments, obligations and policies regarding non-proliferation and its implementation should be adequate to fulfill international standards in the non proliferation regime.</i></td><td colspan="2"><b>CR1.1</b> legal framework</td></tr>
<tr><td><b>IN1.1:</b> States' commitments, obligations and policies regarding non-proliferation established?</td><td><b>AL1.1</b>: Yes, in accordance with international standards.</td></tr>
<tr><td rowspan="4"><b>UR2 Attractiveness of NM and technology:</b> <i>The attractiveness of nuclear material (NM) and nuclear technology in an INS for a nuclear weapons program should be low. This includes the attractiveness of undeclared nuclear material that could credibly be produced or processed in the INS.</i></td><td colspan="2"><b>CR2.1</b> attractiveness of NM</td></tr>
<tr><td><b>IN2.1:</b> Technical indicators:<br>- Material quality.<br>- Material quantity.<br>- Material form.</td><td>Attractiveness of NM considered in design of INS and found acceptable low based on expert judgment.</td></tr>
<tr><td colspan="2"><b>CR2.2</b> attractiveness of technology</td></tr>
<tr><td><b>IN2.2:</b> Nuclear technology.</td><td><b>AL2.2:</b> Attractiveness of technology considered in design of INS and found acceptable low based on expert judgment.</td></tr>
</table>

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[25] BP1 and BP2 in Ref. [2] have been combined to a single BP in this report.

Table A.4. BP, UR and CR for the INPRO area of proliferation resistance [13] (continued)

| **Proliferation resistance basic principle BP:** *Proliferation resistance intrinsic features and extrinsic 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 program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicator(IN)** | **Acceptance Limits (AL)** |
| **UR3 Difficulty and detectability of diversion:** *The diversion of nuclear material (NM) should be reasonably difficult and detectable. Diversion includes the use of an INS facility for the production or processing of undeclared material.* | **CR3.1** quality of measurement | |
| | **IN3.1:** Accountability. | **AL3.1:** Based on expert judgment equal or better than existing designs, meeting international state of practice. |
| | **CR3.2** C/S measures and monitoring | |
| | **IN3.2:** Amenability | **AL3.2:** Based on expert judgment equal or better than existing designs, meeting international best practice. |
| | **CR3.3** detectability | |
| | **IN3.3:** Detectability of NM. | **AL3.3:** Based on expert judgment equal or better than existing facilities. |
| | **CR3.4** difficulty of modification and misuse | |
| | **IN3.4:** Difficulty to:<br>- modify process;<br>- modify facility design;<br>- misuse technology or facilities. | **AL3.4:** Based on expert judgment equal or better than existing designs, meeting international best practice. |

Table A.4. BP, UR and CR for the INPRO area of proliferation resistance [13] (continued)

**Proliferation resistance basic principle BP:** *Proliferation resistance intrinsic features and extrinsic 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 program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.*

| **User Requirements (UR)** | **Criteria (CR)** | |
|---|---|---|
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR4 multiple features:** *Innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures.* | **CR4.1** defence in depth | |
| | **IN4.1:** The extent by which the INS is covered by multiple intrinsic features and extrinsic measures. | **AL4.1:** All plausible acquisition paths are (can be) covered by extrinsic measures on the facility or State level and by intrinsic features which are compatible with other design requirements. |
| | **CR4.2** robustness of PR barriers | |
| | **IN4.2:** Robustness of barriers covering each acquisition path. | **AL4.2:** Robustness is sufficient based on expert judgment. |

Table A.4. BP, UR and CR for the INPRO area of proliferation resistance [13] (continued)

| **Proliferation resistance basic principle BP:** *Proliferation resistance intrinsic features and extrinsic 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 program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR5 Optimization of design:** *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.* | **CR5.1** inclusion of PR in INS design | |
| | **IN5.1:** PR has been taken into account as early as possible in the design and development of the INS. | **AL5.1:** Yes. |
| | **CR5.2** cost of PR features and measures | |
| | **IN5.2:** Cost of incorporating into an INS those intrinsic features and extrinsic measures, which are required to provide or improve proliferation resistance. | **AL5.2:** Minimal total cost of the intrinsic features and extrinsic measures over the life cycle of the INS implemented to increase PR. |
| | **CR5.3** verification approach | |
| | **IN5.3:** Verification approach with a level of extrinsic measures agreed to between the State and verification authority (e.g., IAEA, regional SG organization, etc.)? | **AL5.3:** Yes. |

Table A.5. BP, UR and CR for the INPRO area of physical protection [14]

| **Physical protection basic principle BP:** *A Physical Protection Regime shall be effectively and efficiently implemented for the full lifecycle of an INS.* | | |
|---|---|---|
| **User Requirements UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1 legislative and regulatory framework:** *Prior to the deployment of the INS the legislative and regulatory framework to govern PP should be established.* | **CR1.1** roles and responsibilities of State | |
| | **IN1.1:** Have the competent authorities (such as regulatory authorities, response force authorities, etc.) been designated, empowered and responsibilities defined (or planned)? | **AL1.1:** Yes. |
| | **CR1.2** regulation development | |
| | **IN1.2:** Has the legislative and regulatory framework related to physical protection been developed (or is it under development)? | **AL1.2:** Yes, in accordance with international standards. |
| | **CR1.3** roles and responsibilities of license holder | |
| | **IN1.3**: Have the physical protection responsibilities and authorities of the facility operator been clearly defined? | **AL1.2:** Yes, in accordance with State physical protection regulations and laws. |
| **UR2 Integration of PP throughout INPRO:** *Physical Protection should be integrated into all INPRO areas and throughout all phases.* | **CR2.1** PP integration with PR, safety and operations | |
| | **IN2.1:** Have synergies and divergences between PP, safety, PR, and operations been addressed? | **AL2.1:** Yes, through the review of a joint expert panel. |
| | **CR2.2** PP consideration in all INPRO areas | |
| | **IN2.2:** Is there evidence that assessments in all areas of INPRO have accounted for PP? | **AL2.2:** Yes, as appropriate. |
| | **CR2.3** PP consideration through all phases of INS | |
| | **IN2.3:** Is there evidence of forethought into the issues of PP as the INS is shut-down and decommissioned? | **AL2.3:** Yes. |

Table A.5. BP, UR and CR for the INPRO area of physical protection [14] (continued)

<table>
<tr><td colspan="3"><b>Physical protection basic principle BP:</b> <i>A Physical Protection Regime shall be effectively and efficiently implemented for the full lifecycle of an INS.</i></td></tr>
<tr><th rowspan="2">User Requirements (UR)</th><th colspan="2">Criteria (CR)</th></tr>
<tr><th>Indicators (IN)</th><th>Acceptance Limits (AL)</th></tr>
<tr><td rowspan="2"><b>UR3 trustworthiness:</b> <i>A program to determine trustworthiness should be defined and implemented.</i></td><td colspan="2"><b>CR3.1</b> trustworthiness program</td></tr>
<tr><td><b>IN3.1</b>: Is there a trustworthiness program with established acceptance criteria?</td><td><b>AL3.1</b>: Yes.</td></tr>
<tr><td rowspan="4"><b>UR4 confidentiality:</b> <i>Sensitive information developed for all areas of INPRO should be protected in accordance with its security significance.</i></td><td colspan="2"><b>CR4.1</b> development of confidentiality program</td></tr>
<tr><td><b>IN4.1:</b> Has a program been developed for protecting sensitive information?</td><td><b>AL4.1</b>: Yes.</td></tr>
<tr><td colspan="2"><b>CR4.2</b> implementation of confidentiality program</td></tr>
<tr><td><b>IN4.2:</b> Have procedures been developed and implemented at all levels to identify and protect sensitive information?</td><td><b>AL4.2:</b> Yes.</td></tr>
<tr><td rowspan="8"><b>UR5 threat:</b> <i>The physical protection systems should be based on the State’s current evaluation of the threats.</i></td><td colspan="2"><b>CR5.1</b> development of DBT</td></tr>
<tr><td><b>IN5.1</b>: Is there evidence that a DBT or other appropriate threat statement has been developed?</td><td><b>AL5.1:</b> Yes.</td></tr>
<tr><td colspan="2"><b>CR5.2</b> periodic review of the threat</td></tr>
<tr><td><b>IN5.2:</b> Are there provisions for periodic review of threat by the State?</td><td><b>AL5.2:</b> Yes.</td></tr>
<tr><td colspan="2"><b>CR5.3</b> DBT as basis for PPS</td></tr>
<tr><td><b>IN5.3:</b> Is there evidence that the concept of DBT or other appropriate threat statement has been used to establish the PP systems?</td><td><b>AL5.3:</b> Yes.</td></tr>
<tr><td colspan="2"><b>CR5.4:</b> flexibility in PPS</td></tr>
<tr><td><b>IN5.4</b>: Has the designer introduced flexibility in PPS design to cope with the dynamic nature of threat?</td><td><b>AL5.4:</b> Yes.</td></tr>
</table>

Table A.5. BP, UR and CR for the INPRO area of physical protection [14] (continued)

| **Physical protection basic principle BP:** *A Physical Protection Regime shall be effectively and efficiently implemented for the full lifecycle of an INS.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR6 graded approach:** *Physical protection requirements should be based on a graded approach.* | **CR6.1** consequence limits | |
| | **IN6.1:** Has the state defined limits for consequences of malicious acts directed against nuclear materials and facilities (including transports)? | **AL6.1:** Yes. |
| | **CR6.2** graded approach | |
| | **IN6.2:** Has the concept of a graded approach been used by the State when specifying PP requirements and by the user to define PPS? | **AL6.2:** Yes. |
| **UR7 quality assurance:** *Quality assurance policy and programs for all activities important to PP should be established and implemented.* | **CR7.1** QA policy | |
| | **IN7.1:** Is there a QA policy defined and implemented for all activities important to PP? | **AL7.1:** Presence of periodic review mechanism. |
| **UR8 security culture:** *All organizations involved in implementing physical protection should give due priority to development, maintenance and effective implementation of the security culture in the entire organization.* | **CR8.1** security culture | |
| | **IN8.1**: Has a security culture program been developed and implemented for all organizations and personnel involved in the INS? | **AL8.1**: Yes. |

Table A.5. BP, UR and CR for the INPRO area of physical protection [14] (continued)

| **Physical protection basic principle BP:** *A Physical Protection Regime shall be effectively and efficiently implemented for the full lifecycle of an INS.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR9 PP considerations in siting:**<br>*The PP should be considered when siting INS components.* | **CR9.1** terrain, topography and geography | |
| | **IN9.1:** Has the terrain, topography and geography been assessed to preclude potential benefit to adversaries (high ground to observe, approach, and attack, air approaches, cover and concealment, etc)? | **AL9.1:** Yes |
| | **CR9.2** material transport and off-site response | |
| | **IN9.2:** Has feasibility/flexibility, vulnerability, and efficiency of transportation and offsite response routes been assessed (air, sea, land)? | **AL9.2:** Yes |
| | **CR9.3** future public encroachment | |
| | **IN9.3**: Has future development/ encroachment by public been considered? | **AL9.2:** Yes |
| **UR10 INS layout and design:**<br>*INS component layout and design should be developed to minimize susceptibility and opportunities for malicious action.* | **CR10.1** INS design | |
| | **IN10.1:** Is there evidence that consideration has been given to physical protection in the design of the INS components? | **AL10.1:** Yes |
| | **CR10.2** INS layout | |
| | **IN10.2:** Is there evidence that consideration has been given to physical protection in the layout of the INS components? | **AL10.2:** Yes |

Table A.5. BP, UR and CR for the INPRO area of physical protection [14] (continued)

| **Physical protection basic principle BP:** *A Physical Protection Regime shall be effectively and efficiently implemented for the full lifecycle of an INS.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR11 design of PPS:** *The physical protection system of all INS components should be developed in uniform layers of protection using a systematic approach.* | **CR11.1** PPS an integrated system | |
| | **IN11.1:** Has deterrence, detection, assessment, delay, and response been integrated to achieve timely interruption of malicious act? | **AL11.1:** Yes. |
| | **CR11.2** insider adversary considerations in PPS | |
| | **IN11.2:** Has the PPS been designed with consideration of insider adversaries exploiting capabilities such as access, knowledge, and authority? | **AL11.2:** Yes. |
| | **CR11.3** Defense in Depth | |
| | **IN11.3:** Has the PPS been developed with several uniform layers and methods of protection? | **AL11.3:** Yes. |
| **UR12 contingency plans:** *Contingency plans to respond to unauthorized removal of nuclear material or sabotage of nuclear facilities/transport or of nuclear material, or attempts thereof, should be prepared and appropriately exercised by all license holders and authorities concerned.* | **CR12.1** responsibilities for contingency plans | |
| | **IN12.1**: Have responsibilities for execution of the emergency plans been identified? | **AL12.1:** Yes. |
| | **CR12.2** sabotage mitigation | |
| | **IN12.2:** Have capabilities of the PP regime been established to prevent and mitigate radiological consequences of sabotage? | **AL12.2:** Yes. |
| | **CR12.3** recovery of material and facilities | |
| | **IN12.3:** Have capabilities of PP regime been established to recover stolen nuclear material or recapture facilities before the adversary can achieve its objective? | **AL12.3:** Yes. |

Table A.6. BP, UR and CR for the INPRO area of environment [15]

<table>
<tr><td colspan="3"><b>Environmental Basic Principle BP1 (Acceptability of expected adverse environmental effects):</b> <i>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.</i></td></tr>
<tr><th rowspan="2">User Requirements (UR)</th><th colspan="2">Criteria (CR)</th></tr>
<tr><th>Indicators (IN)</th><th>Acceptance Limits (AL)</th></tr>
<tr><td rowspan="2"><b>UR1.1 controllability of environmental stressors:</b><br><i>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.</i></td><td colspan="2"><b>CR1.1.1</b> stressors</td></tr>
<tr><td><b>IN1.1.1:</b> $L_{St-i}$, = level of stressor i.</td><td><b>AL1.1.1:</b> $L_{St-i} < S_i$, where $S_i$ is the standard for stressor i.</td></tr>
<tr><td rowspan="2"><b>UR1.2 adverse effects as low as reasonable practicable:</b><br><i>The likely adverse environmental effects attributable to the INS should be as low as reasonably practicable, social and economic factors taken into account.</i></td><td colspan="2"><b>CR1.2.1</b> ALARP</td></tr>
<tr><td><b>IN1.2.1:</b> Does the INS reflect application of ALARP to limit environmental effects?</td><td><b>AL1.2.1:</b> Yes.</td></tr>
</table>

Table A.6. BP, UR and CR for the INPRO area of environment [15] (continued)

| **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.* | | |
|---|---|---|
| **User Requirements (UR)** | **Criteria (CR)** | |
| | **Indicators IN)** | **Acceptance Limits (AL)** |
| **UR2.1 Consistency with resource availability:**<br>*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.* | **CR2.1.1** fissile material | |
| | **IN2.1.1:** $F_j (t)$ = quantity of fissile/fertile material j available for use in the INS at time t. | **AL2.1.1**: $F_j (t) > 0$ for all $t < 100$ years |
| | **CR2.1.2** non renewable material | |
| | **IN2.1.2:** $Q_j(t)$ = quantity of material i available for use in the INS at time t. | **AL2.1.2**: $Q_j (t) > 0$ for all $t < 100$ years |
| | **CR2.1.3** power | |
| | **IN2.1.3:** $P(t)$ = power available (from both internal and external sources) for use in the INS at time t. | **AL2.1.3:** $P(t) \geq P_{INS}(t)$ for all $t < 100$ years, where $P_{INS}(t)$ is the power required by the INS at time t. |

Table A.6. BP, UR and CR for the INPRO area of environment [15] (continued)

<table>
<tr><td colspan="3">**Environmental basic principle BP2 (Fitness for purpose) (continued):** *The INS shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources.*</td></tr>
<tr><td rowspan="6">**UR2.1 Consistency with resource availability (continued):**<br>*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.*</td><td colspan="2">**CR2.1.4** end use uranium</td></tr>
<tr><td>**IN2.1.4**: U = end use (net) energy delivered by the INS per Mg of uranium mined.</td><td>**AL2.1.4**: $U > U_0$<br>$U_0$ : maximum achievable for a once-through PWR.</td></tr>
<tr><td colspan="2">**CR2.1.5** end use thorium</td></tr>
<tr><td>**IN2.1.5**: T = end use (net) energy delivered by the INS per Mg of thorium mined.</td><td>**AL2.1.5**: $T > T_0$<br>$T_0$ : maximum T achievable with a current operating thorium cycle.</td></tr>
<tr><td colspan="2">**CR2.1.6** end use non renewable resource</td></tr>
<tr><td>**IN2.1.6:** $C_i$ = end use (net) energy delivered per Mg of limited non-renewable resource i consumed.</td><td>**AL2.1.6**: $C_i > C_0$<br>$C_0$ to be determined on a case specific basis.</td></tr>
<tr><td rowspan="2">**UR2.2 Adequate net energy output:**<br>*The energy output of the INS should exceed the energy required to implement and operate the INS within an acceptably short period.*</td><td colspan="2">**CR2.2.1** amortization time</td></tr>
<tr><td>**IN2.2.1**: $T_{EQ}$ = time required to match the total energy input with energy output (yrs).</td><td>**AL2.2.1:** $T_{EQ} < k*T_L$<br>$T_L$ = intended life of INS.<br>$k < 1$</td></tr>
</table>

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17]

| **Safety basic principle BP1 (defence in depth):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1.1[26] Robustness:**<br>*Installations of an INS should be more robust relative to existing designs regarding system and component failures as well as operation.* | **CR1.1.1** robustness | |
| | **IN1.1.1**: Robustness of design (simplicity, margins). | **AL1.1.1:** Superior to existing designs in at least some of the aspects discussed in the text. |
| | **CR1.1.2** operation | |
| | **IN1.1.2**: High quality of operation. | **AL1.1.2:** Superior to existing designs in at least some of the aspects discussed in the text. |
| | **CR1.1.3** inspection | |
| | **IN1.1.3:** Capability to inspect. | **AL1.1.3:** Superior to existing designs in at least some of the aspects discussed in the text. |
| | **CR1.1.4** failures and disturbances | |
| | **IN1.1.4:** Expected frequency of failures and disturbances. | **AL1.1.4:** Superior to existing designs in at least some of the aspects discussed in the text. |

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[26] Related to: DID Level 1: Prevention of Abnormal Operation and Failures.

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| **Safety basic principle BP1 (defence in depth) (continued):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1.2[27] (Detection and interception):**<br>*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.* | **CR1.2.1** I&C and inherent characteristics | |
| | **IN1.2.1:** Capability of control and instrumentation system and/or inherent characteristics to detect and intercept and/or compensate deviations from normal operational states. | **AL1.2.1**: 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). |
| | **CR1.2.2** grace period | |
| | **IN1.2.2:** Grace period until human actions are required. | **AL1.2.2:** Superior to existing designs in at least some of the aspects discussed in the text. |
| | **CR1.2.3** inertia | |
| | **IN1.2.3:** Inertia to cope with transients. | **AL1.2.3:** Superior to existing designs in at least some of the aspects discussed in the text. |

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[27] Related to: DID Level 2: Control of Abnormal Operation and Detection of Failures.

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

**Safety Basic Principle BP1 (defence in depth) (continued):** *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 (UR)** | **Criteria (CR)** | |
|---|---|---|
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1.3[28] Design basis accidents:**<br>*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.* | **CR1.3.1** DBA | |
| | **IN1.3.1:** Calculated frequency of occurrence of design basis accidents. | **AL1.3.1:** Reduced frequency of accidents that can cause plant damage relative to existing facilities. |
| | **CR1.3.2** grace period | |
| | **IN1.3.2:** Grace period until human intervention is necessary. | **AL1.3.2**: Increased relative to existing facilities. |
| | **CR1.3.3** safety features | |
| | **IN1.3.3:** Reliability of engineered safety features. | **AL1.3.3**: Equal or superior to existing designs. |
| | **CR1.3.4** barriers | |
| | **IN1.3.4:** Number of confinement barriers maintained. | **AL1.3.4**: At least one. |
| | **CR1.3.5** controlled state | |
| | **IN1.3.5:** Capability of the engineered safety features to restore the INS to a controlled state (without operator actions). | **AL1.3.5:** Sufficient to reach a controlled state. |

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[28] Related to: DID Level 3: Control of Accidents.

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| **Safety Basic Principle BP1 (defence in depth) (continued):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1.3[29] Design basis accidents (continued):**<br>*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.* | **CR1.3.6** sub criticality | |
| | **IN1.3.6:** sub criticality margins | **AL1.3.6:** Sufficient to cover uncertainties and to allow adequate grace period. |

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[29] Related to: DID Level 3: Control of Accidents.

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| **Safety basic principle BP1 (defence in depth) (continued):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1.4**[30] **(Release into containment):**<br>*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.* | **CR1.4.1** frequency of release into containment | |
| | **IN1.4.1:** Calculated frequency of major release of radioactive materials into the containment / confinement. | **AL1.4.1:** At least an order of magnitude less than for existing designs; even lower for installations at urban sites. |
| | **CR1.4.2** processes | |
| | **IN1.4.2:** Natural or engineered processes sufficient for controlling relevant system parameters and activity levels in containment / confinement. | **AL1.4.2:** Existence of such processes. |
| | **CR1.4.3** accident management | |
| | **IN1.4.3:** In-plant severe accident management. | **AL1.4.3:** Procedures, equipment and training sufficient to prevent large release outside containment / confinement and regain control of the facility. |

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[30] Related to DID Level 4: Prevention of Major Radioactivity Release.

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| **Safety basic principle BP1 (defence in depth) (continued):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1.5[31] Release into the environment:**<br>*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.* | **CR1.5.1** frequency of release to environment | |
| | **IN1.5.1:** Calculated frequency of a major release of radioactive materials to the environment. | **AL1.5.1:** Calculated frequency $<10^{-6}$ per unit-year, or practically excluded by design. |
| | **CR1.5.2** consequences | |
| | **IN1.5.2:** Calculated consequences of releases (e.g. dose). | **AL1.5.2:** Consequences sufficiently low to avoid necessity for evacuation. Appropriate off-site mitigation measures (e.g., temporary food restrictions) are available. |
| | **CR1.5.3** risk | |
| | **IN1.5.3:** Calculated individual and collective risk. | **AL1.5 3:** Comparable to facilities used for a similar purpose.[32] |

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[31] Related to DID Level 5: Prevention of Containment Failure and Mitigation of Radiological Consequences.

[32] 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 A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| **Safety basic principle BP1 (defence in depth) (continued):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR1.6 Independence of DID levels:**<br>*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.* | **CR1.6.1** independence of DID levels | |
| | **IN1.6.1:** Independence of different levels of DID. | **AL1.6.1:** Adequate independence is demonstrated, e.g. through deterministic and probabilistic means, hazards analysis etc. |
| **UR1.7 Human machine interface:**<br>*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.* | **CR1.7.1** human factors | |
| | **IN1.7.1:** Evidence that human factors (HF) are addressed systematically in the plant life cycle. | **AL1.7.1**: Satisfactory results from assessment. |
| | **CR1.7.2** human response model | |
| | **IN1.7.2**: Application of formal human response models from other industries or development of nuclear. | **AL1.7.2:**<br>- Reduced likelihood of human error relative to existing plants, as predicted by HF models.<br>- Use of artificial intelligence for early diagnosis and real-time operator aids.<br>- Less dependence on operator for normal operation and short-term accident management relative to existing plants. |

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| **Safety basic principle BP2 (Inherent safety):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR2.1 (Minimization of hazards):**<br>*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.* | **CR2.1.1** hazards | |
| | **IN2.1.1:** Sample indicators: stored energy, flammability, criticality, inventory of radioactive materials, available excess reactivity, and reactivity feedback. | **AL2.1.1:** Superior to existing designs. |
| | **CR2.1.2** frequency of AOO &DBA | |
| | **IN2.1.2:** Expected frequency of abnormal operation and accidents. | **AL2.1.2:** Lower frequencies compared to existing facilities. |
| | **CR2.1.3** consequences | |
| | **IN2.1.3**: Consequences of abnormal operation and accidents. | **AL2.1.3**: Lower consequences compared to existing facilities. |
| | **CR2.1.4** confidence in innovation | |
| | **IN2.1.4**: Confidence in innovative components and approaches. | **AL2.1.4:** Validity established. |

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| **Safety basic principle BP3 (risk of radiation):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR3.1 Dose to workers:**<br>*INS installations should ensure an efficient implementation of the concept of optimization of radiation protection for workers through the use of automation, remote maintenance and operational experience from existing designs.* | **CR3.1.1** occupational dose | |
| | **IN3.1.1:** Occupational dose values. | **AL3.1.1:** 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 public:**<br>*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.* | **CR3.1.2** public dose | |
| | **IN3.2.1:** Public dose values. | **AL3.2.1:** 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. |

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| |
|---|
| **Safety Basic Principle BP4 (RD&D):** *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 (UR)** | **Criteria (CR)** | |
|---|---|---|
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR4.1 Safety basis:**<br>*The safety basis of INS installations should be confidently established prior to commercial deployment.* | **CR4.1.1** safety concept | |
| | **IN4.1.1:** Safety concept defined? | **AL4.1.1:** Yes. |
| | **CR4.1.2** safety issues | |
| | **IN4.1.2:** Clear process for addressing safety issues? | **AL4.1.2:** Yes. |
| **UR4.2 RD&D for understanding:**<br>*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.* | **CR4.2.1** RD&D | |
| | **IN4.2.1:** RD&D defined and performed and database developed? | **AL4.2.1:** Yes. |
| | **CR4.2.2** computer codes | |
| | **IN4.2.2:** Computer codes or analytical methods developed and validated? | **AL4.2.2:** Yes. |
| | **CR4.2.3** scaling | |
| | **IN4.2.3:** Scaling understood and/or full scale tests performed? | **AL4.2.3:** Yes. |
| **UR4.3 Pilot plant:**<br>*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.* | **CR4.3.1** novelty | |
| | **IN4.3.1:** Degree of novelty of the process. | **AL4.3.1:** In case of *high degree of novelty:* Facility specified, built, operated, and lessons learned documented.<br>In case of *low degree of novelty*: Rationale provided for bypassing pilot plant. |
| | **CR4.3.2** pilot facility | |
| | **IN4.3.2:** Level of adequacy of the pilot facility. | **AL4.3.2:** Results sufficient to be extrapolated. |

Table A.7. BP, UR and CR for the INPRO area of safety of nuclear installations [16], [17] (continued)

| **Safety basic principle BP4 (RD&D) (continued):** *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 (UR)** | **Criteria (CR)** | |
| | **Indicators (IN)** | **Acceptance Limits (AL)** |
| **UR4.4 Safety analysis:**<br>*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.* | **CR4.4.1** risk informed approach | |
| | **IN4.4.1:** Use of a risk informed approach? | **AL4.4.1:** Yes. |
| | **CR4.4.2** uncertainties | |
| | **IN4.4.2:** Uncertainties and sensitivities identified and appropriately dealt with? | **AL4.4.2:** Yes. |

# ANNEX B
# EXAMPLES OF APPROACHES FOR AGGREGATING INPRO RESULTS OF COMPARATIVE ASESSMENTS

## B.1. Approach No.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 B.1, or in tabular form. Thus, for example, from Figure B.1 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.

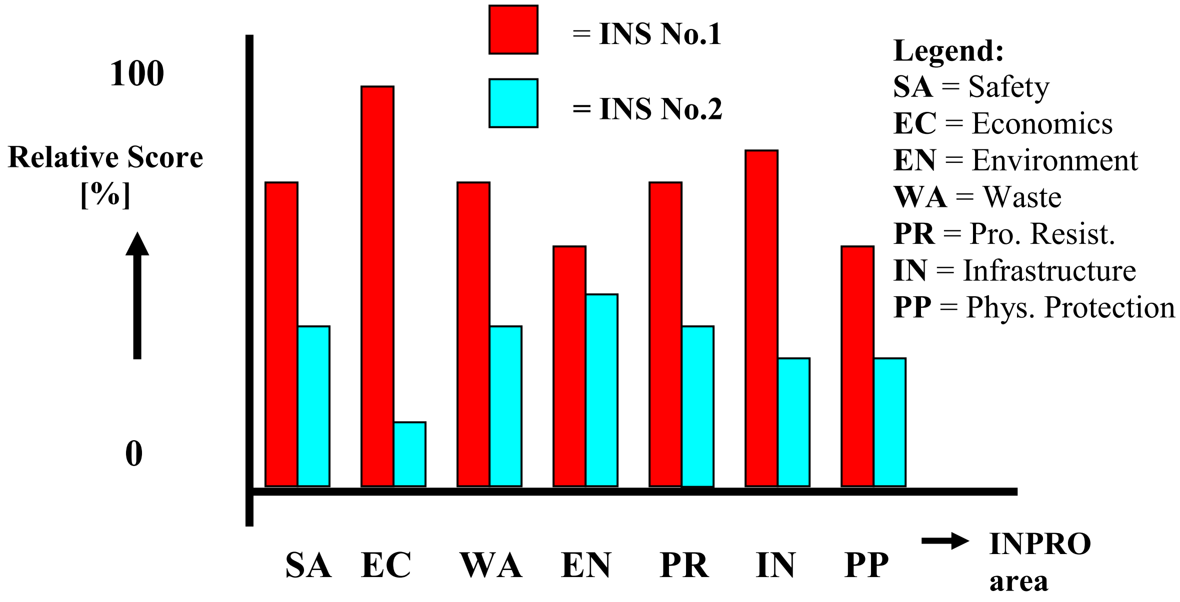

*Figure B.1. Outcome of comparison of capability of two INS.*

In the example illustrated in Figure B.1, 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 B.1 does not reflect the detail that can be seen in Figure 4.3 in Section 4.4.2 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 B.2.

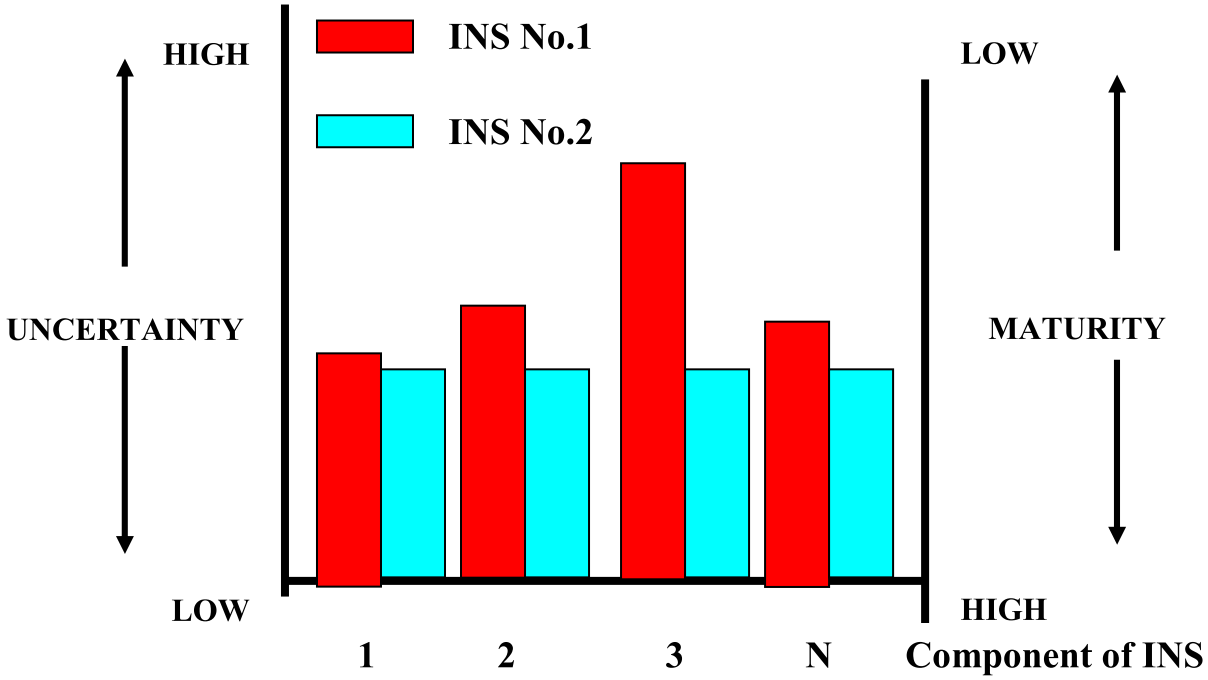

*Figure B.2. Maturity chart comparing components[33] of two INS.*

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

## B.2. 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 B.3 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$_{\text{installed}}$.

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

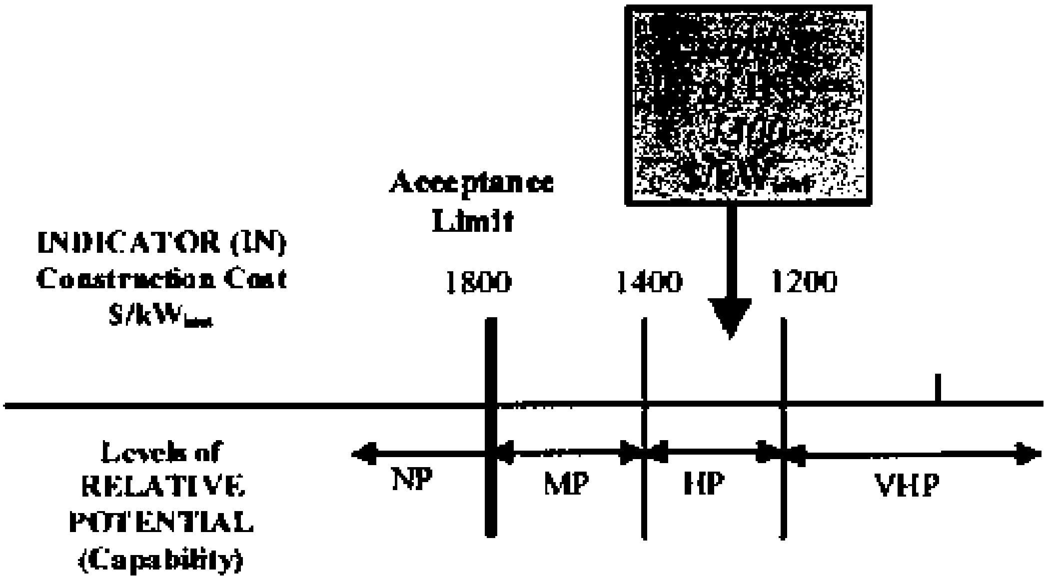

*Figure B.3. Illustration of the judgement procedure with different levels of capability or potential defined.*

The example in Figure B.3 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[33] (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 B.4 illustrates the possible result of such an aggregation process for two different INS.

In the example illustrated in Figure B.4, 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 B.5 illustrates this approach for the indicator "Specific Capital Cost".

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[33] 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.

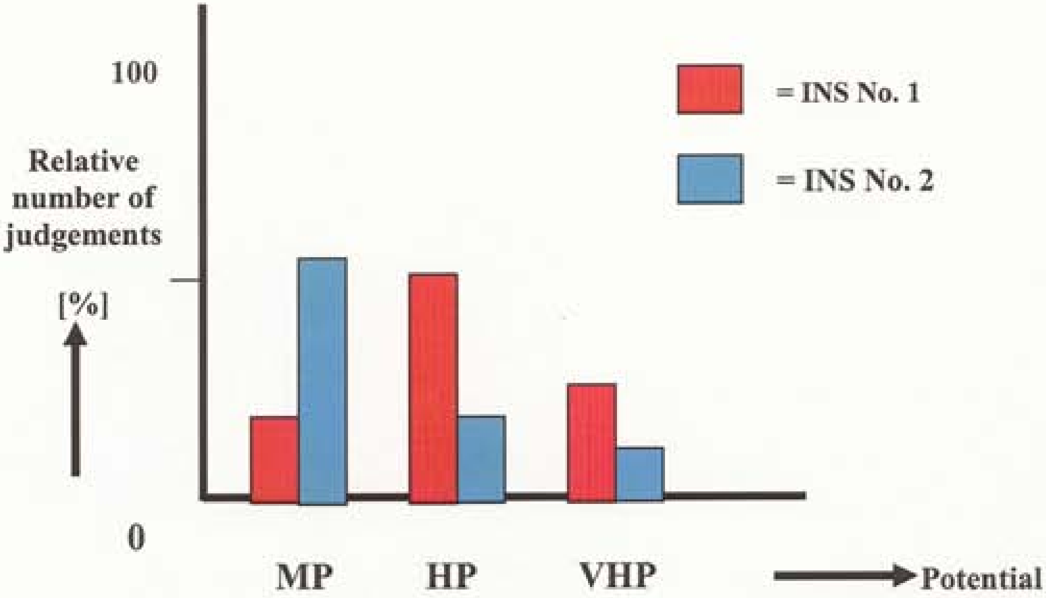

*Figure B.4. Aggregation of judgements on potential for a UR, BP, INPRO area or INS.*

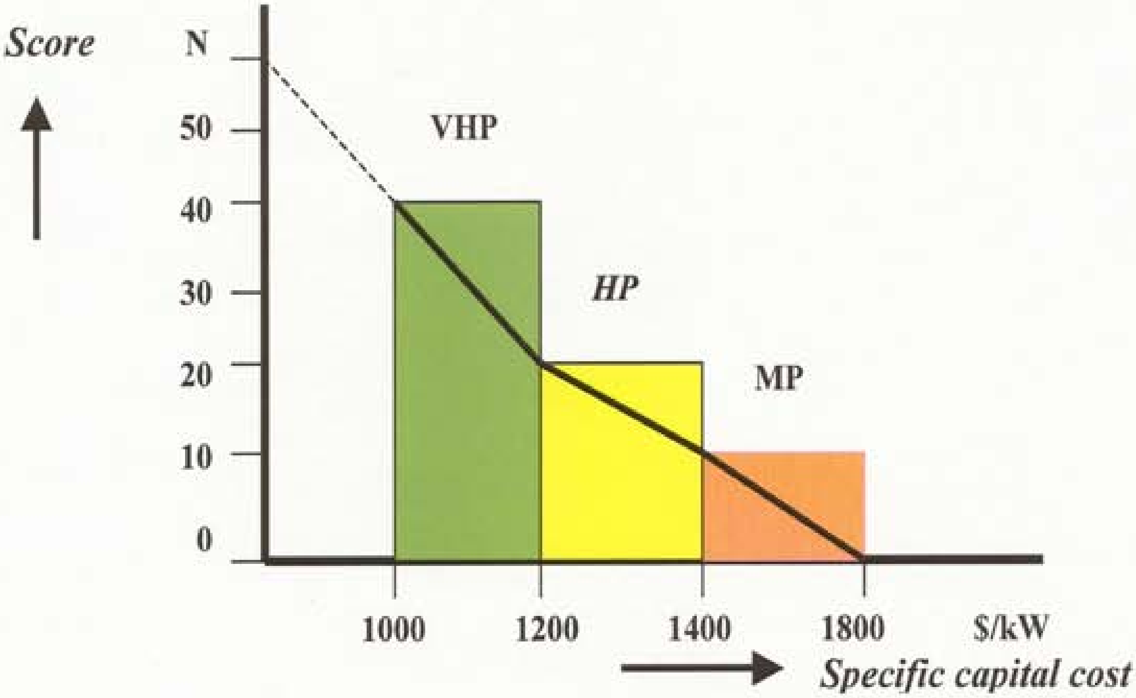

*Figure B.5. Example for the introduction of ranges of potential and scores into the process of judgement.*

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.

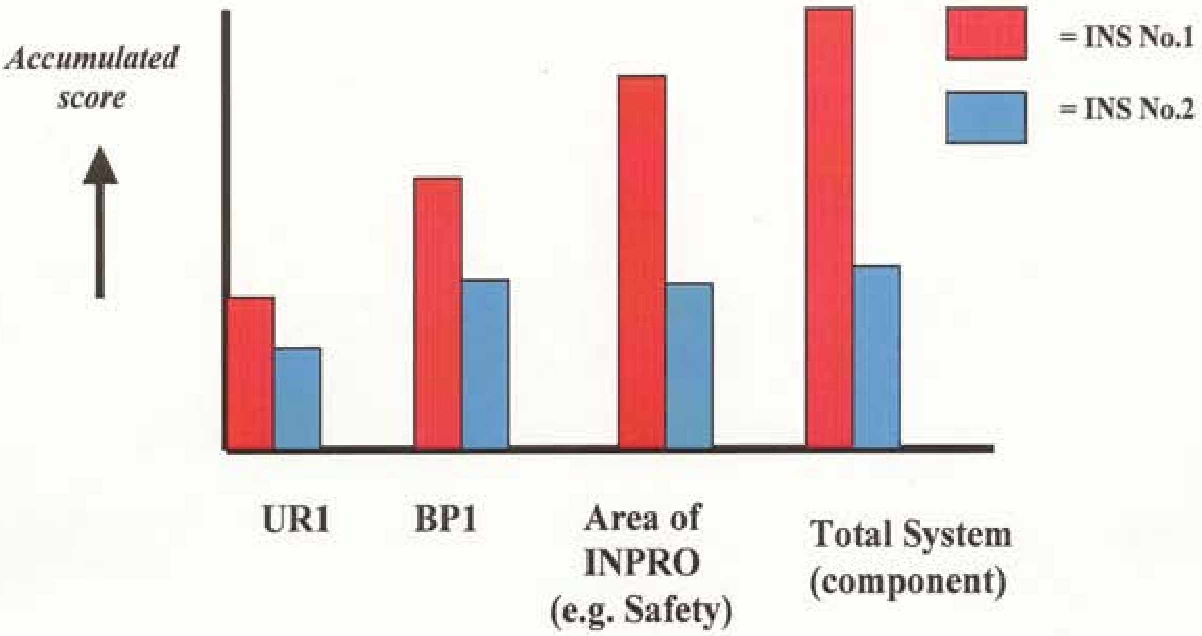

*Figure B.6. Aggregation of judgements using scores.*

The example in Figure B.6 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 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 are presented in the INPRO manuals. 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.

### B.3. Relationship of Relative Benefit Index and the Concept of Relative Potential

The concept of RBI, discussed in Section 4.5.3, can be linked to the concept of relative potentials introduced above as summarized in Table B.1

Table B.1. Correspondence between Relative Potential (RP) and Relative Benefit Index (RBI)

| **R P**<br>**of Indicator (IN)** | **RBI** | **Comment** |
|---|---|---|
| IN < AL,<br>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. |

In order to aggregate the values of RBI and of RRI (see Section 4.5.3) 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.

# ANNEX C
# INPRO PORTAL

The concept of an INPRO information portal was introduced in Section 4.7.1. The following objectives have been identified for the INPRO portal:

- Complement the INPRO assessment method and manuals by providing an assessor hands-on information on needed assessment-data, assessment case studies;
- Provide tools (codes, methods, etc) to perform the assessments.
- Provide guidance on where to find specialised assessment support.
- In addition, it should serve for collecting, preserving and managing knowledge on assessment results allowing information exchange between various assessors.
- Finally, the availability of all data and information needed for the assessments in a unique and coherent portal will facilitate the learning process in performing the assessments.

The information portal should facilitate the application of the methodology and manual by providing hands-on up-to-date information and recommended tools to perform an assessment.

Information, in this context, covers multiple areas, i.e.:

- Description of INS components: This may range from a simple abstract on an INS component concept up to a fully documented engineering design of existing as well as innovative INS components.
- Characteristics describing the various assessment dimensions for an INS component: Ideally, these technical characteristics should correspond to the definitions of data-needs for the various indicators defined in the INPRO manuals and might therefore consist of aggregated data where more detailed information on basic data is provided as reference or document attachments.
- Some of the acceptance limits (AL) have been defined as “superior to existing designs” and require reference to a database containing acceptable values in currently[35] operating plants (Currently operating plants may refer to a set of plants which are currently under operation and are defined to be the most representative within their category). These ranges of AL with respective documentation on the AL in different countries or situations should be included in the portal.
- Country profiles describing various facets of the environment for an INS, e.g.:
  - Institutional framework for INS development;
  - Legislative and regulatory context, e.g. acceptance limits;
  - Historical data on existing nuclear energy systems with data on the existing reactor fleet and fuel cycle facilities;

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[35] Currently operating means here operating in 2004.

  - Inventories of uranium/thorium, spent fuel, separated fissile/fertile materials, waste (different classes);
  - (Nuclear) Energy policy, e.g. energy market organisation, availability of indigenous energy resources, projections of energy and/or electricity demand, etc;
  - Scenario case studies describing the assumptions made in performing assessment studies within the country;
  - Time dependent boundary and initial conditions for the INS deployment (including macro-economic parameters, experience in NE, public acceptance, etc.) should be described and formalised in the database; and
  - Available industrial and institutional infrastructure.

- Tools and methods that might be needed in performing assessments, e.g.,:

  - Descriptions of methods for evaluating indicators; and
  - Description of the tools, and if possible or available, code manuals, reference publications, contact persons, case studies, input file specifications.

- Results of assessment studies: Archiving results including full documentation of approaches taken, tools used, assumptions made and information resources accessed should be integrated within the 'INPRO Assessment Information Portal' for various reasons:

  - Knowledge conservation on nuclear technology;
  - Providing examples to assessors of previous applications of assessment methodology;
  - Filling the database of the 'INPRO Assessment Information Portal' with numerical and non-numerical data;
  - Next to archiving, the 'INPRO Assessment Information Portal' should allow to query these assessment results to retrieve the important information useful for an assessor in new assessment studies;
  - Such archiving would be facilitated if the outcomes of such INS assessment studies would be reported in a structured way corresponding to the database-structure used within this 'INPRO Assessment Information Portal' which, on itself, should be in full compliance with the INPRO manual structure.
- R&D projects aimed at improving the performance of INS components and therefore providing information on possible expected indicator values in the future.

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# 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 |
| GFR | gas cooled fast reactor |
| 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) |
| SFR | sodium cooled fast reactor |
| 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

During Phase 1 (2001 to June 2006) of INPRO the following experts contributed to the INPRO methodology. The participants are listed separately for each volume of the INPRO manual:

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