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Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology. A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

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LESSONS LEARNED FROM NUCLEAR ENERGY SYSTEM ASSESSMENTS (NESA) USING THE INPRO METHODOLOGY

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A REPORT OF THE INTERNATIONAL PROJECT
ON INNOVATIVE NUCLEAR REACTORS
AND FUEL CYCLES (INPRO)

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FOREWORD

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was initiated in 2001 on the basis of a resolution of the IAEA General Conference in 2000 (GC(44)/RES/21). INPRO activities have since been continuously endorsed by resolutions of IAEA General Conferences and by the General Assembly of the United Nations.

The objectives of INPRO are to:

- Help ensure that nuclear energy is available to contribute, in a sustainable manner, to meeting the energy needs of the 21st century;
- Bring together technology holders and users so that they can consider jointly the international and national actions required for achieving desired innovations in nuclear reactors and fuel cycles.

INPRO is proceeding in steps. In its first step, referred to as Phase 1, 2001 to 2006, 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. To provide additional guidance in using the INPRO methodology an INPRO Manual was developed; it is comprised of an overview volume and eight additional volumes covering the areas of economics, infrastructure, waste management, proliferation resistance, physical protection, environment, safety of reactors, and safety of nuclear fuel cycle facilities. 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. As of March 2009, INPRO had 28 members: Argentina, Armenia, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, France, Germany, India, Indonesia, Japan, Republic of Korea, Morocco, Netherlands, Pakistan, the Russian Federation, Slovakia, South Africa, Spain, Switzerland, Turkey, Ukraine, United States of America and the European Commission.

This IAEA-TECDOC is part of Phase 2 of INPRO. The report provides a summary on nuclear energy assessment (NESA) studies (six national ones and one international one) that document the application of the INPRO methodology on national nuclear power programs, on specific designs of nuclear reactors in selected INPRO areas such as economics or safety, or on innovative nuclear energy systems to be deployed in the future.

The report was reviewed by participants of a Technical Cooperation workshop held from 16th to 20th February 2009. The workshop was conducted as part of the IAEA TC project INT/4/141 on Status and Prospects of Development for and Application of Innovative Reactor Concepts for Developing Countries. The IAEA highly appreciates the contributions made by workshop participants, and the valuable guidance and advice provided by the INPRO Steering Committee.

General information about the INPRO project including the progress achieved is available on the IAEA web page (www.iaea.org/INPRO).

The IAEA gratefully acknowledges the contributions from F. Depisch (Austria) for drafting the report and of C. Allan (Canada) for editing.

The IAEA officer responsible for this publication was R. Beatty of the Division of Nuclear Power.

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SUMMARY

Using the INPRO methodology, in total six national INPRO nuclear energy system assessment (NESA) studies have been performed by individual countries (Argentina, Armenia, Brazil, India, Republic of Korea, and Ukraine) and one NESA study was done with international participation of eight countries (Canada, China, France, India, Japan, Republic of Korea, the Russian Federation, and Ukraine).

Planning of energy demand and supply

As a first step, in each of these NESA the results of an energy planning phase were evaluated defining the total increase of power demand and the contribution of nuclear power in meeting this demand. To satisfy the predicted demand, by about 2020, the combined total installed capacity for electricity generation from all sources in the ten countries participating in the NESA should double from about 1000 GW(e) to 2000 GW(e), the main contributions coming from Brazil, China and India.

The combined contribution of nuclear power to electricity generation is predicted to increase from currently 170 GW(e) to 300 GW(e) by about 2020. Thus, assuming an average generation capacity of new reactors of 1000 MW(e) each, the countries involved in NESA would require the construction of about 130 new units for the planned additional nuclear power plus additional ones to replace plants that will be retired within the next 10 to 20 years.

To satisfy their future energy demand China and India assume the biggest (absolute) increase of nuclear capacity within the next twelve and fourteen years, respectively, but, nevertheless, nuclear power will only reach about 4% and 10% of total installed electrical capacity. In both countries, coal is planned to be the dominant energy supply option. In Brazil hydro power will remain the main energy source; the contribution by nuclear power will increase significantly by 2030 but installed nuclear capacity will then still represent less than 4% of total generation capacity.

Definition of national nuclear energy systems

The next step in the NESA was to define the configuration of the nuclear energy system that can fulfill the necessary contribution of nuclear power to the national energy supply in the future as defined in the previous step.

To reach an installed nuclear capacity of about 10 GW(e) in 2030, *Argentina* selected a reactor fleet consisting of different types of water cooled reactors, i.e. six 700 MW(e) PHWR[1], six 300 MW(e) PWR[2] (two of them fuelled 30% with MOX[3] fuel), and two 1000 MW(e) PWR. In addition all facilities of the front and the backend were included in the national nuclear energy system.

Based mainly on security of energy supply considerations, *Armenia* decided to replace the existing nuclear plant of 440 MW(e) by a new nuclear plant of 1000 MW(e) around 2020. No national domestic facilities of the fuel cycle are planned other then waste management facilities.

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[1] PHWR: pressurized heavy water reactor.
[2] PWR: pressurized light water reactor.
[3] MOX: mixed (U-Pu) oxide fuel.

To increase its nuclear capacity from 2000 MW(e) to about 7000 MW(e) by 2030, *Brazil* choose to build one PWR with 1300 MW(e) and four PWR with 1000 MW(e). In the country all facilities of the front end of the fuel cycle are in operation, and also waste management facilities.

To satisfy is future demand of energy *China* sees a need to increase its nuclear capacity significantly from currently about 7000 MW(e) to 40000 MW(e) by 2020 (and about 60000 MW(e) by 2030) installing mainly PWR of different sizes. Starting around 2020, fast breeder reactors are planned to be added and these will become the dominant type of nuclear reactors by the end of the century. In the country a complete nuclear fuel cycle capability has been established.

In *France* nuclear power capacity is assumed to remain about constant until the end of the century. The existing fleet of PWR is to be replaced by about 2030 with EPR[4] reactors. Thereafter fast reactors should become the dominant option of nuclear energy supply. With the exception of mining/milling facilities a complete nuclear fuel cycle capability exists in France.

To satisfy the needed increase of capacity of nuclear power from currently about 3000 MW(e) to about 30000 MW(e) by 2020, *India* choose to build primarily PHWR and PWR. Starting in 2010 a fleet of fast reactors and advanced thorium fueled PHWR are to be installed leading to a total nuclear capacity of 275000 MW(e) by 2050. There is a complete nuclear fuel cycle capability in the country.

After a moderate increase from currently about 47000 MW(e) to 60000 MW(e) by 2030 by installing LWR[5], *Japan* – similar to France – plans to keep the nuclear generation capacity constant till the end of the century. Starting around 2050 fast reactors could gradually replace LWR. Japan has a complete nuclear fuel cycle capability.

The *Republic of Korea* presented several options for satisfying the predicted needed increase of capacity of nuclear power from about 17000 MW(e) to 27000 MW(e) by 2015. One option foresees the instalment of additional water cooled reactors only, and the two other options include the instalment of fast reactors after about 2030.

In the *Russian Federation* the nuclear capacity should increase significantly from currently about 22000 MW(e) to about 35000 MW(e) by 2025 (and 81000 MW(e) in 2050). The existing fleet of WWER[6] is to be replaced by Generation III reactors (of type AES2006) and around 2030 fast reactors are foreseen to replace gradually thermal reactors. There is a complete nuclear fuel cycle capability available in the country.

In *Ukraine* the installed nuclear capacity is predicted to increase from 14000 MW(e) to about 30000 MW(e) by 2030. Different options of a national nuclear energy system were selected consisting of different types of new reactors (WWER, AP1000[7], and EPR), different types of fuel cycle front end facilities (fuel fabrication), associated with an open (direct disposal of spent fuel) and closed (reprocessing abroad) fuel cycle including a fuel leasing scheme. In total fourteen different variants of the configuration of the national nuclear energy system were defined.

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[4] Evolutionary pressurized reactor, generation III+.

[5] Light water reactor, i.e. boiling water reactor and pressurized water reactors.

[6] Water cooled water moderated reactor, Russian type PWR.

[7] AP1000 is the Advanced PWR designed by Westinghouse.

Scope of INPRO nuclear energy system assessments (NESA)

The INPRO methodology was used in a variety of NESA that represented both technology users and developers and different scales of assessments. Assessments covered either a complete nuclear energy system with all facilities, or specific components of a nuclear energy system. In some studies all INPRO areas were assessed, or, in other studies, a limited number of INPRO areas were assessed, and different depths of evaluation were used, i.e. assessment of each INPRO criterion or a scoping assessment at the INPRO basic principle or user requirement level.

Two countries were looking at the sustainability of their planned complete national nuclear energy systems assessing all facilities of the nuclear fuel cycle performing a full depth INPRO assessment on the criterion level: *Argentina* focused its assessment on the facilities of the front and the back end of the national nuclear fuel cycle; *Ukraine* assessed in total fourteen variants of its national nuclear energy system.

Three countries assessed specific reactor designs and associated fuel cycles in selected areas of the INPRO methodology: *Brazil* assessed economics and safety of an integral small PWR design called IRIS, and safety and proliferation resistance of the conceptual design of the Fixed Bed Nuclear Reactor (FBNR); *India* assessed the safety of a high temperature reactor design to be used in a nuclear energy system supplying hydrogen as fuel for transportation in addition to electric power; The *Republic of Korea* assessed the DUPIC[8] fuel cycle in regard to its proliferation resistance thereby developing an qualitative analysis method that was the basis for the INPRO assessment method.

The eight countries (*Canada, China, France, India, Japan, Republic of Korea, Russian Federation, Ukraine*) performing a multinational study, the Joint Study, assessed a nuclear energy system consisting of sodium cooled fast reactors with a closed fuel cycle. The assessment covered all INPRO areas with a different depth of the assessment for each area.

One country, *Armenia*, performed an INPRO assessment, primarily, to familiarize national decision makers with all issues of a planned nuclear power program. This was a scoping assessment covering all INPRO areas using the IRIS reactor as an option to be deployed beyond 2020.

Results of INPRO nuclear energy system assessments

The *Argentine* study assessed the complete national fuel cycle, including all facilities of the front and back end and considered all INPRO areas. The economic evaluation found the investment in the nuclear facilities to be economically viable, and the existing infrastructure for nuclear power to be generally adequate to cover the planned expansion of nuclear capacity, including human resources and legal and institutional factors. A qualitative analysis of the proliferation resistance of the complete fuel cycle showed some weak points; however, it was concluded these could be compensated by increased safeguard measures, and thus, all INPRO requirements are met. There is a well established security regime in the country that fulfils all INPRO requirements in this area. No critical issues were found in the environmental assessment evaluating resources and stressors. The safety of all future nuclear facilities conforms to the requirements defined by INPRO.

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[8] Direct use of spent PWR fuel in CANDU reactors.

The *Armenian* assessor performed a detailed evaluation of the present and future options for energy supply until 2025, with a particular focus on the security of supply and the role of nuclear power. For a reliable supply of electricity, Armenia's currently operating nuclear power plant (supplying about 40% of the country's electricity) should be replaced by a new plant around 2020. For this planned nuclear program, all INPRO areas were assessed using the IRIS reactor design to check the applicability of the INPRO methodology for the specific requirements of the country. No critical issues were found in any INPRO area that could not be solved in the future. The assessment also supported a comprehensive understanding of all issues associated with the installation of new nuclear power plants in Armenia.

In the study of *Brazil* two specific small reactor designs were assessed in two INPRO areas: for the IRIS[9] reactor design the INPRO areas of safety and economics were chosen; for the Fixed Bed Nuclear Reactor (FBNR) design, the areas of safety and proliferation resistance were selected. The safety assessment confirmed the high level of safety reached in the IRIS design, and predicted a similar safety level for the FBNR design, which is in an early design phase. The economic assessment of IRIS was done by comparing the new modular design (three modules) with a large nuclear unit in Brazil (ANGRA-3). The study revealed that three modules of IRIS are an economically viable option compared with installing a single large unit. The assessment of the proliferation resistance of the FBNR design demonstrated the high potential of this new design.

The *Indian* study assessed the replacement of fossil fuel by hydrogen in the transportation sector. Several hydrogen production methods were evaluated together with required energy sources. The study concluded that electrolysis may be the most attractive hydrogen production method during the introduction of a hydrogen system, to be replaced later by other high temperature chemical processes (i.e. iodine–sulphur or copper–chlorine). The energy needed for hydrogen production could be supplied by a high temperature reactor (HTR); several HTR designs were evaluated with different core (e.g. enrichment), fuel designs (blocks, pebble bed) and coolants (helium or lead/molten salt). INPRO requirements for a co-located hydrogen plant were derived. A design specific INPRO assessment of the HTR was performed in the area of safety and several safety related issues for the HTR were identified that need further R&D.

The prime objective of the *Korean* study was to develop a qualitative analysis method to determine the level of proliferation resistance (PR) of nuclear fuel cycles. The method of analysis defined a large number of parameters relevant for PR, i.e. the isotopic composition of fuel. For these parameters qualitative levels of proliferation resistance can vary from very weak to very strong. To test the analysis method it was then applied to the DUPIC fuel cycle, where spent fuel from PWRs is converted to fresh fuel for CANDU reactors.

The *Ukrainian* assessor investigated several options for the national fuel cycle based on different types of new reactors and different assumptions about the use of national production facilities, i.e. producing the fuel elements in a national facility based on the import of enriched UF_6, or leasing the fuel elements from a foreign supplier. A numerical scheme was used to take into account the maturity of each component of the nuclear energy system. Fourteen different variants of a national nuclear energy system were assessed in all INPRO areas (except physical protection). The results of the assessment were numerically aggregated and the variants of the nuclear energy system were compared with each other. Each of the assessed variants showed different strengths and weaknesses in different INPRO areas. The

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[9] International Reactor Innovative and Secure.

variants of the nuclear energy system including the fuel leasing option showed the highest score.

The *Joint Study* was started in 2005 and completed in 2007. *Canada, China, France, India, Japan, Republic of Korea, Russian Federation,* and *Ukraine* participated. The objectives were to assess a nuclear energy system based on a closed fuel cycle (CNFC) with fast reactors (FR) to meet the criteria of sustainability, determine milestones for the deployment, and establish frameworks for, and areas of, collaborative R&D work. It was agreed to use as a reference system a near term CNFC–FR system based on proven technologies, such as sodium coolant, MOX pellet fuel and aqueous reprocessing technology. The main results and findings of the study concerning the multidimensional assessment of the reviewed nuclear energy system are summarized in the following:

- Although the safety characteristics of near term CNFC–FR system are considered to be in compliance with INPRO requirements, further study is required to achieve a lower level of risk of severe accidents;
- In some countries, the introduction of fast reactors might contribute to an efficient use of nuclear fuel resources by increasing the use of plutonium fuels to be generated in the fast reactor blankets, if needed;
- The CNFC–FR system has the potential to meet all of today's requirements of waste management. By developing and introducing novel technologies for an optimal management of nuclear fission products and minor actinides, the CNFC–FR system would have the potential for a 'breakthrough' in meeting sustainability requirements related to waste management;
- Due to the intrinsic, i.e. technological features of the CNFC–FR system, its proliferation resistance could be comparable to, or higher than, that of a once-through fuel cycle. The CNFC–FR system is a key technology for the balanced use of fissile materials;
- A CNFC–FR system requires a regional or multilateral approach to front and back end fuel cycle services and the transition to a global nuclear architecture; and
- The designs of currently operating nuclear energy systems with CNFC–FR do not meet economic requirements. The Joint Study showed that simplifying the design, increasing the fuel burnup and reducing costs by R&D, along with small series constructions, would make the costs of nuclear power plants with fast reactors comparable to those of thermal reactor and fossil fuelled power plants.

Main follow-up actions defined in the NESA

The *Argentine* assessor stressed the point that public acceptance of nuclear power must be gained and kept in all nuclear countries and proposed to study all phenomena associated with public perception of nuclear power in multidisciplinary groups in different countries of the world. To ensure an adequate design of facilities for final disposal of all nuclear wastes that fulfills all INPRO criteria in this area several relevant R&D projects have been initiated by the government. In regard to proliferation resistance the confidence in nuclear related international treaties should be improved by establishing an appropriate legal framework and technical tools are to be developed further to ensure total control against the diversion of nuclear material. The National Atomic Energy Commission should develop guidelines for use of probabilistic safety analysis for different nuclear fuel cycle facilities.

In the *Armenian* study no specific non-agreements with INPRO requirements were identified in the assessed national nuclear energy system. However, a detailed list of requests to potential suppliers of the nuclear power plant to the country was defined. Armenia initiated an INPRO Collaborative Project (CP called **SMALL**) that will deal with issues of nuclear energy in small countries.

In the *Brazilian* study a long list of necessary R&D topics is presented for the two types of reactors assessed. These R&D topics are however not based on the INPRO assessment, but on evaluations of IRIS performed within the program of Generation-IV International Forum in 2002, and on the existing development program of FBNR. The listed R&D safety related issues of IRIS were, however, correlated with INPRO requirements for reactor safety.

The *Indian* assessor provided a list of specific R&D topics related to the development of HTR designs. Several of these specific topics were integrated into INPRO Collaborative Projects (CP):

- Properties of primary coolants for a HTR, i.e. heavy liquid metal and molten salt; to be covered in the INPRO CP called **COOL**;
- Passive safety systems of HTR; to be covered in the INPRO CP called **PGAP**; and
- Safety issues of collocation of a nuclear power plant and a hydrogen production plant; to be covered in the INPRO CP called **HTR-H_2**.

The goal of the *Korean* study was to develop an analysis method to quantify the proliferation resistance of a defined nuclear energy system. In the conclusions of the study it is stated that the analysis method should be developed further, something that is being realized in an INPRO CP (called **PRADA**).

In the *Ukrainian* study, in several INPRO areas, gaps (non agreement) were identified for a number of INPRO criteria, but the assessor did not define corresponding activities, i.e. no R&D proposals and/or follow up actions are documented. However, most of the judgments 'non agreement' were caused by a lack of data necessary to evaluate INPRO criteria.

The *Joint Study* (JS) concluded that a comprehensive program of R&D is absolutely essential in a variety of areas (especially, for economics and safety) with an inter-disciplinary approach and international collaborations wherever possible to make an energy system consisting of fast reactors (FR) with a closed nuclear fuel cycle (CNFC) a viable alternative to conventional sources of power. As capital costs of currently operating FR (sodium cooled) were 40% to up to three times higher than capital costs of thermal reactors, several possibilities for reduction of capital costs were presented in the JS. For the improvement of FR safety R&D is needed to develop efficient and cost-effective shielding materials such as boride/rare earth combinations, and achieve (radiation) source reduction by adequate measures such as use of materials which do not get activated. In the JS the following INPRO collaborative projects related to fast reactors have been proposed and are currently underway:

- A global architecture of nuclear energy systems based on thermal and fast reactors including a closed fuel cycle (called **GAINS**).
- Integrated approach for the design of safety grade decay heat removal system for liquid metal cooled reactor (called **DHR**);

- Assessment of advanced and innovative nuclear fuel cycles within large scale nuclear energy system based on a CNFC concept to satisfy principles of sustainability in the 21st century (called **FINITE**); and

- Investigation of technological challenges related to the removal of heat by liquid metal and molten salt coolants from reactor cores operating at high temperatures (called **COOL**);

Feedback from the NESA on the INPRO methodology

Besides detailed proposals how to improve the INPRO methodology in specific areas several general proposals have been made by assessors to improve the INPRO methodology as set out below.

There is a need to extend the INPRO methodology to enable a clearer distinction (discrimination) between different options of nuclear energy system components under development but also between options of commercial available components, especially, if some components are located in different countries. By comparing options a need for a more precise description how to aggregate assessment results was found by the assessors. In that context, primarily, by technology developing countries a need was expressed to develop an approach how to treat different level of uncertainty associated with stages of development.

In particular for the INPRO area of environment and proliferation resistance a need for further development of the assessment approach was expressed by several assessors.

It was recommended to treat some issues within the INPRO project jointly with other relevant IAEA groups. One issue is security of energy supply that should be taken into account within the methodology appropriately considering its importance in defining the role of nuclear power in a country. Another issue to be addressed is non electric applications of nuclear power.

Lessons learned from the application of the INPRO methodology in NESA studies

A Technical Cooperation workshop[10] was held from February 16th to 20th at the IAEA to discuss the results of the NESA focusing on the recommendations by assessors how to improve the INPRO methodology and ease its application. All eleven countries (Argentina, Armenia, Brazil, Canada, China, France, India, Japan, Republic of Korea, Russian Federation, and Ukraine) who had participated in one of the NESA with the exception of France were represented at this workshop. Based on this workshop, in the following, a summary of lessons learned, is laid out.

There was a consensus among the assessors participating in the workshop that applying the methodology to a nuclear energy system was a worthwhile effort and provided valuable insights, and clear identification of gaps in nuclear power development or deployment programs, leading to follow-up actions.

Participants confirmed that the INPRO methodology can and should be used as a tool for meeting the INPRO objective of assessing how nuclear energy systems ‘contribute in a sustainable manner, to meeting the energy needs of the 21st century’.

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[10] The workshop was conducted as part of the IAEA TC project INT/4/141 on Status and Prospects of Development for and Application of Innovative Reactor Concepts for Developing Countries.

Insights of technology developing countries include the confirmation of the strategy of an ongoing national development program and the knowledge gained about similar programs in other countries highlighting some key global issues. Technology user countries emphasized that they achieved familiarization with all nuclear issues associated with the establishment of a sustainable nuclear power program.

The INPRO Manual is a comprehensive document providing a lot of explanations and background information but – based on feedback from the workshop to ease the application of the INPRO methodology – additional guidance is needed in using it, answering precisely the following questions:

- How to get started with an INPRO assessment and what technical expertise is needed?
- What a newcomer State should do?
- What a technology user country should do?
- What a technology developing country should do?

These questions could be addressed by an additional user guide tailored to the needs of different users of the INPRO methodology.

To further ease the application of the INPRO methodology in the future some additional needs of the assessors were expressed as follows.

- A data base is necessary for all INPRO assessors containing all the information on components (facilities) of nuclear energy systems needed in an INPRO assessment; such necessary data on nuclear technologies should be provided by designers and technology suppliers. The IAEA/INPRO secretariat could play a mediating role to exchange these data.
- There is a need for performing a few examples (also called reference cases or case studies) of a full nuclear energy system assessment (NESA) using the INPRO methodology and a complete documentation thereof should be made available to the different kind of INPRO assessors, i.e. technology developers, technology users, and newcomers. The examples should cover all components of a complete nuclear energy system and all INPRO areas.
- Training courses in the INPRO methodology are needed for potential INPRO assessors before the start of a NESA. During the assessment continuous support to INPRO assessors is needed by means of INPRO methodology expert missions and/or access to IAEA expertise clarifying all issues raised.

Based on the feedback from the workshop it was proposed to develop a nuclear energy system assessment (NESA) support package that integrates all requests listed above into one task. It was recognized that the planning of an INPRO assessment by a country should include also the planning for timely IAEA/INPRO support.

CHAPTER 1. INTRODUCTION

The international Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) has developed an assessment methodology [1] during its Phase 1 (2001 to 2006). This assessment methodology covers holistically all components of a nuclear energy system[11], i.e. mining, milling, conversion, enrichment, fuel fabrication, reactor, reprocessing, depository, during their life time, and all associated institutional measures. The nuclear energy system is to be assessed in seven different areas, i.e. economics, infrastructure (legal frame work and institutional issues, industrial and economic issues, political support and public acceptance, human resources), waste management, proliferation resistance, physical protection, environment (consisting of sustainability of resources and impact of stressors), and nuclear safety.

The INPRO methodology can be applied in different ways: The most challenging way is to assess a planned national nuclear energy system, including the existing installations, if any, to confirm the sustainability of the system; such studies could be called sustainability assessments. A second type of application is to look at specific designs that could be installed in the country in the future assessing specific INPRO areas, such as economics and safety; such a study could be called a design and INPRO area specific assessment. A third way, more suitable for countries that are planning to introduce nuclear power the first time, is to screen their planned nuclear power program or part of it thereby becoming familiar with all issues related to such a program; an appropriate term for such a study could be assessment for familiarization or scoping assessment.

Using the INPRO methodology, in total six national INPRO assessment studies have been performed by individual countries and one assessment study with international participation of eight countries. Two assessors were looking at the sustainability of their existing and planned national nuclear energy system, four studies (including the multi national study) assessed specific reactor designs and associated fuel cycles, and one study was performed primarily to familiarize national decision makers with all nuclear issues of a planned nuclear power program.

Most studies started with an energy planning study analyzing the present and future energy demand and supply options. For all countries participating in INPRO assessment studies the planned role of nuclear power for additional energy supply in the future was defined. Planning of the total national energy supply and the role of nuclear within an energy mix is summarized in Chapter 2. In Chapter 3 the innovative nuclear energy system or a component (reactor design and/or fuel cycle) thereof chosen for the INPRO assessment are described. In Chapter 4 a summary of all assessment results is provided for each INPRO area assessed. In Chapter 5 proposals are provided for R&D and follow up actions that are needed to improve the nuclear energy systems that were assessed. In Chapter 6 feedback from the studies on how to improve the INPRO methodology is presented. Finally, in Chapter 7 lessons learned from the application of the INPRO methodology are discussed.

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[11] In INPRO the definition of a nuclear energy system includes evolutionary and innovative designs of all components. An ‘evolutionary design’ is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining design proveness to minimize technological risks. An ‘innovative design’ is an advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. The term ‘existing design or practice’ is defined in INPRO as the design of operating nuclear facilities in 2004.

CHAPTER 2.
NATIONAL ENERGY PLANNING

As stated in Volume 1 of the INPRO Manual (Ref. [1]) and shown in Figure 2.1 a fundamental prerequisite of an INPRO assessment is that an energy planning study has been performed to define the possible role of nuclear power as an supply option in a mix of available energy sources.

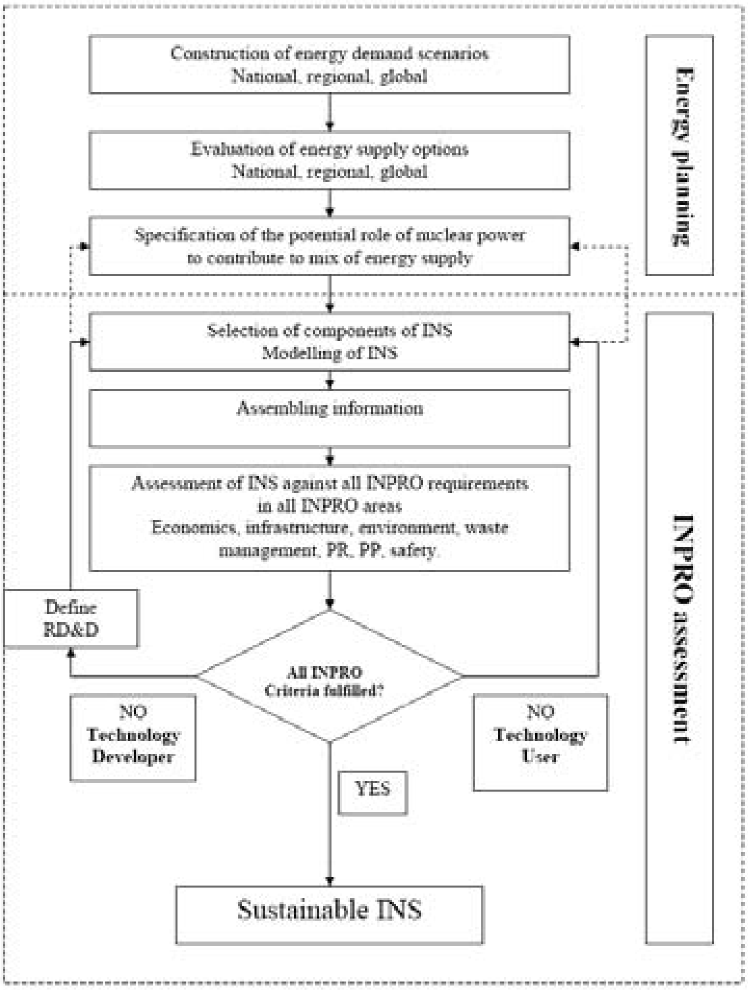

Figure 2.1. Flow chart of an INPRO assessment [1].

The goal of national energy planning is to determine the evolution of the energy demand and supply for the entire energy system at the national level. Important factors determining the development of energy (and electricity) demand are the population growth and the development of economic activities (gross domestic product) and structures (industry, transport, households, etc.).

In the following for each country participating in an INPRO assessment the results of this energy planning phase as documented in the assessment reports are briefly outlined.

2.1. Energy planning in Argentina

The current (2006) installed capacity of 24033 MW(e) in Argentina [2] consists of 54.5% fossil power stations, 41.3% hydro and 4.2% nuclear power plants. Within fossil energy supply, gas is the primary source with about double the capacity of coal. It is important to mention that nuclear energy – primarily operating in base load mode – contributes about 8% to the generation of electricity, i.e. almost double the amount in comparison to the installed capacity.

The national electricity supply system is completely privatized and run by different entities and associations responsible for transmission, distribution and generation. However, the market of the final user of electricity is a regulated monopoly.

No detailed data on the complete national energy planning covering all available energy sources are documented in the Argentine study. However, the planned role of nuclear is specified in detail as shown in Figure 2.2.

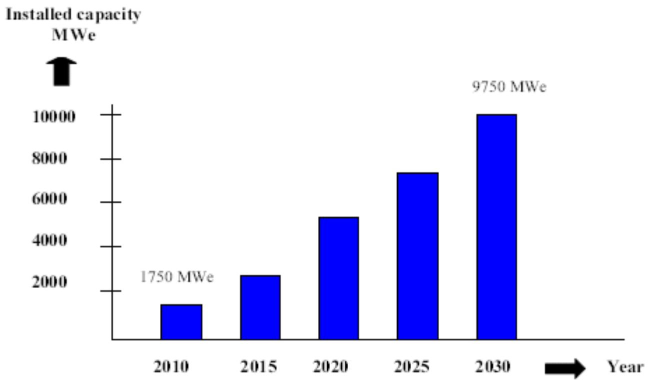

Figure 2.2. Planning of installed nuclear capacity in Argentina [2].

After finishing the Atucha-2 plant in 2010, the installed nuclear capacity will be 1750 MW(e) output and is planned to reach 9750 MW(e) in 2030 consisting of different types of nuclear reactors (as discussed in Chapter 3).

2.2. Energy planning in Armenia

The current (2006) available power capacity of Armenia [3] is about 3100 MW(e); gas fired plants contribute about 1754 MW(e), hydro plants about 1000 MW(e) and one nuclear power plant about 408 MW(e). A detailed study [4] was performed together with the IAEA evaluating the development of energy demand and possible options (hydro, wind, solar, bio mass, geothermal, oil and gas, coal, and nuclear) to supply the needed energy in the future. The result of this study [4] plus additional considerations documented in Ref. [3] lead to the development of an energy supply plan till 2025 as shown in Figure 2.3.

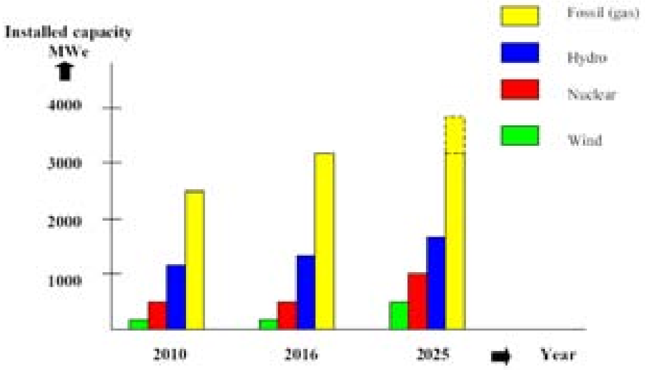

Figure 2.3. Planning of electricity supply in Armenia (Refs [3], [4]).

An overriding consideration in the energy planning is the goal to keep sufficient national energy independence. The total capacity of fossil power plants in 2025 using imported natural gas will be determined based on the actual need in 2025 (indicated by an additional yellow rectangle at the top of the column representing installed fossil capacity). The role of nuclear in the energy supply system is defined by keeping the existing unit (WWER-440) operating till a new nuclear plant will start up around 2017.

2.3. Energy planning in Brazil

In 2005, the installed capacity of power plants in Brazil [5] amounted to 93160 MW(e); the largest contribution of electricity was supplied by hydro plants with a capacity of 70860 MW(e), conventional thermal plants (using gas, diesel and coal) and alternative sources (small hydro, biomass, and wind mill plants) provided 20290 MW(e), and nuclear power 2000 MW(e).

The energy planning predicted an average annual increase of total energy consumption of about 4% from 2005 till the year 2030. To satisfy the specific demand for electricity in 2030 the total capacity of installed power plants should reach more than 200000 MW(e). In comparison to 2005, in 2030 about 88000 MW(e) additional capacity should come from hydro plants, gas (and coal) should contribute about 12000 MW(e), coal about 5000 MW(e), wind and bio mass is expected to add about 19000 MW(e), and nuclear about 5300 MW(e). The planned development of installed capacity of power plants is shown in Figure 2.4.

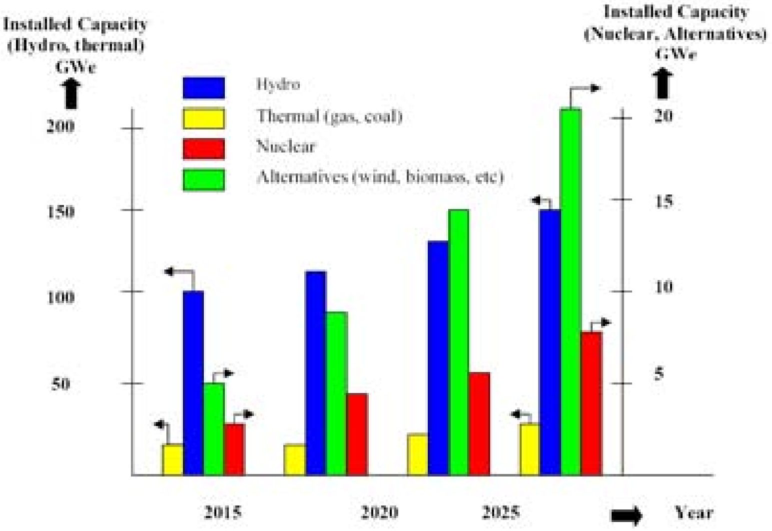

Figure 2.4. Planning of electricity supply in Brazil [5].

Capacity of nuclear power is predicted to grow from 2000 MW(e) in 2005 to 7300 MW(e) in 2030, i.e. about 3.4% of the total capacity and about a third of the alternative energy sources (wind mills, biomass, small hydro, and industrial residues plants) with 20900 MW(e). Hydro plants should reach about 156000 MW(e) and thermal plants (gas, coal, etc.) about 32000 MW(e) at the same time.

2.4. Energy planning in China

According to the goal of the national development, China's GDP should double from 2000 to 2020 resulting in a corresponding growth of energy demand [6]. To satisfy the need for electricity in 2020 the installed capacity of power plants should increase from 400 GW(e) to a range of 960 to 1000 GW(e). More than half of this increase is to be filled by coal fired plants and about a third is to be contributed by hydro plants. The remaining power necessary should be supplied primarily by nuclear power, i.e. the nuclear capacity should be increased from the current 9 GW(e) to about 40 GW(e) in 2020.

In 2050 the total power capacity should reach 1650 GW(e); coal fired plants are predicted to provide 950 GW(e), hydro plants 300 GW(e), and gas fired plants about 120 GW(e). Nuclear power should contribute about 250 GW(e) (48.3 by PWR and 201.7 by fast breeder reactors, FBR) at that time as shown in Figure 2.5.

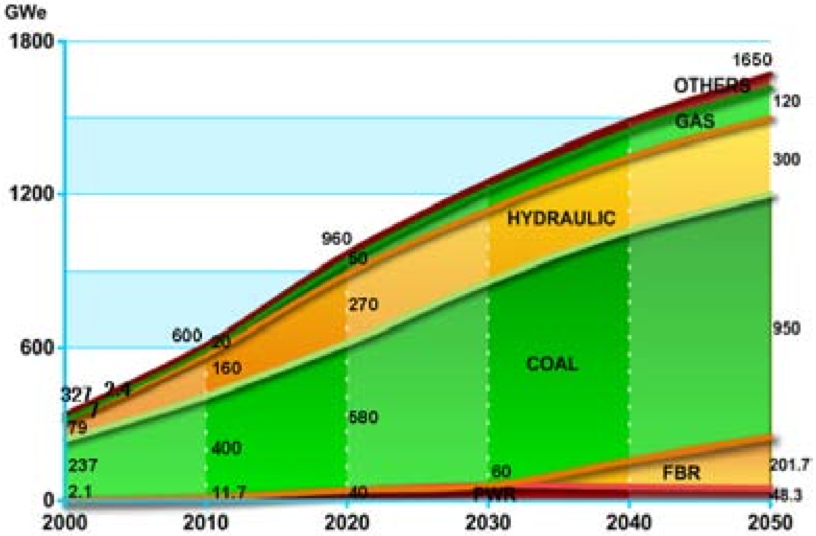

Figure 2.5. Planning of electricity supply in China (Status 2005, Ref. [6]).

2.5. Energy planning in France

No data on energy planning considering all energy sources are documented in the Joint Study in which France participated [6]. The role of nuclear power within the 21st century is assumed, for the purpose of the Joint Study, to remain constant at a capacity of about 63 GW(e).

2.6. Energy planning in India

In 2002, India [6] had an installed total electrical power capacity of about 139 GW(e); within this energy mix, fossil power contributed 105 GW(e), hydro 28 GW(e), non conventional (renewable) energy sources 3.6 GW(e), and nuclear power 2.7 GW(e).

The known indigenous energy resources are about 7.6 TW_eyr for coal, 5.8 TW_eyr for hydrocarbons, 0.33 TW_eyr for uranium used in PHWR (and 42 TW_eyr in fast breeder reactors, FBR), 155 TW_eyr for thorium used in FBR.

In 2052 the total installed capacity should rise to 1344 GW(e) (see Figure 2.6) consisting of 819 GW(e) (about 61%) supplied by fossil plants, 275 GW(e) (about 20%) by nuclear plants, 150 GW(e) (about 11%) by hydro plants and the rest of 100 GW(e) by non conventional plants (about 7%).

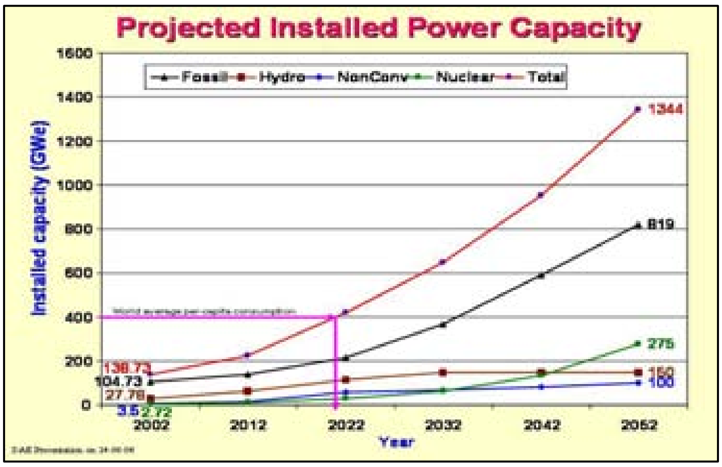

Figure 2.6. Planning of electricity supply in India [6].

In another study [7] of illustrative nature only and not representing formal goals/targets for the country, India assessed the possibility of replacing about 25% of total fossil liquid fuel requirements for transportation by hydrogen. To produce the necessary amount of hydrogen, nuclear power plants having installed capacities in the range of 1500 to 2170 GW_{th} would be required. This would be in addition to the nuclear power plants required for electricity generation. The focus of this study was more on the end goal rather than the path and time frame. As a suitable energy source for hydrogen production nuclear power was selected in this study.

2.7. Energy planning in Japan

Energy consumption in Japan [6] is predicted to peak in 2021 and decrease thereafter mainly because of population decline. However electricity demand should increase steadily till 2030.

The role of nuclear power is predicted to increase from 50 GW(e) (generating about 30% of electricity consumed) in 2006 to 58 GW(e) (satisfying about 38% of electricity demand) in 2030 and remain constant thereafter.

2.8. Energy planning in the Republic of Korea

Energy consumption in Republic of Korea [6] is expected to grow at an average rate of 2.5% from 2006 to 2017. In 2005 the total installed electrical capacity was about 62 GW(e) to which nuclear power contributed about 18 GW(e) (i.e. about 28%). The share of nuclear in the total installed electrical capacity is to increase to about 33% in 2017. The long-term planning of nuclear capacity till the end of the century is shown in Figure 2.7. Installed nuclear power should reach 58 GW(e) in 2100.

2.9. Energy planning in the Russian Federation

Currently (2006), in the Russian Federation [6] about 50% of electricity is generated by gas fired plants, about 18% by coal plants, and hydro power plants as well as nuclear power plants produce about 16% each.

By far the largest indigenous energy source in the Russian Federation is ^{238}U (if used in fast reactors) with a relative energy potential of about 86% of natural resources, followed by coal (about 9%) , gas (about 3%) and oil and ^{235}U together about 1%.

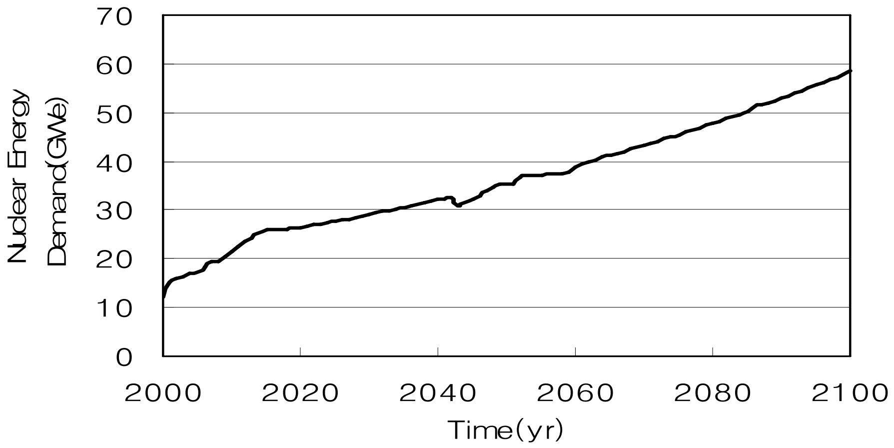

Figure 2.7. Planning of installed nuclear capacity in the Republic of Korea [6].

By 2020 total electricity consumption is predicted to double in comparison to 2006. The share of electricity generated by nuclear power plants should increase from about 16% in 2000 to 23 – 25% in 2020. By 2050 nuclear power should reach an installed capacity about 81 GW(e).

2.10. Energy planning in Ukraine

In 2007 power plants in Ukraine [9] represented a total capacity of 52 GW(e) consisting of fossil plants, 58%, nuclear plants, 26%, and hydro plants, 9%. The nuclear power plants running in base load mode generated about 47% of the total electricity output during that year.

The energy sources used to produce electricity in 2005 and predicted by 2030 are shown in Figure 2.8.

Figure 2.8 indicates the goal of the national energy policy to change from imported energy sources to domestic sources by the year 2030.

The forecast of electricity generation is illustrated in Figure 2.9.

The national GDP is predicted to triple between 2005 and 2030 and the electricity consumption as shown above should more than double within the same time period. The planned role of nuclear power is to supply, continuously, about 50% of all electricity generated. This would require an increase of nuclear capacity to about 30 GW(e) by 2030.

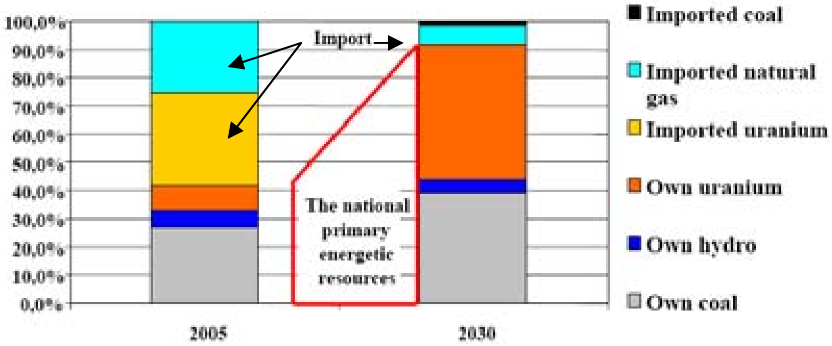

Figure 2.8. Share of domestic and imported energy sources in Ukraine [9].

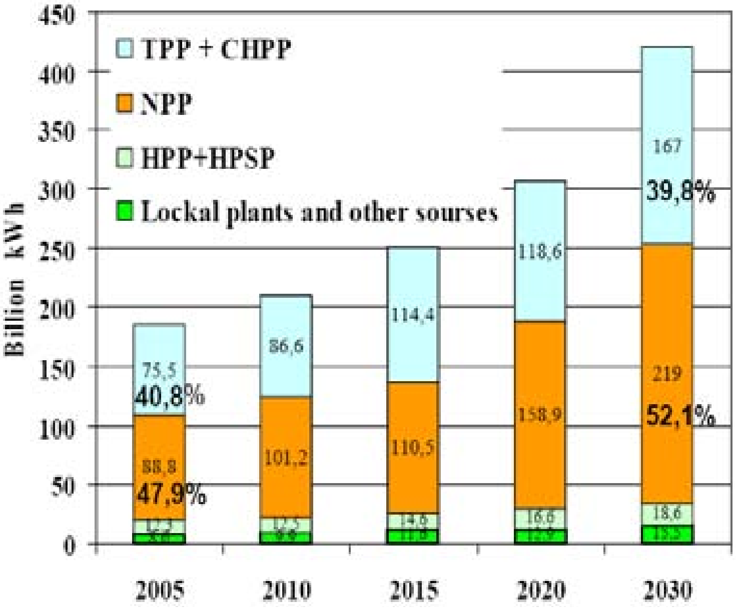

Figure 2.9. Forecast of electricity generation till 2030 in Ukraine [9]. (TPP=thermal power plant, CHPP= central heating thermal power plant, HPP=hydro power plant, HPSP= hydro pump storage plant, NPP=nuclear power plant).

2.11. Summary of the national energy planning studies

Table 2.1 (on the following page) provides a summary of the near term planning of energy supply within the next decades as documented in the national and international INPRO assessment studies (Refs [2], [3], [5], [6], and [9]).

By about 2020 the combined total installed capacity for electricity generation in the ten countries is predicted to double, the main contributions coming from Brazil, China and India. China and India show the biggest (absolute) increase of nuclear capacity within the next 12 and 14 years, respectively, but, nevertheless, nuclear power will only reach about 4% and 10% of total installed electrical capacity. As outlined above, in both countries, coal is planned to be the dominant energy supply option. In Brazil the main energy source is and will remain hydro power; the contribution by nuclear power will increase significantly by 2030 but installed nuclear capacity will then still represent less than 4% of total capacity.

Combined nuclear power capacity is predicted to increase by about 130 GW(e). So, assuming an average generation capacity of new reactors of 1000 MW(e) output, the 10 countries involved in INPRO assessment studies would require the construction of about 130 new units for the planned additional nuclear power plus some new units to replace retired plants within the next 10 to 20 years.

Table 2.1. Overview on energy planning studies used in INPRO assessments

Country	**Population 2007 Millions**	**Current Electricity Capacity (CEC) GW(e)**	**Future Electricity Capacity (FEC) GW(e)**	**Current Nuclear Capacity (CNC) GW(e)**	**Future Nuclear Capacity (FNC) GW(e)**	**Current Nuclear portion (CNC/ CEC) %**	**Future Nuclear portion (FNC/ FEC) %**	**Increase of Nuclear (FNC – CNC) GW(e)**
Argentina [2]	39.4	24 (2006)	70 (2025)	1 (2006)	9.8 (2030)	4.2	14	8,8 (2030)
Armenia [3]	3.2	2.4 (2006)	4 * (2020)	0,4 (2006)	1 (2025)	16.9	25,0	0,6 (2025)
Brazil [5]	189.9	87 (2005)	217 (2030)	2 (2005)	7.3 (2030)	2.3	3,4	5,3 (2030)
China [6]	1321.0	330 (2005)	1.000 (2020)	6.6 (2005)	40 (2020)	2.0	4,0 (2020)	33,4 (2020)
France [6]	64.5	80.1 (2005)	-	63.1 (2005)	63.1 (2025)	78.0	-	0 (2025)
India [6]	1147.9	107 (2005)	295 (2022)	3.0 (2005)	29.5 (2022)	2.8	10 (2022)	25,5 (2022)
Japan [6]	127.3	160.3 (2005)	145 – 193 (2030)	46.5 (2005)	58 (2030)	29	30 - 40	11,5 (2030)
Republic of Korea [6]	49.0	43.0 (2005)	78 (2015)	16.8 (2005)	26.6 (2015)	39	34	9,8 (2015)
Russian Fed. [6]	142.0	135.6 (2005)	140 (2025)	21.7 (2005)	35.0 (2025)	16.0	25	13,3 (2025)
Ukraine [9]	45.9	27 (2005)	57 - 62 (2030)	13.1 (2005)	30 (2030)	48.5	48 - 53	16,9 (2030)
Total	3130.1	996.4	~2100	174.2	300.3	-	-	-

* taken from Ref. [4].

CHAPTER 3.
OVERVIEW ON THE FUTURE NUCLEAR ENERGY SYSTEMS

As shown in Figure 2.1 (Chapter 2), after defining the future demand of energy and the role of nuclear energy in an energy supply mix, the first step of an INPRO assessment is to define the nuclear energy system in accordance with its defined role.

A nuclear energy system in INPRO includes all nuclear facilities of the front and back end of the fuel cycle (mining/milling to final depository), the nuclear power stations and institutional arrangements (i.e. regulatory bodies, legal framework, human resources, etc.) necessary for the safe and secure use of nuclear power.

In the following, the systems chosen by INPRO assessors are briefly described. It has to be pointed out that these systems only represent an option that the assessors deemed as possible to be implemented within their country in the defined time frame.

3.1. Nuclear energy system of Argentina

As laid out in Section 2.1 the total capacity of nuclear power (16 units) is supposed to reach 9800 MW(e) in 2030.

The fleet of nuclear power plants to be constructed consists of the following: By 2030 six PHWR (each with 700 MW(e)), fuelled with natural uranium, should be installed, the first one should be commissioned in 2014 and the following ones every three years thereafter; additionally four PWRs (each with 300 MW(e)), fueled with lightly enriched uranium, the first one should start up in 2016 and the next ones in 3 year intervals; two PWR (each with 300 MW(e)) in 2025 and 2028 using 30% MOX fuel; and finally two large PWR of 1000 MW(e) in 2024 and 2030..

In addition to defining a fleet of different reactors, a complete nuclear fuel cycle (front end and back end) was included into the nuclear energy system consisting of different facilities : uranium mining and milling (total capacity 600 t_U/a), UO2 conversion (600 t_U/a), uranium enrichment (40000 SWU/a), fuel fabrication (pellet and cladding tube manufacturing, fuel bundle manufacturing, 600 t_U/a), dry spent fuel storage, reprocessing (120 kg Pu/a), MOX fuel fabrication (3 t/a), and waste management facilities. The fuel cycle facilities (with the exception of the mining/milling facilities) are planned to be constructed in one location the siting of which has not been decided yet.

The capacity of this planned fuel cycle, however, can only support 4250 MW(e) of nuclear power. In the INPRO assessment only this limited nuclear expansion plan of 4250 MW(e) was evaluated.

The fuel cycle considered was supposed to provide fuel for the two PHWR in operation (Atucha-1, 357 MW(e), and Embalse, 648 MW(e)), Atucha-2, 745 MW(e), three additional PHWR, 700 MW(e) each, MOX fuel elements for one third of a PWR of 300 MW(e) and light enriched uranium fuel for one PWR of 300 MW(e). As for the provision of fuel for the remaining 5500 MW(e) of the nuclear expansion plan, the natural uranium will be supplied by national resources, and other materials and processes would be provided to the extent possible on a national basis, or provided from abroad otherwise.

In the actual national INPRO assessment of the Argentine nuclear energy system all of the existing and planned fuel cycle facilities were taken into account; however, the nuclear power plants themselves were only considered as consumers of nuclear fuel and producers of radioactive waste and spent fuel.

3.2. Nuclear energy system of Armenia

As stated in Section 2.2, the role of nuclear power is to guarantee a sufficient level of energy independence. Keeping the existing nuclear power plant (440 MW(e)) operating until it can be replaced, between 2017 and 2025, by a new one (1000 MW(e)) is the defined role of nuclear in the country.

In addition to the nuclear power plant the national nuclear energy system consists of spent fuel storage and nuclear waste facilities including a planned final depository of high level waste. All nuclear fuel is imported with no domestic participation in its production.

In the actual national INPRO assessment, an innovative medium sized integral 300 MW(e) PWR, called IRIS, was assessed. IRIS is a type of reactor that could be a candidate for installation after 2025, i.e. IRIS could become part of the Armenian nuclear energy system after about 2027.

3.3. Nuclear energy system of Brazil

The capacity of nuclear power in the country was predicted (see Section 2.3) to reach 7300 MW(e) in 2030. In addition to the two operating nuclear units ANGRA-1 (700 MW(e)) and ANGRA-2 (1300 MW(e)), ANGRA-3 with 1300 MW(e) should start up by 2015, and then four 1000 MW(e) units are planned, one to start up in 2020, one in 2025 and two in 2030. The national fuel cycle of Brazil includes facilities for uranium mining and milling, uranium conversion, uranium enrichment, nuclear fuel fabrication, and radioactive waste management.

In the actual national INPRO assessment as potential candidates in the Brazilian nuclear energy system two innovative reactor designs were evaluated in specific INPRO areas: IRIS (as in the Armenian study, Section 3.2 above) in the INPRO areas of economics and safety and FBNR (fixed bed nuclear reactor) in the INPRO areas of safety and proliferation resistance.

3.4. Nuclear energy system of China

As of 2008, the nuclear power program in China [6] foresees a significant increase of nuclear power by 2050 and a constant capacity thereafter until the end of the century. The power is to be primarily generated with PWR until about 2030 reaching a value of 60 GW(e) (a value kept constant till 2040 and decreasing thereafter). Beginning in 2020, fast breeder reactors are planned to be installed and become the primary source of nuclear electricity by 2050 generating about 200 GW(e) (see Figure 2.5 in Section 2.4). In the country a complete nuclear fuel cycle with all front end and back end facilities are part of the national nuclear energy system. In the actual INPRO assessment called the Joint Study [6] – as done by all participating countries in this study – the fleet of fast breeder reactors together with a closed fuel cycle was evaluated (as outlined in Section 3.11).

3.5. Nuclear energy system of France

The nuclear energy system documented in the Joint Study [6] shows a practically constant generation capacity of nuclear power until the end of the century with about 60 GW(e) output. The operating fleet of PWR with mainly Generation-II type reactors will be the main energy source until about 2020. These will then be gradually replaced by thermal Generation-III reactors (evolutionary pressurized reactor, EPR) starting in 2020 till 2035 and after 2035 by fast reactors (FR) of Generation-IV types as shown in a simplified form in Figure 3.1. Starting in 2080 also Generation-III reactors are retired and gradually replaced till 2095 by Generation-IV type of reactors.

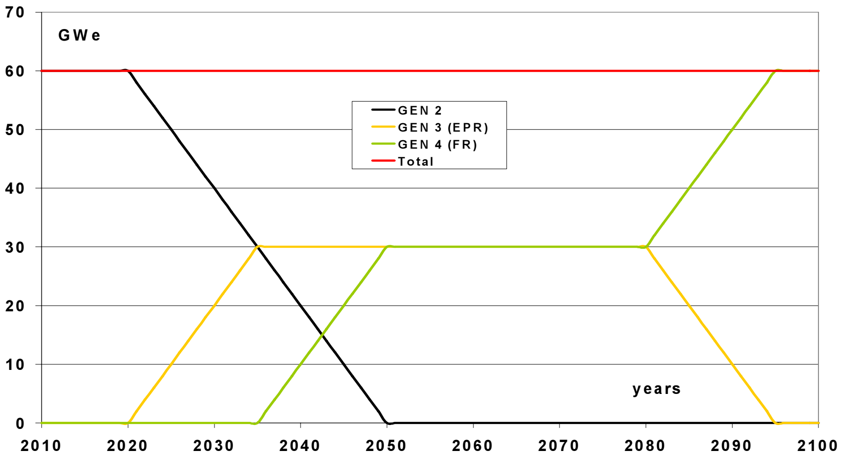

Figure 3.1. Simulated transient nuclear energy system in France [6].

France has a complete national nuclear fuel cycle (with the exception of uranium mining and milling).

In accordance with the objectives of the Joint Study [6] the actual INPRO assessment focused on the Generation-IV system consisting of fast reactors and a closed fuel cycle (as outlined in Section 3.11).

3.6. Nuclear energy system of India

The planned national nuclear energy system foresees an increase of nuclear generation capacity by thermal reactors (PHWR and PWR) to about 26 GW(e) by 2020 (see Figure 2.6 in Section 2.6). Fast breeder reactors (FBR) with 500 MW(e) output each are to be phased in starting around 2010 and should reach about 3 GW(e) in 2020; thereafter a fleet of FBR of 1000 MW(e) capacity are planned to be installed reaching a total capacity of about 260 GW(e) around 2050. In parallel to the FBR advanced PHWR with a thorium fuel cycle are to be introduced. The total nuclear capacity is planned to reach 275 GW(e) in 2050.

In accordance with the objective of the Joint Study [6] the actual INPRO assessment concentrated on the evaluation of the fleet of fast reactors and its associated closed fuel cycle (as outlined in Section 3.11).

In addition to the nuclear energy system presented above, India assessed a separate nuclear scenario [7] with the introduction of high temperature reactors (HTR) dedicated for hydrogen production. These HTR would be used to generate the necessary electricity and heat to produce sufficient amounts of hydrogen to replace about 25% of liquid fossil fuel requirements for transportation. To be able to build up the hydrogen production capacity needed for a country wide introduction of hydrogen for transportation additional nuclear power capacity of 1500 GW_{th} to 2170 GW_{th} would be required. These requirements would be in addition to the nuclear power plants required for electricity generation.

In accordance with the objective of this national study [7] the design of a HTR was assessed focusing on the INPRO area of safety.

3.7. Nuclear energy system of Japan

Total nuclear generation capacity of 58 GW(e) is planned to be kept constant after 2030. The nuclear energy system planned [6] shows a gradual transition from thermal reactors to commercial fast reactors (FR) starting close to 2050. The switchover to a complete FR system occurs around 2110 (see Figure 3.2). There is a complete nuclear fuel cycle (part of it still under development) in the country with the exception of uranium mining, milling, conversion and enrichment.

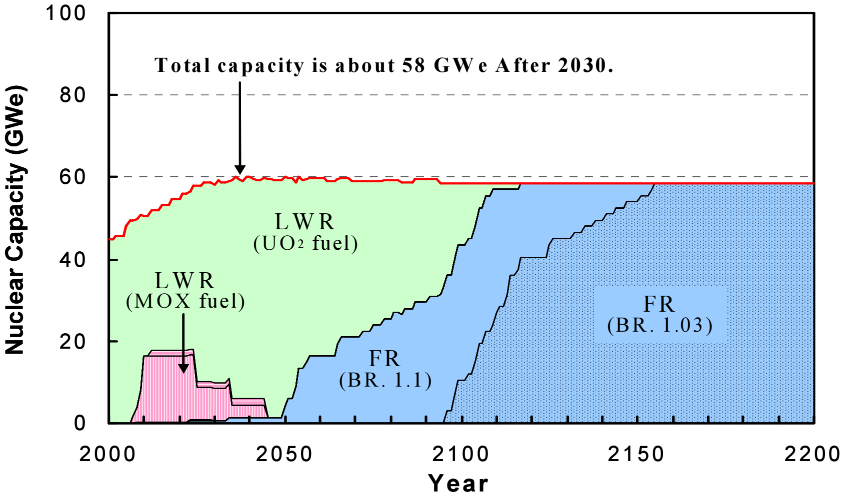

Figure 3.2. Simulated transient nuclear energy system in Japan [6].

In accordance with the objective of the Joint Study [6] the actual INPRO assessment concentrated on the evaluation of the fleet of fast reactors and its associated closed fuel cycle (as outlined in Section 3.11 and Annex 2 of Ref. [6]), which is currently developed as the Fast Reactor Cycle Technology (FaCT) development project in Japan. The Japanese (loop type) sodium-cooled fast reactor (JSFR) with 1500 MW(e) output and a MOX fuel core was chosen as a reference plant, which is also nominated as one of the reference designs of the Generation IV International Forum (GIF). A characteristic of the selected corresponding fuel cycle is a combined recycle plant using an advanced aqueous reprocessing process and a simplified pelletizing process for fuel fabrication with a capacity of 200 t_{HM}/a throughput.

3.8. Nuclear energy system of the Republic of Korea

The role of nuclear power in the 21st century in Republic of Korea was presented in Section 2.8. To satisfy the predicted demand of nuclear power three different scenarios of nuclear energy systems were documented in the Joint Study [6]. The first one, called Case-1, would be a system consisting of PWR and PHWR with no fast reactors (FR). Case-2 and Case -3 assume a replacement of thermal reactors by FR (Kalimer-600) with 600 MW(e) output starting around 2040 as shown in Figure 3.3. Case -2 predicts a gradual replacement of thermal reactors by FR after 2030. For Case-2, total capacity of FR should reach about 21% of total nuclear capacity (60 GW(e)) at the end of the century. Case-3 is an ambitious FR program starting to replace thermal reactors also around 2030 and reaching about 76% of total nuclear capacity by 2100.

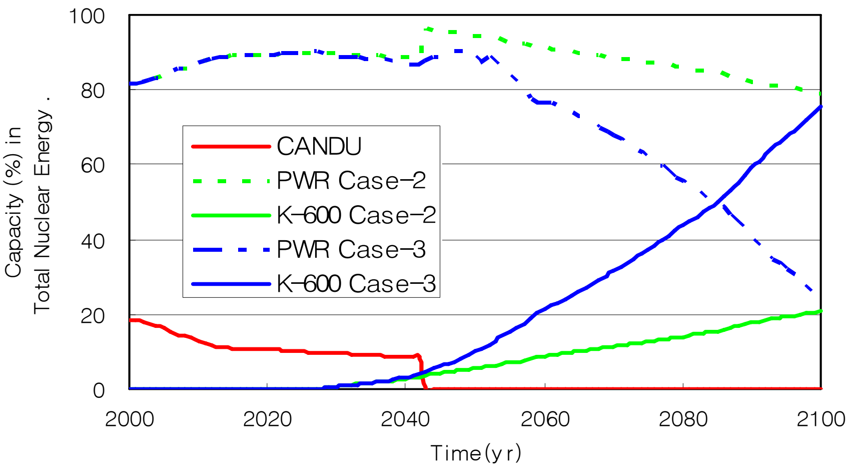

Figure 3.3. Simulated transient nuclear energy system in the Republic of Korea [6]. (K-600=Kalimer-600).

In accordance with the objective of the Joint Study [6] the actual INPRO assessment focused on the evaluation of the fleet of fast reactors and its associated closed fuel cycle (as outlined in Section 3.11).

In addition to the nuclear energy systems presented above within INPRO a study [8] was performed in the Republic of Korea to develop a qualitative analysis method for determining the proliferation resistance (PR) of fuel cycles. This analysis method of PR was applied to the DUPIC fuel cycle where spent PWR fuel is transformed into new fuel for CANDU reactors and was used as a basis for developing the corresponding INPRO assessment method.

3.9. Nuclear energy system of the Russian Federation

The role of nuclear power until the middle of the 21st century was laid out in Section 2.9: from about 22 GW(e) (2005), the installed nuclear capacity should reach about 81 GW(e) by 2050.

Currently, the nuclear energy system in the Russian Federation consists primarily of thermal reactors of type WWER- 440 and type WWER- 1000 plus RBMK[12]. Starting in 2010 a fleet of new Generation III thermal reactors (AES2006) will be added and around 2030 commercial fast reactors (FR) will begin to replace gradually the thermal reactors. Two scenarios are postulated in the Joint Study [6] for the introduction of FR after 2030, a moderate one with installing 1.2 GW(e) additional nuclear capacity per year, and an ambitious one with 3.8 GW(e) added per year. There is a complete nuclear fuel cycle available in the country including all facilities of the front and back end.

In accordance with the objective of the Joint Study [6] the actual INPRO assessment concentrated on the evaluation of the fleet of fast reactors and its associated closed fuel cycle (as outlined in Section 3.11).

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[12] Graphite moderated light water cooled fuel channel reactor.

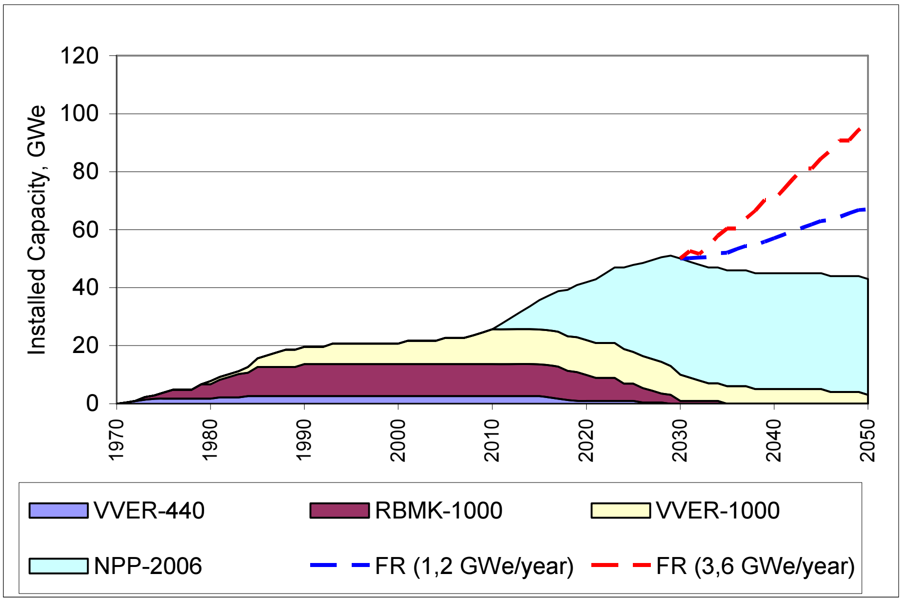

Figure 3.4. Simulated transient nuclear energy system in the Russian Federation [6].

3.10. Nuclear energy system in the Ukraine

The current nuclear energy system [9] consists of reactors of type WWER-440 and WWER-1000. It is planned to keep a constant share of about 50% electricity generated by nuclear power during the 21st century. As stated in Chapter 2.10, the total energy demand is growing and should double between 2006 and 2030. To satisfy this energy demand total capacity of nuclear power is predicted to increase from about 14 GW(e) currently to about 30 GW(e) in 2030. Thus, about 16 new nuclear units (with an average electrical output of 1000 MW(e)) are to be built by 2030 in addition to existing ones, and decommissioned nuclear units are to be replaced by new PWR units.

Within the future nuclear energy system four different types of reactors were considered: WWER-1000/V-392B, WWER-1000/AES-2006, AP1000 and EPR. Two combinations of these four reactor designs were chosen as options for the nuclear energy system to be built till 2030 and 2100, respectively:

- Generation Option-1: two WWER-1000/V-392B, ten EPR by 2030 (plus three more till 2100) and two AP1000 by 2030 (plus 4 more till 2100); and
- Generation Option-2: similar to Option-1 but instead of AP1000 the WWER-1000/AES-2006 was selected.

In addition to looking at different suppliers of the reactors, different options for the front end and the backend of the nuclear fuel cycle were taken into account.

For the front end of the national nuclear energy system three options were selected:

- Front End Option-1; fuel element fabrication starting from imported enriched UF_6;
- Front End Option-2: fuel element fabrication from imported uranium pellets; and
- Front end Option-3: leasing of fuel elements.

Regarding the back end, four options were considered for the national nuclear energy system:

- Back End Option-1 (open fuel cycle): short-term (about 5 years) storage of spent nuclear fuel (SNF) at reactor site, long-term storage (100 years) of SNF in containers in a central national facility and subsequent disposal of SNF in a suitable geological formation in the country;
- Back End Option-2 (closed fuel cycle): short-term (about 5 years) storage of SNF at reactor site, temporary (50 years) storage of SNF in a central national facility in the country, subsequent sending SNF abroad, reprocessing abroad, return of high level waste (HLW) after 50 years from abroad, temporary (50 years) national storage of HLW from reprocessing and final disposal of HLW in the country;
- Back End Option-3 (fuel leasing): the third option is part of a fuel leasing scheme, i.e. the SNF would be returned to the supplier country after some short term storage (about 5 years) at the sites of the reactors and the supplier country would assume ownership and responsibility for the spent fuel; and
- Back End Option-4 (closed fuel cycle): short-term (about 5 years) storage of SNF at reactor site, subsequent sending SNF abroad, reprocessing abroad, return of HLW after 50 years, temporary national storage (50 years) of HLW and final disposal of HLW in the country[13].

All possible options of the front end, the power generation options, and the back end of the fuel cycle are shown in Figure 3.5[14].

In total fourteen (14) different variants (see Table 3.1) of the national nuclear energy system were assessed in the Ukrainian study [9] combining all options of the front end, the generation options and the backend of the fuel cycle.

TABLE 3.1. VARIANTS OF THE NATIONAL NUCLEAR ENERGY SYSTEM (NES) CONSIDERED IN THE UKRAINIAN ASSESSMENT STUDY

NES Variant No.	**Front end Option No.**	**Generation Option No.**	**Back end Option No.**
1	1	1	1
2	1	1	2
3	1	1	4
4	1	2	1
5	1	2	2
6	1	2	4
7	2	1	1
8	2	1	2
9	2	1	4
10	2	2	1
11	2	2	2
12	2	2	4
13	3	1	3
14	3	2	3

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[13] The difference between Back End Option-2 and 4 is the temporary (50 years) storage of spent fuel in a national central facility before sending it to reprocessing abroad.

[14] The ‘options’ are called ‘variants’ in Figure 3.5.

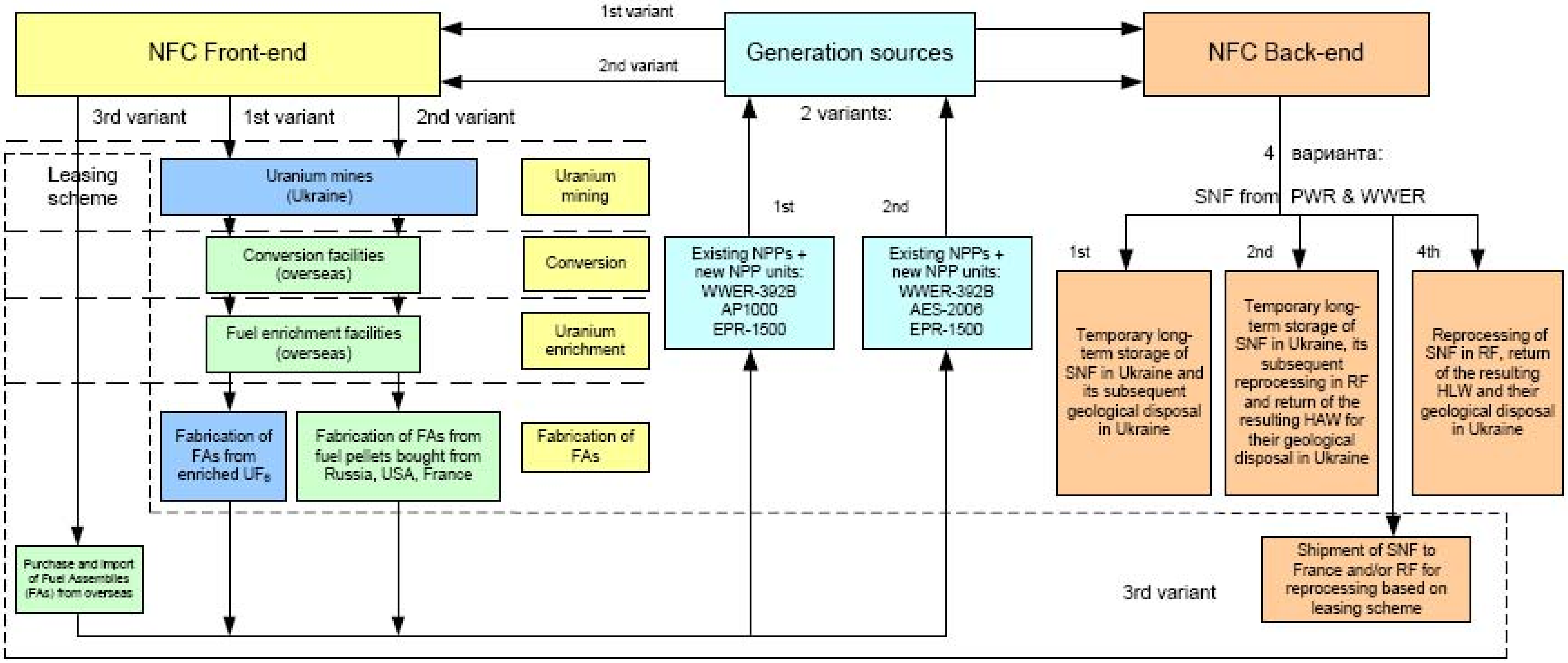

Figure 3.5. Options of Ukrainian nuclear energy system configuration [9]. (WWER=WWER).

To be able to compare the assessment results of individual facilities, of the front end, of the back end and of the different types of nuclear reactors, the assessor applied a simplified aggregation method (similar to the method described in Annex B of Volume 1 of Ref. [1]). Each INPRO criterion that was assessed was assigned a numerical value of 1 if the criterion was fulfilled and a value of 0 if it was not fulfilled. Then the score, i.e. the sum of fulfilled criteria was divided by the total number of criteria assessed resulting in a relative grade of agreement with INPRO requirements for each INPRO area and each facility. Combining facilities to an option of the fuel cycle or generation part of the nuclear energy system the relative grades of agreement were averaged again; and the same procedure was used to generate an average relative score of agreement for the 14 different variants of the complete national nuclear energy system.

In addition to the aggregation method the assessor took the maturity level of each fuel cycle facility and type of reactor into account, assigning numerical values between 0.2 and 1.2, depending on different considerations such as the maturity of development, the location of the facility, and, for domestic facilities, the domestic experience and capability. These maturity levels were directly multiplied with the score of fulfilled INPRO criteria. The consideration of maturity level in the assessment lead, with the exception of the area of economics, to a preference for options with fuel cycle facilities located outside the country, since, in general (not in the INPRO area of proliferation resistance), for these facilities the highest possible score of criteria agreement and maturity levels were selected by the assessor.

3.11. Nuclear energy system of fast reactors with a closed fuel cycle considered in the Joint Study

Within the Joint Study [6], a reference nuclear energy system was defined consisting of fast reactors and co-located fuel cycle facilities. In addition to the reference design some national variants were taken into account as shown in Tables 3.2 and 3.3. For example, most countries who participated in the Joint Study, considered a pool type reactor but Japan assessed a loop type reactor, and several countries based their assessments on MOX fuel but China, India, and Republic of Korea considered metal fuel.

TABLE 3.2. SPECIFICATION OF THE REFERENCE FAST REACTOR (FIRST GENERATION) IN THE JOINT STUDY

Parameter	Reference data	National variant
Power	1000 MW(e)	1500 MW(e) (Japan).
Coolant	Sodium	
Reactor configuration	Pool	Loop (Japan).
Power Plant.	With minimum 2 reactor units.	
Thermal efficiency.	43%	> 39% (Republic of Korea).
Capacity Factor.	85%	
Life.	60 years	
Fuel.	MOX	Metal (China, India, and Republic of Korea).
Construction time.	54 months (from concrete pour to first criticality).	
Breeding Ratio.	1.2	1 (Republic of Korea, France, and Japan).
Minor actinides recycling.	None	Yes (France; as an option: Japan, Russian Federation, Republic of Korea, China, and India.)
Seismicity.	Parametric (depending on region).	
Burnup.	150 GWd/t (average).	120 GWd/t (metal, Republic of Korea).
Specific Steel consumption.	3.5 t/MW(e)	

TABLE 3.3. SPECIFICATION OF COLLOCATED FUEL CYCLE FACILITIES IN THE JOINT STUDY

Parameter	**Reference data**	**National variant**
Fuel Fabrication.	Pellet by powder metallurgy route.	Vibro compaction (Russian Federation), Injection casting (Republic of Korea, China, and India).
Reprocessing.	Advanced aqueous process with Pu loss < 0.05% and minor actinide partitioning. U & Pu oxides to be co-precipitated in co-located and optimized reprocessing, re-fabrication and waste management facility for a number of reactors (variable) in the same site.	Pyro (Russian Federation, Republic of Korea, India, and China).
Cooling time before reprocessing.	4 years.	1 year (China, India, and Republic of Korea).
Solvent used in reprocessing.	Tri-n-Butyl Phosphate or homologue.	
U-Pu separation in reprocessing.	Co-processing with no Pu separation.	
Plant life of reprocessing.	40 years.	
High level waste management.	Glass vitrification.	
High Level Waste (Volume/MW(e)).	To be developed.	

CHAPTER 4.
RESULTS OF THE INPRO ASSESSMENTS

In the INPRO methodology [1] requirements related to a nuclear energy system for seven areas are defined: economics, infrastructure, waste management, proliferation resistance, physical protection, environment, and safety. These requirements are structured in a common hierarchy, the highest level is a *basic principle (BP)*, the next level is a *user requirement (UR),* and the lowest level is a *criterion (CR).* An INPRO BP defines a goal that should be reached via R&D for future designs of nuclear facilities or institutional measures; a UR defines what the main stakeholders in nuclear power, i.e. designer, operator or government, should do to reach the goal defined in the BP, and the CR, consisting of an indicator (IN) and a corresponding acceptance limit (AL), enables the assessor to check whether the main stakeholders have fulfilled the UR addressed to them.

Many of the INPRO assessment studies performed did not cover all seven INPRO areas. Table 4.1 provides, for each study, an overview of the INPRO areas evaluated.

TABLE 4.1. INPRO AREAS COVERED BY ASSESSMENT STUDIES

INPRO areas	**Countries**						
	Argentina	Armenia	Brazil (IRIS, FBNR)	India (HTR)	Rep. of Republic of Korea (DUPIC)	Ukraine	Joint Study (CNFC-FR)
Economics	x	x	x			x	x
Infrastructure	x	x				x	x
Waste Management	x	x				x	x
Proliferation Resistance	x	x	x		x	x	x
Physical Protection	x	x					
Environment	x	x				x	x
Safety of reactors		x	x	x		x	x
Safety of fuel cycle facilities	x					x	x

In the following sections of this chapter, a summary of results is presented separately for each INPRO area for each assessment performed, whether it was of a complete nuclear energy system or selected components thereof.

4.1. Assessment results in the INPRO area of economics

INPRO has developed one basic principle in the area of economics asking for nuclear energy and related products to be affordable and available. The corresponding user requirements demand, firstly, that to be sustainable in a country or region products of nuclear energy (electricity or heat) should be cost competitive with the cost of locally available alternative energy sources (user requirement UR1) such as renewables (hydro, solar, wind, etc.) or fossil plants, and, secondly, that the total investment funds required to design, construct and commission a nuclear energy system can be raised and the risk of investment is acceptable compared to investments into other energy projects (UR2 and UR3). UR4 is directed at technology developers and asks that innovative nuclear energy systems have flexibility to meet requirements of different markets.

4.1.1. Assessment of economics of the Argentine nuclear energy system

As stated in Section 3.1 (Nuclear energy system of Argentina) the planned nuclear capacity is expected to expand to 9800 MW(e) by 2030. In parallel with this expansion, domestic fuel cycle facilities will also be expanded so that for a given fleet of reactors, assumed for purposes of the study, of 4250 MW(e) of capacity will be supported from domestic facilities and 5500 MW(e) of capacity will be supported by imported fuel. The domestic fuel cycle facilities will be brought on line in stages and when complete, in 2024, will comprise mining and milling (600 t_U/a), conversion to UO_2, enrichment (40,000 SWU), fuel rod assembly (600 t_U/a), reprocessing, 120 kg Pu/a, and MOX fuel fabrication (3 t/a).

The economic competitiveness of the proposed fuel cycle facilities was assessed using an economic analysis method adapted from the INPRO methodology, which considered, in the first instance, only the fuel cycle facilities and not the NPPs. For example, the INPRO economic basic principle was modified from

"*Energy and related products and services from innovative nuclear energy systems shall be affordable and available",* to

"The nuclear fuel cycle considered in the innovative nuclear energy systems must be accessible and must be available" and

User Requirement UR1, was modified from

"*The cost of energy from innovative nuclear energy systems, taking all costs and credits into account, C_N , must be competitive with that of alternative energy sources, C_A ,that are available for a given application in the same time frame and region"* to

"The cost of the innovative nuclear energy systems fuel cycle, considering the relevant costs and credits, should be competitive respect to the cost of reference in the same period of evaluation and region."

The economic criteria defined for the modified method were fulfilled and so it was concluded that the proposed fuel cycle facilities had potential to meet the modified economic BP and URs. The conclusions reached were then checked by comparing the cost of electricity from the nuclear power plants (NPP) using fuel from the domestic fuel cycle facilities, with the cost of producing electricity from the same NPP but assuming that they were fueled with imported fuel. It was shown that the cost of electricity produced using fuel from the domestic facilities was cheaper than using imported fuel.

4.1.2. Assessment of economics of the IRIS reactor in Armenia

As stated in Section 3.2 (Nuclear energy system of Armenia) after around 2025 the IRIS reactor is a possible option for installment in the country and was therefore assessed using the INPRO methodology in the area of economics.

The economic competitiveness of installing an IRIS reactor was evaluated in comparison with constructing hydro plants. The capital costs (overnight construction cost plus interest and financing) of IRIS were found to be in the same range as costs for hydro plants in the country, and thus, IRIS will be capable to produce electricity in a competitive way, i.e. fulfilling INPRO economic user requirement UR1[15]. The financial figures of merit related to investing in an IRIS reactor, Internal Rate of return (IRR) and Return of Investment (ROI), were both found to be superior compared with values for investing in a hydro plant, confirming that INPRO user requirement UR2 will be met. Since, at the time of deployment, the IRIS design would be based on proven technology (see also Section 4.7.2), its planned construction time was deemed to be realistic and acceptable, and political support of nuclear power in the long term is assured in the country. Thus, INPRO user requirement UR3 is fulfilled. In summary installment of an IRIS reactor was found to be an economically viable option for Armenia after about 2025.

4.1.3. Assessment of economics of the IRIS reactor in Brazil

As stated in Section 3.3, the Brazilian study focused on the assessment of two small reactors (IRIS and FBNR) as alternative components of a nuclear energy system completed with an open uranium fuel cycle. INPRO methodology was used to evaluate the economic competitiveness of installing three modules of IRIS in comparison to the installation of a large nuclear power plant ANGRA-3, i.e. a reactor similar to the operating nuclear unit ANGRA-2, a 1300 MW(e) PWR.

Based on a detailed evaluation of all INPRO criteria in the area of economics the assessor concluded that the consecutive instalment of three IRIS modules (of 330 MW(e) each) in the country instead of a large nuclear unit of 1300 MW(e) is an economically viable option for Brazil.

4.1.4. Assessment of economics of the Ukrainian variants of a nuclear energy system

All 14 variants (see Table 3.1 of Section 3.10) of the national nuclear energy system were assessed in the area of economics [9]. Because Front End Option-1 (fuel fabrication starting from imported enriched UF_6) and Option-2 (fuel fabrication starting from enriched UO_2 pellets) were found to be equivalent with regard to economic considerations, several variants could be combined, i.e. Variant No.1 with No.7, No.2 with No.8, No.3 with No.9, No.4 with No.10, No.5 with No.11, and No.6 with No.12, thus reducing the number of variants to be assessed to eight (Variant No.13 and 14 remained unchanged).

Regarding the cost of electricity, nuclear energy system Variant No.1 (together with No.7) and Variant No.4 (together with No.10) were found to be most competitive, i.e. showing the lowest costs. The highest production costs are predicted for Variant No.14, closely followed by Variant No.13 (both variants include fuel leasing). The most attractive investment based on general figures of merit (e.g. internal rate of return) was found for Variant No.4 (together with No.10). Considering the risk of investment again Variant No.4 (together with No.10) was found to be the best option.

In summary, Variant No.4 (together with No.10), i.e. an open fuel cycle with production of fuel elements within the country (starting from UF_6 or imported UO_2 pellets), installment of reactors of type WWER-1000/V-392B, EPR and WWER-1000/AES-2006 (instead of AP-1000), and final disposal of SNF in the country was found to be the most economically attractive option for the country (see Figure 4.1).

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[15] Maintenance and fuel costs are not taken into account.

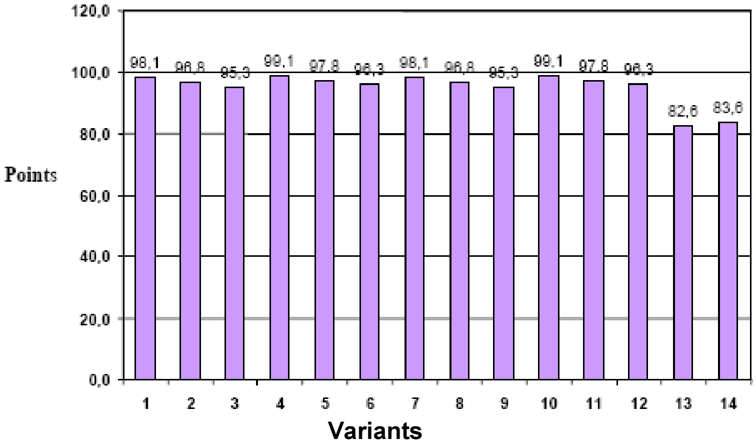

Figure 4.1. Aggregated results of the economic assessment of the 14 variants of the Ukrainian nuclear energy system.

It can be mentioned that the assessor did not perform a comparison of economics of the nuclear option in the country with available alternative national energy sources such as fossil plants (as required by the INPRO methodology in this area to guarantee a sustainable system), but determined the most economically viable variant of a national nuclear energy system in the country.

4.1.5. Assessment of economics of fast reactors with a closed fuel cycle in the Joint Study

Within the Joint Study [6] five of the participating countries with an ongoing development program for fast reactors, i.e. France, India, Japan, Republic of Korea, and the Russian Federation performed a detailed economic INPRO assessment of sodium cooled fast reactors with a closed fuel cycle to be deployed within their national borders. The five assessors evaluated their planned national design of a fast reactor and related fuel cycle system (see Table 3.2 and 3.3 of Section 3.11) and took country or design specific boundary conditions for an economic assessment into account, such as discount rates, construction time, size of output of the fast reactor, cheapest alternative energy source available in the country, etc.

Currently operating systems with sodium-cooled fast reactors and closed fuel cycles cannot compete economically against alternative energy sources including thermal reactors, primarily because of the high upfront investment costs of both the reactor and the fuel cycle facilities. However, the fast reactor and related fuel cycle systems under development promise decisive cost reductions by improvements in the design, such as design simplification, increasing fuel burnup, serial construction, etc. within the next 10 to 20 years.

All planned national nuclear systems with fast reactors and a closed fuel cycle were found to be competitive against the cheapest available national alternative energy source (mostly gas or coal), i.e. they should be capable of producing electricity at an acceptable level of costs, thereby fulfilling the first INPRO economic user requirement UR1.

The ability to finance based on the financial figures of merit (internal rate of return, return of investment, net present value) and availability of national funds was confirmed for all five national fast reactor and related fuel cycle systems, thus, fulfilling the second INPRO economic user requirement UR2.

The risk of investment characterized by the status of licensing, construction schedules, and political environment, and by the robustness of the economical figures against possible changes in boundary conditions was deemed acceptable by all assessors, thereby fulfilling INPRO economic user requirement UR3.

The overall conclusion of the INPRO economic assessment is that a nuclear energy system consisting of a series of fast reactors incorporating improvements to be developed within the next 10 to 20 years will meet INPRO economic basic principle, i.e. the nuclear energy system *will be affordable and available* in 10 to 20 years in the countries mastering this technology.

Economic assessment of the JSFR

As outlined in Section 3.7 (and Annex 2 of Ref. [6]) in the Japanese economic assessment of the FaCT project as an alternative energy source the future Japanese LWR was chosen to be compared to the Japanese sodium cooled fast reactor (JSFR), based on the expectation that the this design will be the strongest competitor to JSFR. The electricity generation costs of the JSFR were found to be lower than the future LWR costs; thus, INPRO economic user requirement UR1 is fulfilled.

Also the evaluated financial figures of merit, i.e. internal rate of return, return on investment, and interest during construction were in favor of the JSFR compared to the future LWR; thus, the JSFR is a more attractive option from the viewpoint of investment, and therefore economic UR2 is fulfilled.

The licensing process of the JSFR is in development and all known regulatory issues are addressed and the corresponding costs included in the project. The construction and commissioning schedules of the JSFR are based on the experience with the construction of the MONJU fast reactor and are therefore realistic; additionally the construction time of the JSFR is comparable to future LWR. The JSFR has sufficient financial robustness, i.e. it is tolerant in regard to future R&D and market uncertainties, i.e. discount rate, construction time and natural uranium price; thus, economic UR3 is fulfilled.

There is a possibility that some of the JSFR components could be transferred to other markets, i.e. the design includes sufficient flexibility to be adapted to different markets; thus, economic UR4 is fulfilled.

The assessment of the JSFR confirmed that all INPRO economic requirements are fulfilled and demonstrated a competitive advantage in comparison to the future LWR in most INPRO economic indicators.

4.2. Assessment results in the INPRO area of infrastructure

INPRO has defined one basic principle (BP) in this area calling for a limitation of the effort necessary for establishing (and maintaining) an adequate infrastructure in a country that intends to install (or maintain) a nuclear energy system. This should be achieved by regional and international arrangements that should be made available to such countries. The corresponding INPRO user requirements (UR) have been specified to ensure that the various factors that need to be taken into account have been evaluated. The UR recognize the need for establishing and maintaining a national legal framework including international obligations, the need to define the necessary industrial and economic infrastructure for a nuclear power program, the need to lay out the appropriate measures to secure public acceptance, and the need to address the availability of adequate human resources. Contrary to all other INPRO areas that, in general, require the designer/developer of a nuclear energy system to perform some activities, in the area of infrastructure the INPRO requirements are directed primarily to the government, the operator of a nuclear facility, and to national industry.

4.2.1. Assessment of infrastructure in the Argentine study

Argentina has had a well established national nuclear infrastructure for a long time. The assessor [2] applied the INPRO methodology to check the adequacy of the national infrastructure with regard to the planned increase of nuclear power (see Section 3.1).

All INPRO criteria of user requirement UR1 (legal and institutional framework) and UR2 (industrial and economic infrastructure) were found to be completely fulfilled. During assessment of infrastructure UR3 (public acceptance) the need for continued and even increased effort was emphasized to maintain public acceptance especially by public information. There are, however, programs initiated to address the issue of communication with the public. In regard to UR4 (human resources) the assessor indicated the need for improvement of the perceived prospects for a professional career in the nuclear field, something that should be achievable in time.

4.2.2. Assessment of infrastructure in the Armenian study

The assessor [3] looked at all INPRO requirements in this area and concluded that the existing and being developed infrastructure is adequate to handle the planned nuclear power program (see Section 3.2) of replacing the existing unit by a larger unit around 2025 and that it covers the associated nuclear waste facilities.

4.2.3. Assessment of infrastructure in the Ukrainian study

The assessor evaluated in a first step all options of the three components of the national nuclear energy system, i.e. the front end, the power generation part and the backend of the nuclear fuel cycle (NFC).

Assessment of infrastructure of the front end of the NFC

Three types of facilities of the front end were assessed in detail using the INPRO methodology: uranium mining/milling, and fuel fabrication starting from imported enriched UF_6 or from imported pellets. Of these three facilities the mining/milling facility (extraction and processing of U-ore) fulfilled 85% of all INPRO criteria. The national facilities for fuel fabrication fulfilled only about 38% and 46% of all INPRO criteria, the better one being the fuel element fabrication facility working with imported pellets (fuel assembly fabrication). The main gaps in fulfilling the INPRO requirements for the two fuel fabrication facilities were found in the area of availability of financing (UR2), policy of information to the public to achieve and maintain public acceptance (UR3), and the availability of personnel to operate these new facilities (UR4). For the mining and milling facilities some gaps in the area of public information and public participation (UR3) were acknowledged. An overview of the assessment results of these three national nuclear facilities for each INPRO user requirement is shown in the following Figure 4.2.

The assessment results of these facilities were combined into the three options of the front end of the fuel cycle with the maturity level of infrastructure for each facility taken into account. Front End Option-1 (includes fuel fabrication starting from imported enriched UF_6) achieves the lowest score in regard to infrastructure, followed by the Front End Option-2 (includes fuel fabrication with imported pellets). Front End Option-3 (fuel leasing) becomes by far the best option, but again due to the treatment of facilities located outside the country, namely assuming highest possible maturity and complete fulfillment of all INPRO requirements for non national facilities.

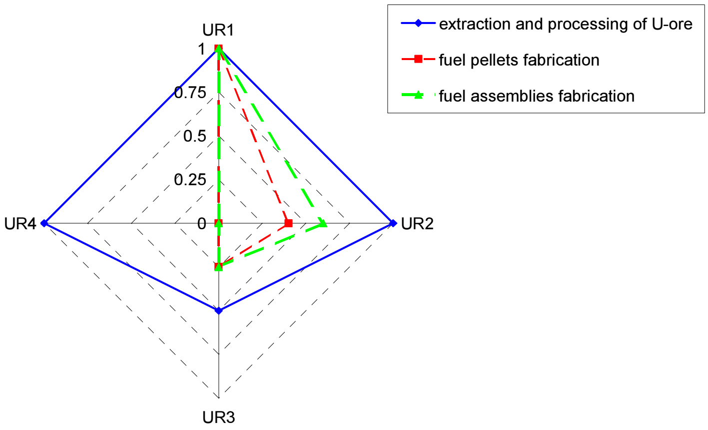

Figure 4.2. Normalized results of the assessment of infrastructure of the front end facilities of the Ukrainian nuclear energy system.

Assessment of infrastructure of the power generation

All four types of reactors considered in the Ukrainian study, i.e. WWER-1000/V-392B, WWER-1000/AES2006, EPR and AP1000 were assessed using the INPRO methodology. The highest total score was achieved for the WWER-1000/V-392B reactor (about 85% of all INPRO criteria fulfilled), followed by WWER-1000/AES2006 (69%) and finally the EPR and the AP1000 with an identical score of 53%. Primarily, non agreements with INPRO criteria were identified for all designs in the area of financing and cost benefit analyses (UR2), and for EPR and AP1000 especially in the area of the support structure needed (UR2) and the availability of human resources for operation (UR4) as shown in the following Figure 4.3.

Taking into account the maturity level of these designs (0.6 for the AES2006, and 0.8 for all the others) and combining the four reactor types into the two options of a reactor fleet in the Ukrainian nuclear energy system (Generation Option-1 with AP1000, and Generation Option-2 with AES2006 instead) no significant differences between the two options were identified.

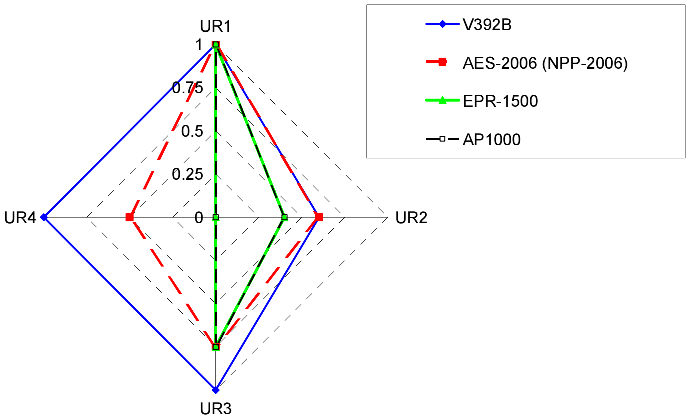

Figure 4.3. Normalized results of the assessment of infrastructure of the reactors considered for the future Ukrainian nuclear energy system.

Assessment of infrastructure of the back end of the NFC

The following elements of the back end of the fuel cycle were assessed separately: storage of spent nuclear fuel (SNF) in three different types of containers, i.e. VCC (ventilated concrete cask), CASTOR and Holtec; and storage of high level waste (HLW) either in containers or in a near surface storage facility. The highest possible score (100%) was achieved for the VCC type container (for storage of SNF) and of the two systems considered for interim storage of HLW, the container system showed a higher score. Thus, for further evaluation, only the superior container option were taken into account. The CASTOR container primarily failed to fulfill INPRO criteria for financing, cost benefit studies (UR2), public information and acceptance (UR3); both CASTOR and Holtec failed in regard to safety culture (UR4). The near surface facility failed to fulfill INPRO criteria for establishment of knowledgeable government organizations (UR1) and for financing (UR2). For transportation of SNF or HLW the same score was assumed of fulfilling the infrastructure requirements as for storage of HLW. An overview of the assessment results of the elements of the back end for each INPRO user requirement is shown in the following Figure 4.4.

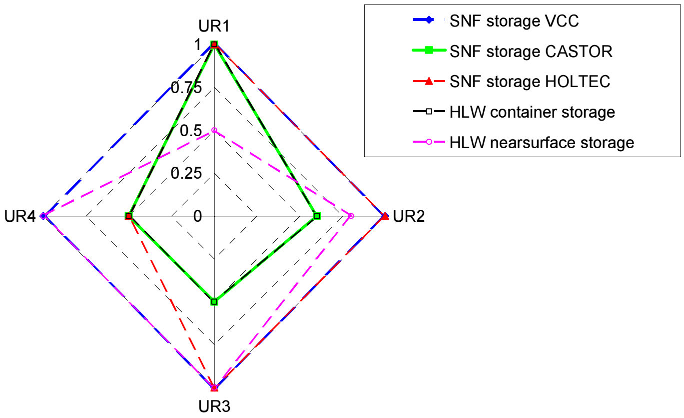

Figure 4.4. Normalized results of assessment of the infrastructure of the elements of the backend of the Ukrainian nuclear energy system.

For the defined four options (see Section 3.10) of the back end the following elements were considered: interim storage of SNF in the country (using the VCC container), reprocessing of SNF outside the country (with the highest possible score), interim storage of HLW in the country (using the container system), and transportation of SNF or HLW. Both Back End Option-1 (open fuel cycle) and 3 (fuel leasing) scored the best results, followed by Back End Option-2 (50 year storage of SNF in the country before transportation abroad for reprocessing) and finally Back End Option-4 (50 year storage of HLW in the country before disposal). The assessment result is influenced by the chosen maturity level of the facilities, i.e. the highest level of maturity is assigned to reprocessing abroad.

Assessment of infrastructure of the variants of a complete Ukrainian nuclear energy system

As outlined in Section 3.10, the different options of the front end, the power generation part and the back end of the Ukrainian fuel cycle were combined to fourteen variants of a possible future nuclear energy system in the Ukraine. The aggregated results for these variants are shown in the following Figure 4.5.

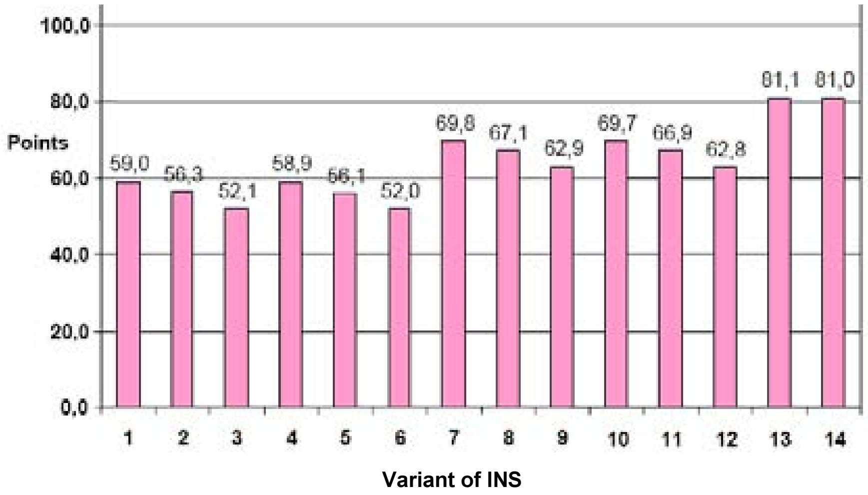

Figure 4.5. Aggregated results of the infrastructure assessment of the 14 variants of the Ukrainian nuclear energy system [9].

As in the other INPRO areas for infrastructure the variants No.13 and 14 (both include fuel leasing) achieved the highest score. This is caused primarily by the treatment of facilities not located in the country, i.e. assigning the highest possible score to such facilities.

To illustrate the influence of taking into account directly the maturity level of elements of the Ukrainian nuclear energy system the following Figure 4.6 is presented.

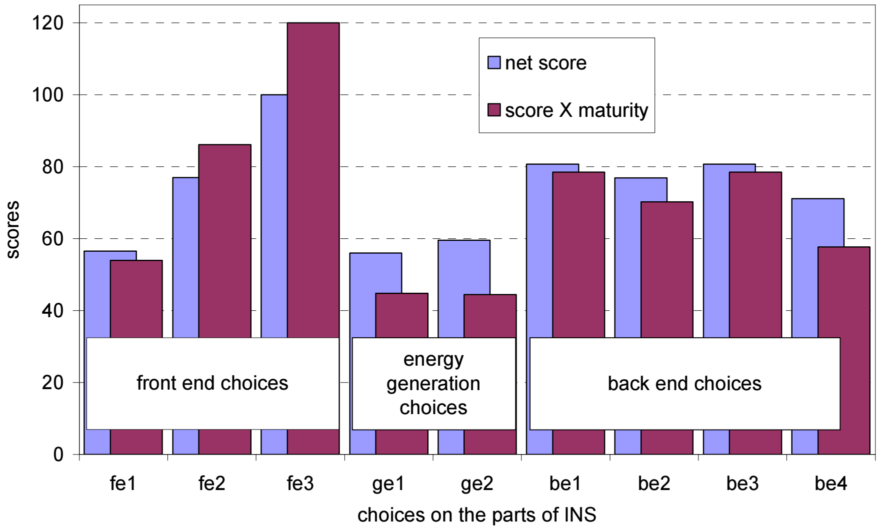

Figure 4.6. Overview of assessment results of the Ukrainian nuclear energy system with and without consideration of the maturity level. (fe1=Front End Option-1, ge1=Generation Option-1, be1=Back End Option-1).

4.2.4. Assessment of infrastructure for fast reactors with a closed fuel cycle in the Joint Study

The participating eight countries of the Joint Study [6], i.e. Canada, China, France, India, Japan, the Republic of Korea, the Russian Federation and Ukraine all have a well established nuclear power program based on thermal reactors and some operate (or will operate soon) prototypes of fast reactors. To successfully operate their nuclear power programs each country has had an adequate infrastructure in place for a long time.

Six of these countries, i.e. China, France, India, Japan, Republic of Korea, and the Russian Federation performed an INPRO assessment of their national infrastructure using the INPRO methodology to check its adequacy also for operating a nuclear energy system with FR and CNFC. Each INPRO criteria was evaluated and full agreement with the acceptance limits was confirmed.

Nevertheless, infrastructure is a critical issue for a nuclear energy system with FR and a CNFC. The survey of the Joint Study has shown complementarity of national conditions that creates prerequisites for mutually beneficial long term collaboration. No single country, taken separately, disposes of the full set of factors favoring development of CNFC a and FR such as high energy demand, high level of nuclear technology and infrastructure maturity, high resources of nuclear fuel, etc. The Joint Study came to the conclusion that the assessed technology is most suitable for realization within a regional or multilateral approach. Such an approach will assure the availability of the corresponding front and backend of fuel cycle services to technology holder as well as to technology user countries within a global nuclear architecture.

4.3.Assessment results in the INPRO area of waste management

The four INPRO basic principles have been derived from the nine IAEA fundamental Principles of Radioactive Waste Management. 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.

4.3.1. Assessment of waste management in Argentina

Argentina already subscribed to the Joint Convention on Safety of Spent Nuclear Fuel and Safety of Radioactive Waste Management in 1997 and has a well established safety regime for radioactive waste treatment.

The assessor evaluated all INPRO criteria in this area and found agreement with almost all of them. Currently, only the safety case for the end state of spent fuel and high level waste in a repository has not been developed but is expected to be available in time. The positive judgment (fulfilling all INPRO requirements) regarding all facilities of the national fuel cycle is mainly based on the fact that most of the facilities are currently operating and licensed by the national regulatory body; the only facility not yet built nor licensed, the reprocessing facility, is planned to use the PUREX process, a well known process licensed in several other countries.

Regarding waste management facilities, the National Atomic Energy Commission is considering a strategic plan for radioactive waste management, which still has to be approved by the corresponding Ministry and by the National Parliament. This plan considers low level waste (LLW), intermediate level waste (ILW) and high level waste (HLW) repositories.

4.3.2. Assessment of waste management in Armenia

The assessment was mainly done on the level of basic principles. The assessor claims that the first basic principle BP1, i.e. minimization of waste, should be primarily covered by the design of the power plant and is, therefore, the responsibility of the supplier; protection of human health and the environment (BP2) is assured by national standards, and undue burdens on future generations (BP3) are avoided by development of a national strategy for spent nuclear fuel and radioactive waste. This national strategy will also cover all aspects of INPRO basic principle BP4.

4.3.3. Assessment of waste management in Ukraine

The assessor, firstly, evaluated each option of the front end, the power generation, and the back end of the fuel cycle separately. Secondly, these options were combined to fourteen different variants of the Ukrainian nuclear energy system as described in Section 3.10.

Assessment of the waste management of the front end of the Ukrainian nuclear energy system

In all three options of the front end of the fuel cycle some non agreements with INPRO criteria were found. Front End Option-1 (fuel fabrication from enriched UF_6) reaches almost the same score of fulfilled INPRO criteria as Front End Option-2 (fuel fabrication from imported pellets). Both options show non agreement with INPRO criteria mainly due to lack of information with regard to availability of necessary resources, time to reach the end state and waste management costs to be included (BP3), and due to absence of a classification scheme of wastes and a process description for the entire life time of the waste cycle (BP4); however, Front End Option-2 is given a higher maturity level and therefore is finally judged as a better option compared with Option-1. Front End Option-3 reaches the highest total score (fulfilling the most INPRO criteria of all three options) but does not reach agreement with INPRO criteria regarding availability of resources and inclusion of waste management costs (UR3) and also in regard to a process description for the entire waste cycle (UR4). This option is also given the highest maturity level of all three options as all facilities of the front end are located outside the country.

An overview of normalized assessment results is shown in the following Figure 4.7.

Assessment of waste management of the power generation part of the Ukrainian nuclear energy system

All types of reactors considered for power generation in Ukraine reached the same score, i.e. 100% agreement with all INPRO criteria in this area. However, the reactor type WWER-1000/AES-2006 was given a lower maturity level and therefore Generation Option-1 with the AP1000 instead of AES-2006 was found to be the better option.

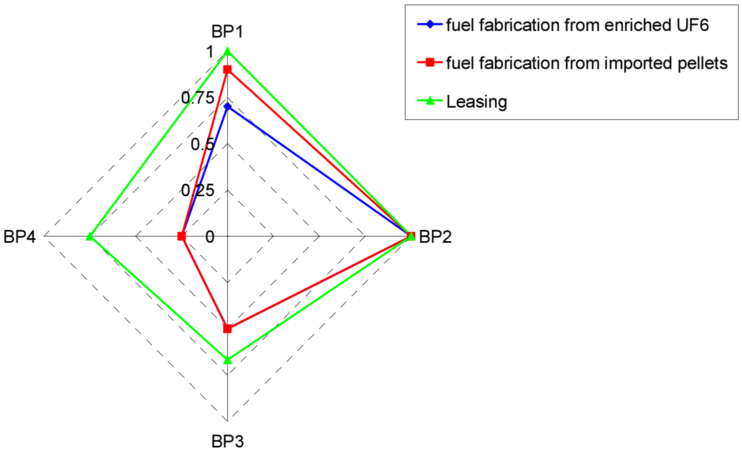

Figure 4.7. Normalized results of the assessment of waste management of front end facilities of the Ukrainian nuclear energy system.

Assessment of waste management of the back end of the Ukrainian nuclear energy system

All four back end options were evaluated by the assessor. The highest score (100%) was reached by Back End Optio-3 (fuel leasing), followed by Option-2 (50 years storage of SNF in the country, reprocessing of SNF abroad, return of HLW after 50 years into the country, 50 years storage of HLW in the country and subsequent final disposal of HLW) and Option-4 (similar as Option-2, but no storage of SNF in the country for 50 years before sending SNF abroad for reprocessing) with the same score (90%), and Option-1 (open fuel cycle, storage and final disposal of SNF in the country) with the lowest score (74%). Both Option-2 and 4 did not reach agreement with INPRO criteria for the time to reach the end state (UR3) and the time to produce waste form for the end state (UR4); Option-1 additionally did not meet the INPRO criterion on reduction of waste at the source (UR1). An overview of the assessment results of all four options of the backend is shown in the following Figure 4.8.

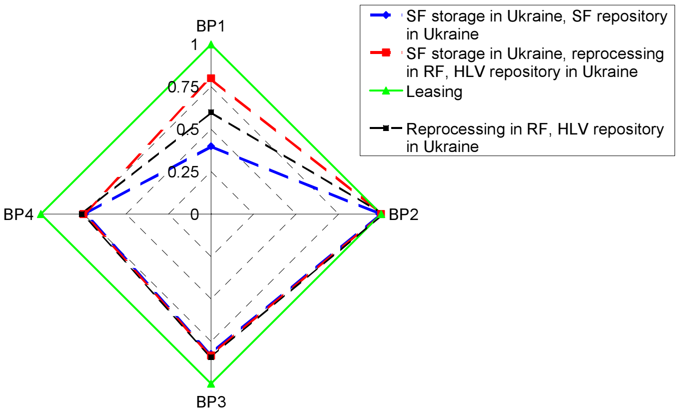

Figure 4.8. Normalized assessment of waste management of the backend of the Ukrainian nuclear energy system.

Assessment of waste management of the complete Ukrainian nuclear energy system

As laid out in Section 3.10, the options of the front end, the power generation and the back end of the fuel cycle were combined to fourteen possible variants of the future nuclear energy system in the Ukraine. The aggregated results of these variants are shown in the following Figure 4.9.

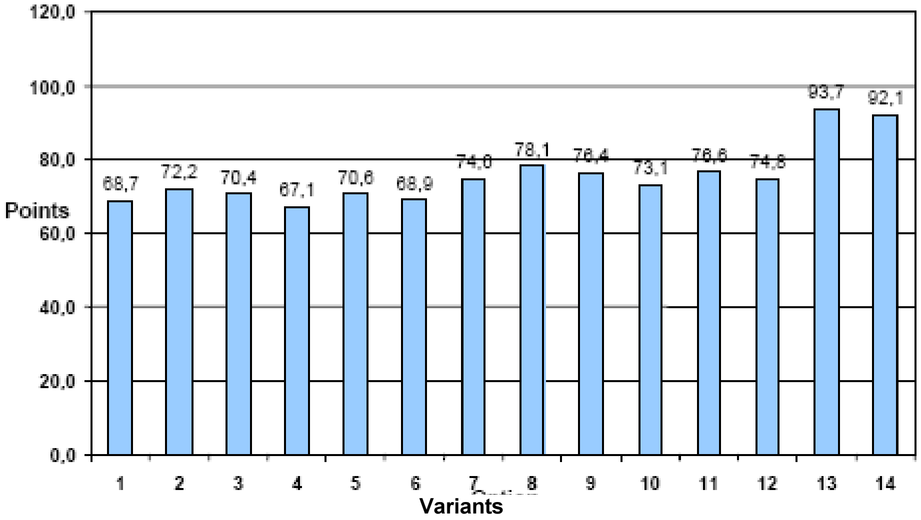

Figure 4.9. Aggregated results of the waste management assessment of the 14 variants of the Ukrainian nuclear energy system.

Variant-13 and Variant-14 (both include fuel leasing) show the highest score due to the favorable treatment of facilities outside the country.

To illustrate the influence of directly taking into account the maturity level of facilities of the Ukrainian nuclear energy system the following Figure 4.10 is presented.

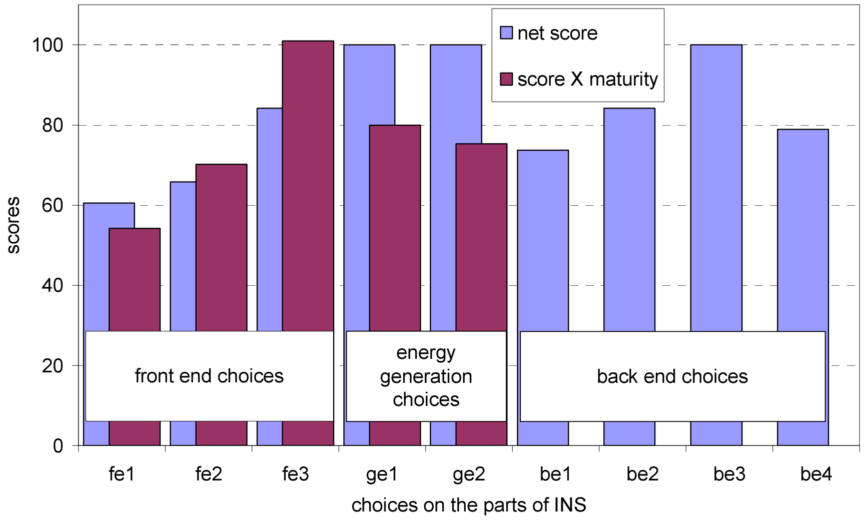

Figure 4.10. Overview of assessment results of the Ukrainian nuclear energy system in the area of waste management with and without consideration of the maturity level. (fe1=Front End Option-1, ge1=Generation Option-1, be1=Back End Option-1).

Figure 4.10 above shows that in case of the power generation part of the nuclear energy system taking into account the maturity the original assessment result of an equal score for both options is changed to a superiority of Generation Option-2. It is also obvious that for the back end facilities the maturity level was not taken into account by the assessor.

4.3.4. Assessment of the waste management of fast reactors with a closed fuel cycle in the Joint Study

In the Joint Study each INPRO basic principle of waste management is evaluated by the assessor.

With regard to INPRO basic principle BP1 (waste minimization by design), a comparison of a light water reactor (LWR) system with an open fuel cycle to a nuclear energy system consisting of fast reactors (FR) with a closed nuclear fuel cycle (CNFC) shows significant advantages of the CNFC-FR system. First of all, a FR is operated at higher temperatures than a LWR resulting in a higher thermal efficiency, thus generating less waste per MW(e) produced. The fast neutron spectrum in a FR offers the potential to use more effectively recycling of fissile material (i.e. Pu) and to apply partitioning and transmutation (P&T) processes in processing spent nuclear fuel to eliminate actinides and long-lived and/or heat generating fission products in nuclear waste.

The following Figure 4.11 illustrates this potential of reduction of radiotoxicity of nuclear waste disposed in a geological depository if actinides are eliminated from waste before disposal. The Figure 4.11 depicts the ratio of radiotoxicity of waste (including spent nuclear fuel, SNF) to the radiotoxicity of natural uranium as a function of time. SNF from an open fuel cycle with enriched uranium operated in a LWR and put into a repository needs several 100000 years to reach an equivalent level of radiotoxicity as natural uranium. Recycling of actinides (plutonium and minor actinides) in a fast reactor system reduces the radiotoxicity dramatically reaching an equivalent level after several 100 years.

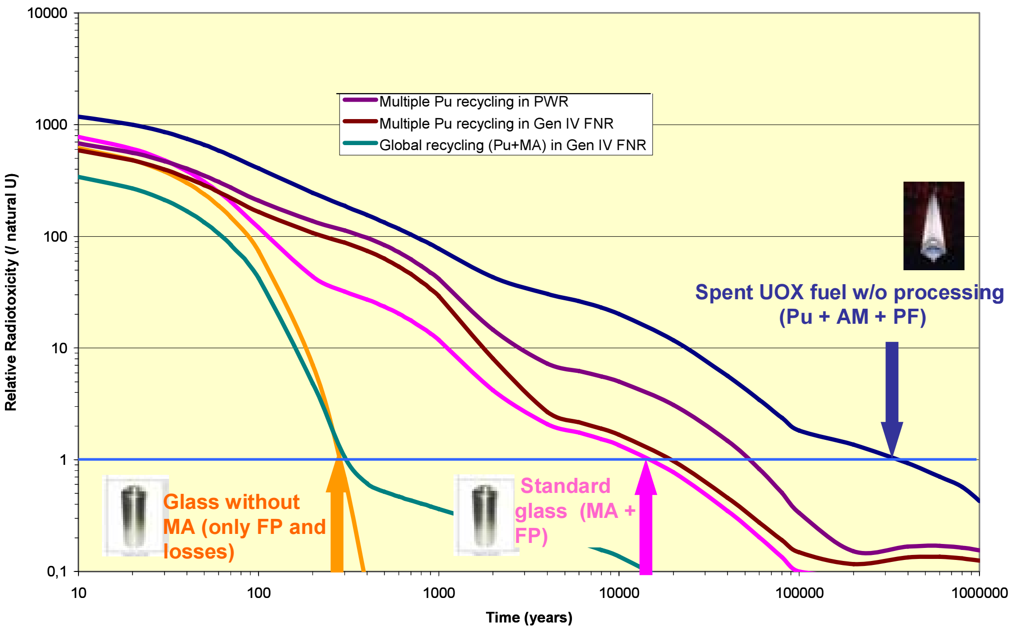

Figure 4.11. Potential radiotoxicity of waste disposed in geological disposal (actinides and fission products) [6]. (AM = MA = minor actinides, PF =FP = fission products, FNR = fast nuclear reactor)

Basic principle BP2 (radiation protection of human health and the environment) is treated primarily in the INPRO area of safety and environment. An example of an inherent feature of sodium cooled fast reactors is the ‘blind’ handling of fuel resulting in very low doses during the performance of such activities.

In regard to INPRO basic principle BP3 (avoidance of burdens on future generations) the assessor claims a very high potential to reduce the radiotoxicity by developing improved partitioning and transmutation processes that should eliminate in addition to actinides also specific fission products from nuclear waste.

The technologies required by INPRO basic principle BP4 (optimization of the waste process) are under development and partially already demonstrated on a non commercial scale.

Assessment of waste management of the Japanese FR development program

Additionally to the evaluation of INPRO area of waste management on the level of basic principles the Joint Study documented the evaluation of waste management on the level of INPRO criteria (in Annex 2 of Ref. [6]) of a nuclear energy system consisting of FR with closed fuel cycle based on the results of the Japanese feasibility study (FS, Phase II final evaluation) on a commercialized fast reactor cycle and the Japanese development program of fast reactor cycle technology called FaCT. All INPRO criteria of all user requirements in the INPRO area of waste management were met by the program.

Regarding INPRO user requirement UR1.1 (reduction of waste at the source) the assessor concluded that a system with FR and CNFC produces less waste than the LWR cycle system currently in operation. User requirements UR2.1 and 2.2 (protection of human health and environment) are fulfilled as all national regulatory standards are met. Resources and sufficient time to develop necessary technologies is available, costs of the development are taken care of thus meeting UR3.1 and UR3.2 (end state of waste and inclusion of development cost). The same classification of waste as for LWR will be used for FR and CNFC system and all intermediate steps of waste management are considered in FaCT, something that is requested by UR4.1 and UR4.2 (classification of waste and intermediate steps of waste management).

4.4. Assessment results in the INPRO area of proliferation resistance

Proliferation resistance (PR) of a nuclear energy system consists of a combination of intrinsic features, i.e. technical design characteristics such as easiness of inspection, and extrinsic measures, i.e. commitments of States such as safeguard agreements. INPRO has produced one basic principle (BP) in this area of PR (Volume 5 of Ref. [1]) that requires intrinsic features to be implemented always together with extrinsic measures in a nuclear energy system throughout the full life cycle. The corresponding INPRO user requirements ask the State to establish and maintain a sufficient legal framework, and the designer to keep the attractiveness of nuclear material (NM) low, make diversion of NM difficult and easy detectable, incorporate multiple barriers, and implement cost effective safeguard measures.

4.4.1. Assessment of proliferation resistance in Argentina

The assessor performed in a first step a detailed analysis to determine the level of proliferation resistance of the planned national fuel cycle facilities to be located at a central fuel cycle facility (FCC). This analysis was performed using the approach described in Annex A of Volume 5 of Ref. [1]. Several evaluation parameters were found in the national fuel cycle that were defined as ‘weak’, i.e. isotopic composition of the spent fuel, operation of enrichment and reprocessing facilities, and absence of an Additional Protocol in force.

In a second step the assessor applied the INPRO assessment method (Chapter 3 in Volume 5 of Ref. [1]) and concluded that although some weaknesses were identified in the Argentine nuclear energy system, they could be compensated by an increased effort of safeguarding and, thus, all INPRO requirements would be met by the national nuclear energy system. He further emphasized that the ‘weaknesses’ found are present in any other nuclear energy system that includes enrichment, reprocessing, PHWR or PWR.

4.4.2. Assessment of proliferation resistance in Armenia

The assessor (Ref. [3]) addressed the first INPRO user requirement in this area, i.e. whether there is a sufficient national legal framework in the country covering all issues related to proliferation resistance. He concluded that there are adequate national laws in place.

4.4.3. Assessment of proliferation resistance of the FBNR in Brazil

The fixed bed nuclear reactor (FNBR) is being developed in Brazil together with other countries. The design of this reactor is at the conceptual level with limited design data available. With regard to proliferation resistance, the key feature of the FBNR design is that under shutdown conditions all fuel elements remain in the fuel chamber where only a single flange needs to be sealed and controlled for safeguard purposes. The assessor evaluated (Ref. [5]) the design data against each INPRO criteria in this area and found full agreement, i.e. no show stopper during the evaluation. He concluded that the FNBR will comply with all requirements in this area.

4.4.4. Assessment of proliferation resistance of the DUPIC fuel cycle in the Republic of Korea

The Korean study (Ref. [8]) was focused on the development of an analysis method to qualify the proliferation resistance (PR) of a nuclear energy system. The INPRO methodology, as documented in Ref. [10], was used as a basis for the development of this analysis method.

To be able to define different levels of PR of components of a nuclear energy system, the assessor utilized, for each INPRO indicator, *evaluation parameter*(s) that could be either logical or numerical. An example of a logical evaluation parameter is the question “Is there a Safeguard agreement pursuant to the Non Proliferation Treaty (NPT) in place?”; an example for a numerical evaluation parameter is the ratio of fissile plutonium to the total amount of plutonium (^{239}Pu/Pu) in the nuclear fuel used in the fuel cycle of a nuclear energy system.

The developed analysis method requires to perform a judgment on these evaluation parameters leading to the following possible results: PR of a specific evaluation parameter can be ‘acceptable’ or ‘unacceptable’ and/or ‘weak’ or ‘strong’, mostly in case of logical parameters (typically associated with a YES or NO answer to a question), and can be, in the case of numerical parameters, within a more detailed scale ‘very weak’, ‘weak’, ‘moderate’, ‘strong’, and ‘very strong’.

To demonstrate the applicability of this analysis method the DUPIC (Direct Use of PWR spent fuel in CANDU reactors) fuel cycle was evaluated. The following Figure 4.12 lays out the concept of the DUPIC fuel cycle. For the analysis the complete DUPIC fuel cycle was broken down into several steps as shown in the following Figure 4.13.

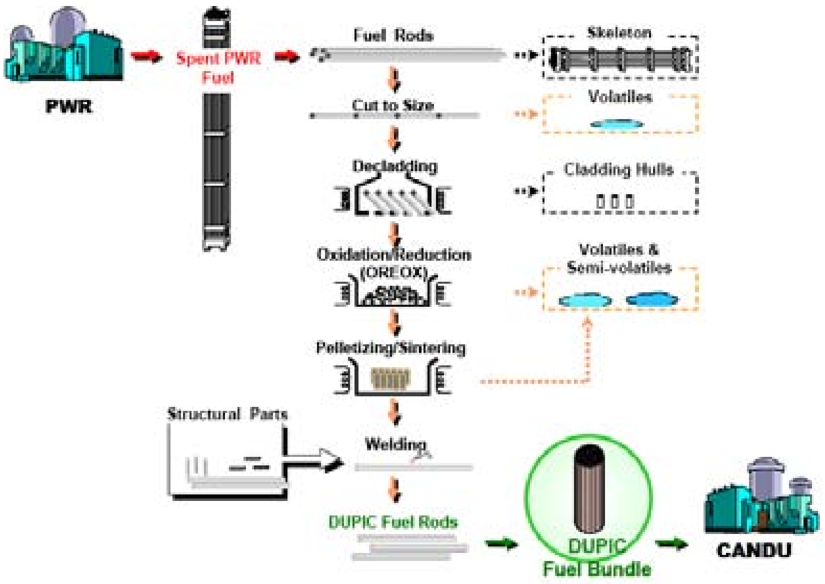

Figure 4.12. Concept of the DUPIC fuel cycle [8].

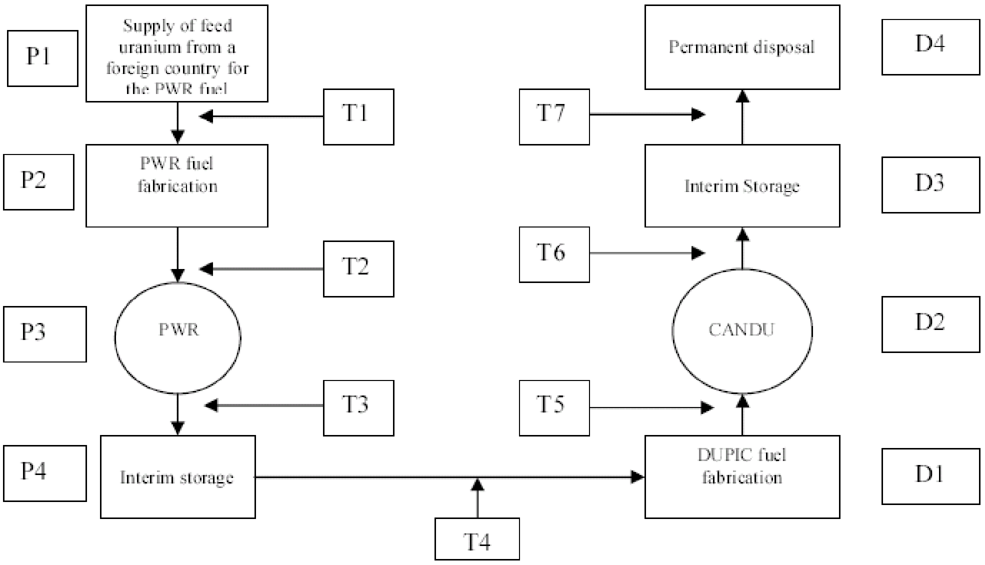

Figure 4.13. Steps of the DUPIC fuel cycle [8]. (P=PWR, T=Transport, D=DUPIC).

Of all steps shown in the above Figure 4.13 the following steps were evaluated in regard to proliferation resistance: P2 (PWR fuel fabrication), P3 (PWR plant), T4 (transportation of PWR SNF to DUPIC fuel fabrication plant), D1 (DUPIC fuel fabrication plant), T4 (transportation of DUPIC fuel to the CANDU plant), D2 (CANDU plant with DUPIC fuel loaded), and D4 (permanent disposal of DUPIC SNF).

In addition to the evaluation of the DUPIC part, the standard nuclear fuel cycle of the CANDU reactor was also considered (not shown in Figure 4.13 above); C1=Natural uranium (NU) fuel production plant, C2=Transportation of NU fuel to the CANDU plant, C3=CANDU plant with NU fuel loaded, C4=Permanent disposal of NU CANDU SNF. The evaluation results of each step (including the NU CANDU fuel cycle) were aggregated as shown in the following Figure 4.14.

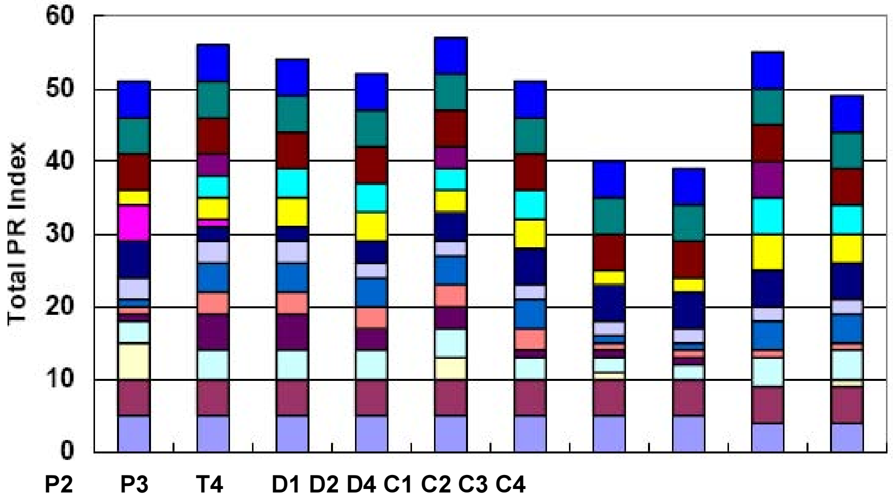

Figure 4.14. Aggregated results of PR evaluation of the DUPIC and the CANDU natural uranium (NU) fuel cycle [8] (P=PWR, T=Transportation of fuel, D=DUPIC fuel cycle, C=NU CANDU fuel cycle).

A higher *Total PR Index* in Figure 4.14 above means a higher level of proliferation resistance. The lowest level of proliferation resistance was found in the steps 'fuel fabrication of NU CANDU fuel (C1)' and 'transportation of NU fuel to the CANDU plant (C2)'. It is also clearly shown that the step 'fuel fabrication of DUPIC fuel (D1)' achieves a higher score than 'fuel fabrication of NU CANDU fuel (C1)'.

The analysis method developed did not include any acceptance limit for evaluation parameters or for INPRO criteria. Therefore no assessment in accordance with the INPRO methodology was performed in this study, but the need for further development of the approach was clearly expressed.

In addition to the development of this qualitative analysis method the INPRO methodology in this area was significantly improved during this study by for instance reducing the number of basic principles as documented in Ref. [11].

4.4.5. Assessment of proliferation resistance of the Ukrainian nuclear energy system

The assessor (Ref. [9]) applied the qualitative evaluation method as described in the previous Section 4.5.4 to determine the level of proliferation resistance (PR) for all components of the Ukrainian nuclear energy system. To aggregate the results each judgment on the level of PR was given a numerical value between 0 and 1; the value of 0 was used in case of an evaluation parameter found to have a 'very weak' or 'unacceptable' level of PR and the value of 1 in case of a 'very strong' or 'acceptable' level. In case the evaluation parameter was assigned an intermediate level of PR, i.e. 'weak' or 'moderate' an intermediate number was chosen like 0.2 or 0.5.

In a first step INPRO user requirement UR1 of PR was evaluated that deals exclusively with the commitments, obligations and policies of the State. The assessor concluded that, practically, all evaluation parameters showed an acceptable level of PR[16], i.e. they were given

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[16] As Ukraine is not part of a nuclear weapon free zone treaty, the assessor defined the INPRO evaluation parameter 'participation in nuclear weapon free zone treaties' as 'non acceptable'. This is most probably a too

a value of 1. The evaluation results of UR1 are valid for all options of components of the Ukrainian nuclear energy system, i.e. this evaluation was not repeated for the different options again.

As a next step all options of the three components, i.e. the front end, the power generation part and the backend (see Section 3.10) of the Ukrainian nuclear energy system were assessed in regard to INPRO user requirement UR2 to UR5 and the corresponding evaluation parameters; contrary to UR1, UR2 to UR5 user requirements are mostly related to the design of nuclear facilities and fuel cycles. For user requirements UR3, UR4 and UR5 also the maturity level of the design was taken into account.

PR assessment of front end options of the Ukrainian nuclear energy system

The normalized results of Front End Option-1 and 2[17] of the Ukrainian nuclear energy system are shown in the following Figure 4.15. A higher value in Figure 4.15 indicates a higher level of PR. The Figure indicates that both front end options practically achieve the same aggregated level of PR, with Front End Option-2 (fuel fabrication from imported pellets) showing in total a slightly higher level of PR compared to Option-1 (fuel fabrication from enriched UF_6). The most favorable option of the front end is Option-3 the fuel leasing option because there is no national facility with a proliferation risk in the country.

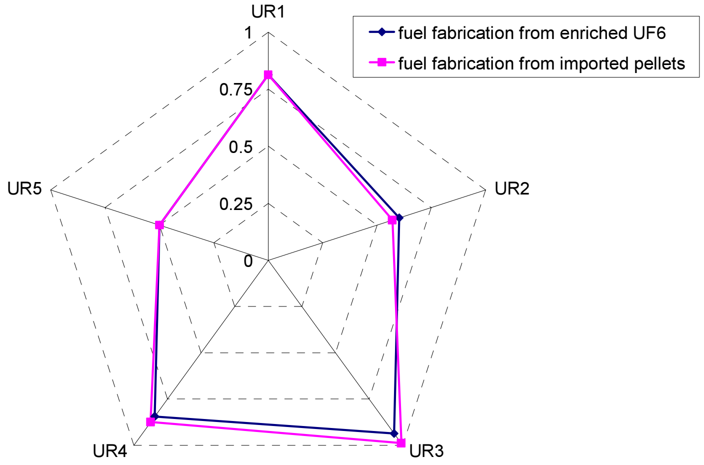

Figure 4.15. Normalized results of the front end options of the Ukrainian nuclear energy system [9].

PR assessment of the options of power generation part of the Ukrainian nuclear energy system

The normalized results of the PR assessment of the two power generation options (Generation Option-1 includes AP1000 in the mix of new reactors to be built, and Generation Option-2 includes AES2006 instead of AP1000) are shown in the following Figure 4.16. Again there is practically no difference in the level of PR between the two options.

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conservative approach; non applicability of this parameter might be a more appropriate solution.

[17] Front End Option-3 with fuel leasing (no national facilities of the front end) is only treated within INPRO user requirement UR1 and therefore not shown in the Figure 4.15.

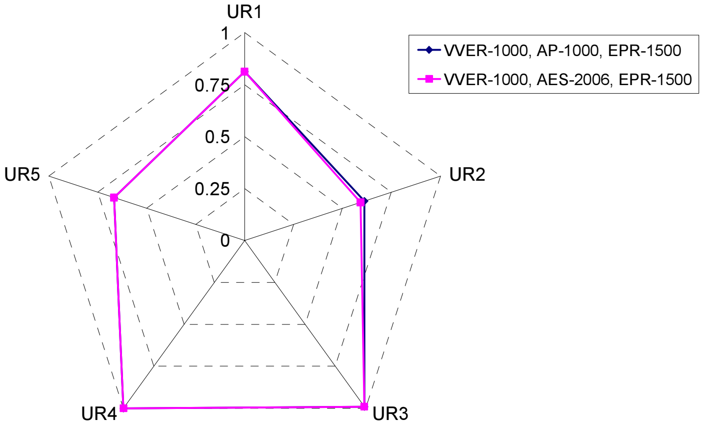

Figure 4.16. Normalized results of the options of power generation part of the Ukrainian nuclear energy system [9].

PR assessment of the options of back end of the Ukrainian nuclear energy system

The normalized results of the PR assessment of the four back end options are shown in the following Figure 4.17. Back End Option-3 with fuel leasing shows the highest score. Again there are only small differences regarding the level of PR among the four back end options.

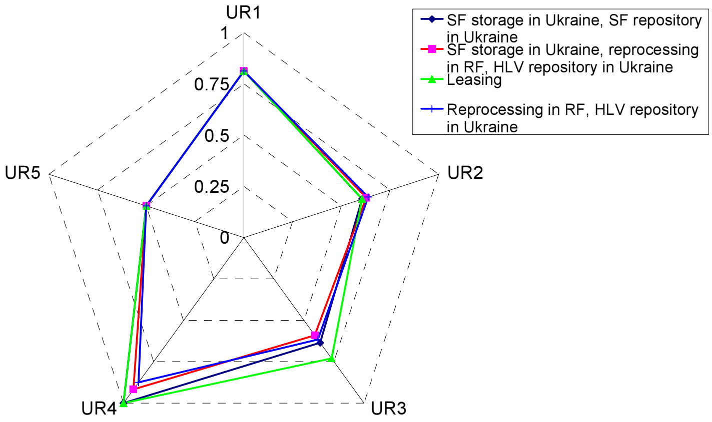

Figure 4.17. Normalized results of the options of back end of the Ukrainian nuclear energy system [9].

Back End Option-2 and 4 have in total the lowest score of PR primarily to the use of a national repository of high level waste in their fuel cycle. As in the case of the front end also for the back end the fuel leasing options shows the most favorable results due to the absence of any back end facility in the country.

PR assessment of the fourteen variants of the complete Ukrainian nuclear energy system

Finally the assessment results of all three components (front end, power generation, backend) were combined to the fourteen possible variants of the future Ukrainian nuclear energy system (see Table 3.1 of Section 3.10) as shown in the following Figure 4.18. A special scale has been chosen to emphasize the rather small differences between the variants in regard to PR. Variant No.13 and No.4 (both with fuel leasing) show the highest score primarily due to the absence of fuel cycle facilities in the country.

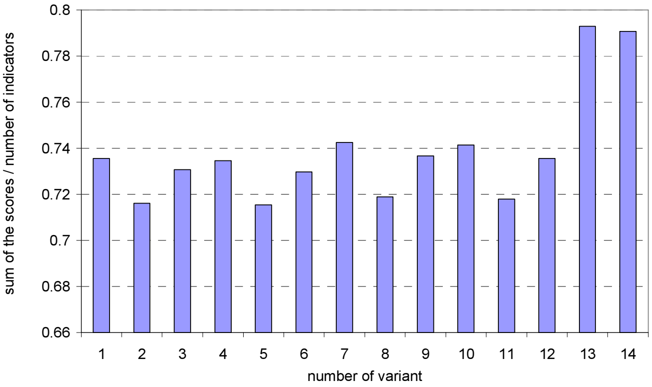

Figure 4.18. Aggregated results of the proliferation resistance assessment of the 14 variants of the Ukrainian nuclear energy system [9].

It is to be emphasized that all variants of nuclear energy system considered were found to be acceptable in regard to proliferation resistance based on the INPRO methodology.

4.4.6. Assessment of proliferation resistance of fast reactors with a closed fuel cycle in the Joint Study

The assessor [6] stated that a fleet of fast reactors (FR) with a closed nuclear fuel cycle (CNFC) will have several features that increase the proliferation resistance in comparison to a system consisting of thermal reactors with an open fuel cycle. First of all such a system will not need enrichment as the fissile material for fresh fuel, i.e. plutonium is produced via transformation (neutron capture) of ^{238}U and made available via reprocessing[18]. Further, to avoid the significant proliferation risk of currently operating reprocessing facilities that produce separated plutonium, the envisaged reprocessing technologies to be used in a CNFC-FR system will always keep uranium and plutonium in a mixture, and additionally certain minor actinides and/or fission products will be added leading to high radiation levels of fresh fuel elements. Reprocessing also reduces the proliferation risk of large quantities of stored and disposed spent nuclear fuel that are currently produced by thermal reactor systems with open fuel cycles.

The Joint Study emphasized the potential key role of multi national fuel cycle centers that could perform reprocessing and fresh fuel fabrication for all countries running fast reactors systems and thereby provide a very high level of proliferation resistance.

Within the Joint Study the Japanese program for developing a nuclear energy system of FR with CNFC (called FaCT) was assessed in detail using the INPRO methodology for this area. All INPRO criteria were found by the assessor to be fulfilled.

4.5. Assessment results in the INPRO area of physical protection

One basic principle has been developed by INPRO in this area asking the state for an effective and efficient implementation of a physical protection regime for the full life cycle of a nuclear energy system. The corresponding twelve user requirements were created with due consideration of the Fundamental Principles of Physical Protection contained in the amended Convention on the Physical Protection of Nuclear material and Facilities.

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[18] Similar arguments could be made for a thorium/uranium cycle.

The INPRO area of physical protection was added to the INPRO methodology late in the project (end of 2006). Thus, this part of the INPRO methodology was not available to most of the assessors during the performance of their assessment study.

4.5.1. Assessment of physical protection in the Argentine study

Argentina has a long history of establishing a security regime in the country for nuclear facilities. Already, in 1988 the Convention on Physical Protection of Nuclear Materials and Facilities was approved in the country and a complete legal framework including the regulatory and related institutions were put in place.

The assessor evaluated each INPRO criterion in this area and found full agreement and provided the rationale for all judgments.

4.5.2. Assessment of physical protection in the Armenian study

Armenia joined the Convention on Physical Protection of Nuclear Materials and Facilities. Related to this convention is a special Armenian government decree defining the strategy of strengthening physical protection and security of nuclear material and power plants in the country.

The assessor concluded that based on these documents all INPRO requirements are fulfilled in this area.

4.6. Assessment results in the INPRO area of environment

In the INPRO area of environment two types of assessment are covered: Firstly, outputs from a nuclear facility, called stressors; examples of stressors are discharges of radionuclides. Secondly, inputs into a nuclear facility that deplete natural resources, such as uranium, zirconium, etc.

Consequently, INPRO has developed two basic principles (BP) in this area. BP1 calls for acceptability of environmental impacts caused by nuclear facilities on humans and the environment and BP2 requires the confirmation of the long term availability and optimized use of material resources needed to operate a nuclear system. The two INPRO user requirements (UR1.1 and UR1.2) corresponding to environmental BP1 ask for environmental stressors, i.e. release and impact of radioactive substances from a nuclear facility, to be within the relevant[19] standards (i.e. national regulatory limits) and the application of the ALARP concept[20]. The first INPRO UR2.1 related to BP2 asks for availability of fissile and fertile materials needed for fabrication of nuclear fuel and of materials needed for construction and operation of nuclear facilities for a period of at least hundred years, and an improved usage of such materials compared to operating nuclear systems in 2004. The second UR2.2 (related to BP2) asks primarily for an adequate energy output in comparison to the energy needed to construct and operate the nuclear system.

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[19] The term ‘relevant’ means at the time of installation of a new nuclear facility.

[20] ALARP means ‘as low as reasonable practicable’. This concept is described in more detail in Section 4.3.2 of Volume 1 of Ref. [1].

4.6.1. Environmental assessment of the Argentine nuclear energy system

As laid out in Section 3.1, in addition to increasing the nuclear capacity to about 9800 MW(e) by about 2030, as part of the future national nuclear energy system, a complete national nuclear fuel cycle will be established. The planned new fuel cycle facilities will have higher capacities than the existing ones of the current nuclear energy system and will be re-located to a new fuel cycle center (FCC) at a new site (the location of the FCC is not decided yet).

The assessor evaluated all INPRO criteria for each facility of the FCC[21], i.e. mining/milling, UO_2 conversion, uranium enrichment, fuel assembly manufacturing, dry spent fuel storage, reprocessing, MOX fuel fabrication, and waste management facilities and found full agreement.

With regard to environmental INPRO user requirement UR1 (controllability of stressors) and UR2 (adverse effects ALARP) the assessed future nuclear energy system shows better or equal results compared with those for the current nuclear energy system in the country. The assessor concentrated on the release of radioactivity as the main stressor and confirmed that the normalized level of stressors (MBq/t_U) of the future nuclear energy system is the same as for the current nuclear energy system, basically, because the same technology will be used in the FCC. The effect of stressors, i.e. the occupational and public doses for the future nuclear energy system, was found to be the same or lower than for the current nuclear energy system because of the use of the same technology. All currently operating facilities of the nuclear fuel cycle are operating with dose rates below the 'Basic Limit' of the ALARP concept and it is expected that the FCC will demonstrate similar behavior.

Regarding INPRO user requirement UR2.1 (consistency with resource availability) the planned capacity of the FCC was found sufficient to support about half (4200 MW(e)) of the planned nuclear energy system (9750 MW(e) total installed capacity till 2030, see Section 3.1) during the lifetime of the nuclear power plants (60 years); the rest of fuel needed for the complete future nuclear energy system is supposed to be delivered from outside the country. In addition to considering the national demand and supply of uranium, the assessor evaluated the global resources of and demand for uranium and found they practically match, especially, because reprocessing and the use of thorium were not taken into account. The global resources of and demand for zirconium, as one of the most critical materials needed for nuclear energy systems, were also studied and sufficiency of this material was confirmed. All other criteria of UR2.1 and UR2.2 (adequate net energy output) were met by the future nuclear energy system.

4.6.2. Environmental assessment of the Armenian nuclear energy system

In the Armenian study [3] only INPRO user requirement UR1.1 (of environmental BP1) was partly evaluated considering the radiation dose on workers in the new nuclear power plant with an IRIS reactor to be built after 2025. The assessment concluded that IRIS would fulfill the corresponding national standard and lead to a significant reduction of this dose compared to occupational radiation exposures in the existing WWER-440 reactor unit during the years 2005 to 2007.

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[21] The nuclear reactors of the future nuclear energy system were not assessed in this INPRO area.

4.6.3. Environmental assessment of the Ukrainian nuclear energy system

Similar to the assessment of safety (see Section 4.1.5) for environmental considerations of the Ukrainian nuclear energy system all different options of the power generation part, the front and the back end of the nuclear fuel cycle, firstly, were evaluated separately, and, finally, the results combined into the 14 possible variants (see Table 3.1 in Section 3.10).

Environmental assessment of reactor designs

With regard to INPRO environmental basic principle BP1, a variety of stressors was taken into account for all types of reactors in the national nuclear energy system (operating units and planned units, i.e. WWER-1000/V-392B, EPR, AP1000 and WWER-1000/AES-2006): release of radio nuclides into the air as aerosols, including iodine and noble gases, and liquid discharge of non radioactive chemicals. The impact of radioactive stressors, i.e. public dose, was calculated for each reactor design.

Regarding environmental basic principle BP2 the study confirmed that sufficient fissile and fertile material for the planned nuclear power program is domestically available in the country till about 2065. No data beyond that date were available to the assessor and also the possibility of using MOX fuel was not taken into account.

The environmental assessment confirmed that all reactor types considered in the national nuclear energy system fulfill all INPRO criteria related to environmental BP1 and BP2. As in the safety assessment for the maturity level of the WWER-1000/AES-2006 design a lower value (0.6 instead of 0.8) was selected in comparison to all other new designs.

As mentioned in Section 3.10, two options were considered for power generation consisting of different combinations of reactor units of type WWER-1000/V-392B, EPR, AP1000 (only in Generation Option-1), and WWER-1000/AES-2006 (only in Generation Option-2).

To produce an integrated result of each generation option the results of individual environmental assessment of each reactor design were aggregated taking into account the number of units of each design, the corresponding public dose and the amount of non radioactive releases, but also the maturity level of each design.

The aggregated environmental result shows an insignificant better value for Generation Option-1 (with some AP1000 units) than for Option-2 (with some WWER-1000/AES-2006 units); however, that is completely caused by the assignment of a higher maturity level to AP1000 compared with WWER-1000/AES-2006.

Environmental assessment of the front end facilities

Within the front end of the national nuclear fuel cycle the following facilities were assessed: The national mining and milling facilities, a national Zirconium production facility, a facility for uranium enrichment located abroad, and two types of national fuel assembly fabrication facilities (FAFF), one starting from imported UF_6 and the other one from imported fuel pellets. The first three facilities were found to completely (100%) fulfill all relevant environmental INPRO criteria, and the maximum maturity level of 1.2 was assigned to all three facilities.

The assessment of the national FAFF producing fuel pellets domestically from UF_6 was based on available data of such a facility located outside the country. Using these data only about

80% of the INPRO criteria were found to be met. A low domestic maturity level of 0.4 was defined for this type of national facility.

The national FAFF starting from imported fuel pellets showed full agreement with all INPRO criteria and was judged to have a domestic maturity level of 0.6.

In the case of leasing the fuel assemblies from a supplier outside the country the highest possible score (100%) of agreement with INPRO criteria and the maximum maturity level (1.2), i.e. the lowest environmental impact was assumed by the assessor, due to the absence of fuel assembly fabrication facilities in the country.

As outlined in Section 3.10, three options of the front end of the Ukrainian fuel cycle were considered in the study. All three options contain the national mining and milling and the national zirconium production facility, and also the enrichment facility located abroad. Front End Option-1 includes a fuel assembly production facility starting from UF_6, Front End Option-2 includes also a fuel assembly production facility however starting with imported fuel pellets, and Front End Option-3 is the fuel leasing option, i.e. importing the complete fuel assemblies.

The aggregated score of the environmental assessment of these three options showed a clear superiority of Front End Option-3 (fuel leasing), followed by Front End Option-2 (imported pellets) and the worst result for Front End Option-1 (domestically produced fuel pellets). The result is mainly caused by the numerical treatment of facilities located outside the country and the assigned different maturity level of facilities.

Environmental assessment of the back end facilities

The following elements of the back end of the national fuel cycle were evaluated in regard to their environmental impact: transportation of spent nuclear fuel (SNF), temporary storage of SNF in a national facility, reprocessing of SNF outside the country, temporary storage of HLW (produced during reprocessing) in national facility, and final disposal of HLW and/or SNF in national depository.

Of these six elements, three elements were assessed in detail using the INPRO methodology: transportation of SNF, the national facility for temporary storage of SNF, and the national facility for temporary storage of HLW. All three elements achieved a 100% score, i.e. they fulfilled all relevant INPRO criteria. However, different domestic maturity levels were assigned to the three elements: the maximum value of 1.2 for transportation of SNF, 0.8 for temporary storage of SNF, and 0.6 for temporary storage of HLW in the country.

The reprocessing facility being located outside the country was assumed to fulfill also all INPRO environmental requirements with the maximum level of maturity (1.2). The facilities for final disposal of SNF or HLW were not included into the numerical assessment primarily due to lack of available data.

As stated in Section 3.10 for the back end of nuclear fuel cycle the assessor chose four options based on the six elements discussed above. As all individual elements considered in the environmental assessment achieved a 100% score, i.e. they fulfilled all relevant INPRO criteria, differences in the four back end options are exclusively based on the assigned maturity levels of the elements. The highest aggregated score was found for Back End Option-3, the fuel leasing option with no back end facilities in the country, and the lowest score for Back End Option-2 with the highest number of national back end facilities including temporary storage of SNF in the country before reprocessing abroad and temporary national storage of HLW. Again the result is caused by the assigned levels of maturity and the favorable treatment of facilities located outside the country.

Environmental assessment of the complete Ukrainian nuclear energy system

The assessor combined the different options of the front end, the power generation part and the back end of the fuel cycle into 14 possible variants of the future Ukrainian nuclear energy system (see Section 3.10). The following Figure 4.19 shows the aggregated results for all 14 variants. The two variants based on leasing of fuel show the highest score in regard to environmental aspects, which, as has been explained above, is caused by the treatment of maturity levels and of facilities located outside the country.

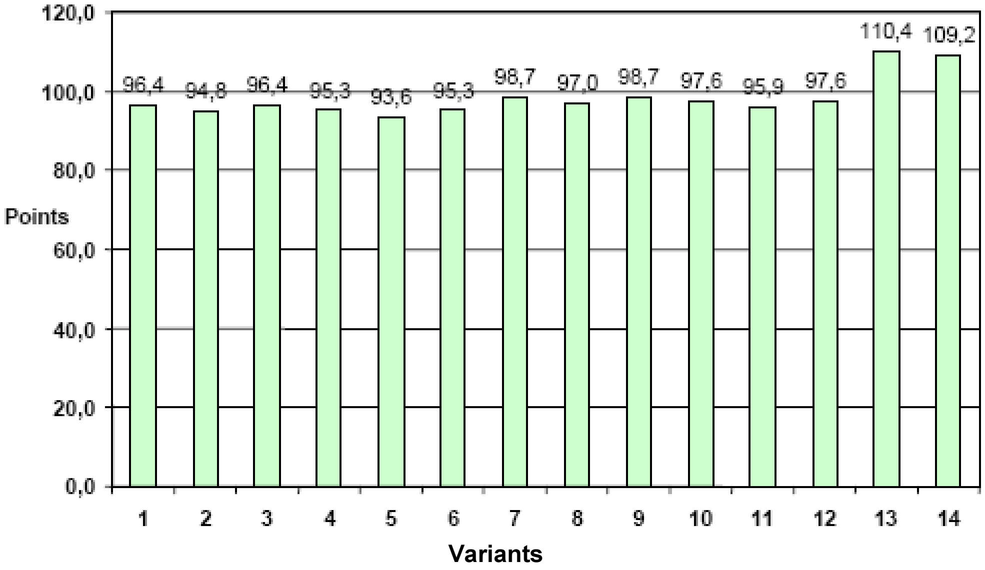

Figure 4.19. Aggregated results of the environmental assessment of the 14 variants of the Ukrainian future nuclear energy system.

4.6.4. Environmental assessment of fast reactors with a closed fuel cycle in the Joint Study

Six different nuclear energy systems were analyzed with a constant power output of 60 GW(e) during the 21st century; the first five nuclear energy systems are 'steady state' scenarios and No.6 is a dynamic scenario. The six nuclear energy systems (NES) evaluated were:

- No.1: PWR fleet with UOX fuel with an open fuel cycle (spent nuclear fuel sent to repository);
- No.2: PWR fleet, with spent UOX fuel reprocessing, vitrification of fission products (FP) and minor actinides (MA), and Pu 'mono'-recycling (spent MOX fuel sent to interim storage);
- No.3: PWR fleet, with reprocessing of all spent UOX and MOX fuel, Pu recycling in MOX assemblies, and vitrification of FP and MA. At equilibrium, the fleet is composed of 74% of UOX loaded PWR, and of 26% of MOX loaded PWR;

- No.4: Mixed fleet with 45% of PWR, 55% of fast reactors (FR) recycling Pu and incinerating 90% of americium in transmutation targets. Neptunium and curium are vitrified with FP;

- No.5: FR fleet recycling all MA together with plutonium (fully closed cycle). Only FP are vitrified; and

- No.6: A reactor fleet starting from a pure PWR fleet at the beginning of the 21st century, after 2020 PWR are gradually replaced by EPR and after 2035 by FR (see Figure 4.20), and becomes a pure FR fleet at the end of the 21st century.

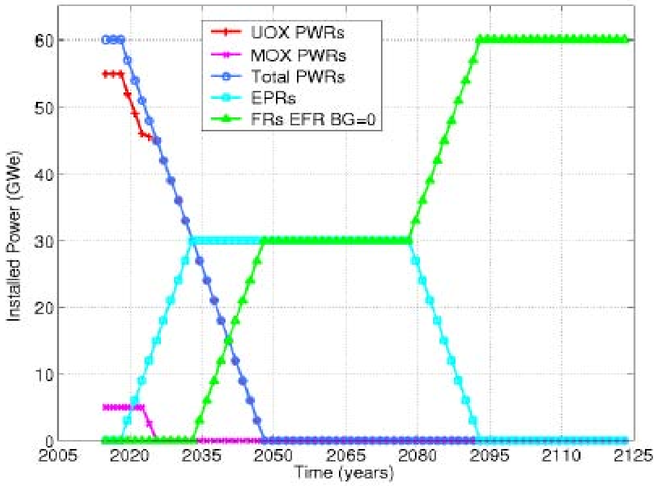

Figure 4.20. Dynamic nuclear energy system No. 6 analyzed in the Joint Study [6].

For these six nuclear energy systems three types of analysis were performed determining several environmentally significant parameters:

- A neutronic calculation using the COSI computer code of the amount (per TWh_e produced) of Pu, Am and Cm sent to waste, number and volume of spent fuel assemblies, volume of vitrified and compacted waste sent to interim storage and final disposal;

- A life cycle analysis (LCA) using the TEAM software determining the consumption (per TWh_e produced) of natural uranium, but also of oil, gas and coal, the equivalent tons of CO_2 produced, and emissions of CO_2, CH_4, N_2O, NO_x, SO_x, and particles; and

- A calculation of dose (mSv per year) for all facilities of the nuclear fuel cycle, i.e. mining/milling, conversion, enrichment, UOX and MOX production, power plants, reprocessing, low level waste storage, interim storage, and high level waste disposal.

The evaluation of the calculated parameters demonstrates that in comparison to an open fuel cycle (Nuclear energy system NES No.1) mono recycling of Pu (as in NES No.2) reduces the amount of Pu/Am/Cm to be put in final disposal by a factor of 1.5, and multi recycling (as in NES No.3) by a factor of 4. All other parameters, i.e. consumption of natural uranium of NES No.2 and NES No.3 are very close.

The most promising results are achieved for NES No.5, i.e. FR with full Pu and MA recycling. For example, the amount of Pu/Am/Cm to be put in final disposal is reduced by a factor of about 200 in comparison to the open fuel cycle of NES No.1. NES No.4 shows (non-surprisingly) an intermediate position between NES No.3 and No.5.

The analysis results of the dynamic NES (nuclear energy system No.6) confirm the results achieved for the 'steady state' scenarios (NES No.1 to No.5).

Based on the analyses above the assessment concluded that all NES evaluated are clearly fulfilling the INPRO environmental basic principle BP1 (acceptability of expected adverse environmental effects). It was further stated that in regard to basic principle BP2 (resource sustainability) NES No.5 with FR and a closed fuel cycle is the optimal solution, and that such an energy system could be called a *de facto* a renewable one.

Environmental assessment of the Japanese FaCT project

As outlined in Annex 2 of Ref. [6] the FaCT project was evaluated using the INPRO methodology for an environmental assessment on a criterion level referring also to the results of the feasibility study (FS) on commercialized fast reactor cycle (Phase II final evaluation).

To confirm the controllability of environmental stressors the key nuclides from the viewpoint of radiological impact on the public were evaluated. The effective dose rates were calculated taking into account these key radioactive nuclides released from both the reactor and the fuel cycle facilities at an assumed specific site. As the calculated dose rates were lower than the applicable standards INPRO environmental user requirement UR1.1 is fulfilled.

To optimize the adverse effects of radioactive emissions for the FaCT project the ALARA (as low as reasonable achievable) concept will be applied that is deemed to be comparable to the ALARP (as low as reasonable practicable) concept asked by INPRO user requirement UR1.2.

In regard to the consistency of resource availability based on a global assessment of demand and resources of uranium it was confirmed that the Japanese nuclear energy system based on FaCT will be able to contribute to the world's energy needs during the 21st century without running out of fissile or fertile material; thus, UR2.1 is fulfilled.

4.7. Assessment results in the INPRO area of nuclear safety

INPRO has developed four basic principles (BP) in the area of nuclear safety based on the IAEA Fundamental Safety Principles (SF1), utility requirements such as EPRI Advanced Light Water Reactor Utility Requirements, and on an extrapolation of current trends assuming a large increase of nuclear power in the 21st century.

BP1 calls for an enhanced application of the concept of defense in depth (DID) with more independence of different levels of protection in the DID strategy. The corresponding user requirements (UR) provide recommendations how the designer/developer can achieve a higher safety level compared to that reference design by intensified use of the DID concept in each of its five levels.

BP2 and the corresponding UR ask the designer – when appropriate – to consider the increased use of passive systems and inherent safety features to eliminate or at least minimize hazards.

BP3 sets a high level goal by requesting the designer to reduce the risk level from nuclear facilities due to radiation exposure to workers and to the public so that this nuclear risk is comparable to the level of risks arising from facilities of other industries with a similar purpose.

BP4 and its user requirements ask for a sufficient level of R&D to be performed for new nuclear designs to bring the knowledge of plant characteristics and the capability of analytical tools to at least the same confidence level as for existing (end of 2004) and well proven designs.

BP1, and also BP2 and BP4, are evaluated primarily by comparing the facility being assessed with a reference design, i.e. a nuclear facility operating end of 2004.

4.7.1. Argentine assessment of safety of nuclear fuel cycle facilities

The INPRO assessment [2] was performed for all nuclear fuel cycle (NFC) facilities[22] currently in operation in the country (i.e. mining/milling, conversion, fuel fabrication and spent fuel storage) and also for a commercial enrichment and reprocessing plant. An enrichment pilot plant has been operated in the past, and Argentina has experience with reprocessing at laboratory scale.

All nuclear facilities, i.e. the operating and the planned ones, were evaluated considering all INPRO criteria in the area of safety. The result is that all of them are judged to have potential to fulfill all INPRO requirements in this area, i.e. all acceptance limits of all INPRO criteria can be met. For the operating facilities the justification of this judgment is mainly based on the existing license (issued by the national nuclear license authority) and corresponding safety related documentation of these facilities (i.e. the final safety analysis report, FSAR), and for the planned enrichment and reprocessing facility on the chosen technology and already performed safety analyses.

4.7.2. Armenian assessment of safety of the IRIS reactor

In this safety evaluation of the IRIS reactor design a general justification was presented by the assessor [3] that all INPRO requirements in the area of safety should be fulfilled because this innovative design is a type Generation-III+ reactor[23]. Additionally, some features of the IRIS design were emphasized that clearly demonstrate an improved safety level compared to the currently operating reactor, i.e. the use of several passive safety systems, PRA results with significant lower probabilities of core damage and major release of radioactivity to the environment after severe accidents, reduction of frequency of initiating events by a concept called ‘safety by design’, etc.

Nevertheless, the assessor as a technology user with limited nuclear experience concluded that to become a real candidate for installment in the country (after 2025) an IRIS reactor should be built outside the country and operated for several years to achieve the status of proven technology.

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[22] The operating and planned new reactors were not assessed but only treated as consumers of fuel and producers of waste.

[23] Generation-III+ is a classification of reactor designs developed by the Generation IV International Forum (GIF), an international initiative lead by the USDOE.

4.7.3. *Brazilian assessment of safety of the IRIS and FBNR reactor*

The safety of two reactor designs, developed with Brazilian participation and with different levels of maturity, was assessed [5]: the innovative design of the IRIS reactor (same as in the Armenian study) that is in a pre-licensing stage, and the Fixed Bed Nuclear Reactor (FBNR) that is in a conceptual stage of development.

For both reactor designs as a reference reactor ANGRA-2 was chosen, i.e. a 1300 MW(e) PWR operating since 2001 in Brazil. All INPRO safety criteria were assessed for both types of reactors.

IRIS is a medium sized (300 MW(e)) integral[24] PWR derived from proven light water technology with innovative features such as passive systems. For IRIS all INPRO safety criteria were found to show either full agreement or at least potential, i.e. agreement will most probably be achieved after some additional experimental or analytical effort already defined. In comparison to the reference reactor ANGRA-2 the IRIS design demonstrated an improved level of safety.

FBNR is a small innovative PWR (70 MW(e)) design without the need for onsite refueling. The assessor claims that the FBNR design has a potential to reach a level of total safety as the law of gravity and heat convection governs its inherent safety characteristics. The core consists of spherical fuel elements held at their axial position by the coolant flow. The coolant pump is normally in ‘off’ position and turns ‘on’ only when all the safety signals are simultaneously met. Under any conceivable accident scenario, the spherical fuel elements fall out of the core down into a fuel chamber where they remain under passively cooled and sub-critical conditions. For the FBNR design also all INPRO safety criteria were found to be in agreement or at least to show potential; i.e. no show stopper was found at this early stage of development. The FBNR design has potential to reach a higher level of safety compared with the reference design of ANGRA-2.

For both reactor designs a comprehensive list of R&D mostly related to safety was presented in the study (see Chapter 6).

4.7.4. *Indian assessment of safety of a HTR reactor*

The assessor [7] evaluated the concept of a high temperature reactor (HTR, 600 MW_{th}) to be installed as energy source primarily for large scale hydrogen production and using reject heat for drinking water and electricity production. Hydrogen was assumed to replace about 25% of fossil liquid fuel requirements for transportation in the country in the future. The reactor is designed to use molten lead or molten salt as a coolant with an outlet temperature of 1000 C, graphite as a moderator and reflector, and TRISO[25] fuel particles either in a pebble bed or in prismatic block configuration with a closed thorium fuel cycle.

Due to the preliminary or conceptual stage of development of the HTR design, the INPRO safety assessment basically resulted in the definition of necessary further R&D to be performed (discussed in Chapter 6). However, even at this early stage of development significant potential for an increased level of safety compared to existing designs was claimed due to specific design features of the chosen HTR concept, such as passive heat removal

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[24] Integral design: pressurizer, steam generators, main coolant pumps and control rod drives are inside the reactor pressure vessel.

[25] Tristructural isotropic.

systems based on natural convection, low power density, inherent safety features due to use of molten lead/salt coolant and TRISO coated fuel particles. The co-location of a hydrogen plant with the HTR – especially, in the case when heat is needed for the hydrogen production process – was found to require specific measures to assure the safe operation of both plants.

4.7.5. Ukrainian assessment of safety of variants of the national nuclear energy system

The assessor looked at various options to extend the existing nuclear power program in the country, i.e. at different reactors designs and different combinations of nuclear fuel cycle facilities of the front and back end of the fuel cycle (as already outlined in Section 3.10).

Safety assessment of reactor designs

Four types of new *reactor designs* were assessed using the INPRO methodology in the area of safety: WWER-1000/V-392B, EPR, AP1000 and WWER-1000/AES2006. For all 4 new designs, the WWER-1000/V-320 was chosen as a reference reactor.

The assessor chose to evaluate the first three[26] INPRO basic principles BP of safety. The assessment shows that all four new designs comply with all INPRO criteria of these three basic principles, although, for some designs, complete information was not available to the assessor.

To be able to compare the four new reactor designs the assessment results were aggregated: each INPRO safety criterion fulfilled was given a value of 1 (and in case of non agreement the value of 0). At the end of the assessment the number of fulfilled criteria was summed. As all four new designs fulfilled all INPRO safety criteria they got the same score, i.e. from the point of view of safety they were found to be equivalent.

However, the assessor took also into account the maturity level of each reactor design, assigning a numerical value for maturity of 0,6 to the WWER-1000/AES-2006 design and 0,8 to the other two new designs, i.e. defining a lower level of maturity to the WWER-1000/AES-2006 design in comparison to the other two designs evaluated. The maturity level (0.6 or 0.8) was multiplied by the score of fulfilled safety criteria for each design, thus resulting in a less favorable judgment on the safety level of the AES-2006 design.

As presented in Section 3.10 (Figure 3.6) above the three new reactor designs were combined in two power generation options consisting of several units of type WWER-1000/V-392B, EPR and either AP1000 (Generation Option-1) or WWER-1000/AES-2006 (Generation Option-2). The overall average score of 80% of fulfillment of INPRO safety requirements (Generation Option-1) and 75.3% (Generation Option-2) of these two options was determined by taking into account the amount of power output and its planned number of installations of each reactor type. As mentioned before the lower relative level of safety associated with Generation Option-2 of the national nuclear energy system is exclusively based on the lower maturity level assumed for the AES-2006 reactor design.

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[26] Basic principle No.4 of the INPRO area of safety dealing with necessary R&D to develop a new nuclear facility was not assessed as Ukraine is a technology user and not a technology developer country and the assessor did not have access to relevant data.

Safety assessment of the front end of the fuel cycle

Within the national nuclear fuel cycle the following *nuclear facilities of the front end* were assessed with regard to the INPRO area of safety: The national mining/milling facility (in operation) and two consecutive steps of a planned nuclear fuel element fabrication process, the first one being the manufacture of fuel pellets starting from imported enriched UF_6 and the second one production of complete fuel elements, i.e. manufacturing of fuel rods and fuel element structure and assembling them into fuel elements.

Similar to the assessment of reactor design for nuclear fuel cycle facilities, also the INPRO safety basic principles one, two and three were evaluated. The operating national mining and milling facility was found to fulfill all INPRO criteria of safety and assigned the highest level of maturity, i.e. expressed by a factor of 1.2. Of the two processes assessed for fuel fabrication, the first one, producing pellets in the country from UF_6, fulfilled all but three INPRO safety criteria (one criterion asking for an expected frequency of DBA of $< 10^{-6}$ per plant year, the second one asking for an expected frequency of a major release of radioactivity to the environment of $< 10^{-6}$ per plant year, and the third one asking for a reduction of frequency of abnormal operation) and was assigned a maturity level of 0.6. The second process for fuel fabrication, i.e. the production of complete fuel elements in the country using imported pellets, was found to fulfill all INPRO criteria of safety and got a maturity level of 0.8.

For the front end of the fuel cycle (as described in Section 3.10) in addition to the existing national mining and milling facility three possible combinations of facilities of the front end (called Front End Options) were selected: The first one has the highest national participation, i.e. with pellet production and complete fuel element production in the country (Front End Option-1), the second one includes importing the pellets from abroad and producing the complete fuel element in the country (Front End Option-2), and finally the third option considers the supply of fuel elements to Ukrainian power plants by a supplier from outside the country and lease of this fuel (Front End Option-3). The lowest total score was found for the first option, followed by the second option. Fabrication of pellets or complete fuel elements outside the country was assumed to be designed and performed completely in agreement with INPRO requirements and therefore given the highest possible score in the area of safety with the highest level of maturity (1.2). Thus, the third option (leasing of fuel elements) of the front end was found to achieve the highest score in the area of safety, but again (similar as for the reactor designs) primarily due to the assigned levels of maturity to each facility.

Safety assessment of the back end of the fuel cycle

Of the *back end of the national fuel cycle* the following components were assessed: Transportation of spent nuclear fuel (SNF), fuel reprocessing, temporary storage of SNF in containers, temporary storage of high level waste (HLW) in containers or in near surface facilities (concrete reinforced), and final disposal of SNF (open fuel cycle) and of HLW (from reprocessing in a closed fuel cycle) in adequate geological formations.

Assessing the safety of transportation of SNF in the country the assessor concluded – based on existing long term experience – that for this component radiation risk for worker's or public health is negligible, i.e. all safety requirements are fulfilled. A similar conclusion was drawn for final disposal of SNF or HLW in a geological depository. As reprocessing was assumed to be performed outside the country this component was found not to pose any risk to the public in the Ukraine.

Safety issues of temporary storage of SNF and HLW was studied in more detail. Firstly, three different containers for temporary dry storage of spent nuclear fuel (SNF) were compared, i.e. VCC, Castor and Holtec[27]. The safety assessment showed that the Castor design reached the highest score, i.e. fulfilled more of the INPRO safety criteria than the two other designs and was therefore selected for further considerations.

Secondly, two options of temporary storage of HLW (returned from reprocessing of SNF) in the country were assessed, one using containers (similar to Castor) and the other one a near surface facility with reinforced concrete casks. The option with containers resulted in a higher score (partly due to a higher level of maturity), i.e. it fulfilled a higher number of INPRO safety criteria and was therefore chosen for further considerations.

For the back end four combinations of facilities were assessed (as already mentioned in Section 3.10): The first option represents an open fuel cycle strategy (Back End Option-1), i.e. temporary storage of SNF (100 years) and final disposal of SNF in a geological depository; the second option is a closed fuel cycle strategy with temporary (50 years) storage of SNF in the country, reprocessing outside the country, return of HLW after 50 years, temporary storage of HLW for 50 years and then final disposal of HLW in a geological depository (Back End Option-2); the third option is part of the fuel leasing scheme (Back End Option-3); the forth option is the same as the second option but avoiding temporary (50 years) storage of SNF in the country (Back End Option-4) and sending the SNF shortly (3years) after unloading for reprocessing abroad.

The highest safety score was found for Back End Option-3, the leasing scheme, followed by Back End Option-2 and then Back End Option-1; Back End Option-4 got the lowest score. The reason for Back End Option-3 achieving the highest score is the fact that no back end facility would be located in the country and therefore no radiation risk would be associated with the back end of the fuel cycle in the country. The lowest score (or highest radiation risk) achieved by Back End Option-4 is caused by inclusion of temporary (50 years) storage of HLW (returned from reprocessing outside the country) in a national facility within the 21st century, something that occurs in Back End Option-2 too but was neglected in the study because it happens later in the 22nd century (the time frame was set in the study till the end of the 21st century).

Safety assessment of the complete nuclear energy system

As already mentioned in Section 3.10 (Table 3.1), the different options of the front end, the generation units, and the back end of the fuel cycle discussed above have been combined by the assessor to 14 different variants of a national nuclear energy system. The outcome of this aggregation of results is shown in the following Figure 4.21.

Figure 4.21 shows that Variant 13 and 14 achieved the highest score in regard to safety; both variants include a leasing scheme for fuel supply from a foreign supplier, thus, no front end (with the exception of a mining and milling facility) or back end facility would be located within the country. The reason for this result is that facilities outside the country were given by the assessor the highest possible score in the area of safety.

This treatment of nuclear fuel cycle facilities outside the country and outside the time frame considered (end of 21st century) chosen by the assessor will be discussed further in Chapter 5.

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[27] VCC is a Russian design, CASTOR is a German design and Holtec is a U.S. design of a container.

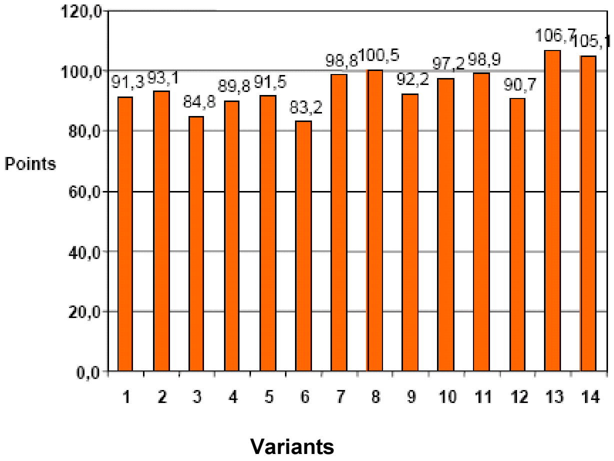

Figure 4.21. Aggregated results of the safety assessment of the 14 variants of the Ukrainian nuclear energy system.

4.7.6. Assessment of nuclear safety of fast reactors with a closed fuel cycle in the Joint Study

Within the Joint Study [6], China, France, India, Japan, and the Russian federation performed an INPRO assessment of the safety of a *fast reactor design*. However, each country looked at its national design that doesn't concur with the chosen reference design of a fast reactor presented in Section 3.11. It was noted that the existing experience with the operation of FR is that personnel working in such units receive low doses. One reason for the low radiation doses is the blind handling of spent nuclear fuel in a sodium cooled reactor, i.e. spent fuel is always covered or shielded by sodium and not visible to the operator.

China looked at their conceptual design of the CFR-1000. This design is characterized by a pool type concept, use of sodium as coolant, provision of small reactivity margins, core with low power density, decay heat removal by natural convection, and a passive shut down system. A qualitative assessment of INPRO safety user requirement UR1.1 (increased robustness of design) was performed.

France assessed the safety of their complete nuclear energy system, i.e. the next generation of PWR to be installed, the EPR (Generation-III+) as well as their designs of fast reactors – sodium or gas cooled – under development. The design of the EPR was found to fully comply with practically all INPRO requirements in the area of safety. The French concept of the fast sodium cooled reactor (SFR) is characterized by an improved (compared to an existing design like the European Fast Reactor) core design with a decreased sodium void coefficient. Also the shut down and decay heat removal systems have been further developed and a core catcher integrated into the design to retain molten core material after a hypothetical severe accident. The assessor concluded that the safety of their fast reactors will at least be comparable to the EPR design.

India performed an assessment of safety of their fast reactor concept, however, no details of the results are provided in Ref. [6].

A complete assessment of safety of the *Japanese* sodium cooled fast reactor (JSFR) using the INPRO methodology (at the criterion level) was performed. This detailed assessment, which is described in Annex 2 of Ref. [6], confirmed that the JSFR design does (or is expected to) fulfill all INPRO criteria in this area. The assessor concluded that the design of JSFR is sufficiently robust, i.e. simple and with enough design margins and that by the inclusion of passive and inherent safety features into the JSFR design an adequate safety level is achieved.

By the *Russian Federation* the BN fast reactor design was assessed in regard to safety, however no details of the results are provided in Ref. [6].

Safety of *fuel cycle facilities* was addressed within the Joint Study by *India* primarily. A detailed description of all safety issues related to the operation of facilities of the front end and back end of a closed nuclear fuel cycle (connected to a fast reactor fleet) is provided in the study but no specific results of an INPRO assessment of safety are presented in Ref. [6].

4.8. Assessment of the complete nuclear energy system in all INPRO areas

Among all INPRO assessment studies performed, only the Ukrainian study [9] aggregated the results of each INPRO area into an overall assessment result for each variant.

The following Figure 4.22 shows the overall results for the fourteen variants of the Ukrainian nuclear energy system. Clearly, Variant No.13 and No.14 achieve the highest score, i.e. the variants using the option of fuel leasing seem to be the most attractive based on the holistic INPRO assessment.

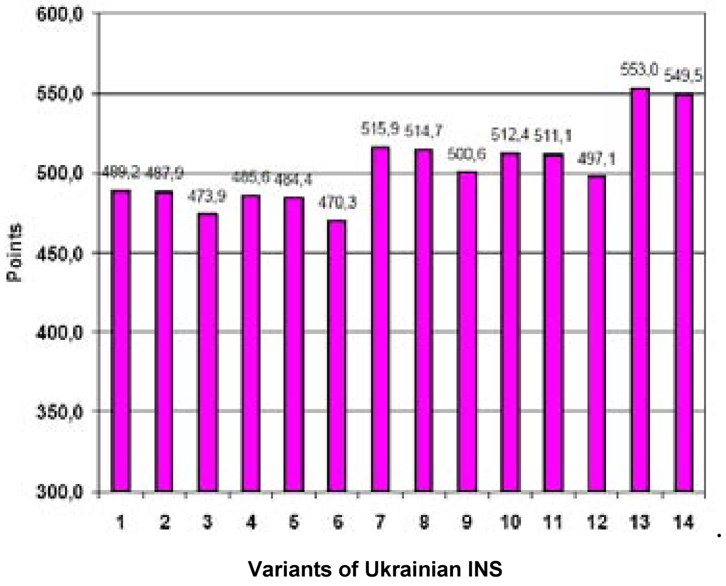

Figure 4.22. Final numerical score of the variants of the Ukrainian nuclear energy system. (Note: Graph shows score above 300 points).

Only slightly worse than Variant No.13 and No.14 are Variants No.7, No.8, No.10 and No.11 (see Section 3.10 for detailed description of the variants); the last 4 Variants all include Front End Option-2 (fuel element fabrication from imported pellets) and either Back End Option-1 (open fuel cycle) or Option-2 (closed fuel cycle with temporary storage of SNF in the country before reprocessing abroad).

The integrated rankings of the fourteen variants are primarily based on the treatment of fuel cycle facilities not located inside the country because, as discussed in Section 3.10, facilities located outside the country are given the highest possible score in each INPRO area, with the exception of economics, and also the highest level of maturity.

CHAPTER 5.
PROPOSALS FOR R&D AND FOLLOW UP ACTIONS

If an assessor using the INPRO methodology finds a gap (non agreement) with an INPRO criterion in the nuclear energy system assessed, he is expected, depending on whether he is a technology user or developer (see Figure 2.1 in Chapter 2), either to modify his nuclear energy system, i.e. replace a component of his nuclear energy system, or to define necessary R&D and/or follow up actions to bring the nuclear energy system in full agreement with all INPRO criteria. These proposals for R&D or other follow up actions could lead to joint action by interested Member States, such as INPRO Collaborative Projects. Several such projects have already been initiated within INPRO.

The following sections summarize the follow-up actions including the R&D proposals from the six national INPRO assessment studies (Refs [2], [3], [5], [7], [8], and [9]) and the international study called Joint Study [6].

5.1. Argentina

As outlined before, the Argentine assessment study [2] looked at all facilities of a complete national fuel cycle assessing all INPRO areas. The assessor defined R&D for several INPRO areas as outlined in the following.

Infrastructure

The assessor stressed the point that public acceptance of nuclear power must be gained in countries embarking on a nuclear power program and kept in all countries with established programs. He further claimed that most probably this issue is not completely solved in any nuclear country of the world and proposed to study all phenomena associated with public perception of nuclear power in multidisciplinary groups in different countries of the world.

Waste management

The facilities for final disposal of low level radioactive waste (LLW), intermediate level waste (ILW) and high level waste (HLW) are in the conceptual design stage in the country. To ensure an adequate design fulfilling all INPRO criteria in this area several relevant R&D projects are ongoing initiated by the government; some examples are laid out in the following:

- long term behavior of engineering barriers in depositories of ILW including bio corrosion of concrete;
- corrosion of containers for HLW; and
- modeling of systems for final disposition of radioactive waste.

Proliferation resistance

The confidence in nuclear related international treaties should be improved by developing an appropriate legal framework.

Technical tools are to be developed further to ensure total control against the diversion of nuclear material, such as: Accountability and control systems, remote monitoring, and systems based on knowledge of reprocessing and enrichment processes that allow the control of input and output of such facilities.

Environment

The priority of R&D efforts should be to minimize the generation of stressors at the source.

Safety of nuclear fuel cycle facilities

The National Atomic Energy Commission should develop guidelines for use of probabilistic safety analysis for different nuclear fuel cycle facilities.

5.2. Armenia

The Armenian study [3] looked at the installation of an additional nuclear power plant in the country and covered all INPRO areas.

In this study no specific non-agreements with INPRO requirements were identified in the assessed national nuclear energy system. However, a detailed list of requests to potential suppliers of the nuclear power plant to the country was defined. Examples are laid out in the following.

The supplier is requested to take into account the existing national infrastructure to the maximum extent possible to optimize the necessary and possible national contribution to the planned nuclear power program. The goal is to utilize existing national capabilities, i.e. for civil works, manufacturing of conventional components, etc., in the first installation of an additional nuclear power plant and further increase these capabilities by relevant training and know how transfer to enable, for example, the performance of maintenance and repair of operating plants with national resources.

The reactor should be designed to allow the use of different suppliers of nuclear fuel and critical components. The supplier should consider transportation to the planned sites of all big components of the plant, i.e. reactor vessel, steam generators, etc., i.e. take into account limitations of national railways, roads, bridges and tunnels.

Guidance for establishment of a safe and sustainable waste management program is requested by the country, especially, for the treatment of spent fuel.

Armenia initiated an INPRO collaborative project (called **SMALL**) that will deal with issues of nuclear energy in small countries.

5.3. Brazil

In the Brazilian study [5] two specific reactor designs that have been (and are being) developed in the country were assessed in selected INPRO areas, the IRIS reactor in the area of economics and safety, and the FBNR in regard safety and proliferation resistance.

The long list of necessary R&D topics presented in the study for the two types of reactors assessed, is however not based on the INPRO assessment, but on evaluations of IRIS performed within the program of Generation-IV International Forum in 2002, and on the existing development program of FBNR. The listed R&D safety related issues of IRIS were, however, correlated with INPRO criteria for reactor safety.

5.4. India

The Indian study looked at a nuclear energy system with high temperature reactors (HTR) coupled to hydrogen plants. Hydrogen could be used to replace organic fuel for transportation in the future.

The assessor provided a list of specific R&D topics related to the development of HTR designs. Several of these specific topics were integrated into INPRO Collaborative Projects (CP) during the assessment studies:

- Properties of primary coolants for a HTR, i.e. heavy liquid metal and molten salt; to be covered in the INPRO CP called **COOL**;
- Passive safety systems of HTR; to be covered in the INPRO CP called **PGAP**; and
- Safety issues of collocation of a nuclear power plant and a hydrogen production plant; to be covered in the INPRO CP called **HTR-H_2**.

The remaining topics deal with behavior of material in contact with HTR coolants at high temperatures, HTR fuel design reaching high burn-up at high temperatures, benchmarking of neutronic design codes and safety analysis codes, design of brittle structural materials like graphite, high temperature hydrogen production processes, transportation of non organic fuel like hydrogen, and specific issues related to coupling of a nuclear power plant and hydrogen plant.

5.5. Republic of Korea

The goal of the Korean study was to develop an analysis method to quantify the proliferation resistance (PR) of a defined nuclear energy system.

In the conclusions of the study it is stated that the analysis method should be developed further, something that is being realized in an INPRO CP (called **PRADA**).

5.6. Ukraine

In the Ukrainian study, in several INPRO areas, gaps were identified for a number of INPRO criteria, but the assessor did not define corresponding activities, i.e. no R&D proposals and/or follow up actions are documented. However, most of the judgments ‘non agreement’ were caused by a lack of data necessary to evaluate the INPRO criteria and so may not represent a short coming of the nuclear energy system.

5.7. Joint Study (JS)

The joint study (JS) focused on a future nuclear energy system consisting of fast reactors (FR) with a closed fuel cycle (CNFC). The participating countries in the JS were Canada, China, France, India, Japan, Republic of Korea, the Russian Federation, and Ukraine.

The JS concluded that a comprehensive program of R&D is absolutely essential in a variety of areas (especially, for economics and safety) with an inter-disciplinary approach and international collaborations wherever possible to make an energy system consisting of FR with a CNFC a viable alternative to conventional sources of power. In the following a summary of these R&D goals is provided.

Economics of FR

Capital costs of currently operating FR (sodium cooled) were 40% up to three times higher than capital costs of thermal reactors. Thus, to become a sustainable option of energy supply there is a clear need to reduce these costs (of construction) via R&D. Several possibilities for reduction of capital costs were presented in the JS. Examples include reducing the reactor size per MW(e) generating capacity, reducing the construction time, reducing the number of components in the reactor and their size, as well as enhancing the operating life of the reactor.

Safety of FR

To improve the safety of FR and reduce the man-rem exposure of workers at the plant R&D is needed to develop efficient and cost-effective shielding materials such as boride/rare earth combinations, and achieve source reduction by use of hard facing materials which do not get activated and by in-vessel purification of primary sodium.

Reduction of public exposure can be achieved by development of advanced cover gas purification technologies that would provide high decontamination factor from the radioactive gaseous fission products.

Prevention of accidents with severe core damage can be achieved by the development of automatic negative reactivity insertion devices, sodium pumps with high inertia and advanced cladding and wrapper materials. Exclusion of re-criticality after a core melting accident is considered as an important feature for enhancing the safety of fast reactors.

NFCF Considerations

As compared to the FR, the safety of the nuclear fuel cycle facilities (NFCF) is more focused on issues such as criticality, corrosion of key equipment such as dissolver, evaporator and waste tanks, and processes for efficient recovery of radioactive materials.

Key to enhancing the economics of fuel cycle operations is increasing robustness and availability of crucial process equipment in reprocessing as well as waste management facilities.

To improve the economics of NFCF equipments (i.e. dissolvers, evaporators, etc) R&D is required, which can reduce the size of process equipment without sacrificing criticality margins, and reduce corrosion losses thereby enhancing the life of these equipments. Advanced condition monitoring systems are to be developed that would provide inputs regarding condition of these equipments.

To increase the proliferation resistance of NFCF, R&D in reprocessing is targeted towards ensuring recovery of uranium and plutonium without mutual separation.

To simplify waste management and reduce the demand for repository space reprocesses are to be developed for recovery of long lived minor actinides and fission products besides. The development of ceramic matrices with long term stability and higher capacity for waste loading is another important area of R&D for final repository.

Proposals for international collaborations

In the JS the following INPRO collaborative projects related to fast reactors have been proposed and are underway:

- Integrated Approach for the design of safety grade decay heat removal system for liquid metal cooled reactors (called **DHR**);
- Assessment of advanced and innovative nuclear fuel cycles within large scale nuclear energy systems based on a CNFC concept to satisfy principles of sustainability in the 21st century (called **FINITE**);
- Investigation of technological challenges related to the removal of heat by liquid metal and molten salt coolants from reactor cores operating at high temperatures (called **COOL**);
- A global architecture of a nuclear energy system based on thermal and fast reactors including a closed fuel cycle (called **GAINS**).

CHAPTER 6.
FEEDBACK ON THE INPRO METHODOLOGY

In this chapter the proposals made by the assessors for modification of or additions to improve the INPRO methodology and ease its application are briefly summarized. The full list of all comments and recommendations presented by the assessors is listed in Annex A; in the following text a reference is given to individual statements listed in Annex A.

The summarized feedback from the assessors on the INPRO methodology was sorted into separate sections, the first one dealing with general proposals how to improve the methodology and ease its application, and thereafter one section for each area of INPRO.

6.1. General recommendations for improvement of the INPRO methodology

The general recommendations made in the assessment studies to improve the INPRO methodology are clearly different for assessors in technology developing countries from assessors in technology user countries.

Comments and recommendations by technology developing countries

Comments by assessors from countries developing nuclear technology focused on the capability of the INPRO methodology to be used as guidance during development of new nuclear technologies.

Firstly, they found that the INPRO methodology for two different designs under development that both fulfill all INPRO criteria cannot define clearly which one is the better option. Thus, they ask for an increased capacity of discrimination between several options of designs to be developed to select the optimum choice (see Annex A, assessor statement GC-21, GC-22, GC-23, GC-24 and GC-26). One possible approach to follow this recommendation could be to introduce scaling for INPRO numerical criteria and taking into account the margin between the value of the indicator and the corresponding acceptance limit[28].

Secondly, the assessors recommended including into the assessment method a clear description how to handle a situation during a development project where further improvement of one INPRO indicator could lead to a degradation of another indicator, i.e. how to achieve a balanced design (see Annex A, assessor statement GC-18, and GC-23) either for a specific component or for the complete nuclear energy system[29].

If a nuclear energy system assessed with the INPRO methodology fulfills all INPRO requirements it is deemed to be a sustainable system of energy supply within the considered timeframe (should be at least a hundred years). However, this doesn’t imply that no further R&D for nuclear components is necessary because alternative energy sources competing with nuclear are continuously improved also. The assessors found that this aspect is not emphasized enough in the existing documentation of the INPRO methodology (see Annex A, assessor statement GC-17, GC-22, GC-24, and GC-25). Thus, the third general

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[28] This approach is described in more detail in Section B2 of Annex B of Volume 1 of Ref. [1].

[29] In regard to a complete nuclear energy system some preliminary ideas how to achieve a balanced design are presented in Volume 7 of Ref. [1] in the INPRO area of environment.

recommendation is to enlarge the capabilities of INPRO methodology to define R&D goals beyond the existing INPRO acceptance limits[30].

Several assessors expressed difficulties to perform assessments of designs under development caused by the non availability of data due to early design stages. One assessor (see Annex A, assessor statement GC-1) proposed to include a new positive judgment on the potential of technologies under development claiming a specific INPRO criterion will be fulfilled by the development effort specified according to schedule. Such a judgment could be called 'conditional' implying the necessary actions are already included in the development program.

One assessor emphasized the need to extend the INPRO methodology to non electric applications of nuclear power, i.e. the production of hydrogen in a plant collocated to a nuclear reactor (see Annex A, assessor statement GC-14). To illustrate this extension of the INPRO methodology the assessor presented some additional requirements that cover a nuclear unit collocated to a hydrogen plant.

Recommendations by technology user countries

In principle the INPRO methodology requires the assessment of the complete nuclear energy system, i.e. all facilities of the front end, the power generation and the back end of the fuel cycle. One assessor evaluated a nuclear energy system that included only a limited number of components within the national borders and compared different options of a nuclear energy system with components inside and outside of the country. The assessor (see Annex A, assessor statement GC-31) recommends including a clear description, in the documentation of the INPRO methodology, about how components (facilities) of a nuclear energy system that are located outside the country, should be treated, especially, if they are compared with an option with the same type of facility located inside the country.

In comparing different options of a national nuclear energy system the need of aggregating the assessment results was noted by some assessors. They recommend to more clearly defining in the INPRO documentation how to aggregate results quantitatively. In that context they also noticed a need to clarify the quantitative treatment of maturity level of components of a nuclear energy system, especially when several designs are compared in an assessment (see Annex A, assessor statement GC-12, GC-29, and GC-30).

Similar to assessors from technology developing countries, the assessors from technology user countries noticed a need to improve the capability of the INPRO methodology to select the optimal design out of several designs available. Another request (similar to technology developers) was raised to add a general judgment for an agreement with an INPRO criterion that would state that the fulfillment of the criterion is planned to be done in foreseeable future; such a judgment could be called 'conditional'.

The absence of specific INPRO Criteria for some nuclear fuel cycle facilities was mentioned by several assessors; it was recommended to create such criteria (see Annex A, assessor statement GC-20, GC-28 and safety statement SF-1).

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[30] Some information on this issue is provided in Section 4.5 of Volume 1 of Ref. [1].

Several assessors emphasized the need to create an online data base that includes all necessary information of currently available reactors and nuclear fuel cycle facilities to be used in an INPRO assessment (see Annex A, assessor statement GC-3, GC-10, GC-11, and GC-19).

One assessor stressed the necessity to include into the INPRO manual an INPRO assessment of the same nuclear energy system to be presented as an example in each INPRO area (see Annex A, assessor statement GC-13). To ease the application of the INPRO methodology one assessor requested the provision of training courses on the INPRO methodology, the translation of the INPRO manual (Ref. [1]) in relevant languages and the addition of a glossary to the INPRO manual (see Annex A, assessor statement GC-2, GC-6, GC-7, and GC-8).

Last not least also the technology user countries emphasized the importance of security of supply to be taken into account in developing the energy supply system of a country (see Annex A, assessor statement GC-27). The development of the energy system and the role of nuclear within an energy mix is, however, not a direct issue to be treated by the INPRO methodology, but is part of the energy planning phase to be performed as a prerequisite for an INPRO assessment.

6.2. Proposals for improvement of the INPRO methodology in the area of economics

Suggestions for improving the INPRO methodology in the area of economics are presented below. In some cases the suggestions reflect specific proposals while in other cases they are generalized to address what seems to be a broader underlying difficulty encountered with the INPRO methodology. Not included are detailed suggestions for correcting errors identified by assessors. These will be reviewed and corrected as a matter of course.

In the area of economics, the Manual (Volume 2 of Ref. [1]) addresses the issue of financial resources required to deploy a nuclear energy system by requesting that the assessment determine whether the total investment required to design, construct and commission new energy systems can be raised in a given market climate. It was suggested (see Annex A, assessor statement EC-3) that some discussion of the financial resources required and the means to raise the necessary funds for development be added to the Manual. As well, the discussion of the investments required to develop a nuclear energy system from the pre-conceptual stage to the commercially proven stage, presented in the Manual should be expanded and criteria related to investments required for development, as distinct from those related to deployment, should be developed (see Annex A, assessor statement EC-16).

The strategic importance of the security of energy supply is mentioned (see Annex A, assessor statement EC-5) as one factor that might be considered when comparing the costs of different energy options in the Manual. Security of energy supply is an important consideration of energy planning, which should be carried out prior to performing an INPRO assessment. Such planning could indicate whether and to what extent a higher cost of energy from a nuclear energy system is acceptable when comparing costs with cheaper energy options. It was suggested that the discussion of this issue be expanded in the Manual. Another related issue that could also be discussed further in the Manual, is the discount rate to be used when comparing costs of energy alternatives, especially when considering the long time frames over which a nuclear energy system is expected to operate, as well as the detailed models that are to be used in calculating costs, i.e. the Merchant Cash Flow (see Annex A, assessor statement EC-14) model used by Massachusetts Institute of Technology (Ref. [12]).

The cost of energy production from a nuclear energy system is based on an assumed operating lifetime for the nuclear power plants (NPP). Investments in fuel cycle facilities that form part of the nuclear energy system are considered as a fuel cost. An INPRO assessment makes use of a reference energy plan. The Manual assumes that costs will be recovered over the operating time of the nuclear energy system and its components but this time frame may extend beyond the time frame of the energy plan, particularly if some fuel cycle facilities and NPP are introduced late in the time frame of the energy plan. Thus, costs may not be fully recovered within the time frame of the energy plan. It was suggested that this issue be dealt with in the Manual (see Annex A, assessor statement EC-2, EC-7, and EC-10).

One assessor stressed the need to broaden the INPRO requirements to focus the economic assessment on nuclear fuel cycle facilities and not only on a comparison with energy generation technologies (see Annex A, assessor statement EC-1, EC-11, EC-12, EC-15, EC-17, and EC-18). In general, it seems that the flexibility offered by the INPRO Methodology to adapt user requirements and, especially, criteria, to reflect different circumstances (country or region specific or technology specific, or perhaps even assessment specific) might be discussed further in the economics manual (Volume 2 of Ref. [1]) and examples might be included based on feedback from the assessments carried out.

Based on the outcome of his assessment one assessor emphasized the need for an increase of discriminative power of the methodology comparing different options of a nuclear energy system in the area of economics (see Annex A, assessor statement EC-8).

6.3. Proposals for improvement of the INPRO methodology in the area of infrastructure

In general, suggestions for improving the INPRO methodology in the area of infrastructure seemed to refer to an earlier draft version of the Manual (Volume 3 of Ref. [1]) and, in many cases, have already been addressed in the published version of the Manual. Some detailed suggestions for correcting errors, i.e. different wording of INPRO criteria used within the text, were identified by assessors. These will be reviewed and corrected in the next revision of the document. The feedback from assessors who have found such errors is much appreciated. Other suggestions are summarized below.

The use of INPRO evaluation parameters for assessing criteria in the area of infrastructure seem to have been appreciated by assessors (see Annex A, assessor statement IN-1, IN-7, and IN-8). This approach might be extended to others INPRO areas, i.e. waste management.

Several assessors stressed the need to quantify the overall added value of a proposed nuclear installation that should compensate the necessary investment in infrastructure to support the nuclear installation (see Annex A, assessor statement IN-13, IN-15, IN-16, IN-17, and IN-18).

Some assessors mentioned the difficulty to assess the infrastructure of a system that is in early stage of development or deployment due to the lack of available data (see Annex A, assessor statement IN-2, and IN-5)

One study (see Annex A, assessor statement IN-3) noted that transportation of heavy components needed for a nuclear energy system, i.e. reactor vessel, steam generators, may be problematic in some countries. Thus, an additional evaluation parameter to address this area could be added for the INPRO indicator of criterion CR2.4, '*Availability of Infrastructure to Support owner/operator*'. Here it may be noted that the methodology enables assessors to modify user requirements, criteria, and by extension, evaluation parameters to meet their national circumstances.

Two assessors express a need to increase the discriminative power of the INPRO methodology in the area of infrastructure (see Annex A, assessor statement IN-4 and IN-11), a request that was already mentioned in the general recommendations (Section 5.1).

Another study (see Annex A, assessor statement IN-6) noted that countries with little or no nuclear experience would benefit if the Manual provided an example of an assessment for such a country and for a country with nuclear power experience. In this connection, it was suggested that countries with nuclear experience might assist in-experienced countries, in performing an assessment in the area of infrastructure with the assistance of the IAEA (Department of Technical Co-operation and Nuclear Power Engineering Section of the Department of Nuclear Energy.)

One study (see Annex A, assessor statement IN-21) questioned the wording of the acceptance limit for the indicator of INPRO criterion CR3.3, '*Public acceptance',* namely, '*Sufficient to ensure there is negligible political risk to policy support for nuclear power'.* Two evaluation parameters have been specified for this criterion, which provide more detailed guidance on determining whether the acceptance is limit is met but, nonetheless, consideration could be given to modifying the wording of this limit.

Finally, the issue of security of supply was raised by one assessor (see Annex A, assessor statement IN-10) pointing out that the supply of large components of a reactor such as the pressure vessel or steam generators must be assured for countries that have no relevant manufacturing capabilities to be able to build their nuclear energy system.

6.4. Proposals for improvement of the INPRO methodology in the area of waste management

Suggestions for improving the INPRO Methodology in the area of waste management are presented below. Many of the suggestions (see Annex A, assessor statement WM-8, WM-9, WM-10, and WM-15) seem to relate to a need to improve the clarity of the Manual (Volume 4 of Ref. [1]). One suggestion for doing so is to utilize evaluation parameters as is done in the INPRO area of infrastructure (see Annex A, assessor statement WM-4). One example of such an evaluation parameter that might be used for INPRO criterion CR3.1.5, *Time for end state',* is the ratio of waste disposed during operation of a nuclear energy system in a given time frame, i.e. the time frame of the energy plan, to the total volume of waste that will be generated over the lifetime of the nuclear energy system (see Annex A, assessor statement WM-7). Another example would be to use only criterion CR1.1.2, *'Minimization study'*, of UR1.1, *'Reduction of waste at the source'* and use the technical indicators specified for CR1.1.1, *'Waste characteristics',* as evaluation parameters for CR1.1.2. The values might be shown in a table when different nuclear energy systems are being compared (see Annex A, assessor statement WM-11). Another related suggestion is to specify the waste management system for a reference nuclear energy system, such as a once through LWR system (see Annex A, assessor statement WM-12), and assess this system. This would necessarily provide a reference set of values for indicators and acceptance limit and a given nuclear energy system could then be compared with the reference nuclear energy system.

One study asked that the INPRO criteria be adjusted depending on the stage of development of a nuclear energy system (see Annex A, assessor statement WM-3). The existing criteria used in waste management represent what should be achieved when a nuclear energy system is fully developed. At an early stage of development it may not be possible to determine whether a given criterion will be met. In such a circumstance the assessment would be incomplete and the criterion in question would have to be re-evaluated at a later stage of development. On the other hand if, at an early stage of development, the judgment is that the criterion might not be met then this result would indicate the need to modify the development plan to address this potential shortcoming of the nuclear energy system.

It was noted that some aspects of waste management are an integral part of operating components of the nuclear energy system, i.e. the NPP, and other aspects are more specific to dedicated waste management facilities, such as disposal facilities. As well, for comparing some different nuclear energy systems, some aspects of waste management would not change significantly. It was suggested that the distinction between these aspects could be clarified in the Manual, in particular, to assist with comparing different nuclear energy systems (see Annex A, assessor statement WM-5, and WM-6).

Given that some wastes produced in a nuclear energy system may be exempt from regulatory control in accordance with clearance levels (see Annex A, assessor statement WM-14) and hence need not be treated as radioactive waste per se, it was suggested that it would be worthwhile introducing a criterion (or evaluation parameter) for UR4.1, '*Waste Classification',* IN4.1.2, C*learance level',* and AL4.1.2, '*clearance level defined by regulatory body that permits unambiguous identification of radioactive waste'.*

6.5. Proposals for improvement of the INPRO methodology in the area of proliferation resistance (PR)

The recommendations by assessors in this INPRO area seems to be mainly based on difficulties with the interpretation of the INPRO documentation provided to assessors, i.e. there were several draft versions of the so-called INPRO Manual for this area distributed to assessors with significant differences in content. The earlier versions of this manual required the assessor to perform an analysis method developed within the INPRO project that produces a detailed description of the qualitative level (within a range of very weak to very strong) of proliferation resistance (PR) of all relevant parameters of a nuclear energy system.

The published version of this Manual (Volume 5 of Ref. [1]), however, tried to distinguish and separate the analysis method (Annex A of Volume 5 of Ref. [1]) from the INPRO assessment method (Chapter 3 of Volume 5 of Ref. [1]). The analysis should be performed by the technology supplier or developer of the technology. The results of this analysis, i.e. levels of PR of evaluated parameters, should be provided to the INPRO assessor (a safeguard expert) as input for his assessment.

In general, assessors both from countries developing and using, respectively, nuclear technology expressed difficulties to get access to design data of nuclear energy system components needed to perform the analysis method discussed earlier (see also Section 4.4.4) that enables a qualification of important parameters relevant to PR (see Annex A, assessor statement PR-3, PR-5, PR-6, PR-9, PR-10, PR-16, PR-17, PR-18, PR-20, PR-22, PR-24, PR-25, PR-26, and PR-28). Especially, technology developers expressed a need for clarification how to deal with lack of existing data in case of early design stages; technology users claimed that in principle design data on PR should be provided by designers something that could be arranged via the INPRO secretariat.

One technology developer country claims that the currently documented INPRO analysis method (Annex A of Volume 5 of Ref. [1]) is providing an unfavorable (negative) picture of enrichment and reprocessing facilities assigning them unjustified low values of proliferation resistance. A specific need to review the methodology is defined and to add new user requirements and evaluation parameters that take into account the safe and secure use of these technologies (see Annex A, assessor statement PR-1).

In one assessment study (see Annex A, assessor statement PR-11, PR-19, PR-21, and PR-23) it was recommended to change the wording of INPRO acceptance limits from ‘equal or better than existing facilities meeting international best practice’ to ‘sufficient according to international best practice’.

Several assessors expressed a need for an internationally accepted standard of proliferation resistance of a nuclear system or component thereof and for a clear description in the INPRO manual of a standardized method how to evaluate the level of PR (see Annex A, assessor statement PR-2 PR-4, PR-7, PR-8, PR-12, PR-13, PR-14, PR-15, and PR-27). It is to be noted that in the area of PR the INPRO methodology is still under continuous development together with the Generation-IV International Forum (GIF) working group on proliferation resistance and physical protection.

6.6. Proposals for improvement of the INPRO methodology in the area of physical protection

As mentioned earlier the INPRO Manual for physical protection (Volume 6 of Ref. [1]) was developed some time later that the other INPRO areas and so, it was not available to most of the assessors during the performance of their studies. Hence, only a limited amount of experience exists with the application of the INPRO methodology in this area.

One technology developer who did a detailed assessment at the criterion level using the INPRO methodology expressed his satisfaction (see Annex A, assessor statement PP-1) with the approach described in Ref. [1]. A technology user performing a scoping assessment asked for more clarification how to use the results of an assessment in this area (see Annex A, assessor statement PP-2).

The INPRO methodology for this area includes a general criterion that asks for inclusion of physical protection aspects during the assessment of all other INPRO areas. This would lead to the consequence that not only physical protection aspects but aspects of every INPRO area must be taken into account in assessments of all other INPRO areas, which would seem to be unnecessary redundancy. One assessor suggested that the criterion in question be eliminated (see Annex A, assessor statement PP-3).

6.7. Proposals for improvement of the INPRO methodology in the area of environment

The INPRO Manual for environment was released to assessors in several versions with significant differences in structure. The final version of the Manual (Volume 7 of Ref. [1]) was not available to all assessors during their assessment. As a consequence many of the proposals received are related to earlier versions of the Manual and have already been taken care of in the latest version thereof. It is to be noted that the existing approach is not yet developed completely, i.e. there are significant scope limitations identified in Volume 7 of Ref. [1].

All assessors expressed a need to clarify in the INPRO Manual how to apply the methodology in this area (see Annex A, assessor statement EV-5, EV-7, EV-14, EV-15, EV-16, EV-17, EV-18, EV-19, EV-20, EV-21, EV-22, EV-23, EV-24, EV-25EV-26, and EV-27).

Some assessors claimed that the INPRO methodology in this area does not include sufficient capability to demonstrate the benefits of introducing partitioning and transmutation (P&T) technologies that have a potential to reduce environmental impacts of nuclear waste (see Annex A, assessor statement EV-1, and EV-3). It has to mentioned, that this aspect is however taken care of in the waste management part of the INPRO methodology (Volume 4 of Ref. [1]).

Another suggestion is to reference, in the Manual, the 'Basic Environmental Law' issued by the United Nations in 1993 (see Annex A, assessor statement EV-4).

As in other INPRO areas some assessors stressed the difficulties to receive the necessary input data for an environmental assessment according to the INPRO methodology (see Annex A, assessor statement EV-6, EV-8, and EV-10).

A general recommendation was made within one study to extend the methodology in this area to cover accident situations (see Annex A, assessor statement EV-2). It is to be noted that accident situations are handled in the INPRO area of safety and physical protection.

The existing version of the Manual states that no method is currently available to treat non radiological stressors. Some assessors expressed a need to add a suitable method to cover this issue (see Annex A, assessor statement EV-12, and EV-13).

6.8. Proposals for improvement of the INPRO methodology in the area of safety

Some assessors defined a need to further develop the INPRO methodology for application on nuclear fuel cycle facilities (Volume 9 of Ref. [1]), particularly, in the area of safety (see Annex A, assessor statement SF-1, SF-4, and SF-8). In the current version no explicit guidance is provided on how to treat storage facilities for spent nuclear fuel.

An overlap of requirements, especially, on the level of criteria, i.e. frequencies of occurrences, consequences of events was noted (see Annex A, assessor statement SF-3 and SF-5) between INPRO safety basic principle BP1 (enhanced defence in depth) and BP2 (inherent safety characteristics and passive systems).

A commonly agreed assessment of an existing nuclear energy system seems necessary to be used as a benchmark (or reference) case (see Annex A, assessor statement SF3); a future nuclear energy system could be compared with such a benchmark and its improved level of safety demonstrated.

Several assessors (see Annex A, assessor statement SF-5, SF-6, SF-7, SF-15, SF-16, SF-17, and SF-18) stated that the documentation of the INPRO methodology in the area of safety needs more explanation of technical terms used in the Manual (Volume 8 and 9 of Ref. [1]).

Similar to requests made in other INPRO areas an assessor, a technology user, stressed the need for creation of an data base at the IAEA (called the 'INPRO portal' as described in Volume 1 of Ref. [1]) that includes all necessary input data of all available designs for an INPRO safety assessment (see Annex A, assessor statement SF-9, and SF-10). The same assessor asked also for clarification how to aggregate the results of an assessment to be able to differentiate between several options of a nuclear energy system (see Annex A, assessor statement SF-11).

Similar to other INPRO areas technology developers requested to clarify how to treat early design stages with a lack of data (see Annex A, assessor statement SF-13, and SF-14).

Technology developers further suggested (see Annex A, assessor statement SF-12) that in case for a design under development a large (excessive) design margin was found for a given INPRO parameter, one might consider whether some trade offs could be considered to balance the overall design.

CHAPTER 7.
LESSONS LEARNED FROM APPLICATION OF THE INPRO METHDOLOGY

A Technical Cooperation workshop[31] was held from February 16th to 20th at the IAEA to discuss the results of the INPRO assessment studies (Refs [2] to [9]) focusing on the recommendations by assessors how to improve the INPRO methodology and ease its application (as summarized in Chapter 5 and listed in Annex A of this report). All eleven countries (Argentina, Armenia, Brazil, Canada, China, France, India, Japan, the Republic of Korea, the Russian Federation, and Ukraine) who had participated in one of the INPRO assessment studies with the exception of France were represented at this workshop.

Based on this workshop in the following a summary of lessons learned, is presented.

7.1. Benefits to assessors from performing an INPRO assessment

The INPRO methodology was used in a variety of studies that represented both technology users and developers and different scales of assessments: covering a complete nuclear energy system with all facilities, or specific components of a nuclear energy system, assessing all INPRO areas, or a limited number of INPRO areas, and achieving different depths of evaluation, i.e. assessment of each INPRO criterion or a scoping assessment at the INPRO basic principle or user requirement level.

There was a consensus among the assessors participating in the workshop that applying the methodology to a nuclear energy system was a worthwhile effort and provided valuable insights, and clear identification of gaps in nuclear power development or installation programs, leading to follow-up actions.

Participants confirmed that the INPRO methodology can and should be used as a tool for meeting the INPRO objective of assessing how nuclear energy systems ‘contribute in a sustainable manner, to meeting the energy needs of the 21st century’.

Insights of technology developing countries include the confirmation of the strategy of an ongoing national development program and the gained knowledge about similar programs in other countries highlighting some key global issues. Technology user countries emphasized the achieved familiarization with all nuclear issues associated with the establishment of a sustainable nuclear power program.

Follow up actions (see Chapter 6 for details) include R&D, some to be performed in multilateral INPRO Collaborative Projects covering technological aspects or analytical methods, i.e. further development of a proliferation resistance analysis method, some to be performed on a national basis, and further studies to close identified gaps.

7.2. Measures to ease the application of the INPRO methodology

The INPRO Manual (Ref. [1]) is a comprehensive document providing a lot of explanations and background information but – based on feedback from the workshop – additional guidance is needed in using it, answering precisely the following questions:

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[31] The workshop was conducted as part of the IAEA TC project INT/4/141 ‘Status and prospects of development for and application of innovative reactor concepts for developing countries’.

- How to get started with an INPRO assessment and what technical expertise is needed?
- What a newcomer[32] State should do?
- What a technology user country[33] should do?
- What a technology developing country should do?

These questions could be addressed by an additional user guide tailored to the needs of different users of the INPRO methodology.

To further ease the application of the INPRO methodology in the future some additional needs of assessors were expressed as follows[34].

- A data base is needed for all INPRO assessors – especially for nuclear technology user countries – that contains all the information on nuclear energy system components (facilities) used in an INPRO assessment to determine the value of INPRO indicators; such necessary data on nuclear technologies should be provided by designers and technology suppliers. A need was specified by the assessors for a mediating role of the IAEA/INPRO secretariat to facilitate exchange of data between assessors and technology suppliers/developers. In the same data base internationally harmonized and standardized values[35] of INPRO acceptance limits in all INPRO areas for all nuclear facilities should be stored.

- A few examples (also called reference cases) of a full INPRO assessment are needed to be performed and a complete documentation thereof be made available to the different kind of INPRO assessors, i.e. technology developers, technology users, and newcomers. The examples should cover all components of a complete nuclear energy system (reactor and fuel cycle facilities) and all INPRO areas; for technology users the examples should primarily include a nuclear energy system with options of commercially available components including a location of fuel cycle facilities outside the assessor's country, and for technology developers several options of components in different stages of development.

- There is a need to provide training courses in the INPRO methodology to potential INPRO assessors before the start of an INPRO assessment. During the assessment continuous support to INPRO assessors is needed by means of INPRO methodology expert missions and/or access to IAEA expertise clarifying all issues raised.

- A translation of the INPRO manual [1] and the new user's guide into the main IAEA languages is necessary to be performed to enable a quicker familiarization with the INPRO methodology.

- In the INPRO manual [1] and the new user's guide a detailed glossary of the important terms and definitions, and an index should be added to avoid misinterpretation of important features of the INPRO methodology.

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[32] A 'newcomer State' is a country with limited experience with nuclear power.

[33] A 'technology user country' applies nuclear technology but does not develop and supply it.

[34] Most of the proposals listed were originally envisaged to be made available to INPRO assessors in the so-called 'INPRO portal' (see Section 4.7.1 of Volume 1 of Ref. [1]).

[35] Harmonization and standardization should be performed by nuclear technology supplier and user countries under the auspices of the INPRO secretariat.

Based on the feedback from the workshop it was proposed to develop a nuclear energy system assessment (NESA) support package that integrates all requests listed above into one task. It was recognized that the planning of an INPRO assessment by a country should include also the planning for timely IAEA/INPRO support.

An important topic in regard to the documentation of the INPRO methodology was raised during the workshop by several assessors: To avoid confusion of the applicants of the INPRO methodology in the future there should be a strict control of versions of INPRO documents send out to Member States, i.e. corrections or modifications should be distributed in the form of addendums or similar procedures.

7.3. General recommendations for improvements of the INPRO methodology

Detailed proposals how to improve the INPRO methodology in general and in specific areas have been made by assessors as outlined in Chapter 5 and Annex A. A short summary of the main proposals are set out in the following.

The INPRO methodology should be extended to enable a clearer distinction (discrimination) between different options of components of a nuclear energy system under development but also between options of commercial available components, especially, if some components are located in different countries. By comparing options a need for a more precise description how to aggregate assessment results was found by the assessors (as outlined above, an example should show a practical application of aggregation).

Primarily by technology developing countries a need was expressed to develop an approach how to treat different level of uncertainty associated with stages of development.

In particular for the INPRO area of environment and proliferation resistance a need for further development of the assessment approach was expressed by several assessors.

Jointly with other relevant IAEA groups some issues should be treated within the INPRO project. One issue is security of energy supply that should be taken into account within the methodology appropriately considering its importance in defining the role of nuclear power in a country. There was consensus that this issue should be considered during the energy planning phase analyzing future demand and all options of future energy supply available in a given country. Another issue to be evaluated is non electric applications of nuclear power.

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ANNEX A
FEEDBACK ON INPRO METHODOLGY

A1. Introduction

This paper is a collection of all modifications of and comments on the INPRO methodology in general, and specifically on each INPRO Basic Principle (BP), User Requirement (UR) or Criterion (CR) in the different INPRO areas (economics, infrastructure, etc) proposed by the INPRO assessors in their studies. To enable an easier evaluation of the specific feedback the full text of all INPRO BPs, URs and CRs are listed in Annex B.

A2. General proposals and comments to the INPRO methodology (GC)

GC-1: Argentina statement (Section 6.2 infrastructure[36]): *The judgment classification 'Conditional' is proposed for those requirements for which no sufficient information is currently available to judge it as 'Potential' or 'No Potential' and future actions or decisions are needed.*

GC-2: Armenia statement (Section 1 Summary): *(First of all) it is highly appreciated to have a 'glossary of INPRO methodology' as separate volume of TECDOC-1575 with detailed definition of the terms, which will help users to find description of any term easy and quickly.*

GC-3: Armenia statement (Section 6.9 conclusions, Section 8.2 recommendations): *The INPRO methodology is a thoroughly deeply developed tool for users to evaluate the innovative nuclear energy systems (INS). However the sources of existing data are few, as well as they do not contain sufficient quantity of information for comprehensive study of INSs by INPRO methodology. According to this, a harsh necessity evolves to complete INPRO information portal implementation that will contain full data base required by the methodology.*

(Secondly) INPRO information portal will be very helpful for users to make evaluative study.

Finalize development and introduction of the INPRO information portal with inclusion of all corresponding information and links to other Web sources.

(At the same time) it should be noted that number of necessary data, requested by INPRO methodology needed for assessment of INS are inaccessible or are absent.

Create data base of default (and/or recommended) values for all acceptance limits and indicators as much as possible. Such a data base should be integrated in INPRO information portal and INPRO examination computer tools.

GC-4: Armenia statement (Section 8.2 conclusions): *Assessment study demonstrates that the comprehensive INPRO methodology allows the user to lead estimation of selected innovative nuclear energy systems (INS) taking into account the specificity at the concrete country level, as well as at the regional and global levels is developed. Practically all the aspects necessary for carrying out the corresponding research of the country's nuclear development are generalized and reflected in the INPRO methodology. Use of the INPRO methodology allows*

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[36] The information given in the brackets refers to the location (section number and title) of the statement in the assessor's report which was published as IAEA working material in 2009.

country decision maker to have a deeply enough both comprehensively studied and analyzed issues of future implementation on INS in the country.

GC-5: Armenia statement (section 8.2 conclusions): *Number of INPRO requirements are intersected, i.e. BP2 of WM with environment, UR1 of PP with infrastructure.*

GC-6: Armenia statement (section 8.2 recommendations): *The guidance for the application of an assessment methodology for INS is necessary to translate to the official languages of the IAEA.*

GC-7: Armenia statement (section 8.2 recommendations): *Realize a cycle of trainings on each area of the INPRO methodology*

GC-8: Armenia statement (Section 8.2 recommendations): *Elaboration of INPRO examination computer tools with integrated data base, allowing user to put the requested data and to take preliminary results of the INS acceptability analysis (for example in format like checklist in guidance). It is advisable to elaborate some kind of universal index which will show the level of readiness (ability) of country in implementing an INS*

GC-9: Armenia statement (Section 8.2, mistakes found): *In Annex B of volume 2 and 3 and Annex A of volume 4of the INPRO manual instead of '....INPRO basic principles, user requirements and criteria in the area of safety', it should read 'economics', 'infrastructure', and 'waste management'.*

GC-10: Brazil statement (Section 6.1 general considerations, section 8.2 conclusions): *the availability of complete technical and economic data from the INS designers (the technology holders) are vital for performing valuable assessments; IAEA should assist the interested assessors/INPRO MS in obtaining such information.*

GC-11: Brazil statement (Section 6.1 general considerations, section 8.2 conclusions): *The (numerical and logical) acceptance limits should be based, to the extent possible, on design data from evolutionary generation III reactors and from fuel cycle technologies already demonstrated (at least in prototype scale) AND should be incorporated into INPRO methodology and Manual. The specification of the acceptance limits for the indicators eventually introduced by individual assessors should obey the same criterion. This procedure shall harmonize the demands on any INSs when assessed by different assessors/countries, something that is desirable in principle.*

GC-12: Brazil statement (Section 6.1 general considerations, section 6.3 feedback from the assessment of FNBR reactor): *The maturity of the INS designs greatly influence the judgment on the INSs potential and the usefulness of the assessment results. As already recognized, not always the criteria of INPRO Manual can be evaluated effectively, as this depends on the development stage of the reactor design being assessed, if conceptual, completed or already in operation. In the FNBR case, for instance, it is not possible to detail more than what had been presented in Annexes 3 and 4, since in its current preliminary conceptual stage it is not possible to derive numerical values for many of the proposed indicators.*

GC-13: Brazil statement (Section 8.2 conclusions): *future editions of the INPRO Manual should refer to the same (and complete) INS in the case examples inserted at the end of each chapter. This approach will make the assessors better appreciate the holistic nature of INPRO assessment methodology.*

GC-14: India statement (Section 5 review of INPRO requirement …): *A preliminary screening of the concept (i.e. hydrogen generating INS) for its compliance with INPRO methodology, as presented in TECDOC-1434, has been carried out. In the process of assessment it was felt that augmentation of certain INPRO areas should be considered for application to hydrogen generating INS. It was observed that in some cases additional indicators might be necessary.*

GC-15: India statement (Section 7, assessment as per INPRO working material …): *(However) the guidelines of assessment, as listed in the manual, have provided valuable directions in which design should progress. This in turn has resulted in identification of newer RD&D areas.*

GC-16: Joint Study statement (executive summary): *The INPRO methodology and manual are estimated by the participants of the Joint Study as a significant advance in development of an instrument for comprehensive analysis of ways to enhancing sustainability features of nuclear power. The procedure for an INS assessment is well formulated and documented. Several propositions of the methodology were found to be especially helpful as a guide in making assessment on an INS: an interdisciplinary approach; consideration of the whole life time (cradle to grave) of an INS; gradation of an INS maturity levels; evaluation of both competitive and synergetic potential of an INS. The INPRO assessment has helped to identify a few weak points of the reviewed system and lay down measures of its improvement with an aim to meet confidently criteria of sustainable energy supply.*

GC-17: Joint Study statement (executive summary): *Neither methodology nor manual make any guidance for an INS improvements after reaching INPRO acceptance limits (ALs).*

GC-18: Joint Study statement (executive summary): *There are no instructions from the assessment method on the user behaviour in case when improvement of some INS indicators induces negative impact on other ones.*

GC-19: Joint Study statement (executive summary, section 2.9.2): *A few directions for improvement of the assessment method were proposed: - standardization of ALs via international harmonization of their values;*

GC-20: Joint Study statement (executive summary, section 2.9.2): *A few directions for improvement of the assessment method were proposed: - introduction of additional ALs for NFCF;*

GC-21: Joint Study statement (executive summary, section 2.9.2): *- development of a more definite guidance in providing adequate conditions of comparison of an innovative NS with existing NS; A more definite guidance in providing of adequate conditions of <u>comparison of innovative nuclear systems with existing ones</u> is needed in an advanced assessment method to assure comprehensive assessment of nuclear systems with <u>different levels of maturity</u>. Citing and analysing of the <u>scale of R&D investments</u> needed to master different components of an innovative nuclear technology, of typical over design problems and growth of the initial projected cost, of delays connected with licensing and construction, etc. could be relevant and useful part of the future manual on assessment of an INS.*

GC-22: Joint Study statement (executive summary, section 2.9.2):- *enhancing of a discriminative power of the assessment method: by introducing of the scaling functions for indicators; through introducing of <u>target values scale</u> in which ALs should be considered as the nearest target value. Introduction of target values for INS indicators which could* *characterize the scale of improvements is a well known approach used in some methods of the management science. An expediency to define target values was also shown in the Report of Phase 1B of INPRO [2-3] but it has not been developed in the current manual to quantitative values.*

GC-23: Joint Study statement (executive summary, section 2.9.2): *-- elaboration of an approach for consolidation of evaluations (judgements) obtained for (specific) separate INPRO (variables) indicators. Results of the joint assessment of the INS CNFC-FR in many areas of assessment have confirmed expediency to increase a discriminative power of the assessment method and at the same time have denoted the need in consolidation of judgments made for different INPRO indicators. When improving of some characteristics of an assessed system leads to degradation of other ones, the necessity to provide balance of assets and liabilities in the system development strategy by introducing of a quantitative measure of significance ('weight') for each indicator of assessment becomes rather evident.*

GC-24: Joint Study statement (executive summary, section 2.9.2): *- Transition from assessing a capability of an INS to be in compliance with sustainability criteria (just to have entered the sustainability area) to making a help in segregation alternatives within sustainability options and selection of nationally preferable design and technological strategies of the CNFC-FR development.*

GC-25: Joint Study statement (executive summary, section 2.9.2): *- The methodological platform built at the first phase of INPRO is a necessary but not sufficient condition to making a comprehensive assessment of an INS and specifying its role in development of national, regional or global energy strategies. Hard and permanent work is still needed to solve this challenging task.*

GC-26: Joint Study statement (Annex Japan, Section 9 conclusions): *In general, the INPRO methodology is useful for INS to develop and assess the conceptual design in an early stage. However, we found it difficult to use some INPRO indicators and evaluate the target by these indicators because of each nation's status, wide-ranging scope, unclear criteria, difficulty of quantitative analysis, and so on. These outstanding issues should be discussed further among the interested countries in order to build a consensus. And then, it could be assumed that improvements will be reflected into the existing INPRO methodology in the future.*

GC-27: Ukraine statement (Section 7.2 recommendations on improvement of INPRO methodology, Section 8 conclusions and recommendations 7.4):
Security of energy supply.
- Leasing options (energy chains No.13 and 14) were granted the highest score. However, lack of some NFC components increases the dependence level of Ukraine on the reliability of nuclear fuel supply, on the schedule of SNF export for reprocessing, etc. Experts believe that the high level of dependence decreases the level of security of energy supply of the state, decreases the sustainability potential.

- Taking into account the above mentioned consideration it is useful to develop a separate thematic area 'Security of energy supply', including appropriate basic principles, user requirements and criteria. It will enable to get more precise evaluation of the energy system sustainability on the whole.

GC-28: Ukraine statement (Section 8 conclusions and recommendations 7.1): *It makes sense to refine the INPRO methodology to assess the NFC components that do not refer to the* *generation itself considering their specifics from the point of nuclear radiation safety regulation as well as other assessment criteria.*

GC-29: Ukraine statement (Section 8 conclusions and recommendations 7.2): *it makes sense to regulate the procedure of evaluation score in separate areas during their aggregation. We think it will enable to assess more correctly the role of various factors during the analysis of INS sustainability.*

GC-30: Ukraine statement (Section 7.2 recommendations on improvement of INPRO methodology):
Uncertainty of the judgment:
- When assessing the INS capability to meet criteria, uncertainty of the judgment may arise, that can play an essential role in the comparative assessment. The reason for such uncertainty is different maturity level of the INS components. The approach that considers the INS maturity level is described in c.4.4.3 of IAEA-TECDOC-1575, Volume 1 (Overview of the Methodology).
- Tables 4.2 and 4.3 in TECDOC-1575 are used by the experts for numerical evaluation of the maturity level by assigning the revise factor. It may lead to collisions during preparation of the summary conclusion on all INPRO areas because tables do not illustrate specific factor values. It means different experts use different values. Taking into account the above mentioned to unify and simplify the numerical evaluation we propose to add a column 'Revise factor' in the table indicating values from 0 to 1 in this column. For instance maturity level 'pre-conceptual' and appropriate uncertainty level of the judgment 'very high' has a factor 0; maximum maturity level and its appropriate complete certainty of the judgment has a factor 1; interim maturity levels have a factor of 0.2.
- We also propose to discuss the expedience of revise factor application during numerical evaluation of every indicator, considering that such factor is understood as uncertainty level of the judgment without reference to the maturity level. In other words, uncertainty of the judgment may arise due to various reasons (e.g. lack of information), and maturity level may be a particular case of uncertainty of the judgment. It will enable to consider the uncertainty of the judgment more acute in those cases when it is doubtful that criteria will not be satisfied for the whole INS, but only for its separate parameters. For instance, during the analyses of proliferation resistance an expert had the uncertainty of the judgment about application of observation capabilities at some stages of nuclear fuel fabrication, meanwhile judgments about other criteria of the same stages were quite certain. This approach will make obvious slight differences in the assessment of various INS options.

GC-31: Ukraine statement (Section 7.2 recommendations on improvement of INPRO methodology, Section 8 conclusions and recommendations, 7.3):
Assessment of the non available INS components:
Experts had conflicting opinions about the assessment methodology of the options that include leasing scheme. Two solutions are possible:

- *not to assess the components that are not available in the country. This approach was chosen in the assessment of proliferation resistance;*
- *to put the highest score to the non available components, explaining it by the fact that critical and dangerous NFC components were transferred outside the country increasing the sustainability potential. This approach was chosen in the assessment of the area of 'safety' and 'environment'.*

Every approach is reasonable but they provide different results during calculation of the final score. Therefore it is necessary to specify the most acceptable approach and include it into the Methodology.

In the following sections proposals and comments of assessors to individual INPRO areas are listed.

3. INPRO area of Economics

3.1. General proposals and comments to INPRO methodology for economics

EC-1: Argentina statement (Section 6. feedback from the application of the INPRO methodology, section 6.1 economics): *"The BP and UR statements are written as a comparison of different energy generation technologies. They are written in a very specific manner, applicable only to the example given in the INPRO manual. These sentences should be expressed in a more general way, so they can be applicable to different innovative nuclear energy system (INS) study cases. In our particular case, for the assessment of the nuclear fuel cycle (NFC) it was necessary to adapt the sentences to use the methodology."*

EC-2: Argentina statement (Section 6.1 economics): *"Another observation is that the methodology only takes account of projects that have a defined life time, static over the time. The example given in the manual takes account of the lifetime of both electricity generation technologies, NPP and NGCC. It does not take account of periodic incorporations or scaling up of productive units from the INS. It should be necessary to compute the reminder value. Since then projects that do not recover the investment during the study period could be studied more accurately. In our particular case it was necessary to compute the reminder value. Whether (if) we do not consider it, the project will be penalized due to the considerable amount of money to invest in later periods to reach the expansion needs in productive capacity of the INS proposed".*

EC-3: Argentina statement (Section 6.1 economics): *"It would be interesting to add to the methodology the study of financial resources to accomplish the project, regarding the important amounts involved. It would be also important to assess the short and long term degree of indebtedness.*

EC-4: Armenia statement (Section 6.2 economics): *Economic BP is rightly formulated but during fulfillment of calculations some difficulties occur, concerning to the shortage of numeric values of prices.*

EC-5: Armenian statement (Annex 1 criteria on economics, Table A.1): *Nuclear energy besides being a source of energy is also an item of strategic significance. For example for the RA it has as well a significance of energy independence and safety, as the nuclear energy is considered to be an internal resource. Therefore, in the problems of nuclear energy development planning, it is necessary to take into account not only the economic criteria, but the above mentioned as well, the transferring of which into economic indices is a rather complex problem.*

EC-6: Joint Study statement (JS Annex Japan, section 2. economics, 2.3 comments): *As for IN1.3.1 "licensing status" and IN1.3.4 "political environment", since both indicators also have aspects of infrastructure, it may be necessary to overview and rearrange the indicators.*

EC-7: Ukraine statement (Section 7.2 recommendations on improvement of INPRO methodology): *Economics: The INPRO methodology is to be improved regarding the acceptability of evaluations of the varied money value in relation to the complicated systems for the long period of time. Issues related to the justifiability of application of discount rate* *should be discussed in relation to the parameters of production output of end product in quantitative model.*

EC-8: Ukraine statement (Section 7.2 recommendations on improvement of INPRO methodology): *Insignificant quantitative differences of initial parameters in the options of the supposed structure of generating capacities in nuclear power of Ukraine and almost complete coincidence for all economic conditions of the activity (excluding the option of nuclear fuel leasing) predetermine a quite insignificant difference range of resultant evaluations. The maximum score exceeds the minimal score (excluding leasing option) only by 3.8%. This fact reduces the level of certainty in validation of single choice among the existing alternatives when there are a lot of risks, uncertainties and limitations in the continuous study.*

EC-9: Ukraine statement (Section 7.2 recommendations on improvement of INPRO methodology, Section 8 conclusion and recommendations 7.5): *There are some recommendations on improvement of the Methodology:*
As for the economic evaluations of multi component systems to validate the acceptability of a distinct option, the INPRO Methodology can be complemented with typical definition about equivalent consumption of relative fuel and specific consumption of nuclear fuel for electricity generation. It will enable to conduct a comparative assessment of economic effectiveness of various options to get additional quantitative characteristics in value terms and to specify the environmental benefits of nuclear energy.

EC-10: Ukraine statement (Section 7.2 recommendations on improvement of INPRO methodology): *There are some recommendations on improvement of the Methodology:*
Obvious irregularity of the accounting methodology is one of the significant drawbacks of the current methodology on accounting of expenses for resource provision of nuclear energy with nuclear fuel. It leads to the essential cost unbalance and diversion of appropriate profit to refill the working assets after accomplishment of appropriate budgetary obligations. In conditions of stare regulation of prices such obligation increases price burden on consumer and market economy enables to reduce the value of investing capabilities of the operating organization. The change of methodology is relatively low cost and feasible enough.

3.2. Proposals and comments for Economic basic principle BP

EC-11: Argentina statement (Section 6.1 economics): Change wording of BP to "*The technologies from innovative nuclear energy systems shall be affordable and available*"

3.3. Proposals and comments for Economic user requirement UR1

EC-12: Argentina statement (Section 6.1 economics): Change wording of UR1 to: "*The cost of product from innovative nuclear energy systems…*".

EC-13: Brazil statement (Section 6.2.2 economics, Section 8.2 conclusions): *Only one minor difficulty was faced when calculating the simplified levelized fuel costs. This relates to the application of equation 35 of Appendix A of INPRO Manual of Economics [13] for calculation of the quantity of heavy metal* HM_n *at stage n per unit of heavy metal finally included in the fuel* HM_{FE}*. The original formula should be corrected to (according [14]):*

$$\left(\frac{HM_n}{HM_{FE}}\right) = \prod_{m=n}^{N_{STAGES}} \left(\left(\frac{HM_n}{HM_{FE}}\right)_{IDEAL} x \left(1 + l_m\right)\right) \qquad (35)$$

$$\left(\frac{HM_n}{HM_{FE}}\right)_{IDEAL} = \begin{cases} F, & n = 1, 2 \\ 1, & n = 3, 4 \end{cases} \qquad (35a)$$

Where F, the ratio between the required units of uranium at enrichment feed ε_F *for isotope balance of a given unit of enriched uranium* ε_P *is given by equation(34) of Ref. [13], and n=1,2,3 and 4 refers to the services of uranium purchase, uranium conversion, uranium enrichment and fuel fabrication, respectively. If this suggestion is accepted, Tables 4.15 and 4.16 of INPRO Manual on Economics shall be modified accordingly.*

EC-14: Joint Study statement (Section 6.6): *(The second comment deals with selection of models for economic calculations.) The well known levelized unit energy cost (LUEC) model was proposed in the Manual for electricity cost calculations. An ability of the model to take into account specific features of the nuclear power economics was discussed in the works [6-10], [6-11]. In order to form position of their own in this regard, participants of the working group on economics together with some members of INPRO ICG have compared electricity cost calculated with the use of LUEC model with those produced by the Merchant Cash Flow (MCF) model developed in Massachusetts Institute of Technology [6-10]. Results of the comparison of these two approaches applied to the NPP with PWR and GT (Gas Turbine) Power Plants are discussed below. (Further details provided in the Joint Study report).*

3.4. Proposals and comments for Economic user requirement UR2

EC-15: Argentina statement (Section 6.1 economics): Change wording of UR2 to: "*The total investment required to design, construct, and commission technologies from innovative nuclear energy systems…*".

3.4.1. Proposals and comments for Economic criterion CR2.1

No comments.

3.4.2. Proposals and comments for Economic criterion CR2.2 (total investment)

EC-16: Joint Study statement (Section 6.6, feedback on the methodology improvement): *The detailed explanation given in the Manual on application of the criterion gives clear guidance to an assessor who is looking at deploying an INS rather than to an assessor who is determining whether to invest in developing of an INS or not. The principle difference between deploying of an INS and its developing consist in amount of investments to be input in RD&D. Even the leaders in mastering of the technology have not reached the state of its development when the use of CNFC-FR is profitable enough to cover cost of RD&D that are still needed to make a conclusive step to commercialization. Comprehensive consideration in the Manual of specific issues related to providing total investments into an innovative NS in comparison with investments into a proven NS would help to make more substantiated judgment on the criterion by different groups of assessors.*

3.5. Proposals and comments for Economic user requirement UR3

EC-17: Argentina statement (Section 6.1 economics): Change wording of UR3 to: "*The risk of investment in technologies from innovative nuclear energy systems…*".

3.6. Proposals and comments for Economic user requirement UR4

EC-18: Argentina statement (Section 6.1 economics): Change wording of UR4 to: "*Technologies from innovative nuclear energy systems…*".

4. Proposals and comments for INPRO area of Infrastructure

4.1. General proposals to INPRO methodology for infrastructure

IN-1: Armenian statement (Section 6.3 infrastructure): *The criteria of this section are presenting requirements to future user country in order for the latter to create conforming legislative framework, normative basis and their corresponding implementing bodies, which are responsible for ensuring their requirements. In our opinion any user country can provide comprehensive answers for these criteria.*

IN-2: Armenian statement (Section 8.2 conclusions): *Some of the user requirements do not concern directly to innovative nuclear energy systems (INS) such as UR1 (legal and institutional infrastructure) and UR3 (political support and public acceptance), as well as partly UR2 (industrial and economic infrastructure). Such kind of information is missing in case if country has no nuclear option yet.*

IN-3: Armenian statement (Section 8.2 conclusions): *There are no user requirements regarding to transportation issues. As the equipment of the nuclear power plant present separate units of great dimensions and mass, for example, body of the reactor, steam generator and etc, then for landlocked countries their delivery is a complex problem. For this reason, in INS development it is necessary to take into account the equipment transportation issue.*

IN-4: Joint Study statement (Section 11.4, feedback to INPRO methodology, Section 11.4.2 general comments): *Japan: Most of the indicators evaluate the nuclear development condition in a country rather than the difference of INS.*

IN-5: Joint Study statement (Section 11.4, feedback to INPRO methodology, Section 11.4.2 general comments): *Japan: There is a difficulty to evaluate some indicators at the stage of project planning. (ex. IN1.1.1, IN1.1.2, IN1.2.1, IN1.3.1, IN1.4.2, IN1.4.3).*

IN-6: Joint Study statement (Section 11.4, feedback to INPRO methodology, Section 11.4.2 general comments): *Republic of Korea: Provision of enough samples and guidance achieved through international collaboration with assessors in undeveloped or un-experienced countries for their successful assessment. In these points, the evaluation of several indicators will become more difficult for the country which has no experience with nuclear power generation. Therefore, the standard procedure should be provided and the revise of acceptance limits might be needed for the manual.*

IN-7: Joint Study statement (Annex Japan, Section 7.3 comments): *For the country which plans to construct an infrastructure from now, these indicators are valid as a check list.*

IN-8: Ukraine statement (Section 7.2 recommendations on improvement of the INPRO methodology, 7.2.8 infrastructure): *During the assessment of the Ukrainian INS infrastructure till 2100 with application of INPRO Methodology the effectiveness and validity of the proposed approach were checked and confirmed. The INPRO Manual on Infrastructure is vivid and easy to grasp due to the vast majority of examples related to the application of* *various assessment approaches. Ukrainian experts believe that the Manual enables to analyze the Ukrainian INS (present and future) gradually and in full scope.*

IN-9: Ukraine statement (Section 7.2 recommendations on improvement of the INPRO methodology, 7.2.8 infrastructure): *Practical use of the INPRO Methodology based on the example of the Ukrainian INS assessment confirmed that some proposed components of the methodology need to be discussed and specified, but others are quite ambiguous and even controversial. Therefore Ukrainian experts consider it to be useful to make the following proposals on further development of the INPRO methodology in the assessment of infrastructure.*

The existing infrastructure in Ukraine was analyzed in 2007, but the numerical score refers to future perspective by 2030.

We believe that it is not correctly to put the highest score 120 points to the NFC components located abroad, because there also may be problems (in the future it will be necessary to take numerical INPRO score of the Russian Federation on these components). It also refers to the leasing fuel that has not been legally developed yet, but gets 120 points.

IN-10: Ukraine statement (Section 7.2 recommendations on improvement of the INPRO methodology, 7.2.8 infrastructure): *the INPRO methodology does not consider the future deficit of large components of the reactor island for the countries which are only the users but not the manufactures of these components.*

IN-11: Ukraine statement (Section 7.2 recommendations on improvement of the INPRO methodology, 7.2.8 infrastructure): *There is no methodology on optimization during the assessment of determination of the Ukrainian participation in the perspective infrastructure of the nuclear industry in Ukraine with reactors EPR1500 and AP1000.*

4.2. Proposals and comments for Infrastructure basic principle BP

No comments.

4.3. Proposals and comments for Infrastructure user requirement UR1

No comments.

4.3.1. Proposals and comments for Infrastructure Criterion CR1.1 (legal aspects)

IN-12: Argentina comment (Section 8.2, conclusions and recommendations regarding the INPRO methodology, section 6.2 infrastructure) to question No.5 of EP1.1.2 Does the present regulatory system involve unnecessary financial or administrative burdens on regulated entities or regulatory agencies that could be reduced in order to improve efficiency? ***"****This question cannot be answered without a certain degree of subjectivity; "unnecessary financial or administrative burdens" will be judged differently in different organizations and by different people".*

4.4. Proposals and comments for Infrastructure user requirement UR2

IN-13: Joint Study statement (Section 11.4.1, feedback to INPRO methodology, specific comments): *Republic of Korea: Need Development of a quantitative method to determine benefits of nuclear program*

4.4.1. Proposals and comments for Infrastructure criterion CR2.1 (financing)

No comments.

4.4.2. Proposals and comments for Infrastructure criterion CR2.2 (energy market)

IN-14: Argentina statement (Section 6.2 infrastructure, Section 8.2 conclusions): *In state owned facilities, as is the case presently and presumably also in the near future in Argentina, financial return is not always a determining condition for the reasonability for the investment.*

4.4.3. Proposals for Infrastructure Criterion CR2.3 (size)

No comments.

4.4.4. Proposals for Infrastructure Criterion CR2.4 (support)

No comments.

4.4.5. Proposals for Criterion CR2.5 added value

IN-15: Joint Study statement (Section 11.4, feedback to INPRO methodology, Section 11.4.1 specific comments): *Japan: This acceptance limit requires cost estimation. However it is difficult to evaluate "Benefits to society" quantitatively. Only qualitative judgment is possible.*

IN-16: Ukraine statement (Section 7.2 recommendations on improvement of the INPRO methodology, 7.2.8 infrastructure): *User requirements mentioned in the INPRO methodology may be applicable to the infrastructure within the INS, but in the assessment of INS components some difficulties related to the application of some user criteria may appear, e.g. CR2.5 "added value". "benefit-cost" analysis could be transferred to the area "economics".*

4.4.5.1. Evaluation parameter EP2.5.1 (cost benefit study performed by national industry)

IN-17: Argentina statement (Section 6.2 infrastructure, Section 8.2.conclusions): *Has a cost benefit study performed by national industry? We don't have that information and, probably, most national planning systems will not either. The private industry will probably be wary of disclosing their strategic analysis. Local industry is generally well aware of the plans for nuclear expansion and there are good reasons to believe they do all the needed analysis to justify their possible investments.*

4.4.5.2. Evaluation parameter EP2.5.2 (study to define benefits of nuclear program to society)

IN-18: Argentina statement (Section 6.2 infrastructure, Section 8.2 conclusions): *Although there are studies that analyze the positive impact of in general high technology projects and in particular nuclear ones these are not quantitative and hence the value of this question should be taken as reminder for such positive impact in a rather qualitative way.*

4.5. Proposals and comments for Infrastructure user requirement UR3

No comments.

4.5.1. Criterion CR3.1 information

IN-19: Joint Study statement (Section 11.4, feedback to INPRO methodology, Section 11.4.1 specific comments): *Japan: It is suggested that the acceptance limit (AL3.1) for indicator IN3.1 is "sufficient according to the international practice" and not "sufficient according to the best international practice". (IN3.1, IN3.2)*

4.5.2. Criterion CR3.2 (participation of public)

IN-20: Joint Study statement (Section 11.4, feedback to INPRO methodology, Section 11.4.1 specific comments): *Japan: It is suggested that the acceptance limit for indicator IN3.2 is "sufficient according to the international practice" not "sufficient according to the best international practice".*

4.5.3. Criterion CR3.3 public acceptance

IN-21: Joint Study statement (Section 11.4, feedback to INPRO methodology, Section 11.4.1 specific comments): *France: the acceptance limit on public acceptance seems difficult to apply.*

4.6. Proposals and comments for Infrastructure user requirement UR4 (human resources)

No comments.

4.6.1. Proposals for Infrastructure Criterion CR4.1 (human resources)

No comments.

4.6.1.1. Infrastructure Evaluation parameter EP4.1.1 (educational and training system for manpower needed in NP projects)

No comments.

4.6.1.2. Infrastructure Evaluation parameter EP4.1.2 (attractiveness of the nuclear power sector)

IN-22: Argentina statement (Section 6.2 Infrastructure): *Although salaries are not competitive compared to those offered by general industry at the moment, the slope is positive and we can trust by 2010 they will. Employment conditions are adequate.*

IN-23: Ukraine statement (Section 7.2 recommendations on improvement of the INPRO methodology, 7.2.8 infrastructure): *It is difficult to assess the acceptance limit EP4.1.2 'nuclear energy sector attractiveness'.*

4.6.1.3. Infrastructure Evaluation parameter EP4.1.3 (capacity to accept the additional load of NP program)

IN-24: Argentina statement (Section 6.2 Infrastructure): *A shortage on human resources in the engineering areas and in the nuclear area in particular is a problem in the whole world.*

4.6.2. Proposals for Infrastructure Criterion CR4.2 (safety and security culture)

IN-25: Ukraine statement (Section 7.2 recommendations on improvement of the INPRO methodology, 7.2.8 infrastructure): *There are difficulties in the assessment of the acceptance limit AL4.2 "evidence that safety protection and culture is prevalent in case periodic reviews on safety protection and culture are available".*

5. INPRO area of waste management

5.1. General proposals and comments to INPRO methodology for waste management

WM-1: Argentina statement (Section 6.3 WM, Section 8.2 conclusions): *The chapter of waste management has undergone different structures of BPs, URs and CRs. The initial structure presented in TECDOC-1362 included 9 BPs (the 9 Fundamental Principles of radioactive waste management defined in Safety Series No. 111-F) 6 URs not linked to the BPs. The final structure presented in TECDOC-1434 included 4 BPs with 7 URs linked to the BPs. ANNEX-B (Ideas of future development of the INPRO methodology in the area of WM) of the INPRO manual of WM proposes a new structure of BP, reducing the 4 BP of TECDOC-1434 to a single one (BP3) and transforming the rest of the BPs and URs. It is worth noting that although the structure of the BP have been modified in the different proposals their final "bulk" content remained the same. Rearranging the structure of the BP or UR may simplify it, but if the final set of concepts defined is the same, the changes do not make much sense, as it does not add nothing substantial to the content of the chapter. This study is of the opinion that the structure of BP of TECDOC-1434 is adequate and the URs although redundant in some cases are clearly linked to each BP and fully cover their scope.*

WM-2: Armenia statement (Section 6.4 WM): *To satisfy the requirements of the given section is out of the users' awareness, as a result of which it is rather difficult to present comprehensive answers.*

WM-3: Joint Study statement (Annex Japan, Section 5.3 comments): *The way of evaluation will be altered according to the progress of the R&D activities. Therefore, they will help users evaluate the waste management area if various sets of criteria corresponding to the different R&D stages are presented.*

WM-4: Joint Study statement (Annex Japan, Section 5.3 comments): *If the EPs (Evaluation Parameters) for the waste management area are presented, it will be beneficial for the users.*

WM-5: Statement Ukraine (Section 7.2 recommendations on improvement of INPRO methodology, 7.2.6 radioactive WM): *Basic principles described in the INPRO Methodology can be applicable to the waste management system in the framework of INS, but application of some user criteria can be problematic in the assessment of INS components. For instance, for Waste Management BP3 (burden for future generations, and partiallyBP4 (optimization of waste management) user criteria accomplishment depends on development of waste management system and does not depend on the selected type of innovative power units. We propose to put those criteria that are necessary conditions for safe waste management and do not depend on the type of selected reactors within INS components into the group separate from the criteria that should be applied for comparison of options related to INS development.*

WM-6: Statement Ukraine (Section 7.2 recommendations on improvement of INPRO methodology, 7.2.6 radioactive WM): *The amount of alpha emitters and other long live radionuclides, total intensity, weight, volume and chemical toxic elements composing radioactive waste per GW(e) are user criteria for waste management BP1 (waste minimization). Facilities of NFC front and back end do not generate electricity and consequently it is impossible to apply these criteria directly in such form. With the purpose to compare the options of NFC front end development we propose to assess the amount and characteristics of waste per ton of relative fuel, and per ton of heavy metal for NFC back end.*

WM-7: Statement Ukraine (Section 7.2 recommendations on improvement of INPRO methodology, 7.2.6 radioactive WM): *Since INS development is considered within a specific period of time, satisfaction of waste BP3 (burden for future generations) it is reasonable to consider the ratio of waste volume that was disposed during the considered period to the full volume of waste that is predicted for this option of system development, as one of the user criteria.*

5.2. Proposals for Waste management basic principle BP1

No comments.

5.3. Proposals for Waste management user requirement UR1.1

WM-8: Argentina statement (Section 6.3 waste management): *The considerations of UR1.1 of the manual of WM read: For geological disposal, the alpha-emitters, with long lived, tend not to be mobile; rather, long lived anionic isotopes such as I-129, Cl-36, C-14 are of more concern. This study concludes that this distinction between them should be indicated in the UR1.1 and its related indicators. UR1.1 should then read: The innovative nuclear energy system (INS) should be designed to minimize the generation of waste at all stages, with emphasis on waste containing long-lived toxic components and those that would be mobile in a repository environment.*

5.3.1. Proposals for Waste management criterion CR1.1.1 (waste characteristics)

WM-9: Argentina statement (Section 6.3 waste management): *Because of the unit is missing in IN1.1.1 (first line) it should read: Total activity of alpha-emitters and other long-lived radio-nuclides per GWa.*

WM-10: Argentina statement (Section 6.3 waste management): *according to the new UR1.1 proposed, a new indicator is proposed: IN1.1.2: total activity of long-lived anionic isotopes mobile in a repository environment per GWa.*

WM-11: Argentina statement (Section 6.3 waste management, Section 8.2 conclusions): *Regarding the indicators related to UR1.1, it is to be noted that, while the concept of ALARP is an adequate Acceptance Limit (AL) to be used in a screening assessment, it does not allow to compare the generation of waste of different INSs in a comparative assessment. This study does not propose to change the AL, but rather proposes that the manual should specifically mention, in the considerations of the UR1.1, that when performing a comparative assessment, besides the use of ALARP as AL, a table should be used for comparing the generation of waste of the different INSs. The table could have the following structure:*

INS	Mining waste	LLW	ILW	HLW
INS1				
Activity per GWa				
Mass per GWa				
Volume per GWa				
INS2				
Activity per GWa				
Mass per GWa				
Volume per GWa				

WM-12: Joint Study statement (Annex Japan, Section 5.3 comments): *ALs for UR1.1 are "ALARPs", but they will make it difficult for users to evaluate INSs. The typical values for the existing LWR cycle may be appropriate as alternative ALs.*

5.4. Proposals for Waste management basic principle BP2

No comments.

5.5. Proposals and comments for Waste management user requirement UR2.1 (protection of human health)

No comments.

5.6. Proposals and comments for Waste management user requirement UR2.2 (Protection of the environment)

WM-13: Argentina statement (Section 6.3 waste management, Section 8.2 conclusions): *IAEA Safety Series No.111-F defines "release" (discharge routine) as: a planned and controlled release of radionuclides into the environment; such releases should meet all restrictions imposed by the appropriate regulatory body. From the definition previously stated, this study concludes that UR2.2 should be excluded from the chapter (manual) of WM, as the subject is already included in the chapter (manual) of environment. UR1.1 of the chapter (manual) of environment reads: The environmental stressors from each part of an INS over the complete life cycle should be controllable to levels meeting or superior to current standards. In the considerations to (environment) UR1.1 it is expressed that the stressors include radioactive and non-radioactive emissions, heat discharges and mechanical energy.*

5.7. Proposals and comments for Waste management basic principle BP3

No comments.

5.8. Proposals for Waste management basic principle BP4

No comments.

5.9. Proposals for Waste management user requirement UR4.1 (waste classification)

No comments.

5.9.1. Proposals for Waste management Criterion CR4.1.1 (classification)

WM-14: Argentina statement (Section 6.3 waste management, Section 8.2 conclusions): *The definition of radioactive waste according to IAEA Safety Series No.111-F is: for legal and regulatory purposes, radioactive waste may be defined as material that contains, or is contaminated with radionuclides at concentrations or activities greater than clearance levels as established by the regulator body, established by the regulatory body in a country or state, expressed in terms of activity concentrations and/or total activities, at or below which sources of radiation can be released from nuclear regulatory control. This study is of the opinion that, in order to avoid unnecessary increasing of the cost and volumes involved in the management of radioactive waste, an unambiguous clearance level should be defined by the regulatory body. So in this manner the complete scheme may be defined as, i.e. (in increasing level of radioactivity): clearance level LLW, ILW, HLW. Accordingly we propose for UR4.1 a new indicator (apart from 'classification scheme'): Clearance level. The corresponding acceptance limit should be: Clearance level defined by regulatory body that permits unambiguous definition of radioactive waste.*

5.10. Proposals for Waste management user requirement UR4.2 (predisposal waste management)

No comments.

5.10.1. Criterion CR4.2.1 (time for waste form production)

WM-15: Joint Study statement (Annex Japan, Section 5.3 comments): *AL4.2.1 should be modified because it is not necessary to observe the principle of "As short as reasonably practicable" at the time of producing the waste form specified for the end state.*

6. INPRO area of proliferation resistance (PR)

6.1. General statements and proposals to INPRO area of PR

PR-1: Argentina statement (Section 6.4 PR, Section 8.2 conclusions): *technically the methodology is well presented and it is easy to understand and work with. Nevertheless, although the evaluation parameters are clear, they are not compared to an AL, and the Potential or No-Potential conditions are not obtained readily from them. The methodology presented in Annex A does not define Acceptance Limits, only qualifies the evaluations parameter values as weak or strong.*

The main conclusions obtained in the PR area was that: Any innovative nuclear energy system (INS) operating PWRs, PHWRs, enrichment or reprocessing facilities, when assessed with the INPRO methodology, presents several weaknesses, meaning that more safeguarding effort is necessary. This result is independent of the signature of related international treaties and/or the implementation of a comprehensive safeguard agreement.

Taking this into account, the methodology should be improved by adding other user requirements and evaluation parameters to take into account the safe and secure use of enrichment, reprocessing and heavy water moderation. For example accountability and control systems, remote monitoring, more value assigned to the agreement with the international treaties, historical background of the country, etc.

PR-2: Argentina statement (Section6.4): *Finally when qualifying some EP many options can be chosen simultaneously e.g. because the presence of three type of material in the INS under evaluation. Some evaluators could choose the best conditions, very strong, while others more conservative could choose moderate.*

PR-3: Armenia statement (Section 6.5 PR): *PR BP requirement is regulated by the internal legislation of the country and international agreements to which the country has joined. In our opinion the users' non provision of answers to detailed requirements is conditioned by the lack of corresponding complete information related to INS.*

PR-4: Joint Study statement (Section 10.4, feedback for improvement of methodology and User's manual): *The intrinsic features and extrinsic measures are clear to understand and utilize for the proliferation of the INS CNFC-FR. However, the selection of the reliable and commonly acceptable values of the acceptance limits still needs further study.*

PR-5: Joint Study statement (Section 10.4, feedback for improvement of methodology and User's manual): *The evaluation of indicators dealing with the multiple intrinsic features and extrinsic measures and their robustness, requires the establishment of comprehensive* *scenarios on acquisition paths for nuclear proliferation. It would be difficult for the assessor to determine them especially in case of an INS under development.*

PR-6: Joint Study statement (Section 10.4, feedback for improvement of methodology and User's manual): *In the cost effectiveness analysis of optimization in the design/engineering phase, it would be difficult especially for the designer to evaluate proliferation resistance quantitatively in a balanced manner for lack of detailed design information.*

PR-7: Joint Study statement (Section 10.4, feedback for improvement of methodology and User's manual): *From the assessment of PR of the INS CNFC-FR (several) the following general finding(s) and feedback(s) for improving the methodology and user's manual (are) is (additionally) given as follows: International societies should reach a kind of International Standard (or consensus) to be attained as an effective acceptable level in proliferation resistance measures. To achieve this goal, it is suggested that the evaluation scales for intrinsic features should be changed, but not to be used as the acceptance limits.*

PR-8: Joint Study statement (Annex Japan, Section 6.3 comments): *Numerical evaluation scales illustrated in the PR manual should be changed to be more qualitative ones.*

PR-9: Joint Study statement (Annex Japan, Section 6.3 comments): *There is a difficulty to evaluate some indicators at the stage of project planning.*

PR-10: Joint Study statement (Annex Japan, Section 6.3 comments): *Evaluation scale "Analysis is not yet done, but to be done" is strongly recommended at the concept design stage.*

PR-11: Joint Study statement (Annex Japan, Section 6.3 comments): *It is suggested that the acceptance limits should be changed to "sufficient according to international practice".*

6.2. Proposals and comments to PR basic principle BP

No comments.

6.3. Proposals and comments to PR user requirement UR1

No comments.

6.4. Proposals and comments to PR user requirement UR2

PR-12: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN2.1 - 2.4), numerical evaluation scales in the user's manual should be defined more qualitative ones.*

PR-13: Joint Study statement (Annex Japan, Table 6.1): *Each scale seems to be without generic guarantee.*

PR-14: Joint Study statement (Annex Japan, Table 6.1): *As the extrinsic measures are implemented on the base of intrinsic features, the evaluation should be modified to integrate the both.*

PR-15: Joint Study statement (Annex Japan, Table 6.1): *Expert judgment should not be done with a single base of low IN or low EP.*

6.5. Proposals and comments to PR user requirement UR3

No comments.

6.5.1. **CR3.1.** quality of measurement system

PR-16: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN3.1 – IN 3.5, IN4.2), it is difficult for the assessor to evaluate the proliferation resistance appropriately especially at very early stages of INS development including project planning because of the lack of detailed information.*

6.5.2. **CR3.2.** C/S measures and monitoring

PR-17: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN3.1 – IN 3.5, IN4.2), it is difficult for the assessor to evaluate the proliferation resistance appropriately especially at very early stages of INS development including project planning because of the lack of detailed information.*

6.5.3. **CR3.3.** Detectability of NM

PR-18: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN3.1 – IN 3.5, IN4.2), it is difficult for the assessor to evaluate the proliferation resistance appropriately especially at very early stages of INS development including project planning because of the lack of detailed information.*

6.5.4. **CR3.4.** facility process

PR-19: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding acceptance limits (AL3.4 to AL3.6), it is recommended that the acceptance limit should be modified to "sufficient according to international practice".*

PR-20: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN3.1 – IN 3.5, IN4.2), it is difficult for the assessor to evaluate the proliferation resistance appropriately especially at very early stages of INS development including project planning because of the lack of detailed information.*

6.5.5. **CR3.5.** Facility design

PR-21: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding acceptance limits (**AL3.4 to AL3.6**), it is recommended that the acceptance limit should be modified to "sufficient according to international practice".*

PR-22: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN3.1 – IN 3.5, IN4.2), it is difficult for the assessor to evaluate the proliferation resistance appropriately especially at very early stages of INS development including project planning because of the lack of detailed information.*

6.5.6. **CR3.6.** facility misuse

PR-23: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding acceptance limits (**AL3.4 to AL3.6**), it is recommended that the acceptance limit should be modified to "sufficient according to international practice".*

6.6. Proposals and comments to PR user requirement UR4

No comments.

6.6.1. Criterion CR4.1 (effectiveness of features and measures)

PR-24: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN 4.1 and IN4.2), the evaluation of the multiple barriers and its robustness requires the establishment of the comprehensive diversion scenarios for the proliferation, which is difficult to determine in the case of INS.*

6.6.2. Criterion CR4.2 (robustness of barriers)

PR-25: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN4.1 and IN4.2), the evaluation of the multiple barriers and its robustness requires the establishment of the comprehensive diversion scenarios for the proliferation, which is difficult to determine in the case of INS.*

PR-26: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicators (IN3.1 – IN 3.5, IN4.2), it is difficult for the assessor to evaluate the proliferation resistance appropriately especially at very early stages of INS development including project planning because of the lack of detailed information.*

PR-27: **Joint Study statement (Annex Japan, Table 6.1):** *CR4.2 is Impossible to evaluate; Robustness is not explicitly explained during the development of the evaluation methodology.*

6.7. Proposals and comments to PR user requirement UR5

No comments.

6.7.1. Criterion CR5.1 (inclusion of PR in INS design)

No comments.

6.7.2. Criterion CR5.2 (cost of proliferation resistance features and measures)

PR-28: Joint Study statement (Section 10.4, Feedback for improvement of methodology and user's manual): *Regarding indicator IN5.2, it is recommended that "Analysis is not yet done, but to be done" should be given as Strong at early stages of INS development.*

6.7.3. Criterion CR5.3 verification approach

No comments.

7. INPRO area of physical protection (PP)

7.1. General statements and proposals to INPRO area of PP

PP-1: Argentina statement (Section 8.2 conclusions): *The methodology applied for the assessment in the area of PP is complete and consistent.*

PP-2: Armenia statement (Section 6.6 PP): *It is desirable to clarify what generalized conclusions can be expected after ticking acceptance limits YES and NO.*

7.2. Proposals and comments to Physical protection basic principle BP

No comments.

7.3. Proposals and comments to Physical protection user requirement UR1

No comments.

7.4. Proposals and comments to Physical protection user requirement UR2

No comments.

7.4.1. Physical protection criterion CR2.1 (PP integration with PR, safety and operations)

No comments.

7.4.2. Physical protection criterion CR2.2 (PP consideration in all INPRO areas)

No comments.

PP-3: Argentina statement (Section 6.5 PP, Section 8.2 conclusions): *This criterion is redundant and should not be included. All the remaining INPRO areas concerns are well defined, and there is no need to consider explicitly PP aspects in any of them. It is obvious that all INPRO areas must implicitly consider the rest of the areas. If this criterion were included, it would make sense to add in each area a criterion as such: Is there any evidence about the fact that the assessment in this area has accounted for economy, safety environment, WM, PR, PP and infrastructure?*

No comments to the rest of URs in the area of PP.

8. INPRO area of environment

8.1. General statements and proposals to INPRO area of environment

EV-1: Joint Study statement (executive summary, Section 2.9.2): *Along with merits of the INPRO assessment method, the study revealed some drawbacks of the approach. Inability to right estimate the options for HLW transmutation allowing to reduce the radio-toxicity inventory and the thermal power in the final disposal was identified in the environmental domain of assessment.*

The joint study has emphasized an expediency to increase the discriminative power of the assessment method with an aim to provide better navigation among the ways of nuclear system development and prioritizing of R&D to be carried out. As for experience of the Joint Study, it failed, using the methodology developed, to discriminate scenarios implementing very different levels of HLW transmutation and assess their environmental benefits at the back end of the innovative nuclear energy system CNFC-FR. As it resulted from calculation analysis, the HLW transmutation would allow reducing the radio-toxicity inventory and the thermal power in the final disposal, and could have a non negligible impact on quality and performance of waste. However, from the criteria of the current INPRO manual, better performance of waste provided by the HLW transmutation does not bias the judgment regarding the health and environmental qualities of the assessed system since all positive changes that happens due to application of transmutation strategies lay in the tolerance range where performance of waste is better than AL.

EV-2: Joint Study statement (Section 7.4, current limitations of the approach used): *Indeed, what should be considered as the approach main limitation is the fact that it makes the assumption of a normal behaviour of all facilities, and therefore excludes any accident. This comment relates not only to the approach used in the study but to the guidance of the INPRO methodology and manual as well. A normal behaviour implies that all safety specifications are respected, with no significant health impact, rendering difficult to discriminate between various nuclear scenarios. But to integrate a risk assessment in INPRO evaluation would* *require a specific and heavy development, taking into account all fuel cycle steps and facilities, with no guarantee of success considering the heterogeneity of the facilities and of the time scales associated to various HLW options, from transmutation to geological disposal.*

EV-3: Joint Study statement (Section 7.5, feedback for the methodology improvement): *An important conclusion of the study is that it is not possible, using the methodology developed for assessing of the environmental and health impact of a nuclear power scenario, to really discriminate scenarios implementing very different levels of HLW transmutation, representative of the whole range of available options.*
This result is coherent with the assumption of normal behaviour of the fuel cycle facilities, complying with safety specifications. Main discrepancies between these scenarios concern the uranium consumption, which is strongly limited in case of FBR deployment, and greenhouse gas emission, which is reduced for FBR fleet, due to the stopping of uranium enrichment by gaseous diffusion. Anyway, this impact remains very low if compared to fossil energy production.
However, other indicators – at the boundary of the scope of this work- may be sensitive to the different scenarios. HLW transmutation would allow reducing the radio-toxicity inventory and the thermal power in the final disposal, and could have a non negligible impact on quality and performance of waste. But these indicators, well representative of reprocessing-recycling and transmutation efficiency, cannot be associated by the methodology used to a health and environmental impact. It means that it is necessary to find other criteria in order to discriminate between HLW management options.

EV-4: Joint Study statement (Annex Japan, Section 3.3 comments): *The relationship to the "Environment Impact Assessment" Laws and Acts, which would have been established in almost all of the INPRO member countries based on the "Basic Environmental Law" (1993) of the United Nations, should be mentioned in the manual because the assessment items are almost common between them as follows:*

- *The environmental stressors assessed in environmental impact assessments (EIA) are stipulated in the "Environmental Impact Assessment Law" in Japan.*

- *As for nuclear power plants, they are raised as special cases regarding the application of the law.*

- *The special provisions are also stipulated in the "Electricity Utilities Industry Law" in Japan. All the innovative nuclear energy systems (INS) will meet the criteria set by the regulatory authorities when they are deployed.*

- *The stressors in the EIA are evaluated for the specific site. (Not site-generic evaluation).*

EV-5: Joint Study statement (Annex Japan, Section 3.3 comments): *The manual should be prepared so as to assess the potential conformity of the INS to the environment according to the instruction manual. (The present manual refers to a lot of documents and shows their studies as examples in many pages, however, it is difficult for our assessors to understand the manual without reading these references.)*

EV-6: Joint Study statement (Annex Japan, Section 3.3 comments): *The manual should distinguish the items to be assessed according to the maturity level (site selected or not, preliminary, conceptual or final design/ construction/ operation etc.) in the development of INS, because the items to be assessed may be limited in the early design stage of INS.*

EV-7: Joint Study statement (Annex Japan, Section 3.3 comments): *It should be cleared that what the meaning of "off-normal events" (mentioned in the present manual on page 9) is. If the "off-normal events" equals to "Abnormal events," it should be excluded from the environmental assessment because they are already considered as the "Abnormal events" in the safety analysis.*

8.2. Proposals and comments for environment basic principle BP1

EV-8: Armenia statement (Section 6.7 environment, Annex 6 Table A.6): *The environment BP1 is generally acceptable, but the user (assessor) is not able to have a full package of information on all stressors for different INS. Also, it is possible that the user has no standards for the stressors which meet the requirement of AL1.1.1.*

8.2.1. Proposals and comments for environment user requirement UR1.1

EV-9: Argentina statement (Section 6.6 environment): *Regarding UR1.1 it must be mentioned that the level of stressors is directly proportional to the capacity of the facility. In order to make a comparison with a standard, it is difficult to find a facility with the same technology and capacity. For this reason, it is proposed to use the Normalized level of stressors (i.e. Bq/tU) normalizing with the capacity of the facility, instead of using the level of stressors (Bq).*

EV-10: Joint Study statement (Annex Japan, Section 3.3 comments): *Concerning UR1.1, it is doubtful that some of the items (i.e. Society, Quality of Life, Biodiversity, Psychology, Property values, Politics and Infrastructure) which are not evaluated in Japan's EIA should be evaluated here, because evaluating such stressors is very difficult and the meaning of the evaluation is not clear. If necessary, the meaning of these items should be mentioned in the present manual.*

EV-11: Statement Ukraine (Section 7.2 recommendations on improvement of INPRO methodology, 7.2.7 environment): *Basic principle BP1, UR1.1, IN1.1.1, Assessment of radiological stressors, List of radionuclides: The results of the Ukrainian INS assessment demonstrated that the list of radionuclides whose environmental impact can be assessed lower that mentioned in the document "Guidance for the application of an assessment Methodology for innovative nuclear energy systems; INPRO Manual-Environment; IAEA Vienna, October 2007" (hereafter - "Manual – Environment"). Long term practical experience of operation of Ukrainian NFC facilities demonstrated that the current control supports the feasibility of assessment related to the impact of the facilities on the environmental institutions and human health.*
We propose to include in the list the following radionuclides which are obligatory for calculation assessment:
<u>A) NFC front end</u>
– uranium ore mining and milling: air – U-238, Ra-226, Th-230, Pb-210, Po-210, Rn-222; water – U-238, Ra-226, Th-230, Pb-210, Po-210;
– zirconium production: U-238, Ra-226, Th-232;
– nuclear fuel fabrication from enriched UF6: air – Ra-226, U-234, 235, 238; water – U-234, 235, 238, Th-234;
<u>B) Electricity generation</u>
The list of radionuclides whose intensity in the Ukrainian NPP discharges is obligatory controlled by organizational control means (according to information from NPPs): Cr-51, Mn-54, Fe-59, Co-58, Co-60, Zn-65, Sr-89, Sr-90, Zr-95, Nb-95, Ru-103, Ag-110m, Sb-124, Cs-134, Cs-137, Ce-144, I-131, Kr-88, Xe-133, Xe-135.

The estimate of H-3 concentration is recommended to be indicated as an obligatory parameter only for surface impoundment next to the NPP. There is no predictive estimate of tritium in the assessment of the Ukrainian INS because the monitoring of tritium in the surface impoundment at some Ukrainian NPPs (Zap NPP, SU NPP and KHNPP) was initiated only in 2004 and there is no information about annual surface impoundment of tritium at every NPP (that is necessary for predictive estimate) in the report documents.

The estimate of C-14 intensity concentration in the air should be made non obligatory for NPPs (based on the wish of the assessor) because C-14 is key radioactive stressor in the discharges of thermal power plants and its share for NPPs in overall discharges is very small (according to the information from the NPPs). Therefore there is no control of C-14 at the Ukrainian NPPs and its input data is not provided.

C) NFC back end

According to the design data for CSFSF the main radionuclides contributing to the possible discharge from the facilities of SNF temporary storage are Cs-137 (less than 0.1%) and Co-60 (more than 99.9%). These radionuclides will be monitored in the discharge and input data on them will be provided for the assessment. We propose to leave only these two radionuclides in the list of the assessed stressors for SNF temporary storages.

EV-12: Statement Ukraine (Section 7.2 recommendations on improvement of INPRO methodology, 7.2.7 environment): *Assessment of non radiological stressors; Acceptance limits: The value of maximum allowable concentrations (MOC) of chemical elements and compounds in the water and in the air is regulated by national (state and industrial) regulatory documents in Ukraine (as probably in many other countries). The MOC values from the international documents recommended in the Manual Environment (Air quality guidelines for Europe, 2nd ed. WHO Regional Publications, European Series No.91, 2002, Guidelines for drinking water quality: incorporating first addendum Vol.1, WHO recommendations, 3rd ed, 2006), may be used as acceptance limits only when there are no appropriate MOC values in the national regulatory documents. We propose to state it clearly in the next edition of the Manual Environment.*

EV-13: Statement Ukraine (Section 7.2 recommendations on improvement of INPRO methodology, 7.2.7 environment): *Assessment of non radiological stressors: Assessment method of the impact of non radiological stressors on humans was not described in the current version of the Manual Environment.*

Based on the experience of assessment performed during the national study of Ukraine we can propose to perform the assessment of concentration of the chemical elements and compounds in the water on the basis of the simplified conservative approach at the current stage of the INPRO methodology development. This approach implies the specification of average (for 5 – 10 years) contribution of the operating typical power unit to the concentration accumulation at the expense of discharges for every NPP (taking into account the values of background concentration). Recalculation is performed for new perspective power units (separately for every NPP) considering the difference in electric power. Annual concentration values due to the NPP discharges (during the whole life cycle) will be determined by accumulation of contribution of separate power units. Implementation of this approach does not require sophisticated software and input data is accessible in the appropriate annual reports on the assessment of NPP environmental impact.

8.3. Proposals and comments for environment basic principle BP2

EV-14: Armenia statement (Section 6.7 environment): *In total for BP2 it should be noted that the criteria have rather some formal and common meaning, and have not been in direct relation with the user.*

EV-15: Joint Study statement (Annex Japan, Section 3.3 comments): *The current name of BP2 should be revised into an appropriate one to understand the content from the name, for example, "Efficient use of non-renewable resources."*

8.3.1. Proposal for environment user requirement UR2.1 (consistency with resource availability)

No comments.

8.3.1.1. Criterion CR2.1.1 fissile material (availability of resources)

EV-16: Argentina statement (Section 6.6): *Regarding Indicator IN2.1.1 all the demand scenarios estimate the future demand in terms of power required (GW(e)). A key parameter that is not considered is the average burnup of the spent fuel that the NPPs of the INS will achieve. This parameter directly influences (in) the rate of consume (consumption) of fissile/fertile material. As a consequence the judgment of the Indicator will depend on the burnup assumed. It would be useful if a burnup future scenario is proposed to be used by all the assessments.*

EV-17: Joint Study statement (Annex Japan, Table3.1, evaluation results): *It is meaningless for each country to evaluate Fj(t) because it depends largely on many factors such as INS installation rate and capability of conventional nuclear facilities.*

8.3.1.2. Criterion CR2.1.2 non renewable material (availability of non-renewable resources)

EV-18: Joint Study statement No.1 (Annex Japan, Table3.1, evaluation results): *Non-renewable resources to be evaluated should be limited to key, critical or strategic non-renewable resources.*

8.3.1.3. Criterion CR2.1.3 power

EV-19: Armenia statement (Annex 6, Table A.6): *It is not understandable how much P(t) should be more than* P_{INS}*?*

EV-20: Joint Study statement (Annex Japan, Table3.1, evaluation results): *Every INS must meet this requirement because we are developing energy generation systems, therefore this AL is nonsense.*

8.3.1.4. Criterion CR2.1.4 (end use uranium)

EV-21: Armenia statement (Annex 6, Table A.6): *It is not understandable how much end use U should be more than max available once through PWR?*

EV-22: Joint Study statement (Annex Japan, Table3.1, evaluation results): *U availability (Utilization factor of U) as an indicator is better than Net Energy U.*

8.3.1.5. Criterion CR2.1.5 (end use thorium)

***EV-23: Armenia statement (Annex 6, Table A.6):** The criteria are acceptable but how much more Th should be available?*

***EV-24: Ukraine Statement (Section 7.2 recommendations on the improvement of the INPRO methodology, 7.2.7 environment):** Basic principle BP2, UR2.1, IN2.1.5: Ukrainian experts believe that the assessment requirement on this indicator with the INPRO Methodology application should be a recommendation (at the discretion of the country assessor). It must be indicated clearly in the Manual Environment. This proposal can be motivated by the following statements:*

- according to strategy of electric power industry development of Ukraine till 2030 non of the thorium cycle elements will be implemented in Ukraine. Therefore this issue will not be solved till 2100.

- according to the Manual Environment data on real thorium resources in the world is limited enough (there is no data on deposits in China, Western and Eastern Europe, former USSR). This will make the assessment results incorrect to make a valid conclusion.

8.3.1.6. Criterion CR2.1.6 (end use non renewable resource)

***EV-25: Joint Study statement (Annex Japan, Table3.1, evaluation results):** the purpose is unknown.*

8.3.2. Proposal and comments for environment user requirement UR2.2 (adequate net energy output)

No comments.

8.3.2.1. Criterion CR2.2.1 (amortization time)

***EV-26: Joint Study statement (Annex Japan, Table3.1, evaluation results):** Energy for decommissioning should be included into the energy input. The Energy Profit Ratio (EPR) is rather suitable for UR 2.2 because TEQ largely depends on an introducing rate of INSs, etc. and it is very difficult to evaluate it. O. Amano, CREIPI estimates the EPRs for LWR and FBR cycles: 17.6 for LWR cycle, around 30-40 for FBR cycle. (J. of Atomic Energy Society of Japan, Vol.48, No.10, 2006, in Japanese).*

***EV-27: Ukraine Statement (Section 7.2 recommendations on the improvement of the INPRO methodology, 7.2.7 environment):** BP2, UR2.2, IN2.2.1.*

Ukrainian experts believe that application of this indicator for the assessment of INS environmental impact is not validated enough. Section 4.3.1 of the Manual Environment does not explain how to use this indicator in the assessment – there is no clear explanation what should be the value of numerical factor k in the assessment with this indicator to consider new INS more acceptable in comparison with the existing INS. This issue must be specified in the next revisions of the Manual Environment.

The ratio "generated INS electricity/consumed INS electricity" for the existing Ukrainian INS is more than 1 (generated electricity significantly increases the amount of electricity consumed by the NFC facilities during their operational period). Since load factor of new power units exceeds the load factor of operating power units in Ukraine at 8-10% in the similar operational conditions, new INS will definitely provide generation of large amount of electricity for the same operational period of power units.

Experts involved in the assessment related to the area Environment think that it is more correctly not to consider this indicator separately from the environment but consider it in the development of INS configuration options. The acceptance limit AL2.2.1 for indicator IN2.2.1 must be satisfied a priori during the selection of number and type of power units, SNF reprocessing facilities and back end facilities.

9. INPRO area of safety

9.1. General statements and proposals to INPRO area of safety

SF-1: Argentina statement (Section 6. feedback from the application of the INPRO methodology, 6.7. safety of NFCF): *the manual of the INPRO methodology on safety of nuclear fuel cycle facilities does not include BPs, URs and CRs for facilities such as refining/conversion and spent fuel storage facilities. As a consequence we consider that these should be included.*

SF-2: Armenia statement (Section 6.8 safety of nuclear installations and NFCF): Innovative nuclear energy system *(INS) unit safety of nuclear installations and nuclear fuel cycle facilities requirements are acceptable unquestioningly that is why the user has nothing to add.*

SF-3: Joint Study statement (Section 8.4, assessment by participants): *India has applied INPRO methodology to CNFC-FR. Certain indicators are found to be duplicated (frequency of occurrences, consequences of events, etc). With the absence of a common benchmark INS, it is not possible to quantify the parameters in the present assessment (design simplicity, robustness, depth of R&D, safety criteria). Only relative assessment is possible. Grading should be assigned for the parameters representing the user requirements.*

SF-4: Joint Study statement (Section 8.4, assessment of FCF): *INPRO assessment [8-13] of CNFC-FR safety indicates that:*

(1) Assessment parameters for FRFCF need to be specific to NFCF and not same as reactors. For example, UR 2.1, sample indicators - available excess reactivity and reactivity feedback- are not relevant for NFCF. UR1.5-Release of radioactivity into confinement/containment and UR1.3- Safe shutdown state- are not relevant for NFCF. One needs to talk about prevention of re-criticality and contamination.

(2) Lack of quantitative parameters for indicators and their acceptance limits is observed. Various initiating events have to be identified and the design basis events defined in a comprehensive manner. For these scenarios, acceptance limits for the indicators (for example, grace time) need to be evolved by consensus.

A consensus on safety analysis methodologies should emerge among various countries after detailed deliberations. Seismicity has to be considered in safety analysis. Probabilistic safety analysis for FRFCF needs to be developed and standardized. This requires considerable international efforts to render it as a viable tool for safety analysis.

SF-5: Joint Study statement (Annex Japan, Section 4.3.1 comments on reactor): *It is recommended to use technical terms in a consistent manner and clarify the definition of the technical terms: IN 2.1.2 (expected frequency of abnormal operation and accidents) in comparison with IN 1.1.4 (expected frequency of failures and disturbances) and IN 1.3.1 (calculated frequencies of occurrence of design basis accidents).*

SF-6: Joint Study statement (Annex Japan, Section 4.3.1 comments on reactor): *It is recommended to use technical terms in a consistent manner and clarify the definition of the technical terms: IN 2.1.3 (consequences of abnormal operation and accidents) in comparison with IN 1.5.2 (calculated consequences of release), IN 3.1.1 (occupational dose values) and IN 3.2.1 (public dose values)*

SF-7: Joint Study statement (Annex Japan, Section 4.3.2 comments on safety assessment manual for reprocessing facility): *It is recommended to use technical terms in a consistent manner and clarify the definition of the technical terms: "Major release" in IN1.4.1 (calculated frequency of major release of radioactive materials into the containment/confinement) and IN1.5.1 (calculated frequency of major release of radioactive materials to the environment) in terms of the difference from IN 1.3.1 (calculated frequencies of occurrence of design basis accidents).*

SF-8: Ukraine statement (Section 6.8 Conclusions on the results of the Ukrainian INS assessment, Section 7.2 recommendations on improvement of the INPRO methodology, 7.2.5 safety): *First of all the INPRO Methodology refers to the assessment of reactor technologies that resulted in the development of user requirements and assessment criteria. As for the front end components it is rather problematic to apply some indicators (e.g. indicators of UR1.5 to nuclear fuel fabrication).*

SF-9: Ukraine statement (Section 6.8 Conclusions on the results of the Ukrainian INS assessment): *The comparative assessment on compliance with the acceptance limits, especially referring to the safety of INS components, require specific input data. Therefore it can be useful to compose a table of necessary technical parameters that can be provided to the project members by the designers of appropriate technologies upon IAEA request. Mechanism of sensitive information transfer should be also be developed.*

SF-10: Ukraine statement (Section 6.8 Conclusions on the results of the Ukrainian INS assessment): *Assessment of compliance with the basic principles refers to the analyses of various technologies and requires specific knowledge and expertise in these technologies (e.g. assessment of reactor installations). Considering the nature of current research and identity of PWR/WWER reactors we can talk about the acceptability of then performed assessments. However, in case of analysis of alternative reactor types (CANDU or FR), involvement of IAEA experts may be required that requires the development of appropriate mechanisms of cooperation between the IAEA and the country assessor.*

SF-11: Ukraine statement (Section 6.8 Conclusions on the results of the Ukrainian INS assessment): *The INPRO methodology includes a comparative assessment, but excludes distinct recommendations on putting numerical score to the INS configuration options. Therefore every country involved in the project has to develop its own instruments of numerical score. Unification of the methodology on quantitative assessment of INS configuration options must be carried out.*

9.2. Proposals and comments for safety basic principle BP1

No comments.

9.3. Proposals and comments for safety user requirement UR1.1

No comments.

9.3.1. Criterion CR1.1.1 (robustness0

SF-12: Joint Study statement (Annex Japan, Section 4.3.1 comments on reactor): *Concerning the simplicity and margins discussed in IN1.1.1 (i.e. robustness of design), if there is an excessive margin in some part of the existing reactor, it should be also regarded as "superior" to reallocate the excessive margin so as to optimize both the entire safety and the other viewpoints; i.e. shortening the piping brings about both the simplicity in prevention system (i.e. reduction of system failure rate) and the capital cost reduction while the structural reliability margin might be relatively reduced.*

9.3.2. Criterion CR1.1.2 (operation)

SF-13: Joint Study statement (Annex Japan, Section 4.3.1 comments on reactor): *Concerning IN1.1.2 (i.e. high quality of operation), it is better to show us the detailed guideline of the estimation methodology. Otherwise, practically it might be better to require the evaluation of this indicator after INS enters the operating phase. This is because no one can prove the reliability of the innovative components/devices equal to or superior to that of the existing ones on the basis of the classic statistical calculation.*

9.3.3. Criterion CR1.1.3 (inspection)

No comments.

9.3.4. Criterion CR1.1.4 (failure and disturbances)

SF-14: Joint Study statement (Annex Japan, Section 4.3.1 comments on reactor): *Concerning IN1.1.4 (i.e. expected frequency of failures and disturbances), it is better to show us the detailed guideline of the estimation methodology. Otherwise, practically it might be better to require the evaluation of this indicator after INS enters the operating phase. This is because no one can prove the reliability of the innovative components/devices equal to or superior to that of the existing ones on the basis of the classic statistical calculation.*

9.4. Proposals and comments for safety user requirement UR1.2

No comments.

9.5. Proposals and comments for safety user requirement UR1.3

No comments.

9.6. Proposals and comments for safety user requirement UR1.4

No comments.

9.6.1. Criterion CR1.4.1 (major release to containment)

SF-15: Joint Study statement (Annex Japan, Section 4.3.2 comments on safety assessment manual for reprocessing facility): *it is better to add more explanations in order to obtain better understanding: The basis of the quantitative acceptance limits of IN 1.4.1 ($<10^{-4}$/y)*

9.7. Proposals and comments for safety user requirement UR1.5

No comments.

9.7.1. Criterion CR1.5.1 (frequency of release)

No comments.

9.7.2. Criterion CR1.5.2 (consequences of release)

SF-16: Joint Study statement (Annex Japan, Section 4.3.2 comments on safety assessment manual for reprocessing facility): *it is better to add more explanations in order to obtain better understanding: The basis of the quantitative acceptance limits of IN 1.5.2 (<1mSv).*

9.8. Proposals and comments for safety user requirement UR1.6

No comments.

9.9. Proposals and comments for safety user requirement UR1.7

No comments.

9.10. Proposals and comments for safety basic principle BP2

No comments.

9.11. Proposals and comments for safety user requirement UR2.1

No comments.

9.11.1. Criterion CR2.1.1 (hazards)

SF-17: Joint Study statement (Annex Japan, Section 4.3.1 comments on reactor): *It is recommended to use technical terms in a consistent manner and clarify the definition of the technical terms: The inventory of "radioactive materials" mentioned in IN2.1.1.*

SF-18: Joint Study statement (Annex Japan, Section 4.3.2 comments on safety assessment manual for reprocessing facility): *it is better to add more explanations in order to obtain better understanding: The air operated motor (appear in the explanation of UR 2.1)*

No comments to safety BP3 and BP4.

ANNEX B
LIST OF INPRO BASIC PRINCIPLES, USER REQUIREMENTS AND CRITERIA

In the following for each area of INPRO tables are provided (copied from Ref. [1]) that list the basic principles (BP), user requirements (UR) and criteria (CR) consisting of indicators (IN) and acceptance limits (AL). Table B1 contains the INPRO BP, UR and CR of economics, Table B2 of infrastructure, Table B3 of waste management, Table B4 of proliferation resistance, Table B5 of physical protection, Table B6 of environment, and Table B7 of safety.

Table B1. Basic Principle, User Requirements, and Criteria for the INPRO area of **economics**

Economic basic principle BP: *Energy and related products and services from Innovative Nuclear Energy Systems (INS) 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. **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 B1. Basic Principle, User Requirements, and Criteria for the INPRO area of **economics** (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	
	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. **AL3.1.2:** *For deployment of a FOAK plant in a country with experience operating NPPs:* Design is licensable in country of origin. **AL3.1.3:** *For development*: Plan to address regulatory issues available and costs included in development proposal.
	CR3.2 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. **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. **AL3.2.3**: *For technology development:* Schedules analyzed to demonstrate that scheduled times are realistic taking into account experience with previous NPP construction projects.

Table B1. Basic Principle, User Requirements, and Criteria for the INPRO area of **economics** (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): *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	
	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): *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.

Table B2. Basic Principle, User Requirements, and Criteria for the INPRO area of **infrastructure**

Infrastructure basic principle BP: *Regional and international arrangements shall provide options that enable any country that so wishes to adopt, maintain or enlarge an innovative nuclear energy system (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)**
UR1 Legal and institutional infrastructure: *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.*	**CR1.1** legal aspects	
	IN1.1: Status of legal framework.	**AL1.1**: Legal framework has been established in accordance with international standards.
	CR1.2 institutions	
	IN1.2: Status of State organizations with responsibilities for safety and radiation protection, environmental protection, control of operation, waste management and decommissioning, security and non-proliferation.	**AL1.2**: State organizations have been established, in accordance with international standards.

Table B2. Basic Principle, User Requirements, and Criteria for the INPRO area of **infrastructure** (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)**
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.*	**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.

Table B2. Basic Principle, User Requirements, and Criteria for the INPRO area of **infrastructure** (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: *Adequate measures should be taken to achieve public*[37] *acceptance of a planned INS installation to enable a government policy commitment to support the deployment of INS to be made and then sustained.*	**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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[37] Public is meant here to be all stakeholders in a nuclear power program, i.e. society.

Table B2. Basic Principle, User Requirements, and Criteria for the INPRO area of **infrastructure** (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: *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.

Table B3.1. Basic Principle BP1, User Requirements, and Criteria for the INPRO area of **waste management**

Waste management basic principle BP1 (Waste minimization): *Generation of radioactive waste in an innovative nuclear energy system (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: *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: - Alpha-emitters and other long-lived radio-nuclides per GWa. - Total activity per GWa. - Mass per GWa. - Volume per GWa. - Chemically toxic elements that would become part of the radioactive waste per GWa.	**AL1.1.1:** ALARP
	CR1.1.2 minimization study	
	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.

Table B3.2. Basic Principle BP2, User Requirements, and Criteria for the INPRO area of **waste management**

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: *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[38].
	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: *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 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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[38] In all cases when the regulatory requirement of a Member State is indicated, any available international guidance should be taken into account as well.

Table B3.3. Basic Principle BP3, User Requirements, and Criteria for the INPRO area of **waste management**

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: *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 B3.3. Basic Principle BP3, User Requirements, and Criteria for the INPRO area of **waste management** (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. (continued)*		
User Requirements (UR)	**Criteria (CR)**	
	Indicators (IN)	**Acceptance Limits (AL)**
UR3.2 Attribution of waste management costs: *The costs of managing all waste in the life cycle should be included in the estimated cost of energy from the INS, in such a way as to cover the accumulated liability at any stage of the life cycle***.**	**CR3.2.1** cost	
	IN3.2.1: Specific line item in the cost estimate.	**AL3.2.1:** Included.

Table B3.4. Basic Principle BP4, User Requirements, and Criteria for the INPRO area of **waste management**

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: *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: *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 (i.e. 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, i.e. - Criticality compliance. - Heat removal provisions. - Radioactive emission control measures. - Radiation protection; measures (shielding etc.). - Volume/activity reduction measures. - 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 B4. Basic Principle, User Requirements, and Criteria for the INPRO area of **proliferation resistance**

Proliferation resistance basic principle BP: *Proliferation resistance (PR) intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that innovative nuclear energy systems (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)**
UR1 State commitments: *States' commitments, obligations and policies regarding non-proliferation and its implementation should be adequate to fulfill international standards in the non proliferation regime.*	**CR1.1** legal framework	
	IN1.1: States' commitments, obligations and policies regarding non-proliferation established?	**AL1.1**: Yes, in accordance with international standards.
UR2 Attractiveness of NM and technology: *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.*	**CR2.1** attractiveness of NM	
	IN2.1: Technical indicators: - Material quality. - Material quantity. - Material form.	Attractiveness of NM considered in design of INS and found acceptable low based on expert judgment.
	CR2.2 attractiveness of technology	
	IN2.2: Nuclear technology.	**AL2.2:** Attractiveness of technology considered in design of INS and found acceptable low based on expert judgment.

Table B4. Basic Principle, User Requirements, and Criteria for the INPRO area of **proliferation resistance** (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: - modify process; - modify facility design; - misuse technology or facilities.	**AL3.4:** Based on expert judgment equal or better than existing designs, meeting international best practice.

Table B4. Basic Principle, User Requirements, and Criteria for the INPRO area of **proliferation resistance** (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 B4. Basic Principle, User Requirements, and Criteria for the INPRO area of **proliferation resistance** (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 (i.e. IAEA, regional SG organization, etc.)?	**AL5.3:** Yes.

Table B5. Basic Principle, User Requirements, and Criteria for the INPRO area of **physical protection**

Physical protection basic principle BP: *A Physical Protection (PP) Regime shall be effectively and efficiently implemented for the full lifecycle of an innovative nuclear energy system (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 B5. Basic Principle, User Requirements, and Criteria for the INPRO area of **physical protection** (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)**
UR3 trustworthiness: *A program to determine trustworthiness should be defined and implemented.*	**CR3.1** trustworthiness program	
	IN3.1: Is there a trustworthiness program with established acceptance criteria?	**AL3.1**: Yes.
UR4 confidentiality: *Sensitive information developed for all areas of INPRO should be protected in accordance with its security significance.*	**CR4.1** development of confidentiality program	
	IN4.1: Has a program been developed for protecting sensitive information?	**AL4.1**: Yes.
	CR4.2 implementation of confidentiality program	
	IN4.2: Have procedures been developed and implemented at all levels to identify and protect sensitive information?	**AL4.2:** Yes.
UR5 threat: *The physical protection systems should be based on the State's current evaluation of the threats.*	**CR5.1** development of DBT	
	IN5.1: Is there evidence that a DBT or other appropriate threat statement has been developed?	**AL5.1:** Yes.
	CR5.2 periodic review of the threat	
	IN5.2: Are there provisions for periodic review of threat by the State?	**AL5.2:** Yes.
	CR5.3 DBT as basis for PPS	
	IN5.3: Is there evidence that the concept of DBT or other appropriate threat statement has been used to establish the PP systems?	**AL5.3:** Yes.
	CR5.4: flexibility in PPS	
	IN5.4: Has the designer introduced flexibility in PPS design to cope with the dynamic nature of threat?	**AL5.4:** Yes.

Table B5. Basic Principle, User Requirements, and Criteria for the INPRO area of **physical protection** (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 PP System?	**AL6.2:** Yes.
UR7 quality assurance: *Quality assurance (QA) 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 B5. Basic Principle, User Requirements, and Criteria for the INPRO area of **physical protection** (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: *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: *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 B5. Basic Principle, User Requirements, and Criteria for the INPRO area of **physical protection** (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 B6.1 Basic Principle BP1, User Requirements, and Criteria for the INPRO area of **environment**

Environmental Basic Principle BP1 (Acceptability of expected adverse environmental effects): *The expected (best estimate) adverse environmental effects of the innovative nuclear energy system (INS) shall be well within the performance envelope of current nuclear energy systems delivering similar energy products.*		
User Requirements (UR)	**Criteria (CR)**	
	Indicators (IN)	**Acceptance Limits (AL)**
UR1.1 controllability of environmental stressors: *The environmental stressors from each part of the INS over the complete life cycle should be controllable to levels meeting or superior to current standards.*	**CR1.1.1** stressors	
	IN1.1.1: L_{St-i}, = level of stressor i.	**AL1.1.1:** $L_{St-i} < S_i$, where S_i is the standard for stressor i.
UR1.2 adverse effects as low as reasonable practicable: *The likely adverse environmental effects attributable to the INS should be as low as reasonably practicable, social and economic factors taken into account.*	**CR1.2.1** ALARP	
	IN1.2.1: Does the INS reflect application of ALARP to limit environmental effects?	**AL1.2.1:** Yes.

Table B6.2. Basic Principle BP2, User Requirements, and Criteria for the INPRO area of **environment**

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: *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 B6.2. Basic Principle BP2, User Requirements, and Criteria for the INPRO area of **environment** (continued)

<table>
<tr><td colspan="3">Environmental basic principle BP2 (Fitness for purpose) (continued): <i>The INS shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources.</i></td></tr>
<tr><td rowspan="6">UR2.1 Consistency with resource availability (continued):
<i>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.</i></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: $U > U_0$
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: $T > T_0$
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: $C_i > C_0$
C_0 to be determined on a case specific basis.</td></tr>
<tr><td rowspan="2">UR2.2 Adequate net energy output:

<i>The energy output of the INS should exceed the energy required to implement and operate the INS within an acceptably short period.</i></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 (years).</td><td>AL2.2.1: $T_{EQ} < k*T_L$

T_L = intended life of INS.

$K < 1$</td></tr>
</table>

Table B7.1. Basic Principle BP1, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations**

Safety basic principle BP1 (defence in depth): *Installations of an Innovative Nuclear Energy System (INS) 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[39] Robustness: *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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[39] Related to: DID Level 1: Prevention of Abnormal Operation and Failures.

Table B7.1. Basic Principle BP1, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations** (continued)

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)**
UR1.2[40] **(Detection and interception):** *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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[40] Related to: DID Level 2: Control of Abnormal Operation and Detection of Failures.

Table B7.1. Basic Principle BP1, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations** (continued)

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)**
UR1.3[41] **Design basis accidents:** *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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[41] Related to: DID Level 3: Control of Accidents.

Table B7.1. Basic Principle BP1, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations** (continued)

<table>
<tr><td colspan="3">Safety Basic Principle BP1 (defence in depth)): <i>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.</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">UR1.3[42] Design basis accidents (continued):

<i>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.</i></td><td colspan="2">CR1.3.6 sub criticality</td></tr>
<tr><td>IN1.3.6: sub criticality margins</td><td>AL1.3.6: Sufficient to cover uncertainties and to allow adequate grace period.</td></tr>
</table>

---

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

Table B7.1. Basic Principle BP1, User Requirement, and Criteria for the INPRO area of **safety of nuclear installations** (continued)

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)**
UR1.4[43] **((Release into containment):** *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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[43] Related to DID Level 4: Prevention of Major Radioactivity Release.

Table B7.1. Basic Principle BP1, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations** (continued)

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)**
UR1.5[44] **Release into the environment:** *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 (i.e. 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.[45]

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

[45] 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 B7.1. Basic Principle BP1, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations** (continued)

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)**
UR1.6 Independence of DID levels: *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: *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:** - Reduced likelihood of human error relative to existing plants, as predicted by HF models. - Use of artificial intelligence for early diagnosis and real-time operator aids. - Less dependence on operator for normal operation and short-term accident management relative to existing plants.

Table B7.2. Basic Principle BP2, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations**

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): *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 B7.3. Basic Principle BP3, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations**

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: *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: *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 B7.4. Basic Principle BP4, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations**

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: *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: *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: *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. 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 B7.4. Basic Principle BP4, User Requirements, and Criteria for the INPRO area of **safety of nuclear installations** (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: *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.

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