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# OVERVIEW OF RESULTS OF INPRO PHASE-IA

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**ABSTRACT**

This paper presents an overview of the results of the International Project on Innovative Nuclear Reactors and Fuel Cycles performed within the Agency. The project is in its first phase, called Phase-IA and has produced an outlook into the future of the energy markets and defined user requirements in the following areas: *Economics*, *Environment, Fuel Cycle and Waste, Safety, Proliferation Resistance* and *Crosscutting Issues*. A frame for a methodology was created how to handle these user requirement in assessing nuclear technologies.

**DISCLAIMER**

The results of the INPRO project presented here are of preliminary nature and do not reflect the view of the member states participating in the INPRO project.

## 1. INTRODUCTION

In 2000 the IAEA initiated the International Project on Innovative Nuclear Reactors and Fuel Cycles called INPRO following a resolution of the General Conference (GC(44)/RES/21). The main objectives of the INPRO project are:

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

To bring together both technology holders and technology users to consider jointly the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles.

INPRO has as of October 2002 participating in the project the European Commission and twelve member states: Argentina, Brazil, Canada, China, Germany, India, Republic of Korea, Russian Federation, Spain, Switzerland, The Netherlands and Turkey. These members have nominated in total 17 experts with assignments from 3 months up to 3 years.

Phase-I of INPRO started in May 2001 and is split into two sub phases:

Phase-IA deals with the determination of user requirements and a suitable methodology to assess the level of fulfillment of these criteria by different future nuclear technologies. In this phase several task groups were established in the IAEA in order to define the *Prospects and Potentials* of nuclear power, User Requirements for *Economics*, *Environment, Fuel Cycle and Waste, Safety, Proliferation Resistance* and for *Crosscutting Issues* and to develop a *Methodology for Assessment* of nuclear technologies

Phase-IB will apply the methodology of assessment in several member states in order to make a judgment on the potential of innovative nuclear technologies.

In the following the main results of each task group are described briefly.

## 2. NUCLEAR POWER PROSPECTS AND POTENTIALS

In the area of the task group for *prospects and potentials* of nuclear energy in Phase-IA, four representative scenarios of the future out of the 40 reference scenarios in the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC 2000) have been selected. The chosen scenarios are characterized by differences in globalization versus regionalization and in the demographic, social, economic, technological and environmental developments (see Figure 1).

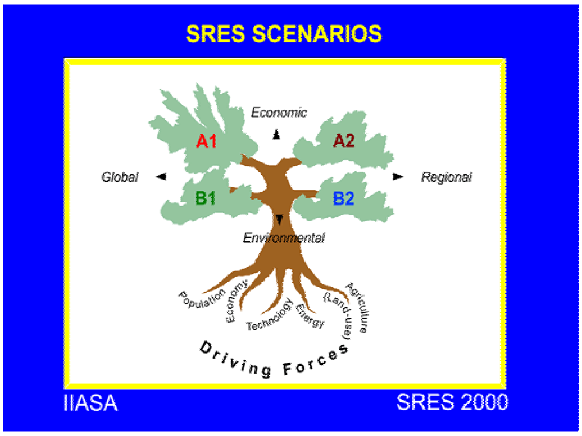


**Figure 1**: ***Schematic illustration of the four SRES storyline families (Source: IPCC)***

The four SRES scenarios depict future worlds of alternative market conditions and technology environments. Hence, the potential of nuclear technologies to gain additional shares differs considerably across the scenarios. First, this is due to the variation of the scenarios' socio-economic assumptions, which result in considerably different energy demand projections. Second, the scenarios differ also with respect to technology assumptions, which drive the evolution of the energy system in alternative directions. By analyzing the scenarios, key markets are identified for additional nuclear shares compatible with the given path-dependent development in each of the four SRES worlds.

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

The A1T Scenario[1] depicts a world of high economic growth and rapid increase of energy demand. The comparatively fast turnover of capital promotes the expansion of nuclear. In the original SRES A1T Scenario nuclear contributes more than 100 EJ to the global hydrogen and electricity production in 2050. Based on specific assumptions, nuclear may increase its contribution by an additional 90 EJ in 2050. In the very long term, the energy supply of the A1T Scenario shifts from fossil-based energy production toward renewable sources of hydrogen. The additional market potential for nuclear is vast, and could increase to 400 EJ of hydrogen and 200 EJ of electricity in 2100. Nuclear energy's biggest competitor is solar-based hydrogen production. Hence, nuclear strategies with focus on the "buy down" of costs in the hydrogen sector seem to be most promising. Due the phase-out of coal and comparatively little use of other fossil fuels, there is only limited potential for nuclear in the heat sector.

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

The B1 world describes a rapidly converging world, characterized by "dematerialization" and the introduction of clean technologies. The slow growth of energy demand and the focus on decentralized energy supply strategies, hinder the diffusion of nuclear technologies. This results in the smallest contributions of nuclear energy across all four SRES scenarios (30 EJ in 2050 and 40 EJ in 2100). In the

[1] The A1T scenario is a variation of the A1 scenario with a strong emphasis on advanced, efficient and clean energy technologies and rapid change toward post-fossil fuel alternatives

long run the energy system is dominated by hydrogen and electricity from renewables and natural gas. The main competitors for nuclear are solar technologies in the hydrogen sector and natural gas and renewable power generation in the electricity sector. Strategies to promote nuclear technologies could increase the contribution from nuclear energy by more than a factor of two. By 2100, this would correspond to additional gains for nuclear energy of about 30 EJ of hydrogen and 50 EJ of electricity. Due to the phase-out of coal and comparatively little use of other fossil fuels, there is only limited potential for nuclear in the heat sector.

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

In the following a short overview is given of the status of User Requirements defined up till now in the following areas: Economics, Environment, Fuel Cycles and Waste, Safety of Reactors and Fuel Cycles, Proliferation Resistance and Cross-Cutting Issues. Last not least the INPRO Methodology for Assessment will be illustrated.

## 3. USER REQUIREMENTS FOR ECONOMICS

Since competitiveness targets are forever moving, in the area of User Requirements for *economics* the work is focused on rates of improvement rather than cost targets at specific dates. The measure of the improvement used is the learning rate. This concept assumes that a technology's performance improves as experience with the technology accumulates. The concept can be used with a variety of different indicators of technological performance and experience, but in this report specific capital costs were chosen as the performance indicator and total cumulative installed capacity as the experience indicator.

Though SRES scenarios use time as independent variable, they may be analyzed by this method because cumulative installed capacity is explicit function of time in each scenario which allows to replace the variable.

The economic model used in calculations was simplified by applying "single global region" approach instead of SRES multi-regional one, but it was elaborated by taking into account knowledge depreciation.

So target learning rates were chosen as the main user requirement for economy. Their estimation was a two-step process. First, a variation of the IIASA[2] MESSAGE model was developed that incorporates endogenous learning (i.e., technology costs decrease as a function of experience rather than time). Second, a variety of improved (i.e., faster) learning rates was tested using this new model to identify those most consistent with the results presented in Chapter 3 for the aggressive nuclear market penetration variation of the A1T Scenario.

The results indicate that to meet those nuclear expansion profiles the learning rate for nuclear technologies would have to reach at least 7% (see Figure 2 for the A1T scenario).

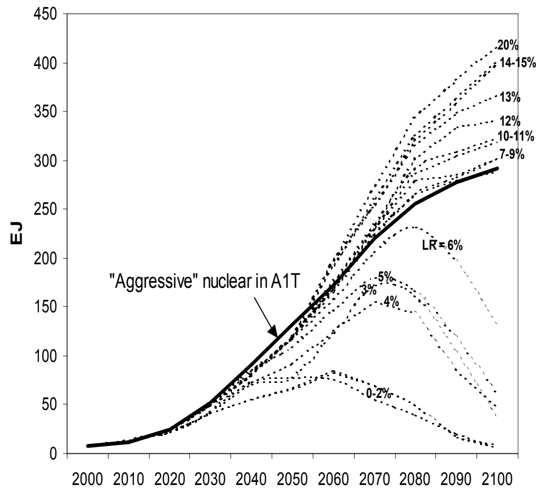


**Figure 2:** ***The contribution of nuclear power generation in the A1T Scenario assuming alternative learning rates. The bold line shows the development of nuclear in the aggressive nuclear improvement A1T Scenario***

Higher learning rates would lead to correspondingly greater nuclear expansion. But not

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less important is the result that for learning rates below 7%, nuclear energy may eventually be “locked out” of the global market.

Conversion of learning rate targets into specific cost targets at specific dates is illustrated by numerical examples (see Table 1).

**Table 1. *Investment costs for electricity and hydrogen production plants in the aggressive nuclear cost improvement A1T Scenario assuming a 7% nuclear learning rate.***

| | Investment costs in the power sector ($/kW) | | Investment costs for hydrogen production ($/kW) | |
|---|---|---|---|---|
| | *2000* | *2050* | *2000* | *2050* |
| Coal | 1000-1650 | 1000-1650 | 1190 | 690 |
| Oil | 600-800 | 440-730 | - | - |
| Gas | 710-1150 | 640-910 | 457 | 253 |
| Nuclear | 1600-2800[3]<br>700-2000[4]<br>700-2000[5] | 1200-1640<br>700-860[4]<br>324-860[5] | 2800<br>2000[4]<br>2000[5] | 1270<br>1150[4]<br>1150[5] |
| Biomass | 1570-1760 | 1240-1300 | 940 | 544 |
| Solar | 2900-5100 | 1150-1780 | 2900 | 2900 |
| Wind | 1400 | 750 | - | - |

Policy options aimed at improving the learning curve can be defined, research and development investment being one of them.

## 4. USER REQUIREMENTS FOR ENVIRONMENT

Four general or top-level User Requirements and three special ones have been defined within the task group for *environment, fuel cycle and waste*. The top-level User Requirements are shown in the following

*No.1: The environmental performance of a proposed technology is to be evaluated by considering, as an integrated whole, the likely adverse environmental effects of the entire collection of processes, activities and facilities in the energy system at all stages in the life cycle*

*No 2: All important material and energy flows in, out, and through the system should be accounted for.*

*No.3: All factors (sources, stressors, pathways, receptors and endpoints) should be considered in the analysis of environmental effects, and emphasis placed on analysis of those factors that are most important to screening and inter-comparison of proposed technologies.*

*No.4: The energy system must be sustainable for a minimum of 100 years.*

The existing methods for quantifying the environmental impact of a nuclear system, called life cycle assessment (LCA) and material flow assessment (MFA) need to be developed further to fulfill the goals of this task group. The corresponding necessary R&D has been defined.

## 5. USER REQUIREMENTS FOR SAFETY

In the area of *nuclear safety of innovative reactors and fuel cycles* four general (or top level) and up to thirty special User Requirements have been created covering the whole nuclear reactor and fuel cycle starting from the mining of fissile and fertile material, the fuel fabrication, the operation of nuclear reactors and the treatment of spent fuel and waste. The following table shows the four general safety related requirements for future nuclear systems:

*No.1: The innovative nuclear reactors and fuel cycle installations shall be so safe that they can be sited in locations similar to other industrial facilities.*

*No.2: The innovative nuclear reactors and fuel cycle installations shall be so safe that they have a lower risk associated with fuel damage than current plants.*

*No.3: The innovative nuclear reactors and fuel cycle installations shall be so safe that they prevent releases of radioactivity that could necessitate evacuation of people living nearby*

*No.4: The innovative nuclear reactors and fuel cycle installations shall be so safe that they ensure safety to people and the environment of the whole fuel cycle.*

The technical approach to achieve the envisaged level of increased safety in innovative nuclear installations is shown in Figure 3.

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[3] 2800 $/kW is the starting cost of a nuclear power plant with hydrogen co-generation.

[4] Assuming the same learning rates as in the A1T aggressive case, but starting values between 700-2000 $/kW.

[5] Assuming a learning rate of 7% for all nuclear technologies, and starting values between 700-2000 $/kW.

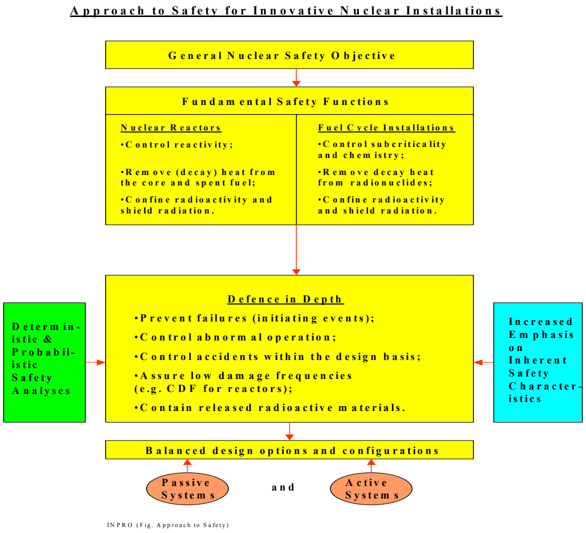


**Figure 3:** ***Approach to Safety for Innovative Nuclear Installations***

In the area of *safety of waste management* the principles defined in the IAEA Safety Series No.111-F have been used as a basis for the following top-level User Requirements.

*No.1: For each waste in the energy system, a permanently safe end state should be defined. The planned energy system should be such that the waste is brought to this end state as soon as reasonably practicable. The end state should be such that, on the basis of credible conservative analysis or demonstrated operation, any release of material to the environment, normalized to unit of energy produced, will be below that which is acceptable today.*

*No.2: Waste management systems should be designed to assure that their associated radiological effects on humans are below the levels acceptable today. Because the waste management systems are integral parts of the overall energy system, their designs should be optimized from a radiological perspective as part of the optimization of the overall energy system.*

*No.3: Waste management strategies should be such that the adverse environmental effects from all parts of the energy system and the complete life cycle of facilities are optimized. The cumulative effects over time and space, without regard to national boundaries, should be considered.*

*No.4: The energy system should be designed so as to minimize the production of wastes and particularly the production of wastes containing long-lived toxic components that would be mobile in a repository environment.*

*No.5: The resources to manage the wastes from their production to their final safe end state should be provided as part of the operating costs of the energy system. The funds for long-term management should be given into safekeeping pro rata as the wastes are generated to ensure that future generations will have the wherewithal to safely manage the waste as necessary. All costs associated with the management of the wastes should be reliably estimated and internalized as part of the overall cost of the energy system.*

The necessary R&D has been defined for these Requirements.

## 6. USER REQUIREMENTS FOR PROLIFERATION RESISTANCE

In the area of User Requirements for *proliferation resistance*, work is still in progress. The proliferation resistance fundamentals and examples given in this chapter were agreed at an international technical meeting convened by the IAEA Department of Safeguards in Como, Italy in October 2002.

***Proliferation resistance*** is defined as that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States intent on acquiring nuclear weapons or other nuclear explosive devices. The degree of proliferation resistance results from a combination of, *inter alia*, technical design features, operational modalities, institutional arrangements and safeguards measures.

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

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

Proliferation resistance is expected to be an important factor in deciding the following for future nuclear energy systems:

The selection of competing future nuclear energy systems for research, development, demonstration and deployment;

The selection of alternative nuclear energy systems by exporting and importing States;

Export policies; and

Verification regimes applied by the IAEA, by regional verification authorities, bilateral regimes and national control bodies.

Proliferation resistance user requirements are provided in the following:

*No.1: Proliferation resistance features and measures should be implemented in the design, construction and operation of future nuclear energy systems with the goal of assuring that such future nuclear energy systems will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme*

*No.2: Proliferation resistance should adopt complementary and redundant features and measures to provide defence in depth*

*No.3: Proliferation resistance will be the most cost effective when an optimal combination of intrinsic features and extrinsic measures, compatible with other design considerations, is included in a nuclear energy system*

*No.4: Proliferation resistance will be enhanced when taken into account as early as possible in the design and development of a nuclear energy system*

*No.5: Intrinsic proliferation resistance features should facilitate the efficient application of extrinsic measures*

*No.6: Extrinsic proliferation resistance measures, such as control and verification measures, will remain essential, whatever the level of effectiveness of intrinsic features.*

*No.7: From a proliferation resistance point of view, the development and implementation of intrinsic features should be encouraged*

Examples of *intrinsic features* and *extrinsic measures* to enhance proliferation resistance have been defined.

Assessments of the proliferation resistance afforded by a given nuclear energy system will facilitate the decisions identified above. Initially, such assessments are likely to be based upon structured judgments following standardized checklists. Qualitative assessments will be pursued through future research and development, as will quantitative assessments. Given the complexity inherent in such assessments, it is likely that an overall methodology may include elements of structured judgments, qualitative and quantitative evaluations. Guidelines for consideration for the development and adoption of a proliferation resistance assessment methodology have also been set forth.

## 7. USER REQUIREMENTS FOR CROSSCUTTING ISSUES

The *crosscutting issues* considered within INPRO are the necessary changes in existing nuclear power infrastructure needed to enable the implementation of innovative nuclear technologies as foreseen in the scenarios for the future. In the following the requirements are shown:

Legal and Institutional Infra-structure:

*No.1: A license for the design and application innovative reactor systems and fuel cycles needs to be accepted by any user country that wants to use these systems*

*No.2: Licenses for innovative reactors should be based on the top-level requirements. These requirements should be internationally agreed*

*No.3: A requirement for the deployment of an innovative nuclear concept may be the establishments of international or regional nuclear authorities and inspection bodies.*

*No.4: Condition for the growth of international operating companies hat is that the insurance of risk attributed to the use nuclear power can be handled in the same way as other industrial risks. The liability issue has to be reviewed as market structures are changing.*

In the area of the Economic and Industrial Infra-structure:

*No.1: Companies involved in research, development and supply of nuclear technology should develop towards global companies*

*No.2: Market demand and the specific needs have to be recognized by the developers*

*No.3: The nuclear power structure could be optimized if components in different countries will be part of an international multi-component system that could respond to the demand for sustainability, including the final storage of waste*

*No.4: The need for infrastructure to operate nuclear facilities may lead to provision of management and operation services in addition to supply of hardware to overcome any local infrastructure deficiency*

*No.5: Industrial nuclear development could take advantage from available technologies and materials developed in other industrial sectors*

*No.6: Development of innovative concepts could be strengthened by cooperation in the field of enabling technologies.*

In the area of the Socio-Political Infra-structure:

*No.1: It should be demonstrated that innovative nuclear concepts are responding to the concerns about safety, waste and proliferation as contribution to the improvement of public acceptance of nuclear power*

*No.2: The main concerns on safety, waste and proliferation that are influencing the public acceptance have to be responded by the world wide application of the top-level requirements. Countries should cooperate in reaching this goal*

*No.3: A general requirement in relation with public acceptance should be the communication between the public and other stakeholders on the scenarios and choices in energy supply. The implementation of nuclear programs and the performance of the nuclear power structures should also be subject of open communication*

In the area of Human Resources and Knowledge:

*No.1: Given the need for human resources and knowledge as a base for the development of innovative nuclear concepts and fuel cycles international cooperation in this field should be enhanced*

An additional important crosscutting issue is the sustainability of an energy system. This issue has been studied in detail in INPRO and a basis for quantification is being developed.

## 8. INNOVATIVE NUCLEAR TECHNOLOGY ASSESSMENT

The INPRO *Methodology for Assessment* of nuclear technologies follows a "top-down" method and has a logical hierarchy of the assessment process. Its multilevel system includes**:**

1) Development and definition of User Requirements in the areas of economics, environment, safety, proliferation resistance and cross-cutting issues,

2) Searching and Compiling of Approaches to meeting all User Requirements,

3) Choosing of Indicators to check the compliance with each of the User Requirement.

4) Formulation of Evaluation Criteria

In the following the definitions of the Approach, Indicator and Criterion are given.

An Approach is the proposed technical or institutional mechanism for meeting User Requirements by means of appropriate steps in all relevant areas (e.g. technology development, economical, political or other institutional measures) and may depend on technology development strategies and regional features.

Two different kinds of Indicators can be defined: Condition and Functional Indicator. The first one is a characteristic of a structure, system or component of a nuclear energy system that can be observed or measured (digital variable). The second one is a direct indication of the current ability of a structure, system or component to fulfill a Criterion (logical variable).

A Criterion is a principle or standard used to make a judgment of a matter and should be a defined limit of an Indicator. It may also depend on the Approach.

In the following examples are given to illustrates the procedure of the assessment methodology in the area of safety:

To fulfill the first two User Requirements in the area of safety (see chapter 5) the following approach is chosen:

- Innovative reactor HTR with molten salt cooling
- Closed fuel cycle with dry reprocessing
- Natural circulation driven core cooling
- Coated particle type fuels
- Use of international waste disposal park (institutional measure)

As an Indicator for the first User Requirement the following variable is chosen: Exposure doses due to releases of radioactive materials and other hazardous materials. The corresponding Criterion is: Meet dose limits defined by regulatory bodies.

For the second User Requirement the Indicator is defined as the Core damage probability. The corresponding Criterion is: Core damage Probability at least 10 times less than accepted values for existing NPPs.

The judgment of the compliance of an Approach of a nuclear system with the corresponding User Requirement is performed as shown in the following Table 2:

**Table 2:** ***Judgment of compliance with User Requirements***

| **The assessment value.**<br>**(The approach of a nuclear energy system is judged as….)** | **Description of assessment value**<br>**(The reason for judgment)** |
|---|---|
| Having a Very High potential to satisfy the Criterion (VHP) | All components (parameters) of the Approach of the nuclear energy system being assessed have been theoretically demonstrated and, where necessary, experimentally verified and meet the Criterion |
| Having a High Potential to satisfy the criterion (HP) | Not all components (parameters) of the Approach of the nuclear energy system being assessed have been theoretically demonstrated or experimentally verified, but there is theoretical evidence that this Approach could meet the Criterion |
| Having Potential to satisfy the Criterion (Possibly satisfying the Criterion) (P) | No theoretical or experimental evidence that the Criterion cannot be met, due to some physical, technological or other limitation which cannot be overcome by later technology developments. |
| Having No Potential to satisfy the Criterion (NP) | Theoretical or experimental evidence that the Criterion cannot be met by means of technology development due to some physical, technological or other limitation**.** Explanation should be provided. |

The methodology for assessment has to be developed further and the Criteria and Indicators for a complete nuclear system must be defined. It is expected that different nuclear technologies will need different Criteria or Indicators. In the planned case studies Member States will perform these steps with the support of the Agency.

## 9. CONCLUSIONS

Four different scenarios for the development of the world within this century regarding the demand of energy in general and specific of nuclear energy have been selected as a basis for the INPRO project. A set of User Requirements has been defined for the chosen areas of economy, environment, safety, proliferation resistance and cross-cutting issues. A frame for the methodology of assessment of innovative nuclear technologies regarding their compliance with the INPRO User Requirements has been created.

As of November 2002 the work within the Phase-IA of the INPRO project is still ongoing. The results produced within the different tasks have reached different level of maturity. Only the task Safety is thought to be practically complete regarding the definition of the corresponding requirements.

The next steps within the INPRO project will be:

- Finalizing of the remaining tasks till the Steering Committee Meeting scheduled for spring 2003;
- The integration of external work packages provided by Member States for specific topics;
- The execution by Member States of selected case studies applying the methodology on specific nuclear systems;
- The arrangement of additional technical meetings at the Agency in areas, which need further work;
- The performance of Coordinated Research Projects (CRP) related to INPRO tasks.

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