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

International Atomic Energy Agency

INPRO: Status, Ongoing Activities and Outlook

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Introduction

- **INPRO : International Project on Innovative Nuclear Reactors and Fuel Cycles.**
- **Basis of INPRO : Resolution at the IAEA General Conference in 2000/2001/2002/2003 in Vienna and at the United Nations General Assembly in 2001/2002/2003.**
- **Text of IAEA General Conference Resolution in September 2000:**
  - IAEA GC 2000 has invited “all interested Member States to combine their efforts under the aegis of the Agency in considering the issues of the nuclear fuel cycle, in particular by examining innovative and proliferation-resistant nuclear technology”

General objective of INPRO

To facilitate decision-making and implementing process for satisfying future energy needs in a sustainable manner through development and deployment of Innovative Nuclear Energy Systems (INS).

These systems will be competitive, safe and reliable, proliferation resistant and environmentally benign, will efficiently utilize resources and will be supported by adequate infrastructure. Having proved the fulfillment of these requirements the INS will be accepted by the society.

Goals of INPRO

- **INPRO Goals (Terms of Reference):**
  1. **To help to ensure that nuclear energy is available to contribute in fulfilling energy needs in the 21st century in a sustainable manner.**
  2. **To bring together both technology holders and technology users to consider jointly the actions required to achieve desired innovations in nuclear reactors and fuel cycles.**
  3. **To create a process that involves all relevant stakeholders that will have an impact on, draw from, and complement the activities at the national and international level.**
- **INPRO Time horizon is 50 years into the future.**

Introduction

- **19 Participants in INPRO (April 2004):**
  - **Argentina, Brazil, Bulgaria, Canada, Czech Republic China, France, Germany, India, Indonesia, Republic of Korea, Pakistan, Russian Federation, South Africa, Spain, Switzerland, The Netherlands, Turkey and the European Commission.**
  - **Number of participants is growing**
- **Several Observers in INPRO (e.g. Australia, Belgium, Chile, Croatia, Japan, UK, USA, OECD/NEA, etc.)**

Status of INPRO

Phase 1 A

- INPRO Phase 1A finished in June 2003
- Formulation of :

  - Basic Principles, User Requirements and Criteria for the assessment of Innovative Nuclear Energy Systems (INS) in thel areas : Economics, Environment, Safety, Waste Management, Proliferation Resistance, Cross Cutting Issues (Recommendations for Infrastructure)

  - Assessment Methodology

- Report of Phase 1 A : IAEA TECDOC 1362

Results of INPRO in the Area Methodology for Assessment of Innovative Nuclear Energy System (INS)

INPRO

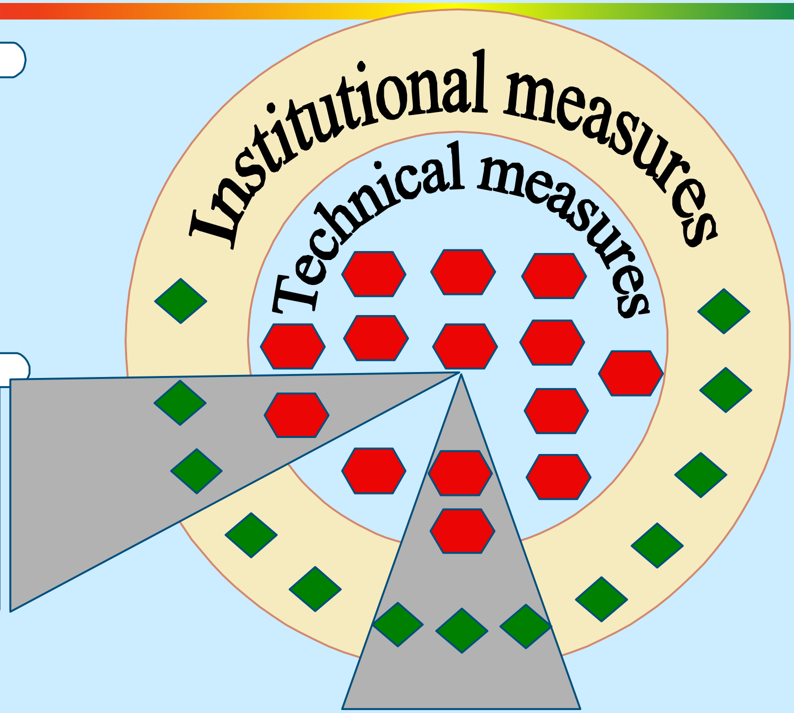
Economics

BPEc1…n
UREc1…n
CEc1…n

INPRO

Environment

BPEn1…n
UREn1…n
CEn1…n



INPRO

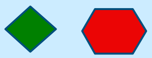
Waste Management

BPW1…n
URW1…n
CW1…n

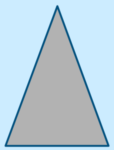
INPRO

Proliferation Resistance

BPPRc1…n
URPR1…n
CPR1…n



= **Components of INS**
(e.g. reactor, fuel cycle installations, safe guards, etc.)



= **Approach of INS**

INPRO

Safety

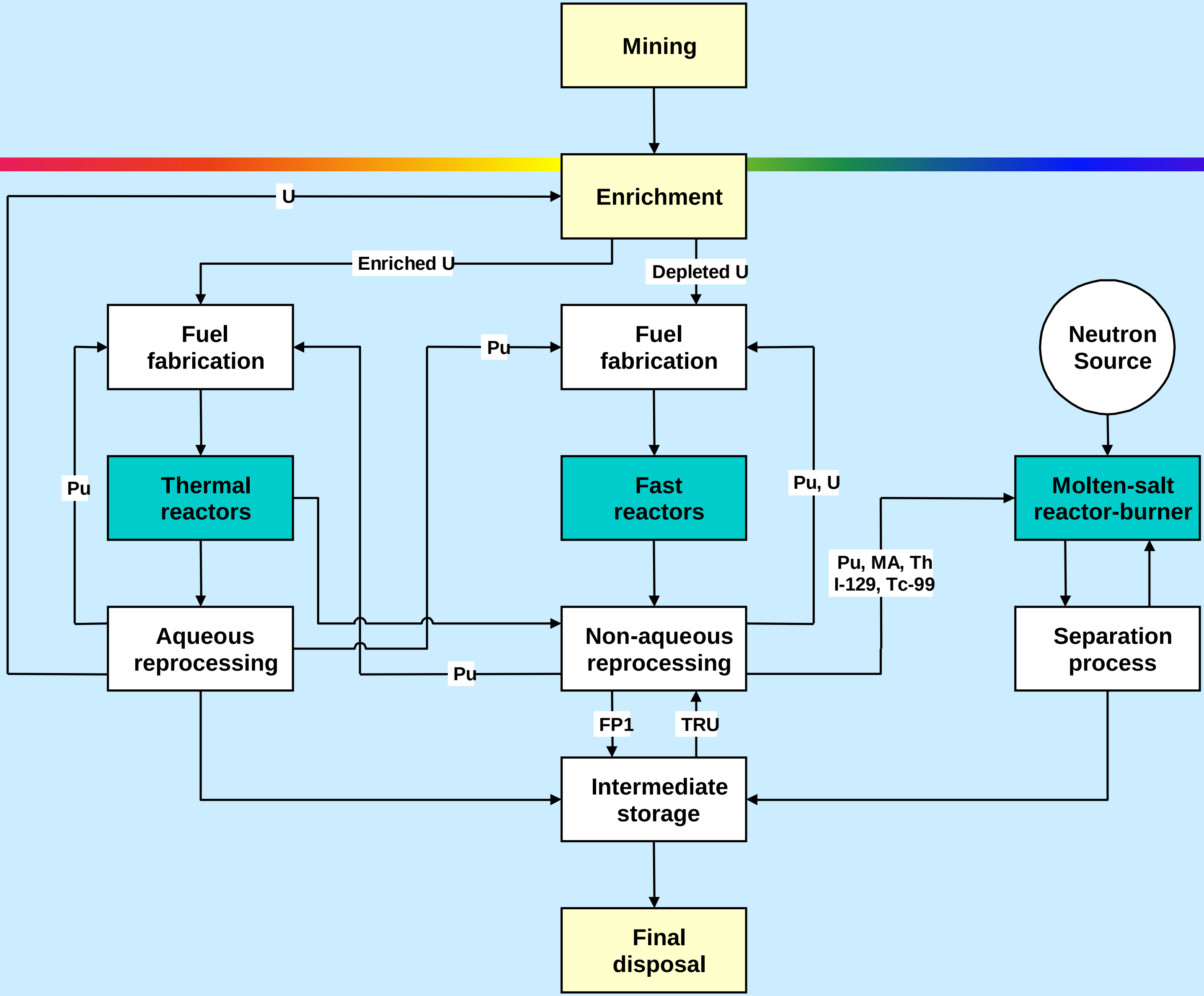
BPS1…n
URS1…n
CS1…n

INPRO

Crosscutting Issues

Recommendations for Infrastructure

Example of INS (Russia)



Status of INPRO

Definitions

- Basic Principle : **statement of a general rule that provides broad guidance for the development of an INS.**

- User Requirement : **condition that must be met to achieve Users' acceptance of a given INS.**

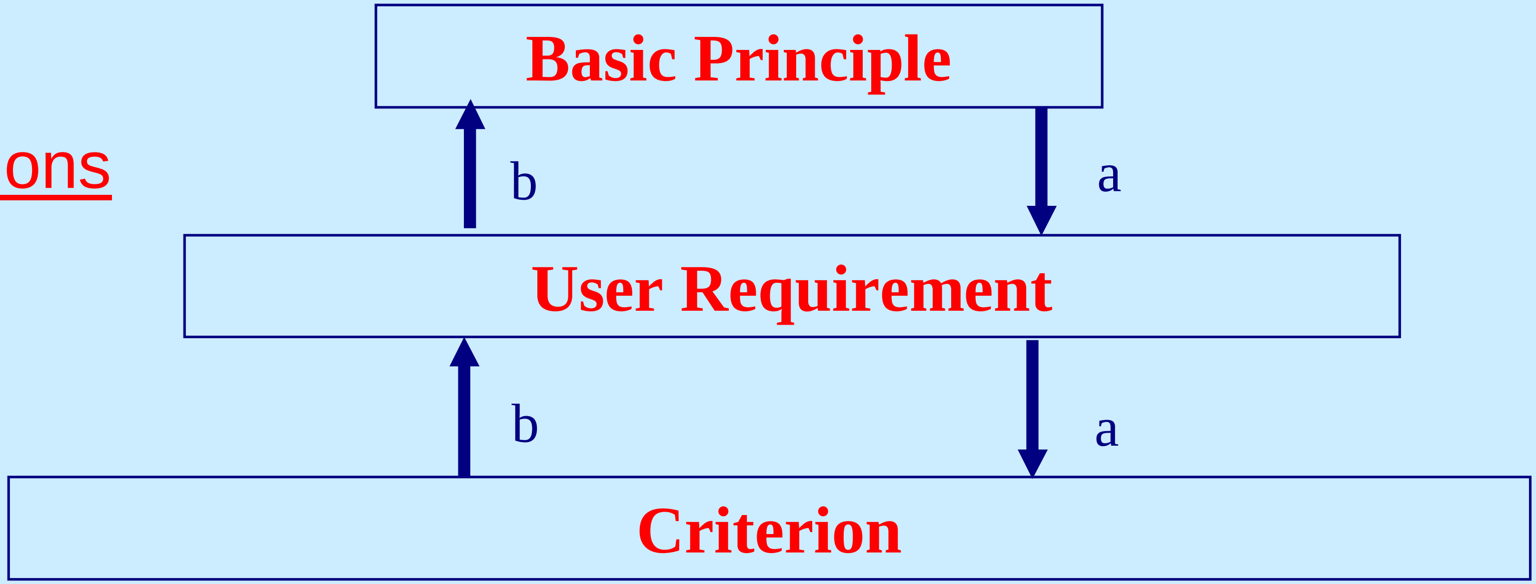
- Criterion : **is required to determine whether and how well a given User Requirement is being met.**

  Includes : Indicator – Acceptance Limit

Status of INPRO

Hierarchy of Demands
on Innovative Nuclear Energy Systems (INS)

Definitions



a = **Derivation**

b = **Fulfilment**

Results of INPRO Phase IA

IAEA-TECDOC-1362 June 2003

Guidance for the evaluation of innovative reactors and fuel cycles

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

Results of INPRO Phase IA

Main chapters of TECDOC 1362

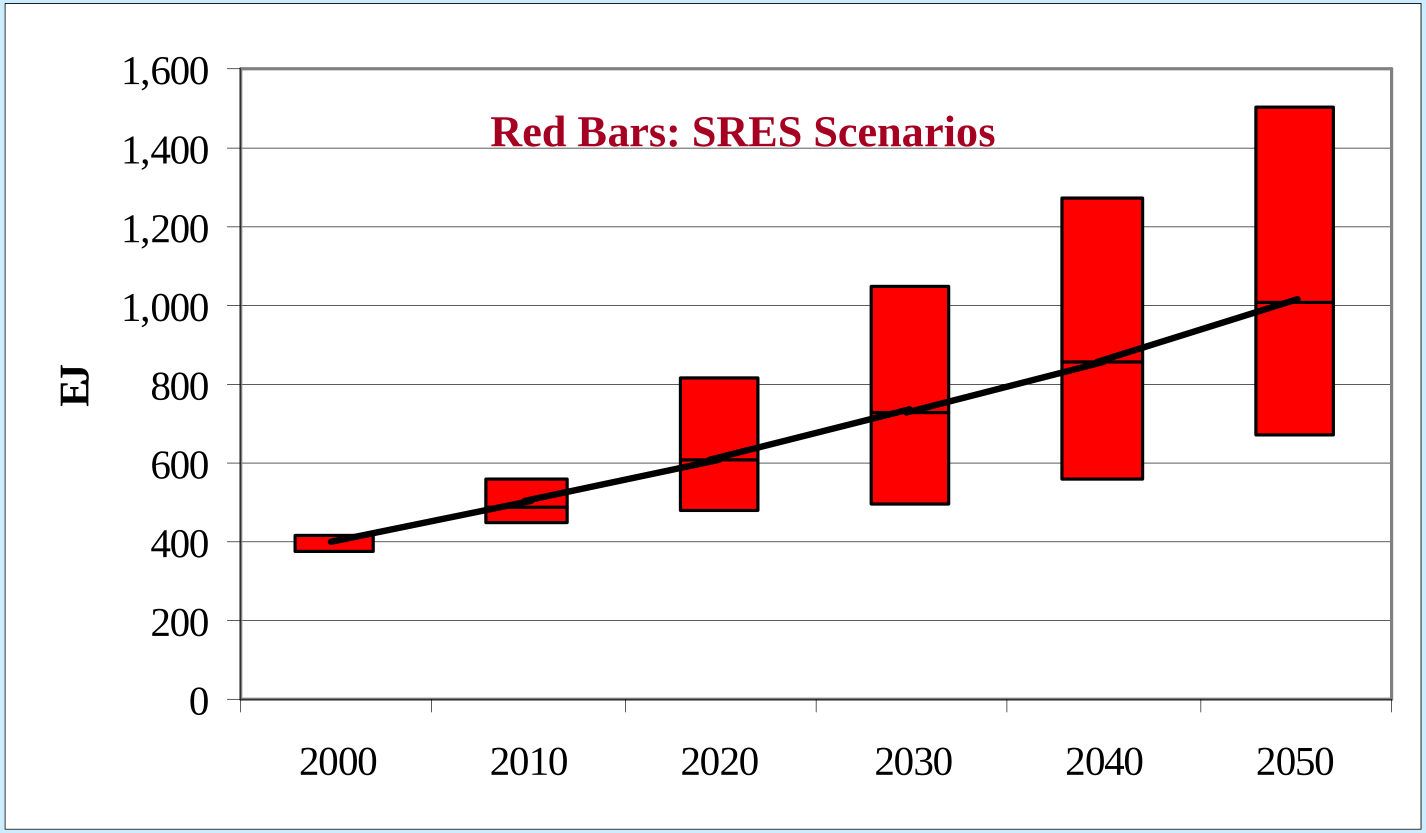
- Nuclear prospects and Potentials
- Basic Principles and User Requirements
  - Economics, Environment, Safety, Waste management, Proliferation Resistance
- Methodology for assessment of INS
- Recommendations for Infrastructure

Phase IA Results of INPRO in the Area Nuclear Power Prospects and Potentials

- Current role of Nuclear Power
  - 442 operating plants supply 16% of global electricity generation
  - Electricity produced by nuclear power: 20% USA, 27% Spain, 31% Germany, 34% Japan, 39% Korea, 44% Sweden, 77% France
  - Steady increase of availability of NP’s
    - Equivalent to 33 new plants with 1000 MWe each since 1990
  - 35 reactors under construction
    - Growth centered in Asia

Phase IA Results of INPRO in the Area Nuclear Power Prospects and Potentials

SRES = Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change (IPCC)

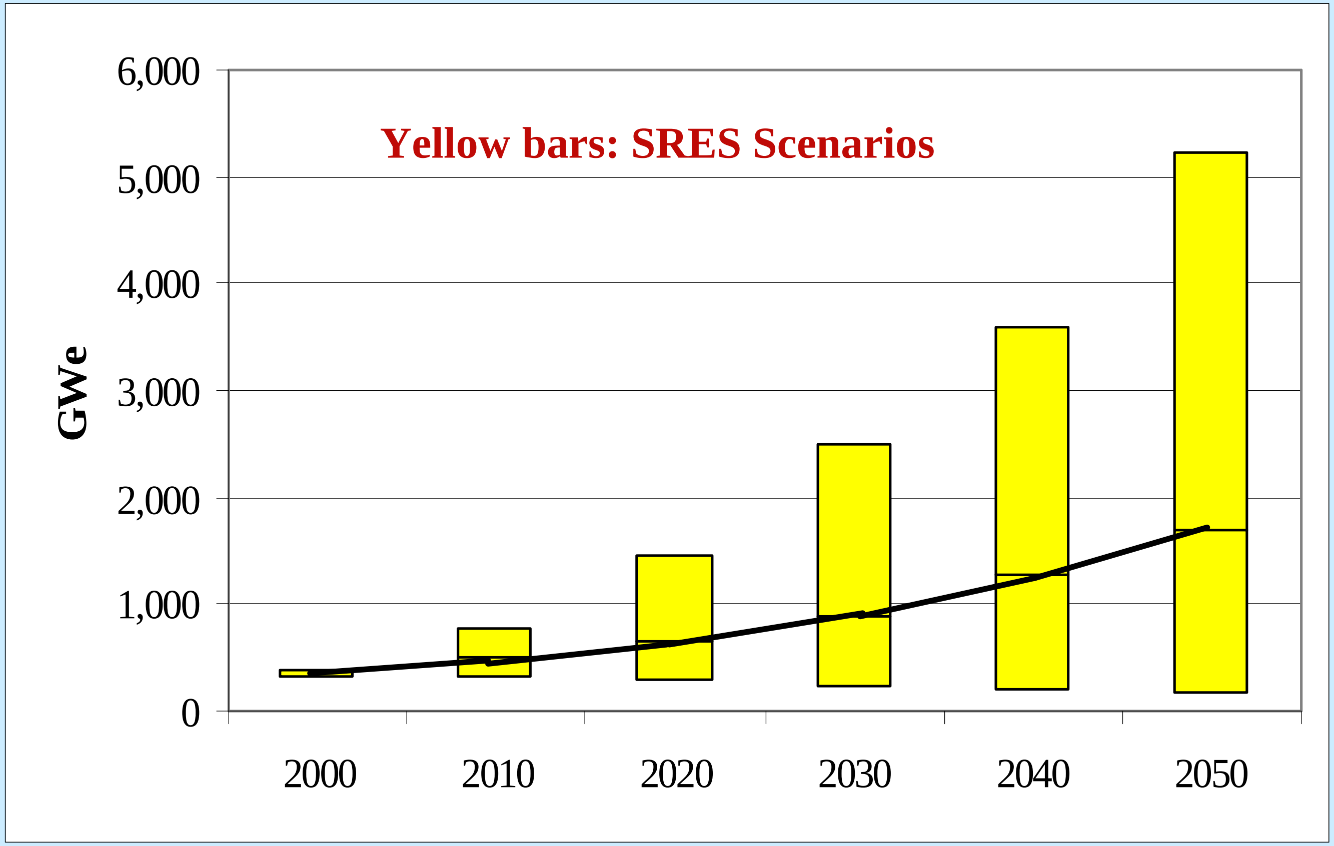


Projected World **Primary Energy** Demand (EJ)

(Source: Intergovernmental Panel on Climate Change, IPCC2000)

Phase 1A Results of INPRO in the Area Nuclear Power Prospects and Potentials

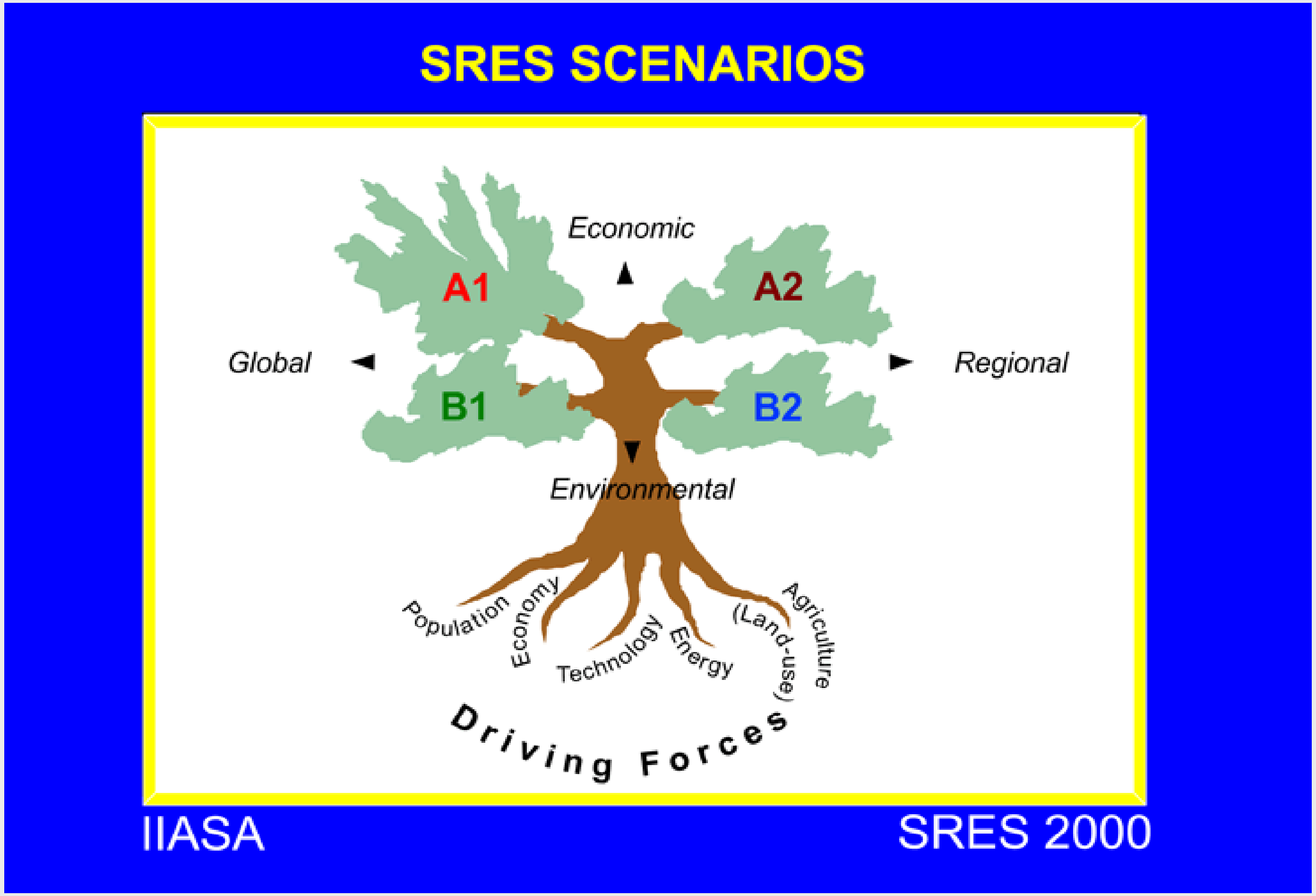
SRES =
Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change (IPCC)



World **Nuclear Electricity** Production (GWe)

(IPCC)

Phase IA Results of INPRO in the Area Economics

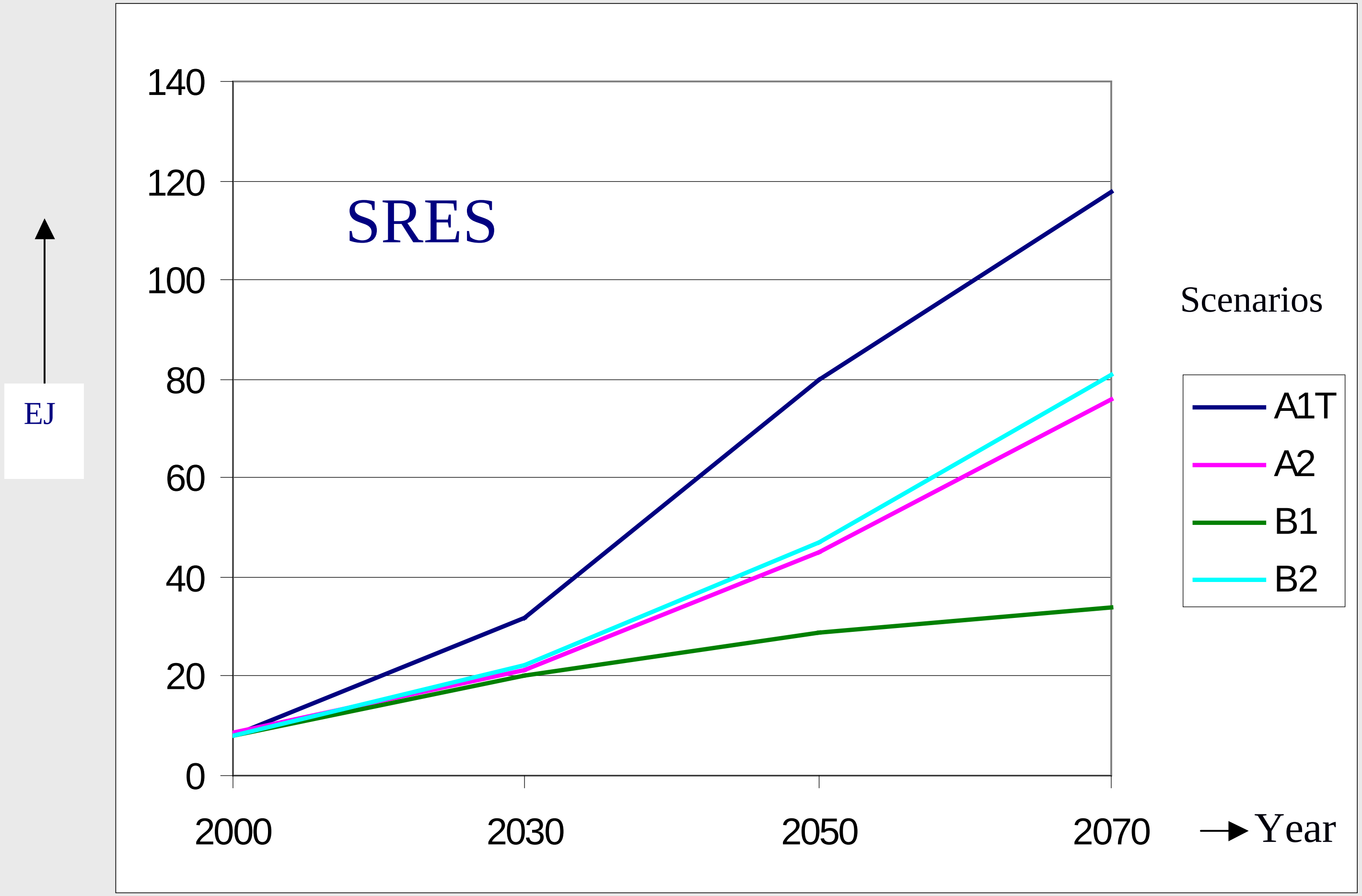


SRES = Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change (IPCC)

IIASA = International Institute for Applied System Analysis

➡ INPRO: Selection of **4 Representative Scenarios** of the Future out of 40

Phase IA Results of INPRO in the Area Economics

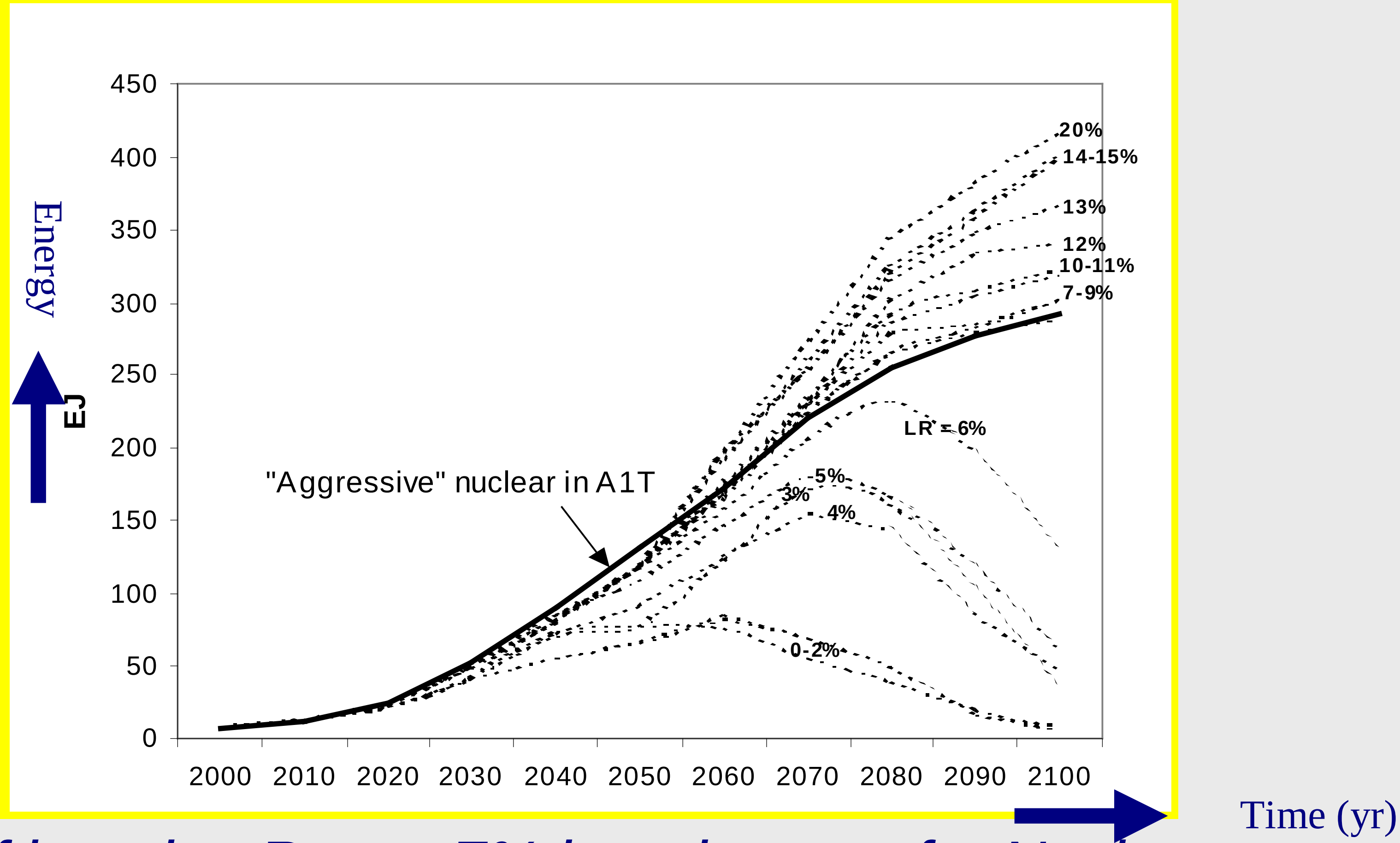


Nuclear electricity production (EJ) for the four selected SRES scenarios

Phase IA Results of INPRO in the Area Economics

- SRES Predictions for 4 Scenarios:
  - Competition to Nuclear is Dependent on Scenario and Region
  - According to SRES the main Competitors to Nuclear are:
    - Solar in Scenario A1T,
    - Coal in Scenario A2,
    - Renewables & Solar in Scenario B1,
    - Coal+Gas+Biomass+Solar in Scenario B2

Phase IA Results of INPRO in the Area Economics



Concept of learning Rates: 7% learning rate for Nuclear necessary to compete against other technologies

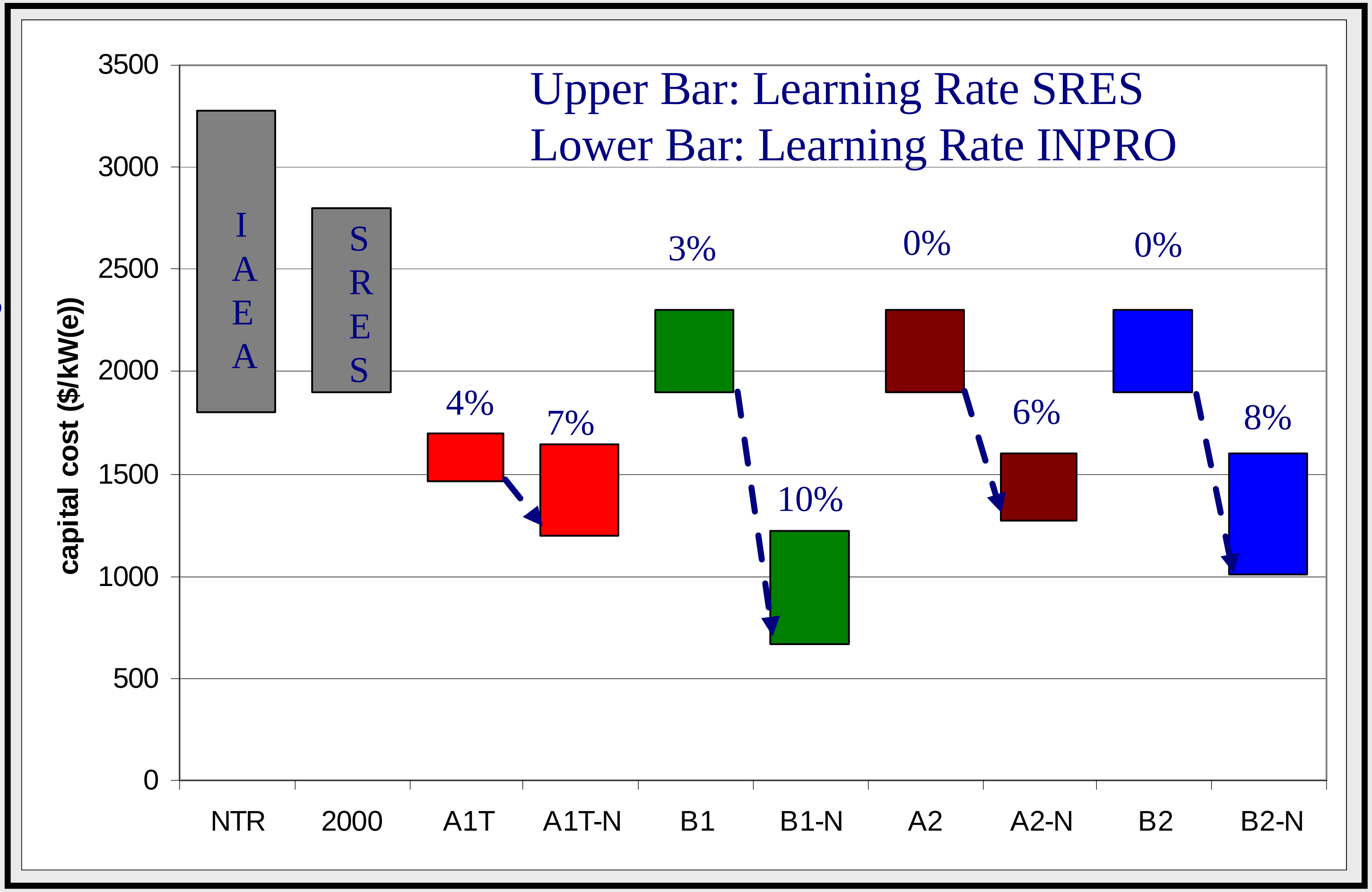
Phase IA Results of INPRO in the Area Economics

NTR = **N**uclear **T**echnology **R**eview (IAEA) in 2002

S-2000 = SRES input for the year 2000

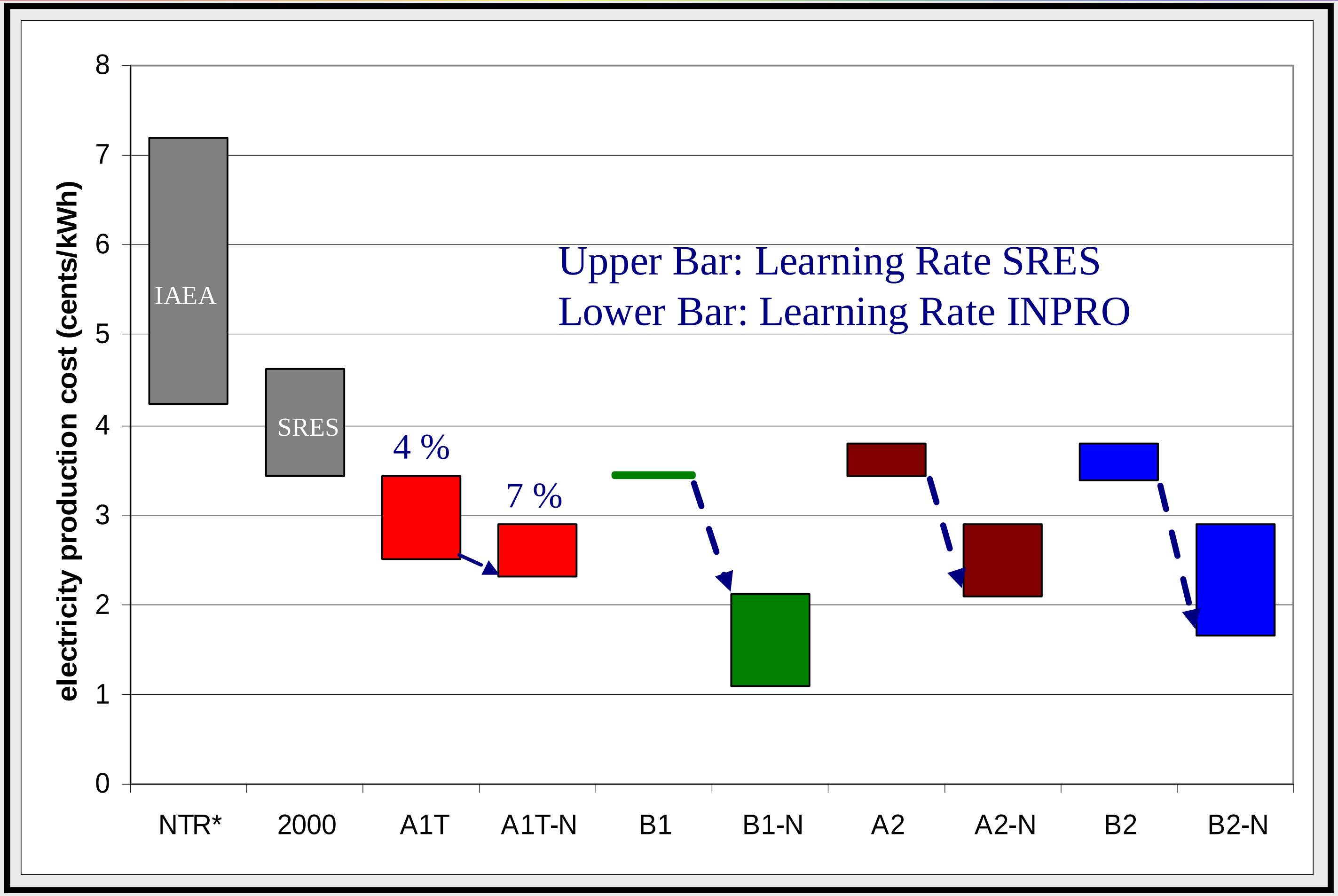
A1T = Costs in A1T as defined in SRES

A1T-N = Costs in A1T with aggressive Learning Rate



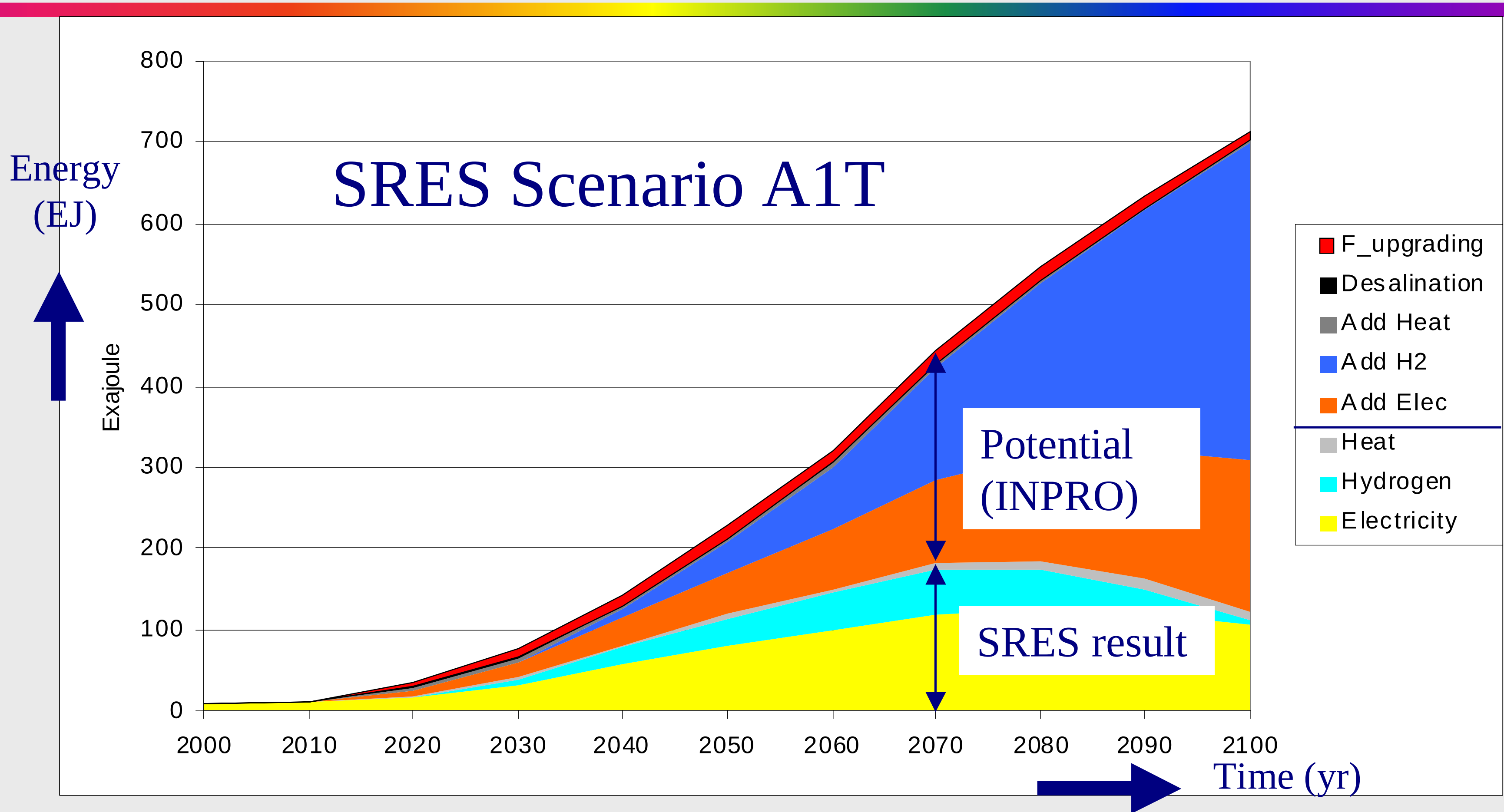
Ranges for Specific Capital Costs in 2050 for NPP (SRES)

Phase IA Results of INPRO in the Area Economics



Ranges for electricity production costs in 2050 for NPP (SRES)

Phase IA Results of INPRO in the Area Economics



Potential Global Market for Nuclear Electricity, Hydrogen, Heat and Desalination for A1T Scenario with decreased costs

Phase IA Results of INPRO in the Area Economics

- **Two Basic Principles defined:**
  - ***The cost of energy from INS, taking all costs and credits into account, must be competitive with that of alternative energy sources***
  - ***INS must represent an attractive investment compared with other major investments***

- **Five User Requirements and Several Criteria defined**

Phase IA Results of INPRO in the Area Economics

<u>Basic Principle 1</u> – *The* ***cost of energy*** *from innovative nuclear energy systems, taking all costs and credits into account, must be* ***competitive with that of alternative energy sources***

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

Phase IA Results of INPRO in the Area Environment

Section 4.2 – Sustainability and environment

- 2 Basic Principles :
  - Acceptability of expected adverse environmental effects
  - Fitness for purpose

- 4 User Requirements for INS

- 4 User Requirements for Assessment Methods

Phase IA Results of INPRO in the Area Environment

BP 1 – Acceptability of expected adverse environmental effects

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

UR 1.1 – Controllability of environmental stressors

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

Indicator : L_{S-i} : level of stressor *i*

Acceptance Limit : $L_{S-i} \leq S_i$; S_i : Standard for stressor *i*

UR 1.2 – Adverse effects as low as reasonable practicable

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

Indicator : E_{ae} : adverse environmental effect

Acceptance Limit : $E_{ae} \leq L_{ALARP}$

Phase IA Results of INPRO in the Area Environment

BP 2 – Fitness for Purpose

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

UR 2.1 – Consistency with resource availability

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

Indicator 1 : F_{ci} : Fuel i consumed in 100 years

Acceptance Limit 1 : $F_{ci} \leq (F_{pri} + F_{ri})$ (proven reserves + reprocessed)

Indicator 2 : M_{ci} : Critical material i consumed in 100 years

Acceptance Limit 2 : $M_{ci} \leq M_{pr}$ (proven reserves)

Indicator 3 : B_{up} : Burnup (MWd / Ton U)

Acceptance Limit 3 : $B_{up} \geq B_{up}$ Ref (reference burnup)

Phase IA Results of INPRO in the Area Environment

User Requirements for assessment methods

1. **Consider all factors**

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

2. ***Complete system approach***

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

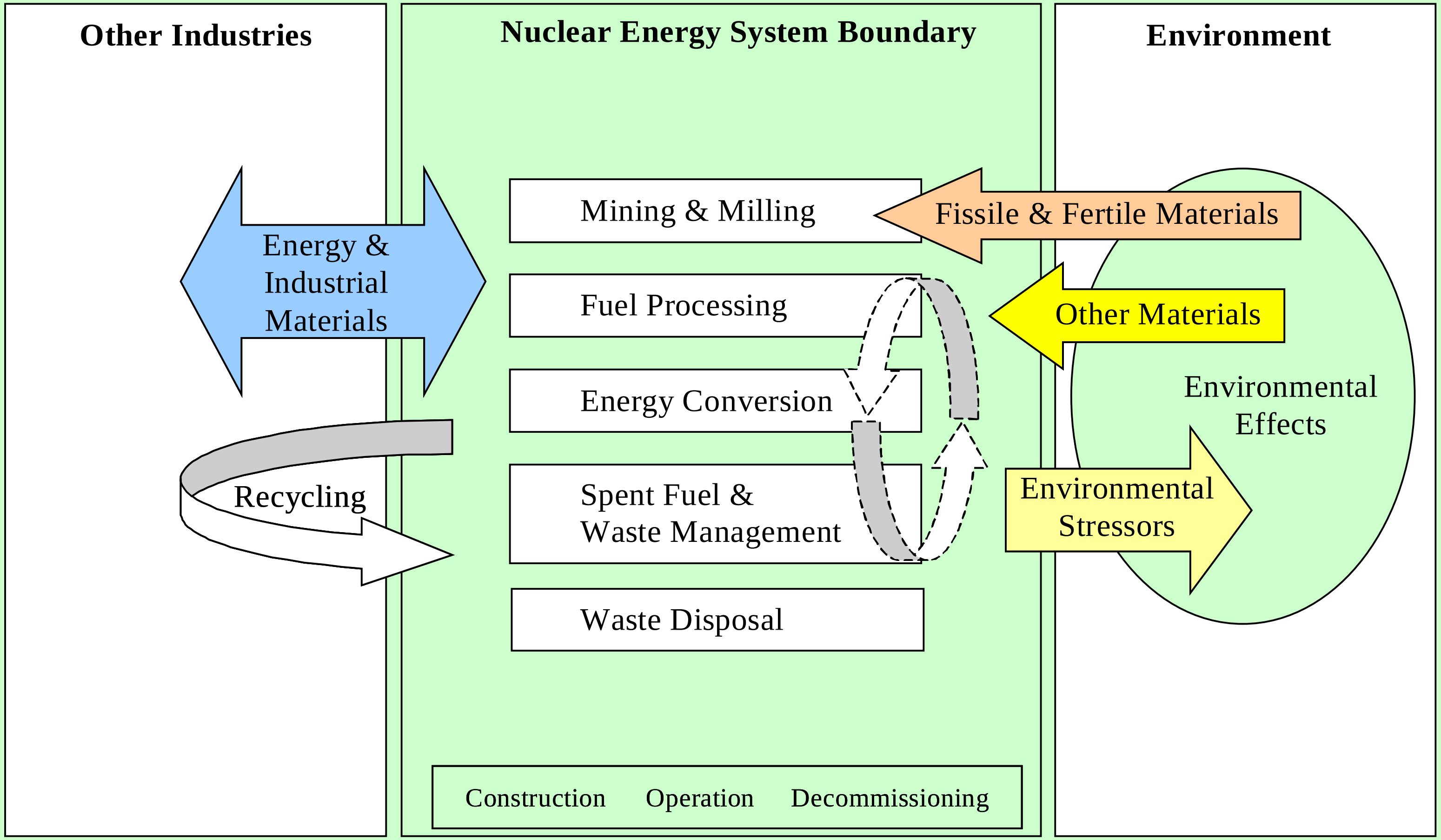
3. **Complete material flow**

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

4. **Non-routine events**

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

Results of INPRO in the Area Environment



- Holistic Approach for Environmental Assessment

Phase IA Results of INPRO in the Area Safety of Nuclear Installations

General Nuclear Safety Objective

Fundamental Safety Functions

Nuclear Reactors
- Control Reactivity
- Remove Heat from Core
- Confine Radioactivity and Shield Radiation

Fuel Cycle Installations
- Control Sub-criticality and Chemistry
- Remove Decay Heat from Radio-nuclides
- Confine Radioactivity and Shield Radiation

Deterministic & Probabilistic Safety Analysis

Defence in Depth
- Prevent abnormal operation and failures
- Control abnormal operation, detect failures
- Control accidents within design basis
- Assure low damage frequencies
- Contain released radioactive materials

Increased Emphasis on Inherent Safety Characteristics

Passive Systems

Balanced design options and configurations

Active Systems

Phase IA Results of INPRO in the Area Safety of Nuclear Installations

Level of defence-in-depth	Objectives	Innovation Direction (INPRO)
1	Prevention of abnormal operation and failures.	Enhance prevention by increased emphasis on inherently safe design characteristics and passive safety features.
2	Control of abnormal operation and detection of failures.	Give priority to advanced control and monitoring systems with enhanced reliability, intelligence and limiting features.
3	Control of accidents within the design basis.	Achieve fundamental safety functions by optimised combination of active & passive design features; limit fuel failures; increase grace period to several hours.
4	Control of severe plant conditions, including prevention and mitigation of the consequences of severe accidents.	Increase reliability of systems to control complex accident sequences; decrease severe core damage frequency by at least one order of magnitude, and even more for urban-sited facilities.
5	Mitigation of radio-logical consequences of significant releases of radioactive materials	No need for evacuation or relocation measures outside the plant site.

More independence of levels from each other

Innovation direction (INPRO) to enhance the levels of Defence in Depth

Phase 1A Results of INPRO in the Area Safety of Nuclear Installations

- **Five Basic Principles defined:**

  The Innovative Nuclear Reactors and Fuel Cycle Installations shall:

  - ***Incorporate enhanced defense in depth***
  - ***Be so save that they can be sited in locations similar to other industrial facilities used for similar purpose***
  - ***Incorporate increased emphasis on inherent safety and passive features***
  - ***Include associated RD&D***
  - ***Include holistic life-cycle analysis***

- **Twenty-seven User Requirements and Several Criteria defined**

Phase IA Results of INPRO in the Area
Safety of Nuclear Installations

Basic Principle 1: ***Innovative nuclear reactors and fuel cycle installations shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and the levels of protection in defence-in-depth shall be more independent from each other than in current installations (continued).***

User Requirement	Criteria	
	Indicators	**Acceptance Limit**
The innovative nuclear reactors and fuel cycle installations shall not need relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility.	Probability of large release of radioactive materials to the environment.	$<10^{-6}$ per plant$_*$year, or excluded by design.

Phase IA Results of INPRO in the Area Safety of Nuclear Installations

Basic Principle 1: ***Innovative nuclear reactors and fuel cycle installations shall incorporate enhanced defence in depth as a part of their fundamental safety approach and the levels of protection in defence in depth shall be more independent from each other than in current installations.***

User Requirements (in total seven for BP 1)	Criteria	
	Indicators	**Acceptance Limits**
1.1 The innovative nuclear reactors and fuel cycle installations should be more robust relative to existing designs regarding system and component failures as well as operation	**Robustness of design (simplicity, margins).**	**Superior to existing designs.**
	Grace time until human actions are required.	**At least one day.**
► (Correlates to Level 1 of Defence in Depth)	**Inertia to cope with transients.**	**No material flow out of the primary system.**

Phase IA Results of INPRO in the Area Safety of Nuclear Installations

<u>Basic Principle 3:</u> *Innovative nuclear reactors and fuel cycle installations shall incorporate increased emphasis on inherent safety characteristics as a part of their fundamental safety approach.*

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

Results of INPRO in the Area Safety of Waste Management

- Nine Basic Principles (from IAEA Safety Series No. 111-F)
  - ***Secure acceptable level of protection for human health and the environment including effects beyond national borders now and in the future*** *(summary of 4 principles)*
  - ***Avoid undue burdens on future generations***
  - ***Minimize waste generation***
  - ***Consider all interdependencies among all steps of waste generation***
  - ***Assure appropriate national legal framework***
  - ***Assure safety of waste facilities during lifetime***
- Six User Requirements and Several Criteria defined by INPRO

Results of INPRO in the Area Safety of Waste Management

User Requirement	Criteria	
	Indicators	Acceptance Limits
5.Reduction of Waste at the Source: *The energy system should be designed to minimize the generation of wastes and particularly wastes containing long-lived toxic components that would be mobile in a repository environment*.	Alpha-emitters and other long-lived radionuclides	ALARP
	Total activity Radiotoxicity	ALARP
	Mass	ALARP
	Volume	ALARP
	Chemically toxic elements that would become part of the radioactive waste	ALARP(as low as reasonable practical, social and economic factors taken into account)

INPRO Approaches in Proliferation Resistance (PR)

Proliferation Resistance

- **Is limited to proliferation by States**
- **does not include protection against the theft of fissile materials by sub-national groups**
- **or the sabotage of nuclear installations or transport systems**

- **Physical protection and security issues are separately dealt with**

New Technology & Future PR

New Reactor

PR

New Fuel Cycle

PR

New Institutions

PR

Future PR Features (Intrinsic & Extrinsic)

“Guideline for Future PR Features”

Intrinsic & Extrinsic

- Intrinsic PR features are

  those features that result from the technical design of nuclear energy systems

- Extrinsic PR measures are

  those measures that result from States decision and undertakings related to nuclear energy systems

Basic Principles for Proliferation Resistance

1. PR should be provided in INS to ***minimize*** the possibilities of misuse of nuclear materials for nuclear weapons.
2. Both ***intrinsic features and extrinsic measures*** are essential, and neither should be sufficient by itself.

(***Extrinsic*** measures will remain essential, whatever the level of effectiveness of intrinsic features. And from a PR point of view, the ***development and implementation of intrinsic features*** should be encouraged.)

Main Messages of INPRO in the Area Crosscutting Issues

- Need of Improvement of:
  - Legal and Institutional Infrastructure
  - Economic and Industrial Infrastructure
  - Socio-Political Infrastructure
  - Human Resources and Knowledge
- Improvement via e.g.:
  - International accepted licensing
  - International multi-component system
  - Application of INPRO requirements
  - Enhanced international cooperation

Results of INPRO in the Area Crosscutting Issues

- **Recommendations** in the area of **Legal and Institutional Infrastructure**:
  - **License** for INS should be based on INPRO Requirements and **internationally accepted**.
  - **International** or regional nuclear **authorities** and inspection bodies should be established.
  - Handling of **liability and insurance risk** should be **comparable to other industries**.

Results of INPRO in the Area Crosscutting Issues

- **Recommendations** in the area of **Economic and Industrial Infrastructure**:

  - Nuclear components in different countries should be part of an **international multi-component system.**
  - **Market demand,** especially that of **developing countries,** has **to be recognized** by developers of INS.
  - **Supply of full scope**, including management and operation.

Methodology for Assessment of INS

- Developed and published in TECDOC 1362
- Validation ongoing by several case studies
- The outcome will be incorporated in a Manual for the application of the Methodology for Assessment of INS

Ongoing activities

Phase 1B

- **Feedback from**
  - **National Case Studies**
  - **Individual Case Studies**
  - **Different categories of users**

  will result in the validation of the INPRO methodology and, where necessary, an adjustment of BP, UR and Criteria

- **Case Studies**

  Case studies are to be performed to gain experience with the INPRO methodology, and to assess :

  - **whether the BP, UR and C are understandable, workable, consistent (avoid redundancy), comprehensive (additional needed ?) and independent of the system studied.**
  - **whether the INPRO methodology is useful for providing an overall assessment of the INS, comparing different INS, identifying regional specificities and identifying R&D needs.**

Outlook: Phase II

Background

- All scenarios (e.g. SRES from IPCC) show a substantially increasing demand for energy (mostly electricity)
- Highest increase of energy demand in developing countries
- INS clearly needed to satisfy the increasing demand for energy
- INS must satisfy special needs of developing countries
- Many innovative nuclear reactors and associated fuel cycles are being developed in Member States

Outlook: Phase II

INPRO approach

- INPRO uses a holistic view for INS assessment (cradle to grave)
- INPRO has created a tool (INPRO methodology) which is capable of defining an optimized INS based on local, regional or global boundary conditions

Outlook: Phase II (INPRO Vision)

- • Further development of INPRO methodology and its establishment as an internationally acknowledged IAEA recommendation for the assessment of INS
- • Assistance to INPRO Members in energy planning and analyzing the possible future role of nuclear energy in global, regional and national context.
- • Identification of technologies (National preferences) and R&D needs, examination of the feasibility of commencing international projects on multilateral or international basis.

Outlook: Phase II (INPRO Vision cont'd)

- • Coordination of R&D Projects carried out by INPRO members, on national, bilateral, or multilateral basis.
- • Promotion of infrastructure development needed for deployment of INS
- • Coordinate and assist INPRO Member States with activities to communicate information in order to support the public acceptance
- INPRO will address the needs of both technology users and technology holders with especial emphasis on the needs of developing countries.
- INPRO will seek cooperation from other international initiatives like GIF.

INPRO-GIF Interactions

- Continuous Participation of IAEA in GIF policy and expert groups
- GIF participated in last INPRO Steering Committee
- Performance of comparison of both assessment methodologies in January 2004, based on GIF peer review of INPRO Methodology
- Co-operation between IAEA-INPRO and GIF in analysis of sustainability, globalisation and safety

CONCLUSIONS

- INPRO has political, financial and technical support from Member States
- Phase IA on the establishment of Basic Principles, User Requirements and Criteria and the development of an Assessment Methodology has been finalised
- Phase IB addresses the validation of the INPRO methodology and the assessment of concepts and approaches
- INPRO is open to all interested Member States and International Organizations