International Atomic Energy Agency

INPRO

International Project on Innovative Nuclear Reactors and Fuel Cycles

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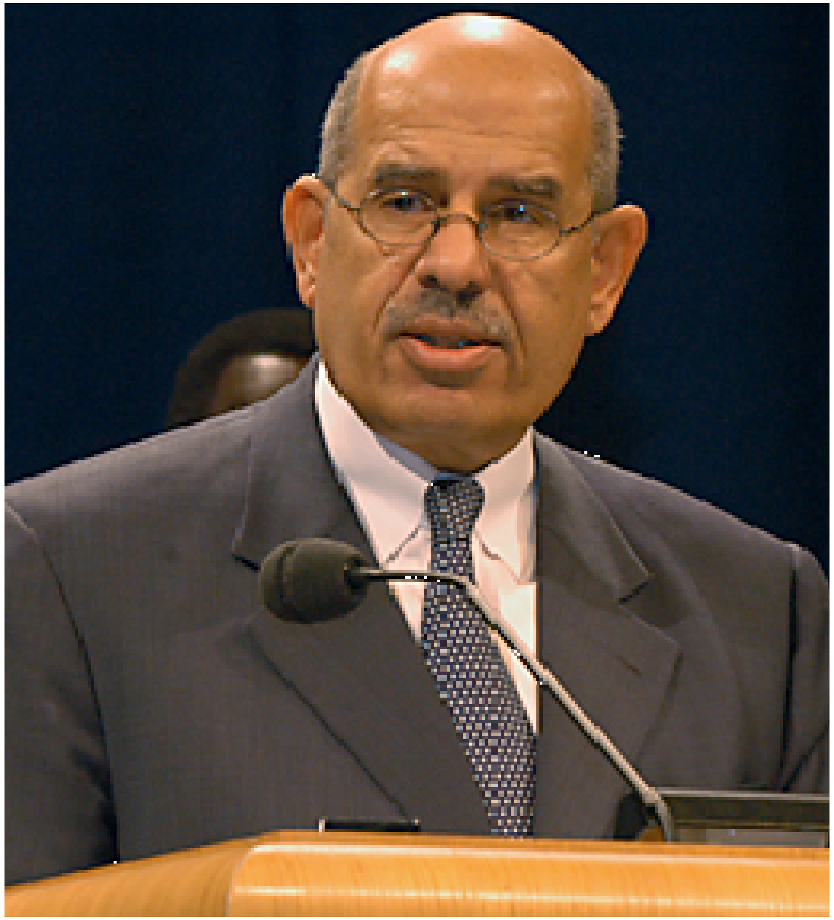
IAEA, Vienna

Content

- Introduction
- Safety of Nuclear fuel cycle installations
- Waste Management
- Environment protection
- Manual preparation
- Conclusions

Introduction

IAEA Director General Mohamed El Baradei delivers his statement to the 49 th General Conference. (Plenary, Austria Center, Vienna, Austria, 26 September 2004).



- ***INPRO´s primary contribution has been to ensure that the future needs of all countries (including developing countries) — related to reactor size, economics and infrastructure needs, as well as to safety, security, proliferation resistance and waste management — are considered when innovative nuclear systems are evaluated.***

IAEA GC(49)/RES/12-2005
Agency Activities in the Development of Innovative Nuclear Technology

- Recognizing the unique role which the Agency plays, and in particular the current role it is playing through the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), by bringing together all interested Member States to consider jointly innovations in nuclear reactors and fuel cycle systems,
- Noting that 22 Member States and the European Union are now members of INPRO, with Armenia, Morocco and Ukraine having joined since the 2004 session of the General Conference, and that the United States of America has announced its intention to join INPRO at this session of the General Conference;
- Stresses the need for international collaboration for the development of innovative nuclear technology and the high potential and added value achieved through such collaborative efforts, as well as the importance of taking advantage of synergies between international activities on innovative nuclear technology development;
- Invites all interested Member States to contribute to innovative nuclear technology activities in terms of scientific and technical information, financial support or technical and other relevant experts and by performing joint innovative nuclear energy systems assessments;

Conclusion of INPRO Phase 1A

- Formulation by INPRO in Phase 1A of Basic Principles, User Requirements and Criteria for Assessment of INS in all Areas (Economics, Environment, Safety, Waste Management, Proliferation Resistance) and Recommendations in Cross Cutting Issues.
- Documentation of Results of Phase 1A in an IAEA report (TECDOC-1362, Guidance for the evaluation of innovative nuclear reactors and fuel cycles) published in June 2003.

IAEA-TECDOC-1362

IAEA-TECDOC-1362

Guidance for the evaluation of innovative nuclear reactors and fuel cycles

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

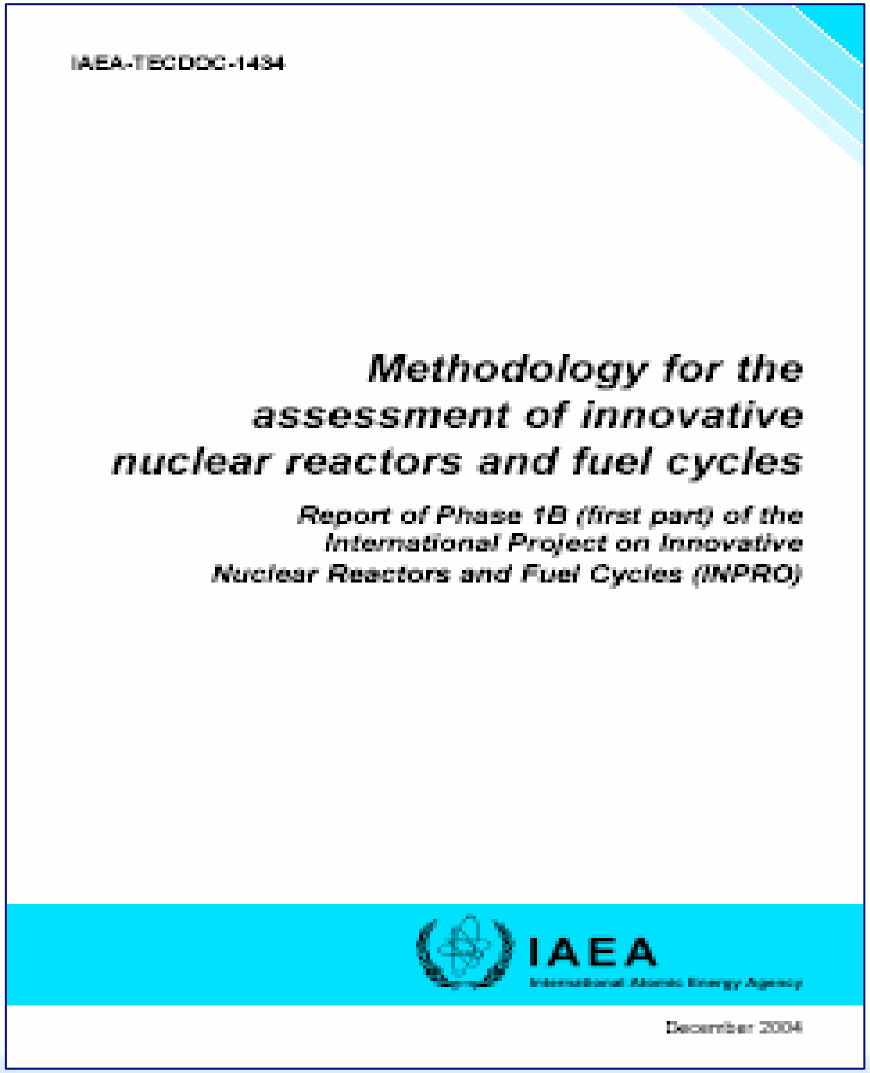
INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

June 2003

Conclusion of INPRO Phase 1B (1st part)

- INPRO Phase 1B (1st part) started in July 2003: Testing/Validation of INPRO Methodology via:
  - 6 National Case Studies performed by MS: Argentina, India, Republic of Korea, Russia, China, Czech Republic.
  - 8 Individual Case Studies performed by experts : Argentina, France, India, Russia.
- INPRO Methodology updated based on results of case studies and consultancies.
- TECDOC-1434 (Methodology for the assessment of innovative nuclear reactors and fuel cycles) published in December 2004.

Results of INPRO
Activities in Phase 1B (1st part)
IAEA TECDOC 1434



IAEA-TECDOC-1434

Methodology for the assessment of innovative nuclear reactors and fuel cycles

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

IAEA
International Atomic Energy Agency

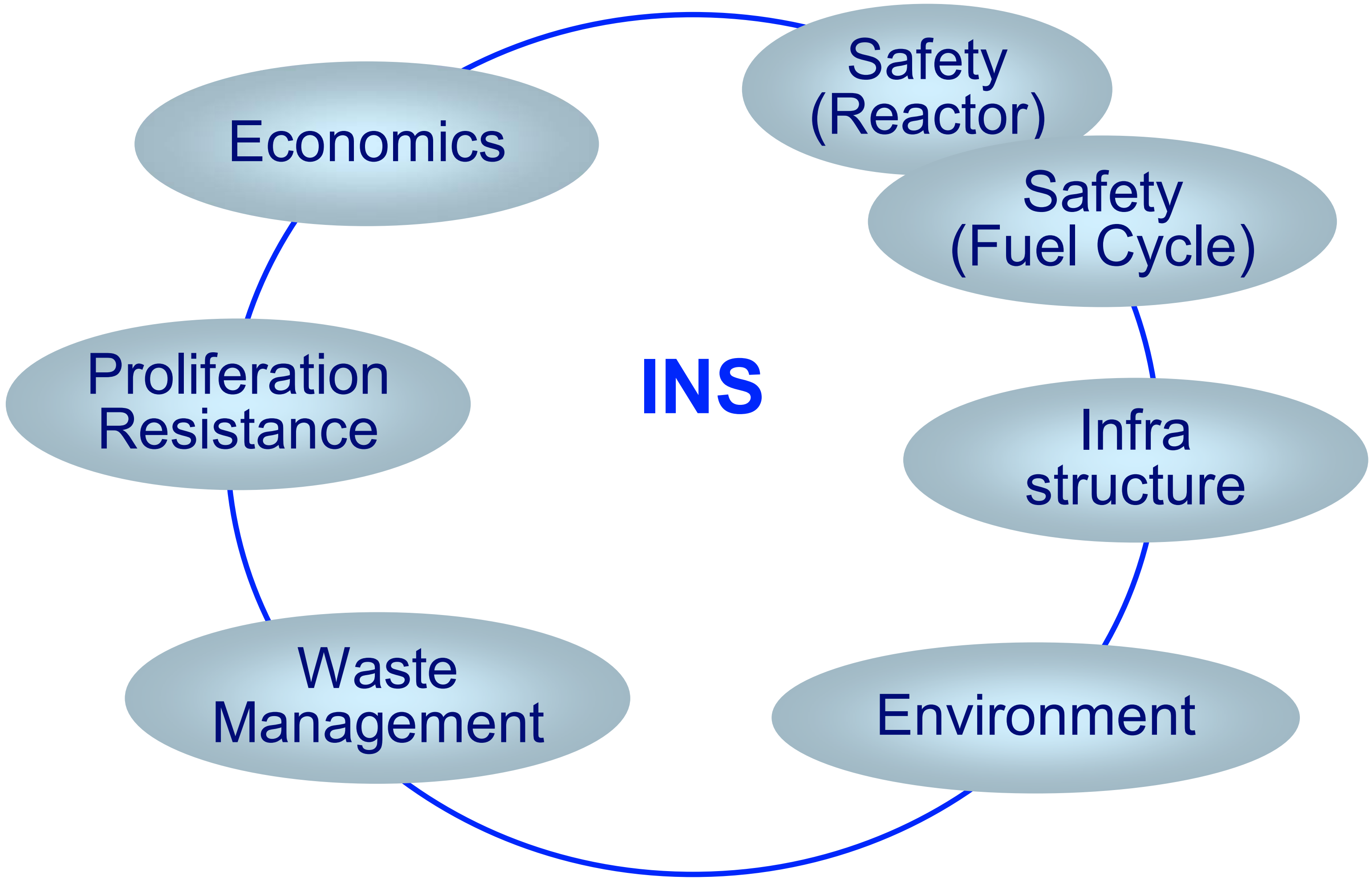
December 2004

Safety of Nuclear Fuel Cycle facilities

General approach

- Look globally, do locally
- All processes related
  - Nuclear material production
  - Fuel design
  - Fuel testing
  - Fuel fabrication
  - Fuel irradiation
  - Fuel recycling
  - SNF management
  - And other
- Should proper consider INPRO BP,UR and Cr in all INPRO areas

INPRO approach

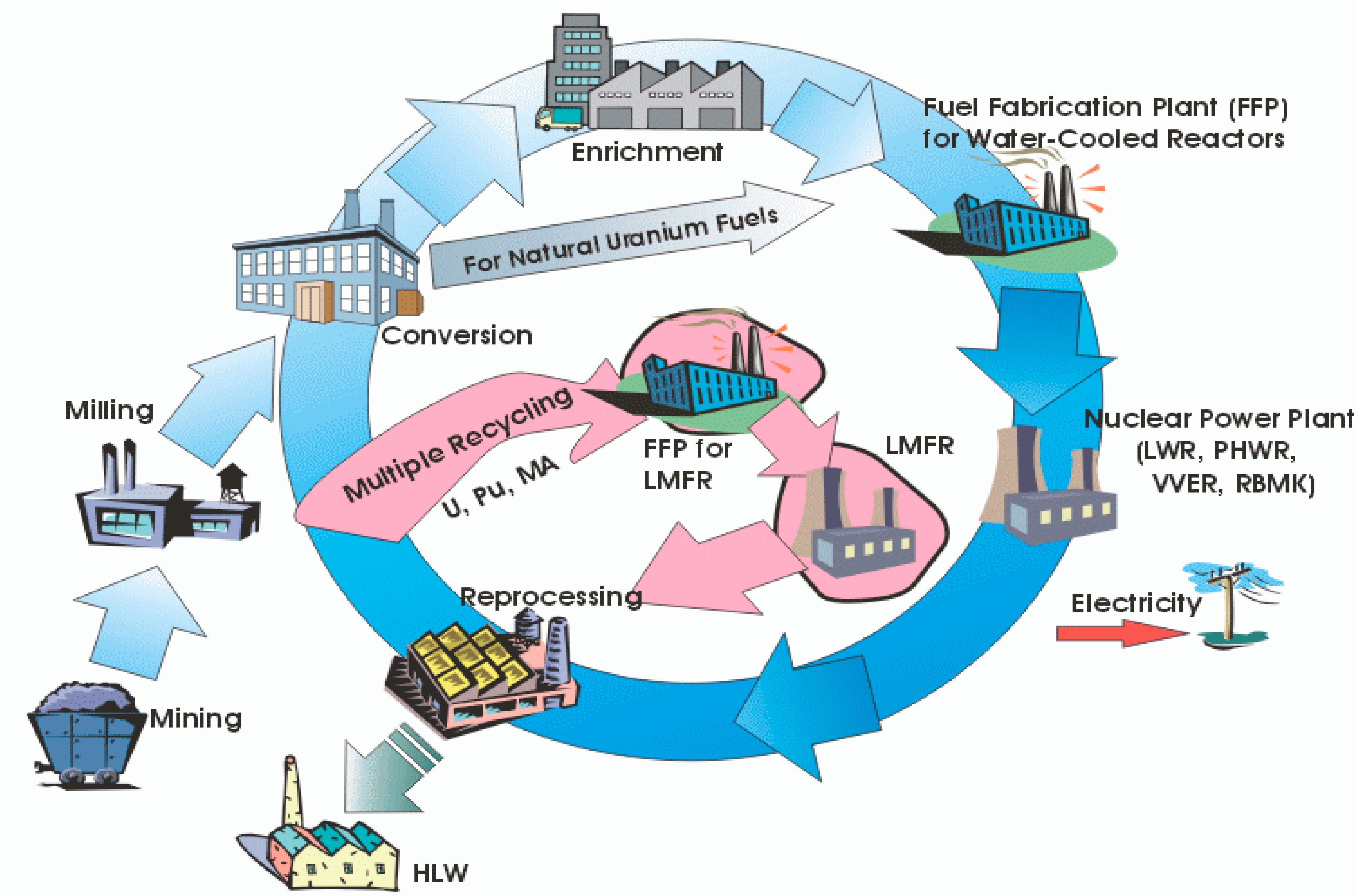


General features of the INPRO Methodology

In the framework of INPRO, an INS includes all components:

- Uranium/ Thorium Mining and Milling
- Uranium Refining and Conversion
- Uranium Enrichment
- Fuel Fabrication
- Nuclear Reactor
- Spent Fuel Storage
- Spent Fuel Reprocessing including MA partitioning
- Re-fabrication including MA fuels and targets
- Radioactive Waste Management
- Waste disposal
- Decommissioning
- Transportation

INPRO Methodology covers the entire NFC Process



General consideration

- It is necessary to emphasize that global success in the growth of nuclear energy to a large extent, depends on the safe and economical operation of the fuel cycle facilities as much as it depends on a safe and economical operation of nuclear reactors themselves.

Typical fuel cycle options

Currently Deployed On Industrial Scale OFC: Once-through fuel cycle HWR (CANDU): Once-through fuel cycle RFC: Recycle fuel cycle-monorecycling
Potential Industrial Deployment in <25 years DUPIC: Direct Use of PWR spent fuel In Candu HTGR: High-temperature gas-cooled reactors RFC-multirecycling LWR-Inert Matrix Fuel (IMF) LWR-Pu+MA recycling
Potential Industrial Deployment in 25-50 years Mixed LWR + FR fuel cycle FR 100% cycle Double strata P&T fuel cycle Thorium-cycle Molten salt fuel cycle

Fuel cycle facility operations specifics

- Fuel cycle operations are more varied in the processes and approaches, as compared to reactor systems due to:
  - That some countries are pursuing storage of spent fuels with long term options, while some others have a policy of closing the fuel cycle.
  - The diversity is large when one considers different types of fuels used in different types of reactors
  - the different routes used for processing the fuels before and after their irradiation depending upon
    - the nature of the fuel (low enriched uranium/ natural uranium/ uranium-plutonium);
    - fuel form: metal/ oxide/ carbide/ nitride) and varying burn-up and cooling times.

Safety of Nuclear Fuel Cycle Facilities (NFCF)

- **Differences between NFCFs and Reactors:**
- **The reactor core of an NPP contains a very large inventory of radioactive material at high temperature, pressure, and within a relatively small volume; an NFCF operates at near ambient pressure and temperature.**
- **In NFCFs, the development of accidents is rather slow except in the case of criticality.**
- **High importance of ventilation systems in maintaining their safety functions, even under normal operation, due to direct contact of materials with ventilation or off-gas systems.**
- **A greater diversity of NFCF processes. In these processes use large quantities of hazardous chemicals are used which can be toxic, corrosive and/or combustible.**

Typical Differences between NPPs, Chemical Process Plants and NFCFs

Feature	NPP	Chemical Process Plant Feature	NFCF
Areas of hazardous sources and inventories	Localized at core and spent fuel pool. Standardized containment system. Cooling of residual heat. Criticality management.	Distributed in the process. Present through out the process equipments.	Consisting both of nuclear materials and chemical materials. Co-existence of NPP features and chemical plant features. Present through out the process equipments in the facility.
Type of hazardous materials	Mainly nuclear materials.	A wide variety of materials dependent on the plant, e.g., poisons, acids, toxins, combustibles and explosives.	Fissile materials, nitric acid, hydrogen fluoride, solvents, process and radiolytic hydrogen, etc.
Physical forms of hazardous materials	The core in general is in solid form. Liquid, gas and dust (aerosol) of radioactive materials released to the environment in accident phase.	A wide variety of physical forms dependent on the process, e.g., as solid, liquid, gas, slurry, powder.	All physical forms of fissile material and a wide variety of chemical materials. Immobilized radioactive materials.

Typical Differences between NPPs, Chemical Process Plants and NFCFs

Typical causes of accidents	Incidents related to the core and the safety system, initiated by internal or external events.	Operator and equipment failures, e.g., Loading of the wrong amount of or wrong raw material into the vessel or storage tank; Accumulation of the reactant in the reactor; Too high temperature of the reactor	Incidents related to safety function and barriers, fire, explosion, loss of ventilation, loss of barriers, transport failures.
Consequences of accidents	Core damage, failure of containment, radioactive release and radioactive exposure.	A wide variety w.r.t the number of casualties and time-scale of the contamination (both onsite and off-site), Releases of toxic gases, Damage to the facility.	Possible radioactive release and exposure to personnel, public and environment, damage due to fire and explosion.
Recommended Probabilistic Safety Analysis (PSA) methodology	Plant specific quantitative risk analysis.	Initially, qualitative analysis for each plant. Based on the qualitative analysis, conduct quantitative analysis for hazard sources.	Hazard identification and screening. Evaluation of accident scenarios and failures of barriers. Combination of qualitative and quantitative analysis.

SAFETY ASPECTS FOR FUEL CYCLE FACILITIES

	Criticality	Radiation	Chemical Toxicity	Fire/ Explo-sion	Product/ Residue Storage	Waste Storage	Ageing Facilities	Decommis sioning	Effluents	Maintenance
Mining/ Milling		@	@	*	@	@	@	@	@	
Conversion	*	@	@	@	*	@	@	*		
Enrichment	*	@	@	@	@		*	@		
Fuel Fabrication	@	@	@	@	@	@	*	@	@	*
Interim Storage	@	@				@	@	*		
Reprocessing	@	@	@	@	@	@	@	@	@	@
MOX fuel fabrication	@	@		@	@	@	@	@	@	@
Transportation	*	@	*	@				*		

Safety

- **Typical safety hazards in fuel cycle facilities (FCF) include:**
  - **the release of radioactivity,**
  - **contamination and exposures of workers,**
  - **criticality, and**
  - **releases of chemical and stored energy (e.g., from radioactive decay heating, chemical reactions including fires, and failure of pressurized systems).**

Safety

- Special attention is warranted to ensure worker safety.
- Potential intakes of radioactive material require control to prevent and minimize contamination and so ensure adherence to operational dose limits.
- Releases of radioactive material into the facilities and through monitored and unmonitored pathways can result in significant exposures, particularly from long-lived radiotoxic isotopes.

Safety of Mining& milling

- The major safety issues in the entire process – mining, milling, leaching, product recovery, storage and disposal of tailings- are dust, noise, chemical and radiation exposure to the workers and to the general public. The aspect of transport of ore or the product from site to site is yet another site-specific safety related issue.
  - The daughter products of natural uranium are in equilibrium with uranium and some of the daughter products such as ^{214}Bi and ^{214}Pb are strong gamma emitters, which pose external exposure hazard. (83% of the gamma energy is from ^{214}Bi and 12% is from ^{214}Pb). A dose rate of 5 μGy/h can be measured from a 0.1% uranium ore body and the annual exposures could be about 50 mSv with an ore grade of about 0.5%
  - As the majority of thorium mining is by open-pit methods or by wet dredging, the radiological problems, particularly inhalation hazards are relatively small compared to underground uranium mining. Thorium bearing monazite usually contains very small amount of uranium, and although the typical ratio of thorium to uranium is 25:1, ^{222}Rn and radon daughters may occur in significant air concentrations along with ^{220}Rn and thorium in the initial chemical treatment areas of the plant.

Safety issues in Fuel Fabrication Facilities

- **As there are various types of reactors, different kinds of fuel are fabricated in different forms.**
- **Criticality accidents and the accidental release of hazardous materials are the major safety issues.**
- **In case of enriched uranium/ mixed oxide, special care to be taken to minimize contamination. Shielding may be needed for protection of the workers due to higher gamma dose rates.**

Safety of MOX fuel fabrication

- **Fuel containing Pu can be in the form of MOX, carbide or nitride. As plutonium is highly radiotoxic, all operations for fuel fabrication involving Pu have to be carried out in glove boxes or hot cells.**
- **Containment and ventilation systems need to be very reliable.**
- **Fabrication of Th-Pu MOX fuel can be done in a similar manner.**
- **Th-Pu MOX can be sintered in air, which adds to economy and convenience.**
- **(Th-^{233}U) MOX fuel fabrication calls for development of automated and remote fabrication technology due to the presence of ^{232}U.**

Safety Issues of Reprocessing facilities

- **Among the nuclear fuel cycle facilities other than reactors, reprocessing facilities are the most complex with respect to safety analysis.**
- **The safety issues related to plants based on Purex process.**
- **The processes use organic and aqueous solvents, materials associated with very high radioactivity and significant quantities of fissile materials in flowing streams.**
- **problems related to criticality, shielding, radioactivity release and contamination.**
- **need to develop safety codes, safety criteria and analysis tools to the same extent as presently available for reactors.**

Safety Issues of Reprocessing Facilities

- The large inventory of radioactive materials stored is a major cause of concern.
- The radioactive materials in process are in dispersible forms, and are subjected to vigorous chemical and physical reactions. Hence containment and off-gas cleanup ventilation systems play an important role.

The major safety concerns:

- Criticality due to unsafe accumulation of fissile material inside the geometrically unsafe process equipment or cell
- Red oil explosion caused by violent TBP-nitric acid reaction and subsequent rapid pressurization (typical place of occurrence: HLW evaporator or Pu evaporator)
- Consequent radioactive contamination, internal and external radiation exposure

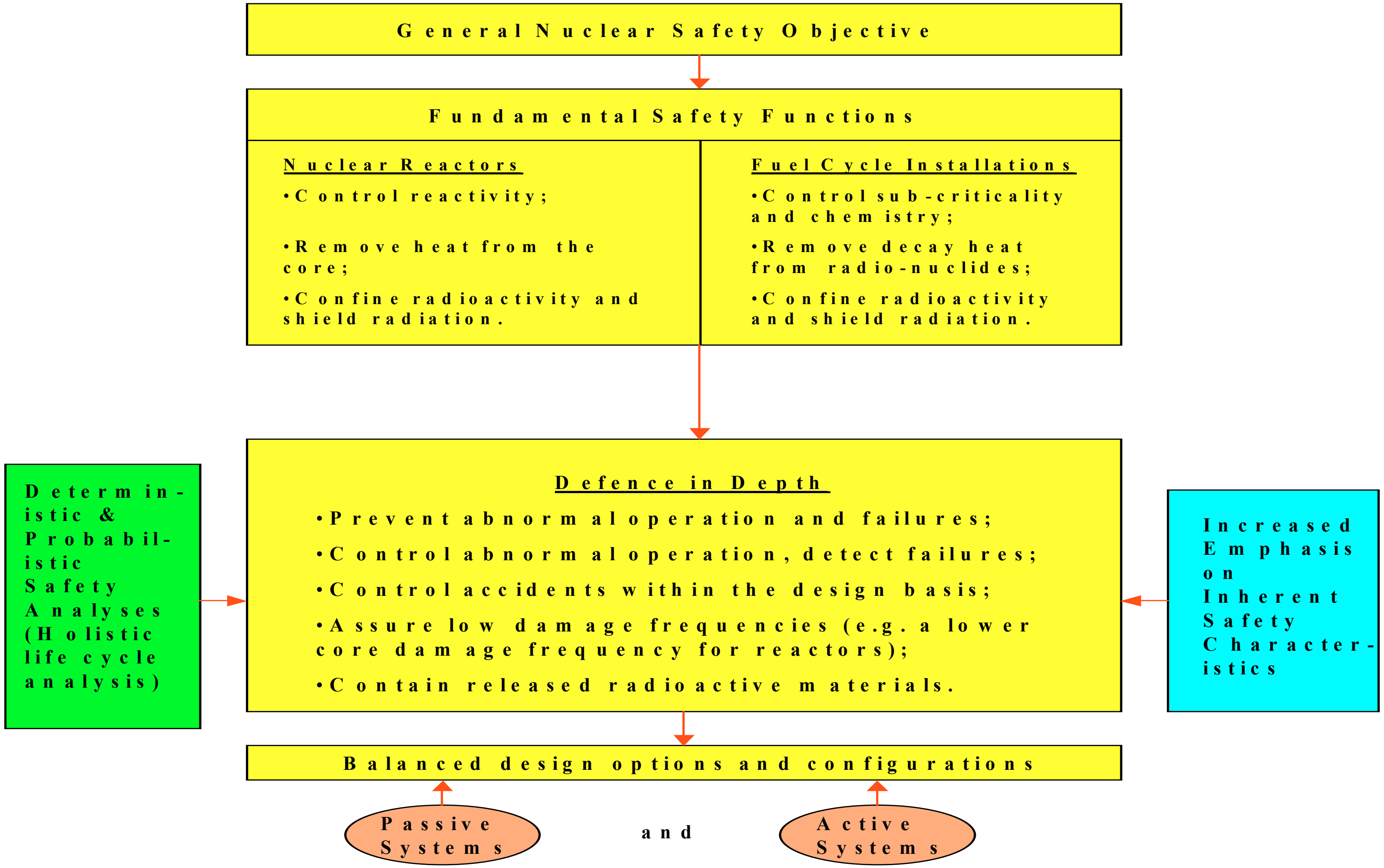
Safety Issues of Reprocessing facilities

- The aqueous route of reprocessing involves handing of fairly high concentration of corrosive acids and high concentrations of electrolyte salts.
- The dissolver has the severe duty of handling highly concentrated nitric acid at nearly boiling conditions. Therefore fabrication of reprocessing equipment requires special materials for fabrication like Nitric Acid Grade (NAG) steels for normal equipments and Zr, Ti or Ti-Ta for the crucial dissolver equipment.
- use of borated steels and poisoned steels with Gd filled structures as well as other specialized materials like ultra-high density concrete for shielding will improve the plant life-cycle and also contribute to safety.

Safety

- For fuel cycle installations the fundamental safety functions are to:
  - control sub-criticality and chemistry;
  - remove decay heat from radio-nuclides; and
  - confine radioactivity and shield radiation.
- To ensure that the fundamental safety functions are adequately fulfilled, an effective defence-in-depth strategy should be implemented.
- For INS, defence-in-depth should include, as appropriate, an increased use of inherent safety characteristics and passive systems in nuclear designs.

Safety



General Nuclear Safety Objective
Fundamental Safety Functions
Nuclear Reactors
•Control reactivity;
•Remove heat from the 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 Analyses (Holistic life cycle analysis)
Defence in Depth
•Prevent abnormal operation and failures;
•Control abnormal operation, detect failures;
•Control accidents within the design basis;
•Assure low damage frequencies (e.g. a lower core damage frequency for reactors);
•Contain released radioactive materials.
Increased Emphasis on Inherent Safety Characteristics
Balanced design options and configurations
Passive Systems
and
Active Systems

Defense-in-depth application for NFCFs

Taking into account the following features of the fuel cycle facilities:

- The energy potentially released in a criticality accident in a fuel cycle facility is relatively small. However generalization is difficult as there is several fuel fabrication or reprocessing options for the same or different type of fuels.
- The power density in a fuel cycle facility is typically two to three orders of magnitudes less in comparison to a reactor core.
- In the reprocessing facility, irradiated fuel pins are mechanically cut (chopped) into small lengths, suitable for dissolution and the resultant solution is further subjected to chemical processes. This makes it possible for larger releases of radioactivity to environment on a routine basis as compared to reactors.
- The likelihood of release of chemical energy is higher in fuel cycle facilities of reprocessing, re-fabrication etc. Chemical reactions are part of the processes used for fresh fuel fabrication as well as for reprocessing the spent nuclear fuel.

INPRO Basic Principles in the Area Safety of Nuclear Installations (IAEA-TECDOC-1434)

- **Four Basic Principles :**

  Innovative Nuclear Reactors and Fuel Cycle Installations shall:

  1. ***Incorporate enhanced defence-in-depth;***
  2. ***Incorporate increased emphasis on inherent safety and passive features to minimize or eliminate hazards;***
  3. ***Be so safe that they can be sited in locations similar to other industrial facilities used for similar purpose;***
  4. ***Provide confidence based upon experience or appropriate RD&D.***

- **14 User Requirements and 38 Criteria**

INPRO Basic Principle BP1 on Safety

- **BP 1:** ***Installations of an 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.***
  - **UR1.1:** ***Installations of an INS should be more robust relative to existing designs regarding system and component failures as well as operation.***
  - **UR 1.2: …**
  - **UR 1.3:** …

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

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

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

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

Example

- INPRO User Requirement UR1.1 on Safety of Fuel Fabrication Facility

Example: Indicator IN1.1.1 of UR 1.1 – Robustness of fuel fabrication facility

Increase of robustness can be achieved by a number of variables :

- Passive cooling systems for high temperature operation;
- Provision of sub-atmospheric pressure in process enclosures and operating areas;
- Use of safe geometry in equipment layout to prevent critical mass configurations;
- Minimization of hydrogenous materials in process and use of neutron absorbing materials are necessary for criticality control

This is qualitative and quantification of Indicator and would depend upon the limits specified which in turn depend on the nature of fuel processes.

For every type of facility, events AL have to be identified and frequency & grace time specified, based on expert opinions and operating experience

RD&D in Nuclear Fuel Cycle Facilities

- Development of frictionless bearings and avoiding external drives for gas transport in uranium enrichment facilities, for improved operation and maintenance, resulting in enhanced safety.
- Better technologies for drilling operations, to reduce occupational exposures in mining activities.
- Development of an integrated high speed network in mines for automation and tele-operation to have lesser human interference, and hence higher reliability and enhanced safety

RD&D in Nuclear Fuel Cycle Facilities

- Recovery and burning of minor actinides and fission products, to reduce radiotoxicity of the high level waste for a long period of time.
- Development of reprocessing processes which would generate less active wastes
- Alternate extractants and resins to achieve better product recoveries and reduced radioactive discharges.
- Development of corrosion-resistant materials for dissolver vessels which would lead to increased life of the plant, safer operation and maintenance.
- Remotisation and automation techniques in reprocessing plants and fuel fabrication facilities to reduce radiation exposure and radioactive contamination.

RD&D in Nuclear Fuel Cycle Facilities

- Long term behavior of fuel storage facilities, such as corrosion aspects, radioactivity release and transport mechanisms.
- Techniques to isolate and contain some of the long lived isotopes, which migrate in soil/water much faster.
- Enhanced emphasis on fabrication technologies such as Sol-Gel microsphere pelletisation process, which would result in less radioactive dust generation.
- Replacement of electrical heating systems by steam heating systems wherever appropriate, for better safety.
- Use of non-hydrogenated media for cooling, in fuel fabrication facilities, for providing better safety features.

Conclusions

- The fuel type should be selected with a high priority given to safety for all portions of the fuel cycle, including, but not limited to, reactors.
- Specific safety requirements for the fuel will depend on the innovative reactor and fuel cycle installation concept.
- The selection of fuel types affects the safety of all steps of the integrated fuel cycle, from mining to disposal, in both normal operation and accident conditions.

Conclusions

- The safety level for the fabrication of advanced fuel should be similar to the safety level for the fabrication of conventional water reactor fuels.
- Other fuel fabrication methods would be required for advanced fuels of innovative reactors, such as vibro-packed, casting, coated particles, and molten salts.
- Criticality control should be addressed using established methods.

Conclusions

- Fuel fabrication installations should make much greater use of advanced instrumentation and automatic monitoring of material quantities and composition
- Expected higher burn up levels will result in higher concentration of Pu and other transuranic elements and increased decay heat generation in the spent fuel.
  - The shielding of fuel handling equipment and spent fuel storage pools, as well as the systems for heat removal, have to be adjusted accordingly.
  - Spent fuel should be stored without systematic fuel failure and release of radioactive material.
  - Fuel in storage, storage containers as well as the facility itself should all be monitored to confirm their integrity.

Waste management

General features of INPRO Methodology

Holistic view on INS (Innovative Nuclear Energy System)

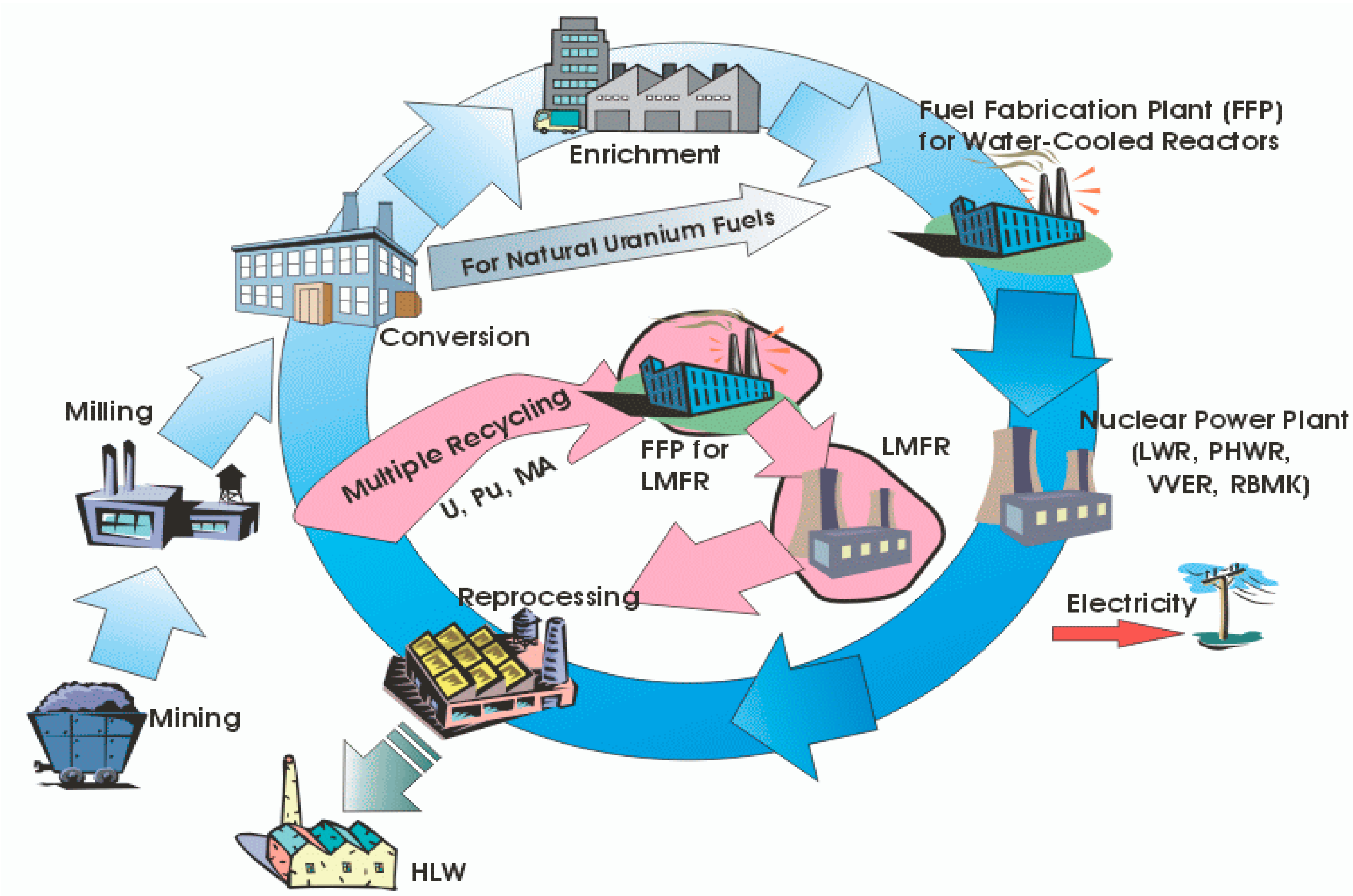
- INS includes Innovative and Evolutionary Designs.
  - ✓ Innovative design : incorporating radical changes in design approaches or system configuration in comparison with existing designs.
  - ✓ Evolutionary design : incorporating small to moderate modifications with strong emphasis on maintaining design proveness

- INS includes all Components:

  Mining and Milling, Fuel Production, Enrichment, Fabrication, Production (incl. all types and sizes of reactors), Reprocessing, Materials Management (incl. Transportation and Waste Management), Institutional Measures (e.g. safeguards, etc.)

- INS includes all Phases (e.g. cradle to grave)

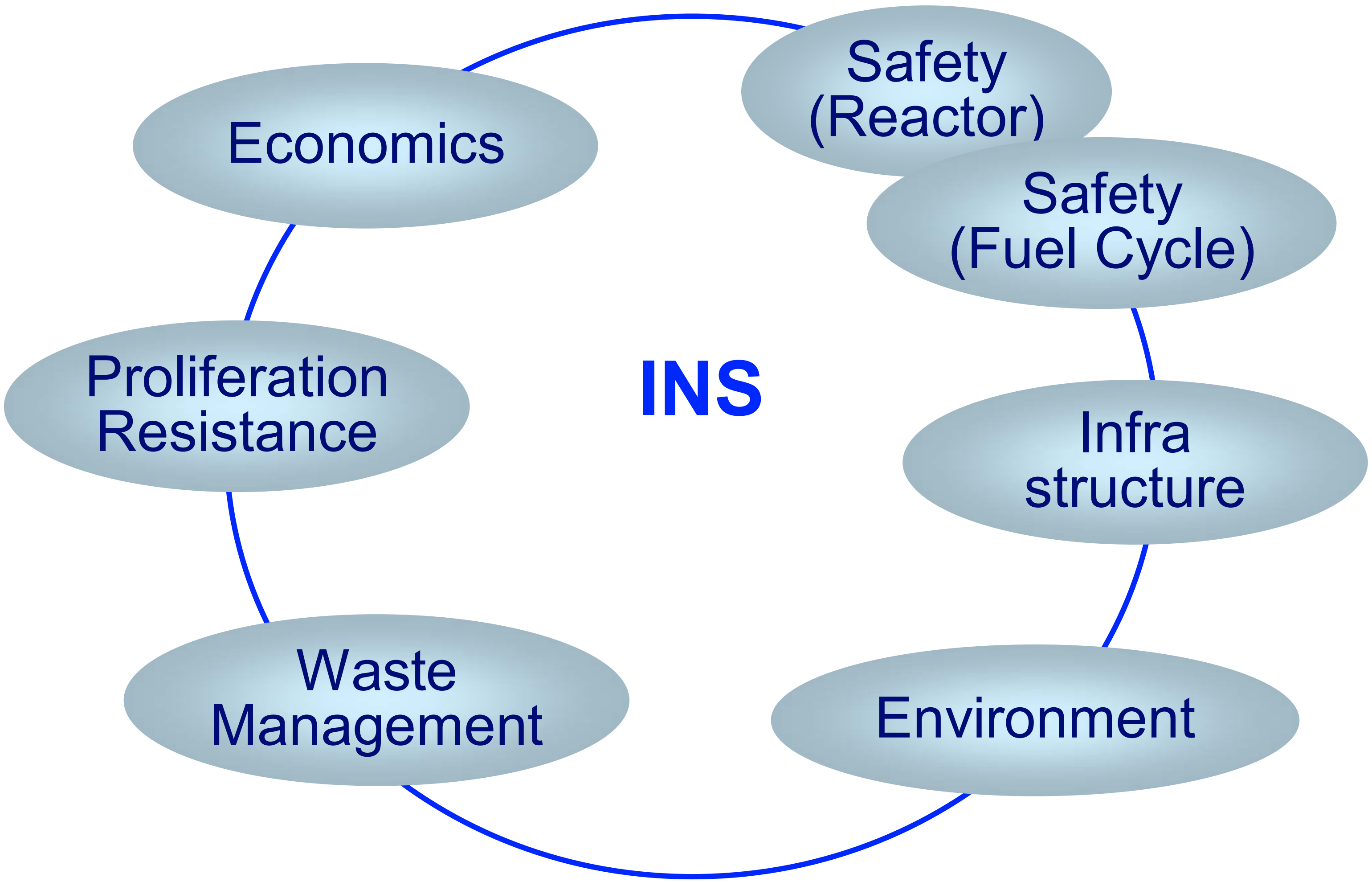
INPRO Methodology covers the entire NFC Process



General approach

- Look globally, do locally
- All processes related
  - Nuclear material production
  - Fuel design
  - Fuel testing
  - Fuel fabrication
  - Fuel irradiation
  - Fuel recycling
  - SNF management
- Should proper consider all INPRO BP,UR in all INPRO areas as well as their interrelations

INPRO approach



Main Messages of INPRO in the Area
Waste Management

- Waste Management Installations shall (IAEA SS 111-F) **secure acceptable level of protection** for:
  - **Human health**
    - **Avoid undue burdens on future generations**
  - **Environment**
    - **Including effects beyond national borders**
- **Minimize waste generation**
- **Consider all interdependencies among all steps of waste generation**

INPRO Methodology
Area of Waste Management (2/4)

- 4 Basic Principles (BPs) ***derived from IAEA Safety Series No. 111-F.***
  - *Minimize waste generation*
  - *Secure acceptable level of protection for human health and the environment*
  - *Avoid undue burdens on future generations*
  - *Consider all interdependencies among all steps of Waste Generation and Management, optimizing Safety*
- **The** 4 BPs **are developed in** Seven User Requirements **and the corresponding** Criteria.

Waste management

- These 4 principles in turn lead to INPRO requirements:
  - to minimize the generation of waste with emphasis on waste containing long-lived toxic components that would be mobile in repository environment,
  - to limit exposures to radiation and chemicals from waste,
  - to specify a permanently safe end states for all wastes and
  - to move wastes to this end state as early as practical,
  - to classify wastes,
  - to ensure that intermediate steps do not inhibit or complicate the achievement of the end state,
  - 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.

Waste management Basic Principle BP1:

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

INPRO Methodology
Area of Waste Management (4/4)

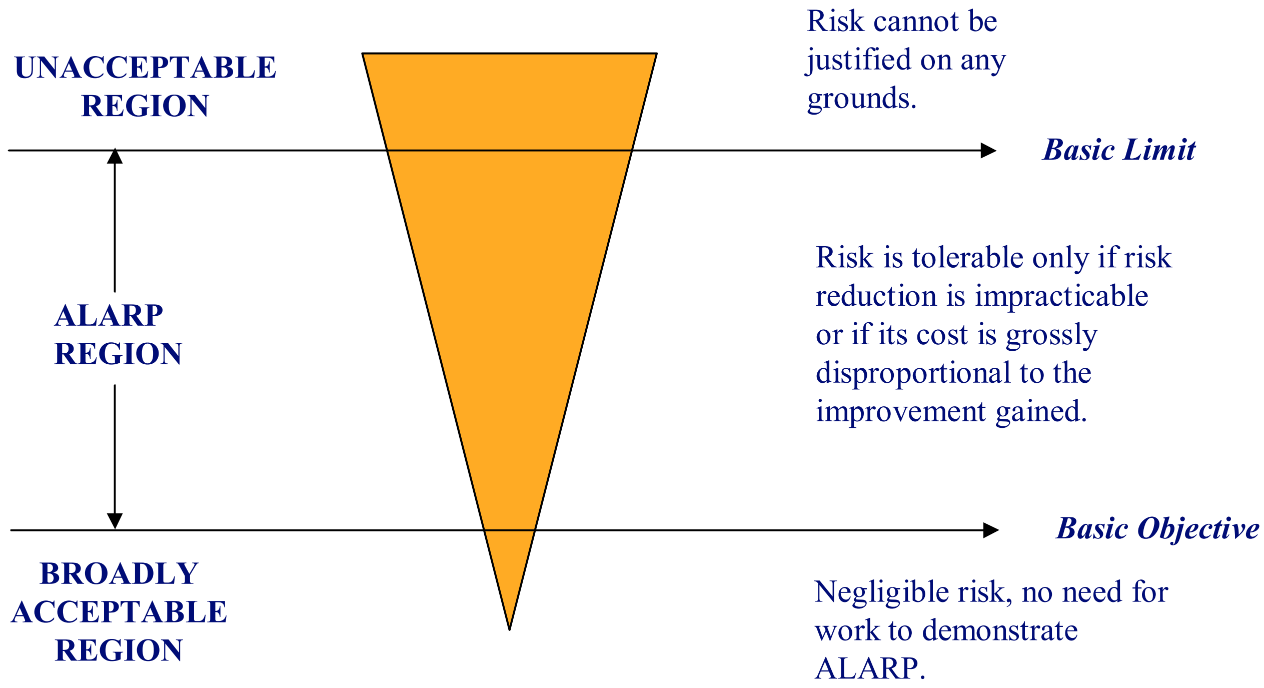


Illustration of the ALARP concept

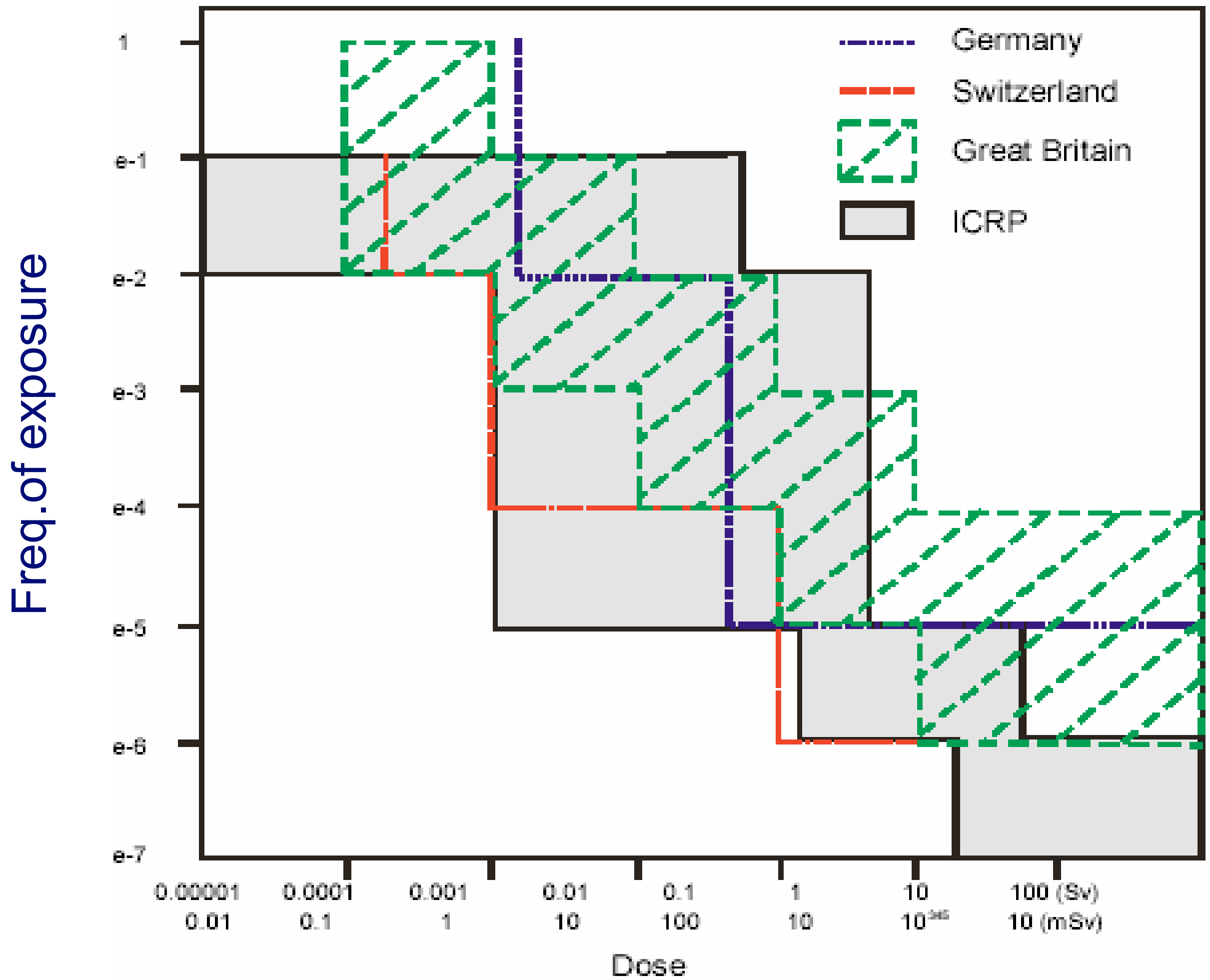
Reducing the radioactive waste

- Methods for reducing the radioactive waste include:
- Segregation of waste streams to avoid cross contamination, to increase the proportion of waste suitable for controlled or free release, and to decrease the volume of material that represents a long-term hazard;
- Recycling and reuse of materials that would otherwise be radioactive waste;
- Optimizing the design to facilitate decommissioning and dismantling of facilities; and
- Extraction of long-lived decay products in mining and milling operations; and
- Reduction of secondary waste from waste management systems.
- Technologies worthy of consideration for further development include:
- Improvement of both aqueous and non-aqueous methods of processing spent fuel;
- Partition and transmutation (P&T) of long-lived radio-nuclides in power reactors or accelerator driven systems;
- Application of advanced materials, such as cobalt-free steels, to reduce activation;
- Improved fuel cycle efficiency;
- Improved efficiency of the energy conversion process at reactors; and
- Improved decontamination technology.

Waste management Basic Principle BP2

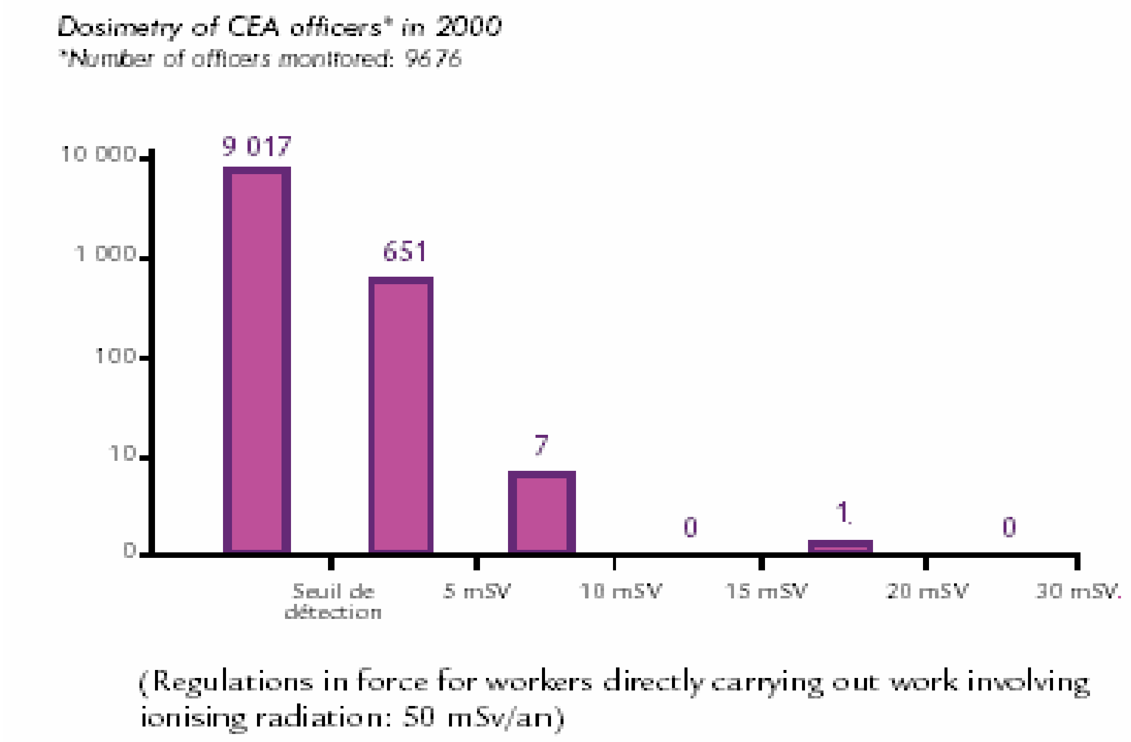
Waste management Basic Principle BP2: (Protection of human health and the environment) ***Radioactive waste in an INS shall be managed in such a way as to secure an acceptable level of protection for human health and the environment, regardless of the time or place at which impacts may occur.***		
User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

Comparison of safety criteria (risk based) for nuclear installations



Frequency of exposure versus the exposure dose

Figure Indicates need for harmonisation



Results reported by CEA illustrating the scope for reduction in annual radiation exposure to workers

Scope for reduction in annual occupational exposure exists

Waste management Basic Principle BP2:

<table>
<tr><td colspan="3">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.</td></tr>
<tr><td rowspan="2">User Requirements</td><td colspan="2">Criteria</td></tr>
<tr><td>Indicators</td><td>Acceptance Limits</td></tr>
<tr><td>UR2.2: (Protection of the Environment)
The cumulative releases of radio-nuclides and chemical toxins from waste management components of the INS should be optimised.</td><td>Estimated releases of radio-nuclides and chemical toxins from waste management facilities</td><td>Meet regulatory standards of specific Member State.</td></tr>
</table>

Examples of NFC technologies minimizing waste generation

- ThO2 fuel: Thorium, an abundant fertile material, is used to produce the fissile isotope ^{233}U, which is recycled. The production of Pu and other actinides is reduced. However new radio-nuclides, such as ^{231}Pa, not existing in the U-Pu cycle, are generated.
- DUPIC fuel: Spent PWR fuel is fabricated into PHWR fuel without aqueous processing, minimizing the generation of HLW and reducing mining and milling waste. Burning actinides in the PHWR can reduce fuel radio-toxicity.
- U-Pu nitride fuel: This fuel type is being investigated in Russia. The spent nitride fuel can be regenerated by non-aqueous technology with less liquid waste and P&T of long-lived radio-nuclides.

Waste management Basic Principle BP3:

Waste Management Basic Principle BP3: (Burden on future generations)
Radioactive waste in an INS shall be managed in such a way that it will not impose undue burdens on future generations.

User Requirements	Criteria: Indicators	Criteria: Acceptance Limits
UR3.1 (End State): *An achievable end state should be specified for each class of waste, which provides permanent safety without further modification. The planned energy system should be such that the waste is brought to this end state as soon as reasonably practicable. The end state should be such that any release of hazardous materials to the environment will be below that which is acceptable today.*	3.1.1 Availability of technology. 3.1.2.Time required. 3.1.3 Availability of resources. 3.1.4 Safety of the end state (long-term expected dose to an individual of the critical group). 3.1.5 Time to reach the end state.	3.1.1 All required technology is currently available[1] or reasonably expected to be available on a schedule compatible with the schedule for introducing the proposed innovative fuel cycle. 3.1.2 Any time required to bring the technology to the industrial scale must be less than the time specified to achieve the end state. 3.1.3 Resources (funding, space, capacity, etc.) available for achieving the end state compatible with the size and growth rate of the energy system. 3.1.4 Meet regulatory standards of specific Member State. 3.1.5 As short as reasonably practicable.
UR3.2 (Attribution of Waste Management Costs): *The costs of managing all waste in the life cycle should be included in the estimated cost of energy from the INS, in such a way as to cover the accumulated liability at any stage of the life cycle.*	Specific line item in the cost estimate	Included.

[1] The word "currently" is used in this document to refer to the time at which the acceptability of a nuclear energy system is being evaluated. The criterion is explicitly intended to allow innovative methods of waste management, such as partitioning and transmutation or advanced waste forms, to be investigated.

Waste management Basic Principle BP4:

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	Criteria	
	Indicators	**Acceptance Limits**
UR4.1 (Waste Classification): *The radioactive waste arising from the INS should be classified to facilitate waste management in all parts of the INS.*	Classification scheme.	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 (e.g., heat removal, criticality control, confinement of radioactive material) are addressed. The processes should not inhibit or complicate the achievement of the end state.***	Time to produce the waste form specified for the end state.	As short as reasonably practicable.
	Technical indicators: e.g., Criticality compliance; Heat removal provisions; Radioactive emission control measures; Radiation protection; measures (shielding etc.); Volume / activity reduction measures; and Waste forms.	Criteria as prescribed by regulatory bodies of specific Member States.
	Process descriptions that encompass the entire waste life cycle.	Complete chain of processes from generation to final end state and sufficiently detailed to make evident the feasibility of all steps.

R&D target

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

R&D target

Waste Management Element	RD&D Targets	Expected time for results
Geological Disposal	Demonstrate disposal technologies. Improve geological characterization. Enhance understanding of hydro-geo-chemical transport processes. Improve long-term monitoring technologies. Facilitate the detailed design of geological repositories. Continue the development of performance assessment methods.	Medium
Long term human factors analysis	Assess risks associated with waste management systems that require long-term institutional controls.	Short
Design-based comparisons of waste arising from proposed advanced reactors and fuel cycles	Incorporate safety of waste management and fuel reprocessing in the fuel cycle evaluations.	Short

Environment

General features of INPRO Methodology

Holistic view on INS (Innovative Nuclear Energy System)

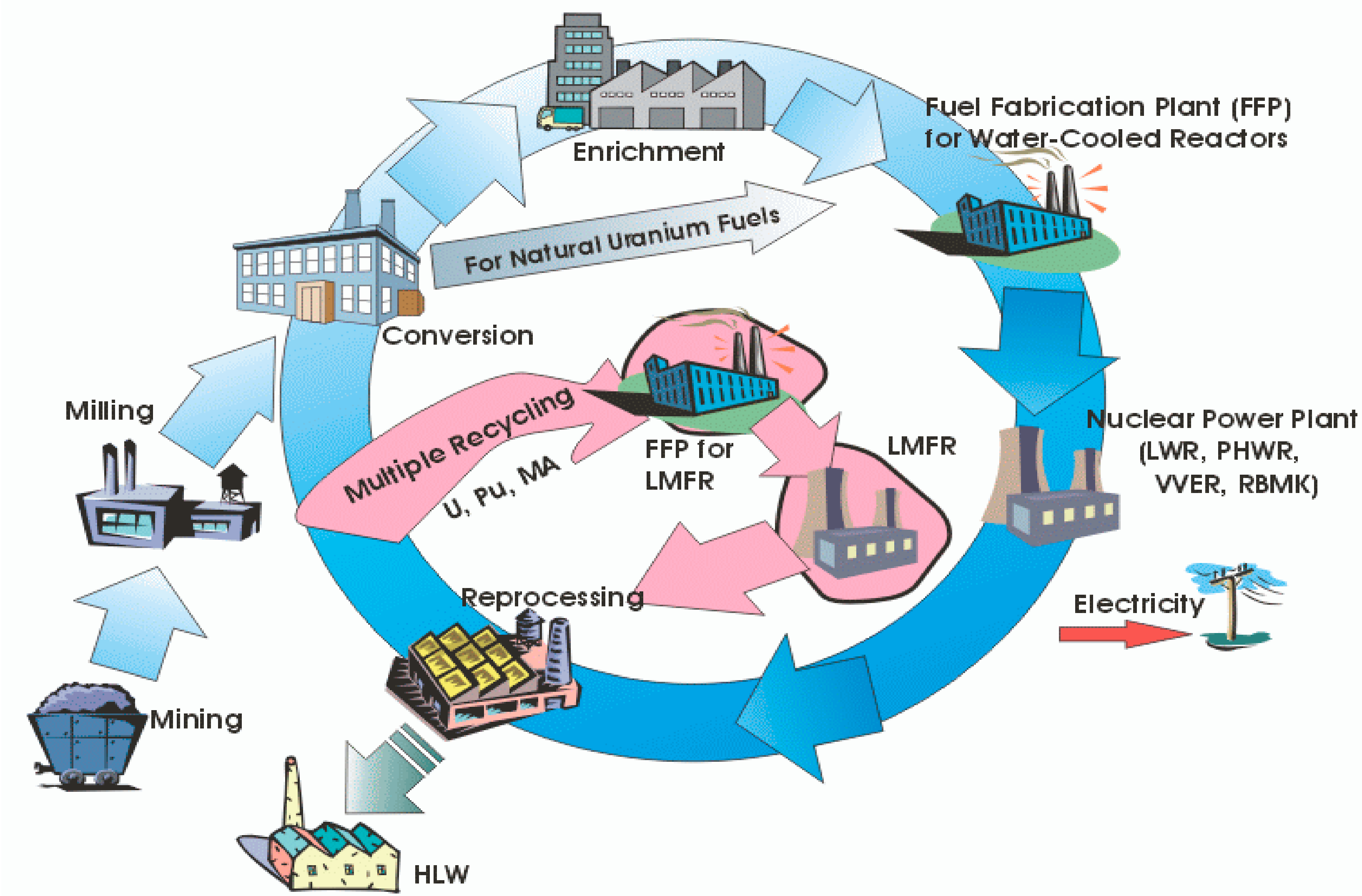
- **INS includes Innovative and Evolutionary Designs.**
  - ✓ **Innovative design : incorporating radical changes in design approaches or system configuration in comparison with existing designs.**
  - ✓ **Evolutionary design : incorporating small to moderate modifications with strong emphasis on maintaining design proveness**

- **INS includes all Components:**

  Mining and Milling, Fuel Production, Enrichment, Fabrication, Production (incl. all types and sizes of reactors), Reprocessing, Materials Management (incl. Transportation and Waste Management), Institutional Measures (e.g. safeguards, etc.)

- **INS includes all Phases (e.g. cradle to grave)**

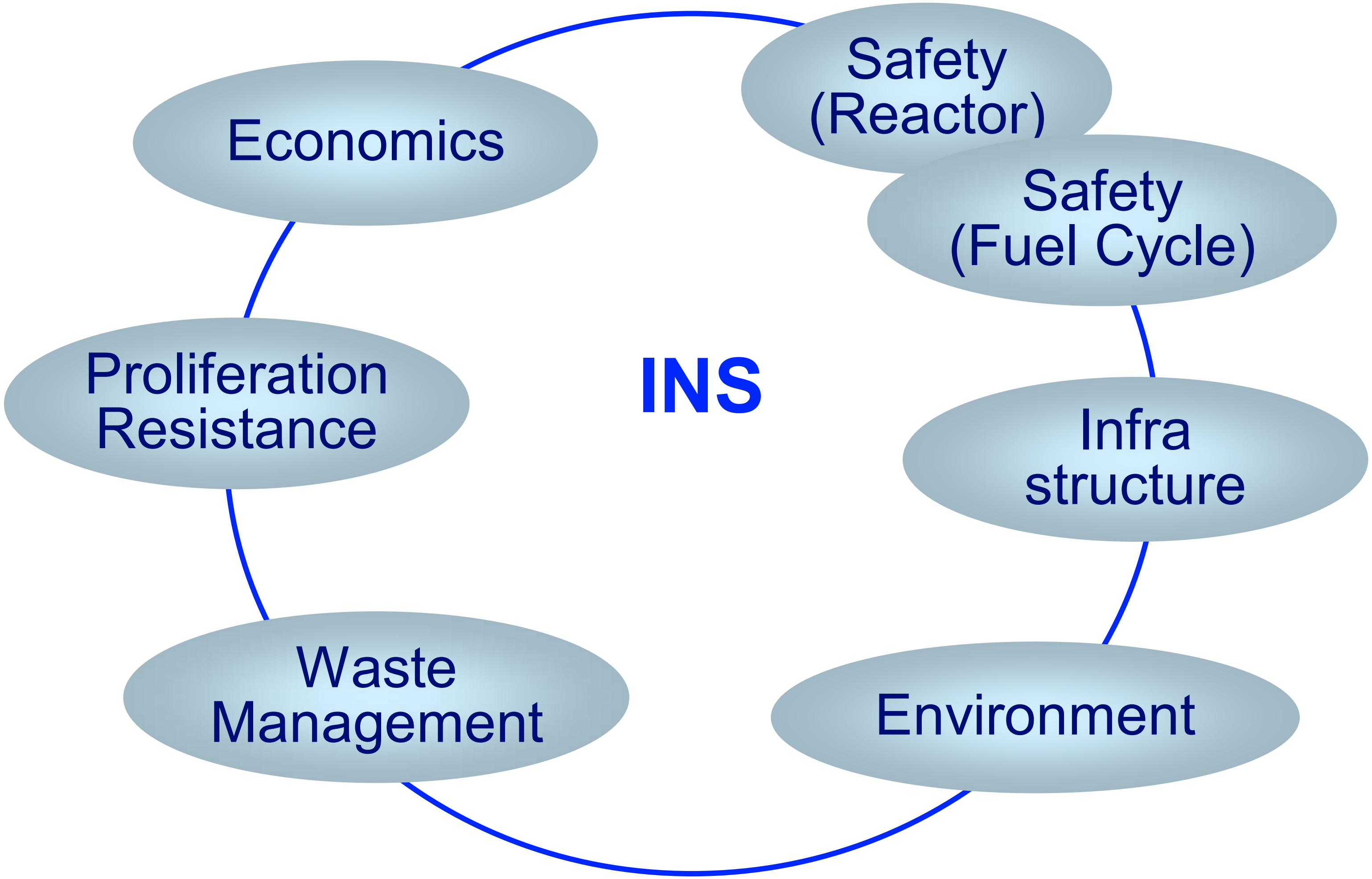
INPRO Methodology covers the entire NFC Process



General approach

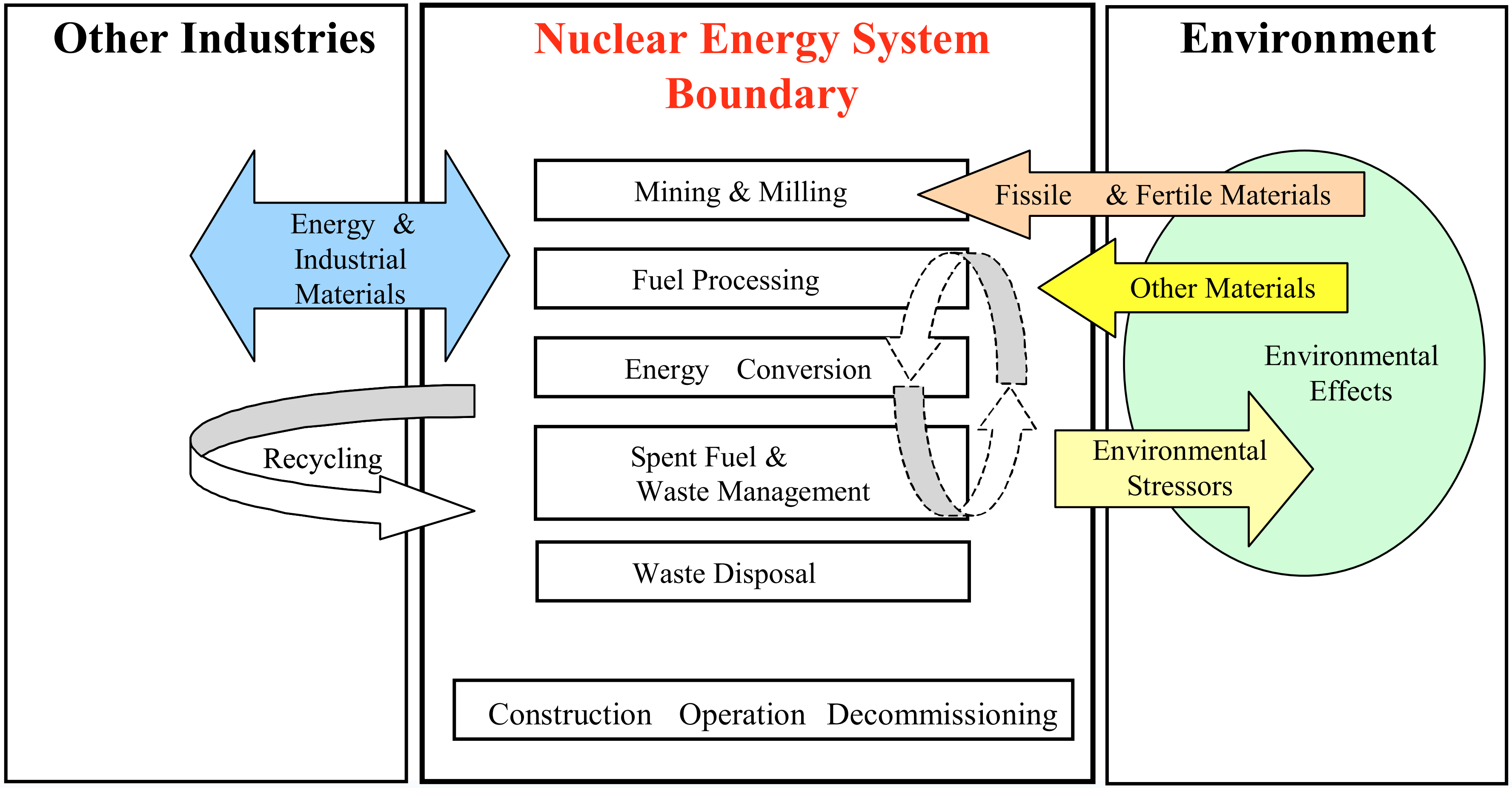
- Look globally, do locally
- All processes related
  - Nuclear material production
  - Fuel design
  - Fuel testing
  - Fuel fabrication
  - Fuel irradiation
  - Fuel recycling
  - SNF management
- Should proper consider INPRO BP,UR in all INPRO areas

INPRO approach



INPRO Methodology
Area of Environment (1/4)

Basic Approach for this Area



Environment

- To be sustainable the INS must not run out of important resources part way through its intended lifetime.
- These resources include fissile/fertile materials, water (when supplies are limited or quality is under stress) and other critical materials.
- The INS should use them at least as efficiently as acceptable alternatives, both nuclear and non-nuclear.

Environment

- Environmental effects (***Both radiological and non-radiological effects as well as trade-offs and synergies among the effects from different system components and different environmental stressors)*** include:
  - **physical,**
  - **chemical or biological changes in the environment;**
  - **health effects on**
    - **people,**
    - **plants and animals;**
  - **effects on quality of life of**
    - **people,**
    - **plants and animals;**
  - **effects on the economy;**
  - **use/depletion of resources; and**
  - **cumulative effects resulting from the influence of the system in conjunction with other influences on the environment.**

INPRO Methodology
Area of Environment (2/4)

TWO BASIC PRINCIPLES ESTABLISHED

(1) Environmental effects by INS

BP1: (Acceptability of Expected Adverse Environmental Effects)
"The expected (best estimate) adverse environmental effects of the innovative nuclear energy system shall be well within the performance envelope of current nuclear energy systems delivering similar energy products".

(2) Resource availability

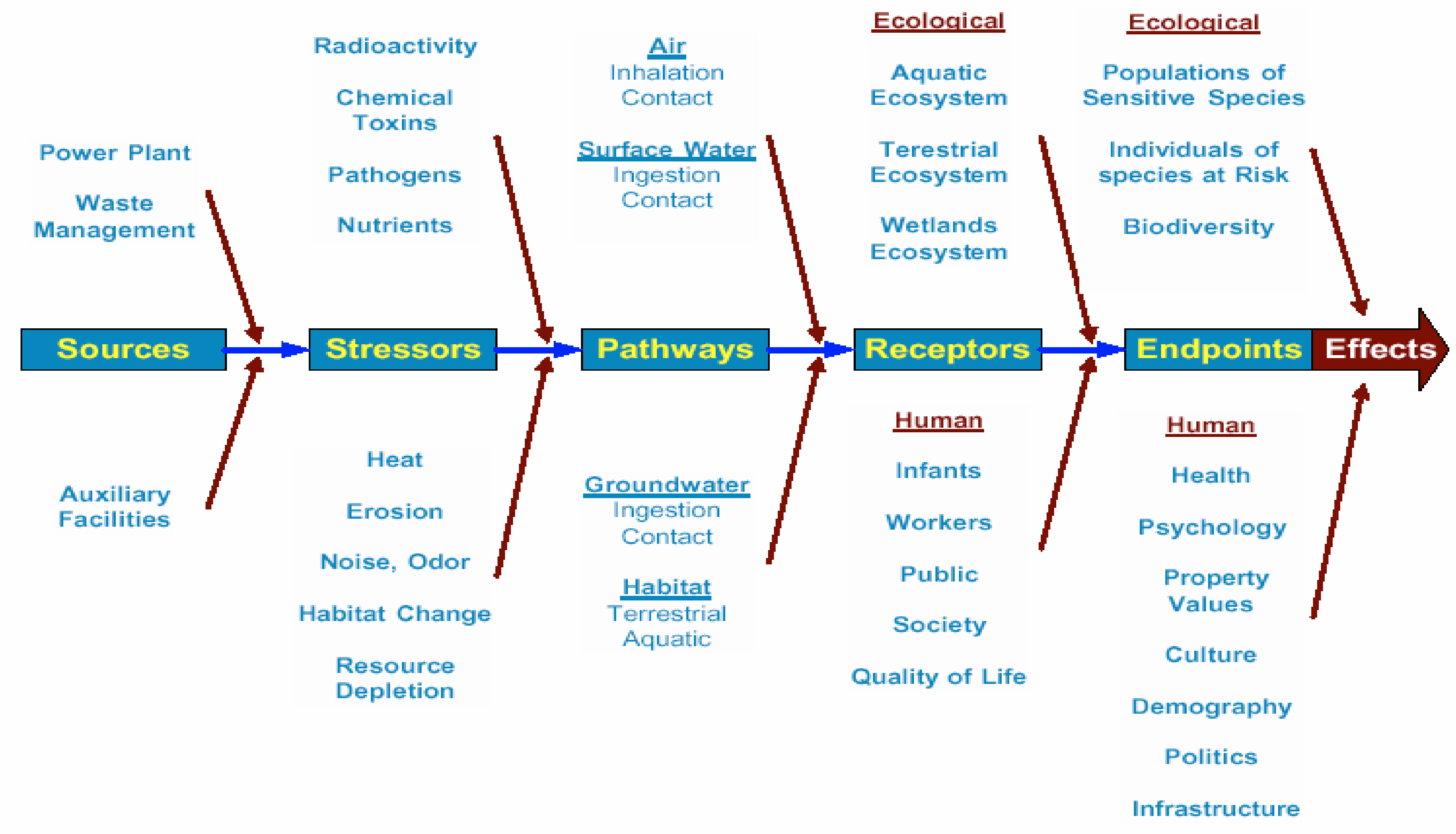
BP2: (Fitness for Purpose)
"The INS shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources"

INPRO Methodology
Area of Environment (3/4)
Example: BP1 and corresponding UR and Criteria

Environment Basic Principle BP1: **(Acceptability of Environmental Effects)**
"The expected (best estimate) adverse environmental effects of the INS shall be well within the performance envelope of current nuclear energy systems delivering similar energy products".

User Requirements	Criteria	
	Indicators	Acceptance Limits
UR1.1 "*The **environmental stressors** over the complete life cycle should be controllable to levels **meeting or superior to current standards**".*	**IN1.1.1:** L_{St-i}, level of stressor *i*	**AL1.1.1:** $L_{St-i} \leq S_i$ where S_i is the standard for stressor I
UR1.2 "*The likely adverse **environmental effects** attributable to the INS should be **as low as reasonably practicable**, social and economic factors taken into account*".	**IN1.2.1:** Does the INS reflect application of ALARP to limit environmental ffects?	**AL1.2.1:** YES

Factors in environmental assessment

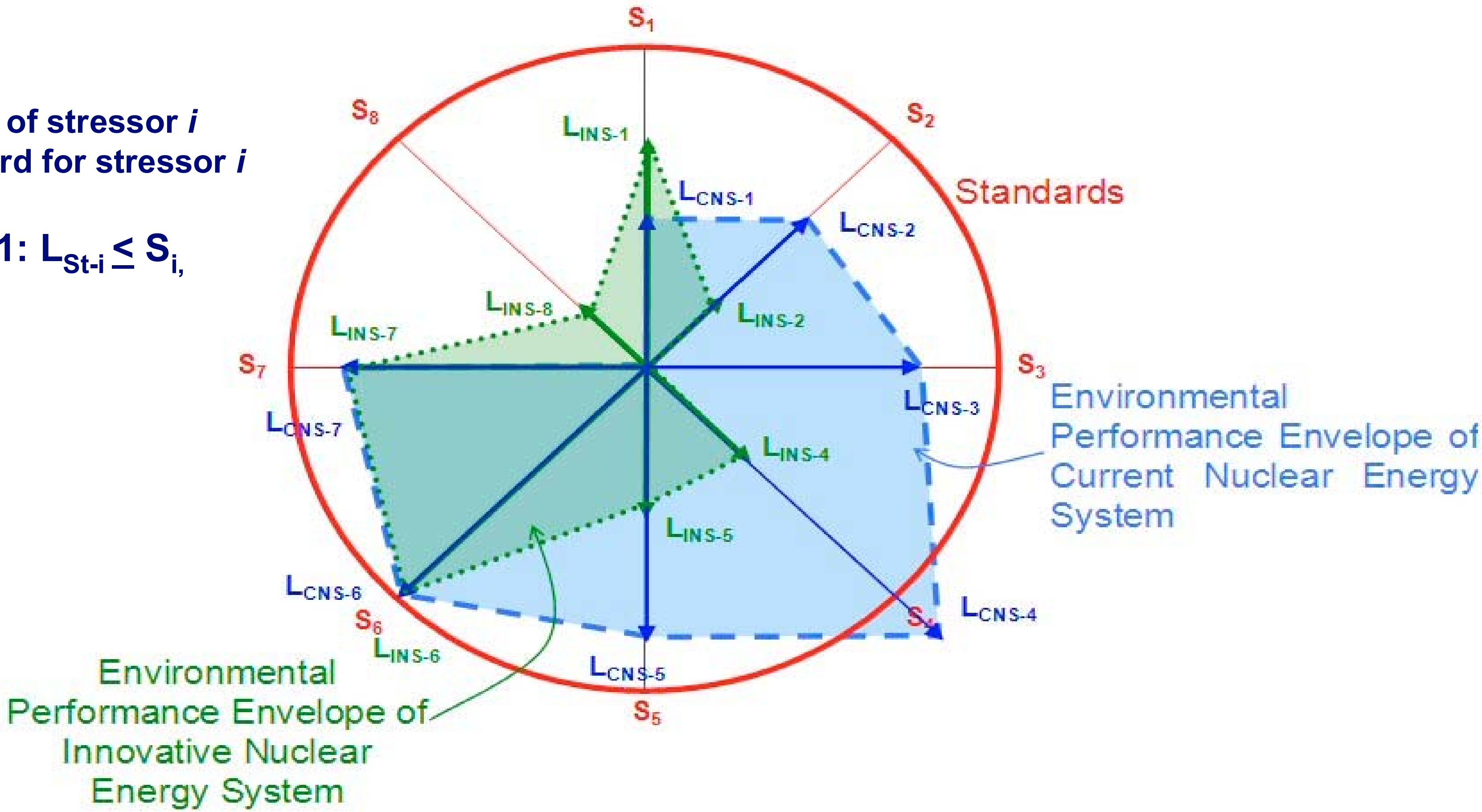


INPRO Methodology
Area of Environment (4/4)

Schematic interpretation of Criterion 1.1

$L_{St\text{-}i}$: level of stressor *i*
S_i : standard for stressor *i*

AL1.1.1: $L_{St\text{-}i} \leq S_{i,}$



Environmental Basic Principle BP2:

Environmental Basic Principle BP2: (Fitness for Purpose) ***The INS shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources***		
UR2.1 (Consistency with Resource Availability) ***The INS should be able to contribute to the world's energy needs during the 21st century without running out of fissile/fertile material and other non-renewable materials, with account taken of reasonably expected uses of these materials external to the INS. In addition, the INS should make efficient use of non-renewable resources.***	2.1.1: F_j (t) : quantity of fissile/fertile material j available for use in the INS at time t.	2.1.1: $F_j (t) > 0 \ \forall \ t < 100$ years[1].
	2.1.2. Qi (t) : quantity of material i available for use in the INS at time t. 2.1.3. P (t): power available (from both internal and external sources) for use in the INS at time t.	2.1.2. Qi(t) >0 $\forall$ t < 100 years. 2.1.3. $P(t) \geq P_{INS}(t) \ \forall \ t < 100$ years, where $P_{INS}(t)$ is the power required by the INS at time t.
	2.1.4. U : end use (net) energy delivered by the INS per Mg of uranium mined. 2.1.5. T : end use (net) energy delivered by the INS per Mg of thorium mined. 2.1.6. Ci : end use (net) energy delivered per Mg of limited non-renewable resource consumed.	2.1.4. U > U0 U0 : maximum achievable for a once-through PWR. 2.1.5. T > T0 T0 : maximum T achievable with a current operating thorium cycle. 2.1.6. Ci > C0 C0 to be determined on a case specific basis.
UR2.2 (Adequate Net Energy Output) ***The energy output of the INS should exceed the energy required to implement and operate the INS within an acceptably short period.***	2.2.1. T_{EQ} : time required to match the total energy input with energy output (yrs).	2.2.1. $T_{EQ} \leq k \cdot T_L$ T_L : intended life of INS k < 1

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

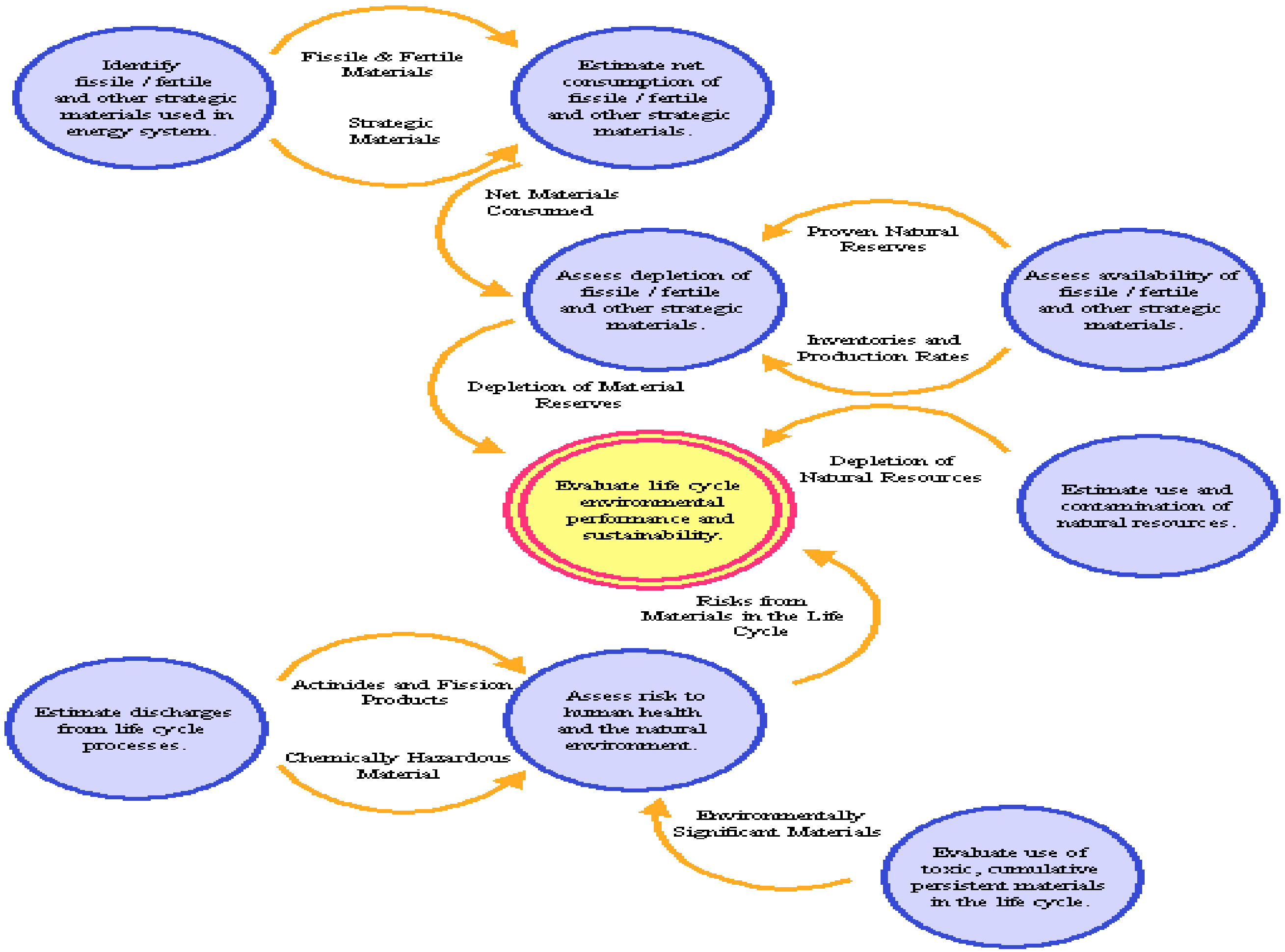
Requirements for assessment methods

- ***Factors to be considered***
- ***All relevant factors (sources, stressors, pathways, receptors and endpoints) should be accounted for in the analysis of the environmental effects of a proposed energy system.***
- ***Complete system approach***
- ***The environmental performance of a proposed technology should be evaluated as an integrated whole by considering the likely environmental effects of the entire collection of processes, activities and facilities in the energy system at all stages of its life cycle.***
- ***Complete material flow***
- ***All important material and energy flows in, out, and through the system should be accounted for.***
- ***Non-routine events***
- ***The likely significance of adverse environmental effects due to events outside of normal operations throughout the system should be evaluated.***

Material and energy accounting

- ***Life Cycle Assessment* Life Cycle Assessment (LCA) is a systematic method used extensively for evaluating environmental effects of a technology or production process from the extraction of raw material to the disposal of wastes (cradle to grave).**
- ***Material Flow Assessment* is method to analyze the dynamics as well as the equilibrium state, which is important for comparing fuel cycles. In particular, the supply and demand of special materials during any initial transient phase of a fuel cycle may need to be considered.**

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



The evaluation includes the following:

- Identification of the materials of primary interest: fertile and fissile materials (e.g., U^{235}, Pu^{239}) as well as other strategic materials. The time dependent net flow is evaluated against proven reserves, inventories and production rates.
- Materials that pose a particular risk (e.g., radioactive/toxic). Included here are flows of materials in the high-level waste stream, including minor actinides and fission products.
- Identification of chemical materials of particular environmental significance. The environmental risks of their manufacture and use within the system are assessed in parallel with those of radioactive materials.
- Assessment of the environmental effects of discharges of radioactive and chemically hazardous materials and heat during normal and outside of normal operation.
- Evaluation of the use and depletion of natural resources (e.g. water and land) and of energy use by all parts of the system.

Measures of environmental detriment

- A systematic and consistent method of measuring environmental detriment of materials and energy exchanged between the system and the environment is essential on a local, regional, national or global scale.
- In some cases it is important to consider maximal effects (the critical group concept), while in other cases it is more relevant to consider averaged or cumulative effects.
- A clear scientific basis is preferable to conservative analysis for determining the environmental detriment associated with various stressors.

Manual preparation

Main Activities in ongoing Phase of INPRO

- Performance of assessment studies using the updated INPRO methodology (TECDOC-1434)
- Production of INPRO Manual
- Improvement of INPRO methodology
- Development of Modeling tools
- Special activities (e.g. Infrastructure needs, MNFC, balance of demands, identification of R&D, country profiles, SMRs, fuel cycles, etc.)

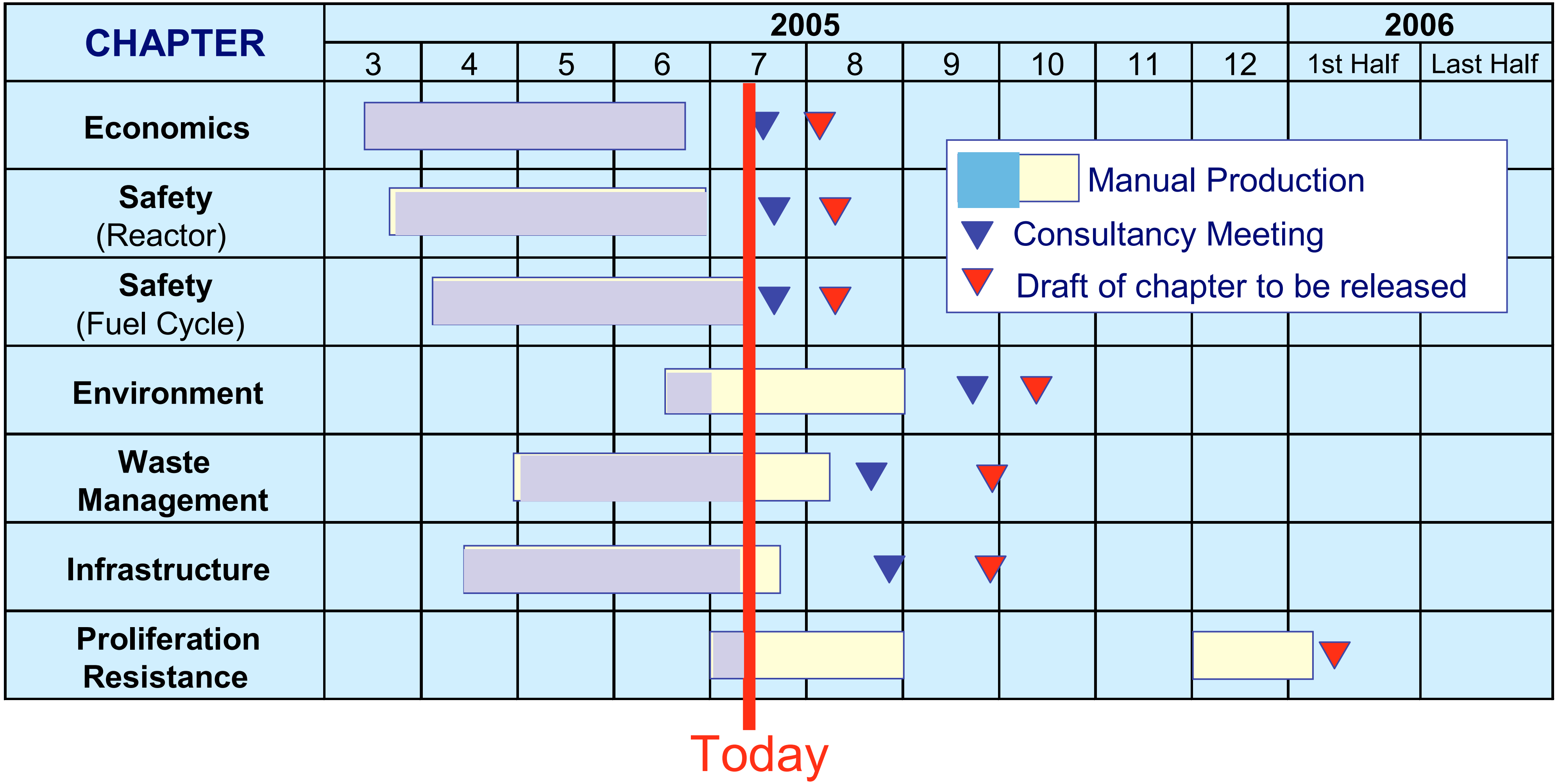
Needs for an INPRO Manual

- Feedback from six national and eight individual Case Studies;
- For the assessment of an INS, the INPRO Manual shall:
  - Provide more background information on INs and ALs;
  - Provide, where appropriate, advice for INs and ALs to be quantified;
  - Provide some illustrative examples which may facilitate the actual determination of INs and ALs.

- Assessment Studies -

- **Joint assessment of INS based on closed fuel cycle and fast reactors (China, France, India, Korea, Russia and Japan as observer);**
- **Study on transition from LWRs to Gen IV fast neutron system (France);**
- **Assessment of INS based on high temperature reactors (India);**
- **Assessment of Additional Nuclear Generation Capacity in the country for the period 2010-2025 (Argentina);**
- **Assessment of INS for country with small grid (Armenia); and**
- **Assessment of whole fuel cycle of DUPIC in the area of PR (Republic of Korea)**

Schedule
- Manual -



Strategy for Phase 1B (2nd Part) Implementation

Methodology Application

Assessment Studies (Task1)

Manual

Feedback

Manual Production (Task 2)

Manual

Methodology Improvement (Task 3)

For large-scale global nuclear energy development (Task 4)

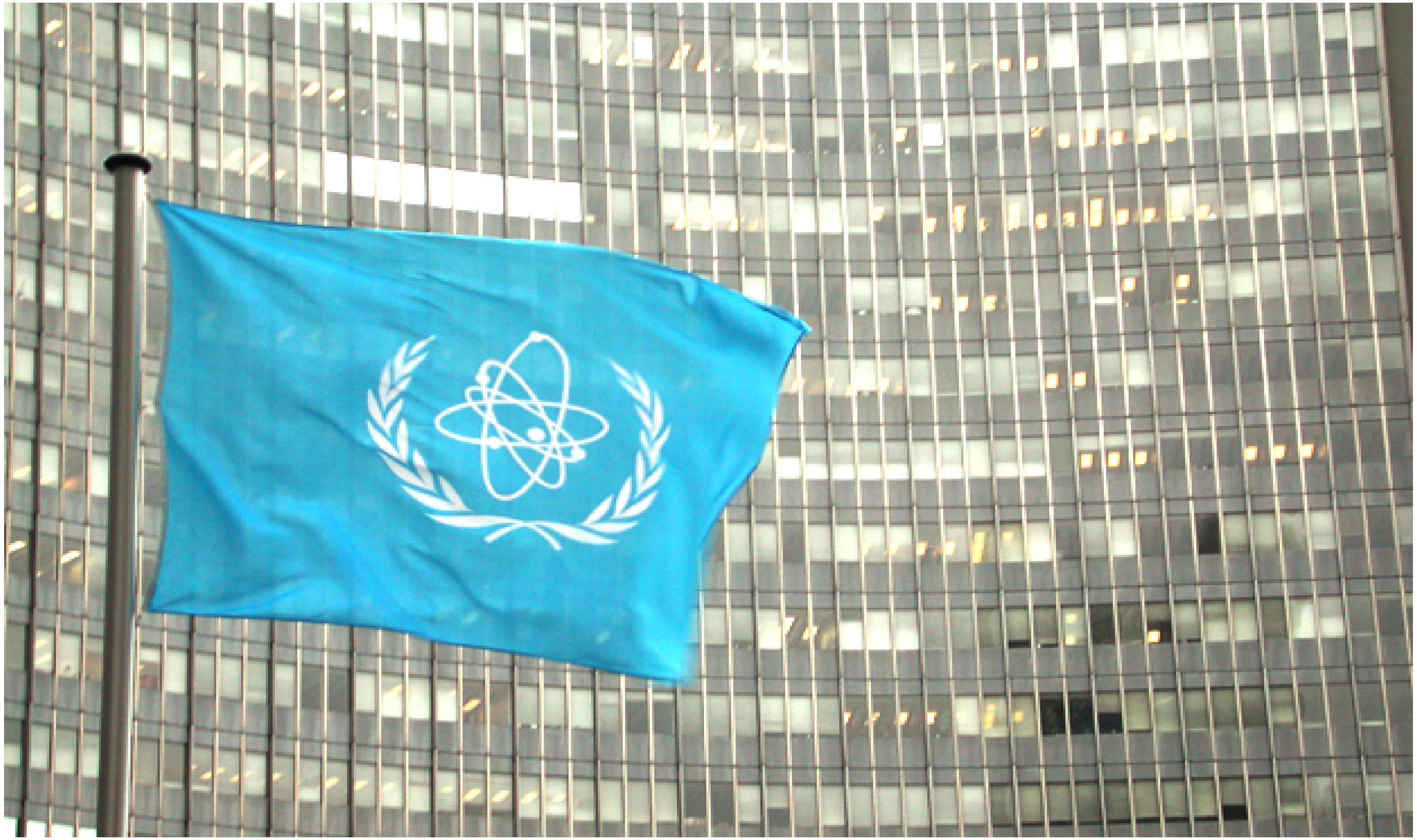
For R&D in Phase 2 (Task 5)

Collaboration with other INS Initiatives(Task 6)

Continuing activities

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



…Thank you for your attention

Thank you

Back up slides

INPRO Methodology
Area of Waste Management (4/4)

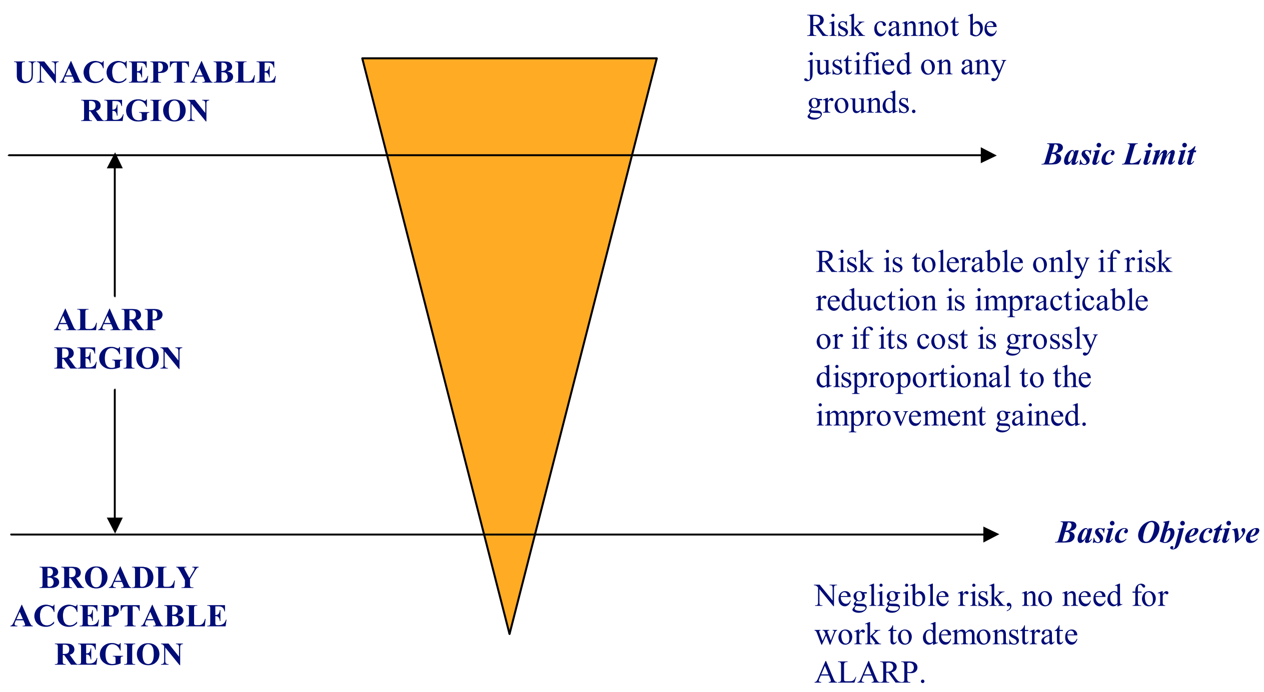


Illustration of the ALARP concept

INPRO User Requirement UR1.1 on Safety of Reprocessing Facility

Example: Indicator of UR1.1 Robustness of a reprocessing facility (simplicity, margins)

Increase of robustness can be achieved by a number of variables (INs) such as :

- Frequencies of failures;
- Prevention against criticality;
- Plant availability factor;
- Grace time.

For every type of facility, processes and events, ALs have to be identified and frequencies of failures and grace time specified, based on expert opinions and operating experience.

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

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

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

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

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

User Requirements	Criteria	
	Indicators	Acceptance Limits
UR1.3[1] *The frequency of occurrence of accidents should be reduced, consistent with the overall safety objectives. If an accident occurs, engineered safety features should be able to restore an installation of an INS to a controlled state, and subsequently (where relevant) to a safe shutdown state, and ensure the confinement of radioactive material. Reliance on human intervention should be minimal, and should only be required after some grace period.*	1.3.1 Calculated frequency of occurrence of design basis accidents. 1.3.2 Grace period until human intervention is necessary. 1.3.3 Reliability of engineered safety features. 1.3.4 Number of confinement barriers maintained. 1.3.5 Capability of the engineered safety features to restore the INS to a controlled state (without operator actions). 1.3.6 Sub-criticality margins.	1.3.1 Reduced frequency of accidents that can cause plant damage relative to existing facilities. 1.3.2 Increased relative to existing facilities. 1.3.3 Equal or superior to existing designs. 1.3.4 At least one. 1.3.5 Sufficient to reach a controlled state. 1.3.6 Sufficient to cover uncertainties and to allow adequate grace period.
UR1.4[2] *The frequency of a major release of radioactivity into the containment / confinement of an INS due to internal events should be reduced. Should a release occur, the consequences should be mitigated.*	1.4.1 Calculated frequency of major release of radioactive materials into the containment / confinement. 1.4.2 Natural or engineered processes sufficient for controlling relevant system parameters and activity levels in containment / confinement 1.4.3 In-plant severe accident management	1.4.1 At least an order of magnitude less than for existing designs; even lower for installations at urban sites. 1.4.2 Existence of such processes. 1.4.3 Procedures, equipment and training sufficient to prevent large release outside containment / confinement and regain control of the facility.

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

User Requirements	Criteria	
	Indicators	Acceptance Limits
UR1.5[1] *A major release of radioactivity from an installation of an INS should be prevented for all practical purposes, so that INS installations would not need relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility used for similar purpose.*	1.5.1 Calculated frequency of a major release of radioactive materials to the environment. 1.5.2 Calculated consequences of releases (e.g. dose). 1.5.3 Calculated individual and collective risk.	1.5.1 Calculated frequency $<10^{-6}$ per unit-year, or practically excluded by design. 1.5.2 Consequences sufficiently low to avoid necessity for evacuation. Appropriate off-site mitigation measures (e.g. temporary food restrictions) are available. 1.5 3 Comparable to facilities used for a similar purpose.[2]
UR1.6 *An assessment should be performed for an INS to demonstrate that the different levels of defence-in-depth are met and are more independent from each other than for existing systems.*	1.6.1 Independence of different levels of DID	1.6.1 Adequate independence is demonstrated, e.g. through deterministic and probabilistic means, hazards analysis etc.

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

[2] 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.

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

User Requirements	Criteria	
	Indicators	Acceptance Limits
UR2.1 *INS should strive for elimination or minimization of some hazards relative to existing plants by incorporating inherently safe characteristics and/or passive systems, when appropriate.*	**2.1.1. Sample indicators: stored energy, flammability, criticality, inventory of radioactive materials, available excess reactivity, reactivity feedback.** **2.1.2. Expected frequency of abnormal operation and accidents.** **2.1.3. Consequences of abnormal operation and accidents.** **2.1.4. Confidence in innovative components and approaches.**	2.1.1. Superior to existing designs. 2.1.2. Lower frequencies compared to existing facilities. 2.1.3. Lower consequences compared to existing facilities. 2.1.4. Validity established.

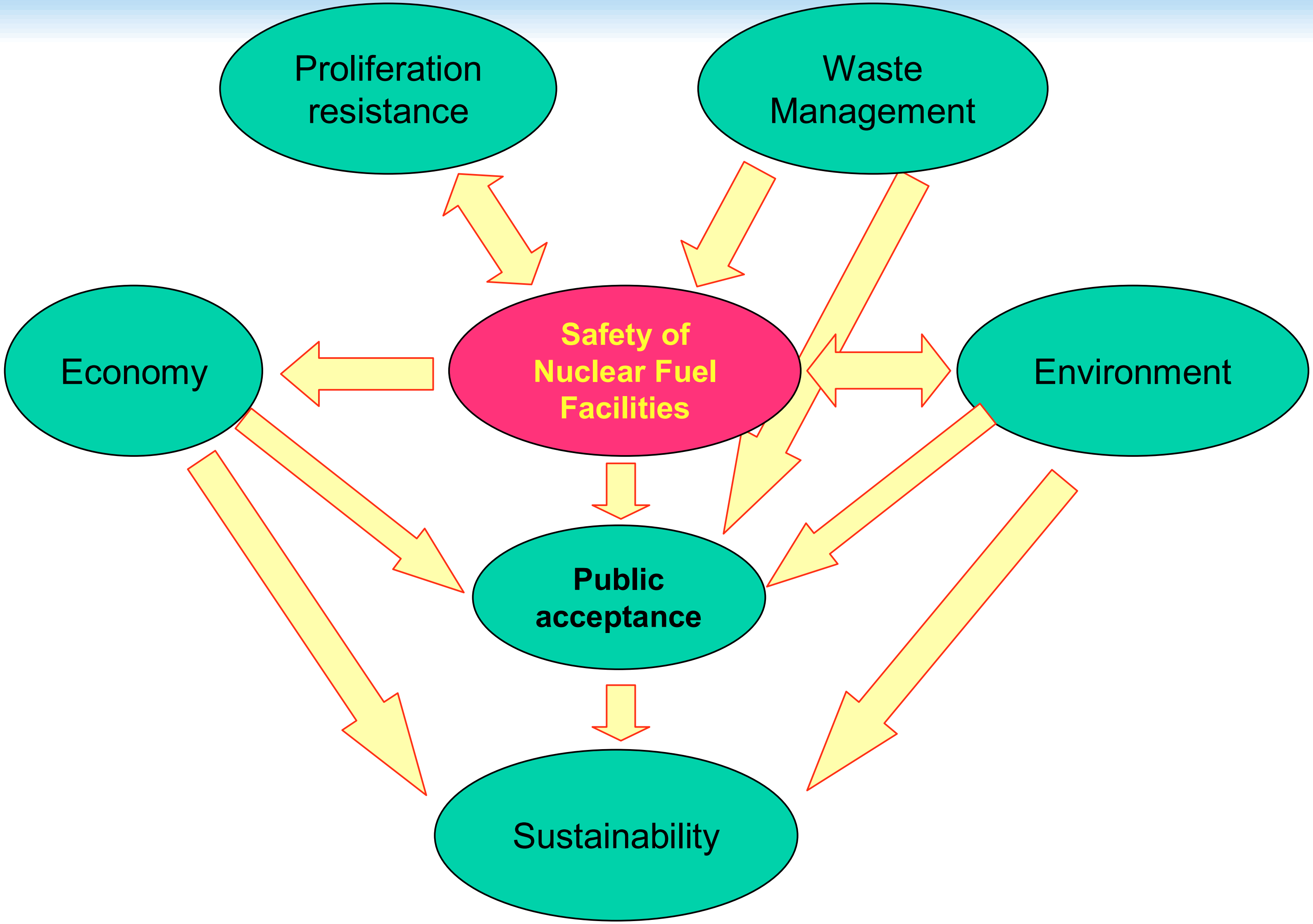
Safety Basic Principle BP3: ***Installations of an INS shall ensure that the risk from radiation exposures to workers, the public and the environment during construction/commissioning, operation, and decommissioning, are comparable to the risk from other industrial facilities used for similar purposes.***

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

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

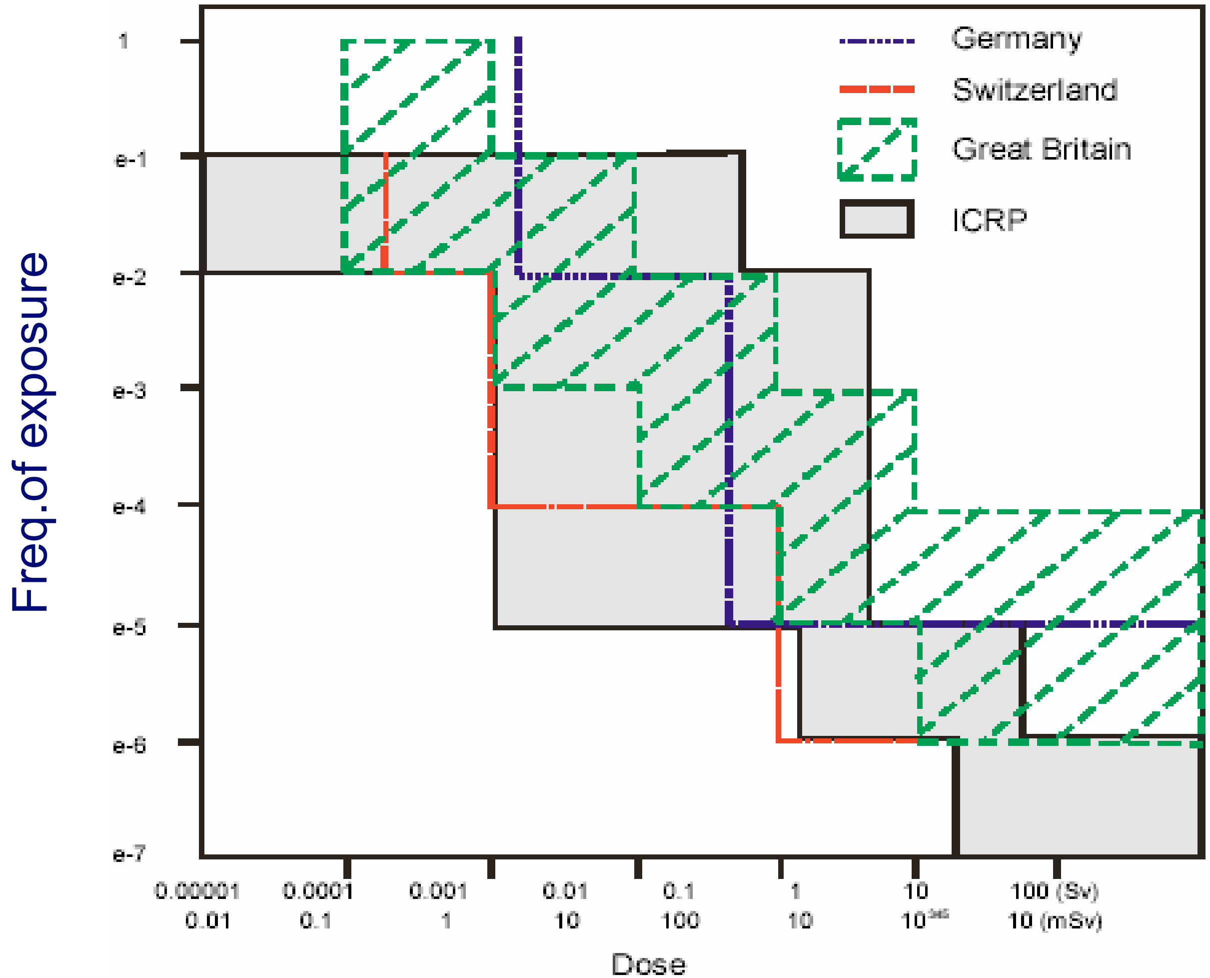
Safety Basic Principle BP4: ***The development of INS shall include associated Research, Development and Demonstration work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing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

User Requirements	Criteria	
	Indicators	Acceptance Limits
UR4.4 *For the safety analysis, both deterministic and probabilistic methods should be used, where feasible, to ensure that a thorough and sufficient safety assessment is made. As the technology matures, "Best Estimate (plus Uncertainty Analysis)" approaches are useful to determine the real hazard, especially for limiting severe accidents.*	4.4.1. Use of a risk informed approach. 4.4.2. Uncertainties and sensitivities identified and appropriately dealt with.	Yes to all.



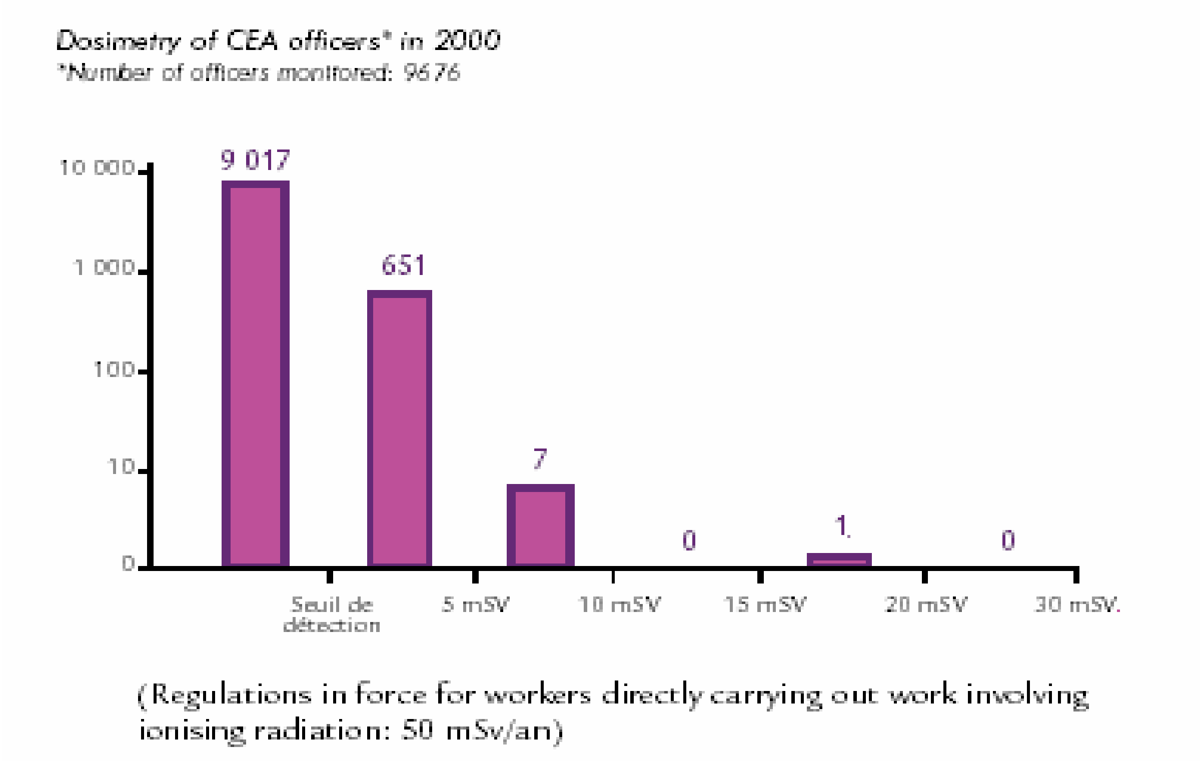
Interplay of innovation parameters

Comparison of safety criteria (risk based) for nuclear installations



Frequency of exposure versus the exposure dose

Figure Indicates need for harmonisation



Results reported by CEA illustrating the scope for reduction in annual radiation exposure to workers

Scope for reduction in annual occupational exposure exists

Examples of Innovations in Fuel Fabrication Facilities

- **Powder-pellet route has several steps involving generation and handling of fine powder and leads to radiotoxic dust. Hence novel Sol-Gel Microsphere pelletisation process to be studied and adapted.**
- **Safe, secured and automated fabrication techniques to be used. Remote handling and automation are to be developed- all the more important for MOX and ^{233}U fuel fabrication facilities**
- **Graded ventilation systems and advanced technologies for ensuring reliability for the ventilation systems**

Examples of Innovations

- Recovery of ^{137}Cs and noble metals
- Recovery and burning of minor actinides- Am, Np and Cm- to reduce radiotoxicity.
- Development of pyrochemical process for high burnup fuels and large scale application.
- Alternate extractants to TBP at high Pu loadings.
- Development of corrosion-resistant materials for vessels
- Remotisation and automation to reduce radiation exposure
- Simulators for training in operation and maintenance

Safety-related RD&D areas

- capability of computer codes to model phenomena and system behaviour for innovative fuel cycle installations to at least the same confidence level as for existing nuclear power plants.
- method for quantifying the safety of such facilities.
- development of Probabilistic Safety Analyses (PSA) methods, including best estimate plus uncertainty analysis, and their supporting data bases
- develop more confidence in the PSA tools by extensive analyses
- achieve an appropriate integration of deterministic and probabilistic analyses, and demonstrate that sufficient DID can be achieved through simpler and cheaper technological solutions

RD&D in Nuclear Fuel Cycle Facilities

- Recovery and burning of minor actinides and fission products, to reduce radiotoxicity of the high level waste for a long period of time.
- Development of reprocessing processes which would generate less active wastes
- Alternate extractants and resins to achieve better product recoveries and reduced radioactive discharges.
- Development of corrosion-resistant materials for dissolver vessels which would lead to increased life of the plant, safer operation and maintenance.
- Remotisation and automation techniques in reprocessing plants and fuel fabrication facilities to reduce radiation exposure and radioactive contamination.

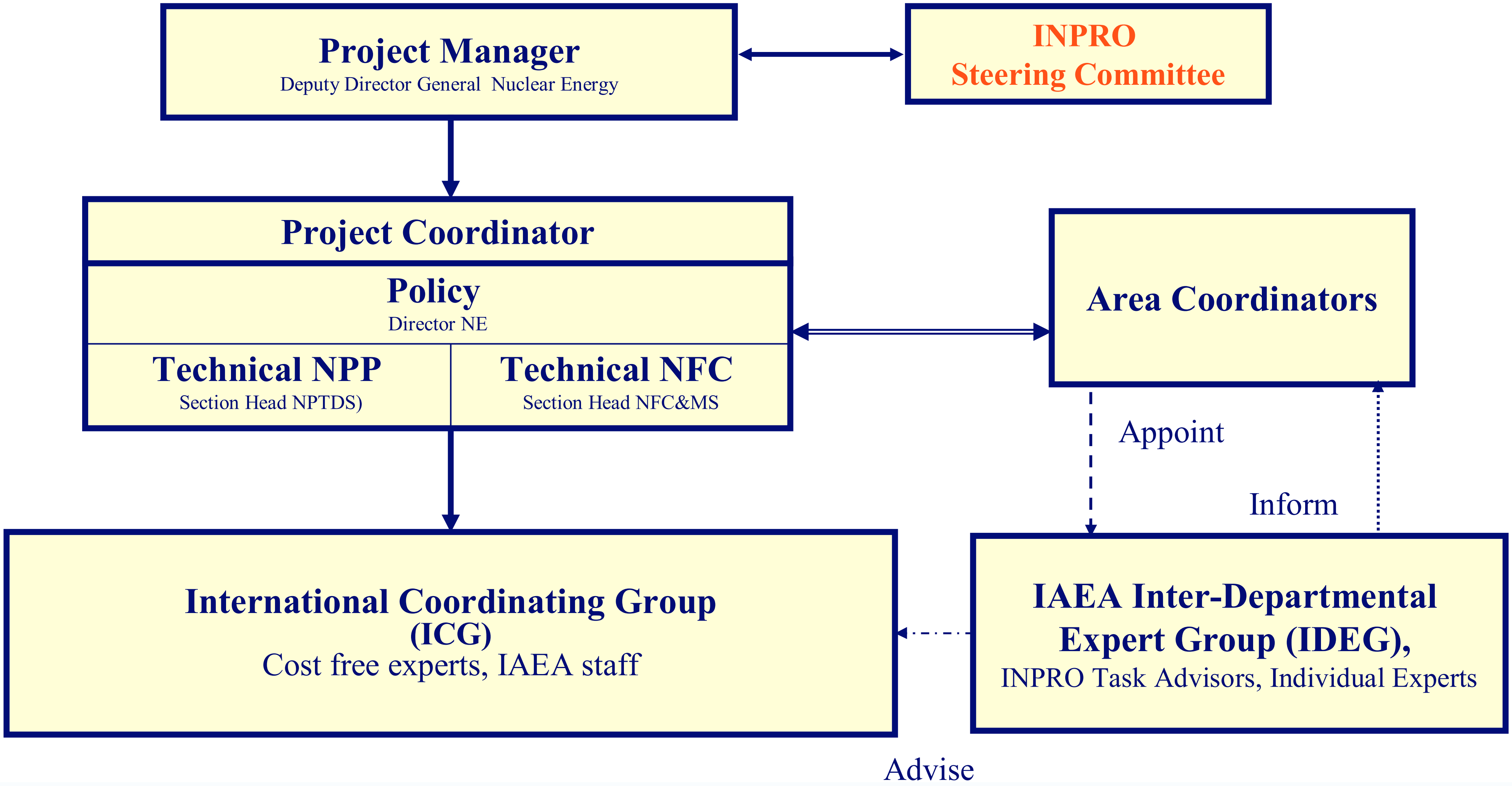
RD&D in Nuclear Fuel Cycle Facilities

- Long term behaviour of fuel storage facilities, such as corrosion aspects, radioactivity release and transport mechanisms.
- Techniques to isolate and contain some of the long lived isotopes, which migrate in soil/water much faster.
- Enhanced emphasis on fabrication technologies such as Sol-Gel microsphere pelletisation process, which would result in less radioactive dust generation.
- Replacement of electrical heating systems by steam heating systems wherever appropriate, for better safety.
- Use of non-hydrogenated media for cooling, in fuel fabrication facilities, for providing better safety features.

RD&D in Nuclear Fuel Cycle Facilities

- Development of frictionless bearings and avoiding external drives for gas transport in uranium enrichment facilities, for improved operation and maintenance, resulting in enhanced safety.
- Better technologies for drilling operations, to reduce occupational exposures in mining activities.
- Development of an integrated high speed network in mines for automation and tele-operation to have lesser human interference, and hence higher reliability and enhanced safety

INPRO Organizational Chart



Example for stepwise use of the INPRO method of assessment

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

Comparison of capability of two INS

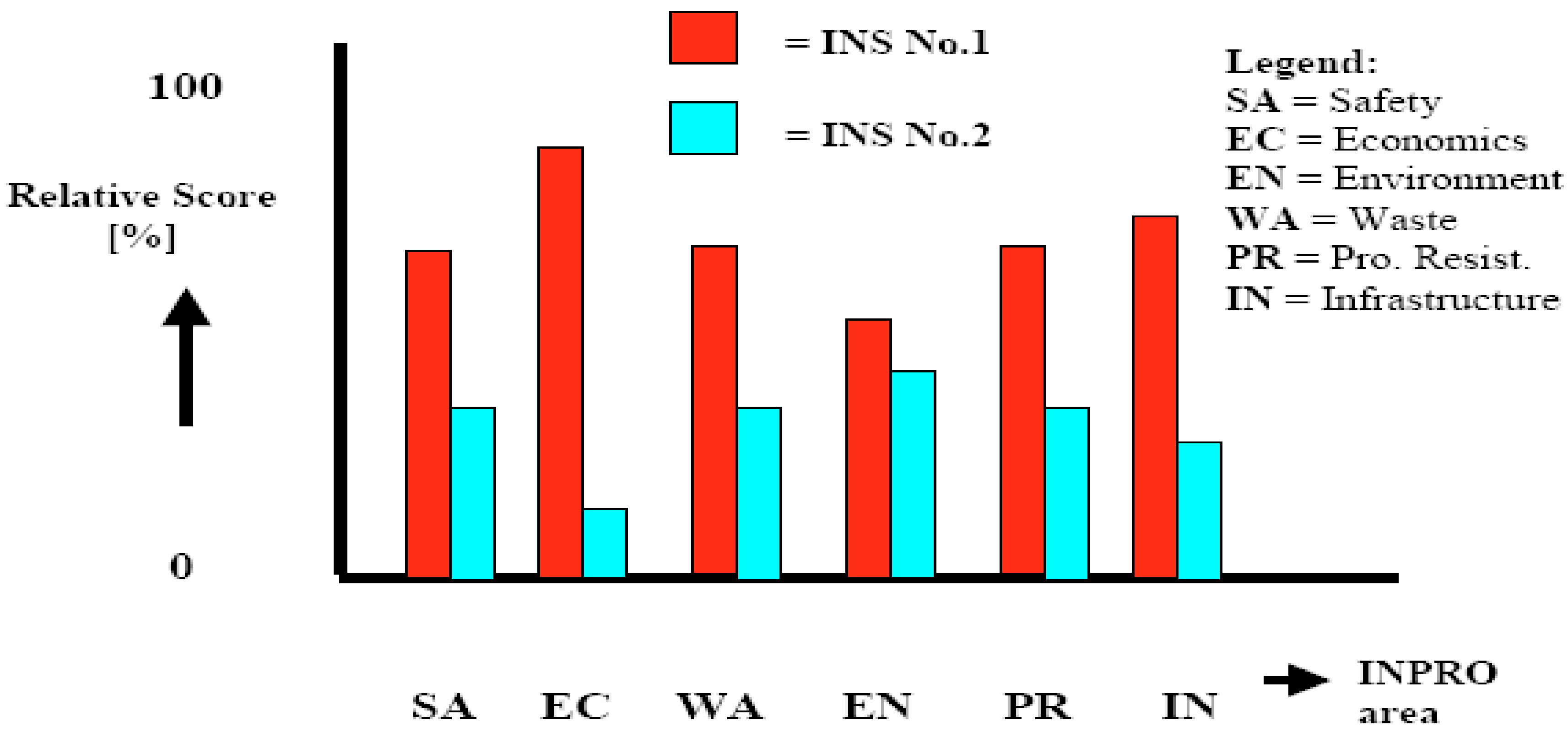


Figure 3.4. Outcome of comparison of capability of two INS.

Judgements on potential for a UR, BP, INPRO area or INS

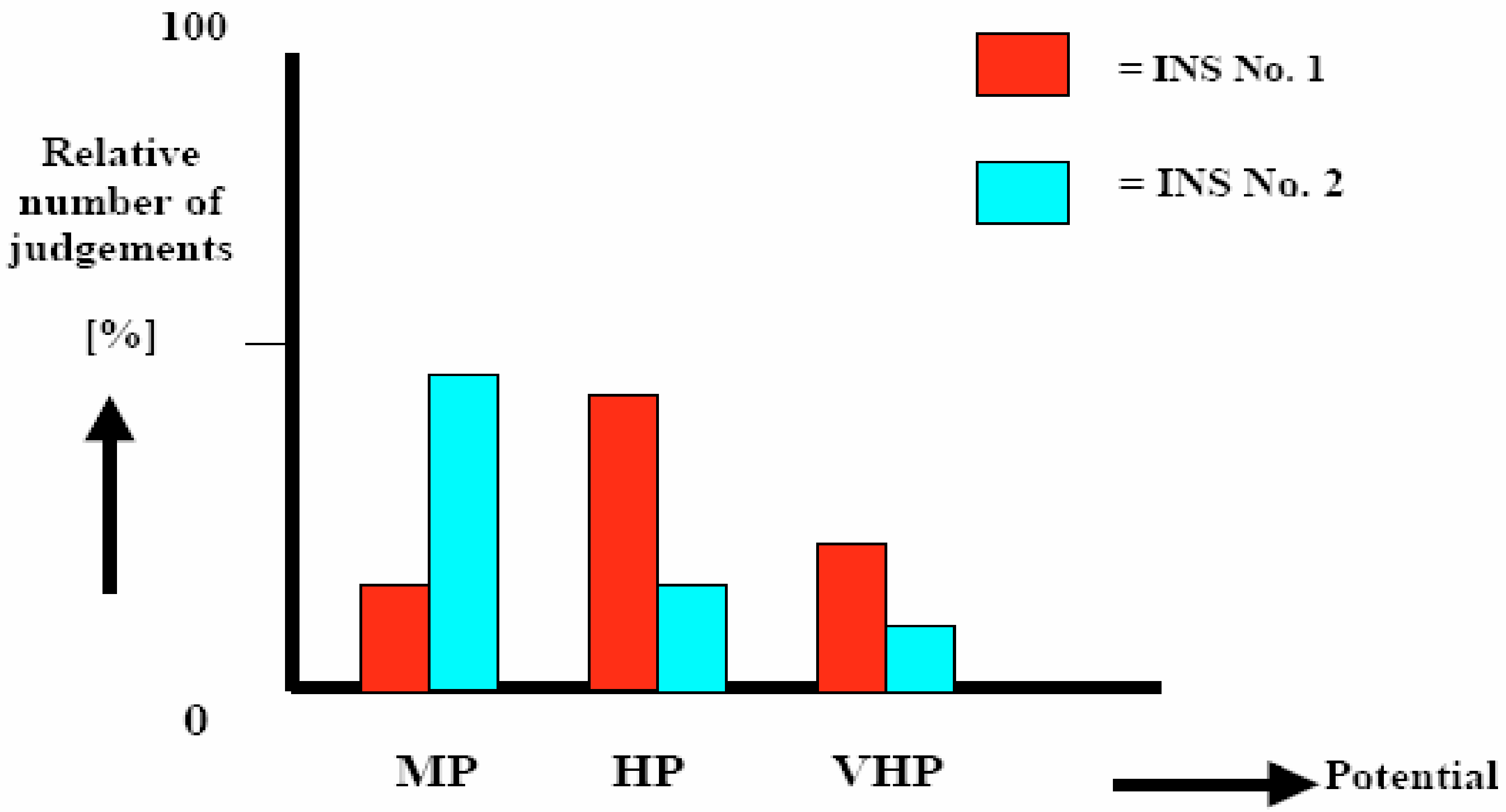


Figure 3.7. Aggregation of judgements on potential for a UR, BP, INPRO area or INS.

Main Activities in ongoing Phase of INPRO

- Performance of assessment studies using the updated INPRO methodology (TECDOC-1434)
- Production of INPRO Manual
- Improvement of INPRO methodology
- Development of Modeling tools
- Special activities (e.g. Infrastructure needs, MNFC, balance of demands, identification of R&D, country profiles, SMRs, fuel cycles, etc.)

Ongoing/next steps in the development of an INPRO PR Assessment Methodology

- Quantification of Acceptance Limits and "ranking" of Variables/Attributes to be used for the evaluation of Indicators and the rationale for such quantification/ranking.

- Development of a way to present results of the assessment to "decision makers" and "designers".

Main Activities
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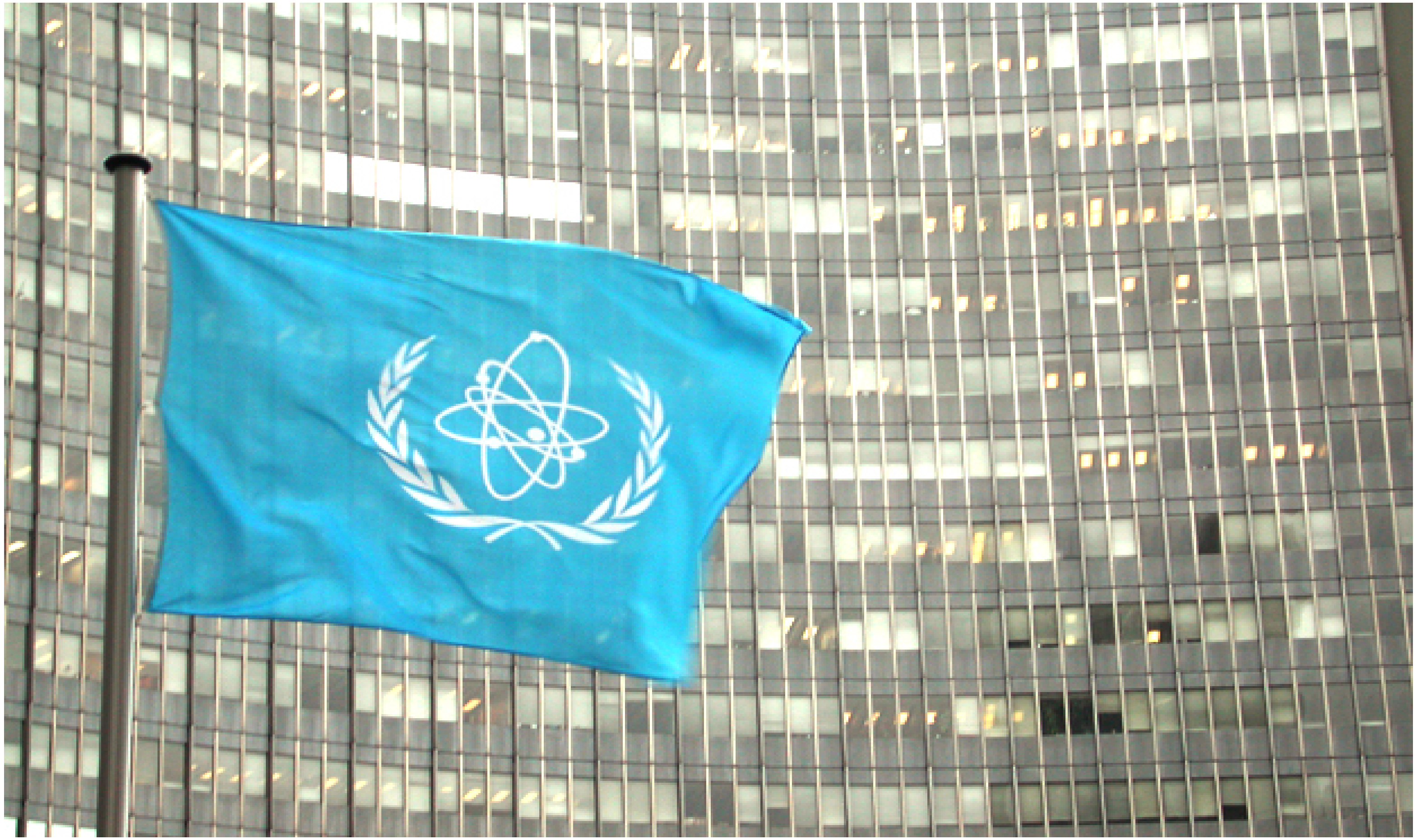


…Thank you for your attention

Results of INPRO
INPRO Schedule

Initiation

(in response to GC Res. 2000)

Phase 1A

(Methodology Development)

Phase 1B (1st part)

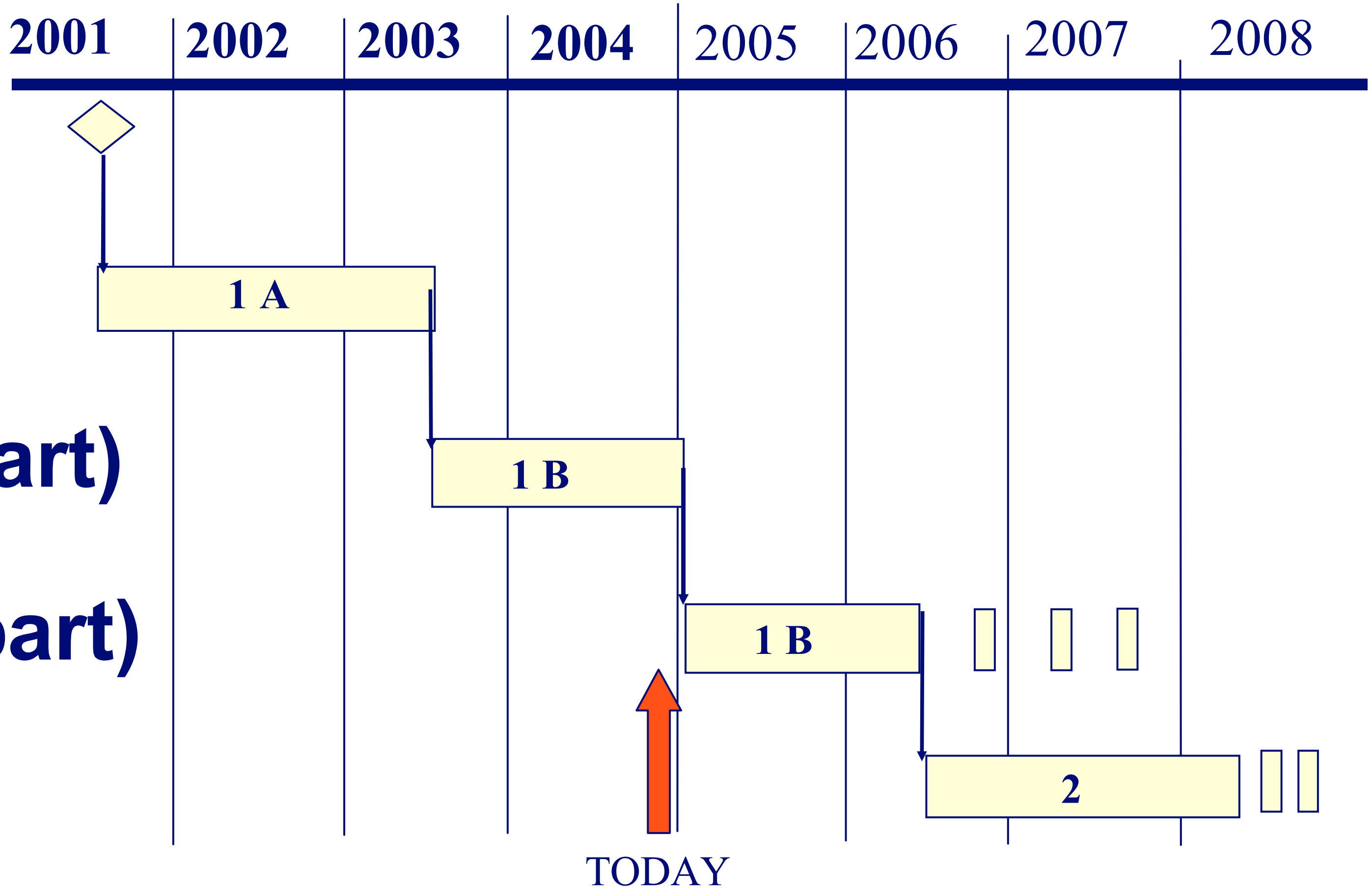
(Methodology Validation)

Phase 1B (2nd part)

(Methodology Application)

Phase 2

(International Cooperation)



UN Concept of Sustainability and INPRO

- History of concept of sustainability
  - Brundtland Report, Agenda 21, Commission on Sustainable Development, WEC, Kyoto Protocol, etc.
- UN concept of sustainability : 4 dimensions
  - Economic: durable growth, financial stability, etc.
  - Environmental: depletion of resources, degradation of environment.
  - Social: equity among groups, stability of cultural systems, safety, proliferation threat, etc.
  - Institutional: legal and policy instruments.
- Energy supply important in all 4 dimensions
  - Development of energy supply needed for sustainable development of world.
  - Development of NE needed for sustainable development of energy supply.
  - INPRO assures that NE is available in sustainable manner.

UN Concept of Sustainability and INPRO

UN General Concept of Sustainable Development
including sustainable development of ENERGY supply

- Economic Dimension
- Environmental Dimension
- Social Dimension
- Institutional Dimension

Sustainable Development of Nuclear Energy

- Economics
- Environment
- Waste Management
- Safety
- Proliferation Resistance
- Infrastructure

INPRO Objectives and Methodology:

MODELLING of energy systems

Assessment using a holistic approach

Decision on Innovative Nuclear Energy System (INS)

General features of INPRO Methodology

Holistic view on INS (Innovative Nuclear Energy System)

- INS includes Innovative and Evolutionary Designs.
  - ✓ Innovative design : incorporating radical changes in design approaches or system configuration in comparison with existing designs.
  - ✓ Evolutionary design : incorporating small to moderate modifications with strong emphasis on maintaining design proveness
- INS includes all Components:

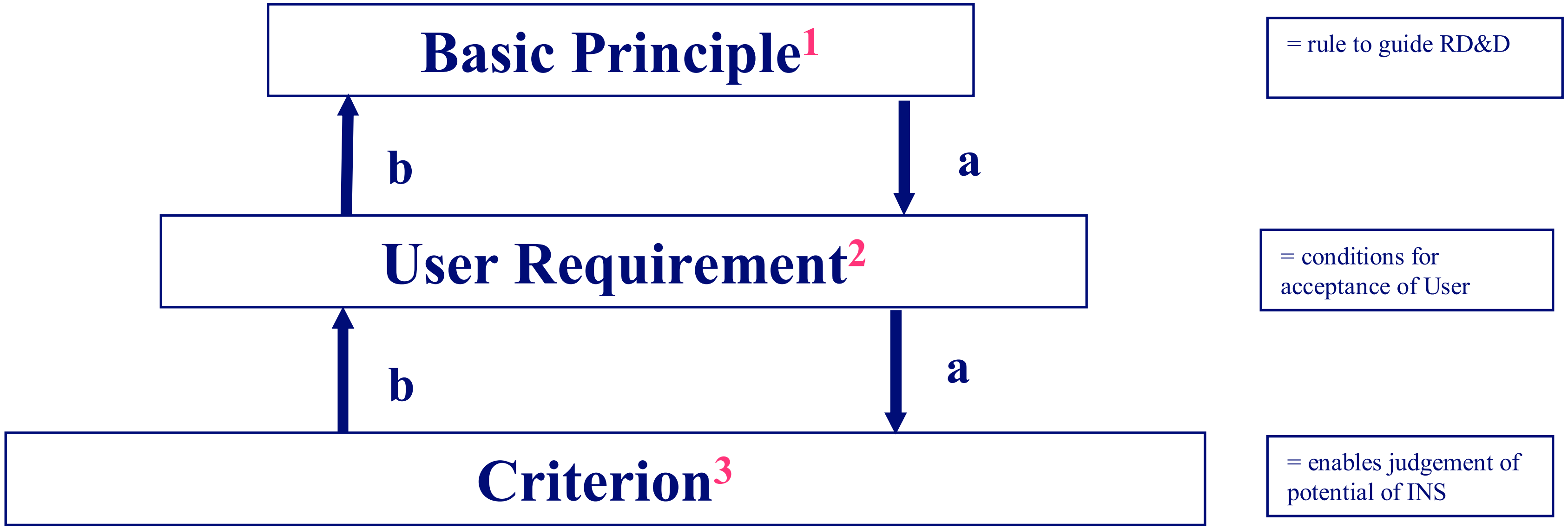
  Mining and Milling, Fuel Production, Enrichment, Fabrication, Production (incl. all types and sizes of reactors), Reprocessing, Materials Management (incl. Transportation and Waste Management), Institutional Measures (e.g. safeguards, etc.)

- INS includes all Phases (e.g. cradle to grave)

The Structure of Basic Principles, User Requirements and Criteria for PR

- INPRO defines the requirements on future Innovative Nuclear Systems (INS)
- Basic Principles, User Requirements and Criteria to assess the compliance of an INS with BPs and URs have been developed top-down
- Criteria are defined through Indicators, Acceptance Limits and Variables/Attributes

General features of INPRO Methodology



a = Derivation of hierarchy
b = Fulfilment of hierarchy

1 ~ Goal in GIF
2 ~ Criteria in GIF
3 ~ Metrics in GIF

INPRO Hierarchy of demands on INS

General features of INPRO Methodology

The INPRO method of assessment provides a tool for:

- **Screening of INS** for their compatibility with the INPRO set of Basic Principles and User Requirements;
- **Comparison of different INS** or components thereof to find a preferred or optimum INS consistent with the needs of a given IAEA Member State;
- **Identification of research and development** needed to improve the performance of existing INS components and for the development of new components.