International Atomic Energy Agency

Assessment Studies of Innovative Nuclear Energy Systems by application of INPRO Methodology

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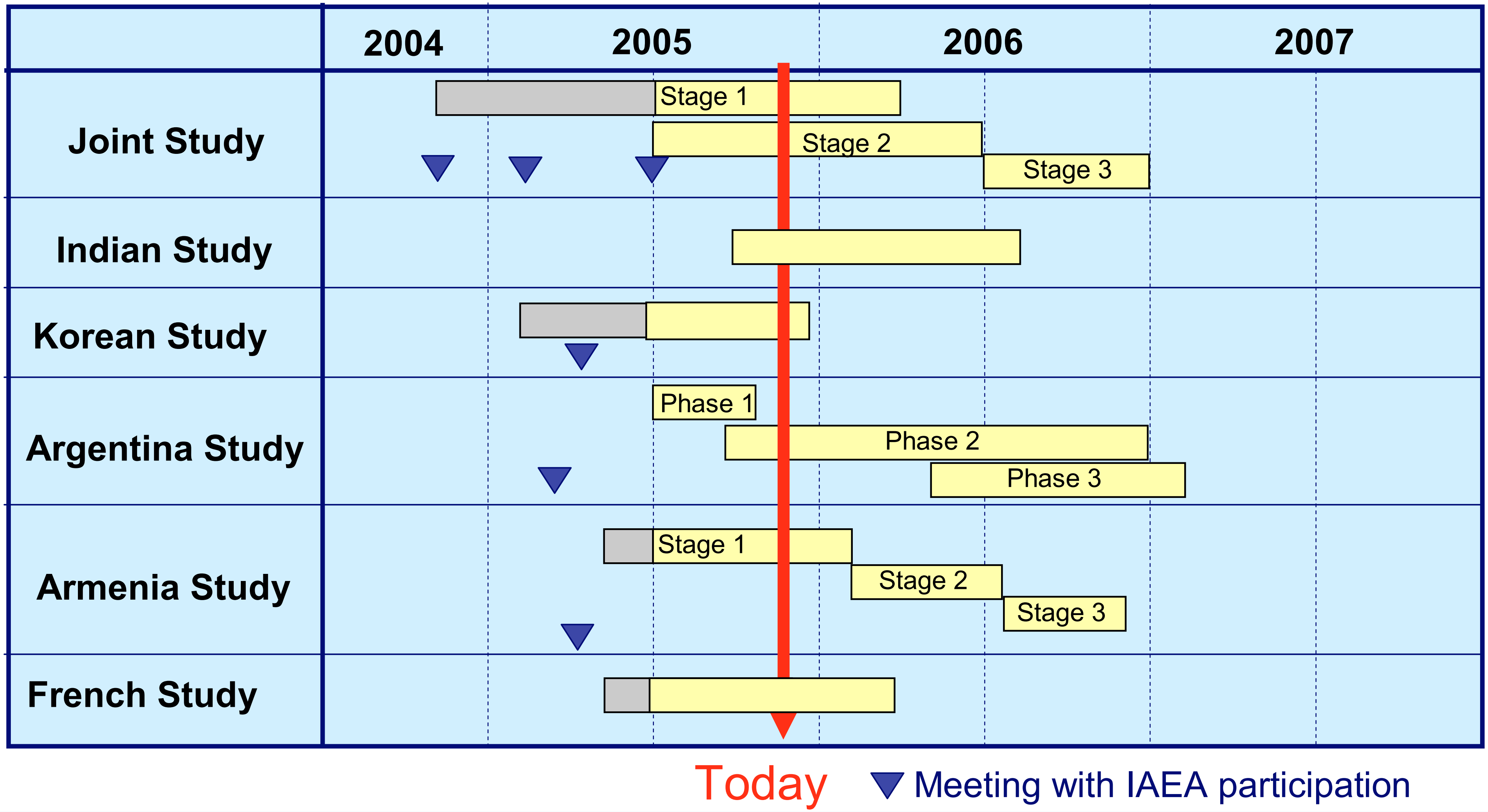
Workshop on Modelling and Quality Control for Advanced and Innovative Fuel Technologies

International Centre for Theoretical Physics, ICTP, Triest, Italy, 14-25 November 2005

- 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
- Assessment Studies -



Joint Study on Assessment of Innovative Nuclear Energy Systems based on Closed Nuclear Fuel Cycle with Fast Reactors using INPRO *Methodology*

(China, France, India, Korea, Russia and Japan as observer);

Initiated by the October 2004 proposal of Russian Federation

Objectives:

- **Joint Study will cover innovative nuclear energy systems based on closed nuclear fuel cycle with fast reactors.**
- **Potential INSs, which, in line with the principles of the INPRO methodology, must satisfy the conditions for sustainable development at global, regional and national level in the 21st century**
- **The INSs will be based on the most promising solutions**
- **The INSs put forward for analysis may include other nuclear facilities, which extend the scope of the energy applications of nuclear power (production of hydrogen and heating, desalination of sea water, etc.).**
- **Assessment will cover all INPRO areas of concern**

Joint Study on Assessment of Innovative Nuclear Energy Systems based on Closed Nuclear Fuel Cycle with Fast Reactors using INPRO Methodology

Dates for the study:

beginning of 2005 – end of 2006

Participants:

- **China,**
- **France,**
- **India,**
- **Russian Federation,**
- **Republic of Korea,**
- **Japan – as observer**

Joint Study stages:

Stage 1: Suggestions of INSs based on a closed nuclear fuel cycle with fast reactors.

Stage 2: Assessment of the proposed INSs using the INPRO methodology.

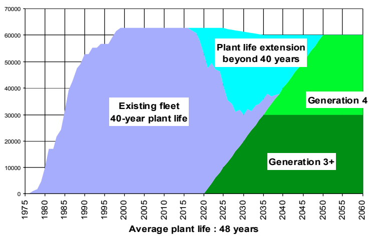
Stage 3: Elaboration and preparation of a conclusion on the long-term viability of INSs.

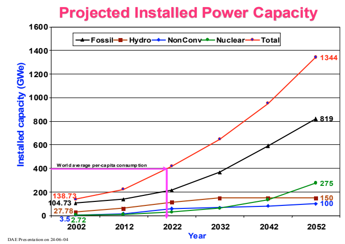
Nuclear Power Growth

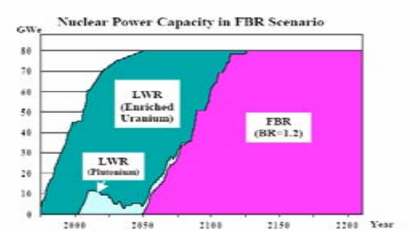
Country	Years	Annual electricity consumption, per cap, kWh	Installed capacity of NP, GW(e)	NP growth, times
China	2002	1380	6,6	5-6
	2020		32-40	
India	2002	420	2,7	10
	2022		29	
Pakistan	2002	480	0,42	10
	2030		4,2	
Russia	2002	5370	22	2
	2020		40-45	
ROK	2005	6190	16,8	1,57
	2015		26,4	
USA	2002	12320	~ 100	~1,1 ?
	2020		~ 110	

1st Scientific and Technical Committee Meeting: 16-17 March 2005, Obninsk, Russia

*** Draft JS Concept presented, discussed and approved in general;**
*** National development/deployment strategies presented:**







- **JS MS identified technologies to be considered as INS CNFC-FR components:**

France – Gas and Na cooled reactor technologies with appropriate fuel cycle technologies

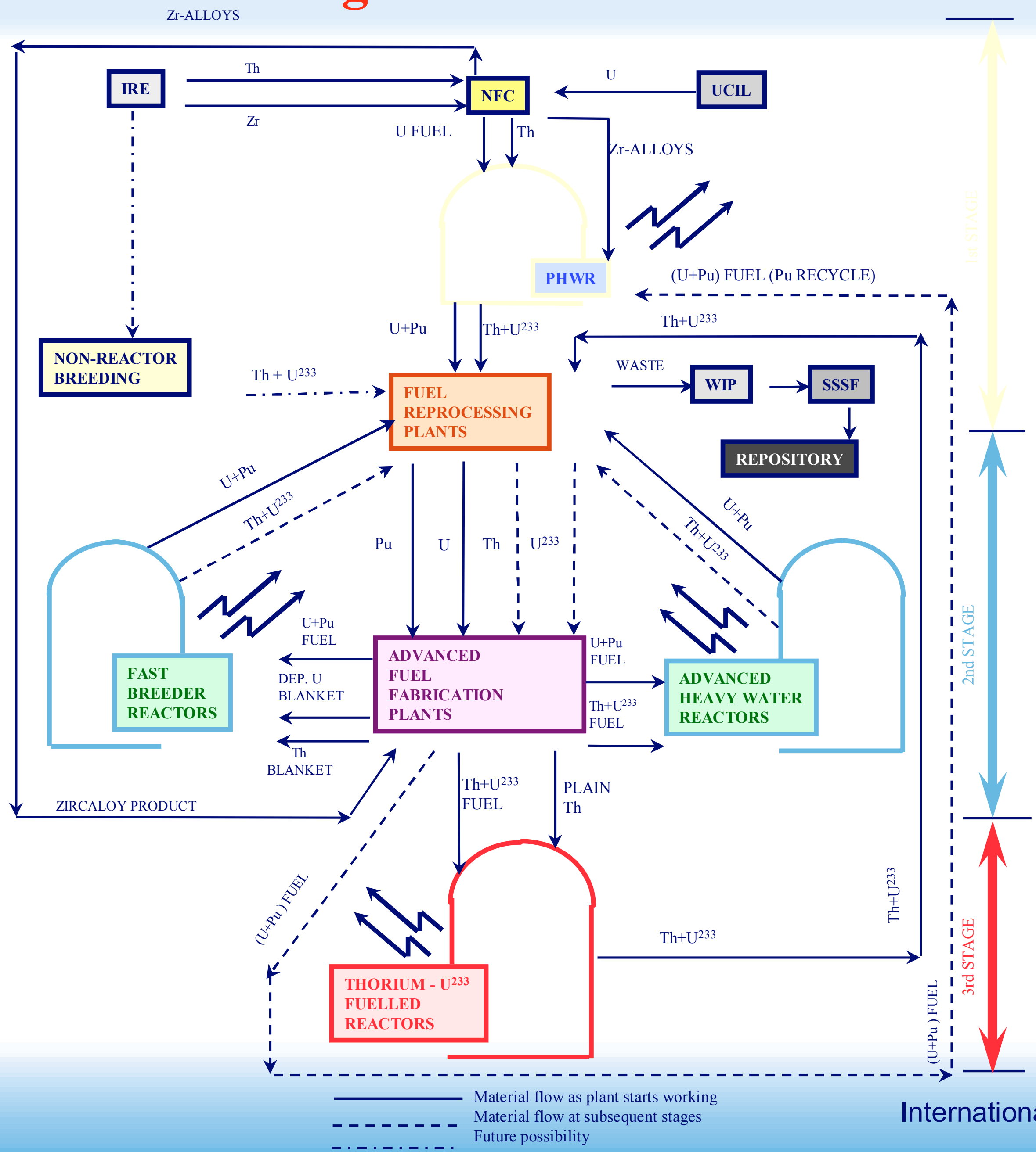
India - Na cooled reactor technologies with involvement of Th fuel and appropriate fuel cycle technologies with high breeding

Korea - Na cooled reactor technologies with appropriate fuel cycle technologies

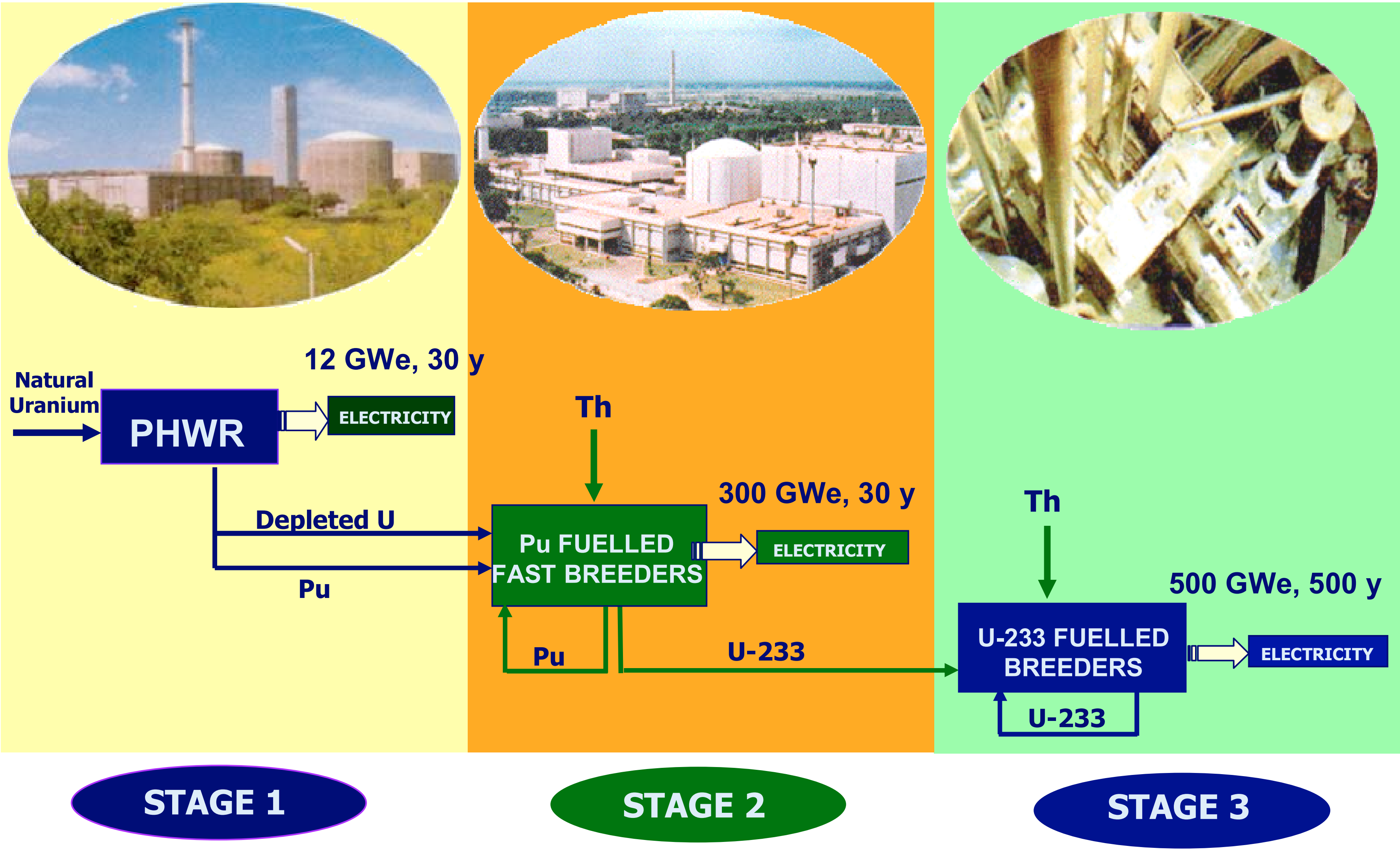
Russia - Na, Pb, Pb-Bi and gas cooled reactor technologies with dry and aqueous reprocessing technologies

Japan - Any promising fast reactor technologies with appropriate fuel cycle technologies

The Three Stage Indian Nuclear Power Programme



THREE STAGES OF INDIAN NUCLEAR POWER PROGRAMME



- Operating : 12 PHWRs, 2 BWRs *Under Design: AHWR, CHTR*
- Under Construction: 6 PHWRs, 1 FBR, 2 VVERs

French INPRO study

Base scenario

- 2015 - Mono-recycling of Plutonium as MOX fuel in PWR-900 and in EPR (>2020)
  - → *Concentration of Pu in Mox fuel*
- 2020 - 2030 Introduction of Global Actinide Extraction and Treatment of spent MOX fuel to constitute a Plutonium stockpile
  - → *Light glass : reduced radio-toxicity and heat release*
  - → *Interim storage of grouped [Pu + Np/Am/Cm]*
- 2035 - Introduction of fast neutron 4th generation systems
  - → *Recycling in Gen 4 FR of grouped [Pu + Np/Am/Cm] from spent LWR Mox and Uranium fuels*
  - → *Integral recycling in Gen 4 FR of Actinides from Gen 4FR spent fuel*

Alternative scenarios (case of postponed deployment of Gen IV systems)

1 – Extension of Pu mono-recycling in PWRs

2 – Multi-recycling of Pu in PWRs to stabilize the Pu stockpile

Argentina INPRO study

Phase I

Determine the need for introducing additional generation capacity in the Argentine Nuclear System in the period 2010-2025

Phase II

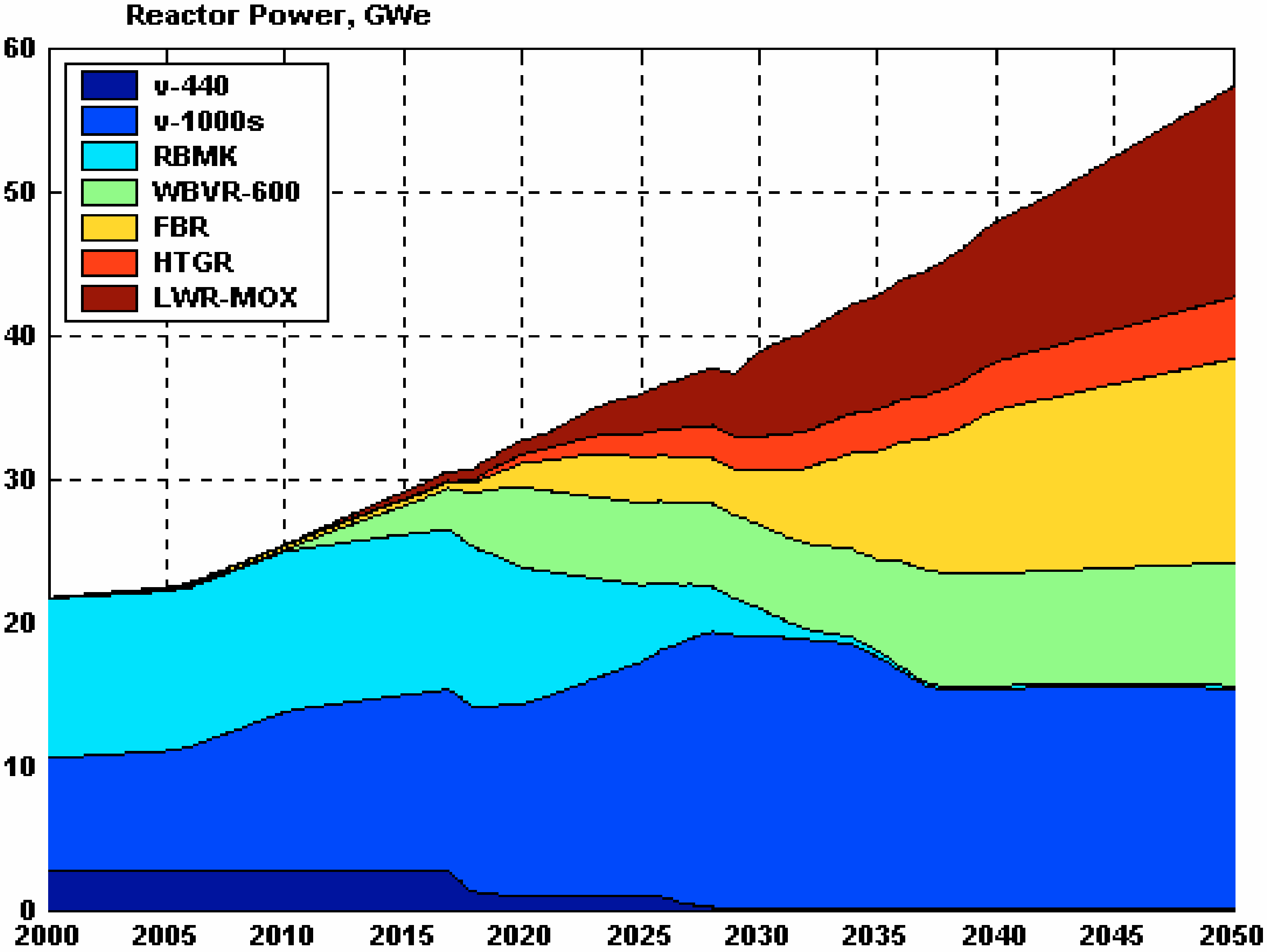
Application of the INPRO Methodology to two selected INSs.

ACR-700 (Canada)
2x CAREM-300 (Argentina)

Phase III

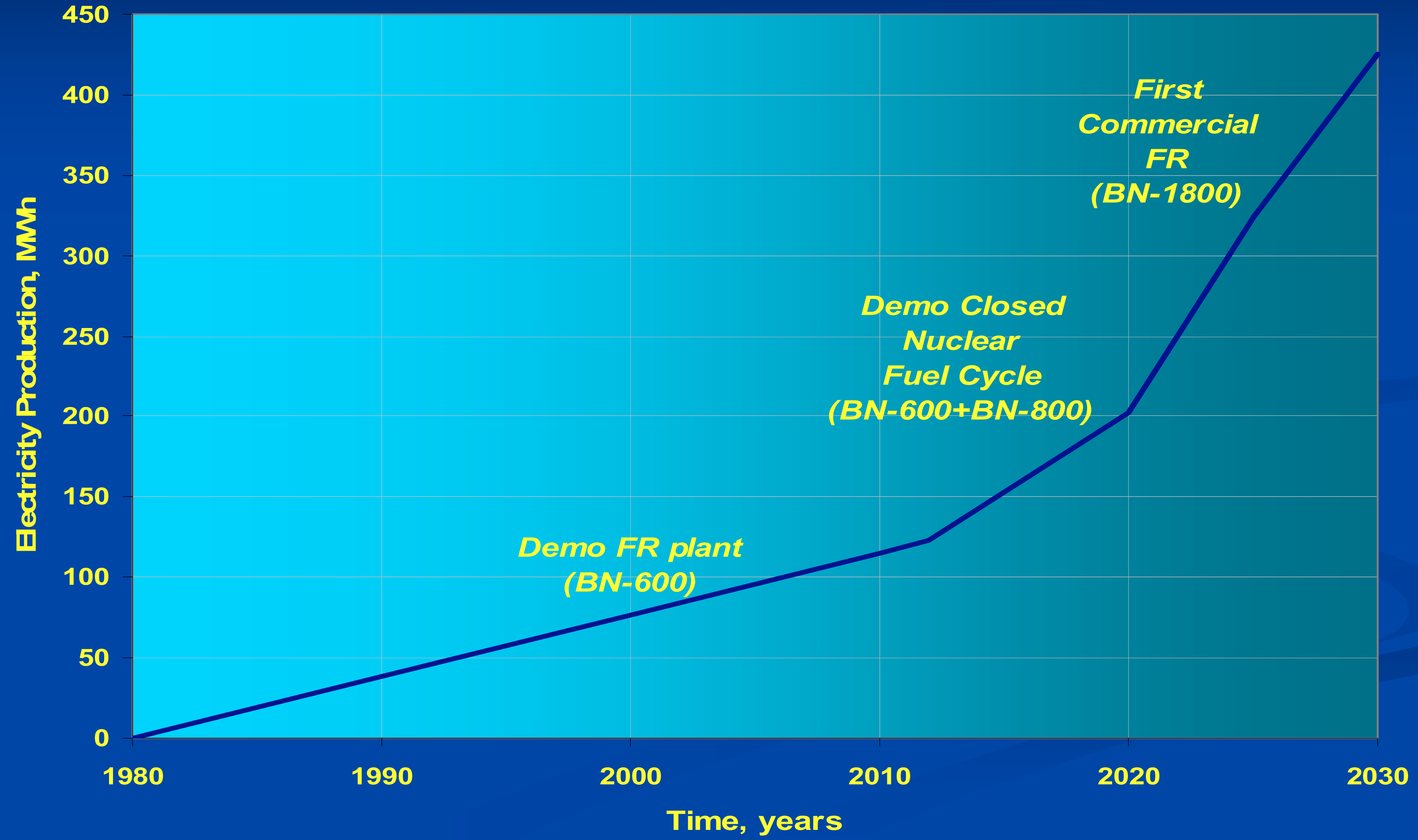
Assess the impact of the Project in the Industrial and Technological Infrastructure of the country. Consideration of the externalities not considered in the Phase I.

Russian Federation Nuclear Energy Strategy up to 2050 on the basis of innovative technologies.

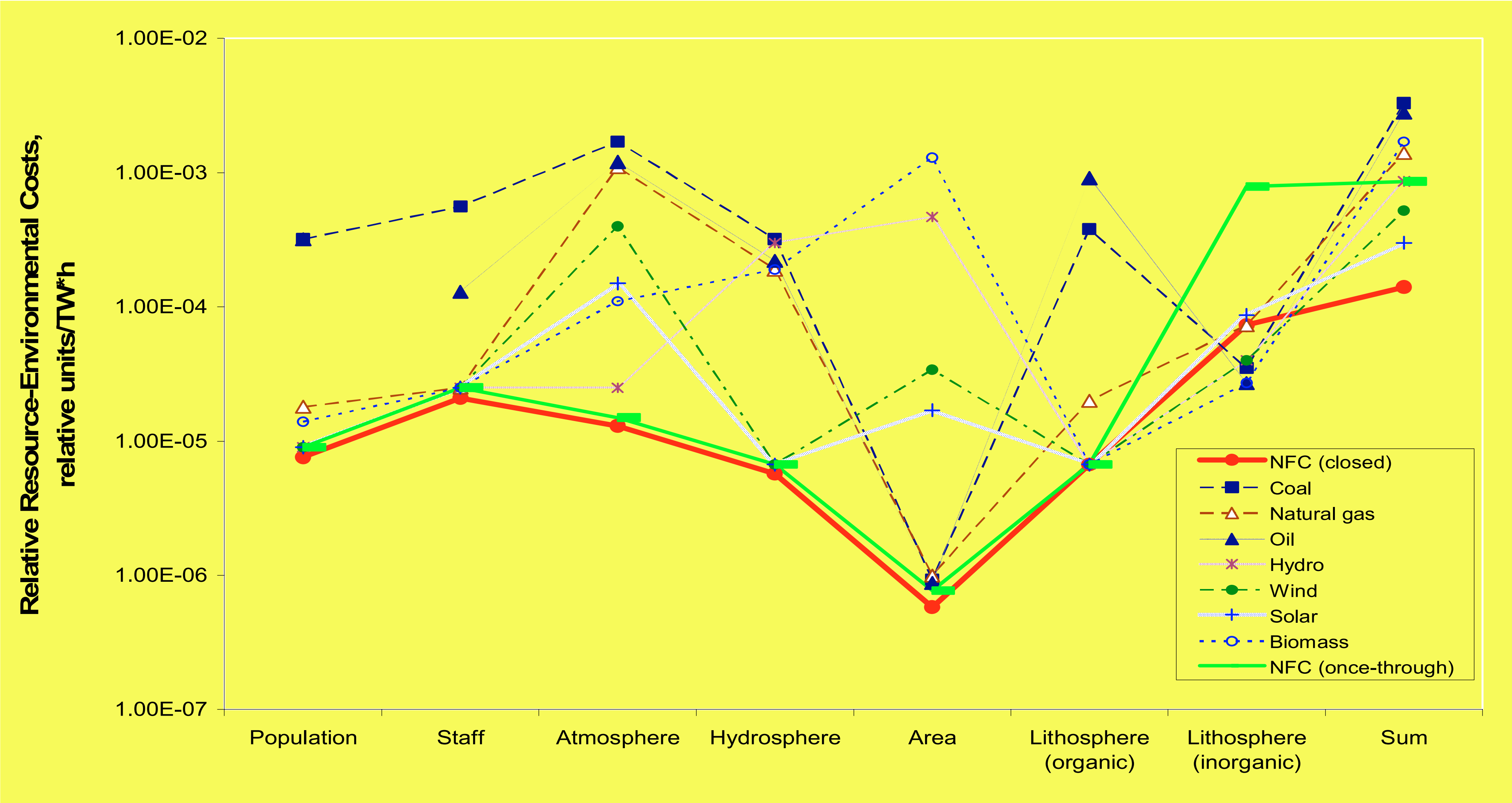


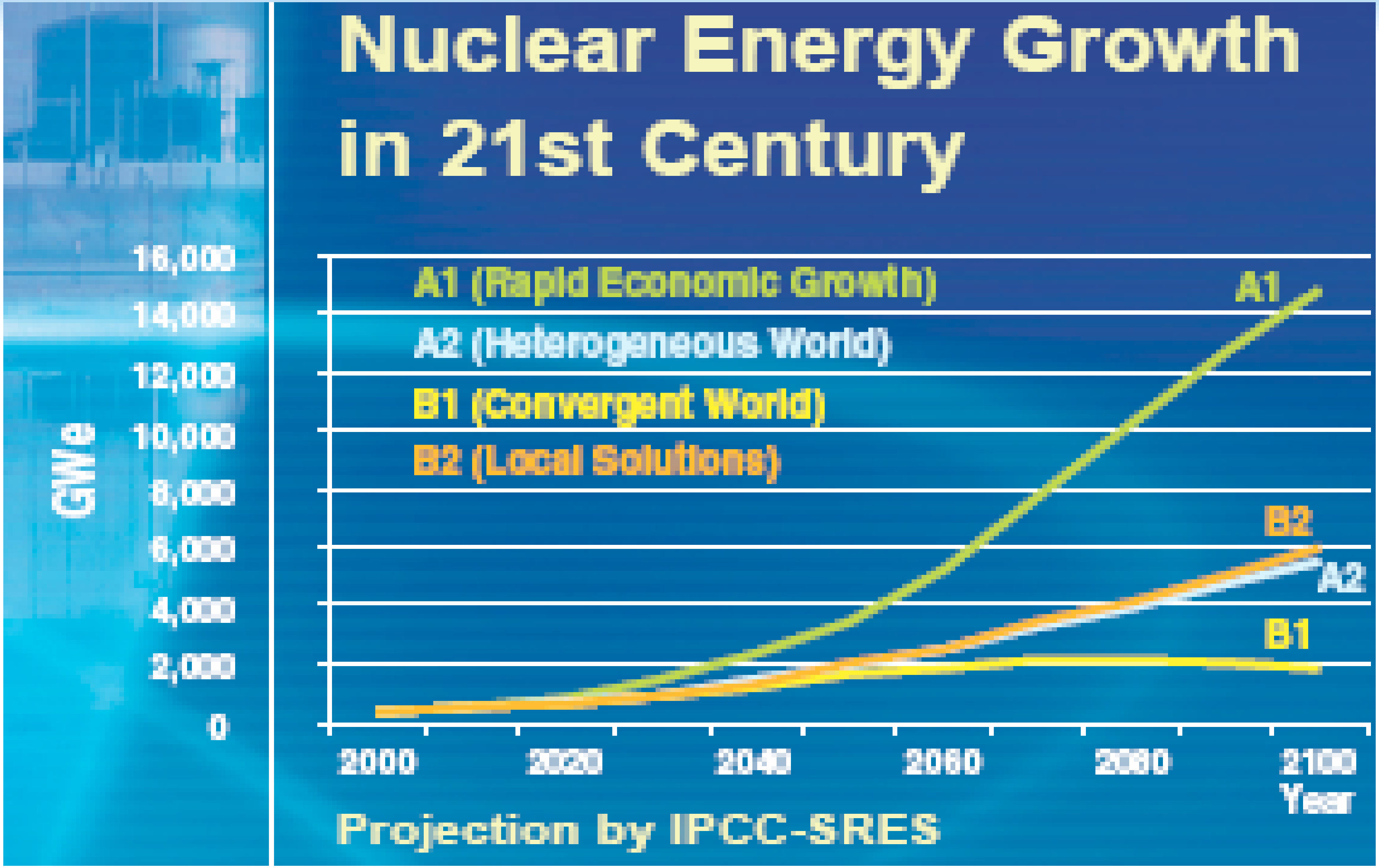
Natural U consumption- 360 000 tonne, Investments 97 billions $

RF plans for CNFC-FR development & commercialization



Total Impact of the power technologies for RF,
relative units (Russian NCS)





International Atomic Energy Agency

Objectives of Joint INPRO study

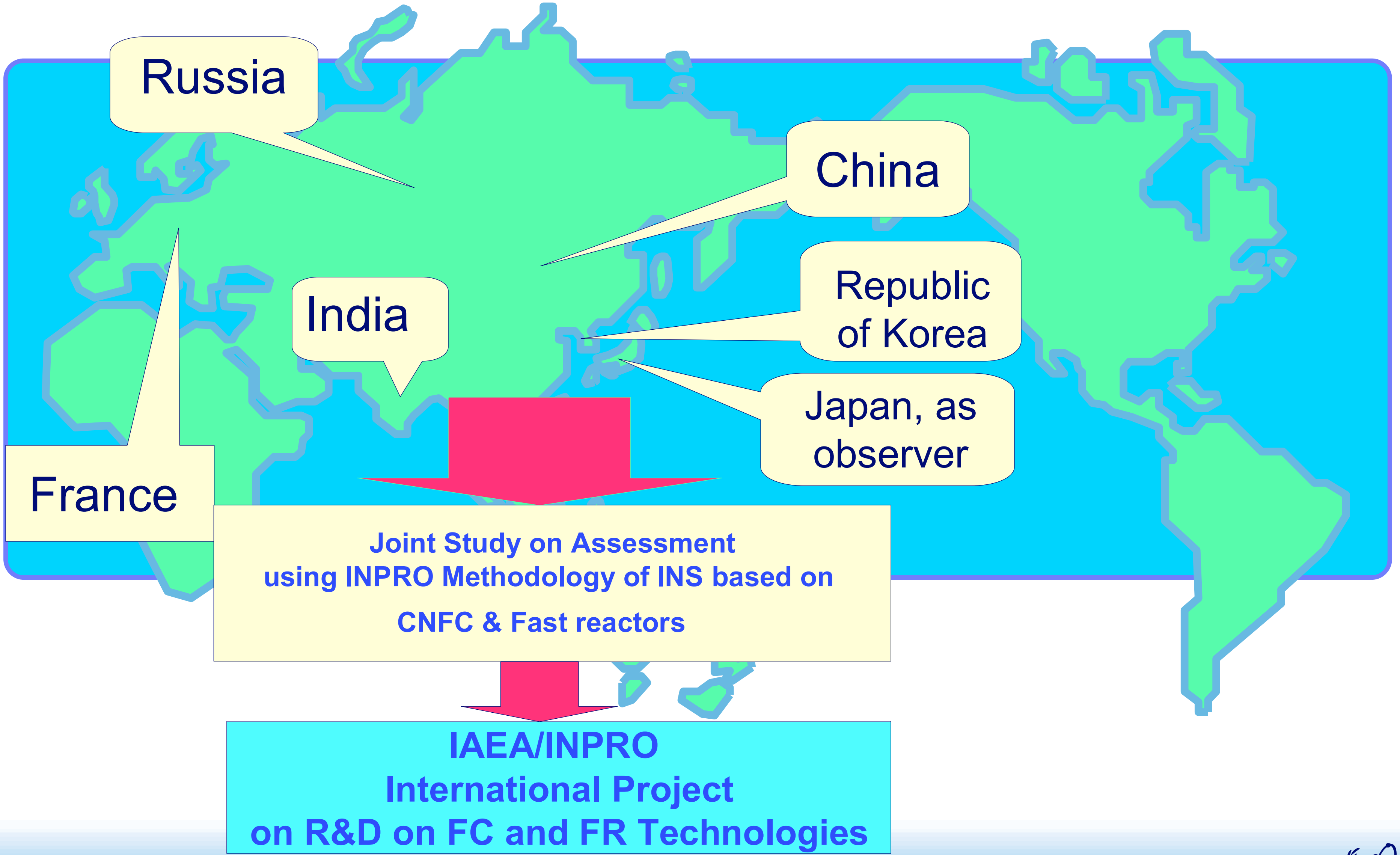
China, France, India, Republic of Korea, Russia and Japan as observer

1) Assessment of potential of the INS (based on closed fuel cycle and Fast Reactors) for satisfying the principles of sustainable development in terms of economics, environment, waste management, safety, proliferation-resistance, infrastructure.

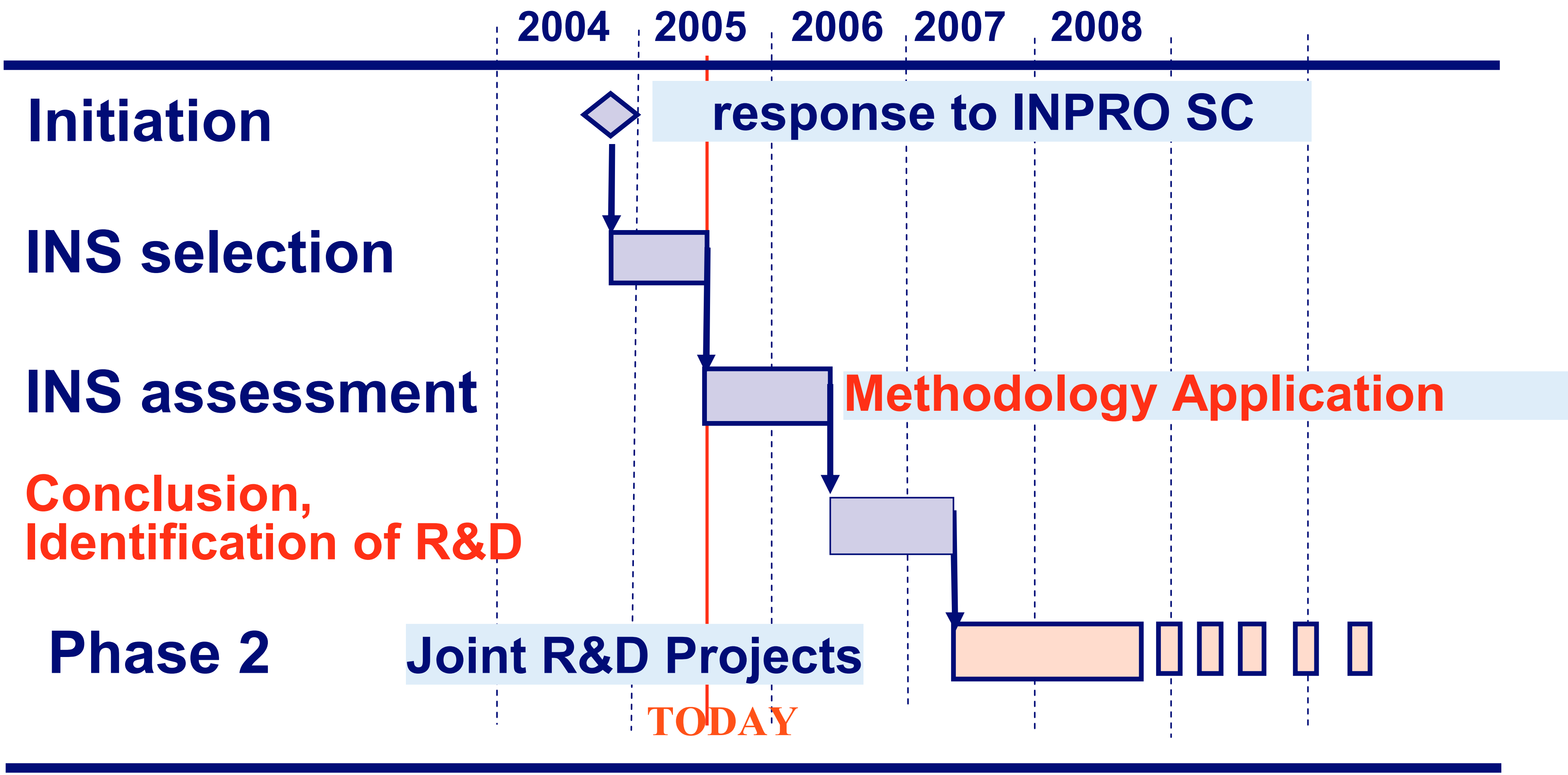
2) Determination of the optimum structure of the system and its components at national, regional, and global level.

3) Identifying the areas of necessary R&D work.

Joint Study Participants



INPRO Joint Study Schedule



Organizational structure

❑ National level:

- Managing of the national teams and financing of their work
- Nomination representatives into Scientific &Technical Committee (STC) of the JS
- Selection from the STC members the STC Chairman on rotating basis
- Creation of working groups on specific INPRO

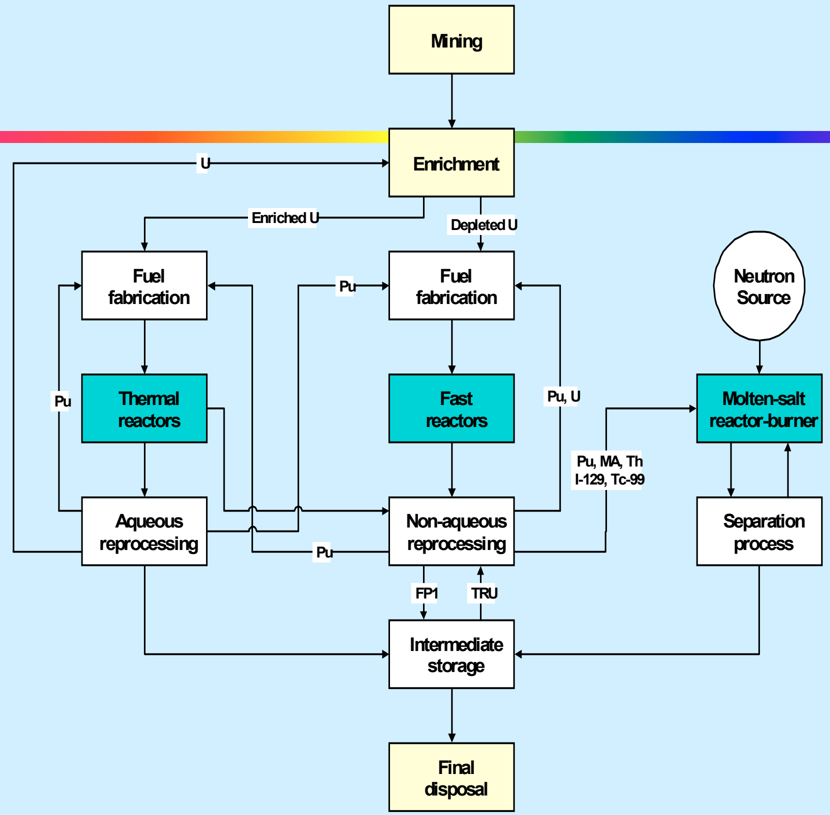
❑ Consultation and coordination with the IAEA

- INPRO ICG, INPRO task managers, etc.
- Main specific documents for the JS guidance:
- TOR – “Terms of Reference”;
- «Concept of the JS»;
- «Roadmap of the JS».

❑ Kick-off meeting (Vienna, December 2004) and two Technical meetings of the STC (Obninsk, March 2005 and Vienna, July 2005)

Six Areas of INPRO Methodology

INS based on Closed nuclear fuel cycle with Fast reactors



Example of INS (Russia)

- **Fast reactors (BR~1, BR>1):**
  - **Sodium**
  - **Lead**
  - **Lead-Bismuth**
  - **Gas**
- **Thermal Reactors:**
  - **PWR**
  - **PHWR**
- **Fuel cycle:**
  - **Fuel types:**
    - **MOX**
    - **Metal**
    - **Nitride**
  - **Fabrication technology:**
    - **Pellet**
    - **Vibro**
    - **Casting**
  - **Reprocessing technology:**
    - **PUREX**
    - **Pyro**
  - **Waste management options:**
    - **LLFP Mgt**
    - **P&T of MA**
    - **Disposal**

Expected Study outcome

- Joint report of countries participating in the Study
  - The role and potential of an INSs based on a closed nuclear fuel cycle with fast reactors in satisfying the conditions for sustainable development at global, regional and national level in the 21st century.
- The Parties will also determine:
  - Priorities for R&D on INSs based on a closed nuclear fuel cycle with fast reactors, and
  - Mutual interest in cooperation in these areas and appropriate recommendations to the INPRO Steering Committee.

Preliminary results of the 1 stage implementation

There are a lot in common in the strategies of development of the INS based on CNFC with FR in the JS member-states:

- **INS based on CNFC with FR is being considered as a prospective energy system in the countries with more than a half of the world's population for sustainable energy supply and for solving the global environmental problems**
- **The essence and terms of the national roadmaps for the CNFC-FR development and deployment have the similar key features, most of the JS participants gives priorities to sodium cooled FRs**
- **National R&DD are focused on reaching the high level of nuclear safety, competitiveness, environment friendliness, improving waste management procedures and proliferation resistant and increase the role of the IAEA in developing the unified requirements in these areas is highly appreciated**
- **All the JS participants are also expect intensification of the international cooperation as an important factor for solving the task of essential increasing of the NP role in the world's energy supply in 21 century**

Preliminary results (2)

Having a lot in common in the general objectives of CNFC development the members of the JS, nevertheless, pose specific national tasks. These tasks distinctly divide the JS participants into two groups:

- France, Russian Federation, and Republic of Korea do not try an acute “energy starvation” and have some realistic energy alternatives to CNFC-FR for covering the energy needs. For them commercial qualities of the CNFC-FR systems and their acceptability by the public are the issues of high priorities.
- For China and India development of NP with FR is so important that these programs are being given the role of some “national idea”. Accordingly, they are supported with all kinds of the governmental assistance. Actually, in these countries the programs of nuclear power development are being constructed based on the requirements of the maximal possible grows of the installed nuclear capacities, and accordingly, breeding ratio.

Conclusions

- INS based on CNFC with FR is being considered as a prospective sustainable energy system in the countries with more than half of the world's population
- There are objective complementary features in different countries in stimulus of the CNFC development, that promises a long-term and fruitful international cooperation in this area
- Without international cooperation scenarios of essential increasing of the NP role in the world's energy production in 21 century have a small chance to be realized
- Intensive international cooperation on INS with CNFC-FR may radically impact the character of national nuclear programs and optimal characteristics of INS based on CNFC with FR
- To realize potential of national and international deployment of CNFC with FR institutional environment should be radically improved

India’s Proposal: Assessment of Hydrogen Generating Innovative Nuclear Systems in National Energy Mix

Bhabha Atomic Research Centre India

An indicative estimate for future requirement of nuclear generated hydrogen in India

- Annual petroleum import 100 million tonnes, progressively growing

- Required HTR capacity to replace 5% of present Indian oil consumption with hydrogen : 15,000 MWth (approx.)

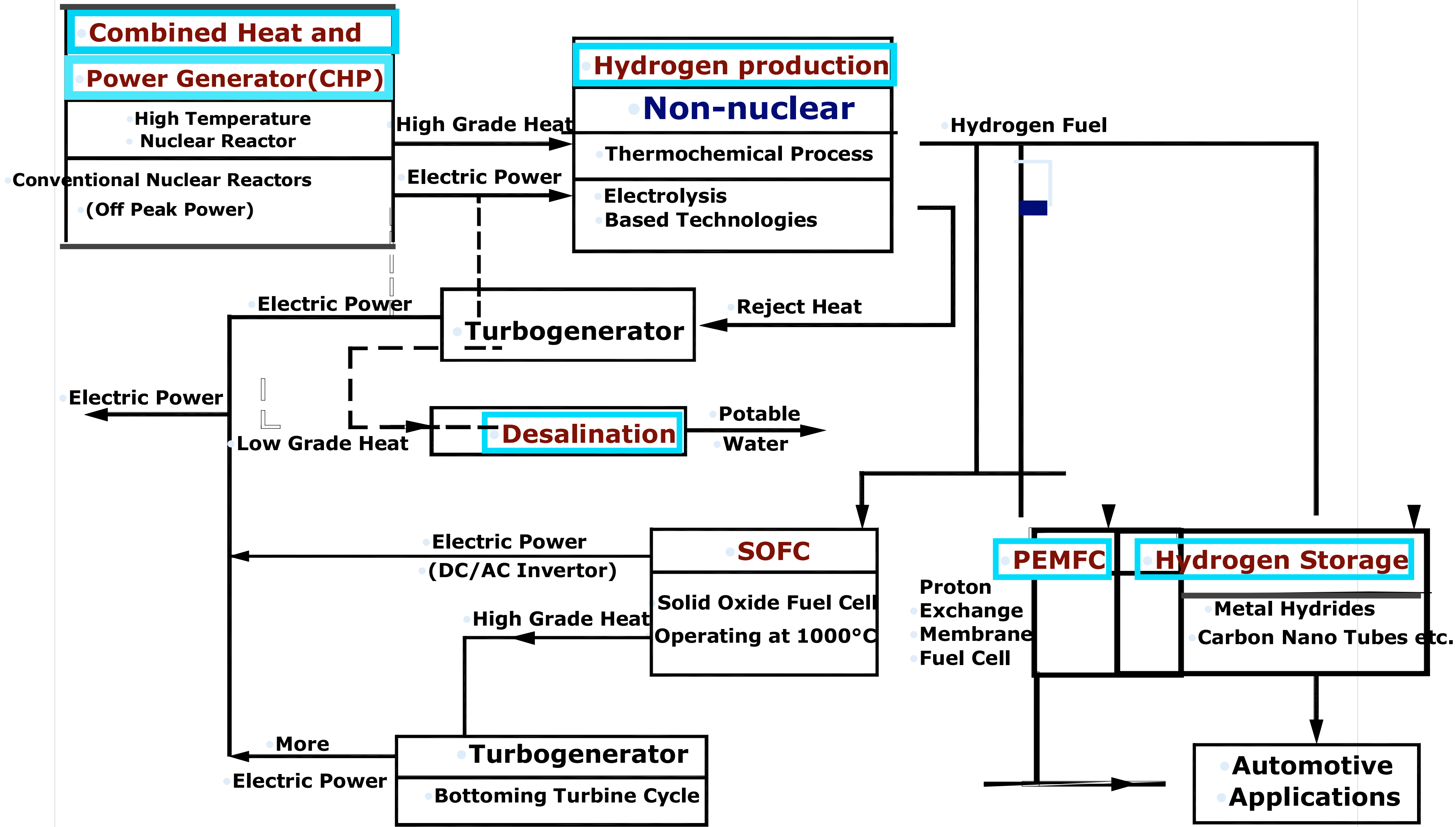
- To consider: future growth in demand, along with future rise in proportion of fluid fuel to be provided by hydrogen.

National Hydrogen Board

- Government of India has recently constituted a National Hydrogen Board.

- BARC has been assigned the responsibility to coordinate all activities relating to hydrogen production on large scale.

Components of proposed Indian hydrogen production system based on nuclear energy



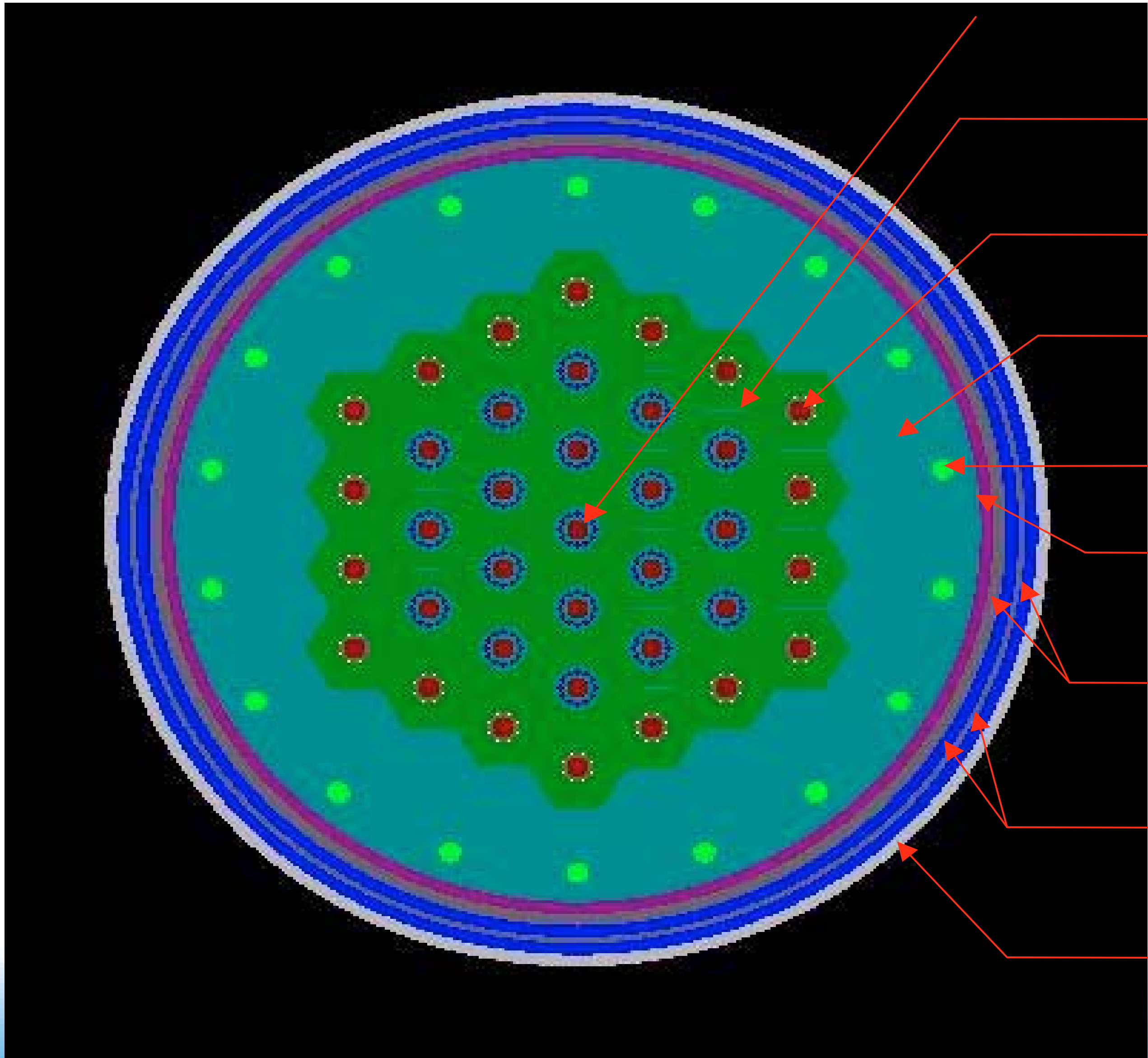
Indian HTR related development plan

Compact High Temperature Reactor
CHTR
Technology Demonstrator (100 kWth), 1000 C, transportable, several passive features
Status - Conceptual design completed, detailed design and development in progress

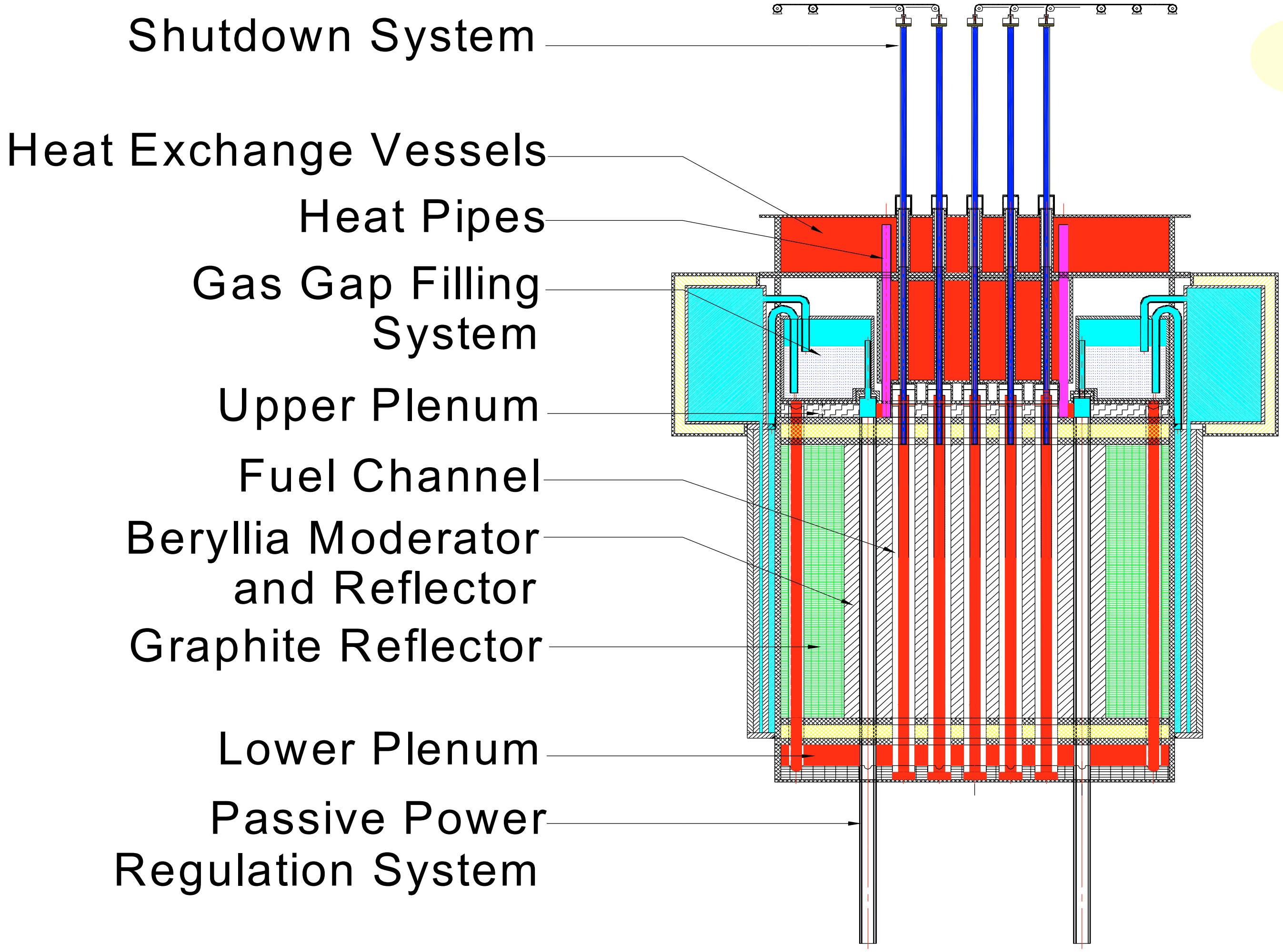
High Temperature Reactor for Hydrogen Generation
HTR-H
600 MWth, ~1000 C
Status - Pre-Conceptual design

Multipurpose Nuclear Power Pack
MNPP
~ 5 MWth, 550 C, passive features, transportable, long life core
Status - Conceptual design (generally similar to CHTR)

CHTR core layout



CHTR will demonstrate technologies related to fuel, materials, passive safety and heat removal systems & HLM coolant technologies for HTRs



Major Design Guidelines

- Use of thorium based fuels
- Passive core heat removal by natural circulation of molten heavy metal coolant
- Passive power regulation and shutdown mechanism.
- Passive rejection of entire heat to the atmosphere under accidental condition
- Compact design to minimise weight of the reactor

Proposal for Assessment under Phase 1(b) Part 2

Assessment of Hydrogen Generating Innovative Nuclear Systems in National Energy Mix

Scope

1) **Assessment of future hydrogen demand in the country and means to meet these demands**
   - **Energy planning studies using IAEA / INPRO tools (MESSAGE, SIMPACT, DESAE, SYRTEX etc.) to the maximum extent.**

2) **Assessment of candidate INS concepts to fulfill the projected demands**
   - **Candidate nuclear hydrogen generating INS concepts offered for assessment.**
   - Possibility for assessments in bilateral or multilateral framework

Individual Case Study 1/6

Global and/or Regional INS in Combination with ***International Fuel Cycle Centres***

(A.Gagarinsky, RRC KI, Russia)

Paper: Applicability of the existing INPRO methodology for assessing global and/or regional nuclear energy systems that are based on the use of innovative technologies in combination with international fuel cycle centers

- *The rates of nuclear energy development higher than those determined by A2 and B2 scenarios currently should be limited by the level of 10 000 GW by 2100*
- *For some regions,* ***small nuclear energy sources*** *may become a quite acceptable option; their production could be launched, in particular, on the base of military plants' conversion. This process may become possible only when an acceptable nuclear fuel cycle based on* ***international fuel cycle centers becomes available****.*
- *It can be supposed that the INPRO-recommended analysis of changes in legislation, administrative structures, the system of international agreements, etc., needed to realize the advantages offered by NFC internationalization, will become a subject of further investigation.*

Individual Case Study 2/6

*Assessment and Analysis for a **Variety of Systems with Fast Neutron Spectrum***

(B. Wiesenfeld, BWM Conseil, France)

Verification and Upgrading of the INPRO Methodology through Performing Assessment and analysis for a Variety of Systems with fast Neutron Spectrum
*Paper titled "**On the potential of fast reactors to meet IAEA INPRO requirements**"*

Several scenarios are considered:

The dominating position of LWR in the NP park

In the "Double stratum" approach,
(the TRU transmutation in the LWR will be replaced (partially or completely) by the transmutation in Fast Reactors-burners)

- ***The dominating position of FR in the NP park***
- ***FR inside of the multiple combinations with other reactors***

Individual Case Study 2/6

Assessment and Analysis for a ***Variety of Systems with Fast Neutron Spectrum***

(B. Wiesenfeld, BWM Conseil, France)

Three concept groups:

- *Most advanced projects: BREST, BN-800 , PRISM*
- *Detailed description of all parameters and of the total design strategy are available.*
- *The projects can be assessed directly with a small uncertainty.*
-
- *Well motivated proposals: GCFR , Steam-water Fast Reactor, Supercritical Reactors (SPFR) and others*
- *Evaluation (without details) of the principal characteristics of cores and less detailed of other parts of NPP are available*
- *Non-traditional concepts:(like Energy Amplifier, WISE, etc.),*
- *Although is based on the NP experience, do not sufficiently developed up to concrete technical design and can be pre-evaluated because it search the promising goals.*

Individual Case Study 2/6

*Assessment and Analysis for a **Variety of Systems with Fast Neutron Spectrum***

(B. Wiesenfeld, BWM Conseil, France)

Main idea:
Addition of special challenging

***"Break-through" BT requirements**.*

*INS should be capable to meet **all Basic Principles and at least one BT.***

Individual Case Study 3/6

*Assessing **Multi-Product Nuclear Energy Systems***

(D. Tsurikov, RRC KI, Russia)

Paper: Applicability of the Existing INPRO Methodology for Assessing Multi-Product Nuclear Energy Systems

An overview of market potential, innovative nuclear system concepts and main challenges for non- electric applications of nuclear energy.

- *Hydrogen production*
- *Water desalination*
- *Industrial industrial process heat applications*
- *District heating*
- *Coal gasification*

Case study on the assessment of an illustrative two product INS (power and hydrogen)

Individual Case Study 3/6

*Assessing **Multi-Product Nuclear Energy Systems***

(D. Tsurikov, RRC KI, Russia)

Main conclusions:

- The market potential of non- electric applications of nuclear power makes from 1120 to 11260 GW of thermal capacity of the NES intended for this purpose

- Creation of high- temperature NES, together with related technologies for hydrogen and other non electric energy carriers production, which should be adequate to nuclear ones will be required. A considerable (over 75%) part of the potential could be covered by using efficient INSs integrated in modular HTGRs and MSC processes

- Compared to the reference versions of LWR based NPPs, such systems are almost twice as efficient with respect to practically all principal specific indicators (specific replacement of hydrocarbons with nuclear fuel with corresponding economic effect, reduction of greenhouse gases' emissions and increased sustainability of the main energy capacious branches of industry and transport.

Individual Case Study 4/6

Evaluation of Nuclear Power Systems with ***Small-Sized Reactor Units***

(S. Subbotin, RRC KI, Russia)

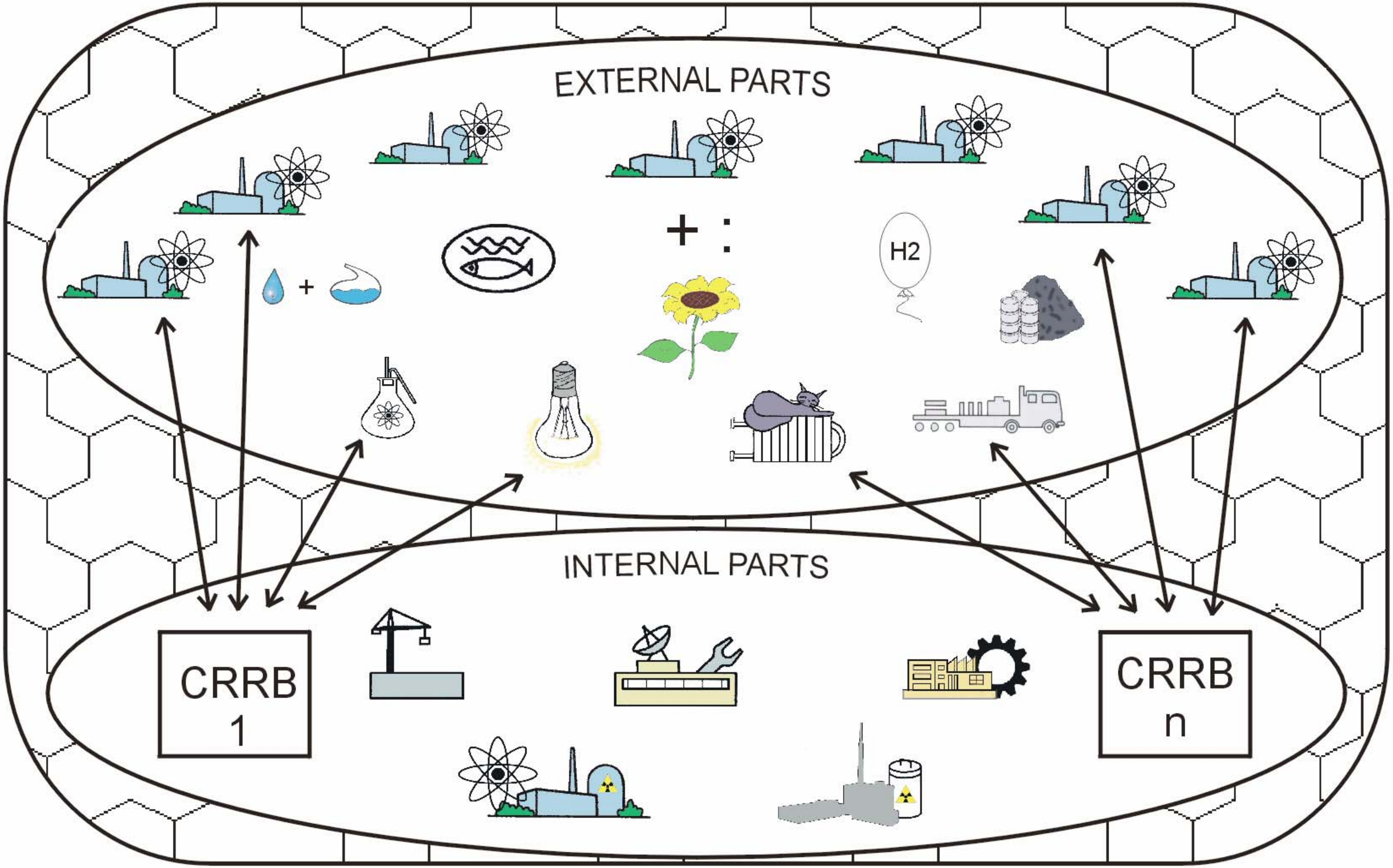
Assessing and Defining the Direction of Enhancement of the Existing INPRO Methodology for its Applicability for Evaluation of Nuclear Power Systems with Small-Sized Reactor Units

Main ideas: INS structure will consist of two parts – External and Internal
External:

- ***40-years experience of creation and operation of transport NPIs of various types for icebreakers, submarines and space ships.***
- ***SNPP should be transportable at factory readiness.***
- ***Projects of small Nuclear Power Installations: KLT-40, ABV (pressurised water); RUTA, ELENA (water with natural circulation); ANGSTREM, TES-M (coolant lead-bismuth).***
- ***ABV-6M - final design; NPI KLT-40S - developed and coordinated design project.***
- ***At the stage of the outline design it is developed power line SNPP from 50 up to 230 MW (e).***

Floating nuclear power water desalination complex (FNDC).

COMPLETE SYSTEM OF SMALL NUCLEAR CAPACITIES



Individual Case Study 4/6

Evaluation of Nuclear Power Systems with ***Small-Sized Reactor Units***

(S. Subbotin, RRC KI, Russia)

Conclusions:

Experience of small power capacity NPI development allows to meet user requirements in autonomous reliable and safe energy sources on quite competitive basis in conditions of commercial interest to them, and also allows NE to go through the period of stagnation of interest to it in large energy systems without loss of potential in the nuclear technologies especially concerning creation of a fuel cycle for future large-scale NE system.

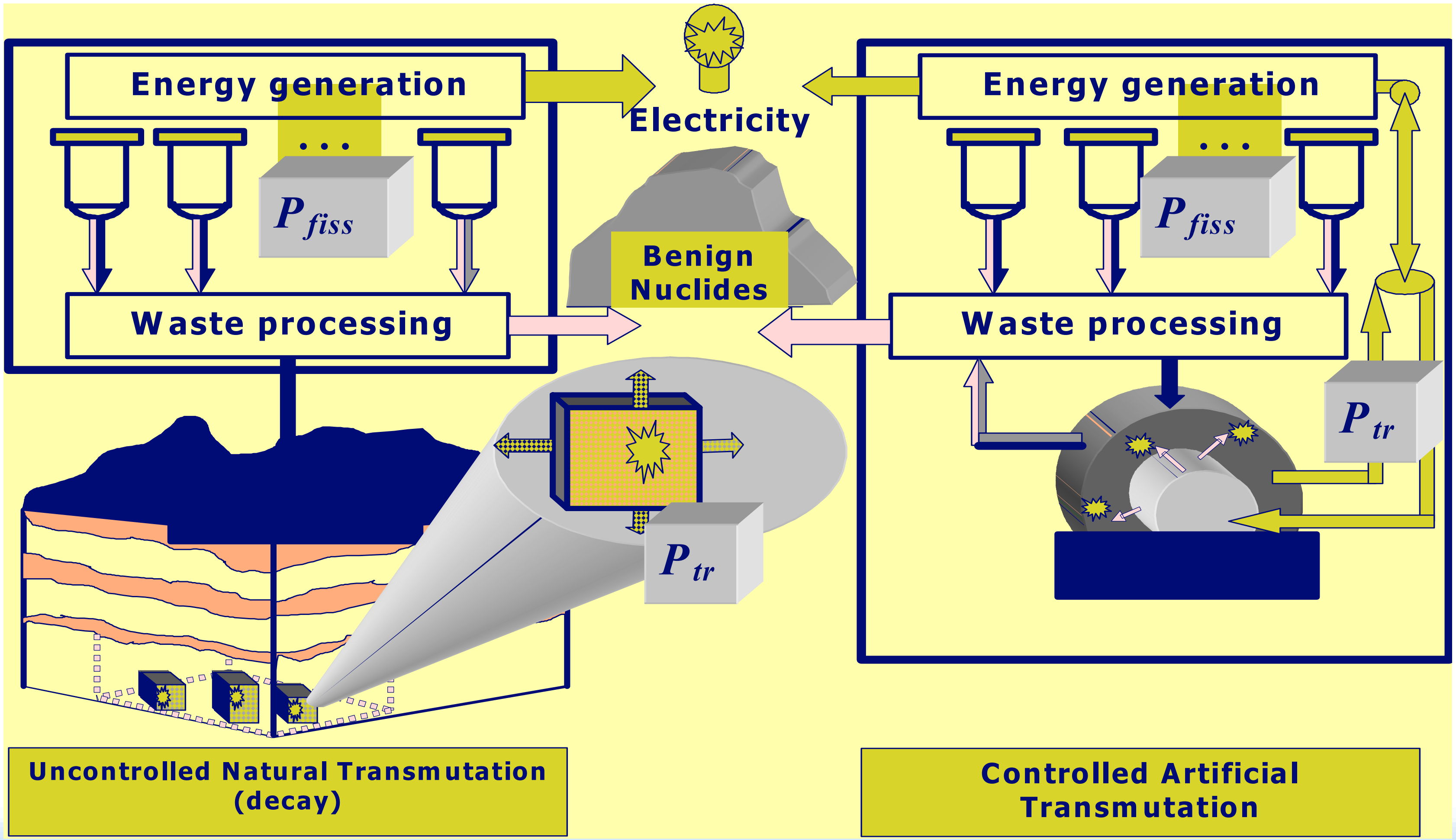
SNPPs system can become experimental site for improvement of technical decisions which may be used for sustainable development of large scale NE system.

Individual Case Study 5/6

INPRO Methodology for its applicability in future for assessing different types of non carbon energy systems, in particular ADS and FUSION

(Yu. Korovin, ***Obninsk State University for Nuclear Power Engineering, Russia)***

Comparative sketch of Nuclear Energy Systems with different methods of waste Transmutation



Individual Case Study 5/6

INPRO Methodology for its applicability in future for assessing different types of non carbon energy systems, in particular ADS and FUSION

(Yu. Korovin, ***Obninsk State University for Nuclear Power Engineering, Russia)***

•CONCLUSIONS

•**Current INPRO methodology does not have enough universalism and completeness to comprise nuclear alternatives (fusion, ADS). It requires further development to response the challenge of nuclear alternatives (Fusion Technology, Accelerator Technology).**

To evaluate Fusion technology the level of Basic Principles requires further development.

• **To evaluate the accelerator technology the level of Acceptance Limits requires further development.**

Individual Case Study (Proposal 1)

Validation and upgrading of INPRO Basic Principles, User Requirements, Criteria and Methodology in countries with planed autonomous Nuclear Fuel Cycle Supply

(R. Cirimello, CNEA, Argentina)

Rationale

- A real technology gap will arise if developing countries reach energy consumption equal to developed countries
- Past and present policy of various developing countries was to establish autonomous Nuclear Fuel Cycle likely with Natural Uranium but not only.
- Evolutionary concepts of HWR are based on in LEU fuel and existing reactors of this kind are already converted or are studies in progress to do so (Atucha I in Argentina and Candu´s 600 in several countries)

Individual Case Study (Proposal 1)

Validation and upgrading of INPRO Basic Principles, User Requirements, Criteria and Methodology in countries with planed autonomous Nuclear Fuel Cycle Supply
(R. Cirimello, CNEA, Argentina)

- **Numeric Indicators additional to the existing "judgment on the approach" in order to combine all Criteria through "load factors" will be analysed**
- **Review of the concept of "advance technology" for developing countries (**since the experience of GIF show that the selected concepts are for developed countries only)
- **Future R & D directions to accomplish previous statement. (***For example VHTR may not be needed to fulfil Economic and Technical competitiveness again CCGT systems***).**
- **The economic analysis will consider CCGT, Coal and Diesel Oil fired stations and hydro as alternative sources. (***The reactor, turbine, diesel motor or turbogroup will de considered as an energy converter in the Fuel Cycle***).**