"Assessment of Compatibility of a System with Fast Reactors with Sustainability Requirements and Paths for Its Development"

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Historical Perspective

- Joint Assessment Study on INS based on CNFC-FR was initiated by Russian Federation in Oct 2004 as an integral part of INPRO Phase I activities on assessment of INS with use of INPRO methodology
- The Study was implemented by Canada, China, France, India, Japan, Republic of Korea, Russian Federation, and Ukraine
- It is completed in November 2007
- Final Report published as an IAEA-TECDOC

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MS - Participants of the JS

MS having more than half the world population and large users of energy in coming decades are participating in JS.

Arrangement of Joint Study

National Level

- Formation of national teams
- Representations in the JS Scientific & Technical Committee (STC)
- Formation of working groups on specific topics

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- INPRO IG, INPRO Task Managers
- IAEA experts

Main documents for guidance

- Terms of Reference and concept of the study
- Roadmap
- INPRO Methodology and Manuals on assessment of compatibility of an nuclear energy system with sustainability requirements

Main Objectives of the Joint Study were to:

- Determine milestones for the INS CNFC-FR deployment at national and global levels
- Assess the INS CNFC-FR for satisfying the INPRO sustainability requirements and identify areas for improving the INS with R&D or/and institutional measures
- Provide feedback on the INPRO methodology improving

Milestones for the INS CNFC-FR deployment at national and global levels

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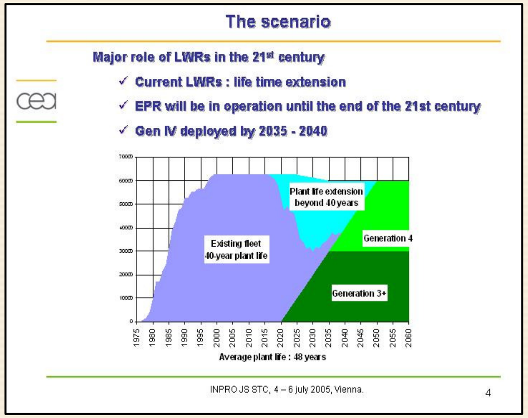
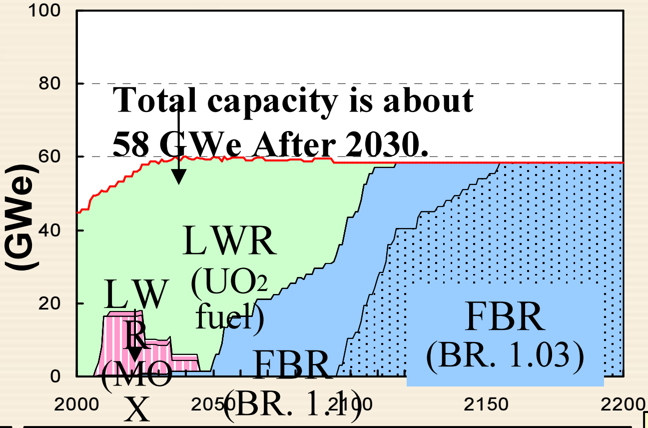
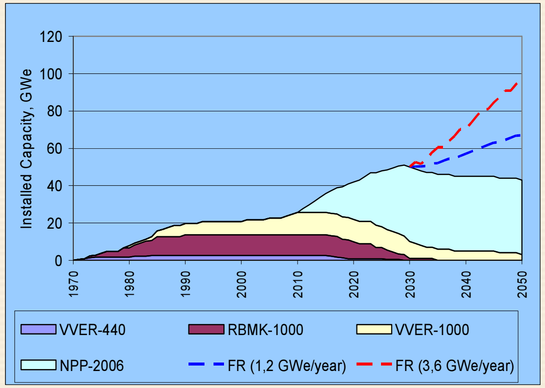
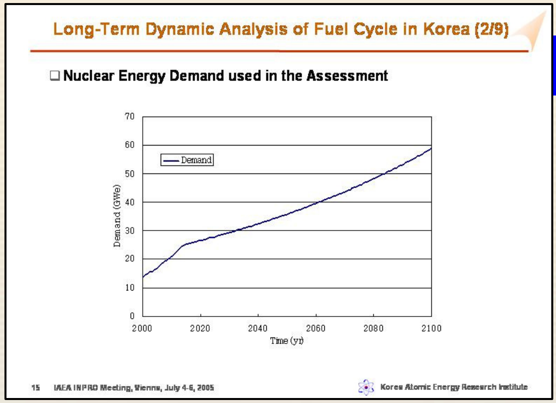
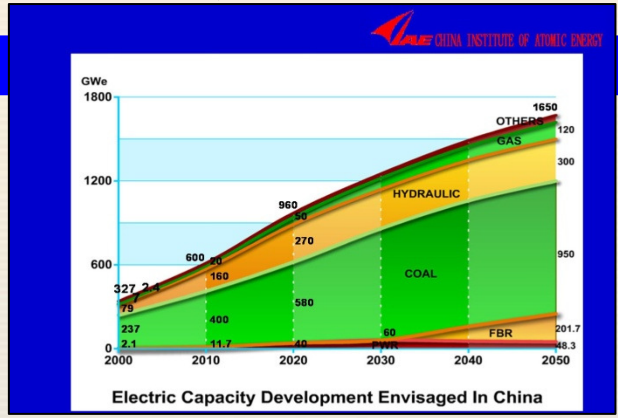
National Strategies and Scenarios

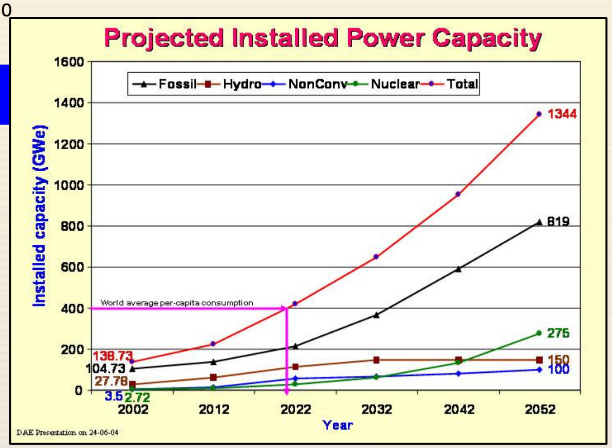






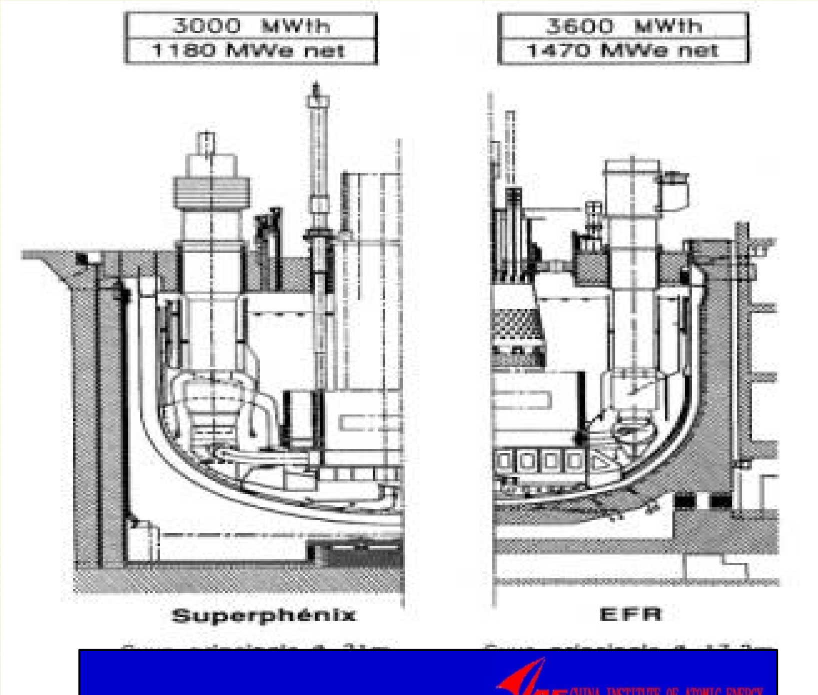


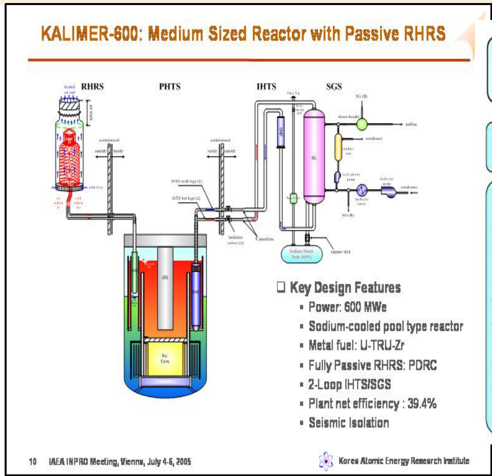


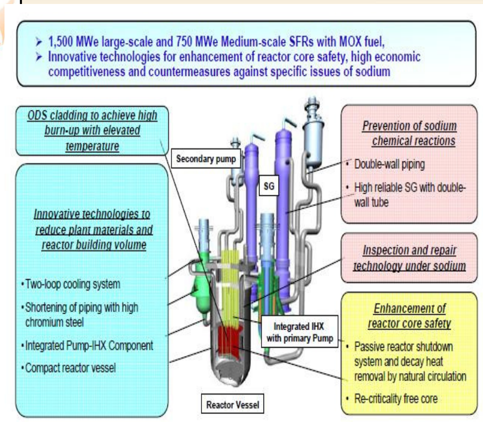


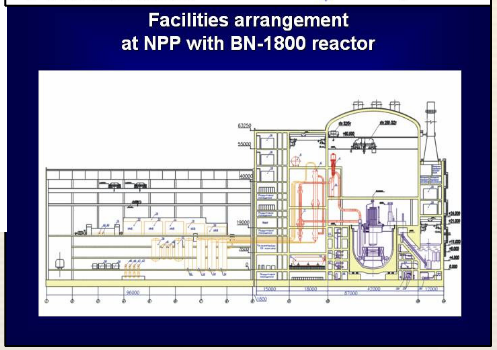
- Various national expectations in nuclear growth: from about zero up to ‘as much as possible’
- Promising global market for INS CNFC-FR: 300-500 GW by 2050
- Different level of the technology development: from research reactors up to pilot commercial NPPs and associated fuel cycle
- Specific focus on the INS role: fuel assurance or waste reduction

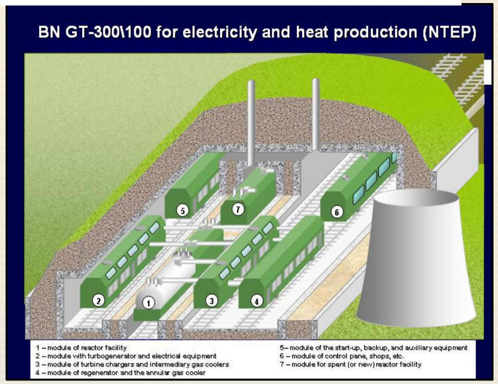
Selection and Evaluation of Technologies

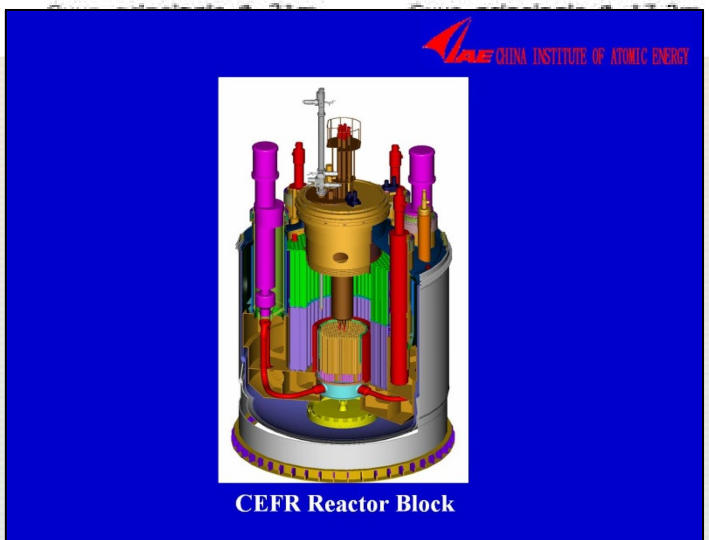


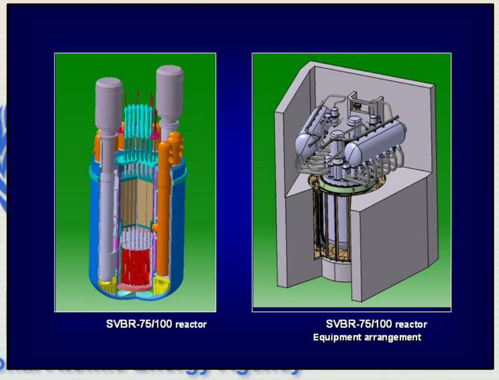


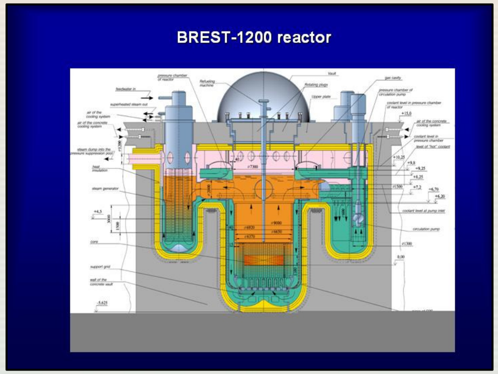












FR related national programms

Country	Coolant	FP type			Fuel	Process
		Experimental	Prototype	Commercial		
Russia	Na, Pb, Pb-Bi	1969, 1973	1980, 2012-2015	2020…2025	UO_2, MOX, nitride	improved PUREX, pyroprocess, vibro-packing
Japan	Na	1977, 1994	2020	2050	MOX, metal	improved PUREX, pyroprocess, injection molding
France	Na, gas	1967, 1973	2020+	2030+	MOX, nitride	improved PUREX, pyroprocess
USA	Na (Pb)	1964, 1980	2014	2023	MOX, metal	pyroprocess, injection molding
China	Na	2008	2020...2025	2030...2035	UO_2, MOX, metal	pyroprocess, injection molding
India	Na	(1984)	2010	2020	MOX, metal	improved PUREX, pyroprocess
Republic of Korea	Na		2030		Metal	pyroprocess

Commonalities among National Scenarios

- Joint scenario: U constraint would be evident by 2050 as well as the problem of SF accumulation in OTFC
- High emphasis on safety, economics, waste, proliferation resistance to meet sustainability requirements
- A small serial of SFRs are to be deployed in 15-20 years
- Generic features of the near/medium CNFC-FR: sodium, pool type, pellet MOX fuel, advanced aqueous reprocessing
- Commonalities provides a basis for building a 'reference model' of near/medium INS CNFC-FR

Variants among National Scenarios

- Times of introduction of FRs
- Deviations in Capacity, Reactor Type (loop – Japan)
- Vision of a robust INS CNFC-FR: variations in coolant, design arrangement (2-circute), fuel options, breeding

Assessment of the INS CNFC-FR for satisfying the INPRO requirements and identifying areas for its improving with R&D or/and institutional measures

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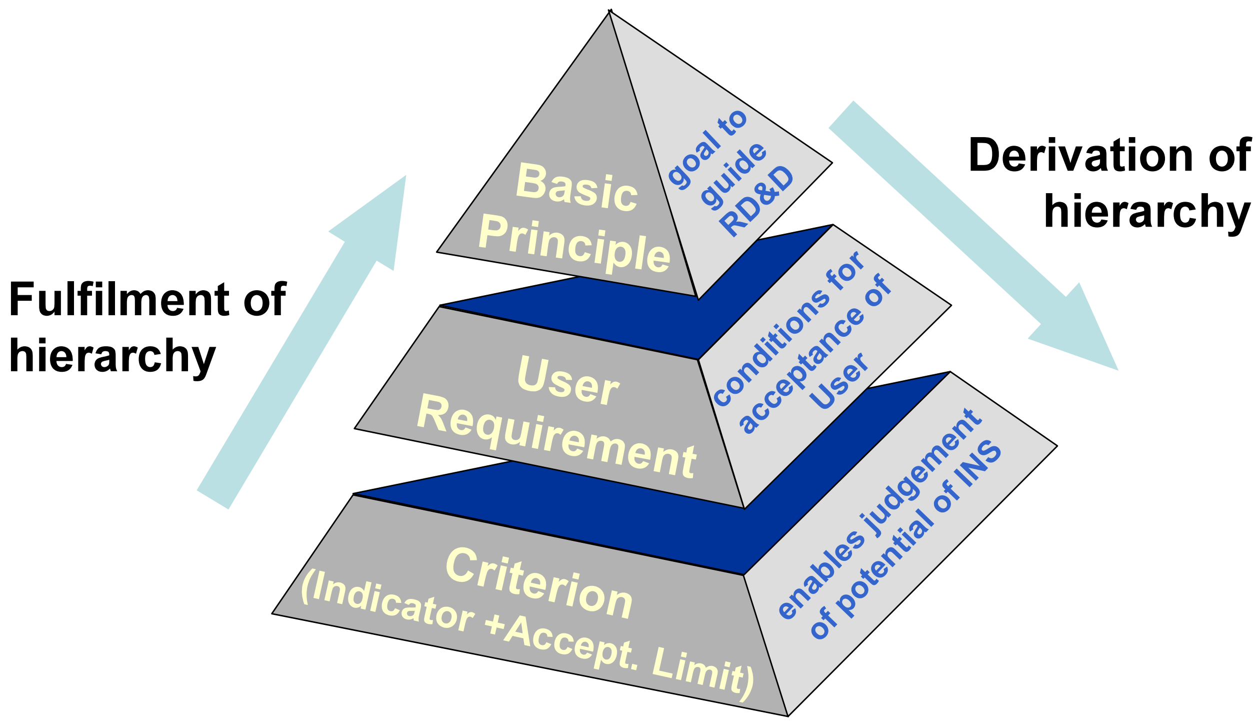
INS assessment in INPRO: bottoms up approach

A criterion (CR) is fulfilled when its indicators comply with Accep. Limits

A user requirement (UR) is met when all its CR are fulfilled

A basic principle (BP) is achieved when all its URs are met



If a criterion is not fulfilled then improving should be addressed including R&D and/or institutional measures

Safety: philosophy and means

- **SFR operational experience as a basis for safety assessment:**

  - evidence to meet requirements of the current regulatory basis;
  - occupational and public exposure at the best level in NP

- **4 INPRO safety Basic Principles (BPs) based on the IAEA Principles, utility requirements & an extrapolation of current trends:**

  - an enhanced application of the concept of defence in depth (DID);

  - increased use of passive systems and inherent safety features;

  - reduction the risk due to radiation exposure to the level of risks arising from facilities of other industries with a similar purpose;

  - sufficient level of R&D to be performed for new nuclear designs.

- **Examples of SFR inherent safety features are:**

  - negative reactivity feedback in power and temperature disturbances, stability of neutron pattern, no poisoning effects;

  - the excellent heat transfer and high boiling point of sodium resulting in a very low pressure and low stored energy of the coolant.

- **An example of engineered safety features:**

  - the installation of double walled pipes and vessels to avoid sodium leaks.

Safety of upcoming INS CNFC-SFR: specific findings

- **Specific findings on upcoming INS CNFC-SFR:**

  - probability for radioactivity release to public domain <10^{-7} per unit year;

  - disadvantages of sodium due to its water/air reactions are minimized with adequate design solutions; sodium leakage and fires do not make a critical input into overall safety of FR

- **R&D programs for the INS CNFC-SFR:**
  - core physics & technology design related to safety;
  - preventive surveillance and inspection aspects;
  - development of sensors and repair of welds in sodium;
  - development and validation of sodium fire models and PSA analysis, etc.

Overall INPRO evaluation gives every reason for a high safety judgement on the INS CNFC-SFR provided that identified R&D are carried out

In spite of high appraisal of the CNFC-SFR safety, the need for development of alternative concepts was clearly stated due to crucial role of CNFC-FR for the NP future.

Safety: long-term expectations & perspectives

Long-range R&D for safety of alternative options:

- lead-bismuth, lead, gas and steam cooled systems;
- SMR of modular type;
- ADS, MSR;
- advanced MOX, metal, nitride and other innovative fuels

Perspective INS CNFC-FR should to provide ability to avoid, in case of a severe accident, a need for relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility used for similar purpose

Excel safety the conceptual INS CNFC-FR designs should be demonstrated together with technical feasibility, reliability, and improved economics

Environment: impact (1/2)

Two Basic Principles are developed in the area:

- BP1 calls for acceptability of environmental impacts on humans & environment;
- BP2 requires the confirmation of the long term availability and optimized use of material resources needed to operate a nuclear system

- **To assess the CNFC-FR impact via releases of toxic elements and depletion of resources, 6 NESs were analyzed**
- **Emissions (t/TWhe) received in a life cycle analysis (LCA) using TEAM software for NFC of France for two NESs:**

Emissions	GHG eq. CO2	CO2	CH4	N2O	NOx	SOx	Particles
OTFC-PWR	4600	4400	6	0.1	15	24	41
CNFC-FR	1400	1400	2	0.02	4	7	2

The emissions are mainly from the fabrication process of the plants and components and not to the electricity production

LCA for coal and natural gas FC: ~10^6 & ~$4.6 \cdot 10^5$ t/TWhe CO2 eq., respectively

The study confirms that NP in the whole, and CNFC-FR especially, are very effective options for GHG emissions reduction

Environment: impact (2/2)

Public exposure (mSv/yr) of OTFC-PWR & CNFC-FR provided by LCA (dose values are based on experience with existing NFC of France):

	Minin/ Mill. [1]	Conver.	Enrich.	Fabric.	NPP	Reproc.	Storag.	HLW dispos. [2]
OTFC -PWR	<1	$2 \cdot 10^{-3}$- $7 \cdot 10^{-2}$	$\sim 3 \cdot 10^{-4}$	$\sim 6 \cdot 10^{-4}$ (UOX)	$\sim 10^{-3}$		$\sim 2 \cdot 10^{-2}$	$< 2.5 \cdot 10^{-1}$
CNFC-FR				$\sim 10^{-5}$ (MOX)	$\sim 10^{-3}$	10^{-2}	$\sim 2 \cdot 10^{-2}$	$< 2.5 \cdot 10^{-1}$

[1] Main contribution; [2] Safety limit

Both OTFC-PWR and CNFC-FR produce a public radiation dose far below the current regulatory limit of 1 mSv/yr for public exposure

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Environment: resource consumption

Table below presents results of LCA for the consumption (t/TWhe) of natural uranium, oil, gas and coal for OTFC-PWR and CNFC-FR

	Oil	Coal	Natural gas	Natural uranium
OTFC-PWR	600	1000	400	23.4
CNFC-FR	100	400	100	1.7

A CNFC-FR provides significant reduction of resource depletion (especially natural uranium) in comparison to a OTFC-PWR

In both cycles, oil, coal, and natural gas consumption relates mainly to the fabrication process of the plants and is hundreds times less than for fossil sources

The environmental effects for CNFC-FR are well within the performance envelope

Having a potential to ensure natural resource for hundreds years of operation, INS CNFC-FR is practically a renewable option

Waste: minimization of waste generation

Starting point:

- The CNFC-FR system has practically showed its potential to meet all today requirements related to waste management
- Conditioning of waste from Pu recycling is industrial reality today and a practical milestone in reaching ultimate goals of the closed cycle strategy

A neutronic calculation (COSI code) was performed to determine waste management parameters

Waste	Pu+Am +Cm[1]	SF assembl	SF assembl	Vitr. waste canisters	Waste to inter. stor.	Waste to final dispos.
Unit/TWhe	kg	number	m^3	number	m^3	m^3
OTFC-PWR	27.9	~1	5	-	-	-
CNFC-FR	0.15	-	-	1.49	0.26	0.59

•In CNFC-FR versus OTFC-PWR Pu/Am/Cm to final disposal is ~200 times less (Np is not considered due to low contribution on radiotoxicity and thermal loading)

•Achieving a 90% reduction of fuel waste requiring repository disposal and a cut off 5-10 times repositories number

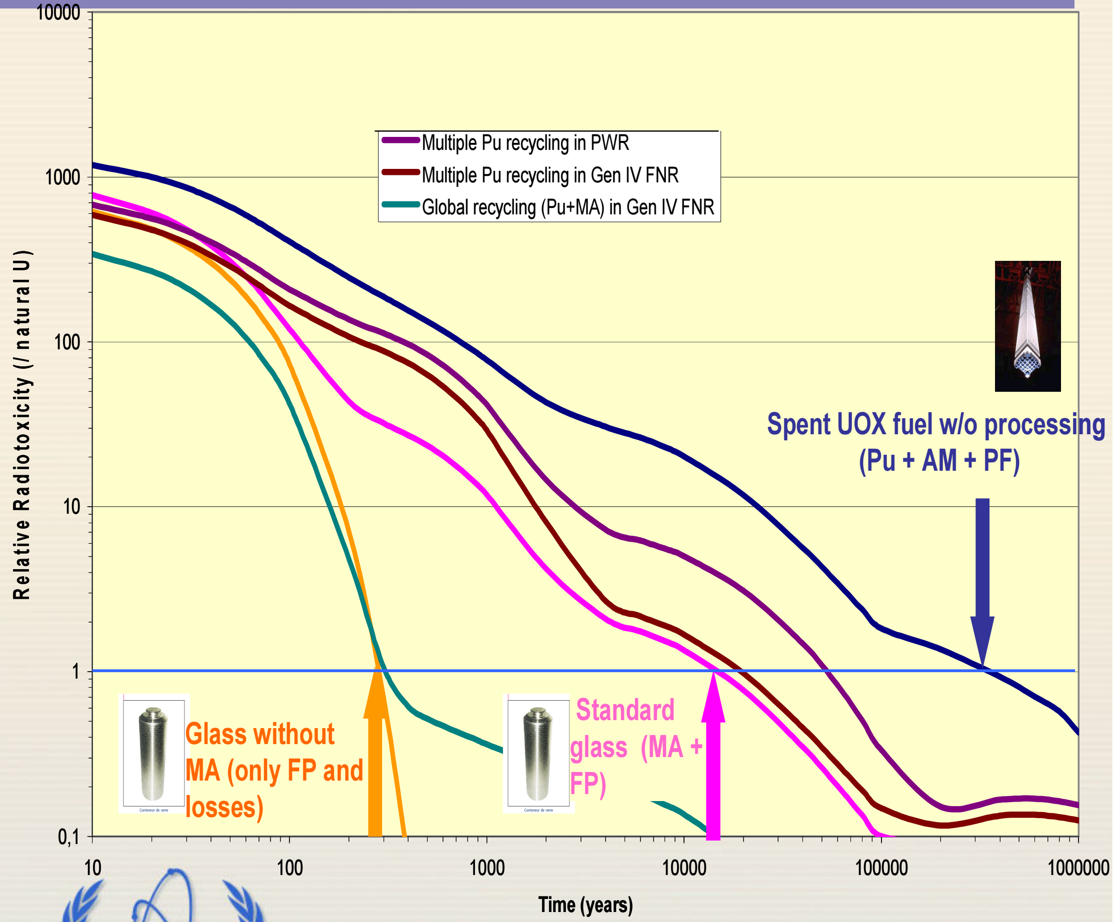
•Recycling & reuse of low radioactive materials from decommissioning should be included into further assessments

Waste: avoidance of burdens on future generations

In OTFC, SF needs several 100000 years to reach an equivalent level of radiotoxicity as natural U ore

Recycling of all actinides helps to meet the criterion in several 100 years (Fig)

The assessors claim that the technology of waste immobilization will be available on an industrial scale on time to achieve a safe end state of nuclear waste of a CNFC-FR



CNFC-FR has a very high potential in waste management area and it is one of the main drivers for the INS introduction in near future

Proliferation Resistance

- **PR intrinsic features:**
  - flexibility in fissile materials management (avoid Pu “mines”);
  - exclusion of Pu separation in reprocessing;
  - possibility to seal a reactor core for fuel campaigns of 10-20 years;
  - limiting fuel transport by co-location of FC facilities & reactors

In spite of wide spectrum of intrinsic features, there is no technical solution of the non-proliferation problem

- **Extrinsic measures & intrinsic features both are essential for PR, while the latter may play a complementary role**

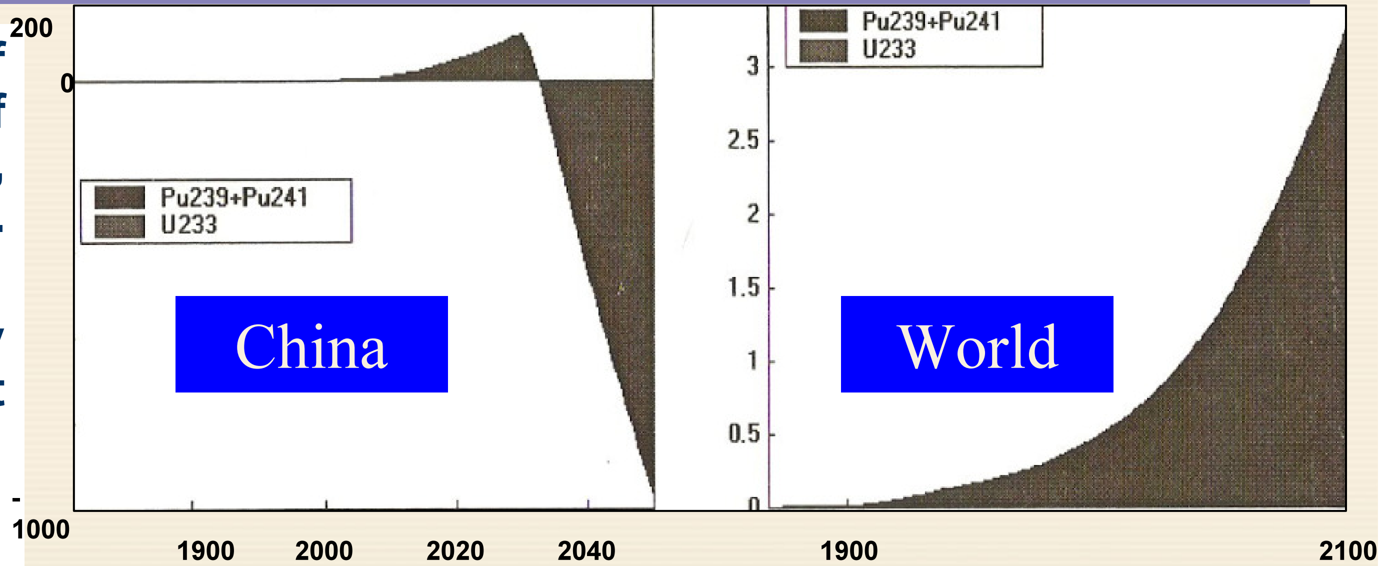
PR of the CNFC-FR due to realization of the intrinsic features could be comparable or higher than PR of OTFC

The INS provides key technologies for balanced use of fissile materials and has a high potential for applying extrinsic institutional arrangements ensuring elimination of their worldwide accumulation

Infrastructure

- **Legal framework of nuc. law in MS of JS is established, role of int. organiz. is important**
- **Long-term policy and commitment by government:**

  - exist but political changes remain possible



Pu balance at national and global level

- **Information to public: risk communication approach**
- **Professional perspectives:**

- not sufficient inflow of young scientists & engineers who could provide a long-term perspective

CNFC-FR - a key element for multinational approach to the NFC since it provides possibility to take back SF as a valuable fuel resource

CNFC-FR: high potential to enhance sustainability of national/global NP by utilizing synergy between TR & FR as well as between countries (Fig) with different approaches to NFC

Economics: to meet Acceptance Limit

- **Factors providing potential of the CNFC-FR competitiveness:**
  - competitive energy cost not sensitive to U market price;
  - U price will partly justify introduction of CNFC-FR, even $/KWe is higher of TR;
  - probable increase of the cost for TR spent fuel disposal.
- **Technical feasibility is demonstrated with electricity cost rather near to the area of competitiveness**
- **The investments required to design, construct, and commission of the CNFC-FR can be raised mainly by the MS with a large nuclear program**

Economics of CNFC-FR is an area that needs further RD&D for demonstration compatibility with INPRO requirements

- **Emphases on R&D reducing capital cost & investments**

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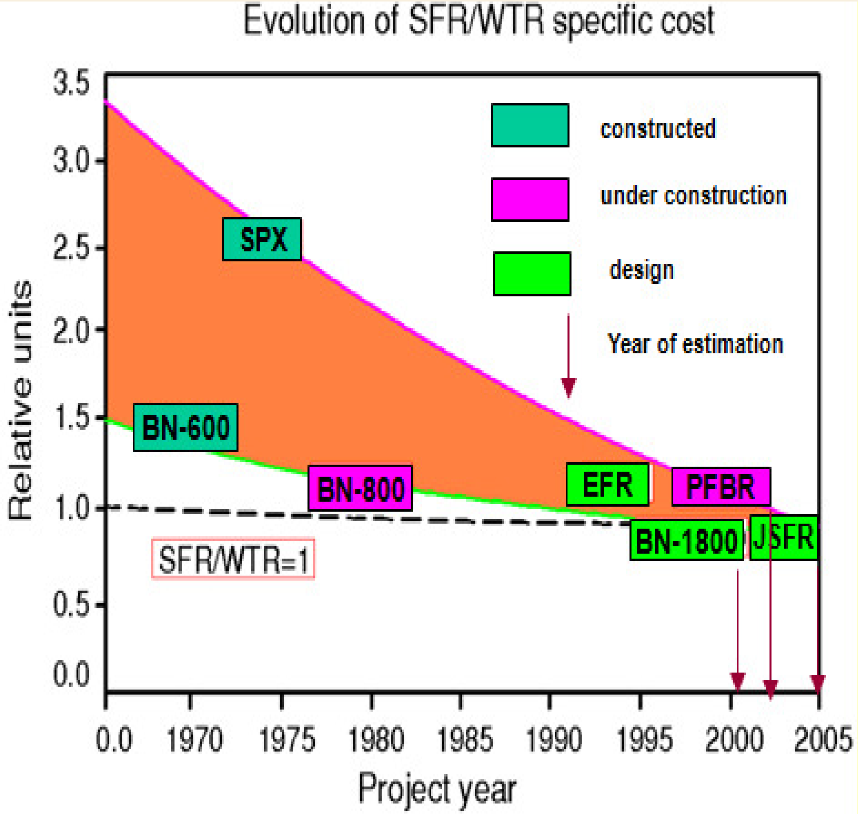
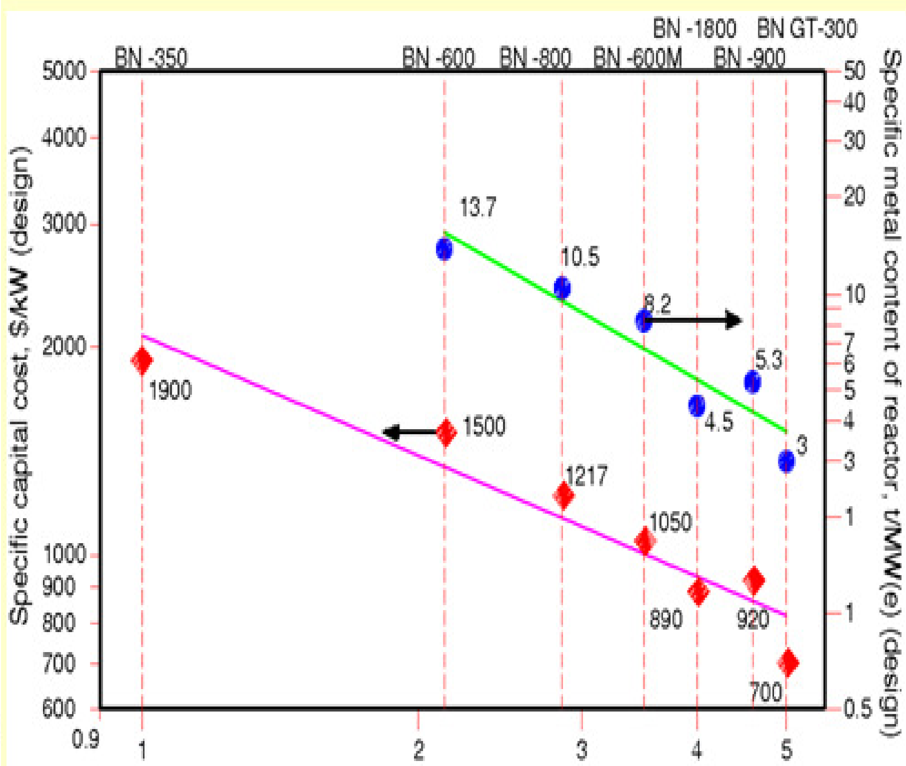
Economics: to meet Acceptance Limit





- **R&D for the near/medium CNFC-FR:**
  - material reduction: less N of loops, thickness of vessels; improving and cut of auxiliary systems, efficient radiation shield; reduction of building volumes;
  - a serial FR: BN (Russia), FBR (India), JSFR (Japan); reduction of a construction time;
  - improving thermodynamics & thermo-efficiency; increasing of burn up; life time extension
- **R&D for radically innovated system:**
  - two-circuit concepts, gas turbine, high temperature designs

Economics: diversity in national conditions & commonality in tasks

JS Participant	CR1.1 Cost of Energy		
	Indicator Value		Acceptance Limit Value AL1.1.1
	IN1.1.1 Cost of nuclear energy, C_N mills/kWh	IN1.1.2 Cost of energy from alternative source, C_A mills/kWh	
France	35.4	44.0	44.0
India	41.0	63.0 – 73.0	45.0
Japan	15.1	26.6	26.6
Korea	31.2	26.0 – 34.0	34.0
Russia	17.7	24.5	24.5

CNFC-SFR: will be affordable in 15-25 years in countries mastering the technology

Beyond 15-25 years: expectation for further economic improvement through identified RD&D and expected industrial deployment

Overall judgment on INS CNFC-FR

- INPRO joint evaluation of the CNFC-FR demonstrates high potential of the system to enhancing sustainable features to NP
- Introduction of the SFR on the basis of synergy with TR will help to solve practical problems of MS, like SF & Pu accumulation or lack of fissile material resource
- In a global perspective, the INS could become a key element for multilateral approach to NFC providing possibility to take back SF as a valuable fuel resource
- R&D are identified as a main condition for commercial introduction of the INS

Collaborative Project Proposals Initiated/Discussed at the JS Meetings

N	INPRO Collaborative Project
1	A Global Architecture of INS based on Thermal and Fast Reactors with the inclusion of Closed Nuclear Fuel Cycle (GAINS)
2	Assessment of advanced and innovative nuclear fuel cycles within large scale NES based on CNFC concept to satisfy principles of sustainability in the 21st century (FINITE);
3	Integrated Approach for the design of Safety Grade Decay Heat Removal System for Liquid Metal Reactor (LMR)
4	Investigation of technological challenges related to the removal of heat by liquid metal and molten salt coolants from reactor cores operating at high temperatures (COOL)

Feedback to the INPRO methodology

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Feedback to INPRO methodology (1/2)

INPRO methodology was found to be a useful guide for the team of qualified experts in assessing a large innovative system of NP

- **Some findings in the CNFC-FR evaluation that were made due to prescriptions of INPRO method to take into account:**
  - the whole life time of the INS (cradle to grave) and all its components;
  - level of maturity of the INS;
  - all subject areas of the INPRO sustainability concept;
  - possible synergy between nuclear systems, not only competitiveness.
- **Proposals for the methodology/manual improvement:**
  - to cut uncertainty of AL values and related ambiguity of judgment by arriving at a kind of International Standards or consensus;
  - to supplement ALs with a target value scale for defining a prospect for INS development for long periods

Feedback to INPRO methodology (2/2)

❖ **Perspective directions of the methodology and manual development:**

- increasing of discriminative power of the method;
- developing an agreed approach for consolidation results received in different topical areas;
- extension of analysis from nuclear to all energy sector for better understanding capability of INS to give a global answer to global energy challenges

Further improvement of INPRO methodology is a challenging task which will require time and resource

Yet, there are important tasks where the developed INPRO method, based on assessing long-term perspective with an aim to define practical steps to be done today, will be very helpful

OUTCOMES

- Innovative and unique multinational organizational structure providing framework for future studies was created
- The assessment helped to tune national strategies to a global framework and discover specific features of the CNFC-FR which, being realized, would ensure higher level of NP sustainability
- Multinational input to improving of the INPRO methodology was provided
- Several INPRO CPs on institutional and technological measures for the system improvement were initiated
- Interactions and understanding with relevant groups (OECD/NEA, Red-Impact project)

…Thank you for your attention

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