PROGRESS AND INTERIM RESULTS OF THE INPRO JOINT STUDY ON ASSESSMENT OF INS BASED ON CLOSED NUCLEAR FUEL CYCLE WITH FAST REACTORS

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The purpose of the work is to review interim results of the Joint Study on assessment of an Innovative Nuclear System based on a Closed Nuclear Fuel Cycle with Fast Reactors (INS CNFC-FR). This study is a part of the IAEA international project for innovative reactors and fuel cycle technologies (INPRO). Now it is being implemented by Canada, China, France, India, Japan, Republic of Korea, Russia, and Ukraine. A report on results of implementation of the first phase of the Joint Study was presented to the INPRO Steering Committee meeting in December 2006. It was also agreed by the Joint Study participants to reveal these results to broader discussion at scientific conferences and meetings. The authors' interpretation of the Joint Study findings and issues is presented in the paper.

I. INITIATION AND SCOPE OF THE JOINT STUDY

Joint Study on Assessment of an Innovative Nuclear Energy System (INS) based on a Closed Nuclear Fuel Cycle with Fast Reactors (CNFC-FR) is a part of the IAEA International Project for innovative reactors and fuel cycle technologies (INPRO). INPRO was launched up in the year 2000, based on resolution of the IAEA General Conference. One of the main goals of INPRO is to help to ensure that nuclear energy is available in the 21st century in a sustainable manner. A set of Basic Principles, User Requirements, and Criteria was developed in the Project in subject areas of economics, safety, environment, waste management, proliferation resistance, physical protection and infrastructure with an aim to enhance contribution of INS to sustainable energy supply. This set of requirements along with a guide on how to apply them to assess a given INS constitutes a background for INPRO methodology.[1,2] Several INPRO members are currently applying the methodology to assess selected INS.

In October 2004 Russian Federation suggested to assess jointly INS based on a CNFC-FR. This initiative was supported by some IAEA Member States. In December 2004 China, France, India, Republic of Korea, Russian Federation, and Japan, as an observer, formed the Joint Study on Assessment of the INS CNFC-FR. To a certain extent, the countries of the Joint Study represent leaders in the FR technology development and they invited other states to join the Study to have holistic global perspective. In 2005 Ukraine joined the Study; in 2006 Japan and Canada became its participants. The assessment is being carried out in accordance with overall objectives of INPRO and guiding documents of the Joint Study developed and approved by the participating parties. The study is scheduled to be completed in 2007.

The main objectives of the Joint Study are to:

- Assess of the INS CNFC-FR for satisfying criteria of a sustainable energy supply;
- Determine the structure and milestones for the INS deployment at national, regional, and global levels, and establish frameworks;
- Identify areas of mutual interest for collaborative efforts, including joint R&D.

Some results of implementation of a first phase of the study fulfilled by China, France, India, Japan, Republic of Korea, and Russian Federation are presented in the paper. The scope of the first phase included (Fig. I): compilation and analysis of country/region/world context data

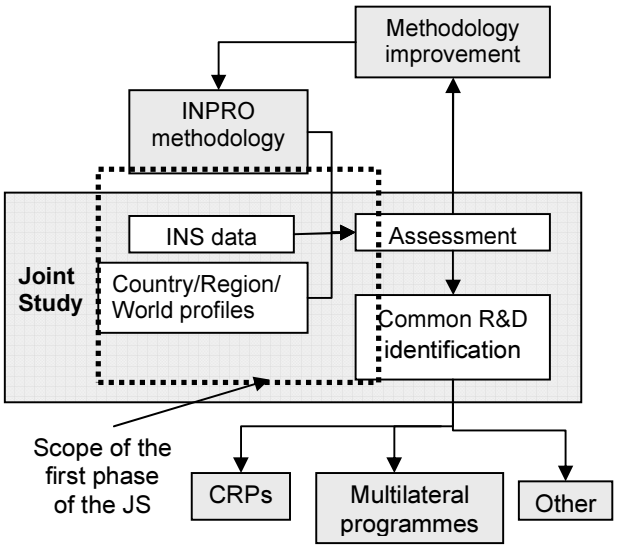


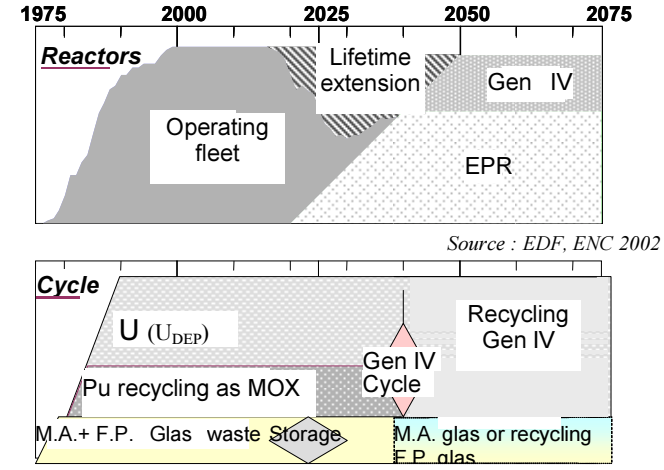
Fig.1. Scope of the first phase of the Joint Study.

profiles (national strategies for FR development, selection of scenarios for nuclear power deployment, etc.); testing of computer tools to be used for dynamic simulation of the system deployment; identification of technologies suitable for the INS and capable to increase its competitiveness; determination of incentives and promising fields of multinational collaboration.

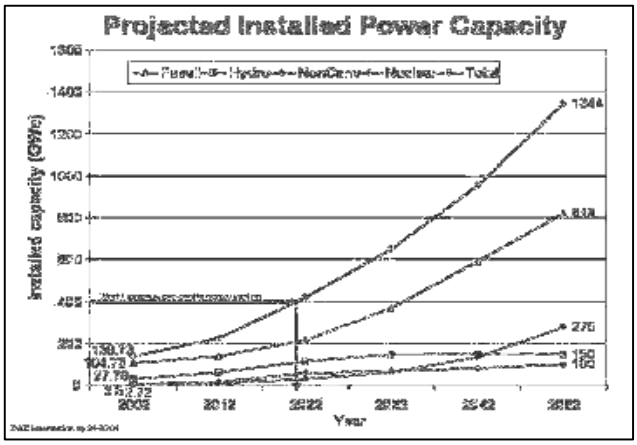
II. COMMON AND SPECIFIC FEATURES IN DEVELOPMENT OF INS CNFC-FR

Overview of national energy strategies has indicated that CNFC-FR is being considered in countries with more than a half of the world's population and large use of energy as a key component of future sustainable nuclear system capable to provide a global response to global energy challenges in 21st century. Generic vision of the role of the INS has a lot in common. As a component of nuclear power, it has to make its own contribution in mitigation of the problems connected with depletion of fossil fuel resources and corresponding growth of prices, greenhouse emissions and health impact, unevenness of primary energy resources allocation, risk of instability in their supply, etc. At the same time, CNFC-FR is being destined to enhance sustainability of nuclear power itself by means of more efficient use of natural uranium, cutting down the amount of storing fissile materials fitting for manufacturing nuclear weapons and explosive devices, reduction of uranium enrichment tails, storages for spent nuclear fuel, geological repositories, etc. Participants of the Joint Study believe that it will help to understand deeper the role of the INS CNFC-FR in the future energy mix and help to provide a new phase of its development based on internationally agreed requirements.

Natural, social and economic conditions in countries participating in the Joint Study differ to a great extent. There is not also much similarity in history, modern status, and projected growth of nuclear power. Fig.2 illustrates differences in expected nuclear growth for France (stabilization since year 2000) and India (steady growth up to 275 GWe by the middle of the century).



a.



b.

Fig.2. Projected growth of installed nuclear capacities in France (a) and India (b)

Remarkable physics of fast reactors and variety of options for closure of the nuclear fuel cycle make it possible to adapt the INS CNFC-FR to specific national conditions and realize diverse aspiration of member states. A drastic reduction of reactor waste requiring repository disposal by reducing the amount of uranium, plutonium, and minor actinides in the waste to be disposed as well as

more efficient utilization of uranium and plutonium are the main incentives for developing of the INS in the countries with a considerable nuclear share in electricity sector and a low or moderate expected growth of nuclear capacities (France, Japan, Republic of Korea). In contrast, fuel assurance through achieving high breeding of fast reactors is a driving force for developing of the INS in countries projecting fast growth of nuclear power from low level of installed nuclear capacities (China, India). For Russian Federation where high growth of nuclear power is being planned to be continued from a rather significant level, both waste reduction and fuel assurance are important reasons for deployment of CNFC-FR.

It was found that despite of some diversity in tuning CNFC-FR to national conditions there is a wide consensus regarding tasks of a transition stage to a mature system of the kind:

- Improvement economic characteristics of demonstrated components of CNFC-FR, including: fast reactor, reprocessing of SNF of thermal reactors, fabrication of fuel for FR;
- Development an optimal strategy for transition to the INS based on thermal and fast commercial reactors with elements of industrial closure of NFC;
- Visualisation of a robust INS based on CNFC as a global energy system, determination of the break-trough requirements to its components in the areas of safety, economics, environment, waste management, proliferation resistance, and infrastructure;
- Identifying R&DD for innovative CNFC-FR with break-through characteristics including new conceptual designs of fast reactors, prospective fuels, advanced technologies of fuel reprocessing, facilities for the final isolation of radioactive waste.

III. APPROACHES TO SELECTION OF DESIGNS AND TECHNOLOGICAL OPTIONS

A summary of approaches of the Joint Study's countries to selection of designs and technologies for development of the fast reactor technology and associated CNFC is presented in Table I.

TABLE I. National approaches to development of the INS based on CNFC-FR

Common & specific features	Stages of development			Coolant	Fuel	Fabrication/ reprocessing	Objectives
	Experimental	Demo prototype	Commercial size				
Common for JS	Loop & pool type	Pool type	Pool type	Na	MOX	Pellet/ advanced aqueous	Enhanced safety, proliferation resistance, efficient use of U, competitiveness, SNF & MA reduction
China specific	CEFR construction	2020-2025	2030-2035	-	UOX Metal	Injection casting/	High breeding, FR-burners &ADS, in-site fuel cycle
France specific	Rapsodie 1967-1983	Phenix 1974 new FR 2020+	Super-Phenix 1986-1996, serial 2030+	Gas	Carbide	Plates (for Gas FR)	Break even cores, MA incineration, hydrogen production
India specific	FBTR 1985	PFBR construction	First serial 2020	-	Metal	Sol-gel microsphere pellets/pyro	High breeding, co-location of FC facilities, thorium fuel
Japan specific	Joyo1977 operation loop type	Monju 1994 JSFR 2025 loop type	First serial 2040-2050 loop type	-	-	-	Enhanced safety, proliferation resistance, SNF & MA reduction
Korea specific		2030 assumed for JS		-	Metal	/Pyro	Rather high breeding
USSR/ Russia specific	BR5/10 1958-2002 BOR60 1969	BN350 1973-1999 UOX, loop type	BN600 1980 UOX;BN800 construction, serial 2020-25	Pb-Bi, Pb	Nitride	Vibro-packing/ pyro	Heavy metal coolants, monolithic and modular designs

Demonstration of a serial commercial fast reactor of the first generation with a matching fuel cycle that would meet requirements of sustainability is first important milestone of national programmes. Pilot commercial NPPs with reactor units of installed capacity 500-1800 MWe based on the evolutionary improved three-circuit scheme with steam turbine are expected to be built in nearby 15-30 years. Pellet technologies for MOX fuel fabrication as well as advanced aqueous and pyroelectrochemical technologies for reprocessing are the most probable technologies to be used at the initial stages of the period.

A steady growth of installed capacity of NPPs based on thermal reactors is expected to continue during this period. Utilization of plutonium from spent fuel of these reactors (partial closure of thermal reactors' fuel cycle) is a key task for fast reactors of the first generation. Other options of plutonium and minor actinides management in a system of thermal and fast reactors may also be realized provided that their efficiency for enhancing sustainability is proved. Sodium cooled, pool type fast reactor is being considered by the participants of the Joint Study as the most mature fast reactor option that has a significant possibility to meet INPRO requirements of sustainability, including economic ones, in 15-30 years. At present, reactors of this type are being constructed in Russian Federation - BN-800 and India - PFBR-500 (Fig.3) with an aim to demonstrate 'by doing' a new level of their cost competitiveness.

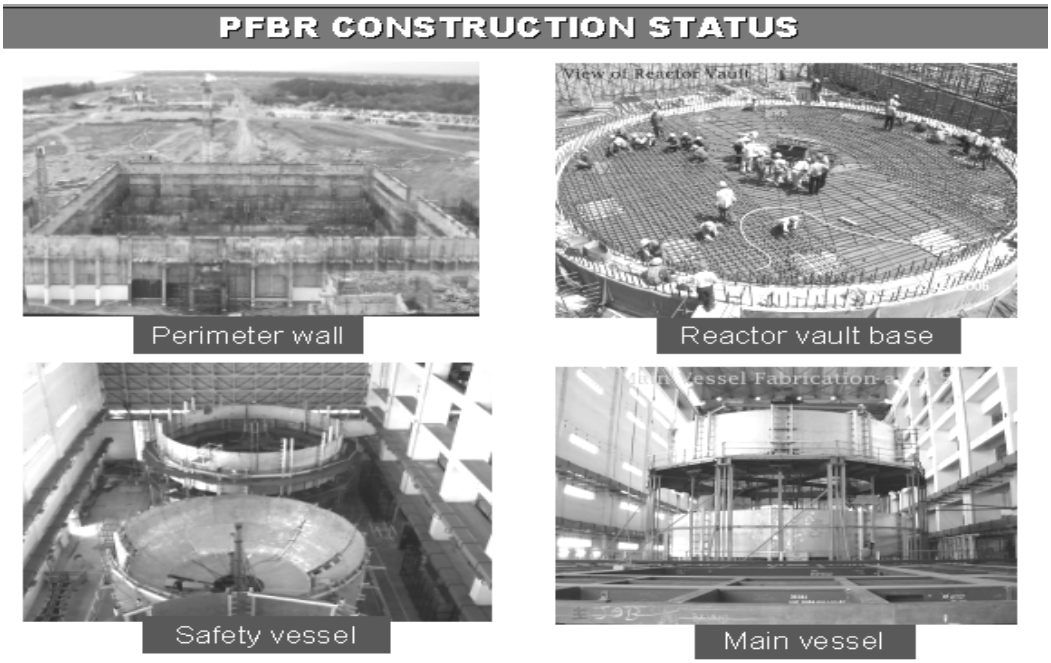


Fig.3. PFBR reactor under construction.

The Joint Study revealed that similarity in strategies of CNFC-FR development at the transition period to its full-scale use is complemented by the variations in specific national conditions. Indeed, stabilized nuclear capacities in countries with high maturity of the nuclear infrastructure restrict incentives for fast development of the CNFC. At the same time, orientation only towards own national resources and infrastructure in the countries with high demand in nuclear energy may lead to strained situation with respect to assuring the necessary rate of development.

The analysis fulfilled in the Report has demonstrated a remarkable effect of country/regional synergy (Table II): while no country of the Joint Study, taken separately, disposes of the full set of factors favouring development of CNFC-FR to the maximum degree (high demand in nuclear energy and electricity, high level of technology and infrastructure maturity, high reserves of plutonium accumulated in SNF), the regional system under consideration does.

TABLE II. Complementarity of national conditions that emphases the need for enhancing collaboration.

	China	France	India	Japan	Rep. of Korea	Russia	Overall potential
Energy demand growth	Very high	Low	Very high	Low	High	High	Very high
Nuclear deploy-ment	Small, fast growing	Very high, stabilized	Small, fast growing	Very high, stabilizing	High, growing	Very high, growing	Very high, fast growing
FR technology maturity	Experi-mental program	Commer-cialization	Demo	Demo	Design works	Commer-cialization	Commer-cialization
CNFC technology maturity	Develop-ment	Highly developed, MOX fuel mastered	Developed, carbide fuel demonstrated, MOX fuel development	Highly developed, MOX fuel development	Develop-ment	Highly developed, UOX fuel mastered, MOX fuel demonstrated	Highly developed, MOX fuel mastered
Pu in SNF	Small	High	Small	High	Moderate	High	High

Thus, the Joint Study confirms expediency of the multilateral approach to the nuclear fuel cycle with an expectation that it would be extended on services related to MOX fuel and other fuels based on plutonium.

Visualization of robust INS CNFC as a global energy system of 21st century is being considered by the countries of the Joint Study as a second milestone of the system development. Contrary to consistency of national approaches regarding INS CNFC of the first generation, current visions of architecture and technologies for robust INS vary to a considerable degree. Innovative concepts based on new coolants are being explored in Russia (heavy metals) and France (gas); a loop-type commercial fast reactor is being designed in Japan (a deviation from a generic pool-type arrangement); modular fast reactors of medium and small capacities are being developed in some countries of the Joint Study as a novel component of CNFC.

There is no common viewpoint on selection of innovative fuels as well. Nitride fuel of equilibrium composition is being considered in Russia as an appropriate choice for the lead coolant fast reactor with enhanced inherent safety characteristics. High-dense metallic fuel as an option for providing high breeding ratio is selected by China, India and Republic of Korea to assure the needs in nuclear fuel. France is examining carbide fuel.

IV. DEFINITION OF GLOBAL AND REGIONAL SCENARIOS

Identifying of an INS with a global perspective that will succeed the INS based on a serial fast reactor of the first generation was determined by the Joint Study as a challenging task that could be a focal point for new collaborative projects. Recognizing national efforts on the perfection of CNFC-FR as a driving force for the technology development, participants of the Joint Study nevertheless note an increasing role of multinational collaboration in visualization of the system. For better understanding the impact of global factors on the performance of the INS participants of the Joint Study compared the results of national long term studies on nuclear power development with a more generic analysis of global scenarios commissioned by Inter-Governmental Panel on Climate Change (IPCC) in a Special Report on Emission Scenarios (SRES).

It was found that the SRES A2, B2 scenarios are rather consistent with the projections of long-term growth of nuclear power in the Joint Study's countries. Some conclusions were derived from comparative analysis of national and global expectations. In particular, it was established that for the most countries of the Joint Study the problem of uranium supply is more strained than for the world in the whole. Up to the middle of the century proven uranium reserves at the price 80-130 $/kgU exceeds the SRES A2, B2 scenarios demand, providing an opportunity to mitigate national problems of uranium fuel assurance by means of entry into the world market.

However, proven reserves are not enough for implementation of the A2, B2 scenarios in the second part of the century in case of application of the one-through fuel cycle. Speculative resources of uranium give possibility to improve the long-term natural uranium production-consumption balance but not to cut the price uncertainty. And what is more, the SRES A2,B2 scenarios are not ultimate scenarios in projections of deployment of the world nuclear capacities. For aggressive nuclear energy penetration to the world market, e.g. for the family of SRES A1 scenarios based on assumption of radical extension of nuclear applications like heat and hydrogen production, water desalination, etc., assurance of global uranium supply at acceptable prices becomes even more questionable. Under the circumstances, it is inevitable that countries with low uranium resources attempt to exploit their resources more efficiently by deploying CNFC-FR.

The Joint Study considers the issue of assurance of uranium fuel supply in close link with the issue of assurance of plutonium-based fuels supply. An example from the national study of China fulfilled with the use of DESAE code[3] shows that some scenarios of China's nuclear power development are not provided with necessary amount of plutonium for fast reactors' fuel (Fig.4, a).

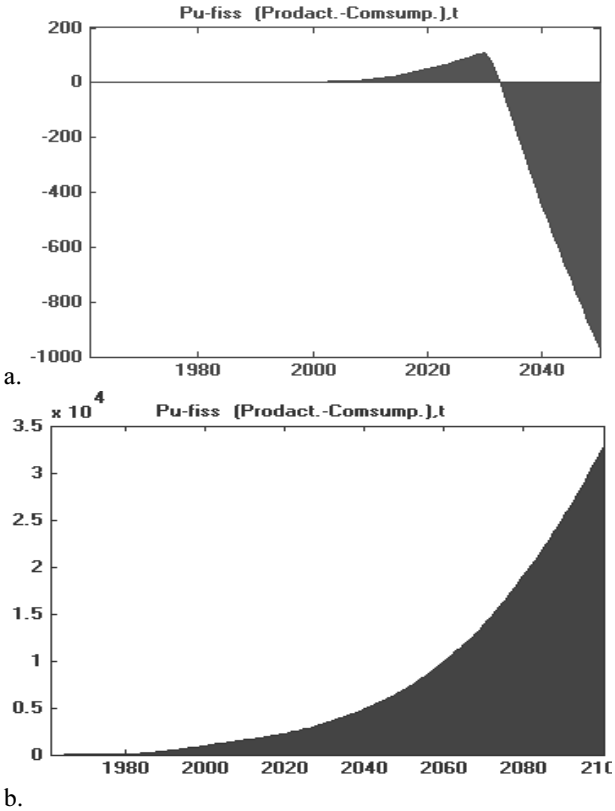


Fig.4. Plutonium balance for China (a) and for the world (b).

At the same time, worldwide, a large amount of plutonium is expected to be accumulated in the spent fuel in case of realization of the B2 scenario with a small share of fast reactors (Fig.4, b).

Thus, the consideration of plutonium balance at national and global levels indicates a principle possibility to use potential of multinational collaboration with an aim to mitigate both the problem of deficiency of nuclear fuel in some countries of the world and spent fuel accumulation in other countries. Also, it would facilitate unification of the world/regional fleets of nuclear reactors, their technical characteristics and performance, thus making a significant input for arriving at an innovative nuclear system tailored to local conditions and at the same time capable to provide energy generation and supply in accordance with internationally unified high standards.

V. TRANSITION TO THE PHASE OF THE INS ASSESSMENT

A lot of commonality in approaches to development of the INS 'CNFC-FR' in forthcoming programmes of countries-participants of the Joint Study creates favourable preconditions for a work on identifying a generic vision of such INS. A model of CNFC-FR based on a serial fast reactor of the first generation with matching fuel cycle to be used at the second phase of the study for assessment of the INS 'CNFC-FR' as a system of regional/global level was defined as the nearest target on the way. Some main technical and economic characteristics of the model were defined based either on operation experience, or on the data of evolutionary designs, or on expert expectations.

The first assessment of economics made jointly clearly shows the confidence that CNFC-FR can be realized on cost competitive basis. There are commonalities and diversities in approaches as indicated by member states. It is also clear that a large knowledge base exists. Particularly, accumulated knowledge reached both by "learning by doing" and "learning by searching" made it possible to decrease projected specific cost of sodium fast reactors (SFR) of rather high capacity (over 500 MWe) to the level of thermal reactors (Fig. 5).

Nevertheless, assessment of expenditures on the INS as a holistic system**,** with all components of infrastructure**,** has revealed that significant investments are required for this realization. It is clear that only rather large reactor fleet would make the system economically sound. Innovations in organization of a global nuclear fuel cycle under assurance of its proliferation resistance would be desirable to accelerate penetration of fast reactors to the world market.

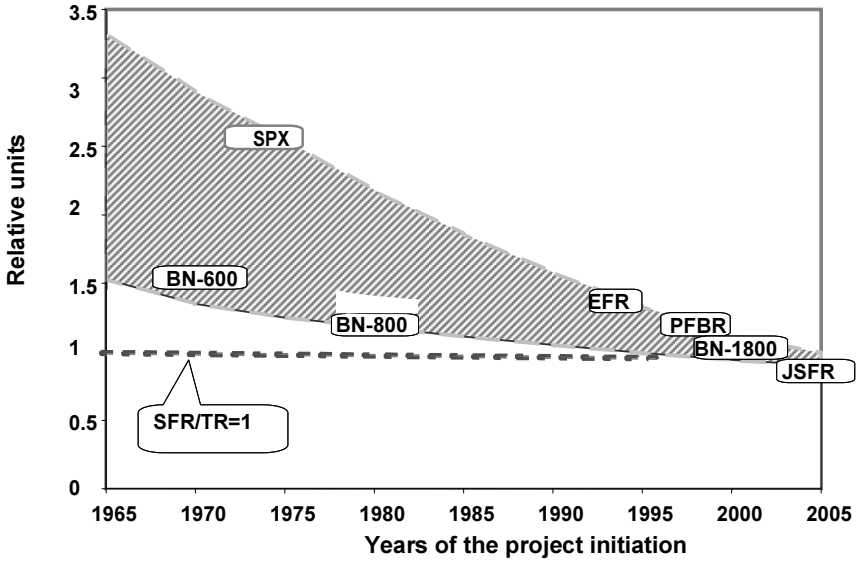


Fig.5. Evolution of a ratio of the sodium fast reactors (SFR) specific capital cost to the cost of thermal reactors (TR).

Implementation of the first phase of the Joint Study has provided a feedback on improvement of the INS assessment methodology. It was established that a generic model of an INS reflecting core features of the system would be very helpful for an assessment procedure at the regional and global levels. Generic vision of the commercial INS CNFC of the first generation has been defined based either on operation experience, or on the data of evolutionary designs, or on expert expectations. It is expected that development of the generic reference model will be completed at the second phase of the study along with identifying R&D to be carried out to reach the main indices of the model.

Regarding the economic methods of the INS assessment, it was found that traditional levelized utility electricity cost (LUEC) model can lead to underestimation of the nuclear power competitiveness in case when discount rate is directly associated with the interest rate (cost of money). This issue was suggested for broader discussion between interested parties. In general, fulfillment of the Joint Study has once again demonstrated necessity in decreasing uncertainty of an INS assessment by means of using common methodology, boundary conditions, methods of calculation and computer codes.

VI. CONCLUSIONS

An overview of national energy strategies has indicated that the INS CNFC-FR is considered in majority of the countries of the Joint Study with more than half of the world's population and a large share of the global energy use as a promising component of the future sustainable energy mix. Comparison of the nuclear strategies has shown that there are a lot in common in understanding of the milestones of the CNFC-FR system development. Demonstration of a serial commercial fast reactor of the first generation with a matching fuel cycle in coming 15-30 years is a common milestone of the national programmes.

Sodium cooled, pool type fast reactor with a steam turbine is being considered as the most mature option that has a significant potential to meet requirements of sustainability in the immediate horizon. Reactors of the type are being constructed in Russia and India with an aim to demonstrate 'by doing' their improved cost competitiveness. Pellet technologies for MOX fuel fabrication as well as advanced aqueous and pyro-electro-chemical technologies for reprocessing are the most probable ones to be used. Vibropack fuel and sol-gel pellet fuel technologies are being developed as improvements on existing pellet technologies. Metallic fuels are future direction to attain high breeding for enhancing growth rates.

Majority of states participating in the Joint Study envisage further development of the national nuclear infrastructure of the CNFC-FR. However, the analysis fulfilled has demonstrated a remarkable potential of international/interregional synergy for facilitating penetration INS based on closed nuclear fuel cycle with fast reactors to energy market.

Global community has the capacity to leapfrog to make fast reactor systems safe, proliferation resistant, and cost competitive under condition of their serial introduction and appropriate organization of the fuel cycle. The assessments that are being made jointly in the Joint Study recognize R&D directions, which can become basis for collaboration to develop competitive CNFC-FR.

Visualization of a robust INS CNFC for more remote perspective is another important milestone of national programmes. Contrary to consistency of national approaches regarding INS CNFC of the first generation, current visions of architecture and technologies for a robust INS as a global energy system of 21st century vary to a considerable degree.

A major gain of the Joint Study is that scientific and administrative structure has been realized under the IAEA auspice to assess a holistic INS system of significant potential to a large number of countries. The participants of the Study do believe that multinational efforts would facilitate to convert the option under consideration into an integral part of a future sustainable energy system capable of providing global response to global energy challenges in 21st century.

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