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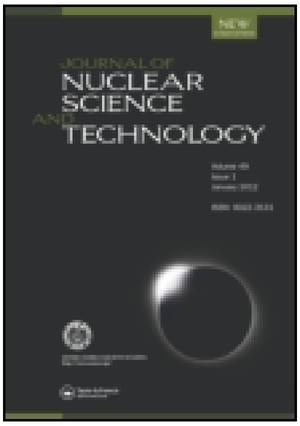

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ARTICLE

Multilateral Assessment of the Fast Reactor System as a Component of the Future Sustainable Nuclear Energy and Paths for the System Deployment

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The paper reviews main findings of the Joint Assessment Study on a Nuclear Energy System (NES) based on a Closed Nuclear Fuel Cycle with Fast Reactors (CNFC-FRs) that was performed within the IAEA project INPRO.

KEYWORDS: INPRO, fast reactors, closed nuclear fuel cycle, sustainability

I. Introduction

The Joint Assessment Study (2005–2007), part of Phase-1 of the International Project for innovative reactors and fuel cycles (INPRO), was initiated by the Russian Federation and performed by specialists from Canada, China, France, India, Japan, Republic of Korea, Russian Federation, and Ukraine.[1)] The objectives were to determine incentives and milestones for the deployment of a Closed Nuclear Fuel Cycle with Fast Reactors (CNFC-FR) system; assess the system's potential for satisfying sustainability criteria as they are defined in the INPRO methodology; establish frameworks for and areas of collaborative R&D work; and provide feedback to the improvement of the INPRO evaluation methodology.

The study was implemented by the participants as a joint initiative endorsed by the INPRO Steering Committee. Each participant was nominated by its responsible organization to perform the activities assigned in the Terms of Reference of the project. Participants contributed data and information available to the public domain. The data and information included elements of national nuclear energy policy and available parameters of current and innovative nuclear energy systems.

II. Common and Specific Features in the CNFC-FR Development

During the first stage of the study, experts from participating countries analyzed relevant data at the country/region/world level, discussed incentives and national/global scenarios for the introduction of a CNFC-FR, identified technologies suitable for such a system, and arrived at a broad definition of a reference CNFC-FR to be used for joint evaluation.[2)] Natural, social, and economic conditions in the countries developing the technology differ to a great extent. Nevertheless, good agreement was found on the inevitability of CNFC-FR and some aspects of the technology development.

The sodium-cooled fast reactor (SFR) was ascertained as the most mature fast reactor option for near-term introduction. Demonstration of a serial commercial SFR with a matching fuel cycle is the first milestone of national programmes. A commercial CNFC-FR based on proven technologies, such as those using the sodium coolant, mixed oxide (MOX) pellet fuel, and advanced aqueous reprocessing technology, and deployable in a 15 to 30 years timeframe was defined as a reference system for the joint assessment. Variants were identified in terms of priorities on the introduction of SFRs, reactor concepts (pool/loop), plant size, fuel cycle options, assessment of costs, and overall perspectives on collaborative research, which are of course inevitable and indeed desirable at the development stage of the technology.

Contrary to rather consistent approaches regarding the near-/medium-term future, long-term vision of the CNFC-FR system varies to a considerable degree. Innovative concepts based on novel heavy metals and gas coolants are being explored in Russia and France, respectively; a large loop-type commercial fast reactor (FR) is being designed in

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Japan (a deviation from a generic pool-type arrangement); modular medium and small FRs are being developed in Russia. There is no common viewpoint on the selection of innovative fuels either. Nitride fuel, promising advance inherent safety features, is being considered in Russia as an appropriate choice for the lead-cooled FR. Highly dense metallic fuel as an option for providing a high breeding ratio is selected by China, India, and Republic of Korea to ensure nuclear fuel supply for the respective ambitious fast reactor deployment programmes. France is examining carbide fuel for the gas-cooled FR.

The remarkable physics of FRs provides the flexibilty needed to adapt the CNFC-FR to specific national conditions and aspirations. At the same time, the participants in the project found it desirable to intensify discussions between technology holders, aiming at advanced agreement on the design requirements for next-generation commercial FR. This could lead to the sharing of the unique, high-cost, and complex facilities needed to advance the R&D of innovative fast spectrum reactors.

III. Results of the Assessment Using the INPRO Methodology

In the second stage of the study, the characteristics of the reference CNFC-FR system, and those of national systems (in case some of their parameters deviated from the reference one), were identified and assessed for compliance vis-à-vis the criteria of sustainability of the INPRO methodology.[3)]

The INPRO sustainability criteria determine whether and how well a given requirement is being met by a system under assessment. INPRO criteria consist of indicators and acceptance limits. The acceptance limits are targets against which the values of indicators can be compared to make a judgment on how well the assessed system complies with the requirements. In some assessment areas (*e.g.*, economics and environment), most of the acceptance limits are general for the energy sector. In the areas specific for nuclear power (*e.g.*, nuclear waste and proliferation resistance), the acceptance limits for an innovative nuclear system have to be comparable with or better than operating systems based on the once-through fuel cycle with thermal reactors (OTFC-TR). The comparison of two nuclear options does not mean giving preference to one of them but identifies targets for enhancing sustainability features of the combined system.

The summary of the results on the assessment of the CNFC-FR is presented below.

1. Safety

INPRO has developed basic principles in the area of nuclear safety based on the IAEA Fundamental Safety Principles (SF1), utility requirements such as EPRI Advanced Light Water Reactor Utility Requirements,[4)] and on an extrapolation of current trends assuming a large increase of nuclear power in the 21st century.

Disadvantages of fast reactor systems related to specific safety features were addressed. For instance, any change of the core arrangement of a FR could lead to an increase of reactivity expressed, for example, by a positive coolant void coefficient. In case sodium in the SFR gets in contact with water or air, the chemical energy of the sodium-water or sodium-air reaction results in sodium fires. The higher burn-up of fast reactor fuel results in a higher specific radioactivity of spent fuel of fast reactors, compared to spent fuel of thermal reactors (TRs).

However, the disadvantages of FRs with regard to safety, as compared to TRs, are compensated by several *inherent features* and by additional *engineered safety measures*. Examples of inherent safety features are negative reactivity feedback in cases of power and temperature increase, stability of neutron distribution, no poisoning effects, the excellent heat transfer characteristics, and high boiling point of sodium that permits the design of the reactor coolant system with a very low pressure, resulting in a low stored energy of the coolant fluid. An example of engineered safety features is the installation of double-walled pipes and vessels to avoid sodium leaks. A comparison of a FR with a TR system showed that disadvantages of the fast neutron system can be compensated by its inherent safety features and additional engineered safety measures.

The study concluded that the CNFC-FR system has the potential to meet the enhanced requirements in the area of safety as formulated in the INPRO methodology. For instance, a probabilistic analysis performed in Russia for the BN-1200 design[5)] has shown that innovative design features lead to a significantly reduced risk of severe core damage (up to 10^{-6} maximum for reactor per year) and to elimination of evacuation and resettlement of population resident near nuclear power plants (NPPs).

In spite of the high appreciation of SFRs and the corresponding fuel cycle, the importance of the development of alternative concepts based on fast neutron spectrum systems, as well as of fuel cycles based on advanced MOX, nitride, and other innovative fuels, was clearly stated in the Joint Study. The excellent safety characteristics of these systems should be demonstrated, along with the technical feasibility, reliability, and improved economics. This would lead to a credible SFR competitor, and thus increase the options for the transition to CNFC.

2. Environment

Various energy systems were analysed with the objective of assessing the CNFC-FR system with regard to its impact on the environment. The environmental characteristics of two nuclear energy systems considered within French scenario studies are briefly discussed below. One of them is a PWR with UOX fuel utilizing a once-through fuel cycle (OTFC-PWR) in which the used nuclear fuel is sent to the repository. The other one is based on the fast reactor, recycling all MA together with plutonium, so that only fissile products are vitrified and disposed of (fully closed cycle—CNFC-FR).

In the INPRO methodology environment area, two aspects are covered, namely, inputs to a nuclear energy system which may lead to *depletion of natural resources* such as uranium and zirconium, and outputs from a nuclear energy system, which represent *environmental stressors*. A break-

Table 1 Life cycle analysis of resource depletion

	Oil (t/TWh_e)	Coal (t/TWh_e)	Natural gas (t/TWh_e)	Natural uranium (t/TWh_e)
OTFC-PWR	600	1000	400	23.4
CNFC-FR	100	400	100	1.7

Table 2 Results of life cycle analysis of nonradioactive releases, t/TWh_e

Emissions	GHG	CH_4	N_2O	NO_x	SO_x	Particles
OTFC-PWR	4,600	6	0.1	15	24	41
CNFC-FR	1,400	2	0.02	4	7	2

Table 3 Evaluation of environmental impact of radioactive releases, mSv/yr

	Mining/ Milling	Conversion	Enrichment	Fabrication	Reprocessing
OTFC-PWR	<1	$2 \cdot 10^{-3}$–$7 \cdot 10^{-2}$	$\sim 3 \cdot 10^{-4}$	$\sim 6 \cdot 10^{-4}$ (UOX)	
CNFC-FR				$\sim 10^{-5}$ (MOX)	$\sim 10^{-2}$

through potential of the CNFC-FR for most INPRO environmental indicators was identified. Recycling of plutonium and uranium leads to practically inexhaustible resources of fissile material (and fertile material), *i.e.*, such a system might *de facto* be considered as a renewable energy source. This feature of the CNFC-FR was found especially important for countries with a high nuclear energy demand (*e.g.*, China and India). Very high breeding, and thus fuel supply assurance, is a driving force for the developing of FRs for the countries in this group. However, globally, there is a sufficient amount of used fuel available for reprocessing plutonium to be used as fuel. Some countries even plan to burn it.

The study concluded that apporoaches to assurance of nuclear fuel supply based on national programmes implemented in isolation are inefficient and there is a need for multinational arrangements. Besides the comprehensive consideration of resources of fissile materials (and fertile materials), which of course is a very important issue for nuclear power deployment, the consumption of other natural resources were also assessed in the study. **Table 1** presents results of a life cycle analysis (LCA) of the consumption (per TWh_e produced) of natural uranium, oil, gas, and coal for OTFC-PWR and CNFC-FR. Oil, coal, and natural gas consumption presented in Table 1 is related mainly to the fabrication process of the plants and components. As follows from this table, the CNFC-FR provides a significant reduction of resource depletion in comparison to the OTFC-PWR. At the same time, both OTFC-PWR and CNFC-FR demonstrate a remarkably low consumption of oil, coal, and natural gas that are hundreds of times less than the consumption of the resources in the life cycle of coal or natural gas energy sources.

CNFC-FR systems avoiding mining/enrichment steps in their fuel cycle show a significantly reduced *environmental impact* caused by a much lower release of nonradioactive elements compared to current licensed thermal reactor systems. **Table 2** shows results determining the emissions of green house gases (GHGs) expressed in equivalent of CO_2 and other nonradioactive elements for all facilities of the nuclear fuel cycle, *i.e.*, mining/milling, conversion, enrichment, UOX and MOX production, power plants, reprocessing, low-level waste storage, interim storage, and high-level waste disposal. These figures, related mainly to the fabrication process of the plants and components and not to the electricity production, are very small compared to the equivalent fossil energy sources. For instance, LCA for coal and natural gas energy sources shows that GHG emissions are ~1 million t/TWh_e and ~460 thousand t/TWh_e of CO_2 equivalent, respectively.

Evaluations of public exposure (mSv per year) for all facilities of the nuclear fuel cycle were compiled taking into account recent evaluations and experience accumulated in the participating countries, especially in France. The values of impact from radioactive releases at the stages of NPP operation, used fuel storage, and high-level waste (HLW) disposal are quite similar for OTFC-PWR and CNFC-FR systems. Differences between the systems are apparent, if one looks at the various stages of the fuel cycle, as presented in **Table 3**. This table demonstrates that the impact of radioactive releases of the OTFC-PWR is higher than that of the CNFC-FR mainly due to the stages of mining and milling. At the same time, both nuclear energy systems produce public radiation doses below the current regulatory limit of 1 mSv/yr for public exposure, and both are clearly fulfilling the basic principle on acceptability of expected adverse environmental effects.

3. Waste Management

Utilization of plutonium from spent fuel of thermal reactors is an important incentive for developing of the fast reactor technology. The first basic principle of the INPRO methodology in the area of waste management states that the generation of waste shall be kept by design to the minimum practicable. With regard to meeting this basic principle, a general comparison of an OTFC-PWR system with a CNFC-FR shows significant advantages of the latter.

The reduction of waste generation in a CNFC-FR can be explained by two main factors. First of all, a FR can be operated at higher temperatures than a LWR resulting in a

Table 4 Results of calculation of waste management parameters, unit/TWh_e

Waste	Pu+Am+Cm[a)] (kg)	SF assembly (number)	SF assembly (m^3)	Waste canister (number)	Interim storage (m^3)	Final disposal (m^3)
OTFC-PWR	27.9	~1	5	—	—	—
CNFC-FR	0.15	—	—	1.49	0.26	0.59

[a)]Np is not considered because of its low contribution to radiotoxicity and thermal loading of the source term.

higher thermal efficiency, thus generating less waste per installed power (MW_e). Secondly, the radiotoxicity of used fuel to be put in final storage in the once-through fuel cycle can be reduced significantly by recycling plutonium and by partitioning and transmutation (P&T) of minor actinides (and specific fission products) in a CNFC system.

To evaluate the influence of recycling plutonium and minor actinides on waste management, the same scenarios as in the assessment of the environmental impact were considered. A neutronic calculation using the COSI computer code[6)] was performed to determine the amount (per TWh_e) of plutonium and minor actinides sent to waste, number and volume of spent fuel assemblies, volume of vitrified and compacted high-level waste sent to interim storage and final geological disposal (**Table 4**). The evaluation of the parameters presented in Table 4 demonstrates that in a CNFC-FR, compared to an OTFC-PWR, the amount of plutonium, americium, and curium to be put in final disposal is reduced by a factor of about 200. However, reprocessing of used nuclear fuel produces several additional secondary waste forms that also need geological disposal.

The ratio between the radiotoxicity of nuclear waste to be disposed of, and the radiotoxicity of natural uranium ore as a function of time is given and discussed in the Joint Study.[1)] This ratio illustrates the gains in radiotoxicity reduction when plutonium and minor actinides are removed from the used fuel before final disposal, as compared to the direct disposal of the used fuel. In the OTFC-PWR operated with enriched uranium, spent nuclear fuel (*i.e.*, the nuclear waste) put into a repository needs several 100,000 years to reach the radiotoxicity level of natural uranium ore. Recycling of all actinides (plutonium and minor actinides) in a CNFC-FR system reduces the radiotoxicity of the nuclear waste dramatically, as compared to an open fuel cycle of a LWR, reaching a level of radiotoxicity in the HLW equivalent to uranium ore after several 100 years.

The study in the area of waste management also concluded that safe conditioning of waste arising from plutonium recycling, which is an important practical milestone in reaching the ultimate goal of the closed cycle strategy, is industrial reality today. The CNFC-FR has demonstrated its potential to meet all current requirements related to used fuel management. With the development and introduction of novel technologies for optimum management of fissile products and minor actinides, innovative nuclear systems based on CNFC-FR have a breakthrough potential to significantly reduce the heat load, mass/volume, and radiotoxicity of high-level waste to be deposited and thus to meet the sustainability requirements related to waste management.

4. Proliferation Resistance

The proliferation resistance of a nuclear energy system consists of a combination of *intrinsic features*, *i.e.*, technical design characteristics, and *extrinsic measures*, *i.e.*, commitments of states such as safeguard agreements.

The CNFC-FR intrinsic features provide high proliferation resistance potential. First of all, a CNFC-FR system will not need enrichment as the fissile material for fresh fuel, *i.e.*, plutonium is produced via reprocessing. Furthermore, to avoid the significant proliferation risk of currently operating reprocessing facilities that produce separated plutonium, the envisaged advanced reprocessing technologies to be used in a CNFC-FR system will always keep uranium and plutonium in a compound. Two types of such reprocessing technologies are being developed: the advanced aqueous and the pyrochemical reprocessing. Pyroprocessing facilities are compact and could, together with a fuel fabrication facility, be collocated with reactors thereby eliminating the need to transport fuel resulting in an increase of proliferation resistance. Advanced aqueous reprocessing facilities are more suited for centrally operated large-scale plants. If such a plant would be an international institution (*e.g.*, a multinational fuel cycle centre) it would meet proliferation concerns and, at the same time, guarantee nuclear fuel supply to states having no access to the reprocessing technology.

Additionally, certain minor actinides and fission products in spent fuel could be recycled and added to fresh fuel leading to high radiation levels. A high radiation level of fresh fuel is regarded as an intrinsic feature for increased proliferation resistance. Reprocessing also reduces the proliferation risk of large quantities of stored and disposed spent nuclear fuel containing plutonium ("plutonium mines") that are currently accumulated in thermal reactor systems with open fuel cycles.

The participants of the study have concluded that the proliferation resistance of the CNFC-FR due to the realization of the intrinsic features could be comparable or higher than that of the OTFC with thermal reactors. At the same time, it was noted that thermal and fast reactors will go side by side during this century. Therefore, intrinsic recycling technology features will enhance the effectiveness and cost-efficiency of the proliferation resistance of the nuclear energy system composed of different types of reactors.

5. Infrastructure

The *industrial infrastructure and human resources* to design, manufacture, construct, and operate a CNFC-FR are available in most countries that participated in the Joint Study. However, *regional and global approaches might*

Table 5 Assessment of electricity cost of CNFC-FR and alternative energy sources

Country	CNFC-FR (mills $/kWh)	Alternative source (mills $/kWh)
France	35.41	44.07
India	41.00	45.00
Japan	15.10	26.59
Korea	31.15	34.00
Russia	17.74	24.50

require a new international legal infrastructure. The CNFC-FR is well suited for, and might require such new regional or international arrangements to provide the opportunity for expanding both fuel cycle front end and back end services to the benefit of both technology holder and technology user countries.

6. Economics

The designs of currently operating FRs are *not completely economically competitive as compared to the thermal reactors or fossil power systems*. Nevertheless, **Table 5** shows that the various national advanced CNFC-FR sysems are expected to become competitive, in spite of the different economic conditions (*e.g.*, different overnight capital costs and discount rates), in the countries in which the assessments were made. To achieve competitiveness in the area of economics primarily the capital costs of fast reactor systems are to be reduced. The necessary R&D aimed for design modifications are integrated into the development programmes of the five countries that participated in the Joint Study.

IV. Research and Development

Possible measures for improving fast reactor economics are, for example, design simplification, reduction of steel consumption by reducing the number of loops and thickness of main components, elimination or reduction of size of reactor systems, using more efficient and low-cost radiation shielding and more compact plant layout, and serial construction with reduction of time of construction. An example of successful research and development (R&D) efforts is the reduction of specific capital costs of the Russian fast reactor BN-800 (under construction) to about a factor of 1.6 as compared to the prototype BN-350. As shown in the Indian case, reduction of fast reactor capital cost along with the increase of fuel burn-up, thermal efficiency, and load factor, extending the life of components, as well as improving manufacturing and maintenance technologies, could reduce the electricity cost produced by advanced fast breeder reactor serial units as compared to the cost of the Indian prototype of fast reactor prototype (PFBR) by approximately a factor of two.

A significant impact of enhanced R&D on capital cost reduction was identified in all countries having sodium-cooled fast reactor development programmes. Studies have indicated that the ratio of capital cost per unit of sodium-cooled fast reactors versus thermal reactors approaches one for the new sodium-cooled fast reactor designs (BN-1800/Russia; JSFR/Japan), and even for the PFBR under construction in India.

Enhancing safety is another area for intensive R&D programmes. Reduction in occupational and public radiation exposure is a universal safety goal. Along with long-term R&D programmes directed to the development of new concepts of fast reactors with enhanced inherent safety features, as well as that of advanced fuel cycles, some specific R&D programmes on core physics and technology design related to safety of the sodium-cooled fast reactors are being implemented including programmes on preventive surveillance and inspection aspects; development of sensors and repair of welds in sodium; development and validation of sodium fire models and probabilistic safety analysis, *etc.* To increase the safety level of fast reactors by reducing hazards of radiation exposure to workers, advanced shielding materials such as boride/rare earth compounds are under development. Other safety-related measures considered are the use of materials that do not get activated and reduce corrosion of components.

Increasing the robustness of important components in reprocessing and waste management facilities is a key to enhancing the safety and economics of fuel cycle operations. To simplify waste management and reduce the demand for repository space, reprocessing technologies must be developed for recovery of minor actinides and long-lived or heat producing fission products. The development of ceramic matrices with long-term stability and higher capacity for waste loading is another important area of R&D for the final repository. To increase the proliferation resistance, R&D of reprocessing technologies is ensuring the recovery of uranium and plutonium without separation.

The Joint Study concluded that it is possible to identify generic areas for international collaboration such as development and testing of materials, in service inspection technologies, modeling and validation of codes, and probabilistic methods for safety analysis of fuel cycle facilities. A high emphasis has been given to share unique and expensive facilities.

V. Conclusions

The INPRO Joint Study was an innovative, unique, and cost- and time-effective multinational effort to assess the role of upcoming and future nuclear energy systems. Multinational inputs have helped to confirm the role of CNFC-FR in a future global nuclear architecture as a key option for enhancing the sustainability features of nuclear power. A rational approach was used to define R&D in priority areas of interest, identify the scope for improvements, and demonstrate the readiness for enhanced collaboration, especially in the areas of safety and economics.

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