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# WORKING MATERIAL

## Technical Meeting on
## Fast Reactors and Related Fuel Cycle Facilities with Improved Economic Characteristics

Conducted within the framework of IAEA Nuclear Energy Department's

Technical Working Group on Fast Reactors (TWG-FR)

**IAEA HEADQUARTERS, VIENNA**

**Building A, Room A0531**

**11 – 13 September 2013**

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# MEETING REPORT

# 1. Background information

As recently reaffirmed in the concluding statement of the International Ministerial Conference on Nuclear Power in the 21st Century, organized by the International Atomic Energy Agency (IAEA) and hosted by the Government of the Russian Federation in Saint Petersburg in June 2013, "*fast reactors, closed fuel cycles and re-using of nuclear fuel are some of the key options in enhancing the sustainability of future nuclear systems. Fast reactors can reduce waste streams and improve efficient use of uranium*".

Actually, fast neutron systems offer the possibility to fully exploit the energy potential of natural resources (uranium and thorium), as well as to transmute the transuranic elements which are responsible for the highest heat load and radiotoxicity of long term nuclear waste. Fast neutron systems will therefore play an increasingly important role in the future, and will help to ensure that nuclear energy remains a sustainable long term option in the world's overall energy mix.

In recognition of the importance of fast reactors for the sustainability of the nuclear option, there is currently renewed worldwide interest in the development of fast reactor technology, as indicated, e.g., by the outcomes of recent scenario studies of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and of the Generation IV International Forum (GIF) where four out of the six innovative systems being developed are fast reactors (the sodium cooled fast reactor, the heavy liquid metal cooled fast reactor, the gas cooled fast reactor, and the molten salt fast reactor). Currently, fast reactor construction projects are under way in India (Prototype Fast Breeder Reactor) and the Russian Federation (BN-800), while in China the first experimental fast reactor (China Experimental Fast Reactor) was connected to the grid in 2011. Innovative fast reactor concepts, in particular sodium cooled systems and heavy liquid metal cooled systems, are under development also in Europe (in particular in France), Japan, the Republic of Korea, China, India, the Russian Federation and the United States of America.

However, in order to fully satisfy all the criteria related to the sustainability of nuclear energy, the development of cost effective fast reactors along with related advanced fuel cycle technologies is also of paramount importance in view of their large scale industrial deployment. Without demonstrating its economic affordability and in particular the possibility to reduce the unit construction cost of a new nuclear power plant, fast reactor technology could potentially fail to become a viable option for sustainable energy development.

In recent years, engineering oriented work, rather than basic research and development (R&D), has led to significant progress in improving the economics of innovative fast reactors and associated fuel cycle facilities, while maintaining and even enhancing the safety features of these systems. Optimization of plant size and layout, more compact designs, reduction of the amount of plant materials and the building volumes, higher operating temperatures to attain higher generating efficiencies, improvement of load factor, extended core lifetimes, high fuel burnup, etc. are good examples of achievements to date that have improved the economics of fast neutron systems.

The IAEA, through its Technical Working Group on Fast Reactors (TWG-FR) and Technical Working Group on Nuclear Fuel Cycle Options and Spent Fuel Management (TWG-NFCO), devotes many of its initiatives to encouraging technical cooperation and promoting common research and technology development projects among Member States with fast reactor and advanced fuel cycle development programmes, with the general aim of catalysing and accelerating technology advances in these fields. In particular the theme of fast reactor deployment, scenarios and economics has been largely debated during the recent IAEA International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios, held in Paris in March 2013. Several papers presented at this conference discussed the economics of fast reactors from different national and regional perspectives, including business cases, investment scenarios, funding mechanisms and design options that offer significant capital and energy production cost reductions.

This Technical Meeting on Fast Reactors and Related Fuel Cycle Facilities with Improved Economic Characteristics addresses Member States' expressed need for information exchange in the field, with the aim of identifying the main open issues and launching possible initiatives to help and support Member States in solving them through international collaboration under the IAEA's aegis.

## 2. Objectives of the meeting

The objectives of the meeting are:

- To identify the main issues and technical features that affect capital and energy production costs of fast reactors and related fuel cycle facilities;
- To present fast reactor concepts and designs with enhanced economic characteristics, as well as innovative technical solutions (components, subsystems, etc.) that have the potential to reduce the capital costs of fast reactors and related fuel cycle facilities;
- To present energy models and advanced tools for the cost assessment of innovative fast reactors and associated nuclear fuel cycles;
- To discuss the results of studies and on-going R&D activities that address cost reduction and the future economic competitiveness of fast reactors; and
- To identify research and technology development needs in the field, also in view of new IAEA initiatives to help and support Member States in improving the economic competitiveness of fast reactors and associated nuclear fuel cycles.

## 3. Summary Report

### 3.1. Session I: Opening and objectives of the technical meeting

The Scientific Secretary of the technical meeting Mr. Stefano Monti welcomed the meeting participants and thanked them for their participation.

Opening remarks were provided by Mr. Thomas Koshy, Section Head of the Department of Nuclear Energy's Nuclear Power Technology Development Section, who opened his speech underlining that the development of fast reactors is crucial for the future of nuclear power, especially in order to address the issues concerning the management of nuclear wastes and the preservation of the limited resources of uranium. Mr. Koshy stressed on the importance of initiatives such as this technical meeting, considering that it is fundamental to find innovative solutions to improve fast reactors economics and make them competitive compared with current commercial nuclear power plants; the achievement of this objective is of paramount importance for the future development and deployment of fast reactors. Concluding his speech, Mr. Koshy remarked also the large participation at the FR13 conference, which testifies the wide interest in fast reactor and related fuel cycles technology.

After a brief self introduction, meeting participants agreed to appoint Mr. T.J. Harrison from USA as meeting Chairman and approved the meeting Agenda, which is reported in Annex I.

***Recent IAEA Achievements in the Field of Fast Neutron Systems and Scope and Objectives of the Meeting***
*Mr. S. Monti, IAEA*

Mr Monti provided the meeting participants with an overview of the IAEA activities in the field of fast reactors and related fuel cycles, as well as of context, scope and main objectives of the technical meeting.

Mr Monti summarized statistics and main highlights of the *International Conference on Fast Reactors and Related Fuels Cycles – FR13*, held on March 2013 in Paris, with special emphasis on the main achievements in the area of fast reactor economics and scenario analyses presented at the conference. Further recent technical meetings, workshops and education and training initiatives were reviewed.

The presentation focused also on recently completed, on-going and planned CRPs. The overall picture of the IAEA activities was completed with a presentation of the recent IAEA publications "*Status of Fast Reactor Research and Technology Development*", the IAEA Nuclear Energy Series "*Liquid Metal Coolants for Fast Reactors Cooled by Sodium, Lead and Lead-Bismuth Eutectic*" and other reports currently under preparation.

## 3.2. Session II: Economic studies on advanced fuel cycles

***Overview of the INPRO project***
*Mr. Z. Drace, IAEA INPRO*

Mr Drace, IAEA INPRO Group Leader, presented an overview of the INPRO project, including key facts about its origins, basic characteristics and structure, objectives and sub-projects. INPRO was established in 2000 to address some key public concerns on nuclear power, especially in the areas of economics, waste management, proliferation, etc., with the final goal of ensuring that nuclear energy will be available to contribute to the future energy needs in a sustainable manner.

More specifically, the main objectives of INPRO can be summarized as follow:

- to help ensuring that nuclear energy is available to contribute, in a sustainable manner, to meeting the energy needs of the 21st century;
- to bring together technology holders and users and other stakeholders so that they can consider jointly the international and national actions required for achieving desired innovations in nuclear reactors and fuel cycles;
- to support national strategic and long range planning and decision making in the field of nuclear energy development and deployment.

The current INPRO programme includes four main projects: 1) National Long Range Energy Strategies 2) Global Nuclear Energy Scenarios 3) Innovations 4) Policy and Dialogue. Detailed information about the INPRO structure, including the integration between the different projects, and about the INPRO methodology for nuclear energy systems assessment (NESA) was provided by Mr. Drace.

***Activities and major finding of the INPRO project "Scenarios"***
*Mr. V. Kuznetsov, IAEA INPRO*

Mr Kuznetsov presented the main results of the INPRO project 2 "Scenarios", established to help participating countries to develop comprehensive national nuclear energy strategies by providing framework for the analysis and assessment of:

- how to make a transition from the current fleet of reactors and nuclear fuel cycles to a future nuclear energy system;
- how national energy system could contribute to, and benefit from sustainability of a regional nuclear energy system;
- the role which cooperation with other countries in nuclear fuel cycle may play in a transition to a future nuclear energy system.

The service provided by INPRO is to assist Member States in nuclear energy development modelling, including material flow analysis, economic assessment and least cost model optimization. The analytical framework developed has several applications:

- developing national nuclear energy strategies
- exploring cooperation/partnerships with other countries in nuclear fuel cycle

- exploring regional options/ solutions for nuclear fuel cycle
- highlighting global trends: how they may affect national developments.

Further details concerning the results of several scenario analyses conducted within the project were discussed by Mr. Kuznetsov.

***Economic Assessment with the INPRO Methodology***
*Mr. A. Korinny, IAEA INPRO*

The presentation made by Mr. Korinny discussed the INPRO methodology in the area of economics, which can be used to assess the following aspects:

- Competitiveness of an NPP against other energy sources (via comparison of production costs of electricity);
- Attractiveness of investment into an NPP (via financial figures of merit);
- Acceptability of investment risk for a deployment and also for development;
- Flexibility of NPP design.

The presentation included cost comparison of different energy sources, considerations on sensitivity of NPP energy cost, examples of cost calculation (including the discussion on several inconsistencies in the models currently used).

***Economics of the Back-end of the Nuclear Fuel Cycle***
*Mr. A. Lokhov, OECD-NEA*

The feasibility and costs of spent nuclear fuel management and the consequent disposal of ultimate waste continue to be the subject of public debate in many countries, with particular concern often expressed over the lack of progress in implementing final disposal. Uncertainties about back-end costs and the financial risks associated with management of the back end have also been singled out as possible deterrents to investment in new nuclear build.

The presentation was based on a report recently published by OECD-NEA, which offers an appraisal of economic issues and methodologies for the management of spent nuclear fuel and high-level waste from commercial power reactors. It includes a review of different back-end options and current policies and practices, with a focus on the cost estimates for these options and the funding mechanisms in place or under consideration in OECD/NEA countries. A generic economic assessment of high-level estimates of back-end cost impacts on fuel cycle costs is undertaken for selected idealised scenarios, by means of a simple static model.

The evaluation of the cost for the total fuel cycle (including both the back-end and the front-end components, so that the use of recycled materials and the resulting savings in the requirements of fresh uranium can be taken into account for recycling options), its breakdown, and a sensitivity analysis of costs associated with the management of spent nuclear fuel from light water reactors (LWRs) were performed for three assumed generic strategies:

- open or once–through FC, with direct disposal of spent nuclear fuel;
- partial recycling or twice-through FC, where REPUOX and MOX are recycled once in LWRs and then disposed of;
- multiple plutonium recycling with LWRs and fast reactors (FRs). This strategy contemplates single MOX and REPUOX recycling in LWRs and multiple plutonium recycling in FRs.

The results of the FC cost calculations performed for the reference case show that costs calculated for the open fuel cycle option are lower than for the other idealized options assessed. Differences among the three options in the total fuel cycle component of the levelised costs of electricity are, however, within the uncertainty bands, given the uncertainties on some cost estimates. For the recycling options, additional costs from reprocessing are being offset by the savings on fuel costs at the front end. Differences are more noticeable in the reference case calculations if the back-end component of the fuel-cycle cost is considered in isolation, since the offsetting effects are not taken into account.

It is important to note that, for all options assessed, the FC cost component associated with the management of SNF represents a relatively small fraction of the total levelised costs of electricity generation. However, these differences could translate into large absolute costs depending on the size of the nuclear programme and the period of electricity generation.

The total cost of the nuclear fuel cycle strongly depends on the cost of fresh UOX fuel (that in turns depends on the prices of natural uranium, conversion and enrichment services, and fuel fabrication costs). Given uncertainties in the input data, it is difficult to accurately estimate the UOX price which renders one or the other strategy more economical. Advanced recycling options will only be economically advantageous if the price of UOX fuel (and thus the price of natural uranium, enrichment services, etc.) increases significantly from the current values. This would imply an even greater increase in the prices of natural uranium. For example, in the analysis of a system of 400 TWh/year and at 3% discount rate, the multiple Pu recycling in LWRs and FRs would become attractive if the cost of fresh UOX was ~50% higher than in the reference case scenario considered in the calculation. This corresponds to prices of natural uranium of about USD 270-300/kgU (for unchanged prices of other front-end services, e.g. enrichment, etc.) i.e. more than 100% higher than on the reference UOX cost assumption defined in this study.

In both the recycling strategies considered in this study, the second largest sensitivity after cost of UOX is the cost of reprocessing.

The fuel cycle cost of the most advanced option Multiple Pu recycling with LWRs and FRs is particularly sensitive to the FR cost premium (Fast reactors are expected to be more expensive than LWRs, thus a special cost premium for their construction and operation is introduced. This extra cost is attributed to the back-end component since, in Multiple Pu recycling with LWRs and FRs strategy, the fast reactors are considered as a means for managing the SNF). The results obtained for the reference cost scenario suggest that this advanced option would be more economical than the direct disposal route only if the FR cost premium is low (i.e. if FRs and LWRs have comparable capital and operating costs).

However, given the uncertainty on the input date, a prudent conclusion from this analysis is that unless the cost premium of fast reactors becomes excessive there is no economic reason not to continue with their development.

***Fast Reactor Fuel Cycle Cost Estimates for Advanced Fuel Cycle Studies***
*Mr. T.J. Harrison, USA*

The presentation discussed the work performed to generate the 2012 Addendum to the Advanced Fuel Cycle Cost Basis, in particular the contents, intended uses, inherent limitations, and sample calculation results obtained using the Cost Basis with a focus on the fast reactor fuel cycle. The work on the addendum began in 2012 to update the Cost Basis from its last edition released in 2009. The Cost Basis is used in “level playing field” economic analysis of proposed nuclear fuel cycles, including fast reactors, using consistent and vetted unit cost values for the various components of the nuclear fuel cycle.

The Cost Basis is a result of the Department of Energy-Nuclear Energy Advanced Fuel Cycle Initiative (DOE-NE AFCI) establishment of an Economics Working Group composed of members of several national laboratories, industry, and universities, to assess the projected life cycle costs of new fuel cycles examined as part of ongoing fuels-related research and development programs. It was recognized that a complete fuel cycle consists of multiple steps; an economic analysis of the fuel cycle therefore requires an economic analysis of each step.

This analysis generates estimates of the unit cost for each step for the Nth-of-a-Kind or steady-state deployment of the fuel cycle step, typically as amount of currency per relevant unit. For example, enrichment unit cost is given in USD per SWU, while reactor variable non-fuel operations and maintenance cost is given in USD per MWeh of electrical generation; these costs are based on current operating and market experience. Fuel fabrication costs for advanced fuel types—such as for sodium-cooled fast reactors—is given in USD per kgHM, assuming the advanced fuel fabrication facility is operated as a commercial facility at full nominal capacity.

This addendum includes cost updates for all the components of the nuclear fuel cycle—from mining through disposal—and also includes components that were not previously included in the Cost Basis. The cost information is taken from multiple sources as available, including industry and academia. The information is then presented as a potential range of costs with a suggested probability distribution, typically either uniform or triangular. These distributions are defined by a "low" cost and a "high" cost, and the triangular distribution includes a mode referred to as the "nominal" cost.

The Cost Basis includes cost on the entire fast reactor fuel cycle, including the mining of natural uranium and thorium; enrichment; fuel fabrication and separations; fast reactor capital and operations costs; and waste management for used fuel or partitioned material.

## 3.3. Session III: Economic features of advanced fast reactors

***Economic issues of fast reactors in China***
*Mr. H. Yang, China*

CEFR, the first Chinese fast reactor, is a pool-type sodium cooled fast reactor. Its power is about 65MWth, corresponding to 20MWe. The first fuel load of CEFR is $UO_2$; future fuel loads foresee the use of MOX. Thanks to passive DHRs and inherent safety design, the general safety characteristics of CEFR are high and comply with the safety and reliability requirements of Generation IV systems. As most of the sodium pool-type fast reactors in the world, the main systems of CEFR include the reactor block, the reactor cooling system, the fuel handling system, the radwaste treat system, the steam and electricity production system and related electrical, I&C and safety systems. There are 219 subsystems in CEFR. The total footprint of the plant is about 90281m$^2$, and the total area of the reactor structures is about 45839m$^2$. There are 2 symmetric intermediate heat transfer systems and every circuit consist of 1 pump, 2 IHX and 1 SG. Only 1 25 MW turbo-generator is installed in the plant.

As the largest project in the national energy program, CEFR was supported by the Chinese high technology plan named "863". The main milestones of CEFR are:

- 1995.12, project approved
- 2000.5, FCD
- 2002.8, close of the reactor building
- 2009.9, end of the phase A commissioning work
- 2010.7.21, first physics criticality
- 2011.7.21, first connection to the national grid and electricity production

It is planned to start CEFR operation in 2013 and increase the power up to 100% rated power.

The final financial statement has been accepted by the government in October 2012. The capital cost of CEFR is about 2.516 billion Rmb (387,135,062 USD), the unit cost is about 125819rmb/kwe or 19357 USD/kwe.

Table 1 provides the final figures of the total capital cost of CEFR and its components.

Table 1 Total capital cost of CEFR

| NO. | Item | Cost | | % |
|---|---|---|---|---|
| | | RMB | USD | |
| 1 | Civil and erection cost | 1,639,528,800 | 252,235,200 | 65.15% |
| 1.1 | Civil engineering cost | 335,053,400 | 51,546,677 | 13.31% |
| 1.2 | Equipment procurement cost | 1,002,590,100 | 154,244,631 | 39.84% |
| 1.3 | Erection engineering cost | 301,885,300 | 46,443,892 | 12.00% |
| 2 | Indirect cost | 695,842,200 | 107,052,646 | 27.65% |
| 2.1 | Design | 109,851,100 | 16,900,169 | 4.37% |
| 3 | First loading fuel | 115,989,500 | 17,844,538 | 4.61% |
| 4 | preparation R&D | 65,017,400 | 10,002,677 | 2.58% |
| | total | 2,516,377,900 | 387,135,062 | 100.00% |

In this table USD to Rmb is about 6.5. From these data, several conclusions can be withdrawn:

I) The unit cost of CEFR is about 125819y/kwe, i.e. higher than the PWR in China. The main reasons are:

- Less mature technology. Being first Chinese fast reactor, the reactor configuration and key systems have been changed during the design. The function of main components has been adjusted during the construction;
- Limited engineering management experience. Engineering management play an important role for the nuclear power plant construction. The integral pool-type design of fast reactors need more experience in the organization and coordination.
- International collaboration. The international collaboration in CEFR project includes consultancy and key components purchase from other countries.
- Long construction time. Plan control is a very important factor for the control of the total capital cost. Due to many reasons, the construction of CEFR took more than ten years, and it is almost double compared with PWR.
- The total capital cost varied over the years. During the construction, the total capital cost of CEFR was adjusted two times. The total capital cost was about 680 million yuan at the preparation stage and then adjusted to 1358.8 million yuan after preliminary design review. At the end of the detailed design, the capital cost landed to 2516 million yuan.

II) The percentage of the equipment procurement cost is relatively low. Normally the percentage of the equipment procurement is about 45% of the overall cost of the nuclear power plant, but for CEFR was only 39%. The main reason is the relative lower cost of the components and equipment and the fact that some components come for the Italian PEC reactor.

III) The percentage of the design cost is relatively low.
The engineering design of CEFR was performed by the China Institute of Atomic Energy and other civil designers, i.e. through a Chinese "self-design" model. As a consequence, the percentage of the design cost is lower than the one of the current PWRs.

IV) The percentage of the indirect cost is relatively high due to:

- Stop of the construction work for unplanned reasons.
- Being a R&D project, CEFR took a longer time, including the preparation stage.
- International consultancy cost also included in the indirect cost.

In summary, the unit cost of CEFR looks very high, but not so high if compared with other fast reactors in the world.

The next stage of the Chinese FR programme is the realization of CFR-600, an industrial size SFR. It is designed to demonstrate breeding capability, safety and reliability, as well as economic affordability of medium scale sodium cooled fast reactor. Some technical features of CFR-600 are derived from CEFR but many innovative design solutions will be adopted to enhance its safety and economic.

The preliminary design of CFR-600 will be finished next year and the construction work is expected to be completed in 2023.

In order to decrease the capital cost of CFR-600, the following features are being implemented:

- High burn-up of the fuel to increase the lag time between two fuel loading;
- Optimize the spent fuel cleaning and new fuel handling program to shorten the fuel reshuffling during longer lifetime;
- Compact reactor building and optimization of the number and footprint of the buildings;
- Modular SG configuration;
- Higher heat efficiency;
- Earthquake isolation design of the reactor building;
- Optimization of the technical specifications based on the PSA to improve the economic during operation;
- Optimization of the reactor block design with 3-D technology to reduce the steel consumption;
- Advanced management system to control the design work, in order to easily handle the modifications, manufacturing, installation, commissioning and operation.

An economic oriented plant evaluation system will be implemented during the design and the whole construction phase. This system can help not only to improve the economic design and construction, but also build a kind of economic design culture.

***Cost survey to cost killing on fast reactors ASTRID***
*Mr. D. Vernher, France*

The preliminary design study of ASTRID was broken down into 2 phases:

- From January 2010 to December 2012 (phase 1), several innovating options were reviewed and the goal set up (for the end of the phase) to limit to a few open design choices.
- From January 2013 to December 2015 (phase 2), ASTRID project team focuses on perfecting the design and improving the strong safety survey and cost value.

<u>Methodologies applied simultaneously in phase 1 (Jan 2010 to Dec 2012) :</u>

A) Option selection process

During this phase, several pre-selected innovating options were assessed according to the following methodology:

a) Pre-design study for each subject, with priority given to innovation.
b) Preliminary review to compare options with assessment of cost value, safety, In-Service Inspection & Repair (ISIR), maintainability/reliability and technology readiness level.
c) Final review with the industrial partners of ASTRID project in order to reach common agreement for the best option.

B) Value analysis

On several transverse topics, engineers of diverse background studied the value of the pre-selected options. This group approach, based on function analysis, performances and cost assessment with a best added value, led to remove all unnecessary items.

C) Global cost estimate for ASTRID

This process was done by implementing analytical methodologies:

- The SEMER software and others tools developed by CEA.
- The cost estimate made by industrial partners.
- The global estimate from the experience feedback of EFR, SuperPhenix and EPR.
- The blind assessment performed by a third-party company independent from the engineering companies concerned and CEA.

The analysis and compilation of results were made within the ASTRID team project and led to a new direction at the beginning of phase 2.

<u>Cost approach in phase 2 (jan 2013 to dec 2015) :</u>

- 1$^{st}$ Step : Cost killing approach (January to July 2013)
  During a specific meeting in January 2013, ASTRID project team decided to select 29 topics which could reveal possibility of savings.
  Expertise coming from the industrial partners was mixed during 3 to 4 months and led to an option selection process as the one used in Phase 1. The team project took the liberty of adapting the performances and the requirements initially fixed at the beginning of the project (performances published in the functional specifications in the middle of 2010). Some preliminary choices of concept were thus modified.
- Other methods which will be applied during phase 2:
  - Assessment of savings in particular volume reduction of process or buildings and identification of technical no-sense in terms of technology, risk and deadlines.
  - Implementation of a “cost driver” guide in order to regularly monitor the project.
  - Implementation of an integrated design work team to study the best technical offers from the partners.

***Lead reactor strategy economical analysis***
*Mr. M. Ciotti, Italy*

The Lead Fast Reactor (LFR) concept is one of the fourth generation reactors selected by GIF.

The LFR concept, consist of a design which employees innovative and reliable technological solutions, as much as possible proven, aiming to increase the safety and reliability of the whole system. This approach has induced a design which is less complex and more compact of the other GEN-IV systems, able to emphasize the inherent safety features of the lead-liquid metal coolant. The roadmap toward the realization of the first reactor goes through the pre-conceptual study and design of a demonstrator named ALFRED (Advanced Lead Fast REactor Demonstrator), being planned in the frame of the LEADER Project (FP7-EU).

The ALFRED design is mainly based on experience gained on the design of the ELSY reactor (ELSY Project, FP7-EU) and of the already operating zero power facility GUINEVERE in Belgium.

Moreover a strong collaboration exists with the design team of the technology pilot plant MYRRHA and by the education and training ELECTRA reactor team in Sweden.

In the framework of the EU FP7 LEADER project the first assessments concerning cost estimates, both for ALFRED and LFR have been performed using two different methodologies:

- Bottom-up estimation, i.e. starting from cost analysis of single components (ALFRED);
- top-bottom one, based on generation III experience (LFR).

Both methodologies have already been discussed in details: in the first case errors could arise from the project limited knowledge, in the second case the estimation is based on past experience, with difficulties on the far future extrapolation. In any case scaling laws can be deduced and brought under discussion.

Finally the financial strategy foreseen for ALFRED and LFR were elucidated and possible approaches to limit the IV generation reactor cost proposed.

***Korean SFR development program and technology activity for improving economic competitiveness***
*Mr. J. Yoo, Republic of Korea*

Korean participant presented "Korean SFR development program and technical activities for improving economic competitiveness". The milestone and roadmap schedule for developing PGSFR (Prototype of Gen-IV Sodium-cooled Fast Reactor) was provided during the presentation as well as the dual strategies of PGSFR development, as a TRU fuel test bed for domestic use and small size SFR for exportation.

The development of PGSFR is now in conceptual design phase. In the course of the conceptual design, trade-off studies on the various concepts of the system and component designs have been carried out with the considerations of economic implications. The trade-off studies includes:

- Trade-off between single and double rotating plugs and those effects on the reactor closure head mass and size;
- Trade-off on the decay heat removal system (DHRS) location and performance and its effect on the PHTS layout and consequent size reduction of reactor vessel size.

A long term potential of supercritical CO2 Brayton cycle as the power conversion system was presented. Also its contribution to decrease the BOP plant size and to increase the plant thermal efficiency was discussed in the meeting.

The deployment scenario of SFR in Korea was also provided during the meeting, which is based upon the previous Basic National Energy Plan of Korea and to be revised in accordance with the change of national energy policy and newly designed commercial TRU burner.

Korea has a plan to estimate the preliminary construction cost of PGSFR and commercial TRU burner in year of 2014 and scenario study on the long-term deployment of SFR will be refined with cost benefit analysis in the future nuclear energy mix.

## 3.4. Session IV: Very innovative fast neutron systems

***Neutronic characteristics of accelerator driven subcritical assembly with fast neutron spectrum utilizing high density low enriched uranium fuel***
*Ms. H. Kiyavitskaya, Belarus*

In the late 1990's, Joint Institute for Power & Nuclear Research (JIPNR)-Sosny, National Academy of Sciences of Belarus has started a theoretical and experimental research programme to study accelerator driven subcritical systems. First, subcritical assembly with thermal neutron spectrum (YALINA-Thermal) driven by a high intensity neutron generator was commissioned in the year 2000. Second, a subcritical assembly with fast and thermal neutron spectrum zones (YALINA-Booster) was started in the year 2005. National and international research activities have been successfully performed utilizing both assemblies and significant analytical and experimental results have been obtained.

A new subcritical assembly with fast neutron spectrum utilizing high density low enriched uranium fuel (YALINA-Fast) has been developed based on the gained experience from the other two assemblies. The activity of the new assembly is being carried out under the ISTC Project B1732P. The construction of YALINA-Fast is under consideration as a future facility for examining the physics of fast accelerator driven systems. At present, the new fuel was designed and fabricated by "LUCH" corporation. The neutronics characteristics of this assembly obtained by SYNTES-QH, MCU and MCNP physics computer programs were presented.

***High burnup of mixed Th-U fuel in advanced fast reactor working in the nuclear burning regime***
*Mr. S. Fomin, Ukraine*

Contribution from Ukraine presented the analysis of main features of innovative concept of fast reactor working in the nuclear burning wave regime (NBW). This concept of fast reactor (also known as a Traveling Wave Reactor or CANDLE) with a long-term operating without refueling and fuel reprocessing was proposed first by Lev Feoktistov in 1988 and further developed by several groups of researchers including Edward Teller, Hiroshi Sekimoto, and others. The results of calculations of Ukrainian research group demonstrate a possibility of realization of self-sustained regime of the running NBW for the mixed Th-U fuel. In this case not only depleted uranium, but also thorium, can be used as a fuel with a high efficiency. The average fuel burn-up of about 50% can be attained for both Th and U fuel components independently from their initial proportion. The calculations show also a notable stability of the NBW regime towards distortions of the neutron flux in the system and fuel non-uniformity. This stability demonstrates the most important feature of the NBW reactor, namely, its intrinsic safety ensured by the negative reactivity feedback, which is inherent to the NBW regime.

All mentioned above features of the NBW reactor makes this concept very attractive from the economical point of view, because it can help to solve all the problems of today's nuclear power, such as the nuclear fuel resources problem (238U and 232Th use as a fuel), non-proliferation problem (no refueling and fuel reprocessing during hole reactor campaign), ecological aspect of nuclear power (possibility of utilization of MA produced by other reactors) and finally, the most important problem: safety of nuclear reactors (no necessity of operative control due to specific type of negative reactivity feedback that gets a possibility, in principle, to exclude so called the "human factor" in reactor operation).

The main problem that balks a progress in creation of such a reactor is high neutron fluence, which is about three times higher than acceptable now for cladding materials. There are two possibilities to solve this problem: first, new cladding materials with high irradiative resistance, and second, a new concept design of the NBW reactor in which the fluence would be suppressed essentially.

### 3.5. Session V: Closing session

Lively discussions followed the presentations given by Member States representatives and interesting considerations were made on key aspects related to fast reactors and related fuel cycle economic characteristics.

The relevant differences between economic features of light water reactors and fast reactors were highlighted during the discussion, including also considerations about the historical reasons and context that facilitated the commercial deployment of LWRs, whose technology development could also benefit of significant resources coming from military interests (submarines propulsion). The participants underlined that the context of a future deployment of fast reactors and closed fuel cycles is completely different.

An element of relevant importance is the need of international cooperation for the realization of fast reactor prototypes. In this regard, it was noted that current initiatives like GIF are mainly aimed at supporting and coordinating R&D programmes, but not at the realization of FR prototypes that will be a necessary step for commercial developments of this technology.

Overall, results of economic analyses on innovative fast reactors and related fuel cycles showed that this technology has the potentialities to economically compete with mature nuclear power plants technologies. To fully achieve this objective, technical innovations will be of paramount importance to bring capital costs of fast reactors construction down. However, it was stressed that currently it is not easy to have an accurate estimation of fast reactors capital cost as there is not a supply-chain for this technology; indeed there is no market for fast reactors key components and equipment, which are usually unique realizations (vessel, primary pumps. heat exchangers, steam generators, instrumentation, etc.). On this aspect, participants underlined that it would be beneficial to develop a sort of catalogue of fast reactors components and equipment with related costs data and information.

A typical reason of high capital costs of fast reactor plants is the long construction periods, often due to a number of stop-and-go that occur during the construction, the complexity of the systems and the large variety of innovative technologies with limited industrial experience. As a consequence, simplification in the design and realization of components and equipment was recognized as a possible important means to shorten construction periods and bring capital costs down. It will be also fundamental an harmonization of safety standards at international level, as well as the development of fast reactors knowledge within national regulator bodies.

Past experience was recognized to be fundamental in relation to many of the key issues related to fast reactors economics. The knowledge gained through the design, construction and operation of commercial demonstrators like PHENIX and SUPEPHENIX in France, BN-600 in the Russian Federation, etc. represents a key resource for future developments.

Participants expressed their appreciation for the organization of this technical meeting, which was a useful initiative to discuss issues and share ideas on a key aspect of fast reactors technology development. The meeting participants expressed also their interest in future activities and collaborations in the field under the aegis of the IAEA.

# ANNEX I: List of Participants

| | | | |
|---|---|---|---|
| Belarus | Ms | Kiyavitskaya, Hanna | Joint Institute for Power and Nuclear Research, SOSNY |
| China | Mr | BAI, Yunqing | Institute of Nuclear Energy Safety Technology |
| China | Mr | Yang, Hongyi | China Institute of Atomic Energy |
| France | Mr | Vernhet, Didier | Project ASTRID, CEA |
| India | Mr | Balasubramanian, Venkatapathi | IGCAR; Department of Atomic Energy (DAE) |
| Italy | Mr | Ciotti, Marco | ENEA |
| Korea, Republic of | Mr | Yoo, Jae Woon | Korea Atomic Energy Research Institute |
| Ukraine | Mr | Fomin, Sergii | Akhiezer Institute for Theoretical Physics; National Science Center |
| United Kingdom | Mr | Gregg, Robert | NNL |
| USA | Mr | Harrison, Thomas, Jay, | Oak Ridge National Laboratory |
| OECD-NEA | Mr | Lokhov, Alexey | |
| IAEA | Mr | Koshy, Thomas | |
| IAEA | Mr | Drace, Zoran | |
| IAEA | Mr | Kuznetsov, Vladimir | |
| IAEA | Mr | Korinny, Andriy | |
| IAEA | Mr | Monti, Stefano | |
| IAEA | Mr | Toti, Antonio | |

# ANNEX II: Meeting Agenda

## WEDNESDAY, 11 SEPTEMBER 2013

| Time | Topic | Speaker |
|---|---|---|
| | *Session I: Opening and TM Objectives* | |
| 09:30 – 10:30 | Welcome and opening remarks | **Mr. T. Koshy** NPTD Section Head, IAEA |
| | Self-introduction of the participants<br>Appointment of the Meeting Chair | All Meeting Participants |
| | Chairperson's remarks | Meeting Chair |
| | Discussion and Adoption of the Agenda | Meeting Chair |
| 10:30 – 11:00 | Recent IAEA achievements in the field of fast reactors and presentation of scope and objectives of the meeting | **Mr S. Monti** NPTDS, IAEA |
| *11:00 – 11:30* | *Coffee Break* | |
| | *Session II: Economic Studies on Advanced Fuel Cycles* | |
| 11:30 – 13:00 | INPRO:<br>• Overview;<br>• Analytical framework for the analysis/ assessment of transition scenarios to sustainable nuclear energy systems and its applications";<br>• Economic assessment with the INPRO methodology | **Mr Drace,** INPRO Group Leader, IAEA<br>**Mr. V. Kuznetsov**, INPRO Group, IAEA<br>**Mr. A. Korinny**, INPRO Group, IAEA |
| *13:00 – 14:00* | *Lunch Break* | |
| 14:00 – 15:00 | OECD/NEA study economics of the back-end of the nuclear fuel cycle | **Mr. A. Lokhov** OECD-NEA |
| 15:00 – 16:00 | Fast reactor fuel cycle cost estimate for advanced fuel cycle studies | **Mr. T. Harrison** ORNL, USA |
| *16:00 – 16:30* | *Coffee Break* | |
| 16:30 – 17:00 | Other contributions, comments and remarks from the participants and general discussion on Session II | All Meeting Participants |
| 17:00 – 17:30 | Wrap-up of the first day meeting | **Chairman** |
| *17:30* | *End of Day 1* | |
| *17:30* | *Cocktail reception organized by the IAEA* | |

## THURSDAY, 12 SEPTEMBER 2013

| Time | Topic | Speaker |
|---|---|---|
| *Session III: Economics Features of Advanced Fast Reactors* | | |
| 09:00 – 09:45 | Economic issues of fast reactors in China | **Mr. H. Yang**<br>CIAE, China |
| 09:45 – 10:30 | Cost survey to cost killing on Fast Reactor ASTRID | **Mr. D. Vernhet**<br>CEA, France |
| *10:30 – 11:00* | *Coffee Break* | |
| 11:00 – 11:45 | Design features and construction strategy for commercial SFR | **Mr. V. Balasubramaniyan**<br>IGCAR, India |
| 11:45 – 12:30 | Lead reactor strategy economical analysis | **Mr M. Ciotti**<br>ENEA, Italy |
| *12:30 – 14:00* | *Lunch Break* | |
| 14:00 – 14:45 | Korean SFR development program and technical activity for improving economical competitiveness | **Mr J. Yoo**<br>KAERI, RoK |
| 14:45 – 15:00 | Other contributions, comments and remarks from the participants and general discussion on Session III | All Meeting Participants |
| *Session IV: Very Innovative Fast Neutron Systems* | | |
| 15:00 – 15:30 | Neutronics characteristics of accelerator driven subcritical assembly with fast neutron spectrum utilizing high density low enriched uranium fuel | **Ms. H. Kiyavitskaya**<br>SOSNY, Belarus |
| 15:30 – 16:00 | High burup of mixed Th-U fuel in advanced fast reactor working in the nuclear burning wave regime | **Mr. S. Fomin**<br>Kharkov Institute, Ukraine |
| *16:00 – 16:30* | *Coffee Break* | |
| *Session V: Identification of Research and Technology Development Gaps and Needs to be Covered Through new IAEA Activities* | | |
| 16:30 – 17:30 | Remarks and proposals from the participants | All meeting participants |
| 17:30 – 18:00 | Discussion and wrap-up of the second day meeting | Chair + All meeting participants |
| *18:00* | *End of Day 2* | |

## FRIDAY, 13 SEPTEMBER 2013

| Time | Topic | Speaker |
|---|---|---|
| *Session VI: Closing Session* | | |
| 09:30 – 10:00 | Conclusions and recommendations of the meeting | Chair + All Meeting Participants |
| 10:00 – 11:00 | Drafting of the meeting report | **Mr S. Monti** with the support of all meeting participants |
| *11:00 – 11:30* | *Coffee Break* | |
| 11:30 – 12:00 | Finalization of the meeting report | **Mr S. Monti** with the support of all meeting participants |
| 12:00 – 12:30 | Closing remarks | Meeting Chairman and IAEA |
| 12:30 | End of the Technical Meeting | |