Overview of the IAEA Activities in the Field of Fast Reactor Technology Development: Current State and Future Vision

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Abstract. Under the project on advanced technology for fast and gas-cooled reactors, the IAEA is carrying out several activities on fast reactor technology development including i) Information Exchange and International Cooperation, ii) Modelling and Simulations, iii) Technical Support, iv) Fast Reactors Safety, v) Education and Training, and vi) Knowledge Preservation.

Technical Working Group on Fast Reactors (TWG-FR) is a one of the main driving forces directing IAEA activities in the field. Eighteen countries and two international organizations are the members of the TWG-FR while six other countries and Generation-IV International Forum (GIF) are observers.

Coordinated Research Projects (CRP) are important IAEA instruments for organizing international research work to achieve specific research objectives consistent with the IAEA programme goals. Several CRPs have been conducted since last FR13 Conference in Paris. IAEA have completed CRPS on Phenix End-of-Life Tests, Monju Natural Convection, and Benchmark on Accelerator-Driven Systems (ADS). A special session on this conference is devoted to the recently completed CRP on benchmark analysis of EBR-II shutdown heat removal tests. CRP on radioactive release from the prototype sodium cooled fast reactor under severe accident conditions is ongoing now. Another in-progress NAPRO CRP is on sodium properties and design and safe operation. A new benchmark CRP on CEFR Physics Start-Up Experiments has been initiated. In addition IAEA is conducting study on passive shutdown systems for fast neutron reactors, an initiative on knowledge preservation, joint IAEA-GIF initiative on safety of sodium cooled fast reactor. There are also a number of activities in the field of fast reactor education and training including annual schools and workshops on innovative nuclear systems and development of the SFR simulator for educational purposes.

The details of the IAEA activities will be presented on the special IAEA corner at the FR17 poster session.

Key words: Fast reactor, Technical working group, TWG-FR, IAEA, Coordinated Research Project. CRP

1. Introduction

The role of fast reactor technology with closed fuel cycles is generally recognized as having a high potential in the long term development of nuclear power as a part of the world's future energy mix [1-4]. Fast reactors (FR) can play an important role in meeting growing energy needs worldwide in a safe, environmentally clean and affordable manner due to a unique potential of this reactor technology as a sustainable energy source. The fast neutron spectrum allows fast reactors to increase the energy yield from natural uranium by a factor of sixty to seventy compared to the thermal reactors. By the achievable breeding ratio and the multi-recycling of the fissile materials obtained from the spent fuel, fast reactors allow fully utilizing the energy potential of the natural resources (Uranium and Thorium), thus secure energy supply for thousands years and drastically enhancing the sustainability of nuclear power, especially in terms of resource preservation and management of high level and long-lived nuclear wastes.

For these reasons fast reactors have been under development for decades in several countries, primarily as breeders and, in recent years, also as high level waste (HLW) burners.

The important role of fast reactors and related fuel cycles for the long term sustainability of nuclear power has been reconfirmed during the International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13), held in Paris in March 2013 and attended by almost 700 experts from 27 countries and 4 international organizations [2].

2. Current state of fast reactors development

There are four major fast reactor options corresponding to four primary coolants. Currently, several fast reactor systems are considered, designed, and operated worldwide. Among them, the sodium-cooled fast reactor (SFR), the heavy liquid metal-cooled (HLM, i.e. lead and lead-bismuth eutectic, LBE) fast reactor, the gas-cooled fast reactor (GFR), and the molten salt fast reactor (MSFR).

Thirteen experimental fast reactors with thermal power ranging from 10–400 MW(th) and seven commercial size prototypes with electrical output ranging from 250–1200 MW(e) have been constructed and operated. Overall, the operational performance of these reactors has been remarkable, with noteworthy achievements such as thermal efficiencies of 43–45 %, which is the highest value in the nuclear power practice.

Great strides have been made in fast reactor technology, which encourage future development. The closed fuel cycle has been demonstrated, an effective breeding ratio was experimentally confirmed, fuel burnup in excess of 130 GWd/t has been reached in several reactors with over 200 GWd/t reached for some experimental pins and major steps towards commercial sodium-cooled fast reactor designs have been made. The worldwide investment already made in the development and demonstration of the sodium-cooled fast reactors unique technology exceeds US$ 50 billion. [1]. Experience in the decommissioning of several of these reactors has been accumulated as well.

The IAEA TECDOC-1691 “Status of Fast Reactor Research and Technology Development” published in 2012 [1] provides a comprehensive overview of the fast reactor technology, whilst the IAEA Booklet “Status of Innovative Fast Reactor Design and Concepts (a supplement to the IAEA ARIS)” published in 2013 [5] presents the innovative fast reactor design and concepts that are currently under development worldwide. A new IAEA TECDOC on “Status of Research and Technology Development for Accelerator Driven Systems” will be published in 2017.

2.1 Sodium cooled fast reactors

Sodium cooled fast reactors (SFR) have a very comprehensive technological basis due to the experimental feedback obtained from the operations of experimental, prototype and commercial size reactors. The international experience of SFR relies on several countries (USA, Russia, UK, France, Kazakhstan, Germany, Japan, India, and China) with a cumulated 420 years of operation (in 2015). Among the fast neutron reactor systems, the SFR has the most comprehensive technological basis thanks to the experience gained from worldwide operation of several experimental, prototype, and commercial fast reactors since the 1940s. In the status report [1] it is outlined that “…a considerable amount of technological experience has already been acquired for the SFR systems, thereby providing a sound basis for the further development and eventual deployment of new SFR designs”.

Recent developments highlight the observation made in the FR status report: the Russian Federation constructed and in 2015 connected to the grid the industrial-size SFRs BN-800.

Today there are seven operational reactors, among which four are actually in-service: BOR-60, BN-600 and BN-800 in the Russian Federation, fast breeder test reactor (FBTR), 40MW(th), 13.2MW(e) in India and China experimental fast reactor (CEFR), 65MW(th), 20MW(e). MONJU and JOYO reactors in Japan are currently under long term shutdown. The booklet on the Status of Innovative Fast Reactors Designs and Concepts [5] provides a summary of the FR operated so far. It is also presented in the Advanced Reactors Information System (ARIS) [6]. SFR system development is based on the vast experience of operation of all of these reactors.

Furthermore, India is currently constructing the prototype fast breeder reactor (PFBR), 500MW(e). Several design projects are currently in progress: commercial fast breeder reactor (CFBR), 600MW(e) in India, Chinese demonstration fast reactor (CDFR), 1000–1200MW(e) in China, and MBIR, up to 150MW in the Russian Federation.

Generation IV International Forum (GIF) is considering five SFR concepts, among them BN-1200 in the Russian Federation, Japan sodium cooled fast reactor (JSFR), 750MW(e), KALIMER - prototype sodium cooled fast reactor with metallic fuel, 150MW(e) in the Republic of Korea, the European Sodium Fast Reactor (ESFR), 3600 MW(th), European Union, and Advanced Fast Reactor (AFR-100), 100MW(e) in the USA. In the USA licensing activity for a super safe small and simple reactor (4S) being designed by the Toshiba company has been initiated in 2007 [5].

2.2 Heavy Metal cooled fast reactors

The operational expe**ri**ence of Heavy Liquid Metal (HLM) cooled fast reactors is limited. The HLM cooled reactor development was initially performed in the former Soviet Union, and its prime objective was the design and construction of nuclear reactors for submarine propulsion [1]. Research and design on the use of the lead-bismuth eutectic (LBE) alloy as a coolant for nuclear reactors was initiated in the early 1950s in the Russian Federation for military submarine propulsion.

The first nuclear submarine with LBE cooled reactor was put into operation in 1963. In total fifteen reactors have been built including three land system reactors, plus one replacement reactor for submarines.

Currently, several LBE cooled and pure lead cooled reactor projects are under development: SVBR-100, BREST-300 and BREST-1200 in the Russian Federation, MYRRHA, ELSY and its evolution ELFR, as well as the LFR-Demo ALFRED in European Union, small sealed transportable autonomous reactor (SSTAR), 10-100MW(e), in USA, PEACER-300 in the Republic of Korea and CLEAR-I in China and several projects in Japan. GIF considers the projects of ELFR, 600 MW(e), BREST, 300 MW(e) and SSTAR system of small size with long core life.

In the Russian Federation the BREST-300 design has been completed and is currently prepared for licensing.

2.3 Molten salt reactors

Molten salt reactors (MSRs) have several benefits and include (somewhat dependent on the specific design, and relative to currently deployed water cooled reactors): (i) higher operating temperatures leading to increased overall efficiencies; (ii) low coolant pressure; (iii) reduced volume and lifetime of high level waste; (iv) salient safety characteristics; (v) in the case of MSRs with molten fuel, elimination of technical challenges associated with solid fuel related to high burn-up effects; and (vi) flexibility of fuel cycles (uranium, plutonium, thorium).

While the IAEA currently does not have focused activities on MSR technology, many countries have reported a growing number of development and near term deployment activities related to this type of reactor technology. Some technical research and technology development areas were identified where the IAEA may play a coordinating role in information exchange on the general technology status.

The IAEA Nuclear Power Technology Development Section (NPTDS) organized a technical meeting in 2016 to address some of the topics related to technology development. The meeting provided the participants from twenty Member States with the opportunity to share their programmes and projects and shape possible future collaborative efforts under the IAEA's auspices. The purpose of the meeting was to exchange knowledge on the status of research, technological developments, reactor designs and operational experience in the area of molten salt fuelled and cooled advanced reactors.

This meeting aimed to bring together all the important players and interested parties in the area of MSR technology development to present the status of their work and to explore the need for closer future collaboration among Member States within the framework of the IAEA.

The meeting initiated information exchange and sharing of experiences, with a view to understanding the technology development challenges faced by current designers of MSRs and facilitating a dialogue between interested Member States, the designers, researchers and technology holders to better understand each other's needs, requirements and capabilities.

3. Future vision: challenges and opportunities for fast reactors

The Generation IV (GEN IV) Technology Roadmap [3] prepared by GIF member countries, has identified six most promising advanced reactor systems and related fuel cycles having potential to meet the new technology goals to improve safety, sustainability, economic competitiveness and proliferation resistance. Among these systems, two fast neutron reactors cooled by liquid metal: SFR and LFR are considered by GIF.

The SFR system is identified in the Generation IV Technology Roadmap (see Ref. [3]) as "a promising technology to perform in particular the missions of sustainability, actinide management and electricity production if enhanced economics for the system could be realized".

The LFR is identified in the GEN IV Roadmap as "a technology with great potential to meet the needs for both remote sites and central power stations" [4]. The GEN IV Roadmap outlined also the R&D necessary to develop these concepts for potential deployment.

At present, there is a wide convergence on the choice of sodium as coolant, with oxide, metal (e.g. for high conversion ratio) or nitride fuel. However, it seems important to explore/develop a viable backup option, such as lead (or lead-bismuth) coolant with oxide or nitride fuel, or gas coolant with carbide fuel.

In this context, an innovative sodium-cooled prototype and a demo/experimental plant for exploring a backup option should/could be the focus of international initiatives.

The following major challenges of FR development have been recognized internationally:

4. IAEA activities in support of development of Fast Neutron Systems

Committed to the sustainability and addressing the technology progression, the IAEA provides support to the Member States covering all technical aspects of current, evolutionary and innovative fast reactors and subcritical hybrid systems R&D, design, deployment, and operation.

The Agency's activities in the field of advanced fast neutron systems research, technology development and deployment are implemented within the framework of the Technical Working Group on Fast Reactors (TWG-FR).

Since 1967, the TWG-FR (former IWG-FR) of the Department of Nuclear Energy represents the keystone of the IAEA's efforts in the field. It consists of a group of experts from the interested Member States who meet every year and provide advice and support programme implementation.

The TWG-FR assists in defining and carrying out the Agency's activities in the field of nuclear power technology development for fast reactors, in accordance with its Statute, and ensuring that all the activities are in line with expressed needs from Member States. It promotes in-depth scientific and technical exchange of information on national and multi-national programmes and new developments and experience, with the goal to identify and review problems of importance and to stimulate and facilitate cooperation, development and practical application of fast reactors and sub-critical hybrid systems. The TWG-FR also supports the publication of IAEA technical documents on different topics of fast reactors research and technology development.

The TWG-FR coordinates its activities with other IAEA projects, TWGs and units, especially the Technical Working Group on Nuclear Fuel Cycle Options (TWG-NFCO), the Department of Nuclear Safety and Security, and the International Project on Innovative Nuclear Reactors and the Fuel Cycle INPRO. It also cooperates with other fast reactors initiatives, implemented within the framework of international programmes such as the Generation IV International Forum (GIF), the Nuclear Energy Agency (OECD/NEA), the European Sustainable Nuclear Industrial Initiative (ESNII), etc.

Currently the TWG-FR consist of: eighteen full member countries (Belarus, Brazil, China, France, Germany, India, Italy, Japan, Kazakhstan, Republic of Korea, Netherlands, Russian Federation, Slovakia, Sweden, Switzerland, Ukraine, UK and USA), as well as the OECD/Nuclear Energy Agency, the European Commission (EC) and six observer countries (Argentina, Belgium, Czech Republic, Mexico, Romania and Spain) and the Generation IV International Forum (GIF)

On the basis of the IAEA priorities related to nuclear energy, the TWG-FR recommendations, the interaction with other international agencies/initiatives (OECD/NEA, GIF, ESNII, etc.), as well as the awareness of the major challenges posed by the FR technology the fast reactor programme carried out by Nuclear Power Technology Development Section (NPTDS) of nuclear energy department of the IAEA is exploiting synergies by working with the INPRO initiative on the long term sustainability of nuclear energy. Implementation of the NPTDS activities planned for 2016-2017 is underway in an effective and timely manner, whukle the programme for 2018-2010 has been approved.

The IAEA programmatic areas in support of fast reactors correspond to the general structure of the NPTDS programmatic activities and have been specified by the TWG-FR as follows:

- Exchange of information and cooperation with other international organizations
- Modelling & Simulation and benchmarking activities for the V&V of nuclear codes for FRs
- Liquid metal cooled fast reactors (LMFR) technology
- Safety of fast reactors
- Education and Training
- Knowledge Preservation

4.1 International Cooperation and Information Exchange

The IAEA regularly organizes conferences, workshops, seminars and technical meetings in the field of fast reactors and related fuels and fuel cycles. The International Conference on Fast Reactors and Related Fuel Cycles, which is organized every four years, represents the most important event on fast reactors and related fuel cycle technology. The last two conferences FR09 and FR13 were held in Japan in 2009 and in France in 2013 respectively. The proceedings have been published by the IAEA [6, 7]. Key topics of the conferences were exchange of information on national and international programmes on fast reactors and related fuel cycles, and more generally on new developments and experiences in the field of fast reactors and related fuel cycles, innovative fast reactor development, coolant technologies, fast reactor component design, safety, materials, fuels and fuel cycles, experiments and simulation, experience in operation and decommissioning, knowledge management. FR13 conference and current FR17 conferences include a very interesting young generation event, dedicated to the young professionals involved in fast reactor and fuel cycle studies and projects.

The TWG-FR offers the largest international forum for exchange and transfer of information in the areas of fast neutron systems. IAEA has been supporting the Member States with a number of activities in the fields of safety, technology development, modelling and simulation, education and training, as well as fast reactor knowledge preservation.

The following objectives of international cooperation are supported and promoted by the TWG-FR. Respectively they are followed by the IAEA NPTDS within its programmatic activities:

- Create an effective platform for exchange of information and lessons learned;
- Carry out focused R&D activities on crucial issues;
- Agree and converge on safety approaches, design criteria and guidelines at the international level;
- Share experimental facilities;
- Develop, verify and validate advanced simulation tools through experimental benchmarking;
- Provide cutting-edge opportunities for education and training;
- Collect, retrieve, preserve and make available existing documents, data and information on fast reactors (i.e. guarantee knowledge preservation on fast reactors).

Several international initiatives have been established in the last years in order to promote cooperation among countries with innovative SFRs development and deployment programmes. The most relevant are the ones carried out under the auspices of the Generation IV International forum (GIF) and the IAEA, which have jointly committed to collaboration between the programmes and to share information in selected areas of mutual interest.

4.2 Modelling and Simulations: Benchmarking activities for the V&V of simulation codes for fast reactors

A successful development of innovative fast neutron systems is strongly linked to the development of powerful and reliable calculation methods and simulation tools to be used for the design and the safety assessment.

Given the wide range of activities and the strong interest of numerous IAEA Member States in this area, a Technical Meeting on “Priorities in Modelling and Simulation for Fast Neutron Systems” was held in April 2014.

The following overall scope and objectives of the IAEA activities in modelling and simulation (M&S) for fast neutron systems have been defined at the technical meeting:

- Promote the exchange of information on projects and programmes on M&S for fast neutron systems carried out at national and international level;
- Present and review advanced (e.g. multi-scale and/or multi-physics) M&S techniques under development worldwide for the design and the assessment of performances and safety of innovative fast neutron systems;
- Discuss accuracy and uncertainties affecting the simulation tools;
- Identify nuclear modelling improvement needs and priorities for further model developments;
- Discuss and propose international initiatives aimed at verification, validation and qualification of advanced simulation codes for fast neutron systems;
- Provide recommendations to the IAEA for future joint efforts and coordinated research activities.

The participants have provided a comprehensive list of priorities in the technical areas of neutronics, thermal-hydraulics, structural mechanics, fuel behaviour, safety, and multi-physics which has been endorsed by the TWG-FR, and this guided the IAEA programmes in the field.

Coordinated Research Projects (CRP) constitute important IAEA instruments for organizing international research work to achieve specific research objectives consistent with the IAEA programme goals in the area of FR modelling, simulations and benchmarking.

Several CRPs have been conducted since last FR13 Conference in Paris. IAEA have completed CRPs on Phenix End-of-Life Tests, Monju Natural Convection, and Benchmark on Accelerator-Driven Systems (ADS).

- The CRP on Control Rod Withdrawal and Sodium Natural Circulation Tests Performed during the PHENIX End-of-Life Experiments was aimed on improving analytical capabilities in the field of fast reactor simulation and design, with particular emphasis on temperature and power distribution calculations, and the analysis of sodium natural circulation phenomena. The specific research objectives of the CRP were: to perform preparatory analyses for two PHENIX EOL tests; to perform blind calculations prior to the tests; to perform the post-experiment analyses. The two PHENIX End-of-life tests have been analysed: "Control Rod Withdrawal Test" (Phenix_CRW) and "Sodium Natural Circulation Test" (Phenix_NCT). The "Control Rod Withdrawal Test" was performed both in the static and dynamic mode: the comparison of the results allowed sensitivity analyses of the two measurement methods, and provided the basis for improving the uncertainty in the determination of power distributions. The objective of the "Sodium Natural Circulation Test" was twofold: the study of the sodium natural circulation in the primary circuit and the determination of the efficiency of natural convection phenomena in the primary circuit, and the qualification of the system codes used to simulate natural convection phenomena. *Participants of the CRP: China, France, India, Japan, Republic of Korea, Russian Federation, Switzerland, and United States of America (two institutes)*
- CRP on Benchmark Analyses of Sodium Natural Convection in the Upper Plenum of the MONJU Reactor Vessel was aimed on improving analytical capabilities in the field of fast reactor in-vessel sodium thermal hydraulics. In particular, the CRP addressed the natural convection behaviour of the coolant in the reactor vessel of a sodium cooled fast reactor. In particular, a review of the detailed description of the boundary conditions of the above mentioned test, as well as of all the experimental data obtained (various sodium temperature distributions in the upper plenum) and specification of the benchmark models has been made; validation of various multi-dimensional fluid

dynamics codes in use in Member States through simulation of sodium cooled fast reactor outlet plenum temperature distributions and comparison with experimental data have been [performed; the weaknesses in current methodologies (e.g. with regard to turbulence models, reactivity feedback models, etc.) and the R&D needs to resolve the identified open issues have been identified. *Participants of the CRP: China, France, India, Japan, Republic of Korea, Russian Federation, and United States of America (two institutes)*

- CRP on Analytical and Experimental Benchmark Analysis of ADS was aimed at *developing and applying advanced technologies in the area of long-lived radioactive waste utilization and transmutation via ADS.* Specific objectives of the study were to: improve the understanding of the coupling of an external n source with a multiplicative sub-critical core; integrate some of the experimental demonstration projects of the coupling between a sub-critical core and an external neutron source (e.g. YALINA Booster, pre-TRADE, KUCA); validate computational methods through analytical and experimental benchmarking; obtain high energy nuclear data; characterize the performance of sub-critical assemblies driven by external sources; develop and improve techniques for sub-criticality monitoring. This study resulted in a new TECDOC, which is currently in progress. *Participants of the CRP: 28 participants from 19 countries. Argentina, Belarus, Belgium, Brazil, China, France, Germany, Greece, Hungary, Italy, Japan, The Netherlands, Pakistan, Poland, Russian Federation, Spain, Sweden, Ukraine, and the USA.*

There are three on-going CRPs being conducted by the IAEA on FR modelling, simulations and benchmarking.

- The CRP on Benchmark Analyses of an EBR-II Shutdown Heat Removal Test (SHRT) addressed the SHRTs performed at the Experimental fast Breeder Reactor EBR-II within the framework of the US Integral Fast Reactor development and demonstration programme. The participants have already produced detailed results both of the blind calculations and the refined simulations on the basis of the experimental data provided by the Argonne National Laboratory. The CRP is practically completed, which allowed improving the participants' simulation capabilities in the various fields of research and design of sodium cooled fast reactors through data and codes validation and qualification. The scope of the CRP was twofold: firstly, validation of the state-of-art liquid metal cooled fast reactor codes and data used in neutronics, thermal hydraulics and safety analyses, and, secondly, training of the next generation of fast reactor analysts through international benchmark exercises. Up to now, the verification and validation exercise have been accomplished. Compilation of final simulation results and development of the consolidated IAEA TECDOC had been finished in the end of 2016. The EBR-II TECDOC is in publishing now. A special session on this conference is devoted to the recently completed CRP on EBR-II shutdown heat removal tests. *Participants of the CRP: 20 organizations from 12 countries: China, France, Germany, Italy, India, Japan, Republic of Korea, The Netherlands, Russian Federation, Switzerland and the USA.*
- The CRP on sodium properties and safe operation of experimental facilities in support of the development and deployment of sodium cooled fast reactors (NAPRO) is focused on the need for a consistent and up to date sodium property data for use by IAEA Member States. In addition, some Member States have expressed their interest in an international effort focused on obtaining and sharing design approaches and guidelines, best practices for operation, and safety of sodium experimental facilities including prevention and mitigation of sodium leaks, prevention and detection of sodium fires, assessment of

sodium impact in the environment after accidental release, hydrogen hazards in cleaning facilities, etc. *Participants of the CRP: Argentina, China, France, Germany, India, Republic of Korea, The Netherlands, Russian Federation, and the USA;*

- The CRP on radioactive release from the prototype sodium cooled fast reactor (PSFR) under severe accident conditions (PSFR Source Term CRP) has been approved and launched. It is focused on evaluation of transport of fission products, sodium and other radioactive materials from the melted core to the cover gas, ejection of fission products, sodium, fuel particles through the penetrations of the top shield reactor structure directly into the containment system and indirectly through the argon cover gas system, and transport of fission products and other radioactive materials through the different containment compartments under various thermodynamics conditions. *Participants of the CRP: 10 institutions from: Canada, China, France, Germany, India, Republic of Korea, Russian Federation, and EC-JRC.*

A new CRP on Benchmark Analysis on reactor physics start-up tests of the CEFR (China Experimental Fast Reactor) is planned. Expression of interest by Members states is in process.

4.3 Technical Support to Member States on liquid metal-cooled fast reactor technologies

In the field of liquid metal cooled fast neutron systems (LMFNS) the IAEA recognizes the importance of international collaboration in the area of gathering data and developing further knowledge related to fast neutron systems development, as well as verification, validation and qualification (V&V&Q) of simulation codes used for the design and the safety analysis of innovative reactors. From this viewpoint, the IAEA fulfils its function in establishing and coordinating the international efforts.

In addition, international coordination and collaboration allows sharing and effective use of the simulation codes, experimental data, and facilities.

In this regard, the identification of the existing experimental infrastructures, as well as of the new experimental facilities based on the recognized R&D needs in the Member States with fast reactor programmes has been performed.

A newly developed catalogue of experimental facilities in support of Development and Deployment of Liquid Metal Cooled Fast Neutron Systems (LMFNS Catalogue) presents an overview as well as detailed information on more than 150 experimental facilities under design, construction or operation in 14 IAEA Member States.

The LMFNS Catalogue contains detailed data and information on 79 facilities in support of the development of sodium cooled fast reactors (SFR), as well as 72 facilities in support of lead and lead-bismuth eutectic cooled fast reactors (LFR). Several facilities are applicable to both SFR and LFR technologies. The detailed facility profiles are categorized according to their most relevant research fields (main application). Multiple-choice filtering options by main research fields, by reactor type (SFR, LFR, cross-cut SFR/LFR application) and by country are available.

By providing the end-users with detailed information on existing and future experimental facilities able to support innovative LMFNS, the open database is aimed at facilitating cooperation between organizations with an active programme on fast neutron systems. It is expected that it will enhance the utilization of these facilities within the associated experimental programmes, and motivate the involvement of young engineers and researchers to be educated and trained in the field of advanced reactors [6].

The newly developed database "Catalogue of Experimental Facilities in support of Development of Liquid Metal Cooled Fast Neutron Systems (LMFNS catalogue)" is available on the web [7]

A related IAEA Nuclear Energy Series publication is expected to be published in 2017.

4.4 Fast Reactors Safety

Enhanced safety has always been a pressing issue and nuclear safety has been dealt with utmost importance in Member States and nuclear industry.

Various CRPs in the area of thermal-hydraulics and safety analysis have been initiated and successfully completed by the IAEA to improve the modelling and simulation capabilities. The recent and ongoing activities run by the NPTDS are:

- CRP on radioactive release from the prototype sodium cooled fast reactor (PSFR) under severe accident conditions (PSFR Source Term CRP) has been approved and launched;
- Study on Safety Design Criteria and Guidelines for GENIV SFR is being jointly implemented with GIF. Annual IAEA-GIF workshop on safety of SFR are held. Sixth meeting took place in November 2016;
- Possible extension of the previous two activities to LFRs is considered;
- Technical Meeting on Passive Shutdown Systems for LMFR Vienna, 20 -22 October 2015 (see a detailed description below);
- Two new studies on relevant aspects of FR safety have been launched in 2016:
    - Update of the IAEA-TECDOC-1180 “Unusual occurrences during LMFR operation” (proceedings of a TM held in November 1998)
    - LMFR Passive Shutdown Systems

4.4.1 Passive shutdown systems for Fast Reactors

Modern reactor technologies incorporate inherent and passive safety features significantly. A major focus of the design of modern fast reactor systems is on inherent and passive safety. The designs of passive shutdown safety systems have reached various levels of maturity and there is need for information exchange related to development, design and operational experience linked to these systems.

Challenges facing the designer of passive shutdown systems include: speed, reliability and predictability of actuation during accident scenarios; testability during operation; lifetime and performance degradation issues; impact on core operation; impact on neutron economy and core design; accurate modelling in safety analysis; needed qualification programs and related costs.

A technical meeting on passive shutdown systems for LMFR was held in October 2015 in order to: promote the exchange of information on projects and programmes dealing with passive shutdown systems for LMFR at the national and international level; present and review advanced safety shutdown system concepts and their impact on core performance, operation, cost and safety; identify transients for which the safety shutdown systems are efficient and analyse the transients for which these systems could have a negative behaviour; discuss the accuracy of the simulation tools used in the analysis of safety shutdown systems and any uncertainties that may affect these; identify needs and priorities for the improvement of system design and modelling to be taken into account in the further development of safety shutdown systems and discuss and propose international initiatives aimed at the V&V&Q of simulation codes used for the analysis of safety shutdown systems.

A NES technical report on "Passive Shutdown Systems for Fast Neutron Reactors" is being prepared to summarise the results of this activity. This document (at final draft stage) will help in identifying priorities based on the analysis of technology gaps to be covered through research and development activities. With a consolidated contribution not only from innovative but existing systems, this document will provide a strong reference for future FNS programs in this area and will help in the R&D needs. The assessment of passive safety systems often requires advanced Modelling and Simulation (M&S), which is complex due to sensitivity to multiple phenomena. The document will help in identifying and analysing current M&S capabilities along with recommendation for future requirements, which is also not yet available in a comprehensive manner.

4.4.2 GIF–IAEA programmes on safety design criteria and guidelines

One of the key areas of emphasis in both the GIF and the IAEA programmes is the safety of SFR and in particular the harmonization of safety approach, safety requirements, safety design criteria (SDC) and guidelines (SDG) for the next generation SFRs under development worldwide. This topic has gained an increased importance in the aftermath of the accident that occurred in 2011 at the Fukushima Daichi NPP, which has drawn renewed attention on nuclear safety and on the importance of an international safety framework for reactors currently in operation as well as new designs.

The development of the SDC was initiated by the GIF Policy Group (PG) in 2011 in order to harmonize safety requirements among the design organizations represented within GIF, and to quantify the high level of safety expected for GEN-IV systems. The SDC, derived from the Generation IV programme goals and developed consistently with the structure of the IAEA safety standards, have been compiled into a Phase 1

Six IAEA-GIF workshops on safety of SFR have been running for the last 6 years. These workshops have contributed to developing SDC and SDG for SFR, which are considered by developers and designers of innovative SFR. These criteria and guidelines are now under review by Regulators of Member States and International Organizations. At the sixth joint IAEA-GIF Workshop on Safety of SFR held in Vienna on 14-15 November 2016 in-depth discussions on the development of SFR SDC/SDG have been continued. A review including detailed comments by IAEA on GIF SDG report on safety approach, the feedbacks and update of GIF SDC report, technical knowledge on the implementation of the SDC/SDG for the innovative SFR design concepts has made. It was concluded that it is important to continue conversation on SFR safety among stakeholders such as GIF, IAEA, developers and regulators/TSOs.

4.5 Education & Training;

In the interrelated area of education and training a principle-based simulator of an innovative generic design SFR is under development. The development of PC based SFR Simulator for Educational Purposes was initiated by the requested by the TWG-FR to support better understanding of fast reactor physics and technology. This activity was co-funded by the IAEA, MEXT, Japan and some interested MSs provided in-kind contributions. The specification for the SFR simulator has been developed. The final detailed technical specification prepared by IAEA is ready for implementation.

Numerous IAEA workshops and schools on innovative nuclear energy systems have been organised. The ICTP-IAEA workshop is regularly held and received high recognition from the IAEA Member States. The recent course of the *Joint ICTP-IAEA workshop on the Physics and Technology of innovative nuclear energy systems for sustainable development was held* 29 Aug - 02 Sept 2016, Trieste, Italy, imparted theoretical foundation of all aspects of innovative nuclear energy systems; familiarized students with models and codes for design and safety analysis; provided an active forum for sharing new ideas

4.6 Knowledge preservation and management

In response to needs expressed by the Member States and within a broader IAEA wide effort in nuclear knowledge preservation, in order to foster the exchange of technical information and to contribute to the preservation of the knowledge base of fast reactor technology, since 2002 the IAEA has been carrying out a dedicated initiative on fast reactor knowledge preservation (FRKP).

The main objectives of the FRKP initiative are to:

- Halt the ongoing loss of information related to FR;
- Collect, retrieve, preserve and make accessible already existing data and information on FR.

These objectives require the implementation of activities supporting digital document archival, data exchange, search and retrieval, as well as facilitating knowledge preservation over the next decades by developing and using advanced information technology tools.

For this purpose, the IAEA developed a new FRKP portal, which provides users with authorized access to:

- Any fast reactor related documentation that Member States wish to share;
- Full papers and other materials of consultancies and technical meetings;
- Documentation from CRPs including the public and working materials;
- Former reports (which will remain available through the INIS repository);
- Document repositories on SharePoint.

Unlike International Nuclear Information System (INIS), which manages publically available information, the FRKP portal is envisioned to control and manage both publically available as well as restricted forms of information. The FRKP portal is designed for the use by a specific community. However web pages providing general information about the FRKP portal, taxonomy applied in the portal have been created and published.

The IAEA knowledge preservation initiatives and tools in the field of fast neutron systems are designed to be of interest to national nuclear authorities, regulators, scientific and research organizations, commercial companies and all other stakeholders involved in fast reactor activities at national or international level like designers, manufacturers, vendors, research institutions, academia, technical support organizations (TSO), safety authorities, etc.

5. Conclusions

Under the project on advanced technology for fast and gas-cooled reactors, the IAEA is carrying out several activities on innovative nuclear systems technology development including

- Modelling and Simulations,
- Technical Support to IAEA Member States,
- Fast Reactors Safety,
- International Cooperation and Information Exchange,
- Education and Training, and
- Knowledge Preservation.

Technical Working Group on Fast Reactors (TWG-FR) is the major IAEA advisor in the field. Eighteen member states and two international organizations are represented in the TWG-FR while six other countries and Generation-IV International Forum (GIF) are observers. Coordinated Research Projects (CRP) are important IAEA instruments for supporting international research work to achieve specific research objectives consistent with the IAEA programme goals. Several CRPs on fast reactor technology have been conducted during last years. IAEA have completed CRPs on Phenix End-of-Life Tests, Monju Natural Convection, and Benchmark analyses on Accelerator-Driven Systems (ADS). A CRP on benchmark analysis of EBR-II shutdown heat removal tests has also been recently completed. A CRP on radioactive release from the prototype sodium cooled fast reactor under severe accident conditions is ongoing. Another in-progress CRP is NAPRO, "Sodium Properties and Safe Operation of Experimental Facilities in Support of the Development and Deployment of Sodium-cooled Fast reactors. A new benchmark CRP on CEFR Physics Start-Up Experiments has been recently proposed by CIAE (China) and endorsed by the TWGFR. In addition IAEA is conducting study on passive shutdown systems for fast neutron reactors, an initiative on knowledge preservation, joint IAEA-GIF initiative on safety of GEN-IV sodium cooled fast reactors. There are also a number of activities in the field of fast reactor education and training, including the development of a PC based principle based simulator of an innovative SFR as well as annual schools and workshops on innovative nuclear systems.

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