TM-50159

TWG-FR/156

IAEA
International Atomic Energy Agency
Atoms for Peace

WORKING MATERIAL

Technical Meeting on Passive Shutdown Systems for Liquid Metal-Cooled Fast Reactors

IAEA Headquarters
Vienna, Austria

20 – 22 October 2015

Ref. No: I3-TM-50159

Reproduced by the IAEA

Vienna, Austria, 2015

CONTENT

MEETING REPORT

I. Background

A major focus of the design of modern fast reactor systems is on inherent and passive safety. Inherent safety means that the reactor design is such that the plant remains in a safe condition solely on the basis of the laws of nature; these laws ensure that all performance characteristics remain within safe bounds under all conceivable circumstances. The definition of passive safety is broader, and implies that no human intervention, no triggering signals and no supply of external energy are required for the reactor to remain in a safe condition. Inherent and passive safety features are especially important when active systems such as the SCRAM-systems for reactor shutdown are not functioning properly. Passive shutdown systems can operate either continuously (analogous to reactivity feedback mechanisms) or function as a backup actuation method for the conventional reactor SCRAM system.

Specific systems to improve reactor safety performance during accidental transients have been developed in nearly all fast reactor programmes, and a large number of proposed systems have reached various stages of maturity. 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
- Costs

The most well-known approaches in shutdown system design can be categorized by their actuation principle as follows:

1. Flow
    a. Flow-levitated absorbers
    b. Neutron leakage probability adjustment (Gas Expansion Module)
2. Coolant temperature
    a. Lithium expansion modules

   b. Lithium thermostat module

   c. Enhanced control rod driveline expansion

   d. Autonomous Reactivity Control (ARC)

3. Curie-point temperature actuated absorbers

4. Rupture discs

Categories 1 and 2 represent continuously operating and self-resetting systems, while categories 3-4 consist of alternative (passive) methods of reactor SCRAM. Category 1 responds only to changes in the primary coolant flow rate, while Categories 2-4 respond to temperature and thus actuate during any postulated accident that raises temperatures above set limits. The objective of all systems (or combination of systems) is to increase margins to failure and avoid coolant boiling during very severe unprotected transients when the conventional SCRAM systems are not functioning as designed.

A technical meeting on this subject has been recommended by the IAEA Technical Working Group on Fast Reactors (TWG-FR) which represents the ideal context for an international discussion on this topic. It should be noted that this meeting was limited to *shutdown* systems only, and did not include other passive features such as natural circulation decay heat removal systems; however the meeting was open to passive shutdown safety devices applicable to all types of fast neutron systems (SFR, LFR, GFR, ADS, etc).

This Technical Meeting on Passive Shutdown Systems for Fast Reactors addressed Member States' expressed need for information exchange on projects and programmes in the field, as well as for the identification of priorities based on the analysis of technology gaps to be covered through R&D activities to be carried out at the international level under the IAEA's aegis.

II. Objectives

The main purpose of the Technical Meeting on Passive Shutdown Systems for Liquid Metal-Cooled Fast Reactors was to:

- Promote the exchange of information on projects and programmes on passive shutdown systems for fast reactors at the national and international level;

- Present and review advanced engineered shutdown safety system concepts and their impact on core performance, operation, cost and safety;

- Identify transients for which the shutdown safety systems are efficient and analyze the transients for which these systems could have a negative behavior;

- Discuss the accuracy of the simulation tools used in the analysis of shutdown safety 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 shutdown safety systems;
- Discuss and propose international initiatives aimed at the V&V&Q of simulation codes used for shutdown system analysis; and
- Provide recommendations to the IAEA for future joint efforts and coordinated research activities in the field.

III. Opening Session

The participants were welcomed by the Director of NENP Mr Dohee HAHN who provided the following opening remarks:

Good morning, everybody.

On behalf of the International Atomic Energy Agency, I would like to welcome you all to Vienna and to the Technical Meeting on Passive Shutdown Systems for Liquid Metal Cooled Fast Reactors.

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

In this effort, the Nuclear Power Technology Development Section of the IAEA has shown a continuous commitment, often in cooperation with the Department of Nuclear Safety and Security, the Generation IV International Forum and INPRO.

A series of IAEA/GIF Workshops on safety of Sodium-cooled Fast Reactors has been running for the last 5 years. These workshops have contributed to developing Safety Design Criteria and Safety Design Guidelines for Sodium-Cooled Fast Reactors, 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.

Various CRPs in the area of thermal-hydraulics and safety analysis have been initiated and successfully completed to improve the modelling and simulation capabilities. A new CRP on the assessment of a postulated severe accident in the Prototype Fast Breeder Reactor is just about to start.

This Technical Meeting represents another effort in the same framework.

Modern reactor technologies incorporate inherent and passive safety features significantly. 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.

It is very important to gather feedback from different organizations involved in developing these kinds of innovative devices. It is also important to identify transients for which the shutdown safety systems are efficient and to analyze the transients for which these systems could have a negative behavior.

As mentioned earlier, there has been significant emphasis on building modelling and simulation capabilities. Our meeting will augment the purpose with progressive exchange of information related to analysis of safety shutdown systems using different simulations tools. The purpose is to build up better understanding of the engineering solutions and their impact on the safety characteristics of LMFR, as well as to facilitate their development and deployment. I am confident that the upcoming sessions will serve the purpose.

I would like to thank Stefano, who is currently serving dual responsibilities as the section head of NPTDS and as the team leader for fast reactor group, for arranging and conducting this important meeting. I would also thank the Technical Working Group on Fast Reactor, which recommended this intriguing and crucial topic for international experts' discussion.

Now the onus is on you to make this meeting constructive and productive. The course of this meeting will be demanding, however, I am certain the outcomes will be far-reaching. Thank you all once again for taking the time to make this meeting successful.

With this short remark, I now declare this Technical Meeting open.

After opening remarks, the meeting participants agreed to appoint *Mr Staffan Qvist* from Sweden to chair the meeting.

The participants agreed the meeting agenda reported in Annex II. The list of participants is reported in Annex III.

Mr Stefano Monti, scientific secretary of the meeting gave a brief overview of the IAEA activities in the field of safety of Fast Reactors and defined the outline of the Technical Meeting. After defining the mission of the department of Nuclear Energy (NE) and Nuclear Power Technology Development Section's (NPTDS) activities he focused on the rationale and programmatic approach for the IAEA fast reactor activities describing in detail the challenges and opportunities for fast reactor technology development. He also discussed the key activities in the area of safety undertaken by the section and provided update on the development of the Safety Design Guidelines (SDG) and Safety Design Criteria (SDC), which is a part of a joint effort between the generation IV International Forum (GIF) and the IAEA. Special discussion was done on the passive shutdown systems in SFR-SDC phase 1 report. After declaring the objectives and rationale of this Technical Meeting, the floor was opened for the participants to present individual contributions.

IV. Summary of Technical Contributions by Participants

As provided by the participants of the Technical Meeting.

i. Belgium

MYRRHA shutdown systems
D. Lamberts, SCK-CEN

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is the flexible experimental accelerator driven system (ADS) in development at SCK•CEN. MYRRHA is able to work both in subcritical (ADS) as in critical mode. In this way, MYRRHA should target the following applications catalogue:

- To demonstrate the ADS full concept by coupling the three components (accelerator, spallation target and sub-critical reactor) at reasonable power level to allow operation feedback, scalable to an industrial demonstrator;
- To allow the study of the efficient technological transmutation of high-level nuclear waste, in particular minor actinides that would request high fast flux intensity
- To be operated as a flexible fast spectrum irradiation facility allowing for:
  - fuel developments for innovative reactor systems,
  - material developments for GEN IV systems, in various irradiation positions, representative irradiation temperature and representative neutron spectrum conditions; the main target will be fast spectrum GEN IV systems;
  - material developments for fusion reactors
  - radioisotope production for medical and industrial applications

MYRRHA is a pool-type system. The reactor vessel houses all the primary systems. The vessel is closed by the reactor cover which supports all the in-vessel components. A diaphragm inside the vessel functions to separate the hot and cold lead-bismuth eutectic (LBE), to support the In-Vessel Fuel Storage (IVFS) and to provide a pressure separation. The core is held in place by the core support structure consisting of a core barrel and a core support.

Positions are available for Multi-Functional Channels (MFC) that can host indifferently:

- fuel assembly and dummy, loaded from the bottom
- IPS, control and scram rods, loaded from the top.

Control rods are extracted downward and rise up by buoyancy in case of SCRAM.

Control rods are placed near the periphery in order to reduce their disturbance on the flux in the middle of the core. Indeed while the reactor is operating, the control rods are most of the time in an intermediate position (partly inserted) allowing reactor tuning. They also have fast shut down ability build in and act as a first Reactor Shutdown System (RSS1).

Safety rods are fully extracted during operation. They are fully inserted in case of fast shut down (SCRAM) and act as a second diverse Reactor Shutdown System (RSS2).

The system has to be robust and simple as possible. The system is engineered so that failure is preferably in the inserted position. In case of loss of signal or (and) power source SCRAM must be passively triggered. Failure driving to extraction should be avoided. The system must allow rod insertion even in case of guide deformation. These systems have ability to be tested in situ and are monitored.

MYRRHA has already inherent safety characteristics, temperature reactivity feedback are negative even concerning temperature of coolant itself. The behavior of core under postulated events is already satisfying.

These systems are actively triggered but passively actuated. In order to improve the passivity of the system, we have studied the implementation of temperature switch, giving a non-intelligent circuit breaking. An advantage is that the sensed temperature could be distributed at several fueled position (where the temperature change is most significant) and it triggers the full insertion of an RSS driving to cold shutdown state.

ii. France

Reflections on the assessment of passive shutdown systems
O. Baudrand, IRSN

Passive shutdown systems (PSS) have been envisaged in the past project EFR developed in the 90's. In practice, passive devices would have not replaced active shutdown systems. The PSS were proposed as a supplementary provision against core meltdown accident. The objective was to enhance the reliability of the emergency shutdown function by adding a completely independent and diversified "third shutdown system" (two active shutdown systems were envisaged in the basic design). In this frame, their efficiency was required essentially in case of postulated failure of the two active shutdown systems. It is to be noted that this approach is consistent with the required independence of the defense-in-depth levels.

The IRSN considers that the shutdown system (I&C plus absorber rods and dedicated subassemblies) is of particular importance due to core physics typical of LMFRs. In relation to this, specific technical capabilities should be proven:

- fast actuation and fall-down to cope with fast reactivity transients,
- effectiveness under earthquake loading (insertion capability in case of core deformation),
- actuation of the system in case of local subassembly fault (requires enhancement of detection for large cores),
- effectiveness in case of partial core degradation

In addition the shutdown system is needed to compensate for the positive coolant void effect (local or global void effect).

In a primary approach, passive systems should comply with standard safety requirements applicable to high level graded safety systems:

- their architecture should ensure redundancy of the safety function performed;
- passive systems should be routinely tested and controlled;
- they are protected to remain operative in case of external and internal hazards (fire, flooding, earthquakes, etc.);
- they should comply with quality and fabrication standards corresponding to their importance for safety.

In general, PSS are deemed more reliable than active ones because:

- they don't rely on I&C and actuators but are directly activated by a modification of the physical state of the core and coolant,
- plant operators have no direct interaction with these systems (activation, set-up of thresholds, etc.), thus minimizing the risk of human error.

Formally, the deterministic safety assessment of PSS should not be different from the one applied to active systems. But several questions arose when applying the standard assessment methods:

- When a safety function is performed by active and passive systems, should the single failure criterion be applied to passive systems?
- What kind of uncertainties should be explored in the performance analysis?
- Are the qualification procedures different from those applicable to active systems?
- How to ensure the sustainability of the performance of the PSS?

Regarding the last point above, it is to be noted that in service inspection and routine test might be an issue for some of the envisaged concepts.

Finally, the assessment of passive systems often requires some modelling which might be complex because of sensitivity to multiple phenomena; generally low driving forces, scale effects, etc.

To address the above questions for passive systems in general, the IRSN has recently set up an internal working group to define a deterministic and probabilistic assessment methodology. In parallel, discussions are organized with designers and plant operators (AREVA, CEA, EdF). These discussions should lead to the definition of a R&D program to investigate several specific passive systems designed for PWRs. Among LMFR concepts, the IRSN effort is concentrated on SFR in the frame of the development of the ASTRID Project. Actions are being carried out mainly in the domain of thermal hydraulics through the development and validation of the computer code ASTEC-Na (computation of Phénix natural convection tests, JASMIN European project, etc.).

iii. Germany

Assessment of the efficiency of a passive safety system for prevention of severe accidents for SFR
E. Bubelis, KIT

The aim of the study was the evaluation of severe transient behavior in Sodium-cooled Fast Reactor (SFR) and of the impact of newly conceived inherent mitigation measures (the use of ASD – additional shutdown device). The SFR design taken for the analysis was the SFR(v2b-ST) reactor design, and the system code to be used was selected to be the SIM-SFR code. The transients chosen for evaluation of the efficiency of mitigation measures were the unprotected loss-of-flow (ULOF) and the unprotected loss-of-heat-sink (ULOHS).

This analysis demonstrated that:

- The sodium-cooled reactor design, called "SFR(v2b-ST)" design, is a viable core and primary system design under nominal power conditions;
- Under ULOF conditions and without a third shutdown (ASD based) safety system, a parameter study has shown, that at least three design modifications need to be made to the SFR(v2b-ST) system design in conjunction in order to accommodate a ULOF – a different primary pump with a run-down characteristic similar to the SPX1 pump would be required in conjunction with an increased height differential between core and the IHX up to at least 4.6 m, and a decrease of the primary system nominal pressure drop down to 2.15 bars;
- Aside of the above indicated design modifications, the only other remaining alternative to the basic SFR(v2b-ST) design would be the introduction of an additional independent device called ASD, as proposed by AREVA, based on fusible materials releasing B_4C absorber pebbles into the fissile core region once certain system temperatures should exceed specified temperature limits;
- Using such an ASD system in the central fuel pins in all of the SAs (or a certain limited fraction, but not less than 50%), this study has shown the effectiveness of such a system in limiting the consequences of a ULOF and ULOHS, should the proposed ASD design actually function within the parameter range as being investigated.

iv. Italy

Analysis of Solutions for Passively Actuated Safety Shutdown Devices
L. Burgazzi, ENEA

In order to enhance the inherent safety of Fast Reactors, innovative reactivity control systems have been proposed for intrinsic ultimate shut-down instead of conventional scram rods, to cope with the potential consequences of severe unprotected transient accidents, such as an energetic core disruptive accident, as in case of Sodium Fast Reactors.

The passive shut-down systems are designed to shut-down system only by inherent passive reactivity feedback mechanism, under unprotected accident conditions, implying failure of reactor protection system. They are conceived to be self-actuated without any signal elaboration, since the actuation of the system is triggered by the effects induced by the transient like material dilatation, in case of overheating of the coolant for instance, according to Fast Reactor design to meet the safety requirements.

This article looks at different special shutdown systems specifically engineered for prevention of severe accidents, to be implemented on Fast Reactors, with main focus on the investigation of the performance of the self-actuated shutdown systems in Sodium Fast Reactors.

v. India

Design philosophy of shutdown systems for future FBRs
R.Vijayashree, IGCAR

India is planning to construct 600 MWe Fast Breeder Reactors beyond Prototype Fast Breeder Reactor (PFBR). The design of these reactors is being augmented from that of PFBR both in terms of economics and safety. The safety criteria for the next generation of FBRs are being evolved taking into account the worldwide trend. This paper briefs the significantly new criteria pertinent to the shutdown systems in the currently evolving safety criteria. According to the evolving criteria the plant shall be designed such that it can be brought into a controlled state from any accident scenario and the containment function can be maintained so that significant radioactive releases would be practically eliminated. This requires identification of design extension conditions in which accidents that are more severe than DBAs or those involve additional failures are to be addressed. This paper briefs about the design extension conditions that would be addressed by shutdown systems and the philosophy adopted to finalize the configuration of shutdown of system for future SFR so as to practically eliminate significant radioactive release to public.

Passive shutdown devices under development for future FBRs
R.Vijayashree

India is planning to construct 600 MWe Fast Breeder Reactors beyond Prototype Fast Breeder Reactor (PFBR). PFBR has two independent fast acting shutdown systems. The absorber rods of the first system are called as control and Safety Rod (CSR) and that of the second system are called as Diverse Safety Rods. Future FBRs will also have two fast acting diverse and independent shutdown systems with few significant augmentations. For the first shutdown system in addition to CSR, in few core locations hydraulically suspended absorber rods (HSAR) are planned to be provided. In order to reduce the consequences due to inadvertent withdrawal of Control and Safety Rod, it is proposed to introduce a stroke limiting devise for the CSRs that are used for power control also. Temperature sensitive magnetic switch that would switch of the current to the electromagnet holding the DSR is planned to be provided as a passive shutdown feature to the second shutdown system. Further special core subassemblies to be inserted in the reactor core at suitable locations are being developed. Different versions of these devices are being developed mainly to take care of design extension conditions where the first two active systems are assumed to have failed. These devices are being designed such that beyond the failure of the two shutdown systems on further rise in outlet temperature of these assemblies, poison would get injected in to the active core zone. This paper briefs about the above mentioned various passive shutdown features/devices under development.

vi. Korea, Republic of

Design Study for Passive Shutdown System of the PGSFR
J. H. Lee, KAERI

There have been no experiences of implementing a passive shutdown system in operating or operated SFRs around the world. However, new SFRs are considered to adopt a self-actuated shutdown system (SASS) in the future to provide an alternate means of passively shutting down the reactor.

The Prototype Gen-IV SFR (PGSFR) developed by KAERI also adopts this system for the same reason. This passive shutdown design concept is combined with a group of secondary control rod drive mechanisms (SCRDM). The system automatically releases the control rod assembly (CRA) around the set temperature, and then drops the CRA by gravity without any external control signals and any actuating power in an emergency of the reactor.

This paper describes the parametric design study of a passive shutdown system, which consists of a thermal expansion device, an electromagnet, and a secondary control rod assembly head. The conceptual design values of each component are also suggested. Parametric calculations are performed to check the suitability of the performance requirements of the thermal expansion device and electromagnets.

The thermal expansion difference is calculated in the range of 1.7 ~ 2.6 mm for the 2.86 m long expansion device of the PGSFR, an additional design study to trigger off the CRA by utilizing the limited length is ongoing.

The electromagnetic forces on the CRA with a 1 mm air gap are in the range of ~ 300 N. Thus, the thermal expansion difference of the thermal expansion device to trigger off the CRA shall be controlled within 1 mm at the setting temperature. Design feasibility tests using the several test mockups of the thermal expansion device as a passive concept of the PGSFR are being performed.

vii. Romania

ALFRED Demonstrator – Safety Rods System
D. Gugiu, INR

The main goal of the ALFRED project is to play the role of a demonstrator for the European concept of a LFR, able to prove the safety and reliability in all operating conditions through the use of some simple engineering solutions while reducing to the largest possible extent the uncertainties related to all development stages: design, construction and operation.

The ALFRED core has been designed taking into account in a comprehensive approach the main goals to be achieved, the safety performances required as well as the main technological constraints that should be fulfilled.

In this context and taking into account the topic of the meeting, the presentation is focused on the safety rod system that has been successfully adapted from the CDT-MYRRHA project.

The SRs targeted performances and their worth will be briefly presented.

Moreover, some results of the preliminary safety analysis will be provided with a focus on the most representative DBA and DEC events, as well as conclusions regarding the safety performances.

viii. Russian Federation

Passive Safety Components for Lead-Cooled Reactor Facilities
M.K. Sarkulov, NIKIET

There is a specific range of engineered features used traditionally in nuclear technology. As a rule, main reactivity control systems use conventional active actuators with solid-body control members and/or liquid systems with active injection of liquid absorber.

Other operation principles are normally chosen for additional systems.

Currently, the traditional approach to improving the reliability of a reactor facility suggests an increase in the number of safety components and systems which provide for mutual assurance or assist each other.

There is a great variety of additional reactivity control members designed for the reactor facility control and shutdown, including hydrodynamic members in the form of rods (acting from the coolant flow); floating-type members (absorbers and displacers); storage-type and liquid members (used in separate channels); bulk members (pebble absorber); gas-based members (with a gas absorber); shape-memory members and others.

Many of these use fluids either as the reactivity control agent (RCA) (liquid, gas, pebbles) or the actuation material (liquid or gas).

Hydrodynamic systems were introduced at Beloyarsk NPP Units 1 and 2 and proposed for use in other facility designs.

Gases and bulk materials have not been commonly accepted: the former because of the high cost of high-efficiency gaseous absorbers, and the latter because of the complecated monitoring of the bulk material position.

It is rather difficult and not always necessary to use the same engineering approaches in new lead-cooled reactor facilities as in traditional ones.

For example, hydrodynamic systems will require to introduce a separate channel for the active flow rate control and a circulation line. Liquid systems injecting the RCA into the coolant cannot be used because of the difficulty of the uniform RCA introduction and dissolution in the lead coolant and the potentiality of compounds to be formed with lead as well as the complexity of its further purification.

At the same time, the properties of lead make it possible to use it also for the performance of safety functions.

Liquid devices using albedo properties of lead and devices with floating solid-body RCA using Archimedes force as the driving force may be also considered as main safety features for lead-cooled reactors.

Dynamic processes in the BREST-OD-300 lead-cooled reactor facility are highly inertial thanks to its physical and neutronic properties. This makes it possible to reduce requirements to the speed of response of safety systems and to switch from active devices with external power sources to passive safety features.

Similarly to the development of traditional safety systems, passive safety components (devices) shall be designed according to the essential requirements of the nuclear regulations of the Russian Federation.

Along with moving away from the traditional approach to ensuring safety, certain regulatory requirements need to be revised. Some of these have been introduced in response to the peculiarities of traditional safety system devices and are inapplicable to new devices. For example, in view of the expectedly (justified) low probability of failure, the requirement for periodic serviceability inspections of event-actuated passive devices is often needless.

ix. Slovakia

Proposal of movable reflector for fast reactor design
B. Vrban, Slovak University of Technology

Since the transient behaviour of the reactor core depends also on the fraction of neutrons that leak out of the core, the core control and reactivity management may benefit from a system of partially moveable reflector incorporated in the design. In fast reactors a larger migration area leading to a significant leak of neutrons can be observed because especially the transport cross-sections are in general smaller as compared to light water reactors. The utilization of a moveable reflector system in conjunction with dedicated safety control rods can increase the ability of accident managing due to enhanced escaping neutrons which otherwise would be reflected back into the fuel zone. The paper demonstrates the possibility of better controlling the transient reactor by additionally moving selected reflector subassemblies equipped with the neutron trap. The main purpose of the analysis of the Gas-cooled Fast Reactor (GFR) presented in the full paper is investigation of the kinetic parameters and of the control and reflector rod worth, as well as optimization of the parts used for partial reflector withdrawal. The results found in this study may serve for future design improvements of other designs such as the liquid metal cooled fast reactors are.

x. Sweden

Autonomous Reactivity Control (ARC) Systems
Staffan A. Qvist, Uppsala University

The next generation of nuclear energy systems must be licensed, constructed, and operated in a manner that will provide a competitively priced supply of energy, keeping in consideration an optimum use of natural resources, while addressing nuclear safety, waste, and proliferation resistance, and the public perception concerns of the countries in which those systems are deployed. These issues are tightly interconnected, and the implementation of passive and inherent safety features is a high priority in all modern reactor designs since it helps to tackle many of the issues at once. To this end, the Autonomous Reactivity Control (ARC) system was developed to ensure excellent inherent safety performance of Generation-IV reactors while having a minimal impact on core performance and economic viability. Properly designed, the ARC-system can act as a thermostat in the core, autonomously controlling temperature without the need for any operator action, electrical systems or indeed any moving mechanical parts. This actuation responds to temperature and relies solely on the laws of physics, and is therefore an inherent feedback mechanism (akin to the fuel Doppler feedback), rather than an engineered "safety system". This paper covers the principles for ARC system design and analysis, the problem of ensuring ARC system response stability and gives examples of the impact of installing ARC systems in well-known fast reactor core systems. It is shown that even with a relatively modest ARC installation, having a near-negligible impact on core performance during standard operation, cores such as the European Sodium Fast Reactor (ESFR) can be made to survive any postulated unprotected transient without coolant boiling or fuel melting.

xi. Ukraine

Passive shutdown of NBW fast reactor using the Autonomous Reactivity Control (ARC) system
O. Fomin, Kharkov Institute of Physics and Technology

A great interest for the future power engineering presents the development of new concepts of nuclear fission reactors with the so-called intrinsic safety, in which the development of uncontrolled chain nuclear reaction is impossible due to the physical principles of their operation. One of such concepts, proposed by Lev Feoktistov in 1988, is based on the self-sustained nonlinear regime of the nuclear burning wave (NBW) in a fast reactor. The critical state in such a reactor is kept automatically without external control due to a special kind of the negative reactivity feedback inherent to this regime. However, this mechanism does not protect the reactor core from overheating at several types of accidents. For this purpose we intend to use the autonomous reactivity control (ARC) system that is actuated by the inherent physical property of thermal expansion, and does not have an identified failure mode that can introduce positive reactivity in to the core.

We present the results of computer simulation of the ARC system performance in the NBW reactor at the loss of flow accident in the second cooling circuit and during the restart of reactor operation after the accident. The problem is studied by means of numerical simulation of the NBW propagation in such a reactor with the depleted uranium metallic fuel and sodium as a coolant. For the neutronics simulation we use the deterministic approach based on solving the non-stationary neutron diffusion equation using the effective multi-group approximation together with a set of burn-up equations for fuel components and equations of nuclear kinetics for precursor nuclei of delayed neutrons. These calculations are complemented with the thermal-hydraulics simulation of the first sodium coolant circuit in the interaction with ARC system.

Our simulation shows that ARC system shutdowns the reactor in a few minutes without fuel and coolant overheating. We analysed also the interference between two negative reactivity feedback mechanisms inherent to the NBW reactor and ARC system, which appears in the form of certain oscillations of the flux in a few days after the reactor shutdown. As a result of this interference, the system stabilizes automatically at the acceptable temperature (below 550 ºC) when almost all intermediate isotope neptunium decays into plutonium.

xii. USA

US Experience and Current Activities Related to Passive Shutdown Systems for Sodium-Cooled Fast Reactors
M. T. Farmer, ANL

A major historical R&D focus area within the United States has been the development and demonstration of inherent safety principles and passive safety shutdown systems for sodium-cooled fast reactors. This presentation provides an overview of historical efforts in this area that included in-pile demonstration of the Gas Expansion Module (GEM) concept to achieve safe shutdown. This test was carried out in the Fast Flux Test Facility (FFTF) under conditions simulating an Unprotected Loss of Flow (ULOF) accident sequence. Similarly, landmark safety tests were carried out in the Experimental Breeder Reactor (EBR-II) at Argonne-West that demonstrated the inherent shutdown characteristics of metal-fueled fast reactor cores during ULOF and Unprotected Loss of Heat Sink (ULOHS) sequences.

Aside from these in-pile demonstrations, there has also been considerable effort devoted to the development of levitated flow absorber concepts that intended to provide passive shutdown capability for large sodium fast reactor cores under Loss of Flow (LOF) conditions. This includes development of passive shutdown assembly concepts that include some novel approaches for de-latching and inserting the poison assemblies in a relatively short after pump trip at a variety of power levels ranging from 40 to 100 %.

Finally, the development of an Autonomous Reactivity Control (ARC) system is currently being pursued as part of collaboration between several universities and Argonne. This is a new safety device that can passively provide negative reactivity feedback in fast reactors that is sufficient to compensate for the positive coolant density reactivity feedback, even in large low-leakage cores.

V. A New Study

- ### IAEA Proposal

Mr Stefano Monti, the scientific secretary of the TM, explained different options of technical documents which can be published by the Department of Nuclear Energy, providing in particular details on the different review and approval processes for TECDOCs and NES technical Reports. It was then decided with mutual agreement by the participants to prepare a Document Preparation Proposal (DPP) to be submitted for approval to the Document Coordination Team (DCT) of the IAEA department of NE for a Nuclear Energy Series (NES) Technical Report. This choice will be confirmed when a first draft of the document will be available.

- ### MS proposal

After deciding the type of document to be produced for the new study, the members worked upon the content and structure of the document, this is shown in Annex I. It gives the content as well the person responsible for specific contributions.

The chairman for the whole NES technical report will be Mr Staffan Qvist.

The study will be conducted through at least two Consultancy Meetings at which representatives of MSs indicated by the participants to this meeting as well as by TWG-FR members not participating to this meeting (see also list of actions) will be invited by the IAEA in due course.

It was also agreed that the IAEA secretariat will draft a DPP for the new NES publication which will be distributed for comments and integrations before being submitted to the DCT

VI. List of Actions, Conclusions and Recommendations

The following list of actions was decided to be taken by the participating members.

List of Actions

1. Working Material and guidelines and example document to be finalized and distributed: IAEA, October 2015
2. Setup SharePoint access : IAEA (tabs for Meetings and by table of content), End of November 2015, End of December-operational
3. List of Additional Contributors to the Study: Russia: SEC-NRS, End of November 2015
4. List of Additional Contributors to the Study: JAEA, CEA, IRSN, China-CIAE.: IAEA, End of November 2015
5. Additional contributors from participating organizations: All, End of November 2015
6. First draft to be given to chapter coordinator: All, June, 2016
7. Reminder to contributors by chapter coordinators: All, April, 2016
8. NES document to be confirmed in First CM.
9. Distribute DPP: End of November 2015

With reference to the above mentioned list of action, the following major timeline events were established, which will be guiding dates for actions to be done.

Major Timeline events (tentative)

Task	Timeline
Setup SharePoint access	November, 2015
List of Additional Contributors to the Study	November, 2015
First CM	October, 2016
Second CM	June, 2017
Final Draft circulated among participants	September, 2017
Final Draft to the DCT	December, 2017

Conclusions and Recommendations

The Technical Meeting was considered to be an important area of interest in the field of fast reactor safety, which demanded the initiation of a new study. Many innovative ideas were presented by the participants that led to productive discussions and understanding of different concepts. Everybody expressed the need to have all this information documented in a well-structured format, which also steered the initiation of a NES document. It was recommended that in this study the focal point will be the passive shutdown systems only and no other passive safety systems in FR. It was also recommended that the existing systems for which an operational experience already exists should also be addressed in the study, along with the innovative concepts under development. Moreover the document should encompass all Fast Neutron Systems and not be limited to Liquid Metal Cooled Fast Reactors.

Annex I

Content and Structure

Title: Passive Shutdown Systems for Fast Neutron Systems

TABLE OF CONTENT

- **4.2. BN 350-Pivovarov**
- **4.3. BN 800- Pivovarov**
- **4.4. France ??-CEA**
- **4.5. JAEA??-**
- **4.6. KFK?- KIT, Raju (for reference)**

5. Innovative Concepts (relevant viable systems): **Qvist max 5 pages per contribution**

- **5.1. Flow- Farmer, Pivovarov, Luley**
  - **5.1.1. Flow-levitated absorbers**
  - **5.1.2. Neutron leakage probability adjustment (Gas Expansion Module)-Luley**
  - **5.1.3. Other Sytems?**
- **5.2. Coolant temperature-**
  - **5.2.1. Lithium expansion modules- *Kambe?, Burgazzi***
  - **5.2.2. Lithium thermostat module- *Wood?***
  - **5.2.3. Enhanced control rod driveline expansion- Lee/KAERI**
  - **5.2.4. Autonomous Reactivity Control (ARC)-Qvist**
  - **5.2.5. Thermo-siphon - Raju**
  - **5.2.6. Other Systems?-**
- **5.3. Curie-point temperature actuated absorbers-IGCAR, CEA?, Japan?, USA?**
- **5.4. Rupture discs/Fusible Melt - Bubelis**
- **5.5. Other Systems? - Lamberts**

6. Plant Transient Analysis: Schikorr

- **6.1. Target plant response : EBR-II (Intro to chapter 6):ANL 2 pages**
- **6.2. French experience? CEA 2-3 pages**
- **6.3. FBTR experience – Raju 2-3 pages**
- **6.4. Results of Transient analysis of some innovative concepts- KIT, Qvist, Gugiu, ENEA, Sarkulov-NIKIET, Raju-IGCAR max 5 pages per contribution (use appendix for extended discussion)**

7. Needs for R&D and Qualification –Lamberts 10 pages

- **7.1. R&D Needs Qvist, ANL, Lamberts**
- **7.2. Out-of-Pile Qualifications- Baudrand**
- **7.3. In-Pile Qualifications- Baudrand**

8. Conclusions and Recommendations (including general comparison related to functional requirements;)

Glossary IAEA

Acronyms All

List of Contributors All

Appendix /Profiles (specific national contributions) **All**

Legend		
	(green)	Contributor
	(blue)	Responsible Coordinator

Annex II

Agenda

Tuesday, 20 October 2015

Time	Topic	Speaker
Opening Session		
10:00 – 10:30	• Welcoming address and opening remarks	**Mr D. Hahn** NENP-Dir, IAEA
	• Self-introduction of Participants	**All**
	• Appointment of meeting Chair	**All**
	• Opening remarks by Chairperson • Discussion and adoption of the agenda	**Chair + All**
10:30 – 11:15	• Overview of IAEA Activities in the Field of Safety of FR • Outline of the Technical Meeting	**Mr S. Monti** NPTDS, IAEA
11:15 – 11:30	*Coffee Break*	
Presentations by TM Participants in Alphabetical Order by Country Name		
11:30 – 12:30	• MYRRHA shutdown system	**Mr D. Lamberts** SCK.CEN, Belgium
12:30 – 13:00	• Primary reflections on assessment of passive shutdown systems	**Mr O. Baudrand** IRSN, France
13:00 – 14:00	*Lunch*	
14:00 – 14:15	• Limited scope INPRO assessment of LMFR	**Mr A. Korinny** INPRO, IAEA
14:15 – 14:45	• Assessment of the efficiency of a passive safety system for prevention of severe accidents for SFR	**Mr E. Bubelis** KIT, Germany
14:45 – 15:45	• Design philosophy of shutdown systems for future FBRs • Passive shutdown devices under development for future FBRs	**Ms V. Raju** IGCAR, India
15:45 – 16:15	*Coffee Break*	
16:15 – 16:45	• Analysis of solutions for passively actuated safety shutdown devices	**Mr L. Burgazzi** ENEA, Italy
16:45 – 17:15	• Design study for passive shutdown system of the PGSFR	**Mr J.H. Lee** KAERI, RoK
17:15 – 17:45	• ALFRED demonstrator – safety rods system	**Ms D. Gugiu** INR, Romania
18:00	***End of Day 1***	
18:15	***Reception offered by IAEA***	

Wednesday, 21 October 2015

Time	Topic	Speaker
Presentations by TM Participants in Alphabetical Order by Country Name (con't)		
09:00 – 09:30	• Passive safety components for lead-cooled reactor facilities	**Mr M. Sarkulov,** NIKIET, Russian Federation
09:30 – 10:00	• Proposal of movable reflector for fast reactor design	**Mr B. Vrban** Slovak University of Technology, Slovakia
10:00 – 10:30	• Autonomous Reactivity Control (ARC) Systems	**Mr S. Qvist** Uppsala University, Sweden
10:30 – 11:00	*Coffee Break*	
11:00 – 11:30	• Passive shutdown of NBW fast reactor using the Autonomous Reactivity Control System	**Mr O. Fomin** Kharkov Institute of Physics and Technology, Ukraine
11:30 – 12:00	• US experience and current activities related to passive shutdown systems for SFRs	**Mr M. Farmer** ANL, USA
12:00 – 12:30	• Simulation of absorber introduction in ESFR during severe accident	**Mr A. Rineiski** KIT, Germany
12:30 – 13:30	*Lunch*	
13:30 – 14:30	• General discussion and recommendations for future IAEA activities	**Chair + All**
A New IAEA Study on Passive Shutdown Systems for LMFR		
14:30 – 15:00	• Proposal by IAEA Secretariat	**Mr S. Monti** NPTDS, IAEA
15:00 – 15:30	*Coffee Break*	
15:30 – 16:30	• Comments and proposals by meeting participants	**Chair + All**
16:30 – 17:30	• Content and structure of an IAEA Technical Report on passive shutdown systems for LMFR	**Chair + All + IAEA**
17:30	***End of Day 2***	

Thursday, 22 October 2015

Time	Topic	Speaker
A New IAEA Study on Passive Shutdown Systems for LMFR (con't)		
09:00 - 10:00	• Preparation of the Document Preparation Proposal for the new IAEA Technical Report	**IAEA + All**
10:00 – 11:00	• Distribution of tasks for the preparation of the new IAEA Technical Report • Time schedule • List of actions	**Chair + All**
11:00 – 11:30	*Coffee Break*	
Closing Session		
11:30 – 12:30	• Drafting of summary report of the TM	**IAEA + All**
12:30 – 13:00	• Wrap-up and conclusions	**Chair + IAEA**
13:00	***End of the Technical Meeting***	

Annex III

List of Participants

COUNTRY /ORGANIZATION	PARTICIPANT	
Belgium	Mr	Lamberts Damien
France	Mr	Baudrand Olivier
Germany	Mr	Bubelis Evaldas
Germany	Mr	Nikitin Evgeny
Germany	Mr	Rineiski Andrei
Germany	Mr	Schikorr Michael
India	Ms	Raju Vijayashree
Italy	Mr	Burggazzi Luciano
Korea, Republic of	Mr	LEE Jae Han
Romania	Ms	Gugiu Daniela, Elena
Russian Federation	Mr	Pivovarov Valerii
Russian Federation	Mr	Serkulov Marat
Russian Federation	Mr	Tochenyy Lev
Slovakia	Mr	Luley Jakub
Slovakia	Mr	Vrban Branislav
Sweden	Mr	Qvist Staffan Alexander
Ukraine	Mr	Fomin Oleksiy

United States of America	Mr	Farmer Mitchell
United States of America	Mr	Van Wert Christopher
IAEA	Mr	Stefano Monti, Scientific Secretary
IAEA	Mr	Chirayu Batra
IAEA	Mr	Dohee Hahn, DIR-NENP
IAEA	Mr	Andriy Korinny
IAEA	Mr	Mikhail Khoroshev