Second Joint GIF – IAEA/INPRO Workshop on

Safety Aspects of Sodium-Cooled Fast Reactors

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DRAFT Summary Report

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1 – Objectives, agenda and participants

The overall objective of the workshop was to share information amongst GIF and IAEA (INPRO and TWGFR) research and development leaders concerning technical issues that are uniquely or particularly relevant to the safety of SFRs. Specific attention was paid to the safety implications of the lessons learned from the Fukushima-Daiichi accident on future areas of emphasis, as the next generation of SFRs is designed.

Another important issue discussed at the workshop was how to harmonize the safety approaches and goals for next generation's sodium cooled fast reactors, thus contributing towards the harmonization of the safety criteria for GEN IV sodium cooled fast reactors.

The agenda was developed in five topics, which included respectively basic safety characteristics of fast spectrum reactors, issues associated with the use of sodium as a fast reactor coolant, historical experience with sodium fast reactor safety issues, proposed approaches to achieving SFR safety, and innovative design concepts.

Specific objectives included:

- Share approaches to identify potentially unresolved technical issues that could be important to the safety of SFR systems, and summarize recent, current and planned R&D activities intended to help resolve those issues.
- Discuss potential implications of lessons learned from Fukushima experience as they relate specifically to SFR safety issues and phenomena.
- Discuss design approaches for safety issues on SFRs

In overall there were 23 presentations from European Commission, France, India, Japan, Republic of Korea, Russian Federation and United States of America plus two presentations from IAEA representatives.

The agenda of the Workshop is provided in Annex I and the list of participants in Annex II.

2 – Opening remarks

The Workshop was opened with introductory remarks by Mr H. McFarlane, who also acted as Workshop Chairman, and Messrs R. Beatty and S. Monti as IAEA Scientific Secretaries of the meeting.

3 – Technical Sessions

Mr S. Monti presented the main activities undertaken at the IAEA in the field of Fast Reactors with special emphasis on safety-related initiatives (CRPs, TMs, TECDOCS, etc.).

Topic 1: Short Overview of Safety of SFR in countries with an active programme and Overview of Safety Approach

France, India, Japan, Republic of Korea, Russian Federation and the United States of America shortly reviewed their national programmes on SFR with special attention to general safety approach and objectives, as well as safety characteristics of the present and future SFR designs. It is worth reminding that:

- France has large experience on SFR based on the design, construction and operation of Rapsodie (1967 – 1983), Phenix (1973 – 2010) and Superphenix (1985 – 1998), as well as on the conceptual design of EFR (1988 – 1998), and is now concentrating the effort on the development of the GENIV SFR prototype called ASTRID which is supposed to enter into operation in 2023;
- Operational experience of India is based on the experimental reactor FBTR in operation since 1985. The first unit of the 500 MWe prototype PFBR is in an advanced phase of construction and its commissioning is expected at the end of 2012; this unit will be followed by other colocated in the same site. This reactor design will be used as basis for the commercial CFBR to be deployed from 2023 onward;
- Japan has more than 30 years of experience with the operation of the JOYO experimental reactor and has operated the MONJU prototype till 1995, when a sodium leak in the secondary loop occurred. Monju is now in its final preoperational stage. Concerning GENIV SFR, Japan, within its FaCT programme, is engaged in the development of JSFR;
- Republic of Korea is developing an advanced SFR based on the design of the previous KALIMER-150 and KALIMER-600;
- Russian Federation has in Beloyarsk the largest SFR in operation, BN-600, which has recently celebrated the 31st anniversary since it was connected to the grid, as well as the experimental reactor BOR60 in Dimitrovgrad. After 44 years of operation, the experimental reactor BOR10 was definitely shut down in 2002 and now it is on the preparatory stage of its decommissioning. Russian Federation is constructing the BN-800 (commissioning scheduled in 2014), and developing the BN-1200 design (to be constructed in 2020) as well as the new multipurpose research fast reactor MBIR (start-up scheduled in 2019).
- The USA has operated a number of experimental SFRs (including EBR-II and FFTF) and the FERMI demonstrator. Considerable effort is spent nowadays to preserve and archive the huge amount of data and knowledge accumulated in the past FR-related activities. Furthermore, the last DOE's Nuclear Energy R&D Roadmap (report to Congress, April 2010) recognizes the fast reactor option as the key advanced reactor technology to meet the Generation-IV actinide management and sustainability mission. The AFR (Advanced Fast Reactor)-100 concept – a small modular fast reactor with long-lived core - is being developed within the DOE ARC-AFR programme.

The following general considerations on safety of SFR can be withdrawn from the presentations and the following discussion.

Sodium-cooled reactors have a number of favourable safety characteristics with respect to other nuclear systems (in particular those using water), i.e.:

- Easy to operate:
  - No pressure at the primary circuit,
  - High thermal inertia,
  - Control by rod position (no xenon effect, no need of soluble neutron poison).
- Radioprotection level higher than in LWR;
- Few effluents;
- High thermal efficiency;
- Large coolant boiling margin;
- Natural convection.

However, sodium-cooled fast reactors (SFR) have characteristics representing design challenges for safe operation, i.e.:

- High power density:
  - Need to provide adequate heat removal under all circumstances;
- Power variation due to neutron leakage at the core boundaries resulted in the need to use ducted subassemblies to ensure adequate coolant flow:
  - Core reactivity is very sensitive to core geometry;
- Core sodium void worth is typically positive;
- Fuel is not in the most neutronically reactive configuration in the reactor core, with a core inventory of many critical masses:
  - Fuel relocation might significantly increase reactivity, potentially leading to very high power generation (1000s x nominal).

SFR safety is first based on the concept of "defense-in-depth" (DiD), i.e. where multiple redundant safety systems, both active and passive, are used to lower the probability of accident occurrence or severe accident consequences. DiD technical features mentioned at the Workshop include the following:

- Two redundant and independent shutdown systems. They have to be diverse [e.g. different latch/touch mechanism, insertion force (gas, gravity), logic circuit, etc.], robust (e.g. insertion capability also in the case of major seismic event) and reliable (based on operational experience and periodical tests);
- Multiple coolant pumps;
- Auxiliary decay heat removal systems, i.e. redundancy and diversification for DHRS;
- Multiple barriers to the release of radioactive materials:
  - Cladding on fuel pins
  - Primary coolant system boundary
  - Containment building

- Negative power and temperature reactivity feedback coefficients.

Further to DiD, inherent characteristics were developed as additional safety means to protect the reactor in case of accidental situations, preventing potential failures of engineered protection systems incorporated, i.e. preventing severe consequences from unprotected accidents. In summary, inherent characteristics:

- Does not require the functioning of any active system because it is based on fundamental phenomena such as thermal expansion, buoyancy-driven flow, and gravity. Although, the quantification of its reliability requires further assessment.
- Mainly addresses accidental conditions such as the unprotected (unscrammed) loss-of-flow (ULOF), unprotected loss of main heat sink (ULOHS), and unprotected inadvertent withdrawal of reactor control rod(s) resulting in a transient overpower accident (UTOP).

The focus of inherent safety is to address the three main conditions for safe operation of the reactor:

- Avoid large uncontrolled increases in core power, by means of favorable reactivity feedbacks;
- Avoid insufficient cooling of the reactor core, by means of natural circulation cooling;
- Avoid rearrangement of fuel that would lead to solid or molten core compaction, due to energetic events, by core or Sub-Assembly design.

With proper reactor safety designs, the ULOF, ULOHS, and UTOP accidents have no serious consequences on the short term. On the other hand, in more challenging accidents, beyond ULOF, ULOHS, and UTOP, the initiating conditions are so severe that fuel pin failure with molten fuel can't be avoided. In such cases inherent safety features are unable to prevent temperature increases, sodium boiling, fuel melting and fuel pin failure. Probability of occurrence for these accident initiators is less than 10^{-6} per reactor.year, and probably much less. Examples include a ULOF with no flow coastdown, possibly as a result of a very large seismic event, or a UTOP where all control rods are uncontrollably withdrawn from the core. The outcome of these events is determined by the preservation of the mechanical integrity of the reactor vessel and the behavior of the molten fuel outside the fuel pin: favorable dispersal of the molten fuel is required both to prevent energetic recriticalities and to maintain core coolability.

In the course of this first topical session, the Korea Institute of Nuclear Safety (KINS) presented its SFR Regulatory Research Programme recently launched in view of the licensing application for the Korean advanced SFR design approval. The programme is of general interest for the whole GENIV SFR community and includes:

- Licensing procedures of design approval for prototype reactors;
- Establishment of national safety requirements for SFRs;

- Identification & resolution of licensing issues (e.g. thermal-fluid phenomena of the primary Na flow, event categorization and acceptance criteria, performance criteria for containment system, source terms, acceptance criteria for core coolability in postulated accident conditions);
- Development of regulatory analysis tools for safety evaluation of the system design (e.g. nuclear and fuel performance analysis, T/H and safety analysis, structural/seismic analysis, PRA, etc.).

Concerning the development of safety requirements, KINS is carrying out the following tasks:

- Review of safety objectives and principles of IAEA, WENRA, GIF and USA;
- Applicability of the LWR safety requirements to SFRs;
- IAEA DS414, i.e. the latest draft of safety requirements for FR design;
- Review of SFR requirements of USA, Japan and the European Commission
- Development of draft safety objectives, principles and requirements for SFRs;
- Development of safety guides for SFRs

KINS is seeking international harmonization in establishment of SFR safety requirements and international collaboration in development of safety analysis tools

Topic 2: Approaches to Resolve Safety Issues Related to Basic Safety Characteristics of SFRs

This session was intended to present and discuss the following technical issues:

- Sodium void, Doppler, reactivity feedback, power coefficient, etc.
- Passive and Inherent Safety
- Prevention/Mitigation of CDA

Presentations were given by representatives of France, Japan and the United States of America.

From a general viewpoint the participants confirmed the understanding that, today, safety of existing SFR is considered equivalent to the one of existing GEN II[1] LWRs and future SFRs should reach at least a GEN III+[1] LWRs safety level. However, some issues can be further improved, in particular vis-à-vis the robustness of the safety demonstration. This is also beneficial for minimizing licensing and financial risks. Safety demonstration is based on accidents prevention and mitigation and in particular:

- Prevention:
  - Extensive use of lines of defense approach (3 or 4 lines of defense), confirmed by PRA;
  - Practical elimination of reactivity accidents;
  - DHR diversification, reliability, passivity;
  - Core control;
  - Sodium accidents.

[1] GEN II and GEN III+ used according to existing GIF terminology

- Mitigation of core damage:
  - Provisions against energetic criticality sequences resulting from core melt down
  - Provisions for core degradation safe management (core catcher, decay heat removal)
- Mitigation of aggressions:
  - Provisions against external hazards (robust containment): aircraft crash, large earthquakes, external attacks
  -

It was reminded the need to increase cooperation between WCR (Water Cooled Reactor) and SFR working groups to identify common safety issues.

In the framework of the ASTRID prototype development programme, France shared several innovative features that are being studied through R&D activities and possibly introduced in the design, e.g.:

- Passive safety devices in the core;
- Innovative fuel assembly design (large-diameter pins and small-diameter spacing wire) for reducing the sodium void coefficient and avoiding the risk of sodium boiling even in the case of unprotected transient of loss of flow;
- Innovative energy conversion systems (e.g. gas Bryton cycle, supercritical CO2 cycle, alternative secondary coolants compatible with water and sodium, robust steam generators, etc.) for minimizing sodium risks;
- New ISI&R techniques;
- Etc.

Topic 3: Approaches to Resolve Safety Issues Related to Sodium as a FR Coolant

This session was intended to discuss:
- Sodium boiling, fires, leak detection, sodium aerosols, etc.
- Sodium Water Reaction
- Steam Generator Tube Rupture
- Sodium radioactivity

Presentations were given by representatives of France, India, Japan Russian Federation and the United States of America.

As already observed, sodium coolant has several advantages which were reviewed in the course of the French presentation, i.e.:

- Low melting point at 97.8°C. This allows maintenance below 200°C, avoids freezing in the Steam Generator Unit and facilitates ISI&R campaigns;
- Large range of the liquid phase 99°C- 880°C. This allows precise measurements of fuel S/As outlet temperature;
- Cheap and largely available;
- Low density and viscosity. Na is easy to pump and can be simulated with water;
- Very high heat conduction which makes sodium one of the best coolant;

- Excellent electrical conductivity which allows the use of electro-magnetic technologies (pump, flow-meter …);
- Low saturation vapor pressure, so that there is limited transfer of sodium in the cover gas plenum and deposits on upper structures;
- Transparent to neutron;
- Low activation (Short decay periods ^{22}Na = 2.6 years, ^{24}Na = 15 hours; No α emitters such as ^{210}Po);
- No specific toxicity;
- Perfectly compatible with steels;
- Very limited amount of particles in sodium, mainly $NaCrO_2$;
- Low oxygen and hydrogen solubility. This allows its purification with “cold trap”;
- Very good wetting which, in particular, improves the quality of ultra-sonic systems.

On the other hand sodium has three major drawbacks:

- Very important chemical reactivity with water, with consequent possible deleterious effects in Steam Generator Units (SGU), in case of pipe rupture. Steam generator tube rupture must be avoided or at least mitigated by design, e.g. adopting double walls or modular SGU, etc. An early detection of water/sodium leak is mandatory (on the other hand the high chemical reactivity with water allows efficient components cleaning even if risk of hydrogen explosion has to be mitigated);
- Liquid sodium spontaneously burns in air. This characteristic induces Na fire and, therefore, there is the need of inert zones and confinement; an early detection of sodium leaks to air is also mandatory.
- Opacity: need of specific equipment for under -sodium viewing and measurements.

Suitable sodium handling technology has been achieved on the basis of the experience accumulated through the design, construction and operation of various SFR and related experimental facilities worldwide.

Several problems have been experienced and overcome, including sodium leaks and sodium-water reactions.

The two major issues with sodium are:

- To ensure high reliability of components in sodium in order to guarantee high plant availability;
- To prevent sodium chemical reactions which can cause core damage under design extension conditions.

To guarantee high reliability, the following issues have to be addressed:

- Sound and simplified structural design;
- High tech manufacturing;
- Reinforcement of coolant boundary (for instance by adopting double walls);
- Sufficient design margins;
- ISI&R and maintainability;
- Prevention of corrosion;
- Early detection of small sodium leak and small water leak from the steam generator tubes.

Several types of leaks detection systems and sodium burning detection systems are used, e.g.:

- ✓ Detection system by short circuit of electroheaters ;
- ✓ Detection system of radioactive sodium aerosols;
- ✓ Smoke detection system;
- ✓ Temperature measurement systems

Examples of actions to be implemented for the reduction of the consequences of a Na leak are:

- Minimization of primary and secondary Na loops;
- Use of passive means to reduce the quantity of burning Na during accidents;
- Implementation of "leak before break" concept.

Of primary importance is the emergency protection system of the Steam Generator based on three levels of defence:

- Early detection of a leak of water in sodium and implementation of measures to prevent further development of a leak (steam generator isolation and draining);
- Reactor shutdown and draining of the loop in case of a large water leak in sodium;
- Passive protection of the SG and over pressure equipment in the secondary loop to be used in case of failure of the two first levels of protection, or in case of rapid development of an accident.

In order to resolve and improve safety issues related to the use of sodium as coolant, several experimental activities have been carrying out in all countries with an active SFR programme. In particular at this workshop the following activities were presented and discussed:

France:

- Modular steam generators;
- Sodium-water reaction phenomena and modeling;
- Development of innovative power conversion systems;
- Innovative intermediate heat exchangers design
- Extended ISI&R programmes and techniques;
- Advanced instrumentation for core control and detection of fuel damage
- Components cleaning technologies

India:

- Sodium-Water reaction test rig (SOWART);
- Multiple tube failure in steam generators;
- Small, medium and large-scale sodium fire studies, including modeling of small scale sodium spray fire;
- Sodium combustion aerosols studies;
- Sodium-concrete interaction studies
- ISI&R techniques
- Sodium sensors

Japan: several and diversified approaches for ensuring reliability and safety enhancement both in DB and DE Conditions and taking into account internal and external events.

Russian Federation:
- Sodium leaks in primary and secondary loops;
- Sodium fires
- Steam generator tube rupture

United States of America: sodium fire research program at Sandia National Laboratory which includes:
- Expert Gap Analysis (PIRT);
- Sodium Spray and Pool Fire Experiments;
- Sodium Pool Fire Computational Model;
- Technical Issues (sodium pool burning, sodium spray fires, etc.).

Topic 4: Safety Implication in the Light of Fukushima NPP Accident

This session was intended to discuss:
- Severe Accident Consideration as Design Extension Condition;
- External Events Consideration;
- Post severe accident management;
- Approach to Back-fit the add-on Countermeasures on Existing and under construction Reactors.

On this topic there were presentations from France, Japan, India and the United States of America.

The Fukushima events were caused by an extreme tsunami that followed a very large offshore earthquake, which resulted in extended station blackout (SBO) conditions for several reactors. The most important safety aspect of Fukushima events is that the potential for all of them has been known for decades. Actually, SBO conditions drive regulations for emergency power backup systems. Nothing about what happened is a surprise, but there are things to learn.

As a first lesson learned from the Fukushima accident, the Japanese government report to the IAEA includes 28 key points grouped in the following 5 Groups:

1. Strengthen preventive measures against a severe accident
2. Enhancement of measures against severe accidents
3. Enhancement of nuclear emergency response
4. Reinforcement of safety infrastructure
5. Raise awareness of safety culture

SFRs have different safety characteristics compared to LWRs: for instance backup decay heat removal systems are typically passive, not requiring electrical power. However the following points from the Japanese government report and related considerations hold also for GENIV SFR:

1.1 Strengthen measures against earthquakes and tsunamis and, in general, extreme external events (with reconsideration of their magnitude during plant design)

1.2 Secure power supply

- For the ‘Emergency power supply’: diversity to the extent practicable and redundancy for suppressing common cause failure including external events.

1.3 Secure a firm cooling function of a reactor and a RCV

- For the ‘Decay heat removal system’: decay heat removal systems for reactor cooling even under loss of all AC power supply; utilization of passive heat removal capability for DEC; diversity of ultimate heat sinks for decay heat removal.

1.4 Secure a firm cooling function of spent fuel pools

- For the ‘Fuel storage systems’: heat removal & status monitoring even under loss of all AC power supplies.

1.7 Consideration on basic design such as location of NPS, etc.

- For the ‘Design extension conditions’: designs for Prevention and Mitigation of the severe accident consequences.

1.8 Ensuring the water-tightness of important equipment facilities

- For the ‘External hazards’: due consideration of loss of all AC power supplies following the extreme external hazards; seismic events may be accompanied by subsequent events.

2.9 Enhancement of prevention of hydrogen explosion

- For the ‘Control of containment conditions’: Prevention/Mitigation of the sodium fire and sodium-concrete reaction; due consideration of the challenges on the integrity of containment.

2.12 Enhancement of the radiation exposure management system at accident

- For the ‘Means of radiation monitoring’: adequate radiation monitoring in DEC.

2.14 Enhancement of instrumentation reactors and PCVs

- For the ‘Fuel storage systems’: adequate heat removal and status monitoring even under DEC including the loss of all AC power supplies.

4.26 Securing independency and diversity of safety system

- For the decay heat removal system: diversity to the extent practicable and redundancy for suppressing common cause failure including external events;
- For the ‘Ultimate heat sink’: diversity of the ultimate heat sinks for the decay heat transfer.

Other considerations coming from the lessons learned from the Fukushima accident put forward at the meeting were:

- ➢ Improvement of DiD application, including for accident situations resulting from external hazards;
- ➢ Combination of events, in particular combination of hazards and combinations of external hazards with accidents;
- ➢ Post-accident management:
  - Consideration of degraded states, not necessarily associated to a well-identified initiator;
  - Specific monitoring devices not sensitive to the accident consequences
- ➢ Identification of cliff-edge effects associated to hazards:
  - Improvement of design margins;
  - Improvement of diversification of equipments;
- ➢ Improvement of grace period in case of failure of off-site equipment;

- ➢ Improvement of diversification of decay heat removal systems and ultimate heat sinks;
- ➢ Improvement of the containment:
  - Reduction of potential bypass;
  - Independence of confinement barriers;
  - Environmental impact of chemically hazardous material (e.g., sodium)
- ➢ Consideration of radiological source terms other than from the core, especially for handling and storage of spent fuel.

However, some accident situations must be excluded by design for the SFR:

- Either because implementation of mitigation devices is not reasonably feasible,
- Or, because the R&D to be developed for demonstrating their efficiency is not reasonably feasible.

The first design objective is to make such situations physically impossible. In compliance with Defence-in-Depth concept, "practical elimination" is acceptable only for a limited number of very well identified situations. In any case, the "practical elimination" of some accident situations requires implementation of independent reliable design features and a robust demonstration of their efficiency, e.g.:

- Combination of active and passive systems.
- Inherent characteristics.
- Operating procedures for verifying efficiency of protection devices (e.g., needs in-service inspection).

Concerning countermeasures to be adopted for existing reactors, it is worth noticing that ongoing stress tests on Japanese nuclear fleet also concern Monju and include evaluation of safety margin for extreme external events (Earthquake and tsunami), station black-out (SBO), loss of ultimate heat sink (LOUHS), combination of severe events, as well as severe accident management. In case of SBO, after reactor shutdown decay heat is removed in Monju by natural circulation. Important facilities, including sodium systems and spent fuel storage facility are located at 21m above sea level. Emergency safety measures are already in place whilst others – as far as securing emergency power supply and final heat removal functions in emergency situations, as well as ensuring the cooling of the spent fuel storage tank and pool and additional measures against severe accidents – have been planned.

Topic 5: Design Concepts for Innovative Sodium Fast Reactors

Innovative SFR concepts with enhanced safety characteristics with respect to present designs were presented by India, Republic of Korea and the United States of America.

In India know-how and experience accumulated during the design and construction of the PFBR is being used to develop the CFBR (Commercial Fast Breeder Reactor). From a general viewpoint CFBR relies on enhanced passive safety features (e.g. for reactor shut down and decay heat removal systems) and in particular the following innovations are being introduced in the design:

- Number of primary pipes increased to 4 per pump;
- In-vessel purification;
- 3 SGDHR circuits with forced cooling (2/3 of heat removal under natural convection) and 3 SGDHR circuits with natural convection cooling each with a power removal capacity of 6 MWt;
- Enhanced reliability of the control rod shut down system;
- Several means for mitigating gas entrainment in the hot pool;
- New ISI&R techniques (e.g. ultrasonic imaging of the fuel SA top, Visual inspection and vibration monitoring of reactor internals, Measurement of Gas Entrainment in Sodium Void meter, Eddy current flow meter and acoustic sensor, etc.);
- Innovative instrumentation;
- Improved core catcher geometry;
- Extensive testing to qualify sodium safety systems;
- Development and qualification of advanced 3-D and integrated simulation tools. From this respect, benchmarking activities to be carried out at international level are considered of paramount importance.

In the Republic of Korea the SFR programme is focused on the development of an advanced SFR, based on the previous work carried out at KAERI on KALIMER-150 and KALIMER-600 and expected to be completed in 2028. It is a 600 MWe pool-type SFR fuelled with U-Zr or U-TRU-Zr and with passive DHRs. In order to reduce the sodium void worth in particular when the core is loaded with TRU, reflector assemblies were introduced in the central region of the core. To improve the performance of decay heat removal system, various concepts were investigated for enhancing the natural circulation and minimizing the heat loss. The integrity of metallic fuel for different cores has been evaluated with respect to three design criteria:

- No fuel melting
- Prevention of eutectic melting between fuel and cladding
- Prevention of cladding mechanical failure

A number of R&D activities aimed at enhancing the safety of the system are in progress; they concern:

- The realization of the STELLA-1 Na loop;
- Metallic fuel rod fabrication;
- V&V of core neutronics code system;
- Validation of safety analysis code models, also through active participation to IAEA CRPs on Phenix, Monju and EBR-II
- Under-sodium view technologies;
- New compact heat exchangers for Na-CO2 Bryton Cycles.

In USA the AFR-100 concept is being developed within the DOE's ARC-AFR programme which is divided into various subtasks:

- Fast Spectrum Reactor (concept development, safety and licensing, advanced materials, inspection technology);

- Revolutionary Reactor Concepts;
- Cross Cutting Research Activities (e.g. energy conversion technologies);
- Generation IV International Support (GIF);
- Modeling and Simulation (NEAMS);
- Nuclear Data.

AFR-100 is a 100 MWe small-modular cold-pool SFR with long cycle length (30 years) adopting:

- Innovative core design technologies (e.g. fission gas vented fuel);
- Advanced materials;
- S-CO2 Bryton cycle
- Direct reactor auxiliary cooling systems (DRACS0 for the emergency DHRS.

The development of this FR represents an opportunity to reactivate the use and update several nuclear codes (NUBOW, SWAAM, SCRAP, SAS4A, etc.) applicable to various SFR simulations. In particular, the safety analyses performed so far by ANL have demonstrated that AFR-100 is able to accommodate protected and unprotected transients.

Safety approach and general safety features of innovative (GENIV) SFRs were discussed during this topical session.

General objectives of the safety approach of new (GENIV) SFR systems are:
- Improved and robust safety demonstration with regard to former fast reactors;
- Enhanced prevention of whole core melting accidents;
- Exclusion in a credible way of energetic accident sequences;
- Robustness to external hazards;
- Safety level at least equivalent to GEN-III+ reactors;
- Long grace time for systems operation in case of failure of on-site and/or off-site equipment;
- Take into account lessons learnt from the Fukushima accident (in particular, radiological source terms other than the core have also to be considered, especially for handling and spent fuel storage).

In addition, as already done in existing SFR, it is necessary:
- To prevent and mitigate risk due to sodium chemical reactivity;
- To avoid chemical interaction between sodium and water in the Steam Generators.

In order to comply with these general objectives, from a general viewpoint it is recognized that future SFR concepts should include the following technical provisions:

- High reliability of the reactor shutdown system (RSS) based on two independent active RSS and one additional passive RSS;
- Maintain coolant level in reactor vessel even in DECs (e.g. by means of guard vessel and guard pipes);
- Diversified and passive decay heat removal systems able to cool the core even in coolant leak conditions (failure of decay heat removal has to be “practically eliminated”);

- Seismic protection devices;
- No impact of sodium leak on the containment vessel in Design Basis Events (thanks to preventive measures) and reduced impact in case of extreme/severe DECs;
- No energetic consequences (no large Na fire) in case of Core Disruptive Accident (CDA). This may be achieved through a combination of **prevention**:
    - Control of reactivity (by absorber insertion, neutron leakage enhancement, inherent characteristics),
    - Maintain core cooling (by diversity of coolant circulation, alternative cooling, coolant re-fill, etc.),
    - Robustness in ultimate heat sinks (by diversity of heat sink and transport pass);

  and **mitigation**:
    - Discharge of fuel material from the core region by swept out of coolant flow, discharged via holes/duct/subassembly gap, etc.),
    - Retention & Cooling of the debris (by debris tray for retention, by diversity in coolant circulation, alternative cooling, coolant re-fill, etc.).

As a very important cross-cutting issue, it is universally recognized the need to improve the performances and the V&V&Q of modelling and simulation tools for the design and safety analysis of innovative SFRs: neutronics, system codes for transient scenarios, thermal-hydraulics (in particular to simulate natural convection in primary vessel and DHR systems), structural and seismic analysis, etc..

4 - Presentations from international organizations

Mr P. Hughes, head of the Safety Assessment Section, IAEA's NS Department, presented the IAEA approach to SFR Safety. He reminded the structure of IAEA Safety Standards subdivided in: safety fundamentals (fundamental safety principles), safety requirements (in particular safety assessment for facilities and activities) and safety guides. The safety assessment consists of probabilistic and deterministic safety analysis from one side, and evaluation of engineering factors important to safety on the other side.

Mr Hughes also provided information on the IAEA generic reactor safety review service (GRSR), i.e. an IAEA tailored project framework to provide Member States with an early evaluation of a vendor's submission of a new nuclear power plant, against the IAEA Safety Standards at the safety fundamentals and safety requirements level. This service, provided by a review team, i.e. a group on independent experts, allows evaluating whether new reactor design safety cases are complete and comprehensive. GRSR has been already applied to various water cooled commercial reactor designs recently licensed or in the course of licensing and is also applicable to SFR designs.

Mr R. Nakai presented the activities carried out by the GIF task force on SFR Safety Design Criteria (SDC).

SDC harmonization is considered indispensible for:

- realization of enhanced safety design common to all GENIV SFR systems, and
- preparation of the forthcoming licensing of some GENIV SFR systems

The work of the TF will be finalized by the end of 2012 and will be based on:

- general safety requirements common to SFR and LWR – IAEA NS-R-1 (DS414);
- specific safety requirements for SFR system, i.e. the safety design requirements reported in the GIF SFR System Research Plan;
- lessons learned from Fukushima accident (strengthen preventive measures against severe accidents, enhancement of response measures against severe accidents, reinforcement of safety infrastructure).

A table of contents for the SDC report has been already agreed within the TF.

Mr L. Ammirabile, from JRC-IE, Petten, presented the Euratom project SARGEN_IV – Safety Assessment for Reactors of GENEration IV. He reminded the active Euratom participation in GIF as well as the launch of the European Sustainable Nuclear Industrial Initiative (ESNII) under the European SET-Plan. ESNII gives support to 4 European Fast spectrum systems, i.e.: ASTRID (SFR), ALLEGRO (GFR), and MYRRHA e ALFRED (LFR).

The scope of SARGEN_IV is to provide a framework for the safety assessment of the European GENIV FRs. The objectives of SARGEN_IV are:

- identify the critical safety features of the selected Generation IV concepts, relying on the corresponding 7th Framework Programme projects (i.e. CP ESFR, GoFastR, LEADER and CDT);
- propose a tentative methodology framework for the safety assessment to be applied to the four ESNII prototypes, to perform a small sample of test applications employing such methodology framework to some event families,
- identify open issues, relevant for research in the safety area, mainly focusing on the safety assessment related aspects and to propose actions and plans for the implementation and the deployment of this R&D,
- disseminate information on the harmonized position issued during the project to important stakeholders, in particular decision-makers (utilities and safety authorities for instance).

The project is coordinated by IRSN (the French TSO) and includes 22 European partners (designers, TSOs, safety organizations, research centers and Universities).

5 - Final comments from the participants

In a "*tour de table*" the participants reported satisfaction with the level of interest of the materials and discussions shared during the Workshop, expressing at the same time a strong support to the continuation of the initiative, applied to agreed topics of SFRs, in the coming years. Specific comments made by representatives from the participant countries are the following:

India is constructing a SFR and highlighted the value of the discussions to confirm R&D trends and activities. Managing the technology implies a high level of excellence in a range of phasis including R&D, design, construction, operation and back-end implementation, and the experience from each of these phasis should be implemented in all the other. IAEA was encouraged to facilitate forums allowing to share the large experience available in SFRs, including failed approaches. In-service-inspection, fuel handling, sodium pumps or heat exchangers are elements having relevant potential for discussion. The convenience to map the matters covered by each of the IAEA forums available (TWG-FR, SFR Workshop, INPRO projects and dialogue forums) having in mind coordination and synergies was also recommended.

France encouraged to fix clear topic/s in each Workshop, structure the corresponding discussions and avoid dispersion or superficial consideration. IAEA forums do not allow sharing detailed information in aspects such as design solutions, due to confidentiality limitations, but can be ideal to discuss other like "severe accident". This topic was proposed for a future Workshop.

Russian Federation announced its intention to enlarge its contribution in future workshops in terms of participants and materials shared, taking into account the level of interest of this Workshop.

United States considered fundamental to share R&D aspects having priority at national level, together with its motivation, approach, validation efforts and results obtained. Licensing was considered an important topic (feedback from the interaction designer-regulator). Support was expressed to [*big*] Workshops covering several topics but allowing its discussion with enough detail. Indian comment about paying attention to specific components like steam generators, pumps or heat exchangers was supported too. Advanced features addressing reactivity effects was mentioned as very relevant topic. Finally it was encouraged a strong international cooperation to cover the large amount of SFR Safety related aspects deserving further attention.

European Commision confirmed its interest in topics related to Safety Assessment, announcing its relevant potential of contribution in the corresponding Workshops.

Republic of Korea expressed strong support to the initiative indicating its preference for practical topics related to Safety issues like sodium fires and severe accidents.

Japan reminded that Safety Approaches are different in each country and recommended further cooperation in this regard. Also in the understanding of "robust design" meaning. Support was given to the discussion of Safety Assessment in future workshops offering to share its views in the next meeting.

OECD informed about the potential of cooperation IAEA-NEA/OECD regarding the IEE (International Evacuation Exercise).

China apologized for the non participation of CEFR/CIAE experts in this workshop. At the same time informed about its interest in considering Safety Requirements for sodium coolant as a topic in future workshops. The other participants expressed the convenience to count with CEFR/CIAE experts in this forum; both GIF management and Secretariat agreed to make its best endeavours for making it possible.

6 - Closing remarks by IAEA DDG-NE

Mr A. Bychkov, IAEA Deputy Director General for NE, thanked the participants for making possible a very successful Workshop with their contributions. He reminded the extensive investigation performed in several countries during long time and the operational experience accumulated regarding fast neutron systems, regretting that part of it is not being applied currently. On the other hand he congratulated the countries devoting significant attention to R&D and operational activities related to SFRs, option having a high potential of deployment in the medium and long term. Specifically he highlighted the valuable contributions that are being made by Japan and also by India which PFBR Project is now in an advanced stage of construction; at this point he informed that BN-800 project is on schedule announcing its completion by 2014 in Russia.

Regarding the key challenges of NE development and deployment in 21st Century, he mentioned both education and training of new engineers and development of closed fuel cycle technologies. CFC option represents a major step to implement sustainable nuclear energy systems due to the improvement of waste characteristics and to the reasonable use of natural resources, and SFR technology is ready for deployment and essential in the CFC concept.

Finally he reminded the support of the IAEA NE Department to all the international activities related to SFRs, especially to those oriented to enhance Safety, encouraging approaching them through international cooperation.

7 - Conclusions and Suggestions for Future Initiatives/Workshops

The workshop represented considerable progress towards outlining current gaps in SFR safety knowledge and summarizing what each country is currently doing in the areas of SFR safety while also looking at common approaches or remaining differences in safety philosophy and licensing strategies.

To achieve safety goals for Generation IV reactor concepts, taking also into account the lessons learned from the Fukushima accident, design measures should be taken under Design Extended Conditions (DECs), including those for external events. In particular, core cooling under long term loss of electric power or failure of auxiliary systems, such as sea water cooling systems, shall be ensured by utilizing diverse decay heat removal systems.

Alternative heat removal measures under core damage situations have also to be considered, as well as countermeasures against natural disasters beyond design basis conditions.

Attention still needs to be put on emergency planning. Any design, regardless of how inherently safe it is, will require continued emphasis on being prepared in case of a severe accident and on attention to the community in which the reactor is located.

International consensus for these kinds of requirements and safety design features is necessary to ensure the global safety of the nuclear power worldwide.

There are advantages of SFR from a technical standpoint which would answer some of the issues associated with Fukushima, e.g. inherent or passive decay heat removal because of the high heat content of the sodium coolant, even without active circulation. These interesting issues show that the innovations that GEN IV reactors are providing will help making nuclear deployment for the future safer and more sustainable.

In the final discussion the participants expressed their appreciation to the IAEA and to the organizers for making excellent arrangements, which allowed the Workshop's success. The participants recognized that the Workshop has brought some important benefits and common grounds, which include both the motivation for further R&D and the exchange of experiences on SFR technology that can be used in R&D, design, construction and operation for its further improvement.

At the end of the Workshop, the following 10 topics were identified for selecting the focus of next GIF/IAEA-INPRO Workshops, or for being taken into account in other technical initiatives in the area of SFR:

- Under sodium viewing for ISI: sodium pumps, heat exchangers (IHX, DHX), SG, fuel handling;
- Severe accidents;
- Approaches to safety and licensing;
- Priorities in modeling and simulation;
- R&D facilities: status and future needs;
- Risks of Sodium as coolant/technology;
- Safety standards (level of requirements and mainly guides) and codes and standards for SFRs;
- Managing SFR technology: use of feedback experience and direction from R&D, design, licensing, manufacturing, operation and decommissioning. (How is handled and where is used the feedback experience from each of these steps);
- Economic impact of safety enhancements;
- Safety systems and monitoring / instrumentation.

ANNEX I

Second Joint GIF – IAEA/INPRO Workshop on

Safety Aspects of Sodium-Cooled Fast Reactors

(30 Nov.-1 Dec., 2011. IAEA HQ, Vienna. Meeting Room: **F0822**)

Final Agenda

Time	Date / Topic	Participant
	Wednesday, 30 November	
09:00 –09:15	Opening remarks Introductory remarks by GIF Self-introduction of the participants Approval of the Agenda Nomination of the workshop Chairman	Mr JK Park Mr H. McFarlane All
09:15 –09:45	IAEA TWG-FR activities in the field of safety of SFR	Mr S. Monti
	Topic-1: Short Overview of Safety of SFR in countries with an active programme	
10’	France	Mr P. Anzieu
10’	India	Mr P. Chellapandi
10’	Japan	Mr R. Nakai
10’	Republic of Korea	Mr M.H. Bae
10’	Russian Federation	Mr I. Pakhomov
10’	United States of America	Mr T. Sofu
	Coffee break	
	Topic-2: Approaches to Resolve Safety Issues Related to Basic Safety Characteristics of SFRs - Sodium void, Doppler, reactivity feedback, power coefficient, etc. - Passive and Inherent Safety - Prevention/Mitigation of CDA	
11:10 –10:30	United States of America	Mr A. Stanculescu *(R. Wigeland)*
10:30 –11:50	France	Mr P. Dufour
11:50 –12:10	Japan	Mr Y. Okano

12:10 –13:00	General discussion. Conclusions and future action for Topic 2	All
Lunch break		
14:00 –14:30	IAEA approach to SFR Safety	Mr P. Hugues
Topic-3: Approaches to Resolve Safety Issues Related to <u>Sodium as a FR Coolant</u> - Sodium boiling, fires, leak detection, sodium aerosols, etc. - Sodium Water Reaction - Steam Generator Tube Rupture - Sodium radioactivity		
14:30 –15:00	Russian Federation	Mr I. Pakhomov
15:00 –15:30	India	Mr P. Chellapandi
Coffee break		
16:00 –16:30	France	Mr P. Anzieu
16:30 –17:00	Japan	Mr S. Kubo
17:00 –17:30	United States of America	Ms T. Olivier
17:30 –18:00	Conclusions and future action for Topic 3	All
18:00	*Get together organized by the IAEA*	All
Thursday, 1 December		
Topic-4: Safety Implication in the Light of Fukushima NPP Accident - Severe Accident Consideration as Design Extension Condition - External Events Consideration - Post severe accident management - Approach to Backfit the add-on Countermeasures on Existing and under construction Reactors		
09:00 –09:20	France	Mr P. Dufour
09:20 –09:40	Japan	Mr R. Nakai
09:40 –10:00	India	Mr P. Kumar
10:00 –10:20	United States of America	Mr T. Sofu *(R. Wigeland)*
Coffee break		
10:40 –11:00	Conclusions and future action for Topic 4	All
11:00 –11:20	*Status of GIF Task Force on SFR Safety Design Criteria*	*Mr R. Nakai*

Topic-5: Design Concepts for Innovative Sodium Fast Reactors Innovative Design Concepts Achieving Enhanced Safety for Next Generation Reactors		
11:20 –11:40	European Commission	Mr L. Ammirabile
11:40 –12:00	Japan	Mr S. Kubo
12:00 –12:20	Republic of Korea	Mr H.Y. Jeong
12:20 –12:40	United States of America	Mr T. Sofu (*C. Grandy)*
12:40 –13:00	India	Mr P. Chellapandi
13:00 –13:30	Discussion. Conclusions and future action for Topic 5	All
Lunch break		
14:30 –15:30	Summary of conclusions and future action from all the topics Discussion. Final outcome of the workshop	Workshop Chair/s All
15:30	Adjourn	

ANNEX II

Second Joint GIF- INPRO/IAEA Workshop on

Safety Aspects of Sodium-Cooled Fast Reactors

List of Participants

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