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Considerations on the safety of LMFRs with a focus on Severe Accidents

Interregional Workshop on Advances in Design of Generation-IV SMRs

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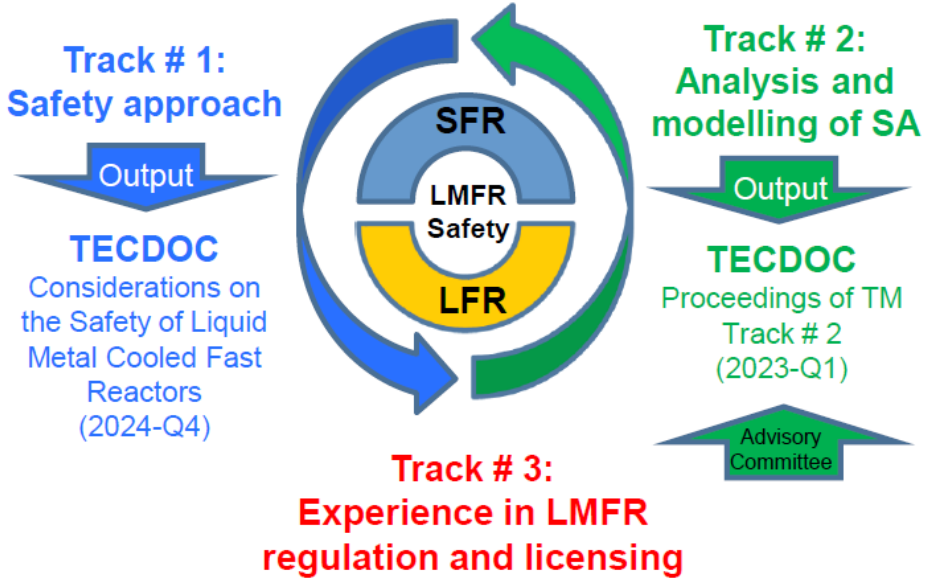
TM on the Safety Approach for Liquid Metal Cooled Fast Reactors and the Analysis and Modelling of Severe Accidents, held on 13-17 March 2023

- 70+ registered participants representing 16 Member States; *Cooperation NS (S. Massara) + NE (V. Kriventsev)*
- 3 sub-tracks:
  1. Safety approach for LMFR and regulatory experiences and activities
     - 15 oral presentations in 4 technical sessions:
       - 1.1 Related IAEA and International Activities
       - 1.2 Safety Approach for SFR
       - 1.3 Safety Approach for LFR
       - 3. Regulatory Experience and Activities
     - This material will contribute to the TECDOC on **Considerations on the Safety of LMFR**
  2. Analysis and modelling of severe accidents (SA)
     - 24 peer-reviewed technical papers + oral presentations in 4 technical sessions:
       - 2.1 SFR: Severe Accident Analysis and Experimental Validation
       - 2.2 SFR: Initiation and Transition Phases of SA of SFR
       - 2.3 SFR: Accident Expansion Phase and Long-Term Behaviour
       - 2.4 LFR: Accident Analysis and Experimental Programs
     - This material will contribute to the TECDOC on **Analysis and Modelling of Severe Accident for LMFR: Proceeding of a TM**
  3. Experiences in LMFR regulation and licensing



- 2 panel discussions:
  – Panel Session # 1: Status of knowledge and challenges for the consideration of severe accidents for SFR
    - 5 panellists from FRA, GER, JPN, USA
  – Panel Session # 2: Status of development and challenges for LFR
    - 4 panellists from BEL, ITA, ROM, USA

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Considerations on the safety of Liquid Metal Cooled Fast Reactors

1. *Introduction*
2. *General features of LMFRs*
3. *Approaches for design and safety assessment for the prevention and mitigation of accidental sequences leading to severe accidents*
4. *LMFRs features which influence safety*
5. *Conclusion*

Regulators/TSOs and designer organizations from BEL, CHN, FRA, IND, JPN, RUS, USA

Objectives and scope

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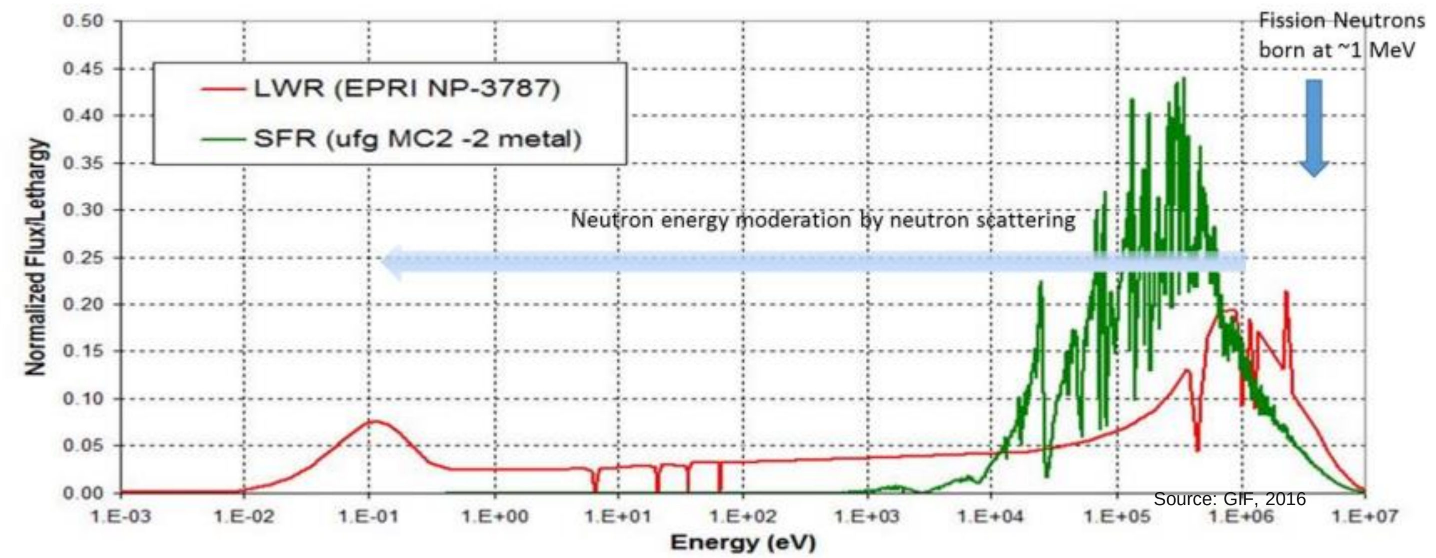
To present safety approaches and design features adopted by Member States in the design and safety assessment of LMFRs (SFRs and LFRs, including LBE) with an emphasis on accident sequences leading to severe accidents.

The TECDOC illustrates practices by design organizations and licensee organizations in developing the safety demonstration related to the consideration of severe accidents, as well as practices by national regulatory bodies in reviewing the corresponding safety.

Target publication date: Q1 2025

Inherent safety characteristics associated to the fast neutron spectrum

- Limited impact on the core reactivity due to the accumulation of fission products
- Smaller changes in reactivity from burnup
- High sensitivity of the core reactivity to modifications of the core configuration (coolant voiding, core compaction)
- Penalised neutron dynamical parameters
- A lower doppler effect



Source: GIF, 2016

Inherent safety characteristics associated to the fuel technology

- Different types of fuel may be used in LMFRs: oxide, nitride, carbide or metallic fuel
  - Different **operating temperatures** (high temperature for oxide fuel and low temperature for the other fuels due to their higher thermal conductivity)
  - A lower fuel temperature is favourable in case of ATWS as the unprotected loss of flow (ULOF)
- High heat transfer properties of liquid metals -> **high-power density**. However, this also leads to a **high decay heat of the spent fuel**

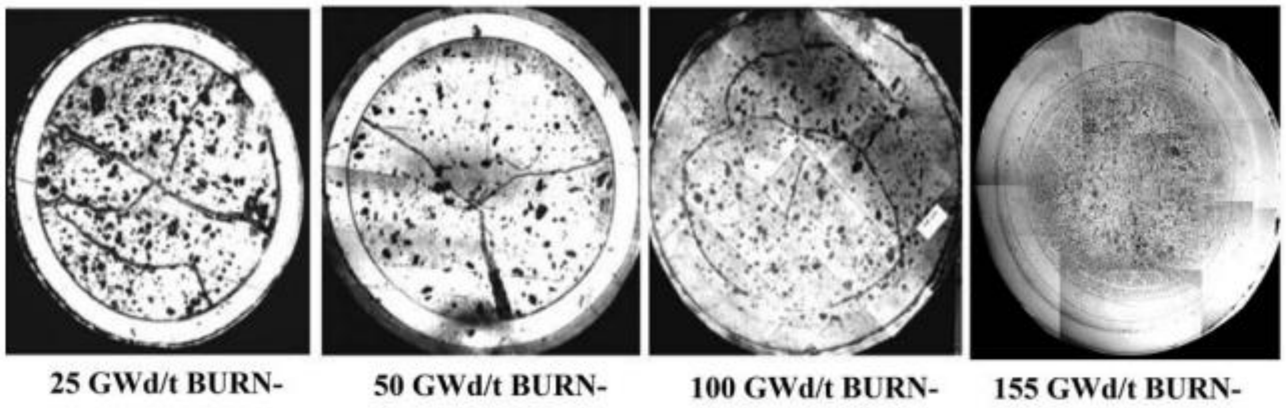
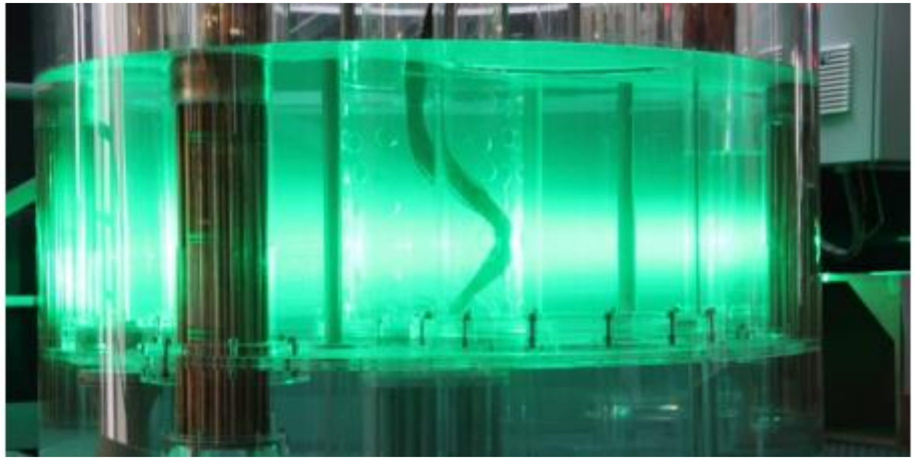


FIG 23. Comparison of ceramographs of FBTR fuel-clad cross-section at various burnup.

Source: IAEA, 2011

Inherent safety characteristics provided by the liquid metal

- **High boiling temperature** -> high temperature increase during the transient, and therefore, high reactivity feedback effect.
- **No pressurized coolant**, as margins to boiling are already large at atmospheric pressure. Large margins to boiling and the high thermal inertia of liquid metals ease removing the decay heat by natural circulation.
- **Large margins to boiling** & **high thermal conductivity** -> prevention of large vapor explosion.
- Chemical properties -> **retaining key fission products** such as iodine and caesium in the primary coolant system.
- **High operating temperatures** -> use of atmosphere as the ultimate heat sink for the decay heat removal.
- **Limited impact of the neutron irradiation** of sodium.
- **Chemical interaction** of lead and LBE with water or air does not lead to energetic phenomena.



Myrrhabelle facility, Belgium. Source: IAEA, 2024

Inherent safety characteristics provided by the liquid metal

- **Limited mechanical resistance** of the structures containing the liquid metal coolant (severe accident, seismic loadings)
- **Blockage of individual sub-assembly** (if subassemblies are designed with a wrapper). In LFRs, blockages and loss of cooling may result from **lead freezing**, and **abnormal lead oxidation**.
- Sodium and lead-alloys are **opaque**
- **Energetic chemical reactions** of sodium with air and water
- Lead and LBE may lead to significant damages of the structures due to **corrosion and/or erosion** phenomena
- With LBE, the neutron irradiation generates **polonium**
- **High freezing temperature** is a challenge for LMFRs

Source: IAEA, 2024

FIG. 3. SOWART Structure with loop pipelines

Severe Accident in LMFR

- IAEA Glossary (2022 edition): *“accident more severe than a design basis accident and involving* ***significant core degradation****”*

- For LWRs, the severe accident is a **core meltdown**

- A core meltdown may also be considered as severe accident for LMFRs (this was the case for previous SFRs)

- The designers of some new SFRs and LFRs, claim that their **inherent characteristics allow to preclude the core meltdown** as candidate for DEC-B severe accidents

<table>
<tr><th colspan="6">Defence-in-Depth Levels</th></tr>
<tr><th>Level 1</th><th>Level 2</th><th>Level 3</th><th colspan="2">Level 4</th><th>Level 5</th></tr>
<tr><td colspan="5">Plant states (considered in design)</td><td rowspan="4">Off-site emergency response (out of the design)</td></tr>
<tr><td colspan="2">Operational States</td><td colspan="3">Accident conditions</td></tr>
<tr><td rowspan="2">Normal operation</td><td rowspan="2">Anticipated operational occurrences</td><td rowspan="2">Design basis accidents</td><td colspan="2">Design extension conditions</td></tr>
<tr><td>Without significant fuel degradation</td><td>With limited core damage</td></tr>
</table>

Source: GIF, 2021

Figure 4. Defence-in-Depth levels and Plant States based on the practical elimination of all Severe Accident Situations with large core melting

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Analysis and Modelling of Severe Accidents for LMFRs: Report of a Technical Meeting

30 representatives, 11 Member States from R&D organizations, design organizations, national regulators and TSO

Objectives and scope

To illustrate the status of knowledge (and in some cases, particularly for SFRs, the state-of-the-art) in the understanding of physical phenomena, development of models and numerical tools, and validation through experimental data, pertaining to severe accident in LMFRs.

The scope covers the various phases of progression of severe accident sequences in SFRs and, as applicable, also to LFRs.

Target publication date: Q4 2024

Analysis and Modelling of Severe Accidents for LMFRs

- The TECDOC encompasses severe accident sequences not ‘practically eliminated’ for LMFRs
  - **Deterministic modelling and analysis** of the severe accident progression
  - **Numerical codes** development and validation
  - Related **experimental programmes** for SFRs and, as applicable, LFRs

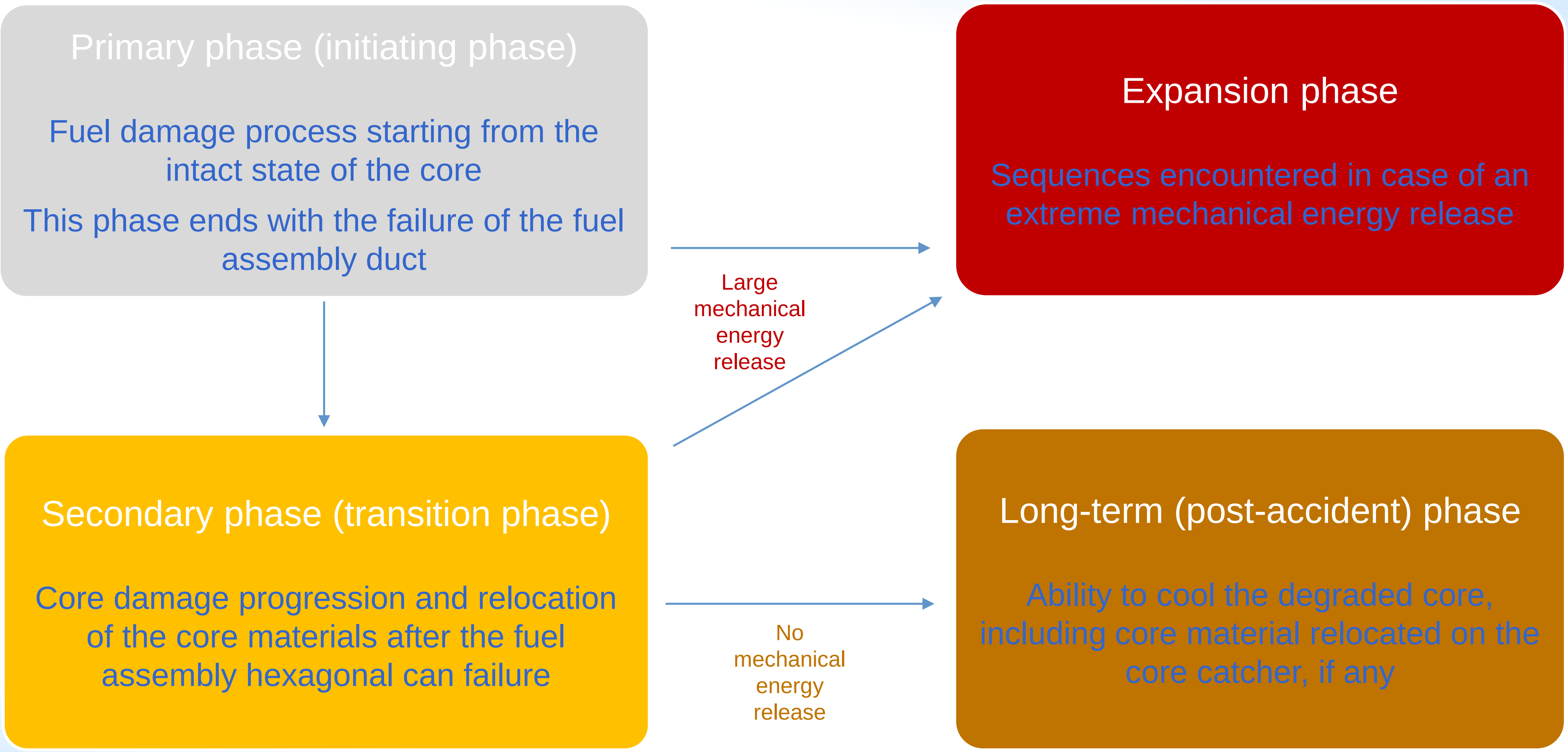
Mechanistic models for core degradation under severe accident conditions:

- fuel pin behaviour
- initiation/primary phase
- transition/secondary phase
- expansion phase
- material relocation
- long-term behaviour

The TECDOC also covers topics related to:

- radioactive material release and transport in-vessel and ex-vessel
- conservative simplified/parametric fast-running models during the core degradation phases
- code development and performance optimization, multi-physics approaches, platform architecture
- experimental programmes, code validation, uncertainty analyses

Phenomenology of Severe Accident Progression in SFRs



Contributions provided at the Technical Meeting

SFR

- Severe accident analysis and experimental validation for SFRs (9 papers, France, Germany, Japan, USA, Russia)
- Primary and transition phases of severe accidents for SFRs (4 papers, USA, Japan, India)
- Expansion phase and long-term behaviour for SFRs (4 papers, Japan, France)

LFR

- Accident analysis and experimental programmes for LFRs (6 papers, Romania, Russia, China, Italy, Egypt)

Conclusions and perspectives

SFR - Conclusions

- Severe accident methodologies have been developed in MS
  - One of the objectives: evaluate the **effectiveness of design measures implemented to cope with SA**
  - It is essential to **simulate all potential phenomena** along with their corresponding **interrelations**
- One important aspect of severe accident analysis for SFRs is to evaluate the **mechanical energy releases which may damage the containment structures**, including the features implemented to maintain sub-criticality and to cool the core debris
- **Progress in the development and improvement of simulation tools for severe accidents analysis to model additional phenomena** and to account for mitigation systems in SFRs designs to achieve higher levels of confidence in safety assessments.
- On-going **experimental programmes** support verification and validation of the physical and mathematical models.

Conclusions and perspectives

SFR - Conclusions

- Simulation tools for modelling the initiation/primary and transition/secondary phases developed and/or expanded to **include modelling of the additional phenomena to reduce the number of conservative assumptions** often made in severe accident analysis
- Simulation tools for the expansion phase and long-term behaviour have reached a **high level of complexity and address the most important phenomena of interest** (e.g. fluid structure interaction, FCI, fuel behaviour in degraded core and on core catcher)
- Complexity of phenomena -> high calculation time -> development of **fast-running codes**
- Efforts are also being devoted towards **high-performance communication** among these simulation tools
- A **rich experimental matrix** has been created. Additional experimental tests are needed to progress in the validation of physical correlations and of calculation tools for specific SFRs designs

Conclusions and perspectives

SFR - Perspectives

- Knowledge and simulation of phenomena likely to damage the reactor structure. R&D is now mainly moving into the later phases of accident
- Integral code system development is underway for the systematic analysis of various accident sequences
- Phenomenological knowledge, analytical models, and experimental data, R&D needs
  - **Primary and secondary phase**: e.g., molten fuel discharge through the steel duct, jet impingement, continued code development to model more phenomena and reduce conservatisms, …
  - **FCI**: e.g., experimental programme to support the validation of FCI with large masses of corium
  - **Expansion phase**: expansion phase and fluid-structure interaction
  - **Long term material relocation and cooling**: debris bed behaviour, molten material behaviour and crust formation in the core catcher, coupling of thermo-hydraulic and neutronic models of the debris bed
  - **FP** release, transport, and retention under severe accident sequences (both for MOX and metal fuel)

Conclusions and perspectives

LFR

- **Lack of consensus on what accidental sequences leading to core degraded conditions are required to be mitigated**. A guidance is needed Integral code system development is underway for the systematic analysis of various accident sequences
- **The information provided on modelling of SA for LFRs is limited**. A good start can be the development of simplified models. A joint effort by the entire LFR community is recommended
- More **information was provided on the research facilities** (phenomena that play an important role in the normal operation and in accident conditions – no link with SA)

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Thank you for your attention

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