Development of Safety Design Criteria for the Lead-cooled Fast Reactor

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Abstract. The Lead-cooled Fast Reactor (LFR) provisional System Steering Committee (pSSC) of the Generation-IV International Forum (GIF) has proposed a set of Safety Design Criteria (SDC) dedicated to LFRs. The objective of the LFR SDC is to prescribe a set of reference criteria for the design of LFR systems, structures, and components with the aim of achieving the safety goals of the Generation-IV reactor system. The LFR SDC has been derived from the already existing Safety Design Criteria for the Sodium-cooled Fast Reactor (SFR), since the GIF LFR and SFR systems share a number of characteristics, design features and some corresponding safety-related phenomenology. For the development of the LFR SDC it was also found useful to use the same structure and methodology of the GIF SFR SDC. A set of reference safety design criteria for LFRs is systematically and comprehensively laid out in the SDC to facilitate the development, safety assessment and licensing of LFRs, including BREST-OD-300, ALFRED, SSTAR, SVBR-100, CLEAR-I, and MYRRHA. The paper summarises results of the steps taken to draft the present set of LFR SDC and provides outlook for further review and development activities, in particular towards individual sets of detailed Safety Design Guidelines.

Key Words: Generation-IV International Forum (GIF), Safety Design Criteria (SDC), Lead Fast Reactor (LFR).

1. Introduction

Nuclear power plants (NPPs) must always ensure the highest level of safety that can reasonably be achieved in order to protect workers at these plants, the public and the environment from any harmful effects resulting from the release of ionizing radiation or other accident consequences. This is valid for all current nuclear power plants and serves also as a guide for the development of the Generation-IV nuclear reactors. The Generation-IV International Forum (GIF) was established in 2000 to coordinate the R&D of the six nuclear systems that were recognized for having the potential to meet the demands for enhanced safety and reliability, economy, sustainability (resource utilisation & waste management), as well as proliferation resistance & physical protection, expected to be required by the middle of this century.

As the high-level safety standard, the GIF Policy Group established the safety and reliability goals for Generation-IV systems in the GIF Roadmap (GRM) [1] and the GIF Risk & Safety Working Group (RSWG) proposed the "Basis for Safety Approach (BSA) for Design & Assessment of Generation-IV Nuclear Systems" [2]. In addition, the RSWG published in 2014 – with the contribution of Lead-cooled Fast Reactor (LFR) provisional System Steering Committee (pSSC) – a white paper on Safety of LFR system [3], while a draft of the LFR System Research Plan [4], hereinafter referred to as the "SRP", has recently been reviewed by the GIF Expert Group (EG) and is planned to be issued in final form in 2017.

It is foreseen that domestic and/or internationally-recognized codes and standards will be used when developing the detailed designs of structures, systems and components. However, there is a large gap between the high-level safety fundamentals and the currently-available detailed codes and standards [5].

The idea to establish "Safety Design Criteria (SDC)" to fill this gap was proposed and discussed at a GIF Policy Group meeting in October 2010. It was recognised that such SDC would fill the middle level of the safety standard hierarchy and would thus be essential to achieve the enhanced safety goals of Generation-IV reactor systems. It was agreed to start with the preparation of the SDC for the GIF Sodium-cooled Fast Reactor (SFR) systems, and a Task Force was set up to draft a specific SDC for this type of a reactor. Additional Safety Guides are subsequently being developed to fill the gap to codes and standards.

Following these prior efforts, the LFR pSSC assessed that the LFR technology was mature enough to start the development of a dedicated LFR SDC. The LFR pSSC started work in 2014 and in December 2015 draft LFR SDC was submitted to the GIF RSWG for review.

This paper summarises the steps taken to draft the present set of LFR SDC. In Section 2, objectives and methodologies are outlined. In Section 3, the paper subsequently discusses the safety goals and safety approach for GIF LFR systems, presenting LFR reference systems and key safety-relevant characteristics considered in the development of LFR SDC. This is followed by conclusions and outline of future plans (Section 4).

2. Objectives and Methodology

International safety fundamentals (e.g., IAEA SF-1 [6]) and safety requirements (e.g., IAEA SSR-2/1 [7]) have been well established for current generation of light water reactor (LWR) systems, and these are extensively used, in parallel with comparable domestic standards, for the design and regulation of LWRs as well as heavy water reactors (HWRs). On the other hand, Generation-IV reactors are advanced/innovative systems utilizing evolving technologies. Therefore, associated safety issues can be anticipated and taken into account from the initial phases of the development.

As discussed above, the GIF has, to date, developed two fundamental safety-related documents, the GRM [1] and the BSA [2], for guiding the development of the Generation-IV reactor systems. The GRM advocates goals for Generation-IV reactor systems in the areas of "Safety & Reliability", while the BSA provides technology-neutral methods on how to meet the safety and reliability goals for Generation-IV reactor systems concerning their design and assessment processes. Moreover, a set of dedicated GIF SFR Safety Design Criteria has been developed for the SFR, applicable to the design of SFR structures, systems and components (including the reactor core, coolant system, and containment) [8].

The development of LFR SDC has been based on the SFR SDC, since the GIF LFR and SFR systems share a number of characteristics, design features and some corresponding safety-related phenomenology. In developing the LFR SDC, it was also found useful to employ the same structure and methodology of the already existing SFR SDC.

The primary users of the LFR SDC are expected to be the GIF LFR developers and designers as well as researchers. It is also conceivable that the regulatory bodies can consider the SDC developed under GIF as a reference for developing domestic LFR safety requirements in the future. The potential users of the SDC may also include developers and designers of advanced nuclear energy systems employing heavy liquid metal coolants outside of GIF.

The primary focus of the LFR SDC is on heavy liquid metals, more specifically pure lead, as the ultimate LFR coolant, but other lead-based coolant options are also considered, especially lead-bismuth eutectic (LBE). Where considerations for LBE coolant differ from those of lead, additional commentaries are included in the LFR SDC in footnotes.

During the formulation of the LFR SDC, the following requirements have specifically been considered (cf. also FIG. 1): (i) the safety level required for Generation-IV reactor systems should be achieved; (ii) the specific technical features and safety-relevant characteristics of LFRs should be considered; and (iii) the latest knowledge should be incorporated as it becomes available, such as R&D results for innovative technologies, as well as lessons learned from accident events, such as those from the Fukushima Daiichi NPP in Japan.

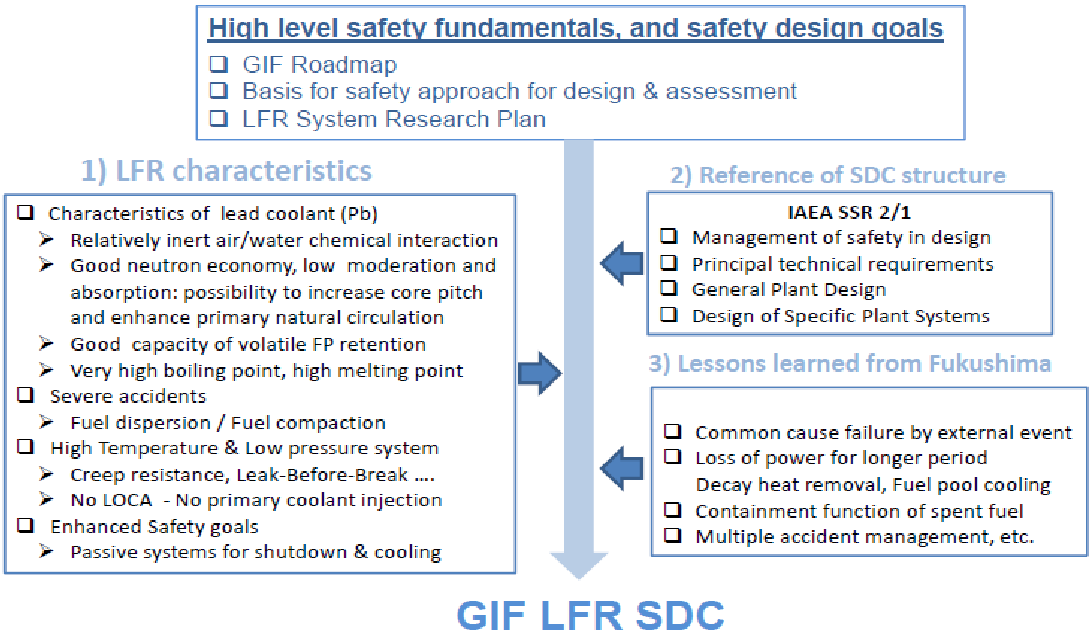

FIG. 1. Basic scheme for the development of the LFR SDC.

Structures, systems and components considered in the LFR SDC include:

- reactor core (fuel elements and assemblies, reactor core structures, reactor shutdown);
- reactor coolant systems (primary coolant system, decay heat removal system);
- containment system;
- supporting and auxiliary systems, fuel handling & storage (lead heating systems, lead purification and conditioning system, cover gas system, fuel handling and storage).

3. GIF Safety Goals and Safety Approach for GIF LFRs

In the GIF Roadmap (GRM), three high-level safety and reliability goals for Generation-IV reactors have been outlined. The GRM also makes note of the essential role that safety has in nuclear energy.

The safety and reliability goals proposed in the GRM are further explained in greater detail in the GIF Basis for Safety Approach (BSA). The following topics are specifically addressed in the BSA: (i) the main safety principles, e.g., Defence-in-Depth (DiD) [9] and risk-informed design; (ii) the basic approaches for safety design and safety assessment; and (iii) the safety assessment methods and tools. The BSA also includes an overview of safety-related technology gaps, assisting in identifying potential safety improvements.

The overall **GIF safety and reliability goals** are outlined in the GRM and the BSA as follows:

1. Generation-IV nuclear energy system operations will excel in safety and reliability, as they focus on robust safety and reliability in DiD Levels 1–2 (i.e., in operational states).
2. Generation-IV nuclear energy systems will have a very low likelihood and degree of reactor core damage. This is envisaged to be accomplished through the reduction of the frequency of initiating events, as well as by the employment of design features for controlling the progress of an accident in response to initiating events and the mitigation of consequences of any initiating events without causing core damage [10].
3. Generation-IV nuclear energy systems will eliminate the need for off-site emergency response, through the implementation of measures preventing significant radioactive material release to the environment. Although this goal does not eliminate the need for off-site emergency response in DiD Level 5, focus is given to the safety designs accomplishing severe accident mitigation in DiD Level 4. The robustness of the design for design extension conditions, as required for a Generation-IV reactor, is achieved by the prevention of their occurrence and/or the mitigation of their consequences.

The definition of Defence-in-Depth and plant state follows the definition in IAEA SSR-2/1 as shown in FIG. 2, which refers to INSAG-12 [11] for the Defence-in-Depth principle.

<table>
<tr><th colspan="5">Defence-in-Depth Levels</th></tr>
<tr><td>Level 1</td><td>Level 2</td><td>Level 3</td><td>Level 4</td><td>Level 5</td></tr>
<tr><td colspan="4">plant states (considered in design)</td><td rowspan="3">Off-site emergency response (out of the design)</td></tr>
<tr><td colspan="2">Operational states</td><td colspan="2">Accident conditions</td></tr>
<tr><td>Normal operation</td><td>Anticipated operational occurrences</td><td>Design basis accidents</td><td>Design extension conditions (including Severe Accident conditions)</td></tr>
</table>

FIG. 2. DiD level and plant states (including severe accidents) based on IAEA INSAG-12 & SSR-2/1.

In other words, operational states include normal operation and anticipated operational occurrences, while accident conditions include design basis accidents and design extension conditions. The latter in turn also encompass severe accidents.

In accordance with the GIF BSA, the **safety approach** for the GIF LFR is based on a combination of following principles: (i) DiD and its further improvements (as a fundamental principle); (ii) risk informed approach; (iii) simulation, prototyping and demonstration; (iv) utilization of passive safety features; (v) prevention of cliff edge effects (in severe accidents); (vi) provisions against internal & external hazards; and (vii) consideration of non-radiological and chemical risks.

3.1 GIF LFR Reference Systems

The target systems for establishing the LFR SDC are LFRs developed under GIF as described in the LFR System Research Plan, i.e. the ELFR (600 MW_e), BREST-OD-300 (300 MW_e) and SSTAR (10-40 MW_e). The LFR SRP provides further information about the configuration of the target LFR systems and explains the Generation-IV system safety and reliability goals in terms of qualitative and quantitative design metrics/characteristics. The developed LFR SDC are applicable to other LFR designs as well.

The specifications of the primarily targeted GIF LFR systems are summarised in Table I.

TABLE I: SPECIFICATIONS OF GIF LFR SYSTEMS

System structure	Pool-type, Large-size, Medium-size, and Small modular
Electric output	10 – 600 MW_e
Coolant system	Primary coolant system utilizing lead coolant
Balance of Plant system	Water/Steam cycle for large- and medium-size Supercritical CO_2 or other gas cycle for small modular
Fuel	Oxides and nitrides of uranium, uranium-plutonium and minor actinides

Technical solutions, based on state-of-the-art R&D [12-13], are used to improve the safety design and to enhance reliability and robustness of LFRs. The ongoing efforts to develop new safety-related technologies for LFRs include industrial partnerships and potential owners/operators as users.

3.2 Considered LFR Safety-relevant Characteristics

A summary of some of key LFR safety-relevant characteristics considered in the development of the LFR SDC is given below.

Core and Fuel Characteristics

LFR fuel assemblies are operated in a fast neutron spectrum under the conditions of high power density, high burn-up, and relatively high coolant temperature. An important characteristic of an LFR (as with other fast reactor systems) is that the reactor core is not in the most reactive configuration under normal operating conditions and that it is possible to postulate a positive void reactivity in the centre area of the reactor core. Considering this characteristic, an excessive reactivity insertion has to be adequately prevented by design. The use of lead coolant presents, in this respect, two advantages: (i) the high boiling point of the lead coolant (1749ºC at 100 kPa [14]) makes coolant boiling highly unlikely; and (ii) the high density of lead reduces the possibility for entrained gas voids to be transported to the core or its vicinity. However, consequences of a fission gas release from failed fuel pins, cover gas entrainment, and steam generator tube leakages or ruptures need to be carefully considered.

Physical and Chemical Properties of Lead Coolant

Density – The high density of lead generates buoyancy forces which have to be considered in design of in-vessel structures, especially moveable equipment, like fuel assemblies and control rod assemblies. Moreover, challenges to the main vessel and reactor components in terms of seismic response need to be specifically addressed.

Boiling/Freezing point – The margin to coolant boiling is very high for lead-cooled systems (cf. vapor pressure of lead is $3 \cdot 10^{-5}$ Pa at 400°C, while boiling point is 1749ºC at 100 kPa [14]). This makes coolant boiling rather hypothetical since system structures would melt well before the onset of boiling, and accident scenarios with boiling lead in the core are therefore considered as highly unlikely. This also allows operating LFRs close to atmospheric pressure. The freezing temperature of lead is 327°C[1], and coolant solidification must therefore be prevented and appropriately mitigated (if feasible). To this end, necessary features for heating of the coolant need to be foreseen to keep lead and LBE at the required temperature in both planned shutdown (including reactor commissioning) and during emergency conditions. Efforts are ongoing to identify a system for freezing prevention and/or for increase of grace time to freezing ensuring also adequate investment protection. As a specific feature related to LBE, a gradual coolant expansion due to phase change needs to be considered after LBE freezing.

Thermal inertia – The volumetric heat capacity of liquid lead is high (roughly 1.54 J/cm^3/K [14]). The high volumetric heat capacity combined with the inventory of the coolant present in the primary circuit provides high thermal inertia, which contributes to the slowing down of any transient related to loss of forced coolant mass flow or loss of heat sink.

Natural convection capability – Molten lead has a large volumetric expansion coefficient ($1.2 \cdot 10^{-4}$ 1/K [14]), and the possibility to operate in a large range of temperatures, typically spanning a few hundred degrees, without boiling or excessive material corrosion/erosion. These characteristics enable core cooling by natural convection, in which pressure losses in the primary circuit are adequately compensated by buoyancy forces. The natural circulation is predicted to be well established in LFR primary systems, due to the simple flow path design and due to neutronic characteristics of lead that allow larger fuel pin pitches and lower coolant velocities, together resulting in low pressure drops [15-16].

Induced radioactivity, coolant activity – Irradiation can, in some materials, lead to the formation of radionuclides that should be confined or their production limited from a radioprotection point of view. These nuclides could also complicate inspection and maintenance of the reactor, as well as its future decommissioning. Note that pure lead[2] is not exempt from polonium formation. However, the rate of polonium production is very small, typically less by several orders of magnitude in comparison to LBE, and the volatility of polonium is further lowered through strong chemical reaction with the lead coolant (e.g., via the formation of lead-polonide [17]). Consequently, only a very small fraction of polonium, depending on the lead temperature, is expected to be volatilized into the cover gas system.

Retention of volatile fission and activation products – Lead provides a relatively good capacity for retention of important volatile fission products as well as activation products. A large body of literature on the chemical and thermo-physical properties of lead and its compounds with caesium, iodine as well as polonium is available and give indications of relatively good retention properties of these nuclides in lead and LBE [17-18]. Nevertheless, further R&D studies are necessary to assess the corresponding retention capabilities in order to evaluate related occupational hazards and possible accidental source terms.

Interaction with oxygen and water – Lead and LBE are chemically relatively inert in contact with water or air. Any postulated leak of lead or LBE from coolant circuits does not cause fire which provides a firm technical basis for the elimination of the intermediate circuit. However, in the case of a steam generator tube rupture (SGTR) event, water interaction with lead or LBE needs to be considered and adequately prevented and/or mitigated, specifically in view of the potential for over-pressurization of the primary circuit, sloshing (e.g., leading to a loss

[1] Freezing temperature for lead-bismuth eutectic is 125°C [14], enabling system operation at lower temperatures.
[2] Polonium (^{210}Po) is formed mainly by neutron absorption on ^{209}Bi and its generation is therefore proportional to the bismuth content in the coolant.

of core geometry) and steam/water entrainment, which might result in a positive reactivity insertion as well as formation of solid PbO causing possible flow blockages.

Fuel-coolant interactions – In case of a cladding failure, oxide or nitride fuels and coolant may come into contact resulting in fuel-coolant interactions. Recent work on the topic has not shown the formation of specifically troublesome compounds, and the interactions have been shown to exhibit low chemical reactivity, favouring safety [17]. Further investigations are however ongoing to better assess the phenomenology of fuel-coolant interactions.

Opacity – In LFR, it is preferable that each component inside the reactor vessel is designed to be removable ensuring adequate in-service inspection (ISI) and maintenance. As such, the principal ISI activities (e.g., visual observation, surface examination, volumetric examination with X-ray or ultrasonic devices) will be performed out of lead. However, further R&D is to be performed on the presence of a residual lead layer on structures and components and its influence on ISI efficiency. Should this approach not be adopted by a specific design, extension of the methodology used for SFRs has to be considered.

Structural Material Compatibility with Coolant / Environment (Corrosion / Erosion)

Flowing heavy liquid metals can be erosive and corrosive and can induce or accelerate a material failure under a static loading (brittle fracture) or under a time-dependent loading (fatigue and creep).

Preventive measures with regard to corrosion risks are the following: LFRs are designed to operate at a low coolant temperature range (based on the structural material used typically at around 400–520°C to keep the fuel cladding temperature below about 570°C) maintaining a controlled concentration of dissolved oxygen in the coolant. This concentration has to be high enough to support the formation of protective layers on surfaces of structures and, at the same time, low enough to prevent the formation of large amounts of PbO precipitation, which might lead to the fouling and slagging of the primary system and subsequently coolant blockages. For traditional materials at temperatures above 500°C, the corrosion protection afforded by the oxide barrier may fail and the application of alternative corrosion-protection surface coatings [19] and composites [20] or the use of steels with addition of silicon or aluminium is therefore considered [21]. Fuel cladding, upper core regions and heat exchanger primary coolant inlet regions are particularly sensitive to corrosion, because temperatures are the highest. At any rate, the integrity of the protective layer has to be ensured during all plant operating conditions, including long-term transients, in order to ensure the integrity of the systems, structures, and components. These surface coatings or functionally graded composite techniques are already applied in conventional plants, and an experimental program is ongoing to validate their feasibility and reliability also in the nuclear field.

LFR Design for Design Extension Conditions (incl. Severe Accidents)

Design extension conditions, including severe accidents, are categorised as Level 4 in DiD, cf. FIG. 2. For example, plant conditions caused by an initiating condition combined with multiple failures of safety equipment or severe external events [22], are postulated as design extension conditions.

TEPCO’s Fukushima Daiichi NPP accidents, caused by the Tōhoku earthquake and tsunami on 11 March 2011, emphasize the need to ensure that sufficient design measures against extreme external events and the ensuing severe accidents have been implemented in the nuclear plant.

Specifically, a fast reactor, including an LFR, is characterised by the fact that its core is not in its most reactive configuration under normal operating conditions. Thus, the core has a possibility to undergo positive reactivity changes when exposed to various initiators that either reduce neutron capture & moderation (by, for example, gas void formation) or increase fuel concentration (by, for example, core compaction by seismic excitation). To manage an excessive insertion of positive reactivity, prevention as well as mitigation measures for such conditions must be provided in the design to maintain fundamental safety functions.

LFR design extension conditions events can specifically be caused by: (i) failure to shutdown (scram) the reactor following an off-normal initiating event (i.e., unprotected events); and (ii) inability to remove heat from the core following an initiating event.

The failure to shutdown can be combined with three typical LFR accident sequences leading to the following design extension condition events: (i) loss of flow with failure to scram; (ii) overpower transient with failure to scram; and (iii) loss of main heat removal capability with failure to scram. Additionally, the inability to remove heat from the core can lead to two other design extension condition events: (i) loss of coolant flow (i.e., flow paths for decay heat removal being disrupted); and (ii) long-term loss of heat sink (with scram).

Concerning the failure to shutdown events, the LFR design needs to prevent such events from damaging the core and mitigate the consequences of core damage to minimize the load on the containment function. To prevent the core damage, the LFR design may make use of passive and/or inherent reactor shutdown capabilities. Restricting generated energy and retaining/cooling the damaged core will further reduce the potential challenge on the containment function. Concerning the loss of heat removal events, the LFR design should provide a means to prevent core damage or loss of containment function by maintaining lead coolant level for core cooling, ensuring decay heat removal under the conditions with or without core damage.

Management of Design Extension Conditions (incl. Severe Accidents)

Management of design extension conditions is based on the application of DiD, involving the control of severe plant conditions, prevention of accident progression, and mitigation of the consequences, including of severe accidents.

Prevention

In LFRs, accident prevention is strengthened by a number of considerations, in addition to the fundamentally advantageous characteristics of the coolant (i.e., its very high boiling temperature and relative inertness in contact with water and air). These additional considerations include: (i) systematic application of the principle of the DiD, incl. the principles of redundancy, independence, and diversity to address risks of common-cause failures; (ii) large thermal inertia of the plant, which provides considerable grace times to prevent further accident progression; (iii) expanded use of passive safety features; (iv) reduced plant complexity (e.g., no intermediate circuit); and (v) optimized human-machine interfaces as well as extended use of information technologies (e.g., augmented controls & displays and virtual reality simulators).

As concerns corrosion-erosion issues, the DiD prevention approach includes: (i) the use of qualified materials; (ii) redundancy (as appropriate); (iii) ISI / surveillance; and (iv) provision of adequate margins and grace times to take corrective actions.

As discussed above, in LFRs, there is a lack of large sources of physical or chemical energy such as primary coolant boiling, large accumulation of hydrogen and rapid chemical reaction between fuel and coolant to challenge safety barriers. In other words, there are no rapid exothermic reactions between lead and water (as well as air), although the phenomenology needs to be fully understood, notably as far as the risk of contact between hot lead and water is involved. Nevertheless, severe accidents that could lead to containment barrier failures shall be considered explicitly in the design process of LFRs to analyze the course of an event and devise appropriate mitigation measures.

Mitigation

Essential objectives of the accident management for LFRs are to: (i) monitor plant status; (ii) maintain core sub-criticality; (iii) protect the integrity of the reactor vessel by ensuring heat removal from the core and preventing excessive loading conditions (both thermo-mechanical and chemical); (iv) limit the release of radioactive material to the environment; and (v) regain and maintain a safe shutdown state.

In a very unlikely event involving loss of all heat sinks (all decay heat removal and secondary systems), the heat in LFRs could be removed by injecting water in the reactor cavity between the reactor and safety vessels, while in case of reactor vessel breach the decay heat can still be removed by the system that cools the concrete of the cavity walls. As discussed earlier, such very ultimate mitigation provisions are possible since lead is relatively chemically inert in contact with air and water so that the reactor could be flooded by water.

4. Conclusions

A set of reference safety design criteria for LFRs has been laid out in the GIF LFR Safety Design Criteria document. This paper summarises results of the steps taken to draft the present set of the LFR SDC. The work specifically considered GIF safety goals, safety-relevant characteristics and technical features of LFRs, as well as the latest R&D results and lessons learned from the accident at the TEPCO Fukushima Daiichi NPP. The draft LFR SDC was submitted to the GIF RSWG for review in December 2015 and the document has already been reviewed by the IRSN and other partners of the Euratom collaborative project ARCADIA. While ensuring consistency with the SFR SDC, the finalized LFR SDC document is well poised for further development towards Safety Design Guidelines for selected topics.

5. Acknowledgements

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