Lead-cooled Fast Reactor (LFR) System Safety Assessment

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3 June 2020

GIF-LFR System Safety Assessment

The Generation IV International Forum Lead-cooled Fast Reactor
provisional System Steering Committee (GIF LFR pSSC)

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in collaboration with
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Summary

The Generation IV International Forum (GIF) Experts Group tasked the Risk and Safety Working Group (RSWG) with assessing the high-level safety design characteristics of all six GIF systems. The objective is to review and identify the main safety advantages and possible challenges of the individual technologies, with a view to assess the current status of safety-related research & development (R&D) activities and identify future R&D needs for each system. In this context, the RSWG requested that the GIF Lead-cooled Fast Reactor (LFR) provisional System Steering Committee (pSSC) prepare a system safety assessment (SSA) document summarizing the safety advantages and challenges of LFR concepts under consideration. The present report is structured according to the "table of contents" below as proposed by the RSWG.

In preparing this assessment, the LFR pSSC has placed emphasis on the outcomes of safety-related R&D for the GIF LFR Reference Systems and the review of LFR safety aspects by the French "Institut de Radioprotection et de Sûreté Nucléaire" (IRSN) [1].

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List of Acronyms

AFA	Alumina Forming Austenitic Alloys
ALFRED	Advanced Lead Fast Reactor European Demonstrator
BREST	Bystryi Reactor so Svintsovym Teplonositelem
CAS	Chinese Academy of Sciences
CLEAR	China Lead-based Reactor
DHR	Decay Heat Removal
DiD	Defense-in-Depth
DOE	U.S. Department of Energy
ELFR	European Lead-cooled Fast Reactor
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EURATOM	European Atomic Energy Community
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
IAEA	International Atomic Energy Agency
INEST	Institute of Nuclear Energy Safety Technology
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
ISAM	Integrated Safety Assessment Methodology
ISI	In-service Inspections
ISI&R	In-service Inspections and Repair
JSC	Joint Stock Company
KIT	Karlsruhe Institute of Technology
KTH	Kungliga Tekniska högskolan
LBE	Lead-Bismuth Eutectic
LEADER	Lead-cooled European Advanced Demonstration Reactor
LFR	Lead-cooled Fast Reactor
MA	Minor Actinide
MIT	Massachusetts Institute of Technology
MN	Mixed Nitride Fuel
MNUP	Mixed Nitride U-Pu
MOX	Mixed Oxide Fuel
MSR	Molten Salt Reactor
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications

NERAC	Nuclear Energy Research Advisory Committee
NIKIET	N.A. Dollezhal Research and Development Institute of Power Engineering
NPP	Nuclear Power Plant
OPT	Objective Provision Tree
pSSC	Provisional System Steering Committee
QSR	Qualitative Safety Features Review
R&D	Research & Development
RSWG	Risk and Safety Working Group
SAMG	Severe Accident Management Guidelines
SCWR	Supercritical Water Reactor
SFR	Sodium-cooled Fast Reactor
SGTR	Steam Generator Tube Rupture
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
SNU	Seoul National University
SSTAR	Small Secure Transportable Autonomous Reactor
ULOF	Unprotected Loss-of-Flow
V&V	Validation and Verification
VHTR	Very High Temperature Reactor
βeff	Effective Delayed Neutron Fraction

1. General overview of the performance goals

The path to develop advanced nuclear reactors offering possible performance advantages over current reactor systems has been outlined in the Generation IV Technology Roadmap, which was prepared by the U.S. Department of Energy (DOE) Nuclear Energy Research Advisory Committee (NERAC) and the Generation IV International Forum in 2002 [2] and further updated in 2014 [3].

The Roadmap defined challenging technology goals for advanced reactor systems in four major areas:

- Sustainability;
- Economics;
- Safety and reliability; and
- Proliferation resistance and physical protection.

In addition, the Roadmap identified six types of reactor systems, collectively known as "Generation IV" or "Gen IV" systems that are considered the most promising reactor technologies to achieve these goals and thereby enhance the future role of nuclear energy. These six reactor types are the Molten Salt Reactor (MSR), the Supercritical Water Reactor (SCWR), the Very High Temperature Reactor (VHTR), the Gas-cooled Fast Reactor (GFR), the Sodium-cooled Fast Reactor (SFR), and the Lead-cooled Fast Reactor (LFR).

In the following sections the four Generation IV goals are analyzed with the aim to show how the LFR can implement such high-level desiderata through specific aspects of the technology. Technology related challenges concerning safety aspects are detailed in the specific and proper sections of the paper starting with section 4 and ending with the R&D needs arising from such analysis in section 8.

1.1 Sustainability

The LFR, as a fast reactor system with its associated closed fuel cycle, is particularly effective in fully utilizing the energy value of uranium, both its fissile and fertile components, as well as thorium as a fertile material. It has been estimated that fast reactor fuel cycles can provide factors of 40 to 100 times greater fuel utilization than existing thermal reactor fuel cycles, depending on the reactor design and the fuel cycle parameters [4]. Additionally, the LFR can effectively consume plutonium and other transuranic elements that have accumulated from past and ongoing Generation I through III+ nuclear fuel cycles. These capabilities thus fully support the first Generation IV goal of increased sustainability. The neutronic properties of lead and lead-bismuth coolants[1] (low neutron absorption and moderation) readily enable sustaining a hard neutron energy spectrum, providing good neutron economy and performance flexibility.

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[1] The principal coolants proposed for LFR systems are pure lead and lead-bismuth eutectic, or LBE, the eutectic alloy of lead (44.5 wt.%) and bismuth (55.5 wt.%). The GIF Reference Systems each use pure lead as the coolant, but other LFR systems being developed globally use LBE.

The LFR can therefore efficiently breed new fissile material, or consume transuranic elements, which have accumulated during past decades, thus minimizing the volume and radiotoxicity of long-lived, high-level waste.

Thorium, which is even more abundant than uranium, could also be used as a fertile material to further burn transuranic elements with little new generation of plutonium and minor actinides (MAs) coupled with generation of ^{233}U.

In summary, the LFR offers the potential for very high efficiency in fuel utilization, burning of long-lived actinide components of high-level waste, and utilization of the thorium fuel cycle, and therefore can be considered a very attractive option to achieve the goal of long-term sustainability.

1.2 Economics

The second goal area for Generation IV systems, economic performance, is generally difficult to quantify for new, advanced systems, yet there are several characteristics of LFR systems that suggest the potential for advantageous economic performance. Key among these characteristics are:

- The relatively inert chemical nature of the lead (or lead-bismuth) coolant should it come in contact with air or water[2], which supports simplified designs that do not require complex and expensive intermediate systems to isolate the primary coolant from its secondary coolant, normally water. The reduced complexity and footprint of such a simplified plant will positively impact capital and operational costs and resulting economic performance;
- The very high boiling temperature of the lead coolant (1749ºC) which virtually eliminates coolant boiling and the related safety challenges present for other liquid coolants enables further simplification of design and safety demonstration;
- The low partial vapor pressure of lead ($2.9 \cdot 10^{-5}$ Pa at 400°C), which allows primary system operation at near atmospheric pressure, avoiding thus the need to maintain complex and expensive structures to provide pressure boundaries in LFR systems;
- The high operating temperature of LFRs, which enables high power conversion efficiencies, likely at or above 40%[3];
- An expected long design life (i.e., up to a 60-year design life) with recognition that there could be a shorter intended operational time-frame for initial LFR demonstrators;

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[2] We use the terms "relatively inert" and "relative inertness" in this document to reflect the fact that there are no rapid exothermic reactions between lead or LBE and air and water.

[3] The efficiency cited here is for LFRs operating at what would be considered safe temperature limits under which the corrosion-erosion effects are well-controlled. Operation at higher temperatures, contingent on use of more corrosion resistant materials and methods to limit corrosion could offer further improvement in economic performance.

- The use of oxide and nitride fuels that can reach high burnup, improving fuel utilization and reducing fuel cycle costs;
- The fact that load following operations are strongly favoured by the small difference between “cold state temperature” and operational temperature;
- Additionally, the longer times between refueling reduce spent-fuel handling and fuel fabrication costs and average refueling outage times.

In addition, for smaller LFRs, similarly to other small modular reactor (SMR) options that might be considered, the limitation on power output may be offset by other factors benefitting from: (i) the increased compactness and simplified designs, with increased factory-fabrication of (primary) components; and (ii) the application of the “economy of replication”, with mini-serial production, standardization, improved quality, and wider supply chain options.

In summary, good economic performance of LFRs can be expected due to the favorable inherent characteristics of the lead coolant leading to: (i) system compactness, greatly reducing plant footprint and use of materials; (ii) simplification of design and operation at near atmospheric pressure, with reduced size (and number) of the components; (iii) enhanced retention of radioactive materials, reducing the resulting source term and consequent requirements for emergency planning zone; and (iv) reduced severe accident probability, and the related costs for prevention and mitigation measures. The latter two aspects are further discussed in Sub-section 1.3.

1.3 Safety and reliability

The third goal area for Generation IV systems related to increased safety and reliability is receiving increasing emphasis and is expected to be a major condition for public acceptance of nuclear power.

In the area of safety, LFR systems are expected to excel due to the following factors related to the favorable basic and intrinsic characteristics of lead as a coolant:

- The ability to operate at low system operating pressure together with the possible leak-before-break nature[4] of the reactor coolant system boundary, resulting in fault-tolerant characteristics;
- The high primary coolant boiling temperature, well above the melting point of the cladding and other structural materials, making the voiding effect associated to a “stable” bulk boiling very unlikely, and its consideration hence unnecessary;
- Concerning the transient presence of voids in the core, for some designs (for example BREST-OD-300), the analysis indicates that the presence of steam bubbles (possibly

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[4] The resistance of structural materials to unstable crack growth in heavy liquid metals is currently being studied, cf. also Sub-section 4.3.1.

due to SGTR) do not lead to an increase in reactivity, also benefitting from the high hydrostatic pressure in lead[5].

- A complete loss of coolant is prevented by the absence of coolant boil off and low chemical interaction potential with environment fluids (water and air);
- The capability to design an LFR core with a large pitch-to-diameter ratio, providing enhanced safety against flow blockage and improved heat removal through higher natural circulation;
- The lead coolant properties in combination with application of dense (U-Pu)N fuel allows the breeding of fissile materials in the reactor core with a small reactivity margin preventing uncontrolled power increase[6];
- The relatively inert chemical nature of the lead coolant, its high thermal inertia and its favorable natural circulation capability promote benign behavior in accident situations as well as successful mitigation;
- As such, because of effective passive decay heat removal due to natural circulation, LFR systems are not dependent on off-site power or emergency on-site back-up power for successful mitigation of accident conditions[7];
- Possible severe accident initiators related to coolant boiling reactivity void effects are highly unlikely due to the very high coolant boiling temperature, even in the case of loss of off-site and on-site backup power. In LFRs, high-temperature creep and corrosion do not typically challenge structural integrity in the medium-term during loss of off-site and on-site backup power [5-6];
- In accident situations such as those that might be triggered by extreme (i.e., beyond design basis) external events, dedicated experiments and code qualification activities [7] have shown that adequate decay heat removal can be achieved using natural circulation of the already-available lead coolant in the primary circuit, relying at the same time on available ultimate heat sinks such as air or water. Loss of off-site power and on-site diesel generators is not considered an extreme event since the entire safety analysis is normally performed assuming an absence of external and on-site power supply[7];
- The lead coolant provides a capacity for retention of volatile fission products, such as cesium and iodine, so that significant accidental release outside the primary coolant system is considered to be unlikely [8];
- Compared to other technologies, the accumulation of hydrogen does not occur, as hydrogen production due to any possible primary coolant interaction with water is

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[5] Such scenarios as well as scenarios involving multiple cladding ruptures (leading to the introduction of non-condensable gases to the primary coolant) are included in the safety analysis and have to be analyzed for other designs as well.

[6] In case the reactivity margin would erroneously be introduced due to equipment failures or operator errors.

[7] R&D is on-going to confirm the conditions of establishment of adequate natural circulation in the system and its reliability, cf. also Sub-section 3.

strongly limited. Moreover, the phenomenology of hydrogen production by metal-water interaction, as occurred in Fukushima accident, is excluded by design.

Finally, with respect to reliability, high levels can be achieved both through design as well as using passive safety systems such as natural circulation without pumps, based on fundamental physical principles without the need for external power for their operation.

The implementation of passive safety systems and the principle of Defense-in-Depth (DiD) have been introduced into LFR designs from the very early stages, ensuring that safety features are “built in” rather than “added on”.

1.4 Proliferation resistance and physical protection

The last goal area for Generation IV systems aims at increased proliferation resistance and physical protection. These characteristics are enhanced for LFR systems for the reasons that follow:

- As with other fast reactor concepts, the fuel cycle of LFRs is self-sustaining, not requiring the generation / supply of additional enriched uranium, plutonium or other fissile material. For some designs (cf. SSTAR or battery type designs) fuel reprocessing will be conducted less often and with less generated new fissile material, enhancing thus the proliferation resistance. Moreover, recycling and consumption of Pu and MAs from existing spent fuel lowers their content in the ultimate waste (hence lowering another possible source for proliferation).
- Some LFR concepts integrate / co-locate fuel reprocessing and fabrication functions into the reactor site so that only natural uranium is transported to the site as fuel feed and only fission products leave the site for disposal;
- The possibility of long or very-long core life (and the corresponding increase of the time between refueling operations) reduces the proliferation risk associated with fuel handling operations. Some designs exist (e.g., SSTAR, CANDLE) which could operate for very long periods without refueling;
- The design robustness, high temperature environment, small footprint, minimization of active safety components, and need for remote handling of spent fuel provide basic contributions to physical protection.

In summary, due to the potential for substantial improvements arising from the intrinsic characteristics of the coolant as well as from design and safety choices implemented in the considered LFR designs, in light of the technology advances and studies completed in recent years, it is appropriate to consider that the LFR could provide significant advantages in each of the four GIF goal areas.

2. Historical review of, and feedback from, past construction and operation experiences

Leo Szilard first proposed the use of a heavy liquid metal (i.e., bismuth) as a reactor coolant in 1942. Subsequently, the earliest exploration was conducted at the Brookhaven National Laboratory in the U.S.A. After encountering difficulties related to the structural material compatibility with heavy liquid metals, specifically in oxygen-contaminated systems, the U.S. effort was discontinued with all results published in the 1950s [9].

A major contribution to the development of lead-cooled reactor technology has been accomplished by Soviet and then Russian scientists and industries by actively pursuing R&D in the field over a period beginning in the 1950s and continuing to the present day. In the early 1950s, research and design related to the use of lead-bismuth eutectic (LBE) as the coolant for nuclear reactors was initiated in the Soviet Union by Academician A.I. Leipunsky who developed an oxide passivation approach to manage materials corrosion through chemical (i.e., oxygen) controls in systems involving heavy liquid metals. The principal objective of these efforts was the design and construction of nuclear reactors for submarine propulsion.

In 1963, the first nuclear submarine with LBE-cooled reactors was put into operation in an effort entitled “Project 645”. Since 1971, a series of nuclear-powered submarines of the so-called “Alfa-class” (in the NATO terminology, “Lira-class” in the terminology of the former Soviet Union) were put into operation. In total, seven nuclear submarines of the “Alfa/Lira-class” or “Project 667” and “Project 705/705K” types were constructed and operated, in addition to the previous submarine of the “Project 645” type, and two land-based prototypes. Overall, about 80 reactor-years of experience and feedback were accumulated during operation of these facilities.

During the land-based testing of prototype LBE-cooled reactors and during submarine operations, valuable operating experience feedback was gathered to demonstrate the potential of this reactor technology, while also identifying further R&D needs and areas for improvement of the implemented technological solutions. Among others, the latter involves [10-12][8]:

- Prevention of water ingress into the reactor from a steam generator tube leak;
- Prevention of the consequent formation of solid oxide particles in the LBE coolant, which might be transported into the core and cause local coolant blockage and subsequent partial core melt;

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[8] It must be pointed out that the accidents occurred during submarine operations and they need to be interpreted in the context of military/defence applications. For example, as there was the need of continuous operation for propulsion purposes also in presence of water leakages on primary side, it led to excessive oxide formation causing the accident. Obviously no LFR will be operated in such conditions for civil use: the leakage will be detected and repaired before recovering the operation. Water-induced corrosion was not related to the LM technology, while LBE freezing was a problem related to compactness of the loop design. As far as ^{210}Po is concerned, there was no evidence of crews increased morbidity respect to crews operating submarines with LWR technology.

- Prevention of water-induced corrosion of the outer piping surfaces, which might lead to LBE leakage;
- Prevention and management of local LBE coolant freezing (e.g., due to heater failures); and
- Prevention and management of radiotoxic ^{210}Po.

Consequently, in addressing the identified R&D needs, a large experience/knowledge base has been acquired in the areas of lead and lead-bismuth coolant technology, corrosion inhibition, mass transfer in lead and lead-bismuth circuits, as well as in ^{210}Po management.

The new Gen-IV nuclear reactor designs based on lead coolants leverage this extensive experience which has been further extended by recent experimental work and other technological developments.

As also discussed in the following sections, steam generator leakages can be effectively prevented/mitigated by employing more resistant materials and cover gas monitoring systems. The past experience with LBE leakage in the primary system specifically highlights the importance of strict water and heavy liquid metal chemistry control. The risk of heavy liquid metal freezing, pertinent in particular to the loop-type designs, can be effectively managed by employing pool-type designs. Finally, the production of ^{210}Po can be minimized and managed by employing pure lead and using Po-removal systems, respectively.

3. Level of ongoing safety-related research and development

Among the performance goals set for future nuclear energy systems, improved safety and higher reliability are recognized as essential priorities. In this respect, the IAEA fundamental safety objectives, safety principles, and design safety requirements, including the application of the concept of Defense-in-Depth, form the basis for the development of LFR designs [13-14]. In further support to the LFR design efforts, safety assessments, and a dedicated set of GIF-LFR Safety Design Criteria to guide design and licensing processes are also being developed [15].

In addition, design philosophy, safety characteristics, implemented safety features, and assessment methodology follow the high-level safety goals, guidelines, and recommendations set for Generation IV reactor concepts [2-3, 16-17].

Consequently, the safety architecture of LFRs is based on the following design principles:

- Safety shall be "built-in" during the design process rather than "added on" at a later stage;
- Defense-in-Depth principles shall be fully implemented in a manner that is demonstrably exhaustive, progressive, tolerant, forgiving, and well-balanced (e.g., avoiding "cliff edge effects" and providing a sufficient grace period as well as the possibility of repair/recovery during accidental situations);
- A "risk-informed" approach shall be used in the design process, with the deterministic approach complemented by a probabilistic one; and

- The Integrated Safety Assessment Methodology (ISAM) shall be adopted. In particular, the Objective Provision Tree (OPT) methodology[9] is the fundamental tool used throughout the design process of LFRs.

The application of the above components shall proceed progressively as the design develops using a so-called “graded approach”.

Additionally, a full description of the safety approach used for the design of LFRs in the European Union (EU) can be found in [18]. This, among others, aims at the application of the DiD in a balanced and practical way, achieving high robustness of the plant in response to accident initiators, but avoiding an “over-design” when added cost would provide only minimal or no additional safety benefit.

An overall analysis of LFR risk and safety features, including the pilot application of the ISAM involving the overview of LFR designs’ safety architecture characteristics and performance through Qualitative Safety Features Review (QSR) and OPT is presented in the GIF White Paper on LFR safety [19]. This paper was prepared in cooperation between the RSWG and the GIF LFR provisional System Steering Committee.

As is the case for some other reactor systems, LFR concepts considered within GIF strongly rely on passive safety features. This is the case of all three GIF LFR Reference Systems: ELFR (EU), BREST (Russian Federation), and SSTAR (US). It has to be particularly noted that the decay heat removal (DHR) systems immersed in primary pools of certain LFRs rely on natural circulation on both the primary and secondary side (where water or air is usually used). Additionally, control rod and shutdown systems rely on buoyancy or are gravity driven.

These systems have been the subject of experimental qualification programs; for the DHR systems in particular, R&D activities are investigating the degree and stability of the established natural circulation flow. The relevant qualification programs have either been completed or are currently underway.

Further safety-related R&D is currently ongoing and is expected to be augmented, specifically in the area related to fuel-coolant thermodynamic and chemical interactions, including the behavior of dispersed fuel, fission, activation, and corrosion products in heavy liquid metal. The knowledge of the phenomenology related to lead-water/steam interactions (including the degree of steam entrainment, pressure wave propagation, and damping) needs to be improved for validation and verification (V&V) of computational tools to analyze Steam Generator Tube Ruptures (SGTRs). The facilities to investigate the interaction of heavy liquid metal with high pressure water/steam have already been built and are under operation to support these

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[9] The OPT is a top-down method which, for each level of DiD and for each safety objective/function, identifies the possible challenges to the safety functions, their related mechanisms and the provisions needed to prevent, control or mitigate their consequences.

investigations. Further code V&V efforts are also necessary for studying possible sloshing phenomena related to the high density of lead.

These activities will together provide necessary insights for a possible practical elimination of severe accidents or for implementation of robust measures for their management and for the development of related severe accident management guidelines (SAMG).

Lastly, R&D on material compatibility with heavy liquid metals has historically been and continues to be a main R&D topic related to the LFR technology and structural material qualification (cf. Sub-section 4.3.1 and Section 8).

R&D activities are being conducted in the frame of and in support to several LFR technology projects, which are currently implemented through respective national programs and conducted in international collaborative efforts: MYRRHA in Belgium (SCK•CEN), BREST in the Russian Federation (NIKIET), URANUS in Korea (SNU-NUTRECK [20]), CLEAR in China (INEST) and ALFRED in Europe.

4. Achievement of fundamental safety functions

In LFRs, in accordance with safety requirements, the fundamental safety function with respect to reactivity control is realized by using at least two independent and diversified systems for shutdown of the reactor. Shutdown is then followed by the actuation of dedicated decay heat removal systems.

Each LFR system has specific approaches for the achievement of the reactivity control and (decay) heat removal safety functions; however as outlined above, in each case the shutdown systems and DHRs operate passively, generally falling into the category of actively actuated, passively operated systems (Category D [21]).

4.1 Reactivity control

4.1.1 Control (and shutdown) systems

The GIF LFR reference systems feature at least two independent and diversified shutdown systems consisting of control rods and shutdown safety rods. Consistent with the single failure criterion requirement, one of the two systems is sufficient to shut down the reactor, and the shutdown function is also accomplished even when the most reactive rod becomes stuck out of the core.

In some designs, an active mode of operation is also provided, but a back-up passive mode is always available. Rods are either inserted from the top of the core using ballast in the upper part of control rod assemblies, or they are located below the core and driven up by buoyancy force available in lead. In the case of BREST additional reactivity control passive feedback based on neutron leakage is also available. Its operation principle lies in changing the neutron leakage from the reactor core and, accordingly, the reactivity by means of passive change of the lead column height in the reflector blocks according to the reactor coolant head (flow rate)[10]. (Category B [21]).

The facilities for experimental testing of control (shutdown) systems and their components have already been built and tested in lead environment (BREST), or are being planned, in support to the qualification of these systems at representative conditions.

4.1.2 Risk of re-criticality

The risk of re-criticality is considered to be diminished by the inherent characteristics of lead and mitigated by LFR design provisions and especially by its neutronic core design.

As discussed above, lead has a very high boiling temperature (1749ºC), making coolant boiling during accident conditions extremely unlikely. This together with low or negative coolant density and void reactivity coefficients (even though such coefficients are typically positive in the center of the core) strongly relaxes risks for reactivity insertions during accidental coolant heat-up. During the postulated unprotected accidents studied in the design extension domain, LFR concepts typically exhibit an overall negative reactivity feedback.

Challenges to functionality of the control and shutdown rod system, which could be impaired by coolant oxidation or excessive corrosion and erosion (possibly also causing blockages due to accumulation of oxides or corrosion products) or by coolant solidification due to overcooling, should be prevented by reliable control of oxygen dissolved in lead and control of heat transfer conditions at the secondary side, respectively. Possible options remain under investigation in terms of systems and devices and their reliability targets. This topic is identified as a priority R&D need (see Section 8).

Loss of core geometry (core compaction) is prevented by design provisions such as wrapped and/or rigid fuel assemblies, application of fuel assembly distance pads, and seismic isolators. Mechanical analyses should demonstrate that the radial pin support (grids/wires) is able to maintain core (pin and sub-assembly lattice) geometry, taking into account the relatively large pin pitch-to-diameter ratio featured in LFR designs.

Likewise, the consequences of SGTRs, possibly leading to loss of core geometry and/or water/steam entrainment and positive reactivity insertions, are prevented and mitigated by design provisions, including the design location of steam generators and the associated lead flow path, implementation of rupture disks connected to pressure suppression systems to prevent over-pressurization, and adoption of corrosion resistant materials or surface treatment for SG tubes. However, calculations show that in situations when water/steam bubbles would be entrained in liquid lead as a consequence of a SGTR, the associated reactivity effects in the core would be minimal. These situations are planned to be demonstrated in the next two years through experiments at the BFS critical facility in the Russian Federation. Nevertheless, as

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[10] There are no mechanical moving parts.

discussed above, further analytical and experimental R&D assessments are necessary to improve our knowledge on the phenomenology and possible consequences of SGTRs [22-23].

The risk of re-criticality in case of postulated core disruptive accidents is, based on phenomenological analyses and engineering judgment, considered to be low, due to very similar densities of lead and mixed oxide or nitride fuels, which is hypothesized to favor fuel dispersion (by the buoyancy force) rather than compaction, cf. also Sub-section 5.1. As mentioned earlier, further R&D is necessary to understand severe accident phenomena in LFRs comprehensively (including phenomena such as fuel dispersion / dissolution / segregation vs. aggregation), serving as a basis for the possible practical elimination of severe accidents or development of severe accident management strategies. These studies may also lead to the establishment of a requirement for specification of a maximum MOX or mixed nitride fuel density for the LFR.

4.2 Decay heat removal

4.2.1 Thermal inertia and grace period

Due to the large volumetric heat capacity of lead (1.54 J/cm^3/K) combined with the large inventory of the coolant in the primary circuits, LFRs are particularly effective in providing a high thermal inertia. This contributes to the slowing down of any transient related to loss of forced coolant mass flow or loss of heat sink, resulting in very long grace time periods that are available for operator actions [24].

Due to the favorable neutronic characteristics of lead allowing larger pin pitches and simple flow path designs, that together result in low pressure drop, LFRs typically also feature a high natural circulation capability of the coolant in the primary circuit. Hence, even in the case of an Unprotected Loss-of-Flow (ULOF) accident, benefitting from the high degree of established natural circulation flow, the structural integrity of LFR components and vessel are typically not challenged in the medium term. As an example, a preliminary ULOF analysis performed for the ALFRED LFR concept in the frame of the EURATOM collaborative project LEADER has shown that the mean time for failure is always longer than 24 hours. A sufficient grace time (>> 30 min) is thus available for operator intervention to terminate this transient by shutting down the reactor manually and to ensure decay heat removal from the primary circuit [24].

Lead has a high freezing point (327°C) with the potential for coolant solidification. This might lead to the formation of blockages impairing coolant flow and consequently challenging the (decay) heat removal function. LFRs therefore adopt reliable monitoring of coolant temperature as well as control of heat transfer conditions at the secondary/tertiary side (including actuation logics and modes of operation of the DHR systems) to prevent excessive cooling and accidental coolant freezing. To support qualification of the envisaged DHR systems and testing of their reliability in all operation modes (active/passive), experimental facilities are already in operation or are currently being constructed. In addition, it must be noted that the coolant solidification was an issue associated with very compact loop configurations (see Section 2). In a pool configuration, the situation is different and with multiple flow paths it is extremely difficult to get a simultaneous solidification. Note also that a solidification occurring simultaneously for all flow paths has a low probability to occur since once a solidification occurs in one of the flow paths, it is less likely to occur in other parts. Oxide particles have low thermal conductivity so that an accumulation probably reduces the chance of solidification by decoupling primary from the secondary.

Adequate systems for heating of the coolant are also provided, in cases when the decay heat of the core would not be sufficient to keep the lead coolant above its melting point. Proper coolant melting sequences are devised to avoid mechanical stresses exerted on structures during melting operations. Some R&D activity is also needed on this topic, although it is considered a lower priority.

As already discussed above, the accumulation of corrosion products, which might also lead to coolant blockages challenging the (decay) heat removal function, should be prevented by reliable monitoring and control of the oxygen content in the lead coolant and appropriate systems dedicated to maintaining the chemistry and purification of the coolant. This topic is also identified as a R&D need (see Section 8).

4.2.2 Diversification, active and passive systems

As mentioned earlier, LFRs rely strongly on passive safety systems for both reactivity control and decay heat removal, for which the design principles of Defense-in-Depth (i.e., independence, diversification, and redundancy) are implemented in all GIF LFR reference concepts. The diversity is provided in system configurations and component designs, working fluids (lead, water, air), and operational principles (forced circulation, natural convection on both the primary and secondary side). Similar to what is already customary for some licensed Generation-III/III+ plants (AP1000), the approach to provide protection against abnormal occurrences and accidents is usually characterized by the use of non-safety grade active systems and non-safety grade emergency supply systems, which is followed by the use of safety-grade passive systems in case the active systems are not available.

The above-described approach is intended to achieve robust safety performance of the plant, while substantially reducing the overall “safety cost”. It is facilitated by the specific characteristics of lead that support a strong focus on safety which designers implement from the very beginning of the system design process.

These characteristics also support the strategy of decay heat removal in the case of postulated core disruptive accidents, like in the case of extreme earthquake. The reactor and safety vessels of LFRs are arranged such that a leak in reactor vessel does not result in the uncovering of steam generator inlets, and the coolant flow path can hence be maintained, including through the DHR systems. In addition, due to the high melting point of lead (327°C), any coolant leakage from the primary system will likely start solidifying, preventing a large loss of primary coolant. In the case of a very unlikely simultaneous unavailability of steam generators and all dedicated DHR systems, the implemented and considered options for ultimate diversified DHR include: (i) utilization of the reactor cavity concrete cooling system; and (ii) flooding of the reactor cavity with water, see also Section 5. The improved understanding of the severe accident phenomena in LFRs will provide the necessary basis for possible practical elimination of severe accidents or lead to the development of detailed severe accident management strategies and guidelines. The considered options and systems for achieving the DHR removal function in case of postulated core disruption accidents needs also to be further assessed.

4.3 Confinement of radioactive materials

4.3.1 Materials

Molten lead is corrosive, and may erode, or otherwise degrade the mechanical properties of structural materials; such phenomena, if not adequately controlled, could increase maintenance and repair costs and ultimately could also challenge confinement barriers, in particular the fuel cladding. In addition, the risk of loss of structural integrity associated with high-temperature creep which could result from high coolant temperatures during accidental conditions needs to be assessed. Material behavior in heavy liquid metals has therefore historically been a main R&D topic related to LFR technology. In this domain, some important technological advances have recently been made, although the approach differs substantially in the individual countries.

The approach adopted by the Russian Federation is an evolution of the experience developed in construction and operation of lead-bismuth eutectic cooled reactors for submarine propulsion. It is based on the control of oxygen content dissolved in the heavy liquid metal and on appropriate coolant purification. Special ferritic-martensitic alloys (with added Si) have been developed, and the oxygen control strategies for such systems have proven to be effective in corrosion-erosion control, benefiting from investigations conducted in experimental loops with controlled temperature and flow conditions as well as in pool configurations[11].

Even though material development has played a very important role in the nuclear industry from the beginning because of the need to qualify materials (taking into account ageing effects and consequent change in mechanical properties due to exposure to service conditions), this has posed serious challenges to the application of new materials in advanced reactor concepts, in particular in Europe. The reason has been the absence of irradiation facilities able to reproduce the conditions of a fast reactor in a reasonable time frame and at a reasonable cost. As a consequence, R&D efforts are now following a different strategy: using materials already previously qualified for fast reactor environments, applying corrosion resistant coatings (surface modifications) and providing adequate chemistry control of the coolant quality.

These functionally graded composite coating processes allow for the optimal combination of a base metal with proven mechanical properties with a thin and stable outer layer of corrosion-resistant material. This includes SiO_2 surface layers (developed by MIT) and aluminum-oxide layers (developed by KIT). A new class of alumina (Al_2O_3) forming austenitic alloys (AFA), which display extraordinary corrosion resistance in lead/LBE[12], has also been developed (at a number of different institutions including SNU, KTH and ORNL). The long-term behavior of these coatings and alumina forming austenitic alloys, considering irradiation, thermal and

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[11] The experience with oxygen / chemistry control in pool configuration includes, among others, the CIRCE facility in ENEA Brasimone, Italy (8.5 m height, 1.2 m diameter, ~90 t LBE inventory) and CLEAR-S at CAS/INEST Hefei, People's Republic of China (6.5 m height, 2 m diameter, >200 t LBE inventory).

[12] Long-term corrosion tests of AFA steels (19,000 h) have been performed in lead at 550°C.

mechanical stresses and the effect of the lead coolant environment, requires an adequate qualification program.

As the primary pump impeller may be exposed, in some LFR designs, to a coolant velocity of up to 10 m/s, the special corrosion-erosion resistant technological solutions for this component need to be qualified as well.

4.3.2 Safety barriers

In accordance with the principle of Defense-in-Depth, LFRs adopt several levels of protection including successive safety barriers preventing the release of radioactive material to the environment. These include the fuel matrix, the fuel cladding, the boundary of the reactor coolant system, and the containment system. The safety concept includes protection of the barriers by averting damage to the plant and to the barriers themselves. It further includes mitigation measures to protect the public and the environment from harm in case these barriers are not fully effective. Specifically, for LFRs, due to the high density of lead and its total primary inventory, challenges to the effectiveness and functionality of safety barriers in case of external excitations are carefully considered. This includes related mechanical effects due to sloshing.

For fuel cladding, design limits are established on the basis of the maximum fuel temperature and burn-up (residence time), with due attention to the accumulated corrosion-erosion and irradiation performance data. This includes the data on fuel-cladding interactions, which for MOX types of fuel benefit from the extensive operating and qualification feedback conducted in the frame of SFR programs (cf. also Sub-section 6.1).

For the reactor coolant and cover gas boundary, all GIF LFR Reference Systems employ pool-type configuration with integrated primary components to prevent the loss of primary coolant. The considered options are a stainless-steel reactor vessel (for ELFR and SSTAR) and a steel-lined thermally insulated concrete vault (for BREST). The integrity of the boundary is maintained during the plant's lifetime by limiting the maximum coolant temperature and time at that temperature, while also controlling chemistry (oxygen content) in the coolant.

The configuration of the containment boundary includes safety vessel (for ELFR and SSTAR) and multilayer metal concrete structure (for BREST). Their function is to prevent primary coolant loss which would result in the uncovering of steam generator inlets (ensuring thus the DHR function), as well as to withstand mechanical and thermal loads in accident conditions, preventing release of radioactive material to the environment.

Further details of the related methodology applied in Europe are well described in the Safety approach developed in the frame of the EURATOM 7th Framework Programme collaborative project LEADER [18]. The approach adopted in the Russian Federation can be considered equivalent and substantially in-line.

4.3.3 Source term

Concerning the source term, the use of lead coolant is deemed to provide several advantages.

There are both analytical and experimental indications that lead has a good tendency to retain volatile fission products iodine and cesium, as well as polonium[13], out of which only small fractions are expected to be released to the cover gas and containment [8, 25-27].

Source term analyses performed in the frame of the EURATOM collaborative project LEADER have determined the upper theoretical limits for the releases of iodine, cesium, and polonium in case of a postulated core disruptive accident involving the rupture of all claddings of all fuel assemblies. It was determined that only a small fraction (depending on the coolant temperature) is expected to be volatilized into the cover gas system. Moreover, these results indicated that the accompanying source term and the related doses inside the containment are relatively low, and the resulting dose in the containment has been evaluated to be below the allowable limit to the population (outside containment) during normal operation. In Europe, further R&D studies are currently ongoing to verify the corresponding retention capabilities of lead in order to reliably evaluate related occupational hazards and possible accidental source terms. It is to be noted that these results are specific to the LEADER design concepts, but similar characteristics have also been confirmed by studies performed in the Russian Federation and are expected to apply to other LFR designs as well.

In addition, as mentioned earlier, the chemical interaction of lead with water and air is very slow / relatively inert, not supporting significant energy release in the event of accidents. In fact, although the reaction is exothermic, reaction kinetics and oxide formation are slow and the energy releases small [28]. It has been demonstrated experimentally that in situations mimicking steam generator tube ruptures, involving injection of a pressurized steam/water into high-temperature molten lead, steam explosions do not occur. Consequently, a rupture of a single SG tube has been shown to be limited and will not develop into multiple ruptures of SG tubes [29]. Sloshing-related fluid motion is also well bounded in a domain beyond the steam generator [30]. For what the oxide formation is concerned during an SGTR, the duration of the transients is not expected to give rise to an amount of oxides able to impair safety functions or systems, thanks to the slow progression of the oxidation chemical reaction compared to the time scale of the accident (usually terminated by SG isolation procedure).

It is important to emphasize that the performance of LFRs with respect to source term minimization, considering that the lead coolant exhibits high radionuclide retention and is able to provide robust and benign behavior in essentially any accidental conditions, results in the possibility of achieving the goal of eliminating the need for off-site emergency response. This has been one of the most important drivers for the development of LFR technology both in the EU, the Russian Federation, and elsewhere.

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[13] In LFRs, small amounts of ^{210}Po are formed due to extended activation of lead. Systems cooled by lead-bismuth eutectic would require an efficient polonium purification system due to the significantly larger rate of production from activation of ^{209}Bi, cf. also Sub-section 6.3.

4.3.4 Containment bypass

In accordance with the single failure criterion, all lines that penetrate the containment and/or that are connected to the cover gas space are fitted with at least two containment isolation valves or check valves arranged in series and provided with a suitable leak detection system preventing containment bypass.

The risk for containment bypass due to SGTRs is normally prevented, at design level, by adoption of rupture disks on the reactor roof connected to a pressure suppression system and SG isolation.

In case of a severe accident, the risk for containment bypass (specifically if SGs would be depressurized) needs to be further evaluated, and a detailed severe accident management strategy developed. In this context, it is important to note that it is possible to isolate the SGs, since DHR can be achieved by diverse means.

5. Management of design extension conditions (severe accidents)

Management of design extension conditions is based on the application of Defense-in-Depth, involving the control of severe plant conditions, prevention of accident progression, and mitigation of the consequences of severe accidents (if not practically eliminated[14]). Such plant conditions of very low probability may be caused by multiple failures or by an extremely unlikely event, such as an extreme earthquake.

5.1 Prevention

In LFRs, accident prevention is strengthened by several considerations, in addition to the fundamentally advantageous characteristics of the coolant (i.e., very high boiling temperature, relative inertness in contact with water and air, etc.). These additional considerations include:

- Systematic application of the principle of the Defense-in-Depth into the design at all levels. As for the independence of the different levels of DiD, design features such as system and component redundancy, independence (physical separation), and diversity are expected to be applied to address the risk of common-course failures (an example for the DHR function is given in Sub-section 4.2.2);
- The large thermal inertia of the plant, which provides considerable grace time (with regard to structural integrity) to prevent further accident progression, allowing employment of additional non-safety grade and support systems to control and manage the accident effectively;
- Expanded use of passive safety features to achieve the fundamental safety functions (control of reactivity and heat removal);

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[14] As one of the key design features, GIF LFR designs aim at practical elimination of severe accidents,

- Reduced plant complexity (no intermediate circuit as well as other features); and
- Optimized human-machine interfaces as well as extended use of information technologies (e.g., augmented controls and displays, virtual reality simulators and training tools for which development and qualification for NPP is needed).

As concerns corrosion-erosion, the Defense-in-Depth approach includes: (i) the use of qualified materials; (ii) control of oxygen content in the coolant; (iii) redundancy (as appropriate); (iv) in-service inspections (ISI) / surveillance; and (v) adequate margins / times to respond.

Analyses of GIF LFR designs performed according to the established safety approaches in the design extension domains have up to now not identified accident sequences which would lead to generalized core meltdowns[15]. In the BREST design, implementing wrapper-less fuel assemblies, safe operation limits of the cladding are predicted to be maintained during the postulated total instantaneous blockage of seven fuel assemblies [29].

There is a lack of large sources of physical or chemical energy such as primary coolant boiling, large generation, and consequently accumulation of hydrogen, as well as a lack of rapid chemical reaction between fuel and coolant to challenge safety barriers. There are no rapid exothermic reactions between lead and water (as well as air). The phenomenology needs to be more fully understood notably as far as the interaction between hot lead and water is concerned. This topic is also discussed in Sub-section 4.3.3.

Nevertheless, severe accidents that could lead to containment barrier failures are considered explicitly in the design process of LFRs to analyze the course of an event and devise appropriate mitigation measures (if not practically eliminated).

5.2 Mitigation

As discussed in reference [19], the essential objectives of the accident management are:

- To monitor plant status;
- To maintain core sub-criticality;
- To protect the integrity of the reactor vessel by ensuring heat removal from the core and preventing excessive loading conditions (both thermo-mechanical and chemical);
- To limit the release of radioactive material to the environment; and
- To regain and maintain a safe shutdown state.

In a very unlikely event involving loss of all heat sinks (all DHR and secondary systems), the possibility to remove heat by injecting water in the reactor cavity between the reactor and safety vessels can be considered, while in case of reactor vessel breach, decay heat can still be removed by the reactor cavity concrete cooling system. As discussed earlier, such very ultimate provisions can be considered since lead is relatively chemically inert in contact with air and

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[15] Fuel damage is predicted to be limited to seven fuel assemblies.

water so that the reactor could be flooded by water. As mentioned earlier, further R&D is necessary to assess these options for the ultimate DHR comprehensively.

5.3 Situations that are practically eliminated

The practical elimination of certain accident situations in LFRs is based on utilization of the intrinsic features of lead as a coolant (high boiling point, relative inertness in contact with air and water, natural convection capability, and thermal inertia) as well as the application of the fundamental principles of Defense-in-Depth. In terms of the decay heat removal, this particularly concerns the enhanced redundancy, independence as well as diversity in operational modes (forced/natural convection on both primary and secondary side), system/component designs, and use of working fluids (lead, water, air), cf. Sub-section 4.2.2.

In Europe, in the frame of the EURATOM project LEADER, the following initiating events and sequences have, among others, been identified as “practically eliminated” [22]:

- Large core compaction due to changes in core geometry as a result of large internal or external excitations (e.g., due to an extreme earthquake);
- Large removal of absorbing material;
- Core uncovering due to primary coolant loss (resulting in loss of DHR function). Note that one goal of LFR design is that the simultaneous rupture of the reactor vessel and the safety vessel can be demonstrated to be extremely unlikely with a high confidence level, and needs not to be considered;
- Reactor vessel break (the vessel support function).

The categorization and any possible related justifications allowing the “practical elimination” of these initiating event and sequences will be further developed in concert with the progress of the design and current state of knowledge developed on the basis of ongoing R&D.

6. Safety of the fuel cycle

6.1 Type of fuel

The reference fuels considered for deployment in the LFR are of the oxide or nitride ceramic types.

MOX fuels have been developed in the framework of SFR deployment, mainly in Europe and Japan. Several technologies available or being currently developed are directly applicable to LFRs. This concerns in particular the choice of a recycling strategy, related fuel fabrication (including the application of advanced – minor actinide bearing – fuels) as well as reprocessing technologies. Further advancements are envisaged for LFRs, including the evaluation of new fuel cladding materials.

Mixed nitride fuels (MN) have been adopted as a reference in the Russian Federation, since they provide a number of advantages, such as high density, high thermal conductivity, lower operating temperatures (with a consequent higher coefficient of Doppler reactivity feedback), high melting point and higher capability to retain fission products, as well as lower gas pressure in the cladding.

A specific feature of nitrides is their susceptibility to decomposition into a liquid or gaseous metal and nitrogen gas at very high temperatures (e.g., during transient involving power excursion). A fuel qualification programme for the use of mixed nitride fuels under operational and accidental conditions is ongoing in the Russian Federation [31]. While the BREST concept uses nitride fuel with a natural isotopic composition of nitrogen, enrichment of nitrogen in ^{15}N is also considered for commercial units to further improve the economic performance and avoid the production of radiologically hazardous ^{14}C, which in any case is immobilized during fuel reprocessing in solid phase. Note that a nitride fuel processing facility is expected to come online as part of the BREST development in Russia in 2022.

With oxide or nitride fuels, fuel-cladding chemical interaction can be prevented, hence enabling load-following operations with a fast peak-load management capability which can enable generation of electricity at the highest rates in certain areas. For this purpose, further R&D and continuation of the fuel qualification programs is also required.

6.2 3Management of waste (quantity, quality)

Spent fuel can be recycled using both aqueous and dry (pyro) processing, with the recycled waste conditioned and disposed of using the technologies developed in the framework of the SFR deployment programs.

In this context, pyro-processing has been developed in the U.S.A and elsewhere to reduce oxides to metals for processing. The metallic product can then be oxidized to fabricate fuels. Recently, it has been shown at laboratory scale that the final salt wastes can be decontaminated to leave only intermediate level wastes for disposal, as summarized by SNU.

In Russia, non-aqueous technologies of spent nuclear fuel (SNF) reprocessing have been under development for many years, including reprocessing of the dense fuel from fast reactors. These technologies are characterized as being compact, radiation resistant and producing low amounts of secondary wastes.

However, somewhat low decontamination factors might be their disadvantage. The use of combined technologies based on non-aqueous methods and aqueous processes for reprocessing of SNF with high burn-up and short cooling time could lead to significant cost cutting. These methods utilize non-aqueous head operations, allowing the cleanup of fissile materials from fission products by 2–3 orders of magnitude, and then reprocessing them using hydrometallurgical methods. For fast reactor mixed nitride U-Pu (MNUP) spent fuel it has been suggested to combine the primary pyrochemical processing with hydrometallurgical refining. These technologies also enable recovery of ^{15}N and separation of ^{14}C for recycling and disposal, respectively.

All these experiences are directly applicable to LFR fuel recycling.

Disposition of the lead coolant at the end of the plant life could be carried out by solidification and storage / disposition.

The feasibility of a possible re-use / recycling of lead, further supporting the objective of sustainability, is a subject of ongoing R&D.

6.3 Radiation protection

Radiation exposure to LFR operating personnel is expected to be low since most of the maintenance operations will be performed remotely. The radiation shielding properties of lead coolant are an additional benign factor. It is noted that pure lead is not exempt from the formation of polonium, albeit at very low levels. This is due to ^{209}Bi impurities present in lead and ^{209}Bi generation after an extended operation through the (n,γ) reaction on ^{208}Pb, followed by further activation of bismuth. However, the production rate of polonium in lead coolant is very low, depending on its purity, and at least three orders of magnitude lower than in LBE. Additionally, a preliminary analysis has shown that due to the tendency of lead to retain polonium and other radioactive elements, only a small fraction of polonium and other radioactive elements is expected to be volatilized to the cover gas, thus controlling risks to operating personnel. Further R&D is necessary to confirm these conclusions.

7. Other risks

7.1 Chemical risk

As mentioned earlier, lead has been chosen in great part because of its relative chemical inertness in contact with air and water. From the toxicological point of view, the operating conditions of LFRs are such that they ensure that concentrations of lead vapor in the cover gas will be maintained well below the limits for occupational exposures benefitting from the low partial pressure of lead vapor ($2.9\cdot10^{-5}$ Pa at 400ºC). The risk is considered to be very well manageable due to such low partial pressure in typical environmental conditions and during operations conducted by the personnel.

7.2 Others

Similarly to other liquid metals, lead is opaque. The consequent lack of ability for visual inspection makes fuel handling and in-service inspections and repairs (ISI&R) of internal components difficult. ISIs are typically carried out by ultrasonic devices, for which the technology has been developed in the context of SFR programs. Inside the containment, ISI activities are performed during outage periods. In this context, considerations need to be given to relatively high temperatures of cold shutdown of LFRs (ca. 380°C).

In Europe, each component inside the LFR reactor vessel is designed to be removable for inspection and maintenance. As such, all inspection activities (e.g., visual observation, surface examination, volumetric examination with X-ray or ultrasonic devices) will be performed out of lead and thus under the full visibility. Also, refueling operations can be done without a need for in-vessel machines. The in-service inspection of the reactor vessel (forming part of the second barrier) can be accomplished by ultrasonic inspection.

In the Russian Federation, the approach to ISI&R is similar, but refueling is done by in-vessel machines.

A method for high-temperature chemical cleaning / removal of the residual lead layer from the components for ISI&R has been developed and experimentally tested.

Large quantities of coolant in the main vessel pool of LFRs may lead to complex flow patterns and interactions between the coolant and structures, specifically in case of large external excitations (such as an extreme earthquake). Coolant sloshing is taken into account in the mechanical design of the components. Application of dedicated anti-sloshing devices is also envisaged to prevent / suppress the sloshing effects. In Europe, the topic is addressed by the adoption of 2D seismic isolators under the primary building that reduce loads caused by horizontal oscillations. While substantial progress has been made, further R&D is necessary in the field, including possible development of dedicated anti-sloshing devices.

8. Summary of progress needed

Safety-related R&D is currently ongoing in relation to the needs of the individual GIF LFR concepts, notably in the Russian Federation (to increase the level of design justification in support of licensing of the BREST-OD-300 system), in Europe (in support to further design development of the MYRRHA irradiation facility and ALFRED demonstrator), in Korea (in support of small modular reactor URANUS), and in China (in support to further design development and licensing of the CLEAR series).

Based on the LFR project needs, further safety-related R&D efforts are expected to focus on the following topics:

- Structural materials compatibility with heavy liquid metals, including the synergetic effects (of thermo-mechanical load and irradiation exposure);
- Development and qualification of new corrosion resistant materials (including surface modifications) to increase operating temperatures;
- Coolant chemistry, oxygen control, and purification, especially for large pools and with the aim of maintaining the coolant specifications and functionality of the main safety systems;
- Phenomenology and prevention of coolant freezing, with particular reference to decay heat removal systems;
- Phenomenology of lead-water/steam interactions to analyze consequences of SGTR;
- Fuel-coolant thermodynamic and chemical interactions, including the behavior of dispersed fuel, and retention of fission and activation products in heavy liquid metal, forming also a basis for practical elimination or development of severe accident management strategies and guidelines;
- Seismic isolation and prevention / mitigation of possible sloshing;
- Innovative technologies for ISI&R and fuel/component handling;
- Innovative MA-bearing, high burn-up fuels, in the conditions of closed fuel cycles;
- Further development and qualification of LFR-specific modelling methodologies, as well as design and safety assessment tools;
- Development of design codes and standards for design of mechanical components taking into account environmental effects of heavy liquid metals.

Gaining safety and operational experience feedback from licensing and operation of demonstration plants is considered a necessary step to further improve safety, reliability, and operational performance of Generation IV LFR concepts.

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