# examples of areas of novelty in liquid metal fast reactors to consider in the review of applicability of the IAEA Safety Standards

Fission product retention barriers: differences between liquid metal fast reactors and light water reactors

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**Abstract**

The International Atomic Energy Agency (IAEA) is reviewing the applicability of the IAEA safety standards to novel advanced reactors including fast reactors. The applicability review first relies on the identification of areas of novelty in the lifecycle of the novel advanced reactors when compared with land based water-cooled large reactors. The paper presents examples of areas of novelty related to typical barriers to fission product release for Sodium cooled Fast Reactors (SFR) and Lead cooled Fast Reactors (LFR) when compared to a Light-water Cooled Reactors (LWR) Reference Point. First, the paper provides a description of the technologies considered as part of the LWR Reference Point. Second, the paper summarises key aspects of the identification of areas of novelty related to fission product barriers in SFR and LFR. The paper concludes with a brief discussion on the path forward to complete the safety standards applicability review.

## INTRODUCTION

The IAEA safety standards [1] predominantly reflect member states’ experience and knowledge in the designing and operating land based water-cooled large reactors. The IAEA is reviewing the applicability of the IAEA safety standards to novel advanced reactors and particularly small modular reactors (SMRs) [2], transportable SMRs, high temperature gas cooled reactors (HTGR), lead cooled fast reactors (LFR), sodium cooled fast reactors (SFR) and molten salt reactors (MSRs). The high-level review of the applicability of the safety standards to these technologies covers all lifecycle stages (siting, design, construction, commissioning, operation, and decommissioning), radioactive waste management, safety assessment and regulation.

The applicability review first relies on the identification of areas of novelty in the lifecycle of the novel advanced reactors when compared with land based water-cooled large reactors. This identification is developed by systematically comparing the characteristics of novel advanced reactors with a *Light-water Cooled Reactor (LWR) Reference Point*. For that, high-level characteristics regarding the defence-in-depth and barrier concept, safety functions, supporting systems, protection against hazards, accident management, radiation protection construction, operation, decommissioning, and radwaste were evaluated.

The comparison reflects designers’ current practices and claims and has been developed based on expert knowledge, literature review and detailed questionnaires responses by technology developers. On a second stage the information was reviewed by regulatory authorities, technical support organisations and other organisations and amended, additional reviews are planned as part of the on-going IAEA activities and further revisions to these tables will be necessary to capture the full range of expert judgement and regulatory experience.

The paper presents examples of areas of novelty related to typical barriers to fission product release for SFR and LFR. First, the paper provides a description of the technologies considered as part of the LWR Reference Point. Second, the paper summarises key aspects of the identification of areas of novelty related to fission product barriers in SFR and LFR (when compared to the LWR Reference Point). The paper concludes with a brief discussion on the path forward to complete the safety standards applicability review.

## Light-water Cooled Reactor Reference Point

In order to define a common reference point for the identification of areas of novelty, an enveloping characteristic of LWR nuclear power plant (NPP) features is provided. This is based on the following considerations. Evaluating the latest power reactors overview by the IAEA [3], the LWRs consist of 300 pressurised water reactor (PWR) units in operation and 65 boiling water reactor (BWR) units. Next are 48 pressurized heavy-water reactor (PHWR) units, which are already out of scope. Looking at large operating fleets of reactor series, a reasonable selection appears to include:

1. VVER-1000 (with several design variants) with 37 units in total and one in construction
2. BWR-5/BWR-6 series with in total 25 units in operation
3. P4/N4 REP series with in total 24 units
4. CPR-1000/ACPR-1000 with in total 20 units and more planned or under construction
5. APR-1400/OPR-1000 with 14 units in operation and more APR-1400 under construction
6. ABWR series in Japan with 4 units in operation (in order to cover advanced BWR designs)

This can be extended by major new designs entering the market, which are currently being built:

1. AP-1000/CAP-1400, with 4 units of AP-1000 in operation and several in construction.
2. VVER-1200 (several design variants, as an evolution of the VVER-1000 designs) with 3 units in operation and several in construction.
3. EPR design, with 2 units in operation and 4 under construction.
4. HPR1000 reactor design with several units under construction.

For all of these reactor designs, it can be assumed that they have been reviewed and licensed by regulators. Together, they cover the majority of characteristics tried (and tested) for LWR reactors, which establishes an adequate envelope for identifying areas of novelty. This envelope has been summarized in a separate working document available via the IAEA, which also includes the relevant references [4]. It has then been the basis for filling out the identification tables column on the LWR reference, with examples shown in Section 3. In addition, it has also been used for a comparison with water-cooled SMRs.

## SoDium and Lead Cooled Fast Reactors

The paper considers liquid metal-cooled fast reactors (LMFRs) of the SFR and LFR type [3] [4] [12]. Typical SFR systems include loop-type, pool-type designs with electric outputs between 10 - 2000 MWe, thus covering SMR designs as well as large reactors. The primary coolant system and secondary (intermediate) coolant system utilizes sodium coolant. The balance of plant system is based on water/steam cycle, and alternative concept is based on supercritical CO2 or other gas cycle. The fuel is mixed-oxides (MOX), metal fuel, nitride (ceramic) and carbide fuels, amongst others. Examples of SFRs considered in the exercise of the SMR type include ARC-100, 4S and Natrium.

Typical LFR systems include pool-type with electric outputs between 1 - 1200 MWe, thus covering large reactors, SMRs and microreactors. The primary coolant system utilizes lead (in some cases lead-bismuth) and the balance of plant system is based on a water/steam cycle, supercritical water or CO2. The fuel is metal fuel, UO2, MOX, mixed nitrides (MNUP). Minor actinide-bearing fuels may also be used for implementation of a closed fuel cycle. Examples of LFRs considered in the exercise include the ELFR (European Lead Fast Reactor), BREST-OD-300, SEALER-UK and the European LFR demonstrator ALFRED.

LMFR technologies, particularly SFRs have been established in many countries since the beginning of nuclear power programmes. The world’s first nuclear fast reactor to generate electricity was achieved by an SFR, called the experimental breeder reactor I (EBR-I) in the United States [13], and since then, experimental SFRs have been built and operated in the U.S., Russia, the U.K., France, Germany, and Japan. Although some programs were halted by government decision in prototype stages, knowledge about design and operation has been accumulated in those countries. BN-600 and BN-800 are in operation and BN-1200 is under preparation for its construction in Russia. China is constructing the CFR-600 building on experiences with the CEFR. In India, the prototype fast breeder reactor (PFBR) is in commissioning. Other SFR projects were conducted only at the level of design works and related R&D activities in Japan and France for the Japan Sodium-cooled Fast Reactor (JSFR) and ASTRID in the last decades. The U.S. conducted the preapplication safety review of PRISM in the 1990s. For LFR, the former Soviet Union developed lead-bismuth cooled reactors as a power source for submarines, which has established the basis of LFR technology. Today, Russia is constructing BREST-OD-300, with the foundation stone laid on June 8th 2021 and in Europe, specific research activities are in progress, notable in conjunction to the MYRRHA design.

## IDENTIFICATION TABLES

The study presented in the paper is extracted from a detailed comparison table [5] comparing the LWR Reference Point and LMFR barriers to fission product release, safety functions, supporting systems, protection against hazards, accident management, radiation protection construction, operation, decommissioning, and radwaste. The selected topis of comparison were identified by the IAEA as the necessary information to start the review of applicability of the safety standards to novel advanced reactors.

The comparison builds on several publications by the Generation IV International Forum (GIF). The forum was created to promote development of advanced reactors including SFRs and LFRs. As a part of its activities, GIF has developed safety design criteria for SFRs and LFRs and is developing safety design guidelines for SFRs to contribute to the harmonization of safety standards [6][7][8]. These documents can be used as reference for this study, because they are based on IAEA’s safety design standards and have been developed considering differences in design features between SFRs, LFRs, and existing LWRs.

The study is also utilising several SMR vendors’ response to a questionnaires on the novel feature of their SMR design concept, and the authors’ expertise on the safety designs and operational and R&D experiences, as well as the feedback from participants including regulatory authorities in the dedicated consultancy meetings. The contents of the paper are qualitative and may not fully cover technical details but point out high-level differences in features between LMFRs and existing LWRs.

The concepts of barriers are based on IAEA Safety of Nuclear Power Plants: Design SSR-2/1 [9] and expert judgment captured in the detailed comparison table [5]. The first barrier is fuel matrix; the second, fuel rod cladding; the third, reactor coolant boundary; and the fourth, confinement. These are basically similar to what is used in LWRs, because LMFRs and LWRs resemble in some respects. An LMFR core, which contains fuel elements consisting of solid fuel enveloped by metal cladding tubes, is installed within reactor coolant boundary, allowing its heat to be removed by liquid coolant circulating in the reactor coolant system. But technical challenges and requirements for the barriers will vary depending on design features. Also, LWRs and LMFRs need different concepts of structures, systems, and components to remove the heat from the reactor core under operational states and accident conditions. Unlike LWRs, LMFRs use a liquid metal as coolant whose boiling point is sufficiently higher than its normal operation temperature ranges; pressurization of coolant systems, therefore, is not required. The tables considered typical SFR and LFR technologies and features as described below, including important aspects considered in the design basis as well as safety requirements and recommendations for operation and accident management.

### First barrier

The fuel matrix provides the first fission product barrier comprising oxide fuel pellets, metal fuel slug for SFRs and UO2, MOX, MNUP or metal fuel for LFRs. Different key operational challenges and phenomena during accident conditions when compared to LWR Reference are summarised in Table 1.

When LMFR fuel is oxide, the rate of fission product retention in the fuel matrix is lower than that of LWR fuel, because LMFR fuel is exposed to temperatures higher than those in LWR during normal operation. The higher temperature leads to increase mobility of fission products in the matrix. In addition, it increases thermal stress in the fuel pellets, causing cracks in fuel pellets and thus more transport pathways for volatile fission products. Larger gas plena, therefore, should be provided to retain fission products released from the fuel matrix.

TABLE 1. Comparison of challenges and failure modes on the first barrier

|  |  |  |
| --- | --- | --- |
| **Reference LWR** | **SFR** | **LFR** |
| The fuel matrix in an imperfect barrier as volatile FP (noble gases, Cs, I) migrate into gas gap during normal operation.  Main failure modes:   * Cracking due high burn-up (operationally tolerated) * Fracturing due to overpower event Local melting due to excess central temperature * Eutectics formation with Zr or steel during core degradation (excluding metal fuel) * Melting of UO2/PuO2 into corium Cermet fuels are at least investigated for VVER designs | Differences in operational challenges:   * Fuel pellet cracking may happen in oxide fuel. Fission product retention in fuel matrix is evaluated by taking the pellet cracking into account. * Certain amount of noble gases are released into gas plenum inside fuel pin. Volatile FPs migrate into gas space between fuel matrix and cladding tube. The pressure increase must be taken into account.   The failure modes during accident conditions are similar to LWR with the exception that the cladding do not use Zr. As a consequence, no eutectic formation between oxide fuel and steel cladding during fuel degradation can take place. | |

### Second barrier

The fuel rod cladding provides the second fission product barrier. Different key operational challenges and phenomena during accident conditions when compared to LWR Reference are summarised in Table 2. Although the main function of the cladding is the same for the three technologies, materials, corrosion mechanisms as well as irradiation level (thermal versus fast neutrons) introduce important differences to be taken into account.

In terms of irradiation levels, fuel rod cladding of an LMFR is required to withstand higher neutron fluence and higher temperatures than LWRs during its residence time in the core. Creep failure should be prevented since the cladding will be exposed to high temperatures and high inner pressures.

TABLE 2. Comparison of challenges and failure modes on the second barrier

|  |  |  |
| --- | --- | --- |
| **Reference LWR** | **SFR** | **LFR** |
| * Pinhole or small crack failures (mainly operational wear & tear, fretting, flow-assisted corrosion, electrochemical effects, etc.) * Pellet-cladding interaction with local hot spots triggering failure * Local critical heat flux (CHF)/Dryout (both operationally and in transients) leading to excess zirconium alloy oxidation and brittle failure * Local overpower events leading to excess circumferential stress * Overpower events leading to over pressurisation and over heating with subsequent ballooning * Attack by H2O-Zr-oxidation at high temperature | Typical operational challenges:   * Cumulative creep damage due to internal pressure (fission gas or dimensional change of metallic slug with power) and high temperature, irradiation effect and Fuel-Cladding Mechanical Interaction (PCMI) are taken into account * swelling due to irradiation, corrosion due to Fuel-Cladding Chemical Interaction (FCCI)   Typical failure modes during accident conditions:   * Over heating rupture, * Fuel cladding mechanical interaction in case of fuel central part melting, remaining outer solid part contact pressure affects the cladding * No H2O-Zr interaction since Zr not used for cladding * CHF is not used due to high boiling point   For LFR: A potential for corrosion/erosion based on different mechanism  respect to LWRs | |

### Third barrier

There are some differences among the technologies on the provisions associated to the third barrier, the reactor coolant boundary, that are identified in Table 3. Key different operational challenges and phenomena during accident conditions are summarised in Table 4.

A key difference highlighted in Table 3 are the claims on the effectiveness of sodium and lead as fission product retention barriers.

The effectiveness of sodium as retention barrier for fission products (I and Cs) depends on temperature. Equilibrium partition coefficients were experimentally measured for volatile fission products of caesium and iodine between liquid sodium pool and the inert cover gas [10].

The effectiveness of lead as retention barrier for fission products depends on temperature, which sets the saturation concentration of the dissolved species. For LEADER project the calculations included: Kr, Xe, I, Cs, Sr, 3H, Po and the results shown the radioactivity reaching the cover gas is well dominated by contributions from noble gases. At temperatures predicted for accidental conditions (i.e., 700 °C), the observed release fractions for I, Cs and Sr (the top ranking species for dose to the population and environmental contamination) are not less than 1e-5, i.e.: more than 99.999% is stably retained in the lead melt [11].

It should be noted that there is limited experimental data available on this topic in the public domain. As part of licensing processes, it is expected that the applicant will be requested to provide analysis and experimental supporting data.

An important difference captured in Table 3 is the consequences of a potential reactor coolant boundary failure in a LMFR. The high boiling point of the liquid metals allows operation at low (atmospheric) pressure. Providing a guard vessel or other structure for retaining leaked coolant allows core fuel to be kept immersed in liquid metal coolant even if an accident occurs. As previously mentioned, if fuel cladding immersed in liquid metal fails, the coolants have an additional retaining capability of fission products according to the physical properties of the specific coolant.

TABLE 3. Comparison of design features on the third barrier

|  |  |  |
| --- | --- | --- |
| **Reference LWR** | **SFR** | **LFR** |
| Reactor pressure boundary (Very high integrity components, class 1 piping, plus valves, etc. at interfaces) | Sodium coolant has retention capability of I and Cs, and other non-volatile fission products such as Sr | Lead coolant is an efficient barrier to fission products (I, Cs, Sr and as well Po)  Low-Pressure Reactor coolant boundary (pressure variation with depth to be taken into account):  Reactor coolant boundary includes cover gas purification system and other systems attached to the roof of the reactor  Safety Vessel to maintain coolant level for natural circulation (in case of Reactor Vessel failure) |
| Low pressure reactor coolant boundary (Primary vessel for pool-type design, primary vessel and closed primary loop for loop-type design), reactor roof and, cover gas system which contain the reactor cover gas  Guard Vessel has role to keep reactor coolant in case of reactor coolant leaks |

TABLE 4. Comparison of challenges and failure modes on the third barrier

|  |  |  |
| --- | --- | --- |
| **Reference LWR** | **SFR** | **LFR** |
| * Small leaks through all kinds of wear and tear (local corrosion of all kinds, fatigue, etc.) * Breaks (i.e. wall through-cracks) of different sizes * Overpressure failure * Valves stuck open/ inadvertently open * Overtemperature failure of seals, gaskets, etc. * Elastic failure at high temperature/pressure at weak points (e.g. U-tubes, welds, reactor pressure vessel (RPV) bottom penetrations) * Ablation by corium attack * Melting by corium attack | Different operational challenges:   * Creep-fatigue due to cyclic thermal stress, * Buckling due to seismic load, * Overpressure failure is unlikely   Different failure modes during accident conditions:   * Creep failure due to excessive temperature increase * Dynamic pressure loading in case of hypothetical core damage and core expansion (Some SFR SMRs aim at practical elimination of severe accident situations with large core melting.) | Different operational challenges:  - Thermal stress, corrosion, seismic loads including coolant sloshing   * Overpressure failure is unlikely   Different failure modes during accident conditions:  - Creep Failure due to excessive temperature increase |

### Fourth barrier

There some differences among the technologies on the provisions associated to the fourth barrier, the confinement, that are identified in Table 5. Different key operational challenges and phenomena during accident conditions are summarised in Table 6. As a general consideration, while for LWR technology one of the main design parameters for the confinement (the containment) is the maximum pressure reached during the limiting design basis accident or design extension conditions, typically a Loss of coolant accident (LOCA) or a main steam line break, for LMFRs the confinement is provided by a low pressure containment due to the atmospheric conditions of the coolant. SFR should consider however sodium leakage and combustion as a contributor to pressure increase and develop mitigation measures for this event.

As described in the previous section, even if the reactor coolant boundary failed, an LMFR operated under low pressure can prevent loss of coolant due to boiling and maintain its coolant level above the core with static components such as a guard vessel. Therefore, the reactor coolant boundary failure doesn’t cause the pressure loads on the containment. Large-scale SFRs that run on oxide fuel are designed to retain degraded core within their reactor vessels if core damage occurs under a severe plant condition involving multiple failure of safety systems. SMR vendors pursue prevention of significant core melt by using inherent reactivity characteristics or passive reactor shutdown mechanisms, passive decay heat removal systems in their design concepts. The effectiveness of such concepts is yet to be demonstrated.

TABLE 5. Comparison of design features on the fourth barrier

|  |  |  |
| --- | --- | --- |
| **Reference LWR** | **SFR** | **LFR** |
| Containment (steel shell or pre-stressed concrete walls, usually with a steel liner) | A containment system (for SMR, it is not limited to building) that houses the reactor coolant boundary (Low-pressure containment) and protects NSSS from external events  Guard Vessel has role to keep reactor coolant in case of reactor coolant leaks  Some SFR SMR design adopt guard vessel as a part of containment system  Reactor vessel has the role to retain the degraded core (IVR: In-Vessel Retention) (Some SFR SMRs aim at practical elimination of severe accident situations with large core melting.) | A containment system (for SMR, it is not limited to building) that houses the reactor coolant boundary (Low-pressure containment) and protects NSSS from external events  Safety Vessel (or liner) used to maintain reactor vessel coolant level (normally part of containment) except for BREST adopting an innovative concept of multi-layered Main Vessel. |
| Reactor building/ secondary containment (Concrete and reinforced concrete, including internal walls, HVAC systems + filters, doors) | Reactor building may have a role to complement containment function |  |

TABLE 6. Comparison of challenges and failure modes on the fourth barrier

|  |  |  |
| --- | --- | --- |
| **Reference LWR** | **SFR** | **LFR** |
| * Open access-ways (airlocks, hatches, etc) * Failure to isolate (mainly valves – leads to containment bypass events) * Under pressure failure (e.g. local liner failure) * Integral overpressure failure (e.g. failure of pressure limitation in case of LOCA) * Overtemperature failure at seals, gaskets, welds * Pressure peak failure (e.g. hydrogen deflagration) * Structural collapse (e.g. beyond design basis accident earthquake) * Corium attack   Note: Outside of areas designated as secondary containment, the reactor building will not be leak-tight at all. Main failure modes:   * Open doors, hatches, etc. * Failure of isolation devices or filters * Spurious opening of an isolating device * Local structural failure * Structural collapse | Sodium leakage and combustion as pressure and heat source (this can be prevented and mitigated by design measures such as double wall structure, inertization of the containment atmosphere). | No causes for pressure peaks or pressure integral increase are, in principle, expected. |

## way forward

The input presented in this paper as well as other important novelties are considered in the review of applicability of the safety standards to be published as a Safety Report. Based on the identified areas of novelty, this report will identify areas of the safety standards that are applicable or non-applicable to the novel advanced reactors technologies and areas that need additional clarification. The work will also identify potential gaps with the aim to guide future publications and safety standards development for advanced reactors, and support member states safety evaluation of these technologies.

ACKNOWLEDGEMENTS

The large team of IAEA experts and international experts from member states supporting the development and implementation of the presented work will be acknowledged in the Safety Report publication.

Abreviations

BWR Boiling water reactor

CHF Critical heat flux

EBR-I Experimental breeder reactor I

ELFR European Lead Fast Reactor

FCCI Fuel-Cladding Chemical Interaction

GIF Generation IV International Forum

HTGR High temperature gas cooled reactors

IVR In Vessel Retention

JSFR Japan Sodium-cooled Fast Reactor

LFR Lead fast reactors

LMFRs Liquid metal-cooled fast reactors

LOCA Loss of coolant accident

LWR Light-water Cooled Reactor

MNUP Mixed nitrides

MOX Mixed-oxides

MSRs Molten salt reactors

NPP Nuclear power plant

SFR Sodium fast reactors

SMRs Small modular reactors

PCMI Fuel-Cladding Mechanical Interaction

PHWR Pressurized heavy-water reactor

PFBR Prototype fast breeder

PWR Pressurized water reactor

RPV Reactor Pressure Vessel

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