LFR Technology Development

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IAEA Training Course, Bucharest, Romania, 16-20 February 2026

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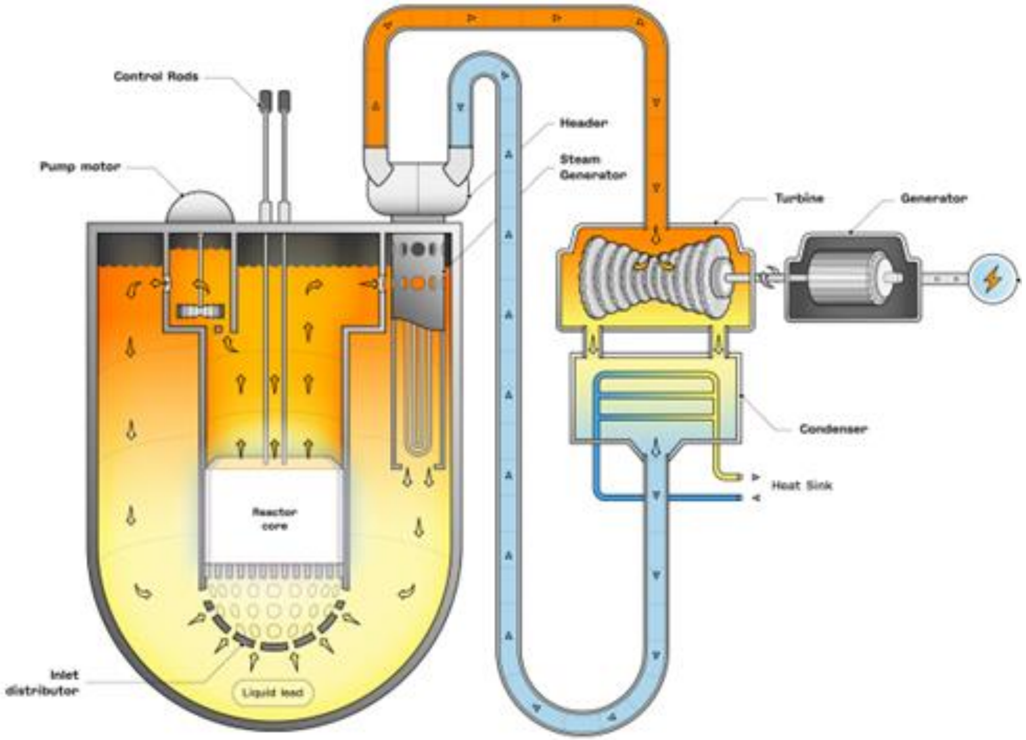
Outlines

- LFR Technology: Benefits and Issues, Development Activities in USA
- LFR Safety: Safety System, Testing and Analysis
- LFR Safety: Regulations, and safety principles, licensing interaction



PART III: Regulations and Licensing Interaction

Safety Objective of LFR

Excellent Safety Features of LFR

- Enhanced passive safety systems
- IAEA passive safety category B for key systems
- Intrinsic safety of lead coolant:
  - High boiling point
  - Atmospheric pressure operation
  - Lack of exothermic reactions
  - Radionuclide retention capability
  - Excellent gamma shielding and neutronic properties

Implement Safety Guidance in Design

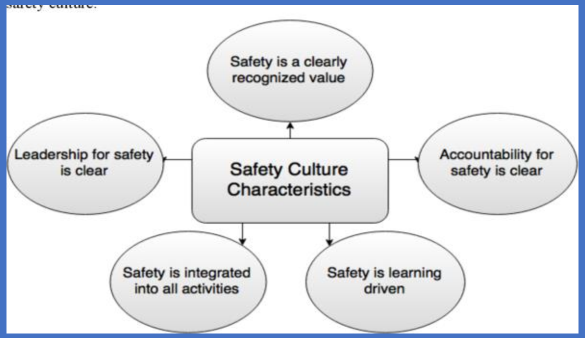
- US NRC Regulations
  - 10 CFR 50, 52, 53, LMP
- UK ONR SAPs and TAGs
- IAEA Safety Requirements

Superior Safety Performance

Develop a Strong Safety Case

- Ensure fundamental safety functions
- Implement defense in depth
- Robust safety case structure
- Engagement with regulators

Organization’s Safety Culture



IAEA Safety Standards

- The IAEA establishes internationally recognized safety standards that Member States use as the basis for national regulations. These are structured hierarchically as:
  - Safety Fundamentals
  - Safety Requirements
  - Safety Guides

Regulation and Licensing in USA

The Nuclear Regulatory Commission

- Established by the Energy Reorganization Act of 1974
  - Dissolution of the Atomic Energy Commission
  - Separation of regulatory and promotional functions
- Most licensing and regulatory authority transferred to the NRC
- Independent federal agency
  - Commissioners only removed for cause
  - Executive branch does not approve agency activities
- Congressional oversight

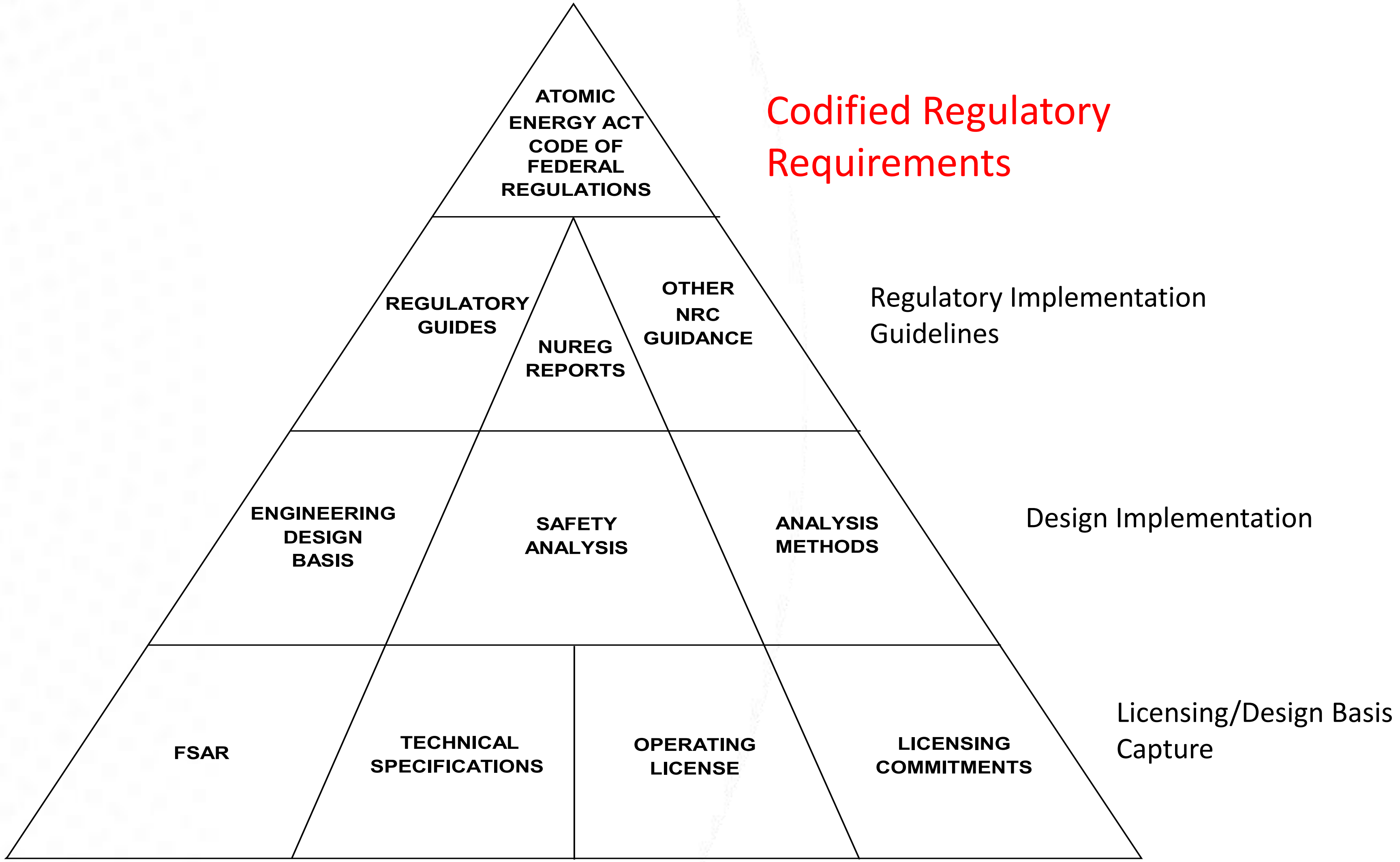
The Commissioners

- 5 member Commission
- Appointed by the President and Senate confirmed
- 5 year staggered terms
- No more than 3 of the same political party
- Can only be removed “for cause” (inefficiency, neglect of duty, or malfeasance)
- Chairman is also a Commissioner (i.e. same authorities over policy-making)

Commission Authority

- The Commission as a body has authority over:
  - Rulemaking
  - Adjudication
  - Policy formulation
- "Areas of doubt" settled by majority vote
- Each Commissioner has one vote, equal authority, and full access to all information from the staff
- Action of Commission decided by majority
- Quorum (3) required for action

Regulatory Hierarchy of Documents in USA



Title 10 Code of Federal Regulations

NRC Regulations are binding legal requirements documented in *Title 10, Energy, of the Code of Federal Regulations (10 CFR)*

- Contain the detailed requirements for regulating nuclear materials and activities
- Can be regarded as the NRC's interpretation of the Atomic Energy Act, the National Environmental Policy Act, and the Energy Reorganization Act
- Provisions are binding on the NRC and licensees unless successfully challenged in legal proceedings (challenges are seldom successful)
- Structured in numerous "Parts" that contain requirements for specific aspects of nuclear regulation

Title 10 Code of Federal Regulations

- 10 CFR – Energy, Table of Contents

Title 10 Code of Federal Regulations

- **Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors**

Part 31 General domestic licenses for byproduct material
Part 32 Specific domestic licenses to manufacture or transfer certain items containing byproduct material
Part 33 Specific domestic licenses of broad scope for byproduct material
Part 34 Licenses for radiography and radiation safety requirements for radiographic operations
Part 35 Medical use of byproduct material
Part 36 Licenses and radiation safety requirements for irradiators
Part 39 Licenses and radiation safety requirements for well logging
Part 40 Domestic licensing of source material
Part 50 Domestic licensing of production and utilization facilities
Part 51 Environmental protection regulations for domestic licensing and related regulatory functions
Part 52 Early site permits; standard design certifications; and combined licenses for nuclear power plants
Part 53 Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors (proposed)
Part 54 Requirements for renewal of operating licenses for nuclear power plants
Part 55 Operator's licenses
Part 60 Disposal of high-level radioactive wastes in geologic repositories
Part 61 Licensing requirements for land disposal of radioactive waste
Part 62 Criteria and procedures for emergency access to no-federal and regional low-level waste disposal facilities
Part 63 Disposal of high-level radioactive wastes in a geologic repository at Yucca Mountain, Nevada
Part 70 Domestic licensing of special nuclear material
Part 71 Packaging and transportation of radioactive material

Title 10 Code of Federal Regulations

- <u>10 CFR – Energy, Table of Contents (continued)</u>

10 CFR Part 50

- Traditional two-step licensing process
  - Step 1 - Construction permit (PSAR)
  - Step 2 - Operating license (FSAR)
- Most of nuclear power plants in US are under Part 50
- Similar processes are adopted world widely
- Extensive lessons learned

10 CFR Part 52

- Combines a construction permit and an operating license, with certain conditions, into a single license.
- Under either process, before an applicant can build and operate a nuclear power plant, it must obtain approval from the NRC.
- ➡ Plant Standardization.
- Design Certification (under Part 52).
  - AP1000, AP600, System 80+, ABWR, ESBWR
- Combined Operating License for sites
  - Vogtle 3/4, Summer 2/3, etc.

10 CFR Part 53 (Proposed)

- Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors
- Alternative to Part 50 and Part 52
- The regulatory requirements use methods of evaluation, including risk-informed and performance-based methods, that are flexible and practicable for application to a variety of advanced reactor technologies.
- The proposed rule accommodates all reactor technologies and includes self-contained licensing framework featuring safety approach that aligns with the U.S. Department of Energy cost-shared, industry-led Licensing Modernization Project (LMP) methodology.

Comparison Between US Part 50/52 and UK GDA

Aspect	UK GDA (Generic Design Assessment)	US 10 CFR Part 50	US 10 CFR Part 52
What it assesses	**Generic reactor design** (no site, no operator)	Site-specific **construction permit + operating license**	**Design certification**, **early site permit**, and/or **combined license**
Mandatory?	**Voluntary** (but strongly expected)	Mandatory if licensing under Part 50	Mandatory if licensing under Part 52
Site-specific?	❌ No	✅ Yes	✅ Yes (except design certification)
Output	**DAC (ONR)** + **SoDA (EA/NRW)**	Construction Permit → Operating License	Design Certification, ESP, or COL
Does it authorize construction or operation?	❌ No	✅ Yes	✅ Yes (COL)
Purpose	De-risk design early; separate design from siting	Traditional two-step licensing	Front-loaded approvals with regulatory finality

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Pre-Licensing Interaction in United Kingdom

UK-BEIS Advanced Modular Reactor (AMR) Program

- Program run between 2017-2023
- Stemmed from UK Government's interest to revitalize UK's nuclear industry and achieve NetZero emissions by 2050.
- Emphasis by the UK Government was on both light water SMRs and on nuclear technologies with improved economics and applications beyond baseload electricity (AMRs).
- In 2017 the Department for Business Energy & Industrial Strategy (BEIS*) launched the 2-phase AMR program:
  - Phase 1 - Feasibility study (2017-2019): provide evidence of the feasibility of the LFR reactor design and associated development, both from the technical and business case standpoint
  - Phase 2 - Development (2019-2023): demonstrate the viability and performance of key LFR materials, systems and components to further advance readiness of the LFR
- Westinghouse participated in the AMR program since its inception. It was down-selected to move into Phase 1 and subsequently into Phase 2, the latter with a ~£9M award leading a team of nine international partners.
- **The AMR program included engagement activities with UK regulators, Office for Nuclear Regulation (ONR) and Environment Agency (EA), to seek and receive the regulators' feedback on topics of interest to support and streamline potential future licensing activities in UK and beyond.**

*BEIS changed designation and it is now the Department for Energy Security and Net Zero (DESNZ).

Westinghouse AMR Phase 2 Program

- Led by Westinghouse, in collaboration with nine international partners. Executed between July 2020 - March 2023
- 12 Work Packages focused on the design, construction and first operation of eight state-of-the-art LFR test facilities
- Collected experimental data to confirm technical feasibility/performance of key materials/components/systems and to validate modelling & simulation tools.
- **Engagement with ONR/EA was an important part of Phase 2 program and is summarized in the next few slides.**

Work Package	Work Package title	Scope area
1	Training on lead technology and lead R&D	Training
2	Corrosion/erosion testing of materials at very high temperature in liquid Pb	Materials
3	Liquid lead chemistry control in pool-type configuration	Coolant chemistry
4	Structural materials mechanical property assessment in liquid lead	Materials
5	High-priority comp. testing and demonstration: HX and fuel bundle mockup	Comp/sys testing
6	Fuel system development - Part 1	Materials (fuel)
7	Passive Heat Removal System testing and demonstration	Comp/sys testing
8	Pump testing and demonstration	Comp/sys testing
9	Testing of relevant phenomena: Primary Heat Exchanger failure and Pb freezing	Comp/sys testing
10	Under-lead viewing technology development	Comp/sys testing
11	Activities in support of efficient plant delivery	Plant layout / modularization
12	Fuel system development - Part 2	Materials (fuel)

AMR Phase 2 ONR/EA Engagement Stages

Stage	Engagement Activities	Participation of Westinghouse LFR Team
Stage 1	Introductory meeting on key regulatory topics and expectations	Yes
Stage 2a	Engagement with vendors not selected by BEIS for Phase 2 funding	No
Stage 2b	Engagement meeting with vendors selected by BEIS for Phase 2 funding. Present progress in research, design and safety case since Phase 1 and identify key topics for Stage 3 engagement.	Yes
Stage 3	Multiple (4) engagement meetings on selected key topics	Yes
Stage 4	Final engagement to conclude discussions and resolve actions from Stage 3	Yes
Stage 5	Regulators project review meeting (no vendor participation)	No

Summary of Phase 2 Engagement Meetings

Stage and meeting No.	Date	Participants	Topic
Stage 1	Jan 13, 2021	ONR, EA, Westinghouse (+ Ansaldo Nucleare, ENEA), and the other awardees of AMR Phase 1	Introductory meeting on key regulatory topics and UK regulator's expectations.
Stage 2b	Mar 22/24, 2021	ONR, EA, Westinghouse (+ Ansaldo Nucleare, ENEA)	Overview of the Westinghouse LFR and the AMR Phase 2 scope. Introduction of each WP in Phase 2.
Stage 3, 1st meeting	Jul 8, 2021	ONR, EA, Westinghouse (+ Ansaldo Nucleare, ENEA)	Proposed structure of the Westinghouse LFR safety case, SSC categorisation, best practice in lead auxiliaries & handling
Stage 3, 2nd meeting	Dec 16, 2021	ONR, EA, Westinghouse (+ Ansaldo Nucleare, ENEA)	LFR core design, reactivity control, and shutdown strategy
Stage 3, 3rd meeting	Apr 12, 2022	ONR, EA, Westinghouse (+ Ansaldo Nucleare, ENEA)	Lead coolant properties, lead activation and lead management
Stage 3, 4th meeting	Dec 5, 2022	ONR, EA, Westinghouse (+ Ansaldo Nucleare, ENEA)	LFR primary heat exchangers and associated failure mode assessment
Stage 4	Mar 15, 2023	ONR, EA, Westinghouse (+ Ansaldo Nucleare, ENEA)	Overview of AMR Phase 2 achievements, summary of regulatory engagement, and assessment of how Phase 1 comments were addressed in Phase 2

Stage 3 Engagement Meetings
- 1st Meeting: Golden Thread (an approach to development of safety case)

- This meeting focused on the proposed structure of the LFR safety case.
- The LFR safety case structure was based on the UK regulatory environment. It leveraged previous GDA experiences and considered international adoption in future.
- The approach to the safety classification of the LFR Systems, Structures and Components (SSC) was presented.
- The methodology for the fault schedule adopted for UK licensing was presented, including example cases.
- An overview of the lead coolant auxiliary systems for the LFR was presented.
- Best practices in Pb handling with regards to personnel safety was presented by ENEA, leveraging their extensive experience in the field.

Proposed outline of the LFR safety case structure

- Chapter 1 – Introduction
- Chapter 2 – Site (site envelope for generic LFR safety case)
- Chapter 3 – Design of structures, components, equipmt, and systems
- Chapter 4 – Reactor
- **Chapter 5 – Reactor coolant system and connected systems**
- Chapter 6 – Engineered safety features
- Chapter 7 – Instrumentation and controls
- Chapter 8 – Electric power
- Chapter 9 – Auxiliary systems
- Chapter 10 – Steam and power conversion
- Chapter 11 – Radioactive waste management
- Chapter 12 – Radiation protection
- Chapter 13 – Conduct of operation
- Chapter 14 – Initial test programme
- **Chapter 15 – Accident analysis**
- Chapter 16 – Technical specifications
- Chapter 17 – Quality assurance
- Chapter 18 – Human factors engineering
- Chapter 19 – Probabilistic safety assessment
- Chapter 20 – Lead management
- Chapter 21 – Decommissioning
- Chapter 22 – ALARP summary

- Chapter 5 – Reactor coolant system and connected systems
  - 5.1 – Summary description (claims and arguments)
  - 5.2 – Integrity of reactor coolant boundary
  - 5.3 – Reactor vessel design description
  - 5.4 – Component and subsystem design description

- Chapter 15 – Accident analysis
  - 15.0 Introduction (provides introduction and basis for analysis including but not limited to;
    - Plant characteristics
    - Initial conditions
    - Protection and safety monitoring system setpoints
    - Fission product inventories
    - Computer codes used
    - Operator actions
    - Fault groupings
    - Diverse protection system
    - ALARP)
  - 15.1 through 15.13: analysis of accidents

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Stage 3 Engagement Meeting
- 1st Meeting: SSC classification

- Safety functions are categorized in accordance with the importance of the function for ensuring nuclear safety of a nuclear reactor.
- Classification of structures, systems, and components (SSCs) is used to identify SSCs that are important for providing a function ensuring nuclear safety of a nuclear reactor.
- The safety class of an SSC defines the requirements placed during design and manufacture, and maintenance through life; it also determines which codes, standards, and seismic design considerations are appropriate for the design and manufacture of that SSC.

LFR safety function categorization

- Safety Category (A, B or C) indicates how important a function is in maintaining nuclear safety
- In accordance with the SAPs:
  - **Category A** – any function that plays a principal role in ensuring nuclear safety
    - Removing the nuclear core decay (or residual) heat from the reactor coolant
    - Controlling reactivity of core
    - Confining radioactive material
  - **Category B** – any function that makes a significant contribution to nuclear safety
    - Examples: maintaining Category A safety functions after 7 days following an accident; functions that provide a backup or alternate actuation of a Category A safety function
  - **Category C** – any other safety function
    - Examples: monitoring radioactivity released into the environment; functions to monitor for the occurrence of, and alert personnel to take mitigating action following, internal hazards events (e.g. fire, flood)

SSC Safety Categorization and Classification

- The primary safety functions for all design basis events are mitigated by A1 (category A, class 1) SSCs.
- The reference LFR design principles require all class 1 SSCs to be passive and require no operator action.
- Frequent faults (IEF>10-3/year) require diverse safety systems to perform primary safety functions. These are either class 1 or class 2 SSCs.

Classification / Categorization	1	2	3
A	X	X	-
B	-	X	X
C	-	-	X

Example of Major SSCs of LFR and their classification

SSC	Description	Classification
Passive heat removal system (PHRS)	Removes residual heat from core to ambient	A1
Reactor vessel (RV)	Transfers residual heat to PHRS; confines radioactive material	A1
Guard vessel (GV)	Transfers residual heat to PHRS; confines radioactive material	A1
Primary heat exchangers (PHE)	Part of normal residual removal system; barrier between lead and secondary coolant	B2
Passive core shutdown system	Shutdown reactivity of core in emergency	A1
Shutdown assemblies	Shutdown reactivity of core	B2
Lead heating system	Heating system to prevent lead freezing in safety shutdown mode that could impair lead’s natural circulation	B2

Stage 3 Engagement Meeting
- 1st Meeting: Fault Schedule

- Fault analysis identifies all initiating faults having the potential to lead to any person receiving a significant dose of radiation or to a significant quantity of radioactive material escaping from its designated place of residence or confinement.
- The Fault Schedule determines key safety requirements on structures, systems and components (SSC), including human action if needed.
- The Fault Schedule lists:
  - Initiating events (IEs)
  - Initiating event frequencies (IEFs)
  - Safety measures (SSCs plus any human actions)
  - Mitigated consequences
  - and the overall protection claims
- Events include internal faults, internal hazards, and external hazards.

Approaches to Fault Schedule
- Example of Initiating event categorization

Category name	Frequency	Consequences	Requirements for Safety measures
Frequent fault (FF)	IEF > 10^{-3}/y	Public dose < 1 mSv or worker dose < 20 mSv.	Two diverse mitigation capabilities are required for each Category A safety function. At least one capability must be Class 1. The other may be Class 2. Analysis of the plant with consideration for a common cause failure may be performed with less conservative methods and/or inputs and may apply relaxed acceptance criteria.
Infrequent fault (IF)	IEF between 10^{-3}/y and 10^{-5}/y	Public dose < 10 mSv or worker dose < 200 mSv for events between 10^{-3} and 10^{-4} /yr Public dose < 100 mSv or worker dose < 500 mSv for events between 10^{-4} and 10^{-5} /yr	One Class 1 mitigation capability is required for each Category A safety function
Beyond design basis (BDB)	IEF less than 10^{-5}/y	Consequences higher than IF events	No formal requirement except for demonstrating event considerations are ALARP.
All other faults		No radiological consequences expected.	No formal requirement except for demonstrating event considerations are ALARP.

Example of Fault Schedule – LFR Station blackout (SBO) (<7days)

- Initiating event: loss of offsite power
- IEF: ~10^{-2}/year (subject to further PRA study)
- Category: frequent fault
- Sequence: Loss of offsite power leads to loss of the power to all RCPs and PHE feeding. Loss of capability to remove heat from reactor core.
- Safety functions
  - Primary function:
    - Reactivity control: passive shutdown system (class A1).
    - Core heat removal: lead coolant (A1), RV (A1), GV (A1), PHRS (A1)
    - Confinement of radioactive material: fuel rod cladding (A1), RV (A1).
  - Diverse function:
    - Reactivity control: control assemblies (B2), shutdown assemblies (B2) and plant control system (B2).
    - Core heat removal: PHE (B2) and plant control system (B2)
- Operational mode: 1 (power operation), 2 (startup).
- Comments:
  - The normal case is shutdown rods, PHE and plant control system could be active within 7 days and mitigate the accident.

Approaches to SSC classification – LFR safety class of SSC

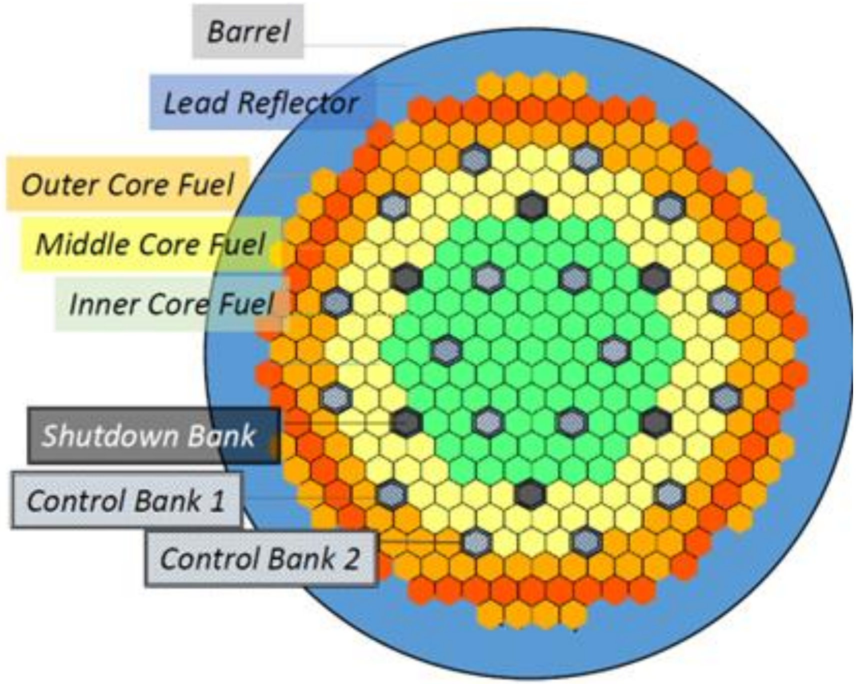
The safety class of an SSC takes the safety category of the functions performed by the SSC into account, and considers the extent to which the SSC supports the safety function with which the safety category is associated:

- **Class 1** SSCs provide the principal means of fulfilling a Category A safety function
- **Class 2** SSCs are a principal means of fulfilling a Category B safety function, or a significant contributor to fulfilling a Category A safety function such as backup means to perform a category A function
- **Class 3** SSCs are all other SSCs that are not Class 1 or Class 2 that provide contributions to maintaining nuclear safety and include SSCs identified to support the operation of Class 1 and Class 2 SSCs
- **GNS**: General Non-Safety (GNS) SSCs are those that do not contribute to maintaining nuclear safety, as determined by the safety case.

Stage 3 Engagement Meetings
- 2nd Meeting: Reactivity Control Strategy

- This meeting focused on the reactivity control strategy of the LFR.
- Westinghouse presented the preliminary core design, which can interchangeably accommodate the near-term fuels (UO_2 and MOX) as well as the longer-term advanced fuel option (UN)
- Westinghouse provided an overview on the core design/analysis method and the integrated suite of modeling tools for this purpose.
- The reactivity control and shutdown strategy was established accounting for redundancy and diversity, relying on control/shutdown rods but also including the potential for using an innovative non-rod-based passive shutdown system.
- The optimization of core and reactivity control was undertaken with support from safety analysis and fuel rod performance assessments.

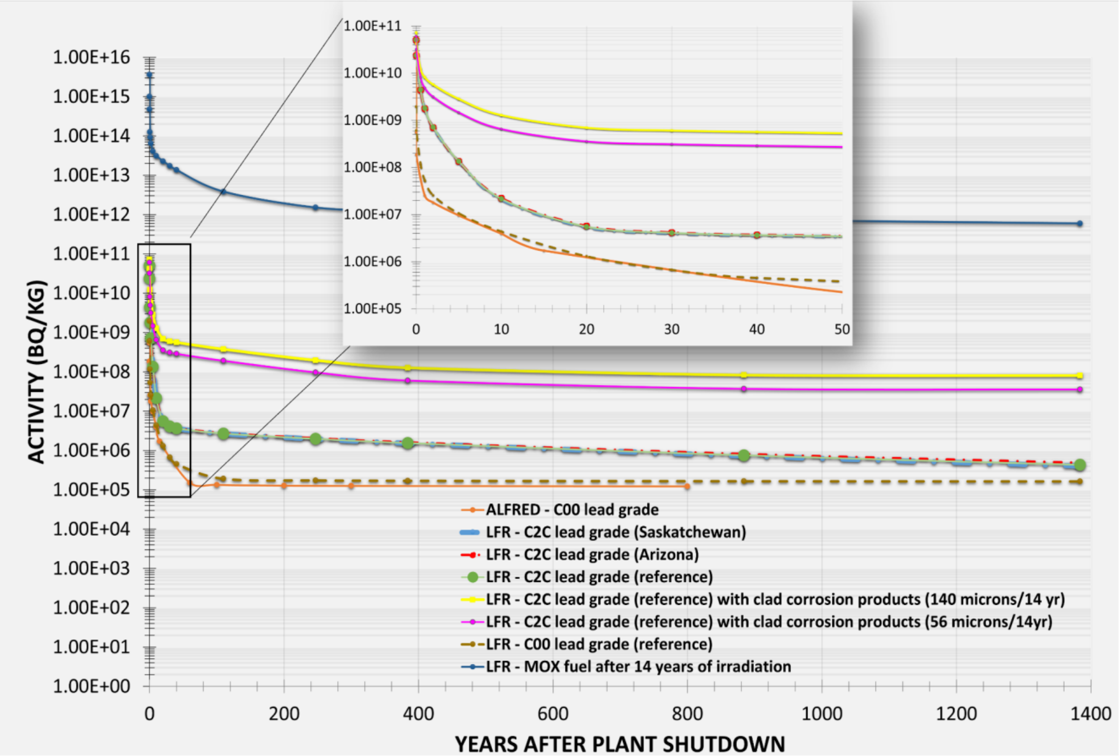
Representative core design with shutdown systems of LFR



Stage 3 Engagement Meetings
- 3rd Meeting: Lead Management

- The AMR Phase 1 feedback from ONR/EA included a comment on the need to provide more information on lead management and disposal in the UK
- Topics presented:
  - Overview on Pb properties, followed by an in-depth description of best practices in Pb handling offered by ENEA.
  - Progress in the development of Pb management and Pb waste handling/disposal strategies in the UK.
  - Results on Pb coolant activity levels during and after LFR operation as a function of purity levels (of the as-purchased Pb) and extent of corrosion of structures during operation.
- No insurmountable obstacle related to Pb management toward licensing was identified
- However, the team acknowledged the need to assess the effect that Pb coolant purification technologies may have in easing and broadening the disposal or recycling routes for activated lead.

Preliminary assessment on lead activation in LFR



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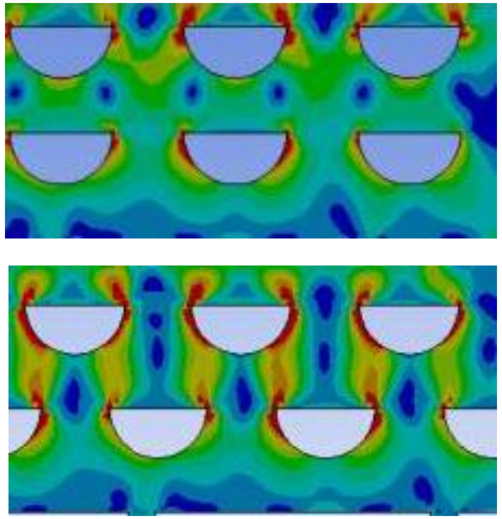
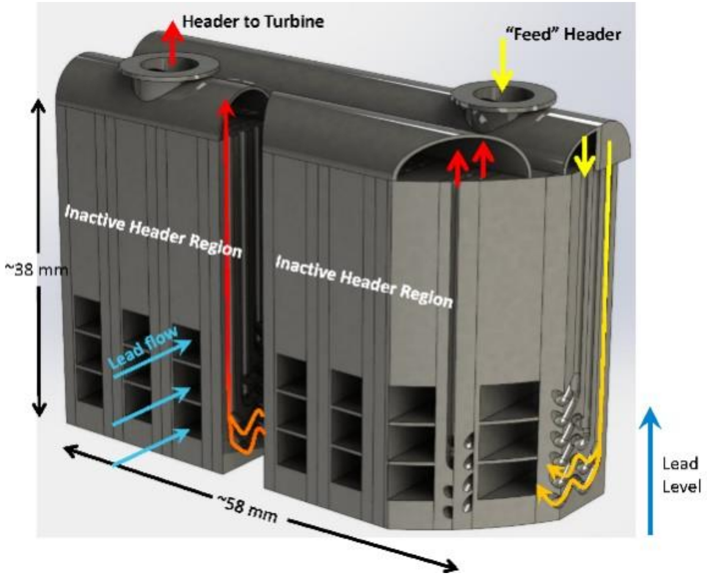
Stage 3 Engagement Meetings
- 4th Meeting: Primary Heat Exchanger (PHE) Failure



- LFR technology allows elimination of the intermediate loop typical of other AMR technologies, and positioning of primary heat exchangers inside the reactor vessel
  - Sys simplification and capital cost reduction. However, introduction of PHE failure as initiating event
- The reference LFR adopts an innovative printed circuit-type heat exchanger (PCHE) design
  - Extremely compact, allowing significant reduction in reactor vessel size/weight
  - Reduces frequency and consequences of postulated heat exchanger failure
- Westinghouse presented:
  - Overview on PCHE technology, including design, manufacturing, and inspection processes envisioned for hybrid microchannel PHE in LFR together with the associated material selection.
  - PHE failure mode assessment, which indicated the lack of credible failure modes between the primary and secondary sides due to the unique characteristics of PCHE technology.
  - Assessment of the effects of micro-channel misalignment and incomplete plate bonding on stresses
  - Bounding assessment of reactivity insertion in the core upon PHE failure, showing extremely low effects because of the small break flow rate of the secondary fluid and buoyancy of vapor bubbles in lead coolant.
- Westinghouse also presented progress in PHE failure testing in the LEWIN (LEad-to-Water INteraction) facility built as part of the AMR program.



Stage 4 Engagement Meeting

- In the last meeting with the UK regulators, Westinghouse summarized the main achievements attained throughout the AMR Phase 2 program, the highlights of each engagement meeting, and additional progress made by Westinghouse on each of the topics discussed during these meetings.
- Westinghouse also presented the progress made against each of the Red ratings identified by the regulators in Phase 1, demonstrating that they had been partly or completely addressed as part of the Phase 2 program or through separate activities.
- An update on LFR development activities outside of the UK was also given to highlight the rising interest in LFR technology.
- In the meeting, both ONR and EA presented their summary of the Phase 2 engagement activities and how the original objectives for the engagement were met.
- Both the Westinghouse LFR team and the UK regulators agreed that the engagement opportunity enabled by the AMR program was reciprocally beneficial.

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