LFR Technology Development

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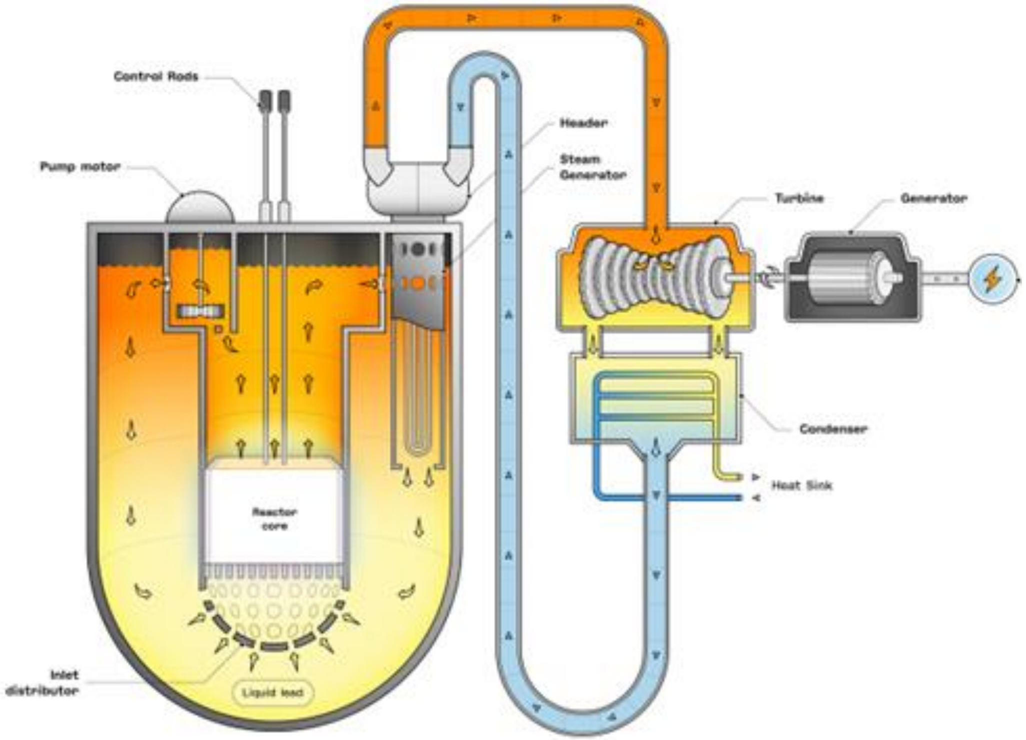
Jun Liao (Westinghouse Electric Company, USA)

- Consulting Engineer at AI and Innovation
  - Development of advanced reactors: Lead cooled fast reactor, eVinci microreactor, AP300 SMR, AP1000, Westinghouse SMR.
  - Tech Lead of Dynamic Simulation Laboratory
- Expertise:
  - Thermal hydraulics of nuclear reactors, nuclear safety, development of advanced reactors, architect of modeling and simulation, passive safety system, and innovation in machine learning and AI for nuclear engineering.
- Education:
  - PhD, University of Florida, 2005.
  - MS, Xi'an Jiaotong University, 1997.
  - BS, Huazhong University of Science and Technology, 1994.
- Fellow of American Nuclear Society (ANS)
- Fellow of American Society of Mechanical Engineers (ASME)
- Associate Editor, ASME Journal of Nuclear Engineering and Radiation Science.

Outlines

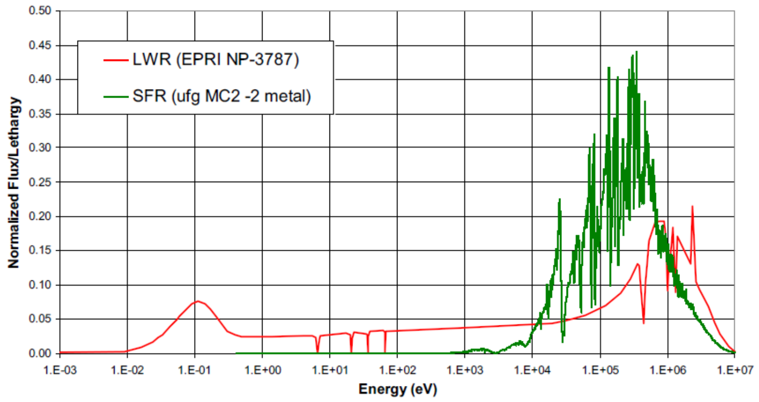
- LFR Technology: Benefits and Issues, Development Activities in USA
- LFR Safety: Safety System, Testing and Analysis
- LFR Safety: Regulations, and safety principles, licensing interaction

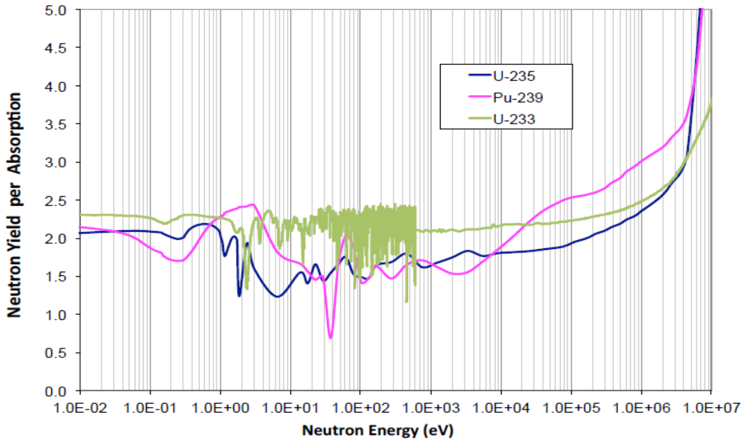


Part I: LFR Technology: Benefits and Issues, Development Activities in USA

Historical motivation for developing fast reactors
Fast vs thermal neutron spectrum

- In light water reactors, a moderator (water) is used to slow neutrons down. Most fissions occur near the 0.1eV thermal peak.
- In fast reactors, neutron moderation does not occur and fissions occur in the fast neutron energy range.
- Fissile isotopes (235U and 239Pu) are fissioned in both thermal and fast spectrum.
- 238U (main constituent of the fuel mass) can only be fissioned in fast spectrum.
- Analogously, actinides (long-term nuclear waste) are much more efficiently consumed in fast spectrum than in thermal spectrum.
- However, higher enrichment required in fast spectrum to sustain criticality, and fuel reprocessing facilities are required to close the fuel cycle.
- LFR is one of the four fast reactors within the six so-called Gen-IV reactor technologies





The motivations for developing LFR have evolved over the years, and are now beyond fuel cycle implications

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LFR Technology Benefits

Safety characteristics of lead coolant

High thermal conductivity

Very high boiling point (~1740°C)

Atmospheric pressure operation

Does not react exothermically with water and air

Enhances Defense-in-Depth by retaining radionuclides

Excellent neutronic properties allow opening fuel lattice → reduced core pressure drop → enhanced natural circulation during accidents

Favorable economic attributes

Technology is conducive to design simplicity and robustness, supporting enhanced modularity in construction

No intermediate heat transport system due to lead's compatibility with power conversion system fluid

No high-pressure-resistant containment: no containment construction-dictated schedule

High plant efficiency (41-50%), limited by progress in materials (not by coolant boiling concerns)

Enhanced sustainability

Uranium resource utilization and fuel cycle advantages from operation in fast neutron spectrum

Adequate technology readiness

Numerous test facilities already exist and have been operated

No need for a never-ending R&D program

Corrosion

- Addressed by temperature selection and **material development**

High melting point coolant

- Addressed by system design

Opaque coolant

- Addressed by **advancements** in inspection and under-lead viewing technology

High-density coolant

- Addressed through **innovative** solutions promoting vessel compactness

Additional challenge (common to the vast majority of non-LWRs): availability of adequate fuel cycle infrastructures

Challenges of LFR technology are not inherent showstoppers to safety or economics. They can be addressed through proper engineering and innovation

Lead Fast Reactor vs. Sodium Fast Reactor

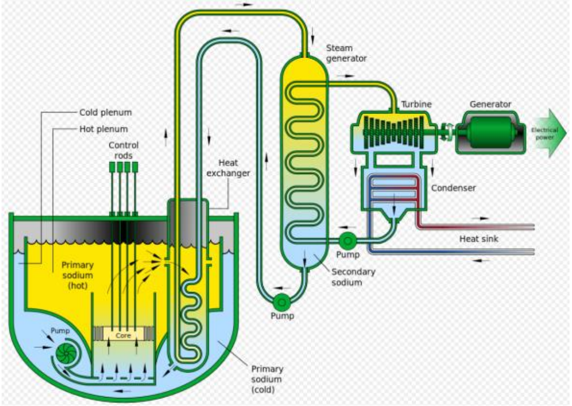


Illustration of generic SFR

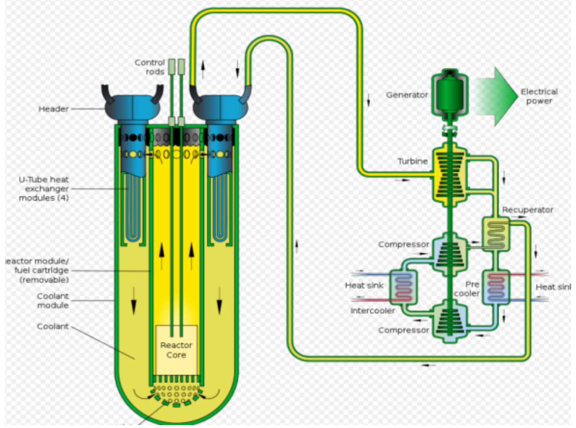


Illustration of generic LFR

Similarities:

- Coolant has superior heat transfer capabilities
- Operation in fast neutron spectrum, enabling closed fuel cycle
- Similar modeling and simulation tools
- Common technology basis for material selection (steels)

Major differences:

- Na reacts exothermically with air and water. Pb does not
  - SFR requires an intermediate loop. LFR does not
  - SFR does not allow using water in the vicinity of the primary system
  - SFR requires provisions for sodium fire, the associated radionuclide source term, and H_2 generation
- Melting temperature (Na 98°C vs. Pb 327°C)
  - LFR needs active heating system when decay heat is not sufficient (e.g., fresh core)
- Boiling temperature (Na 883°C vs. Pb 1749°C)
  - Na boiling is a concern in BDBAs, requiring additional safety features
  - LFR has instead the capability to eliminate severe accidents
  - Na boiling limits SFR's max temperature to ~530°C, thus limiting plant efficiency to ~41%
- Pb has much higher (~12x) density than Na: good and bad
- Pb is much heavier than Na -> system weight and seismic consideration.
- Pb is more corrosive than Na → material selection more challenging, and incompatible with metallic fuel
- Pb absorbs/moderates neutrons much less than Na, allowing a more open fuel lattice which eases nat. circulation
- Operating experience: much greater and more easily accessible with SFRs (400 reactor-yrs internationally) vs limited reactor-yrs for lead-based reactors (limited to Russian submarines)
- Experiments with Na require extra safety provisions, making them more demanding than with Pb

Lead-cooled Reactor vs. Lead-Bismuth Eutectic (LBE) Reactor

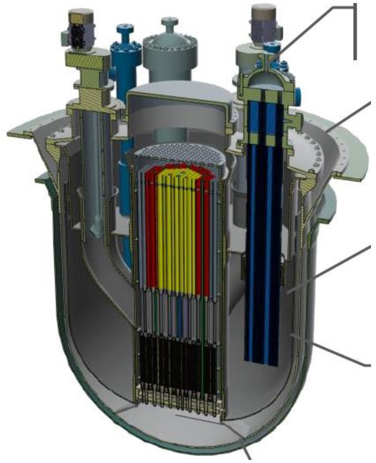
LBE is a eutectic alloy of lead (44.5 %) and bismuth (55.5 %)

Similarities:

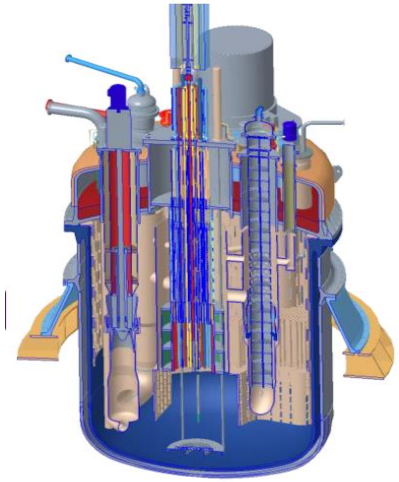
- Thermo-physical properties are similar (with some notable exceptions)
- Reactor designs are similar
- Share most experimental data, especially thermal-hydraulic ones
- Share modelling and simulation tools

Major differences:

- Melting temperature (LBE 124 °C vs. Pb 327 °C)
  - LFR needs enhanced heating system when decay heat is not sufficient to keep coolant molten (e.g. fresh core)
- Polonium production
  - LBE produces much more (4-5 orders of magnitude more) Po-210 than pure lead.
  - Po is highly radio-toxic
  - Po-210 is a significant contributor to source term during accidents, and to decay heat.
- LBE is more corrosive than Pb at the same temperature, making corrosion data in LBE not applicable to pure Pb
- LBE is more expensive and bismuth availability is limited
  - Pb is preferable for a commercial plant because of high availability and cost benefits.



ALFRED lead-based



MYRRHA LBE-based

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LFR Design

Reactor Development

- Guidance
  - General Design Criteria
  - Utility Requirements Document/European Utilities Requirements
  - Regulatory requirement (NRC/ONR/ASNR/CNCAN…)
  - IAEA guidance
- Development Phase
  - Conceptual Design
  - Preliminary Design
  - Intermediate Design (may skip)
  - Final Design

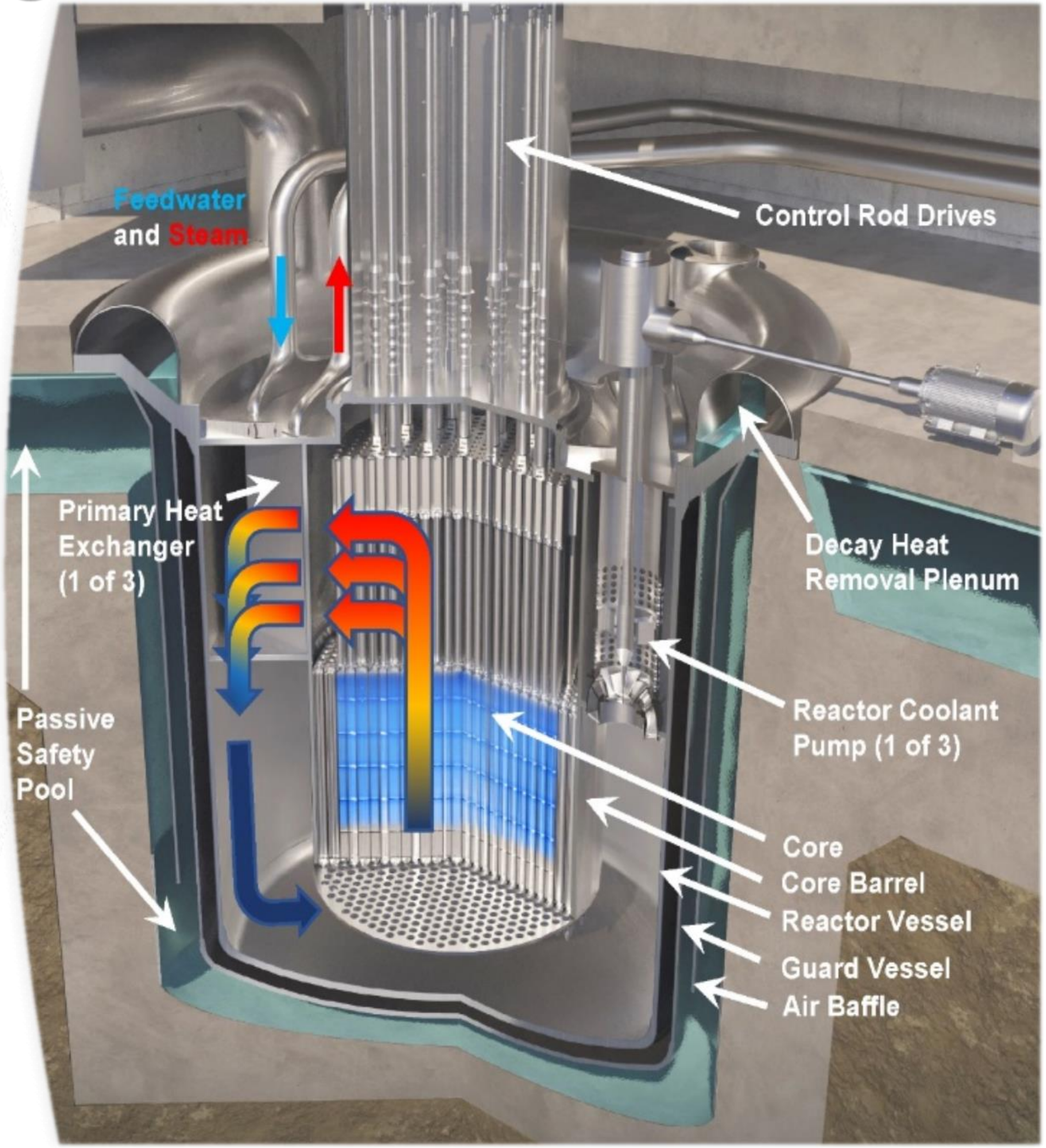
Overview of Reference LFR Design

Compact, passively-safe, modular-construction pool-type LFR

Economically Competitive

Air-cooled (to enhance site-ability) and provided with an integrated energy storage system (for load-following)

Reactor power	450 MWe Net (950 MWt)
Primary / secondary coolant	Liquid lead / Supercritical water
Number of pumps / HXs	3 / 3
Ultimate heat sink	Atmosphere, through air-cooled condensers. No water bodies required in the vicinity of the plant
Load following	600 MWe peak through thermal energy storage system
Fuel	Oxide (near-term); Advanced fuel (nitride) (long-term)
Fuel cycle	Open (ref.). Capable to accommodate closed cycle
Operating pressure, MPa	0.1 (primary) / ~34 (secondary)
Lead coolant min/max temperature, ˚C	390 / up to 530 (Phase 1); 390 / 650 (Phase 2)



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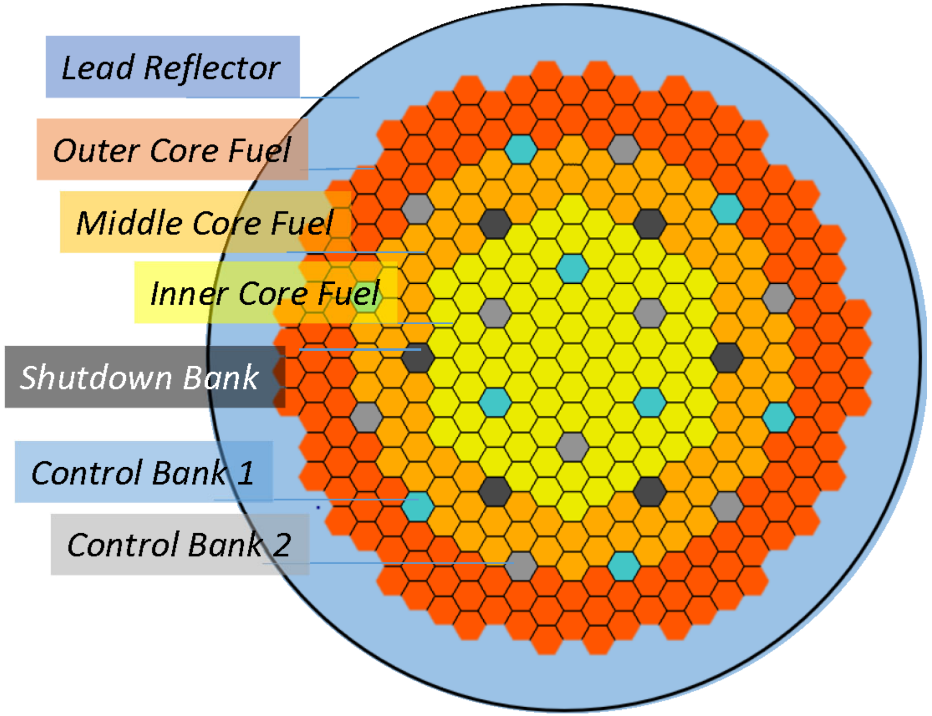
Reference LFR Fuel and Fuel Cycle

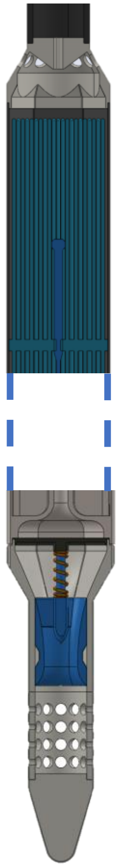
Fuel materials

- UO_2 with steel cladding for LFR start-up core
- UN with advanced cladding (steel or SiC) for future performance enhancements
- MOX for Pu recycle if/when pursued
- Advanced fuel options are backfittable, no change to internals or control system will be required for incorporation

Fuel cycle and refueling

- Reference fuel cycle: open
  - Flexibility to transition to semi-open or closed cycle if pursued by national policies
- Cycle length: 4 years, single batch
- Refueling scheme: direct-to-cask with no assembly shuffling. No spent fuel pool





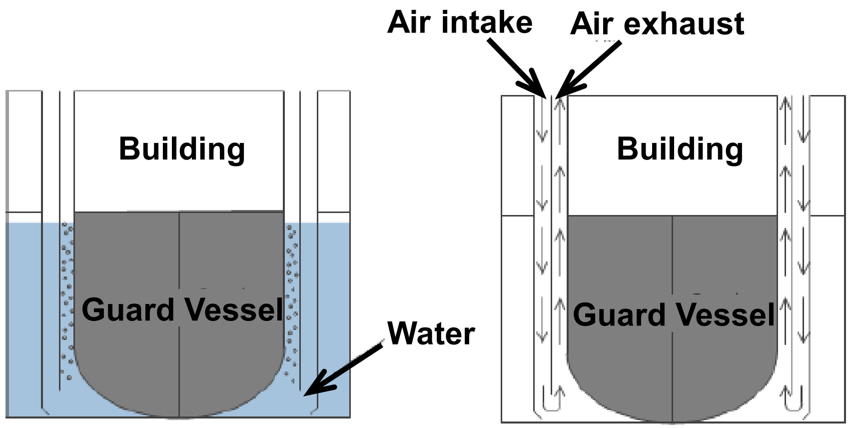
Passive Heat Removal System (PHRS)

PHRS design features

- Pool of water surrounds Guard Vessel.
- In accident, water cooling is provided for 7 days
- Transition to (indefinite) air-cooling in extended long-term cooling
- IAEA passive category B
  - No moving part
  - No I&C support, no need for actuation
  - No need for external power
- System always on
  - Parasitic heat loss is addressed in the engineering design.

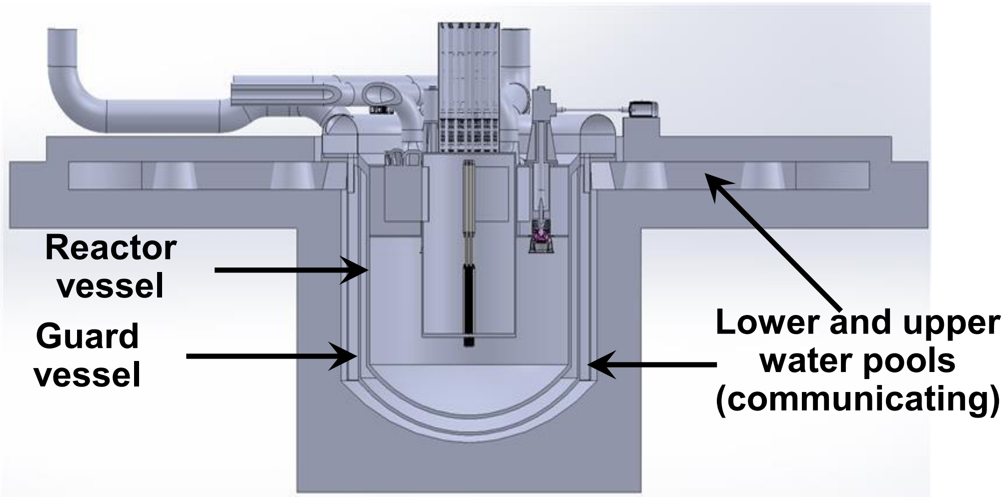
Important T/H phenomena in PHRS are identified in the LFR PIRT.

Both analysis (system level and CFD) and testing to demonstrate the performance of PHRS.



Water-cooling mode (notional)

Air-cooling mode (notional)



LFR Technology Development in USA (Westinghouse)

LFR Technology from Westinghouse: (1 of 2)

- Westinghouse is Top-Tier Service Provider to Gen-IV and Fusion developers, including LFR developers
- Cross-cutting engineering services to Gen-IV developers, leveraging Westinghouse's 60+ years experience in NPP commercialization (e.g., plant layout development, fuel development and manufacture, licensing support, digital engineering, component manufacturing, etc.)
- Technology development opportunities that can benefit from utilizing Westinghouse-owned LFR test rigs
  - MELECOR (high-temperature flowing Pb corrosion facility)
  - HIGHSC (high-temperature static Pb corrosion facility)
  - LEFREEZ (Pb freezing facility)
  - LEWIN (Pb-to-water interaction test facility)
- Collaboration opportunities on selected cross-cutting technologies

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LFR Technology from Westinghouse: (2 of 2)

- Collaboration with Unviersities:
  - **RELIEF (Radionuclide Retention in Liquid Lead Experimental Facility) at Virginia Tech**:
    - Facility setup & installation have been completed
    - Evaporation tests have been conducted (with Cs, Rb next) and retention tests are ongoing
  - **Corrosion tests at the University of Pittsburgh**:
    - Completed SS316L and HT9 tests at low temperature (400°C) and velocity (~1 m/s) for 500 and 1000 hrs. Facility has only recently been brought to full-temperature capability (600°C) in order to subsequently conduct higher-temperature/velocity tests

RELIEF test facility for radioisotope retention capability at Virginia Tech

- Collaborations with Argonne National Laboratory:
  - **Core design optimization**: Methodology developed and used to optimize Westinghouse LFR core. *See N. Stauff et al., "Core Design Optimization of the Westinghouse Lead Fast Reactor" presented at ICAPP-24*
  - **Development of an integrated computational framework for core analysis (PyARC)**: beyond capabilities demonstrated through core design optimization (e.g., integrated core deformation analysis with NUBOW).
  - **Further enhancement of SAS4A/SASSYS-1 capabilities** (e.g., coupling with radionuclide transport code FATE for mechanistic source term analysis): *See S.J. Lee et al., "Coupling SAS-FATE for Mechanistic Source Term Analysis of Lead-cooled Fast Reactors" to be presented at ATH-24*
  - **Implementation of a Pb corrosion model in system code SAM** (collaboration with Argonne, Virginia Tech and Bangor Univ): See *E. Cervi, et al., "SAM Code Enhancements for Modeling of Liquid Metal-Cooled Fast Reactor Concepts" (ANL/NSE-24/3) and T. Mui, et al., "Implementing a Corrosion-Oxidation Modeling Capability in SAM for Lead-cooled Fast Reactors" to be presented at ATH-24*

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Other LFR Developers in USA

- First American Nuclear Co. (Richland, Washington)
  - EAGL-1 SMR (240MWe)
  - LBE, UO2 fuel

- Subcritical Systems Inc. (Austin, Texas)
  - Accelerator driven
  - Lead