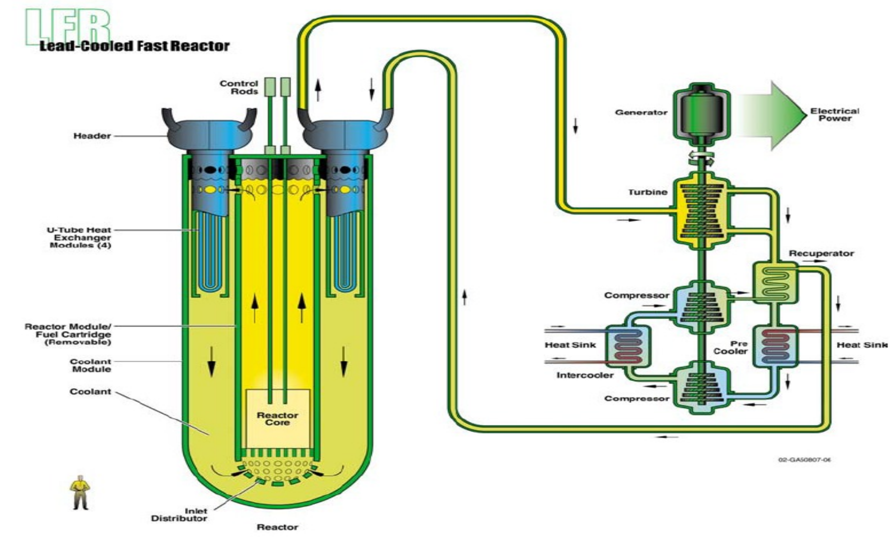
OVERVIEW OF LEAD-COOLED FAST REACTOR (LFR) TECHNOLOGY



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Fast Reactor Technology Training
U.S. Nuclear Regulatory Commission

OUTLINE

- Comparisons to SFR systems
- Unique LFR characteristics
- LFR fuel forms
- Material challenges
- Example LFR designs: ALFRED and BREST-OD-300, SSTAR
- LFR safety approach
  - Unique LFR accidents
  - Reactivity feedback mechanisms
  - Practically eliminated accidents
- What to look for in LFR design review
- Ongoing R&D support for deployment

COMPARISON TO SFR

- LFRs have similar sustainability and safety advantages as SFRs
  - Can support a closed fuel cycle for efficient resource use and waste reduction
  - Can breed-and-burn to achieve long core life
  - Can use oxide, metallic, or nitride fuel forms to achieve high-burnup
  - Can be pool- or loop-type
  - An unpressurized system with comparable inherent safety and passive decay heat removal characteristics
    - No LOCA concern, or need for high-pressure injection system
    - Reliance in a guard vessel to maintain coolant inventory
- Some advantages over SFRs:
  - Much larger margin to boiling (1740^{o}C boiling point for lead)
  - No exothermic reaction concern for lead coolant
  - Larger thermal inertia with longer grace period due to ~40% larger heat capacity
  - Similar density between coolant and fuel favors fuel dispersion vs compaction
- On the other hand:
  - Lead or LBE are more corrosive than sodium on most structural steel
  - For the same flow geometry, denser lead or LBE require greater pumping power
  - High melting point (330^{o}C for lead) can be a safety concern
    - Requires heating systems and operating procedures to address freezing

UNIQUE LFR CHARACTERISTICS (1/3)

- Lead does not react with water or air
  - Steam generators can be installed inside the reactor vessel
  - Eliminates the need for intermediate heat transport loop
- However, it is a corrosive/erosive coolant; can degrade typical structural steels and, if oxygen is not properly controlled, cause slugging of coolant
  - Controlled by coatings, oxygen control, and limit on lead velocity and temperature
  - Erosion is a major problem for the primary pumps' impeller blades, which can be exposed to >10 m/s relative lead velocity (exacerbated if pump is in hot leg)
- Very high boiling point (1740°C for lead) reduces the risk for core voiding
  - Thermal creep induced failure is a more limiting factor than coolant boiling
- Practically no lead deposition on cold surfaces due to very low vapor pressure
  - However, lead is a toxic element and would still require effective filtration systems to limit exposure of workers
- Some LFR designs can be open lattice (no assembly-can that wraps individual fuel assemblies)
  - Can be an advantage against coolant blockages (no total instantaneous blockage)

UNIQUE LFR CHARACTERISTICS (2/3)

- Compared to sodium, lead is a low moderating medium with a low absorption cross-section
  - Allows adoption of less compact fuel lattice arrangement (larger P/D) without appreciable neutronic penalty, resulting in:
    - Reduced core pressure drop and improved natural circulation potential for passive decay heat removal
    - Reduced vulnerability against flow blockages
    - Flexibility to use grid spacers (instead of wire wraps)
    - Generally lower power density than SFRs
  - Nevertheless, compact designs are still feasible and some LFRs pursue them for economic reasons
- High lead density provides unique buoyancy advantages and challenges
  - Favorable dispersal of debris from failed fuel pins (no need for core catcher) but, unless prevented, fuel assemblies may also float
  - Can be a challenge for reactivity control or safety rod insertion into the core (however, introduces possibility for bottom inserted reactivity control and safety rods without penetrations through the vessel head)
  - Increased seismic risk due to very large coolant mass inside the vessel

UNIQUE LFR CHARACTERISTICS (3/3)

- Lead-Bismuth Eutectic (LBE) is also an LFR coolant option
  - Lower melting point of LBE (~125^{o}C vs ~330^{o}C for pure lead) is a significant advantage against freezing risk
  - However:
    - Bi produces Po^{210}, a potent and toxic alpha emitter
      - Pure lead can also produce Po^{210} (due to Bi^{209} impurities and its generation through irradiation of Pb^{208}), but Po^{210} generation in lead is ~4 orders of magnitude lower than in LBE
    - Bi abundance on Earth is very limited, which challenges its use for sustaining a commercial fleet
    - LBE is more corrosive than pure lead (when compared at the same temperature)
    - LBE also thermally expands upon freezing exerting high stresses on the walls of a vessel it is contained in

COMPARISON OF LEAD, LBE AND SODIUM

		Lead	Lead-Bismuth	Sodium
Melting point (^oC)		330	125	100
Boiling point (^oC)		1735	1670	880
Conductivity* (W/m-K)		18	15	67
Density* (g/cm^3)		10.45	10.0	0.830
Specific heat*	c_p (J/K-kg)	145	140	1260
	ρc_p (J/K-cm^3)	1.5	1.4	1.05
Viscosity* (10^{-4} Pa-s)		18	13	2.3
Thermal expansion* (10^{-6} K^{-1})		122	128	282

*At 500°C

LFR FUEL FORMS

- Reference fuels considered for LFR deployment are oxide or nitride ceramic types
  - Metallic fuel may also be an option for low temperature operations
- MOX fuels that have been developed in the framework of SFR deployment are directly applicable to LFRs
  - Selection influenced by the choice of reprocessing and recycling strategy, and fuel fabrication experience (including minor actinide bearing fuels)
  - Further advancements envisioned for LFRs include new cladding materials
- Mixed nitride fuels have been adopted as a reference in Russian designs
  - Advantages include lower operating temperatures, high melting point and higher capability to retain fission products
  - But, nitride fuel forms are also susceptible to decomposition into a liquid or gaseous metal and nitrogen gas at very high temperatures
  - N^{15} enrichment is considered to improve the economics and avoid the production of radioactive C^{14}
- With oxide or nitride fuels, FCCI is not expected to be a concern, FCMI needs to be evaluated (although fission gas pressure is likely a bigger concern)

MATERIAL CHALLENGES (1/3)

- Depending on the material and operating conditions, lead may degrade the mechanical properties of structural materials because of corrosion, erosion, and liquid metal embrittlement
- In addition to maintenance and repair costs (operational concerns), it could also challenge confinement barriers and safety function of SSCs operating at high temperature and exposed to high lead velocity
  - Heat exchangers
  - Primary pump impeller (may be exposed to >10 m/s coolant velocity)
  - Cladding may also be a concern even though fuel stays in the core for only 3-5 refueling cycles (exception for long-life battery concepts)
- Main parameters impacting the corrosion rate of steels in lead or LBE are:
  - Chemical and metallurgical features of the steel
  - Temperature
  - Dissolved oxygen concentration
- Preserving material integrity against erosion imposes a limit on coolant velocity
  - Some literature sources report a limit of about 2 m/s for conventional steels, even though material-specific testing is needed as little data exist
  - Promising candidate materials for pump impellers include silicon carbide and titanium based alloys with tantalum or alumina coating

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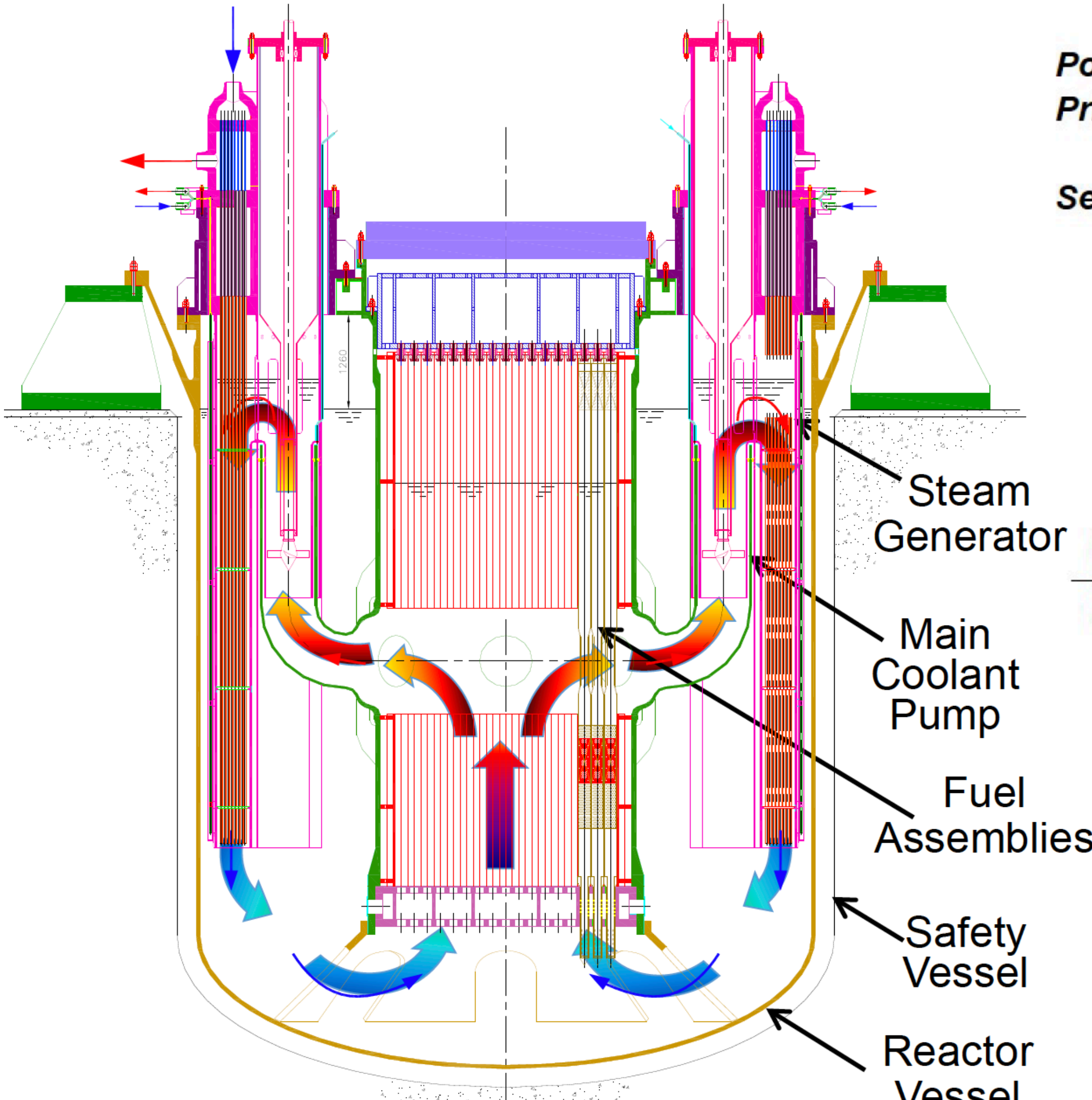
MATERIAL CHALLENGES (2/3)

- Historically, the most common strategy proposed for corrosion protection in LFRs has been relying on self-passivating alloys and controlling oxygen concentration in the coolant within a range:
  - Higher than a minimum required value to ensure formation of passive layer
  - Lower than a maximum allowed value to avoid precipitation of lead oxide
  - The larger the difference between cold and hot leg temperature, the narrower the range and the more challenging is the oxygen control
- Use of more traditional materials has limited hot leg lead temperature to ~500^{o}C
  - Austenitic low-carbon steels (e. g. AISI 316L) can tolerate relatively low temperatures (up to ~500^{o}C) and low irradiation flux as is the case with the reactor vessel
  - 15-15/Ti austenitic steel is candidate for cladding (better irradiation performance than 316SS, but temperature still limited to ~550^{o}C)
  - Ferritic-martensitic steels are proposed when better irradiation performance than austenitic steels is sought
- Progress in materials engineering and advanced manufacturing in the last 10-15 years resulted in a wider set of material options available to LFR developers today than in the past

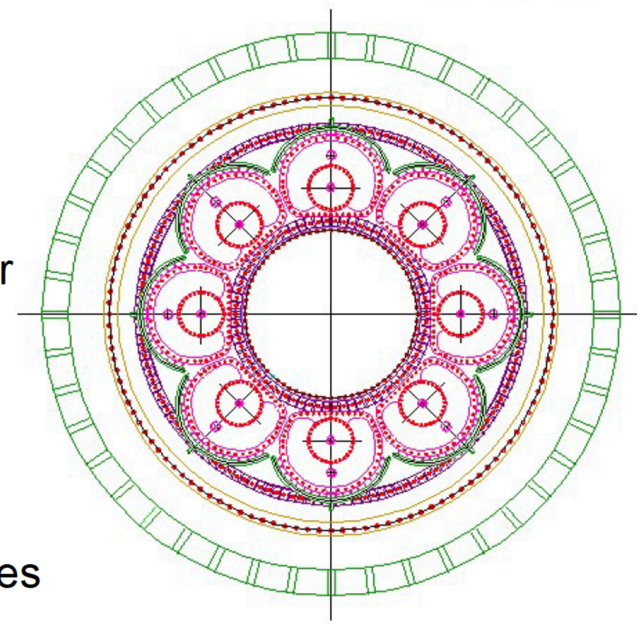
MATERIAL CHALLENGES (3/3)

- Progress in materials engineering is being leveraged by some developers to:
  - Relax the dependence of corrosion performance on oxygen concentration for certain components, as to broaden the permissible oxygen concentration range and simplify operation (e.g. use of coatings/layers which do not require a minimum oxygen concentration)
  - Increase operating temperature to increase efficiency and enhance economics
- In the high temperature range (above 500^{o}C), today's R&D focuses mainly on self-passivating alloys, corrosion resistant coating/clad applied on qualified fast reactor base materials, and use of non-metallic materials (e.g. SiC composites):
  - Self-passivating steels generally rely on formation of Al_2O_3 (e.g. Alumina-Forming Austenitic (AFA) steels)
  - Functionally-graded composites for optimal combination of a base metal with proven mechanical properties and a stable, corrosion-resistant outer layer (SiO_2 or Al_2O_3). Different deposition/cladding techniques result in different layer thicknesses and base-layer interface characteristics
- Considering irradiation, thermal and mechanical stresses, and the effect of the lead coolant on coating still requires an adequate qualification program

ALFRED: EU PROTOTYPE LFR DESIGN (1/2)



Power:	***300 MWth***
Primary cycle	***Atmospheric***
	400-480 °C
Secondary cycle	***1.8 Mpa***
	335-450 °C

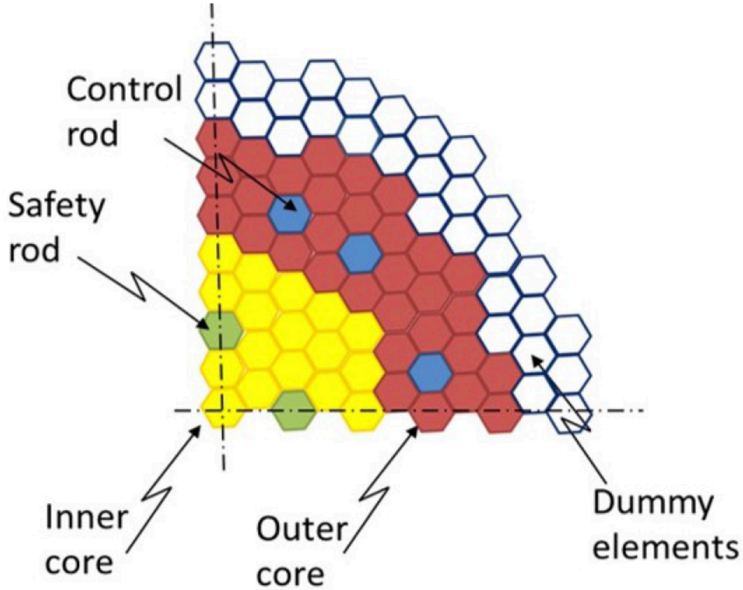


TOP VIEW

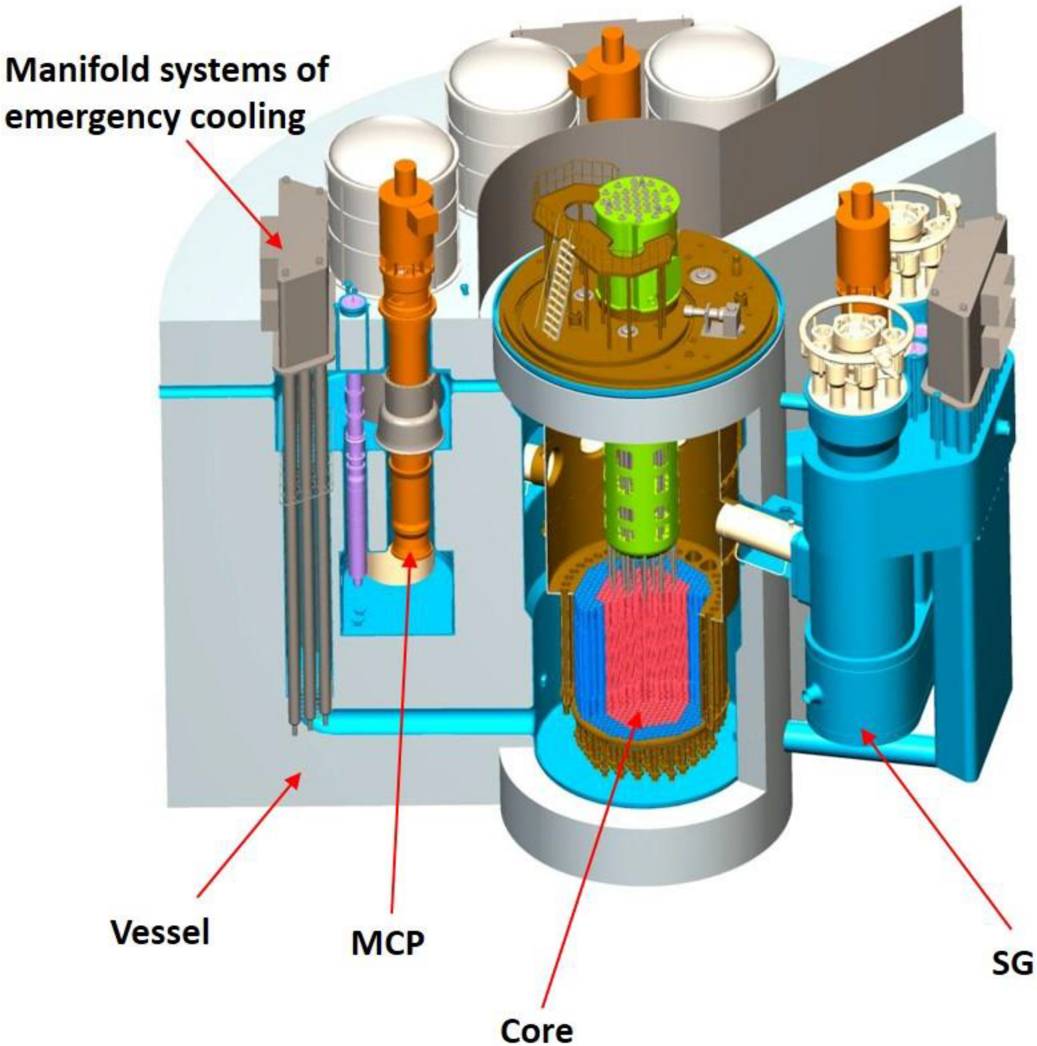
ALFRED: EU PROTOTYPE LFR DESIGN (2/2)

Primary system	Pool-type, compact
Coolant circulation Normal operation Accident conditions	 Forced (8 pumps) Natural (pressure drop 0.15 MPa)
Pressure	< 0.1 Mpa
Temparature	400-480°C
Flowrate	26 000 kg/s
Reactor vessel	Austenitic SS, hung
Safety vessel	Anchored to the pit
Inner vessel (Removable)	Cylindrical, Integral with the core support grid and the hot collectors
Steam generators	8, bayonet type with double walls,
Primary pumps	8, integrated with the SGs, in hot leg
Fuel assembly	Closed (with wrapper), Hexagonal, forced in position by springs
Control/Shutdown Systems	2 diverse and redundant systems concept derived from MYRRHA
Decay Heat Removal	2 separate and redundant systems of 4 Isolation Condensers connected to the Steam Generator (actively actuated, passively operated)
Refuelling System	No refuelling machine stored inside the Reactor Vessel

FA	171, hexagonal, wrapped
Inner	57 (21,7 at.%)
Outer	114 (27,8 at.%)
Dummy	108 (ZrO_2-Y_2O_3)
FA lattice	Triangular (127 pins)
Pins p/d	1,32
Cladding	15-15 Ti
Fuel	MOX, 25.77 at% (avg)
Residence	5 years

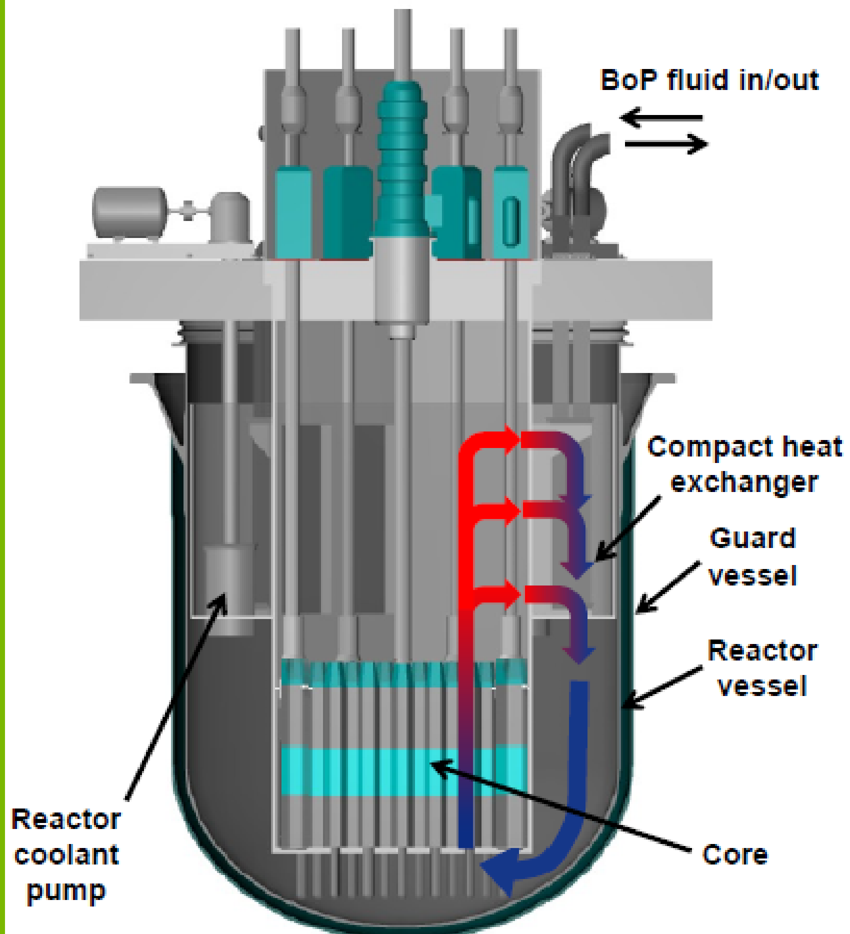


BREST-OD-300: RUSSIAN LFR PROTOTYPE



Coolant	Lead
Thermal Power	700 MW
Electric Power	300 MW
Number of loops	4
Inlet temperature	420^{o}C
Outlet temperature	535^{o}C
Fuel	U-Pu nitride
# of fuel assemblies	169 (no can)
Fuel charge	20.6t
Conversion efficiency	43.5%

WESTINGHOUSE LFR



Plant characteristics	
Electric power, MWe	~450 (Fleet) ~300 (Prototype)
Safety philosophy	Passive plant
RCS layout	Pool type
Intermediate circuit	None
Number of HX/RCP	6 / 6
Plant's efficiency	Up to ~50% (Fleet) 41-43% (Prototype)
Core Tin, °C	~420
Core Tout, °C	Up to 650 (Fleet) 530 (Prototype)
Balance of plant	Supercritical CO_2
Fuel	UN (Fleet) UO_2 (Prototype)

Some innovation relative to more traditional LFRs:

- Microchannel HX to compact the vessel and reduce likelihood and consequence of HX rupture
- High-performance materials pursued to increase operating temperature above 550°C
- Thermal energy storage for flexible operation

SAFETY APPROACH

Similar to SFR safety approach

- Plant states considered in the design include
  - AOOs that can be handled via non-safety grade systems (reactivity control system and BOP for heat sink) for prevention of operational failures and control of abnormal operation
  - DBA that are handled via safety grade systems (shutdown system and DHRS as a path to ultimate heat sink) for control of accidents within the design basis
  - BDBAs that are handled by inherent features or non-safety-grade “systems” for control of severe plant conditions, including prevention of accident progression and mitigation of its consequences
    - Inherent safety and/or passive reactivity reduction devices (plus an ultimate shutdown system that can be manually operated)
    - Diverse DHRS options such as flooding the reactor cavity with water
- Diversification and independence of design measures in different DiD levels
- Major thermal-fluid design parameters
  - Peak fuel centerline temperature, margin to fuel melting
  - Peak cladding temperature, margin to cladding failure
  - Peak coolant temperature, margin to creep and corrosion induced failures
  - Peak coolant velocity, to limit corrosion/erosion of SSCs important to safety

UNIQUE LFR ACCIDENTS

In addition to common LOF, LOHS, TOP, and station blackout

- Overcooling transient (usually on the secondary side) that may cause freezing
  - May be exacerbated by lead-oxide precipitation on cold surfaces (inlet or HX channels)
  - Open lattice core designs are more tolerant to coolant channel blockages (safe operation is predicted against postulated total instantaneous blockage of seven fuel assemblies in BREST)
- Steam generator (or HX) tube rupture in designs without intermediate loops
  - High pressure steam injection can pressurize the lead pool and cause steam entrainment through the core (although huge density difference between lead and steam results in significant buoyancy forces on the latter)
  - Consideration of mitigation measures that may include rupture disk and safety valves to limit maximum pressure
    - A rupture disk will likely bypass the vessel head, and even containment, to vent steam/cover gas/contaminated lead vapor (potentially via filters)
  - Although lead does not chemically react with BOP fluid (water, s-CO_2), physical interaction between hot lead and water needs to be fully understood
- Seismic events: Potentially greater sensitivity of the reactor vessel to seismic impact including the mechanical effects due to very heavy liquid-metal sloshing

REACTIVITY FEEDBACK MECHANISMS

- Doppler feedback: Lead (in comparison to sodium) hardens it, but oxide or nitride fuel forms softens the neutron spectrum
- Core radial expansion: Can still be a significant feedback mechanism due to enhanced leakage similar to an SFR
- Coolant density and void worth: Since lead does not moderate or absorb neutrons as much as sodium does, this feedback mechanism is more likely negative due to enhanced neutron leakage
- Fuel axial expansion and control rod drive line expansion are less minor contributors to negative reactivity at temperatures elevated above normal
  - For bottom inserted rod design, control rod drive line expansion effects would be quite different

PRACTICALLY ELIMINATED ACCIDENTS

Accidents that are not considered in design (no mitigation measure)

- 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)
- Removal of absorbing material
- Complete loss of DHR function or core uncovering due to primary coolant loss
  - Simultaneous rupture of the reactor vessel and the safety vessel should be demonstrated to be extremely unlikely with a high confidence level
- Failure of core and vessel support structures

WHAT TO LOOK FOR IN AN LFR REVIEW? (1/2)

- Common features with SFRs:
  - Design should employ a guard vessel to keep the core covered and decay heat removal capability maintained
  - Reactivity control and shutdown systems should have sufficient reactivity to secure a safe shutdown from the most reactive core state assuming failure of the highest-worth control assembly
  - Decay heat removal system should have sufficient capacity to avoid fuel failures and assure integrity of coolant boundary
  - Core vs. SG elevation difference should facilitate natural circulation
  - Diversification and independence of design measures in different DiD levels
    - Unlike SFRs, water is an option in extreme emergencies in level 4/5
- Strong prevention and mitigation measures against SG tube ruptures—if SG is inside the reactor vessel (no intermediate loop)
  - Consideration of double-wall SG tubes and monitoring system to detect leaks
  - Pressure suppression system
  - Rupture disk (a potential containment bypass?)
- Robust in-service inspection and surveillance plan (a challenge due to opaqueness of lead and high-temperatures)

WHAT TO LOOK FOR IN AN LFR REVIEW? (2/2)

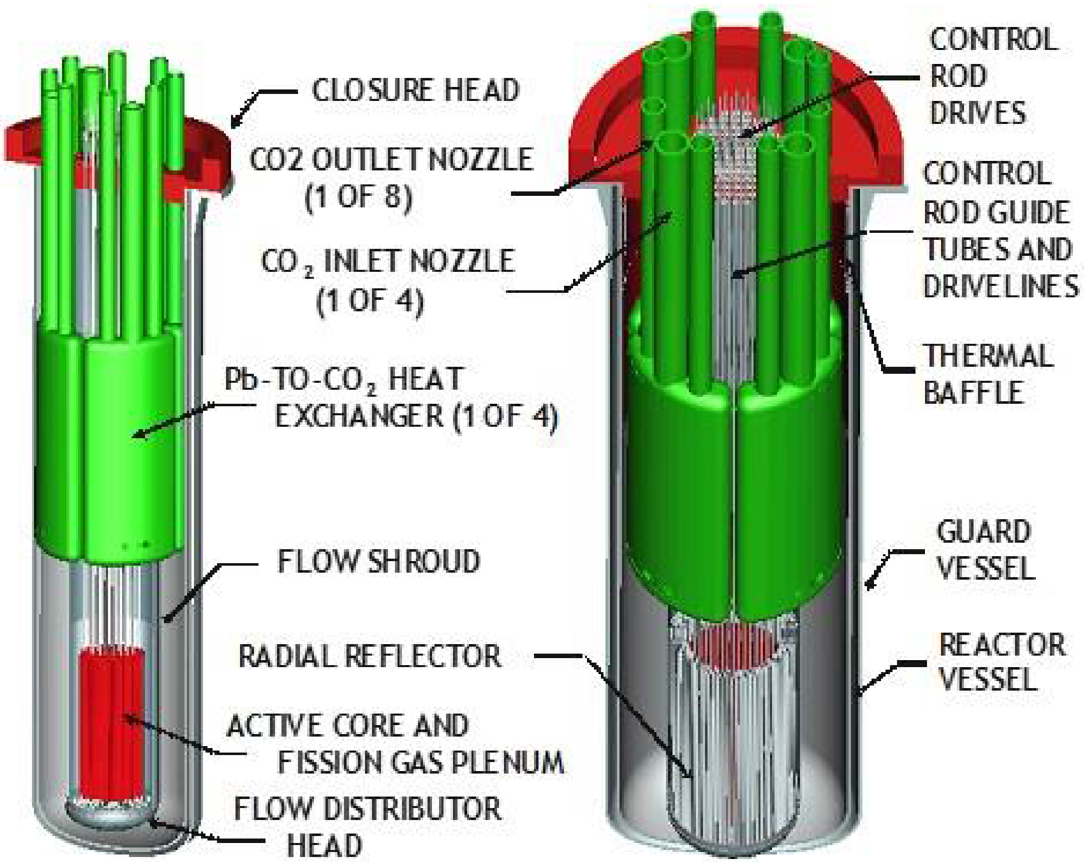
- Prevention/mitigation measures against coolant freezing that could result in formation of blockage and potentially challenge decay heat removal function
  - Reliable monitoring of coolant temperature and flow rate
  - Control of heat transfer conditions at the secondary side to prevent excessive cooling and accidental coolant freezing
  - Ad-hoc system (e.g., heaters) to keep coolant liquid with sufficient margin, or melt after a freezing, when decay heat alone is not sufficient
  - Consideration of cases with and without the heat load from the spent fuel stored in-vessel in accident analyses
- Active/passive system interference:
  - Coolant can freeze if both SG and DHRS are functional at decay heat levels (although time to freeze may be very long in some cases)
  - Depending on the design, passive reactivity reduction devices, if relied on, may not be effective when pumps are running
- Monitoring and control systems for coolant purity to avoid accumulation of oxygen and corrosion products
- Mechanisms to prevent the fuel assemblies from floating up
- Seismic isolators and/or anti-sloshing devices to suppress the sloshing effects

ONGOING R&D SUPPORT FOR DEPLOYMENT

- Development and qualification of new corrosion/erosion resistant materials (including surface modifications) to increase operating temperatures
- LFR-specific coolant chemistry, oxygen control, and purification technologies
- Phenomenology of lead-water/steam interactions to analyze consequences of SG tube ruptures
- Qualification of nitride fuel forms
- Fuel-coolant thermodynamic and chemical interactions, behavior of dispersed fuel
- Retention of fission and activation products in heavy liquid metal
- Seismic isolation and prevention/mitigation of sloshing
- Innovative technologies for ISI&R and fuel/component handling
- Effect of lead freezing on adjacent structures
- Development of codes and standards for design of structures and mechanical components considering their compatibility with lead and other environmental effects

BACKUP PAGES

U.S. NUCLEAR BATTERY CONCEPT: SSTAR



Coolant	Lead
Fuel	Metal/Nitride
Power	10-100 MWe
Core life	30 years
Circulation	Natural conv.
Inlet temp.	420^{o}C
Outlet temp.	567^{o}C
Power conversion	Brayton cycle
Conversion efficiency	44%

Sealed unit, manufactured in a facility and transported to the site, autonomous fully passive operations with load following capability