The Lead-cooled Fast Reactor:
Status Report for 2012 GIF Symposium

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Overview of Presentation

- Overview and historical backdrop of LFR development
- The present status of GIF-LFR-PSSC
- Summary of three reference LFR systems
- Advantages and challenges facing LFR development
- Some considerations in light of the Fukushima event
- Future demonstration activities: MYRRHA, ALFRED, BREST et al.

Overview of LFR Technology

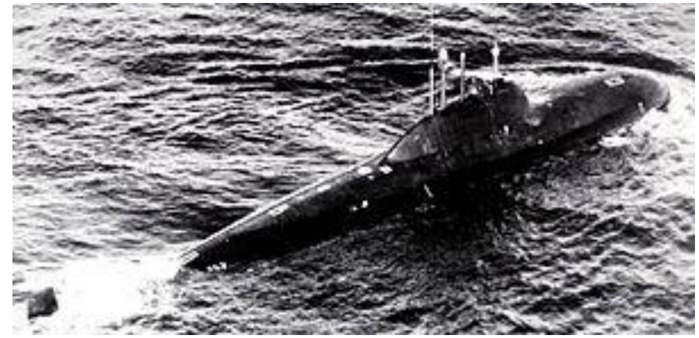
- The LFR is a reactor technology characterized by a fast neutron spectrum; a liquid coolant with a very high margin to boiling and benign interaction with air or water; and design features that capitalize on these features.
- LFR concepts offer substantial potential in terms of safety, simplification, proliferation resistance and the resulting system performance. Key is the potential for benign end state to severe accidents.
- However, certain drawbacks must be overcome, including the need for coolant chemical (oxygen) control, prevention of corrosion by materials selection and design features, seismic/structural issues and in-service inspection (ISI).

Lead as a primary coolant: some safety and design simplification considerations

- No exothermic reaction between lead and water or air ➔ elimination of intermediate circuit ➔reduced footprint, complexity and overall cost.
- High boiling point of lead (1749°C) ➔ eliminates risk of core voiding due to coolant boiling.
- High density of lead ➔fuel dispersion instead of compaction in case of core destruction.
- High heat of vaporization of lead ➔ low primary system pressure ➔ reduced reactor vessel thickness.
- High thermal capacity ➔ significant grace time in case of loss-of- heat-sink.
- Lead retains iodine and cesium at temperatures up to 600°C ➔ reduces source term in case of volatile fission products release.
- Lead density ➔ shields gamma-rays effectively.
- High thermal exchange ➔ some components (e.g., Steam Generators) can have innovative and compact design and can be placed in the hot leg allowing a simple flow path design.
- Low moderation of lead ➔ greater spacing between fuel pins ➔ low core pressure drop and reduced risk of flow blockage.
- Simple coolant flow path and low core pressure drop ➔ natural convection cooling in the primary system for shutdown heat removal

International Activities in LFR R/D

Russia - Mid 1960's to present



- 4 reactors (73MWt) in prototype submarines
- 7 “Alpha Class” subs (155 MWt)
  + 1 replaced reactor
- 15 reactors total, including 3 on shore reactors
- ~80 reactor-years experience
- Accelerator Driven Subcritical (ADS) reactors
- Reactor systems (BREST; SVBR), GIF MOU

Europe - 2000 to present

- ADS efforts (EFIT, MYRRHA)
- Numerous experimental initiatives using Lead and Pb-Bi
- European Lead-cooled System (ELSY➔ELFR), ALFRED and MYRRHA, GIF MOU

Asia - 2000 to present

- Japanese LFR design work (LSPR, PBWFR, JAEA Fuel Cycle Study, Pb-Bi-cooled 4-S, CANDLE)
- Korean LFR design work (PEACER, BORIS)
- GIF MOU (Japan)

U.S. Programs - 1997 to present

- LANL, ANL and UNLV – Lead corrosion and thermal-hydraulics testing
- UC-B Encapsulated Nuclear Heat Source (ENHS) and related studies
- Small, Secure Transportable Autonomous Reactor (STAR-SSTAR)
- MIT - alloy studies to mitigate corrosion; GenIV Energy, SUPERSTAR; E-SSTAR

LFR Compliance with Generation IV Goals

Generation IV Goal Areas	Goals for Generation IV Energy Systems	Goals Achievable via	
		Ineherent features of lead	Specific Engineered Solutions
Sustainability	Resource utilization	• Low moderating medium • Low neutron absorption • Core with fast neutron spectrum also with large coolant fraction	• Conversion ratio close to 1 (without radial blanket)
	Waste minimization and management		• Flexibility in fuel loading, homogeneous dilution of MA in the fuel
Economics	Life cycle cost	• Does not react with water • Does not burn in air • Very low vapour pressure • Not expensive	• Reactor pool configuration • No intermediate loops • Compact primary system • Simple internals design • High efficiency
	Risk to capital (Investment protection)		• Small reactor size and/or • in-vessel replaceable components

LFR Compliance with Generation IV Goals

Generation IV Goal Areas	Goals for Generation IV Energy Systems	Goals Achievable via Ineherent features of lead	Goals Achievable via Specific Engineered Solutions
Safety and Reliability	Operations excel in safety and reliability	• Very high boiling point • Low vapour pressure • High γ shielding capability • Fuel compatibility and fission product retention	• Atmospheric pressure primary • Low coolant ΔT between core inlet and outlet.
	Low likelihood and degree of core damage	• Good heat transfer • High specific heat • High expansion coefficient	• Large fuel pin pitch • High Natural circulation • Decay Heat Removal coolers in cold collector • Negative reactivity feedback
	No need for offsite emergency response	• Density close to that of fuel (reduced risk of re-criticality accidents) • Fission products retention	• Requirements on fuel porosity/density
Proliferation Resistance and Physical Protection	Unattractive route for diversion of weapon-usable material		• Small system, sealed, long-life core and/or • Fuels with MA increase Proliferation Resistance

Current Status with regard to LFR PSSC

- Provisional System Steering Committee (PSSC) was formed in 2005
  - Members included EU, US, Japan and Korea
  - Prepared initial draft LFR System Research Plan (LFR-SRP)
  - Systems included a large central station design (ELSY) and a small transportable system (SSTAR)
- In 2010, an MOU was signed between EU and Japan causing a reformulation of the PSSC
- In 2011, the Russian Federation added its signature to the MOU
- In April, 2012, the reformulated PSSC met in Pisa and began the process of revising the LFR-SRP
  - Members are signatories of the MOU: EU, Japan and Russia
  - US invited to participate as observer
- The new PSSC envisions various updates to the central station and small reactor thrusts while adding a mid-size LFR (e.g., the BREST-300) as a new thrust in the SRP

Current Activities of the LFR-PSSC

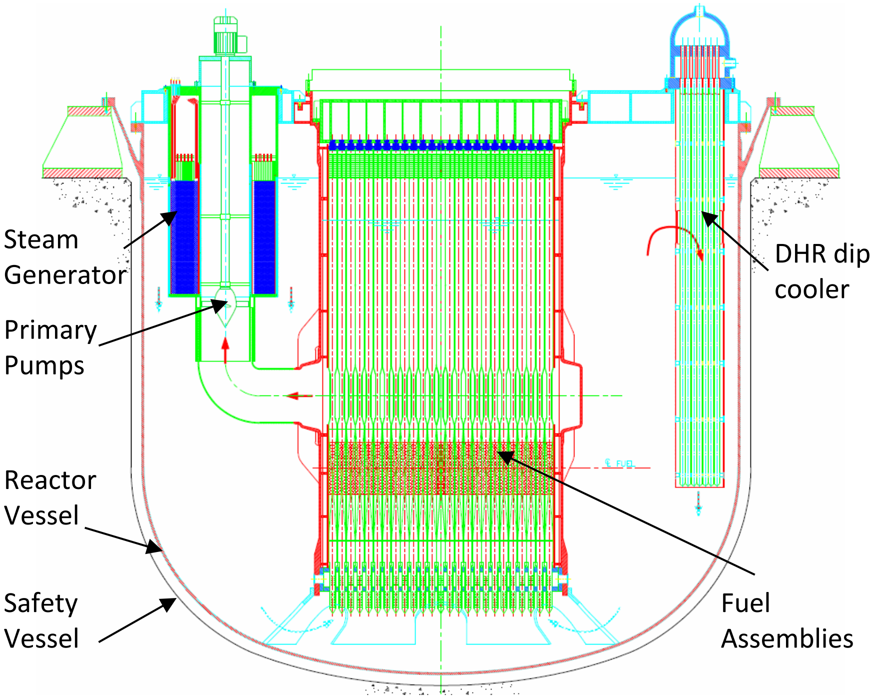
- The new PSSC met in Pisa, Italy in April, 2012
  - Representatives present from EU, Japan and Russian Federation
  - Additional participants from US and OECD/NEA
  - Actions included:
    - ✓Decision to expand the initiative to three thrusts (large, medium and small LFRs)
    - ✓Agreement to prepare PSSC position paper describing the basic advantages and remaining research challenges of the LFR
    - ✓Invitation to US representative to continue in observer status
    - ✓Initiation of a significant revision to the SRP to be completed in 2012

- Follow-on meeting of the PSSC : November, 2012 in Tokyo, Japan

- System designs representing the three thrusts are the following:
  - The European Lead-cooled Fast Reactor (ELFR) for the large, central station plant
  - The BREST-OD-300 for the medium size plant
  - The Small Secure Transportable Autonomous Reactor (SSTAR) for the small system

The European Lead-cooled Fast Reactor ELFR

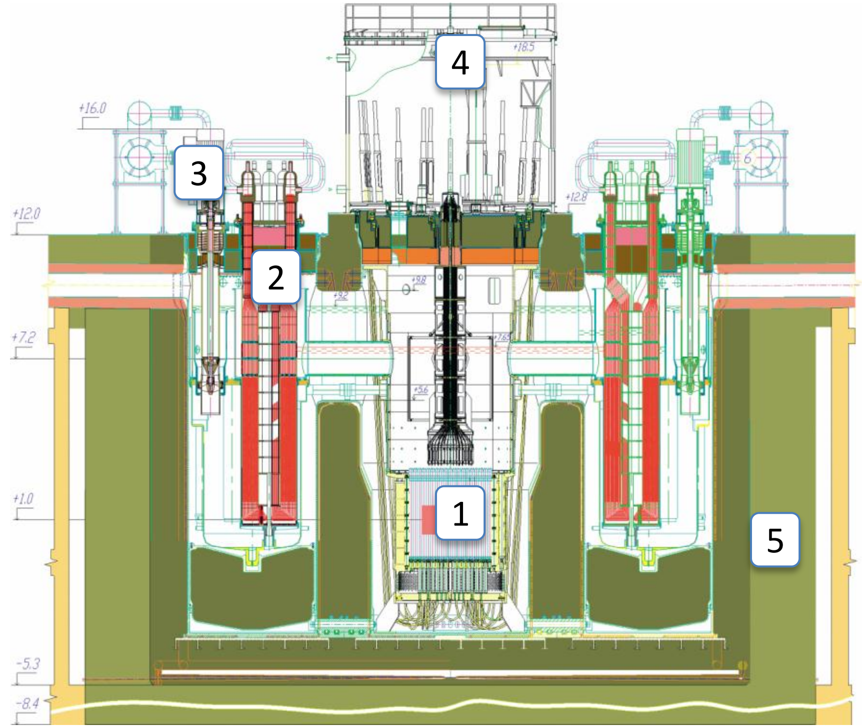
- Power: 1500 MW(th), 600 MW(e)
- Core diameter, 4.5 m
- Core height, 1.4 m
- Core fuel MOX (first load)
- Coolant temp., 400/480ºC
- Maximum cladding temp., 550ºC
- Efficiency: ~42%
- Core breeding ratio (CBR) ~ 1



Notable attributes include extended fuel assemblies, integrated pump/steam generators and decay heat removal by secondary side isolation condensers plus dip coolers

The BREST-OD-300 Russian Lead-cooled Reactor

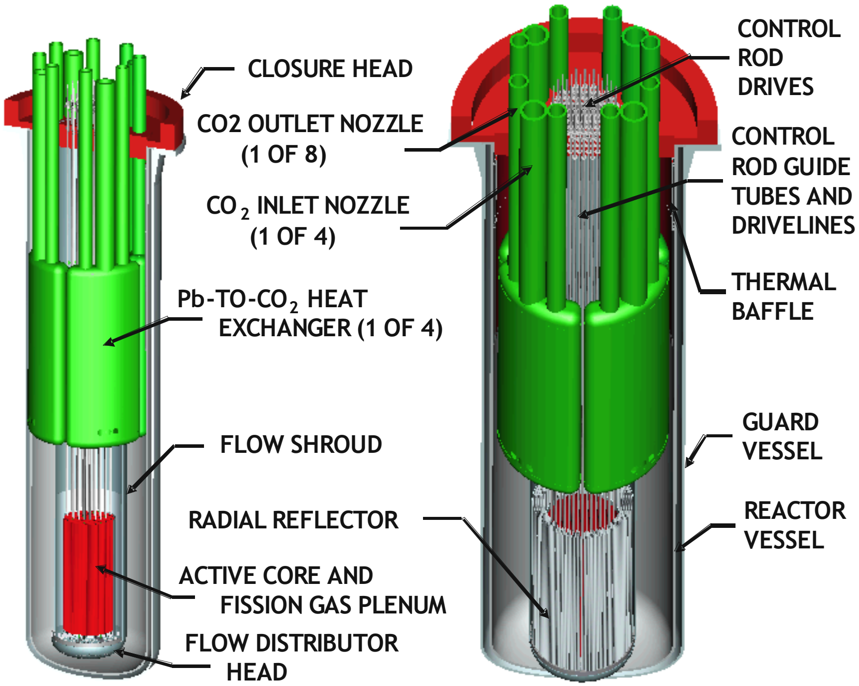
- Power: 700 MW(th), 300 MW(e)
- Core diameter, 2.6 m
- Core height, 1.1 m
- Core fuel UN + PuN
- Coolant temp., 420/540^{o}C
- Maximum cladding temp., 650^{o}C
- Efficiency: 43-44%
- Core breeding ratio (CBR) ~ 1



1 Core, 2 steam generator, 3 Pump, 4 refueling machine, 5 Reactor Vault

Notable attributes include concrete Reactor Vault, fuel reprocessing in dedicated building integrated with the plant

The Small Secure Transportable Autonomous Reactor (SSTAR)



- Power: 45 MWt/20 MWe
- Fuel: Nitride enriched in N_{15}
- Coolant temp., 420/567°C
- Maximum cladding temp., 650°C
- Power conversion: S-CO_2 Brayton cycle
- Efficiency: 44%
- Core life: 15-30 years
- Core breeding ratio (CBR) ~ 1

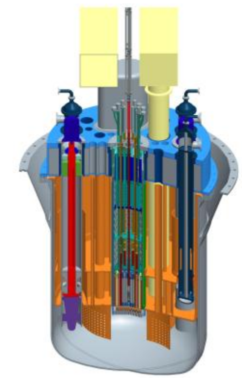
Notable attributes include advanced power conversion system, use of natural convection cooling and a long-life core in a small, modular system.

Several major test and demo activities are planned

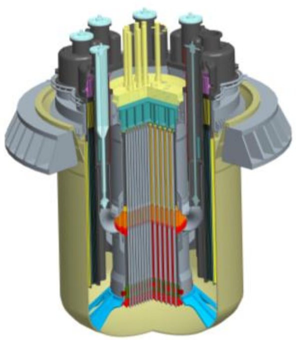
- GUINEVERE
  - Experimental ADS facility for subcritical and critical near-zero Power test in operation in Mol Belgium since February 2011
- MYRRHA
  - Multipurpose Flexible Irradiation facility operating in critical and subcritical mode foreseen in operation in Mol Belgium in 2025
- ALFRED
  - Lead Fast Reactor Demonstrator Plant foreseen in operation in 2025 (Romania has officially asked to host the ALFRED)
- ELECTRA
  - Proposed LBE-cooled 1 MW reactor to be installed in Swede funding level 165 Meuros;
- BREST
  - Lead-cooled Fast Reactor foreseen in operation in Russia in 2020

GUINEVERE

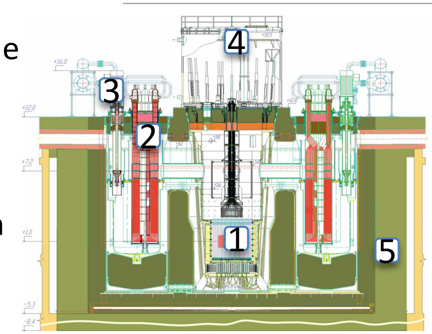
MYRRHA



ALFRED



ELECTRA



BREST

LFR Infrastructure in Europe

34 Experimental Facilities are in Operation or under Construction in 10 European Research Institutions

1 ATHENA (Advanced Thermal Hydraulic Experiment for Nuclear Application)
2 CICLAD (Corrosion Induced by the Circulation of a LeAD alloy)
3 CIRCE (Circolazione Eutettico)
4 COLONRI I & II (Convectional Loop)
5 CALLISTO (Static LM embrittlement)
6 COMPLOT (COMPonent Loop Tests)
7 CORELLA (Corrosion Erosion Test Facility for Liquid Lead Alloy)
8 CORRIDA (Corrosion in Dynamic Alloys)
9 COSTA (Corrosion test stand for stagnant liquid lead alloys)
10 CRAFT (Corrosion Research for Advanced Fast reactor Technologies)
11 CRISLA (Creep-to-Rupture Tests in Stagnant Lead Alloys)
12 ELEFANT (Experimental LEad FAcility for Neutron production Targets)
13 E-SCAPE (European SCAled Pool Experiment)
14 FRETHME (Fretting Tests in Heavy Liquid Metal)
15 HELENA (Heavy Liquid Metal Loop for small components testing)
16 HELIOS3 (Heavy Liquid Oxygen conditioning System 3)
17 KALLSTARR (KALLA Steam Generator Tube Ruprture Facility)
18 LECOR (Lead Corrosion)
19 LEVUSE (LBE Vessel for UltraSonic Experiments)
20 LIFUS 5 (Heavy liquid metals interaction with water)
21 LIMETS1 (Liquid Metal Embrittlement Testing Station 1)
22 LIMETS2 (Liquid Metal Embrittlement Testing Station 2)
23 LIMETS 3 (Liquid Metal Test Facility)
24 LINCE (forced convection loop)
25 LISOR Lead-Bismuth Loop
26 NACIE (Natural Circulation Experiment)
27 OSCAR (Oxygen Sensor Calibration Rig)
28 RHAPTER (Remote HAndling Proof of principle Test Experimental Rig)
29 SCC at JRC (Lead loop for SCC testing at JRC-IE, Petten)
30 SLEEVE (Small Lead Bismuth Eutectic Evaporation experiment)
31 STELLA (Standard Technology Loop for Lead Alloy)
32 TALL (Thermal-hydraulic ADS Lead-bismuth Loop)
33 TELEMAT (Test Loop for Lead Material testing)
34 THEADES (Thermal-hydraulics and ADS Design)

Research challenges remain

Research challenges remain due to: the high melting point of lead; its opacity; coolant mass; and potential for corrosion when the coolant is in contact with structural steels.

- The high melting temperature of lead (327°C) requires that the primary coolant system be maintained at temperatures to prevent the solidification of the lead coolant. This presents design as well as engineering challenges during the operation and maintenance.

- The opacity of lead, in combination with its high melting temperature, presents challenges related to inspection and monitoring of reactor in-core components as well as fuel handling.

- The high density and corresponding high mass of lead require careful consideration of structural and seismic design.

- Significant challenges result from the phenomenon of lead corrosion of structural steels at high temperatures and flow rates. These phenomena require careful material selection and component and system monitoring during plant operations.

LFR and EXTREME NATURAL EVENTS

Response to earthquakes enhanced ➔ adoption of seismic isolation

Decay Heat Removal (DHR) Systems independent, redundant, diverse, and passive. Only actuation (through valve alignment) is active, using local stored energy ➔ <u>Station Blackout does not present a threat; any initiating event is managed without AC power.</u>

Even in the case of Station Blackout without DHR systems available, safety analyses demonstrated that fuel and cladding temperatures do not reach critical levels.

Complete core melt is extremely unlikely due to favorable intrinsic lead characteristics: high thermal inertia, very high boiling point, higher coolant density than oxide fuel resulting in fuel dispersion as opposed to compaction.

In the very unlikely event of an extreme Fukushima-like scenario (or beyond) leading to the loss of all heat sinks (both DHR and secondary systems), the heat can still be removed by injecting water in the reactor cavity between the reactor and safety vessels, while in case of reactor vessel breach the decay heat can still be removed by using this system to cool the concrete of the cavity walls.

From ICAPP 2011, Paper 11465

Effect of Potential Energy Stored in Reactor Facility Coolant on NPP Safety and Economic Parameters

G.I. Toshinsky, O.G. Komlev, I.V. Tormyshev

STORED POTENTIAL ENERGY FOR DIFFERENT COOLANTS

Coolant	Water	Sodium	Lead, Lead-bismuth
Parameters	P = 16 MPa T = 300 ºC	T = 500 ºC	T = 500 ºC
Maximal potential energy, GJ/m^3, *including:*	~ 21,9	~ 10	~ 1,09
Thermal energy / *including* compression potential energy	~ 0,90 / ~ 0,15	~ 0,6 / None	~ 1,09 / None
Potential chemical energy of interaction	With zirconium ~ 11,4	With water 5,1 With air 9,3	None
Potential chemical energy of interaction of released hydrogen with air	~ 9,6	~ 4,3	None

Some final comments

- Lead- and LBE-cooled systems offer great promise in terms of fast reactor plant simplification and performance
- The Russian experience demonstrates that the LFR can be produced and operated on an industrial scale
- Some important areas for R&D include:
  - Completion of designs
  - Testing of special materials for use in lead environment
  - Fuel studies including recycle
  - Special studies (seismic; sloshing; LBE dust/slag formation)
  - Evaluation of long term radioactive residues from fuel and system activation
  - Technology pilot plant/Demo activities
- In the post-Fukushima environment, the unique safety potential of the LFR should be recognized