Lead-cooled Fast SMR's: (S)STAR, ENHS and ELSY

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Presentation Outline

- Historical Background (STAR, ENHS, SSTAR, ELSY)
- Virtues and drawbacks of lead (or Lead-Bismuth alloy, LBE) as a reactor coolant
- Technology overview of selected LFRs
- International interactions/directions

Historical background: International Activities in Lead/PbBi Small Reactors

Russia - Mid 1960's to 1990

- Built and operated 7 "Alpha Class" Submarines (~70-140 Mwe)
- Built 2 on shore prototypes
- 80 reactor-years experience
- Ongoing work on ADS systems and new reactor designs (BREST; SVBR-75/100)
- Possible collaboration with Europeans on ELSY

Europe (Germany, Sweden, Italy, etc.) and Asia (Japan, Korea) - 2000 to Date

- Numerous experimental test loops using Lead and lead--Bismuth
- Toshiba concept of a Pb-Bi cooled 4-S reactor
- Korean design work
- Ongoing ADS systems
- European Lead-cooled System (ELSY)

U.S. Programs - 1996 to Date

- LLNL Study on small proliferation resistant systems
- Los Alamos National Laboratory - Delta Loop Full Operation in FY 2003; corrosion testing
- MIT - alloy studies to mitigate corrosion
- STAR-SSTAR

Historical background: US efforts in Lead/PbBi systems

- 1996 – LLNL initiative to identify a nuclear power concept that would be highly proliferation resistant and user-friendly; suitable for developing countries: STAR (Secure, Transportable, Autonomous Reactor)
- 1997- 98 – UCB & LLNL study on Pb-Bi cooled variants of the CRIEPI-TOSHIBA 4S (Super-Safe, Small, and Simple) concept
- 1998 – LLNL assembled a team with ANL, LANL, UCB, Texas A&M and Westinghouse to develop STAR (Secure Transportable Autonomous Reactor) concepts. Ultimately this effort resulted in 12 proposals to the initial NERI program
- 1999 – NERI contracts awarded for several STAR projects, including STAR-LW, STAR-LM and ENHS. Lasted for 3 years (to 2002)
- 2002 –SSTAR selected as the US concept for the GEN-IV LFR category of reactors. (SSTAR was the only early concept intentionally designed as a small system)
- Coordinated GIF-LFR PSSC research plan for SSTAR and European Lead-cooled System (ELSY)

The STAR concept represents a novel approach to proliferation resistance

- Sealed core: no on-site refueling
- Transportability: entire core and reactor vessel remain as a unit
- Long-life Core: 30 year core life is a target
- Simple integrated controls: minimum operator intervention or maintenance required
- Local and remote observability
- Minimum industrial infrastructure required in host location
- Very small operational (and security) footprint

Some Basic Characteristics of Liquid Metal Coolants

Coolant	Melting Chemical Point Reactivity (°C)	(°C)	Boiling Point (w/Air and Water)
Lead-Bismuth (Pb-Bi)	125	1670	Inert
Lead (Pb) 327	1737 Inert		
Sodium (Na) 98 883 Highly	Reactive		

Lead/LBE Coolants Provide Promising Overall Characteristics While Sodium Coolant Technology is More Difficult but Better Understood

Properties of lead coolant suggest that the LFR can very safe and economically competitive.

	(a) ***High atomic mass***	*(b)* ***Low chemical reactivity***	*(c)* ***High boiling point***	*(d)* ***Retention of fission fragments***	*(e)* ***High density***
Effects on reactor design.	**Low moderating medium**	**No chemical reaction with water or air** **No fire in case of lead leakage**	**No pressurization of the primary system.** **Low contamination of the cover gas.**	**Volatile contaminants retention in case of core damage**	**Minimum/no risk of core compaction**
Potential design features	**Flexibility in fuel loading including MA.** **Sealed, long-life core.** **Large fuel rod pitch:** **- Low core pressure loss** **- Open fuel element**	**No intermediate loop.** **Elimination of reactive or flammable coolant materials in the plant**	**Reactor pool configuration.** **Simplification of the refueling system** **Simplification of the containment system.**		**Core cooling and containment function preserved in case of core melt**

Notes:

1- Core pressure loss can be limited to about one bar in spite of high lead density.

2- Open fuel elements reduce the chance of fuel melt accidents resulting from inlet coolant flow blockage as occurred in October 1966 at the Fermi 1 plant.

Technological development and design provisions are necessary to alleviate the impact of drawbacks.

Lead drawbacks	*(f)* *High Density*	*(g), (h)* *Opacity and High Melting Point*		***(i)*** *Corrosion of structural materials*	*(l)* *Issues of lead technology*
	Increased mechanical loads	Refueling made difficult	ISI&R made difficult	Available structural materials not adequate	Slag formation, Dust formation; Activation.
Proposed solutions	Compactness *(needed also for economics)*	Refueling machine operating in the gas above the coolant	Reduced need of ISI&R. Components replaceable	**Low operating temperature.** **New materials** **Corrosion protection of structural materials**	Use of pure lead

Status of activities performed in European projects to alleviate the impact of drawbacks.

Lead drawbacks	*High Density*	*Opacity and High Melting Point*		*Corrosion of structural materials*	*Issues of lead Technology*
	Increased mechanical loads	Refueling made difficult	ISI&R made difficult	Available structural materials not adequate	Slag formation. Dust formation. Activation.
Proposed solutions	*Compactness (needed also for economics)*	Refueling machine operating in gas.	*Reduced need of ISI&R in lead* *Replaceable components*	*Low operating temperature. New materials. Corrosion protection of structural materials*	Use of pure lead
Preliminary status	*Solved*	*Solved*	*Components (e.g., SG) can be removed for inspection. In the long term progress is necessary.*	*Additional progress is necessary.* *Potential critical issue of LFR*	*Advantages of pure lead not yet sufficiently assessed*

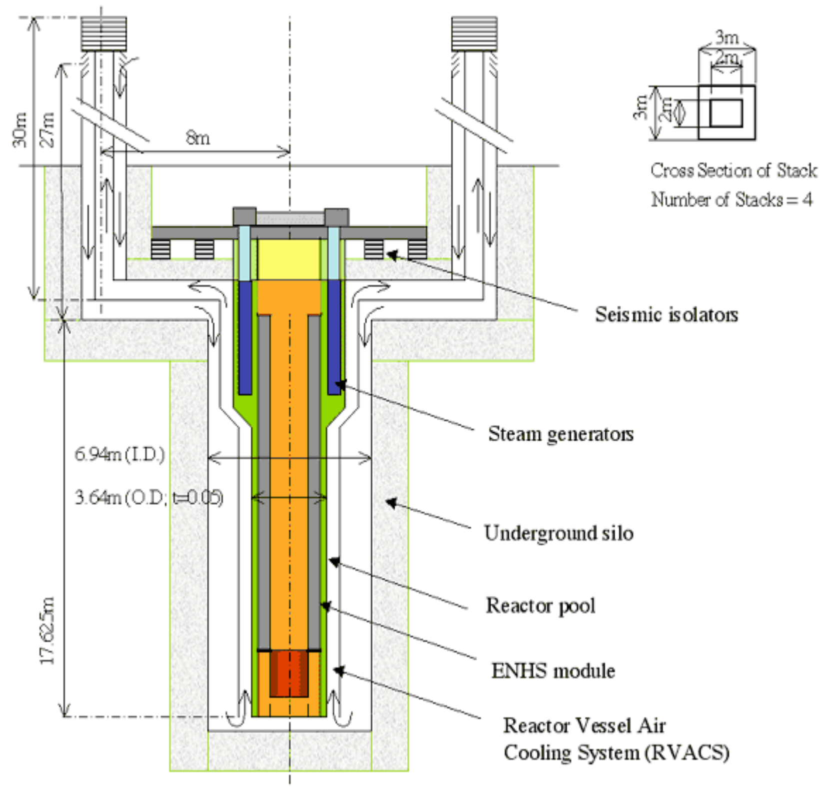
Pros (+) and cons (-) of pure lead vs LBE

Melting Point (°C)	Pb has a higher (327 °C) melting point than LBE (125 °C)	-
Melting expansion	Pb has a higher volume increase upon melting	-
Expansion at solid state	Pb does not expand at solid state	+
Boiling Point (°C)	Pb has a slightly higher (1737 °C) boiling point than LBE (1670 °C)	+
Thermal conductivity	Pb has a higher thermal conductivity (17,7 W $m^{-1}K^{-1}$) than LBE (14,3 W $m^{-1}K^{-1}$), (data at 500 °C)	+
Slag formation	First tests do not show slag formation in Pb	+
Dust formation	Strongly reduced	+
Polonium generaton	Reduced by about four decades	+
Long term Radiotoxicity (Inalation)	Reduced by about four decades	+
Long term Radiotoxicity (Ingestion)	Reduced by about three decades	+
Use of radiogenic lead	Several neutronic advantages (Availability and cost to be evaluated)	+
Availability	Pb is largely available	+
Cost (°C)	Pb is cheap	+

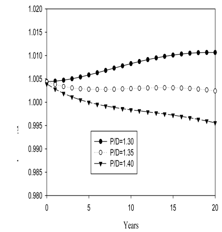
The STAR-ENHS (Encapsulated Nuclear Heat Source) concept was developed by a UC Berkeley-Led Team

- 3-year NERI study with UCB, ANL, Westinghouse, LLNL, KAIST and CRIEPI completed in FY02
- Evolutionary concept developed from CRIEPI-Toshiba 4S reactor
- Natural circulation cooling
- Reactor core heat transferred from primary to secondary Pb-Bi through capsule wall
- Fuel contained in capsule throughout fuel cycle
- Engineering feasibility demonstrated but economic feasibility is uncertain

Schematic vertical cut through the ENHS reactor

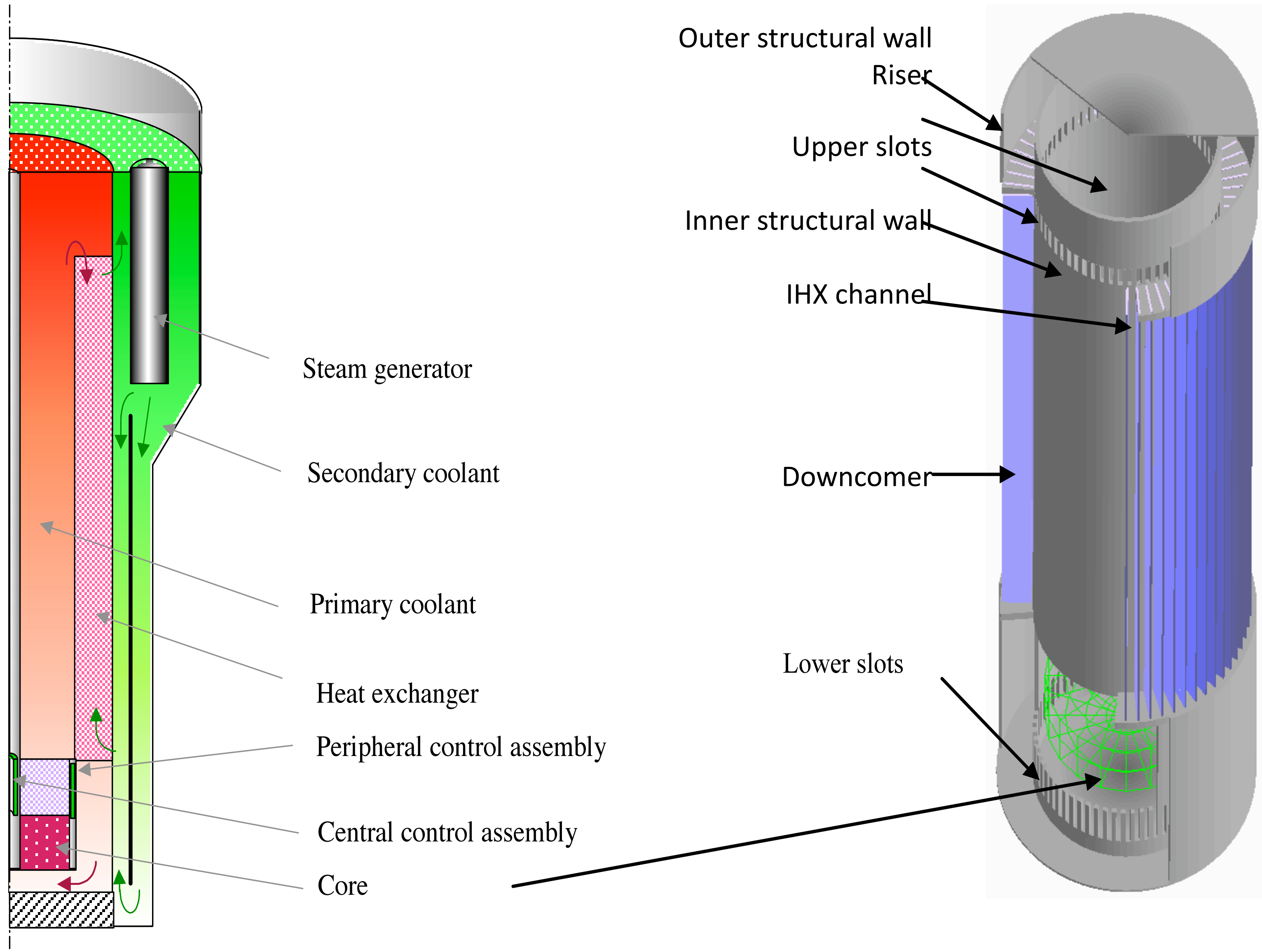


ENHS reactor design approach



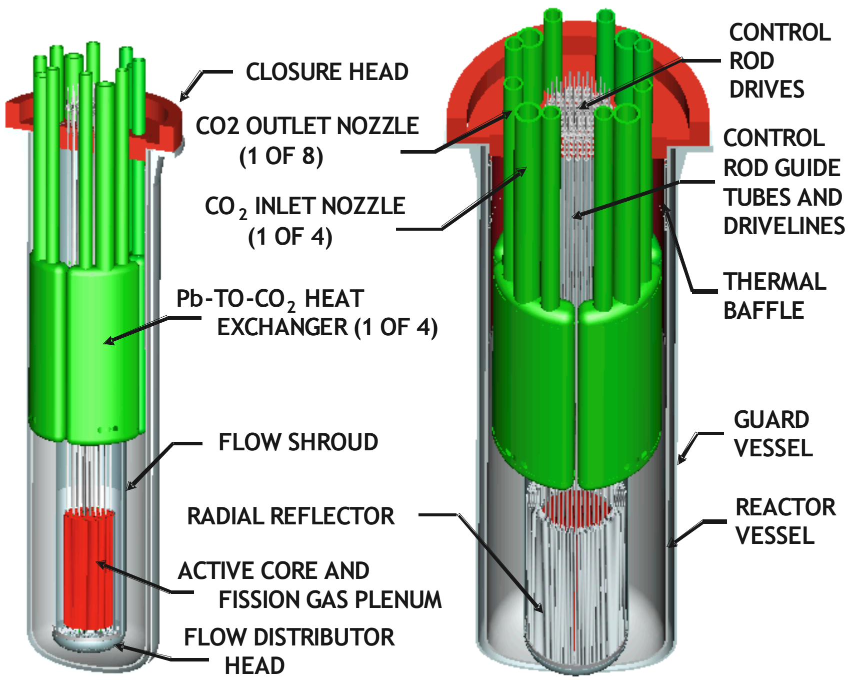
- Nearly no change in k_{eff} over 20 years (EFPY) by designing core to have breeding ratio = 1+ ε
- Full power heat removal by natural circulation
- No mechanical connections between ENHS module and the energy conversion system
- No fuel handling on site (in host country)
- No access to neutrons

Schematic view of the ENHS Module and pool



ENHS Module

The Small Secure Transportable Autonomous Reactor (SSTAR)



SSTAR is a small natural circulation fast reactor of 20 MWe/45 MWt, that can be scaled up to 180 MWe/400 MWt.

The compact active core is removed by the supplier as a single cassette and replaced by a fresh core.

Key technical attributes include the use of lead (Pb) as coolant and a long-life sealed core in a small, modular system.

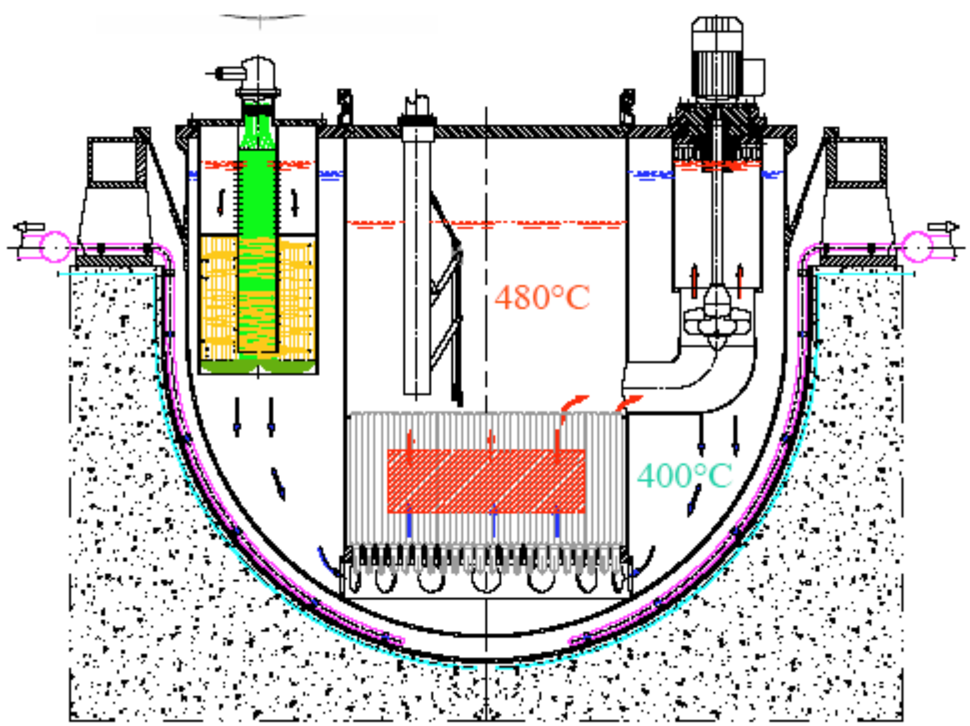
SSTAR Reactor Core Parameters

Coolant	Lead
Fuel	Transuranic Nitride, Enriched in N_{15}
Enrichment, %	5 Radial Zones, TRU/HM 1.7/3.5/ 17.2/19.0/20.7
Core Lifetime, years	30
Core Inlet/Outlet Temperature, ºC	420/567
Coolant circulation	Natural convection
Average (Peak) Discharge Burnup, MWd/Kg HM	81(131)

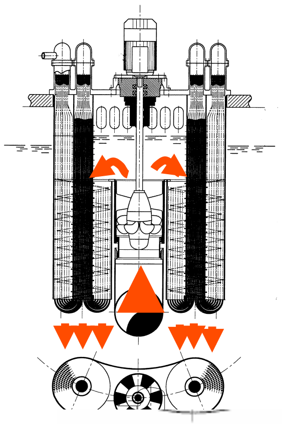
Peak Fuel Temperature, ºC	841
Peak Cladding Temperature, ºC	650
Fuel Pin Diameter, Cm	2.50
Fuel/Coolant Volume Fractions	0.45/0.35
Active Core Dimensions, Height/ Diameter, m	0.976/1.22
Power conversion	S-CO_2 Brayton cycle

ELSY (European Lead-colled System) is a 600 MWe LFR

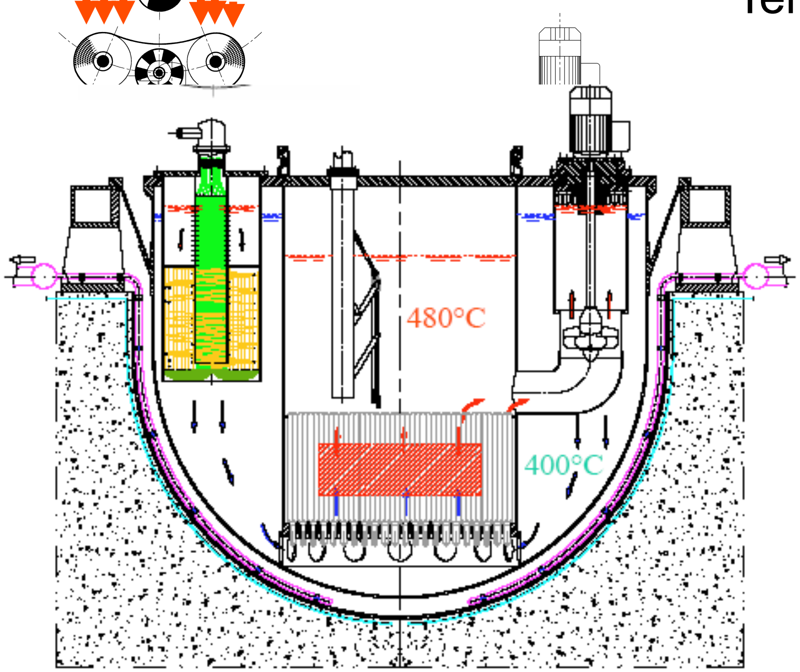
- *Project funded at 7M Euro level, supported by EC and national programs*
- *Pure Lead coolant*
- *Forced cooling*
- *Small temperature rise across the core*
- *Integral steam generators and pumps*
- *Substantial simplification in contrast with other LM reactors*

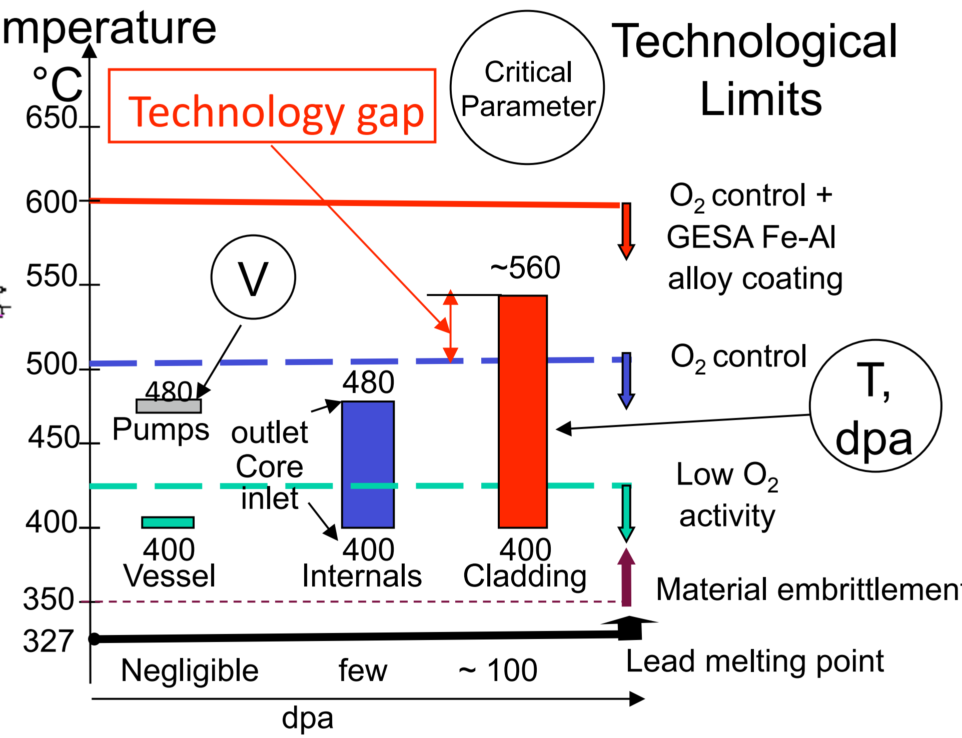


ELSY applies innovation in thermal cycle and materials to address corrosion issues



- ✓ Low-temperature thermal cycle to limit corrosion
- ✓ Use of aluminization of fuel cladding and SG tubes
- ✓ New material for pumps (MAXTHAL)

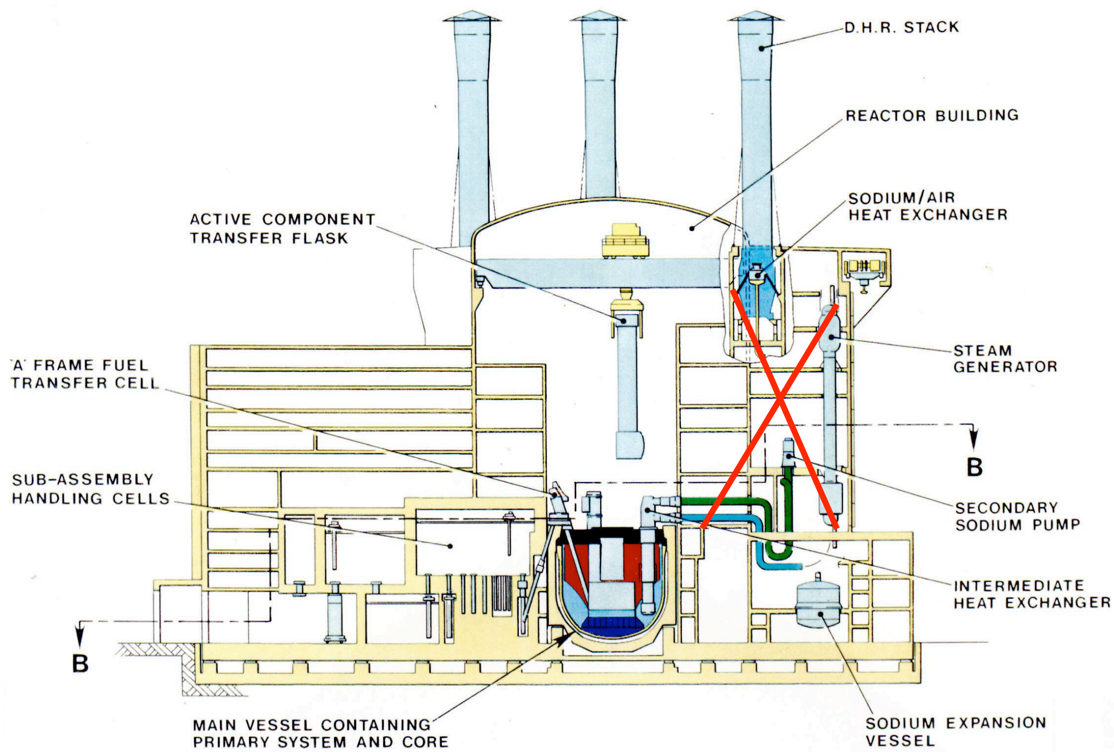


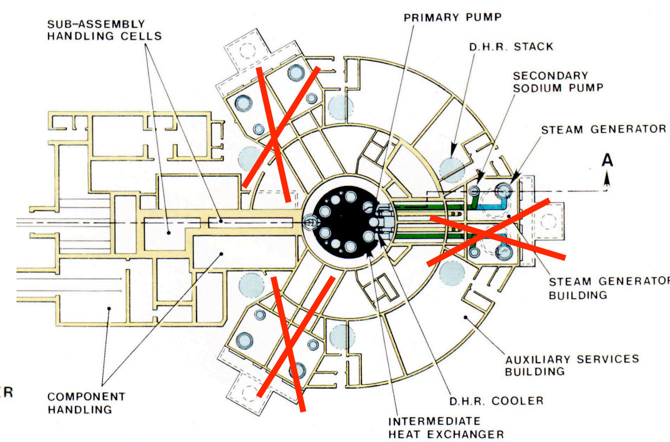


ELSY Parameters	
Power	600 MWe
Thermal efficiency	42 %
Primary coolant	Pure lead
Primary system	Pool type, compact
Primary coolant circulation (at power)	Forced
Primary system pressure loss (at power)	~ 1,5 bar
Primary coolant circulation for DHR	Natural circulation + Pony motors
Core inlet temperature	~ 400°C
Core outlet temperature	~ 480°C
Fuel	MOX and nitrides (with and without MA)
Fuel cladding material	T91 (Fe-Al alloy coated)
Fuel cladding temperature (max)	~ 550°C
Main vessel	Austenitic stainless steel, hung, short-height ~ 9 m
Safety vessel	Anchored to the reactor pit
Steam generators	N° 8, integrated in the main vessel
Secondary cycle	Water-superheated steam at 180 bar, 450°C
Primary pumps	N° 8, mechanical, suction from hot collector
Internals	Removable
Inner vessel	Cylindrical
Hot collector	Small-volume, enclosed by Inner Vessel
DHR dip coolers	N° 4, immersed in the cold collector
Seismic design	2D isolators supporting the reactor building

The elimination of the intermediate loops is the key for compactness of an LFR plant

No intermediate main loops, (S. G. inside the reactor vessel)





Reduced reactor building footprint

Reduced reactor building elevation

The GIF-LFR System Research Plan

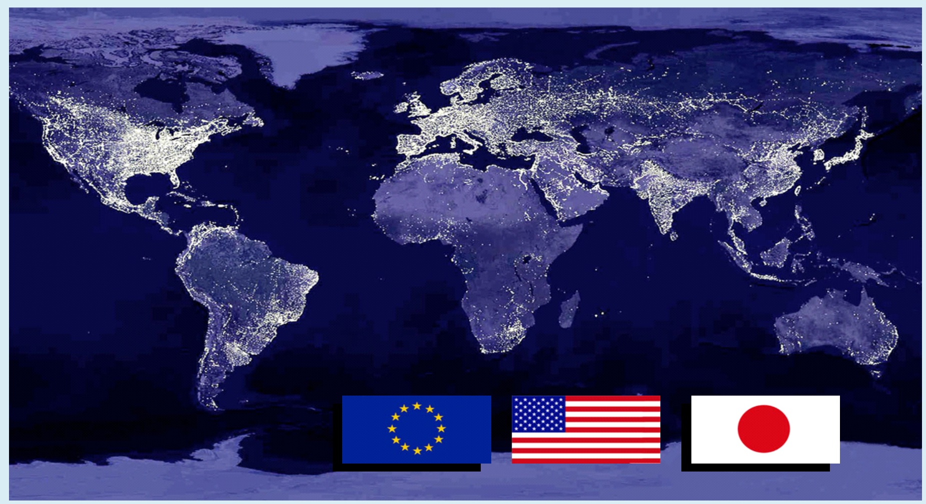
- The GIF-LFR Steering committee has operated since 2004 with participation of representatives from Euratom, USA, Japan and invited experts from Korea.

- Revision of the SRP is ongoing to include the progress in SSTAR and ELSY, updates on programmatic plans, etc.

Generation IV Nuclear Energy Systems

System Research Plan
for the Lead-cooled Fast Reactor

Preparing Today for Tomorrow's Energy Needs

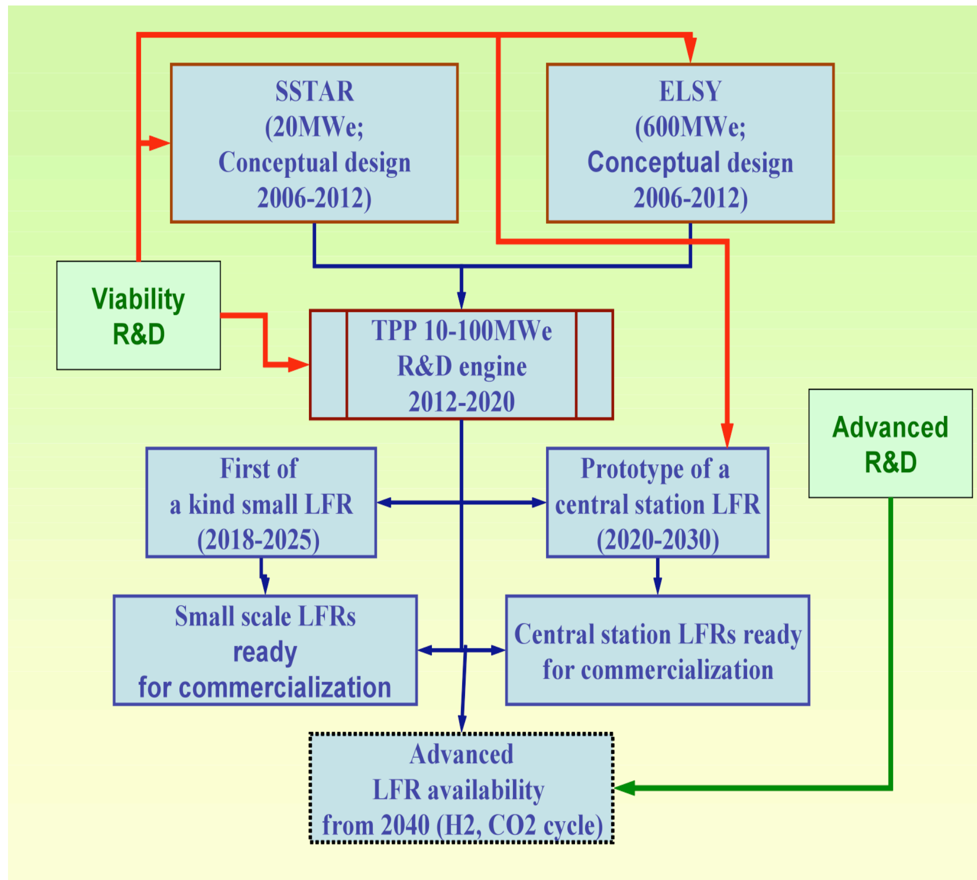


Generation IV International Forum
Issued by the
LFR System Steering Committee

Lead-Cooled Fast Reactor Systems (LFR) under GIF:

The GIF-LFR System Research Plan (SRP) recognizes two principal technology tracks for pursuit of LFR technology

- A small, transportable system of 10–100 MWe size that features a very long refueling interval. (SSTAR)
- A larger-sized system rated at about 600 MWe, intended for central station power generation and waste transmutation. (ELSY)



Critical ongoing discussions related to the TPP or DEMO

Some concluding comments

- The STAR concept, and particular examples such as ENHS and SSTAR represent a novel approach toward proliferation risk management
- More broadly, LFR technology shows great promise for small and medium systems with robust design, excellent safety potential and economical performance while delivering the material management capabilities of fast spectrum systems