GEN IV International Forum

LEAD-COOLED FAST REACTOR (LFR)

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June 12, 2017

Meet the presenter

Prof. Craig Smith, Naval Postgraduate School, Monterey, CA, USA received his Ph.D. in Nuclear Science and Engineering from the University of California, Los Angeles (UCLA) in 1975 and his B.S. in Engineering, *summa cum laude* from UCLA in 1971. He is a Fellow of the American Nuclear Society and the American Association for the Advancement of Science.

He is a nuclear engineer with research experience in nuclear energy, radiation detection, and nuclear forensics. His previous employers include the US Army, Science Applications International Corporation (SAIC), Booz Allen and Hamilton, and Lawrence Livermore National Laboratory (LLNL). At LLNL, he was a Deputy Associate Director and he led the Fission Energy Program. Beginning in 2004, he became the LLNL Chair Professor at the Naval Postgraduate School (NPS) in Monterey, CA. After retirement from LLNL, he assumed his current position as Research Professor of Physics at NPS.

He has published a number of articles, papers and book chapters on topics related to the Lead-cooled Fast Reactor, and he additionally co-authored several books on topics related to advanced information technology. He serves as the US observer representative to the GIF Provisional System Steering Committee for the Lead-cooled Fast Reactor.

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The Limits of Our Present Nuclear Reactor System

- At present, nuclear reactors produce more than 10% of world's electricity, and much higher levels than that in several countries (e.g., France 72%, Belgium 50%, Korea 30%, USA 20%). However,

  - Current thermal reactors use only about 0.6% of the mined natural uranium
  - They produce long-lived transuranics as nuclear waste or spent fuel
  - They represent low-efficiency electricity production (efficiencies about 33%).

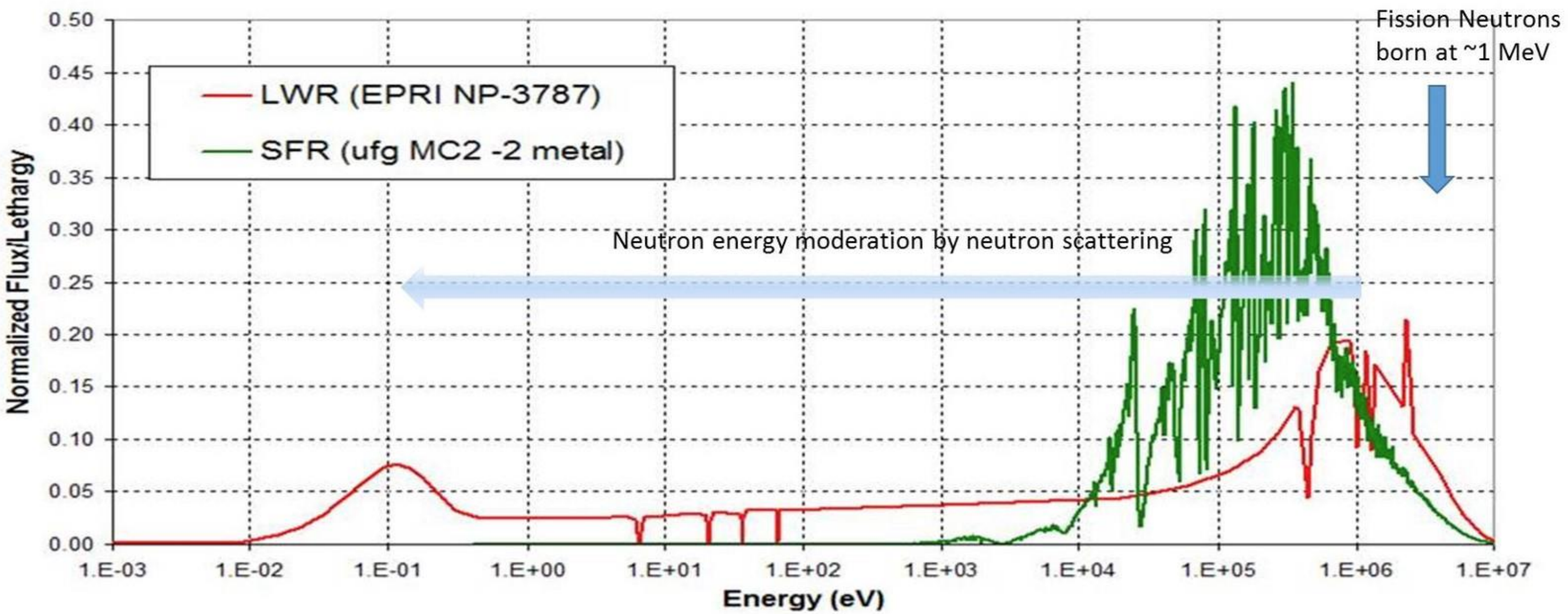
- Gen-IV Fast reactors, and the Lead-cooled Fast Reactor (LFR) in particular, can offer strong improvements to address these and other issues associated with the current generation of reactors
- Today's presentation provides some background on fast reactors and then a more detailed description of the development and current status of the LFR

Outline

- Some background on fast reactors – Physics recap
- Characteristics and challenges of advanced LFRs
- Historical development of the LFR and Gen IV status
- GIF Reference System summaries
- Additional systems being developed
- Summary

A Recap on Fast Reactor Physics

Comparison of fast (SFR) vs. Thermal (LWR) spectra

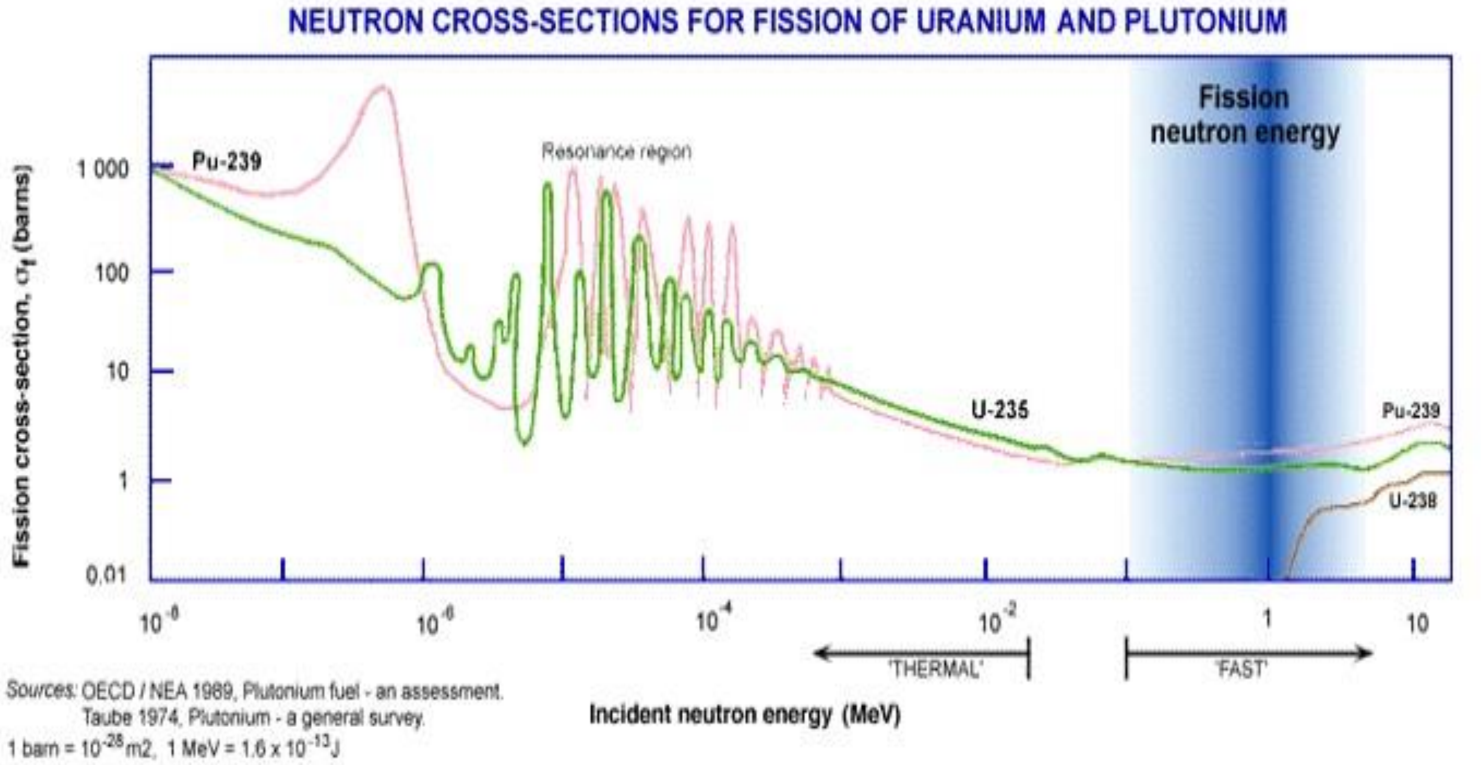


- In thermal reactors such as LWRs, most fissions occur around the ~0.1 eV “thermal” peak
- In fast reactors such as LFRs or SFRs, neutron energy moderation is avoided – fissions occur mainly in “fast” energy range

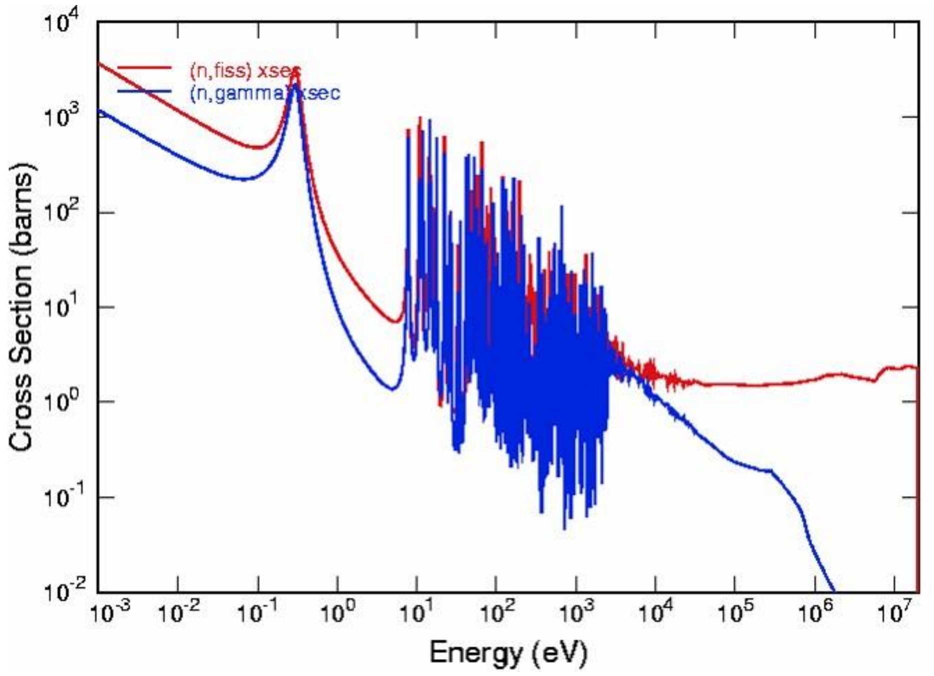
Graphic courtesy of Dr. Robert Hill, GIF Webinar on the SFR.

Fission and Capture Cross Sections

Fission cross sections for Pu-239 and U-235



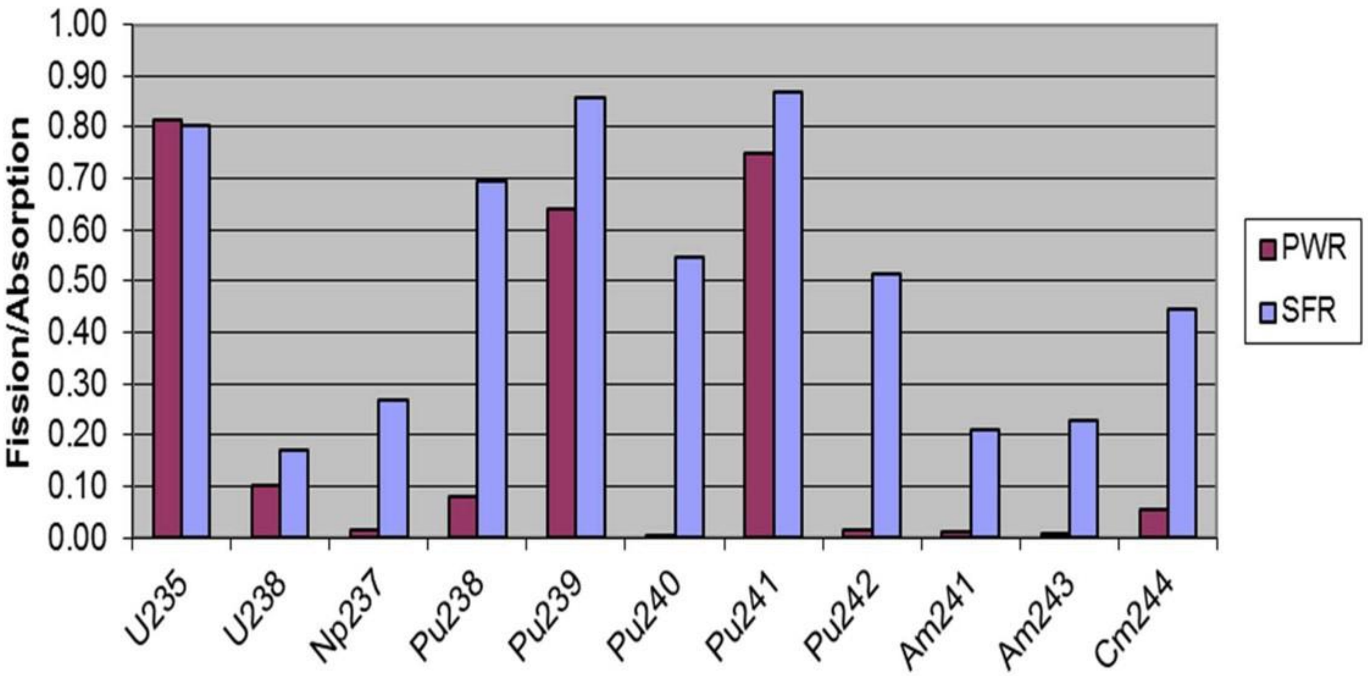
Fission and capture cross sections for Pu-239

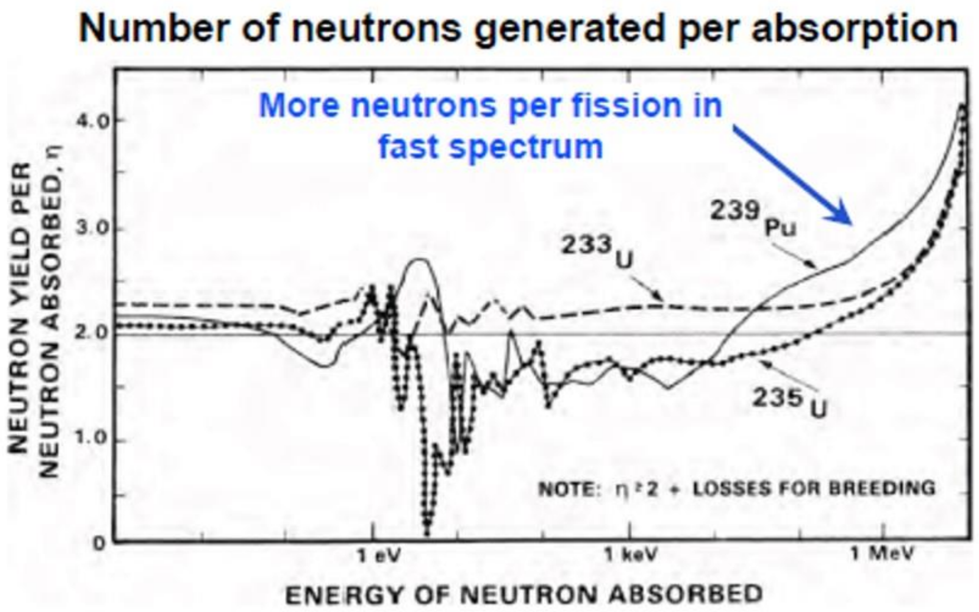


Fission cross sections are ~3 orders of magnitude higher in thermal than in fast spectrum

There is a sharp decrease in capture cross sections at high energy

Impact of Energy Spectrum on Fuel Utilization and Minor Actinide Consumption





- Fissile isotopes (U235 and Pu239) are likely to fission in either thermal or fast spectrum
- Fertile isotopes (e.g., U-238) are more likely to fission in fast spectrum
- Higher actinides (e.g., Pu, Np, Am and Cm) which are responsible for long-term nuclear waste radiotoxicity, are much more efficiently consumed in fast spectrum than in thermal spectrum
- More excess neutrons available in fast spectrum

The net result is better fuel utilization and significant actinide consumption in fast reactors

Sustainability of Fast Reactors

- Consider the nuclear material requirements (tons) needed to produce 100 TWh
- (~ 30% of the annual demand of electric energy in UK).

		Baseline scenario: Thermal Reactors, No Recycle	Near term scenario: Fast reactors without Minor Actinide recycling.	Long term scenario (after 2040): Fast reactors with Minor Actinide recycling.
Natural Uranium		2100	10.8 -- or a+b+c	10.43 -- or a+b+c+d
Unused uranium	Depleted Uranium from enrichment.	1900 (a)	--	--
	Uranium from spent fuel.	184 (b)	--	--
Net generated Pu		2.6* (c)	Negligible **	Negligible**
Nuclear waste	Minor Actinides (Np, Am, Cm)	0.38 (d)	0.36	Negligible**
	Fission fragments	13	10.43	10.43

* It is possible to reduce the plutonium inventory, however with increased production of Minor Actinides

** Reprocessing losses

Why LFR Technology?

- As with other Fast Reactors, LFRs offer:
  - Significant advantage in sustainability/uranium utilization – better use of natural resources
  - Potential for dramatic reduction of high level waste if full recycle (closed fuel cycle) is used
- Relative to other fast reactors, LFRs have a unique combination of favorable features:
  - Very high boiling point (1737°C)
  - Benign chemistry (no rapid chemical reaction with water/air)
  - Low vapor pressure
  - Excellent neutronic properties for fast spectrum operation
- These features are inherent in the properties of the lead coolant and can be exploited through proper plant design.

However, There are Challenges to Address

- **Corrosion potential**
  - Operate at temperatures low enough to avoid corrosion (current materials can be used)
  - Use advanced materials for higher temperature operation, to enhance economics
    - Silicon or Aluminum enhanced materials (i.e., Alumina Forming Austenitic (AFA) steels and Silicon enhanced steels)
    - Surface coating with corrosion-protective materials for higher temperature operation (cladding + steam generator)
    - Functionally graded composite materials
  - In any case, methods must be implemented to monitor/control oxygen content to maintain protective oxide coatings and avoid the formation of PbO
- **High melting point (327°C)**
  - Proper engineering to avoid lead freezing
- **Seismic/structural considerations due to heavy coolant**
  - Compact size mitigates this challenge
  - Seismic isolation
- **Opaque, high-temperature coolant**
  - Similar in service inspection issues and solutions as for SFR
  - Accessibility/replaceability of components
  - Newer acoustic methods

These challenges are generally technical in nature and can be overcome through proper engineering and R&D work

Some Chemical and Thermal Characteristics of Liquid Metal Coolants

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

Lead and LBE Coolants Provide Promising Overall Characteristics while Sodium Technology is More Highly Developed

The Pb-LBE Choice

- LFRs can be cooled by either pure lead or by the alloy mixture of lead and bismuth – LBE, or Lead Bismuth Eutectic
- The major advantage of LBE is that it has a much lower melting/freezing point – 125° C versus 327° C for lead – reducing engineering difficulty and allowing lower temperature operation.
- On the other hand, LBE in the presence of neutrons produces Po-210:
  $^{209}Bi + n \rightarrow {}^{210}Bi$ (β- ; 5 days) $\rightarrow {}^{210}Po$ (α, 138 days)
- Po-210 is a potent and radiotoxic alpha emitter and produces a significant heat load in the coolant itself.
- Bi is more expensive than Pb, and its limited availability may inhibit large scale deployment of reactors cooled by LBE
- GIF reference designs feature lead as the coolant, but several other reactor designs being pursued use LBE

LFRs Have the Potential to Excel in Safety

- The very high boiling point of lead (~1737°C):
  - Allows reactor operation at near atmospheric pressure
  - Eliminates the risk of core voiding due to coolant boiling
- No rapid chemical reactions between lead and either water or air
  - No energetic releases or hydrogen production from chemical reactions
  - Use of water as ultimate heat removal fluid is conceivable, should other heat removal systems fail
- The thermal capacity of lead combined with the large mass of coolant
  - Significant thermal inertia in the event of hypothetical accident initiators.
  - Long grace time (the need for operator's intervention is eliminated or significantly delayed)
- Lead shields gamma radiation and retains iodine and cesium up to 600°C
  - Reduced source term in case of fuel rod failure → enhanced Defense-in-Depth.
- The low neutron moderation of lead allows greater fuel spacing without excessively penalizing neutronic performance:
  - Reduced risk of flow blockage
  - Reduced core pressure drop and simple coolant flow path allow decay heat to be removed through natural circulation

Stored Potential Energy for Different Reactor Coolants

Coolant	Water	Sodium	Lead, LBE
Parameters	P = 16 MPa T = 300 ºC	T = 500 ºC	T = 500 ºC
Maximal potential energy, GJ/m³, *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	~0
Potential chemical energy of interaction of released hydrogen with air	~ 9.6	~ 4.3	None

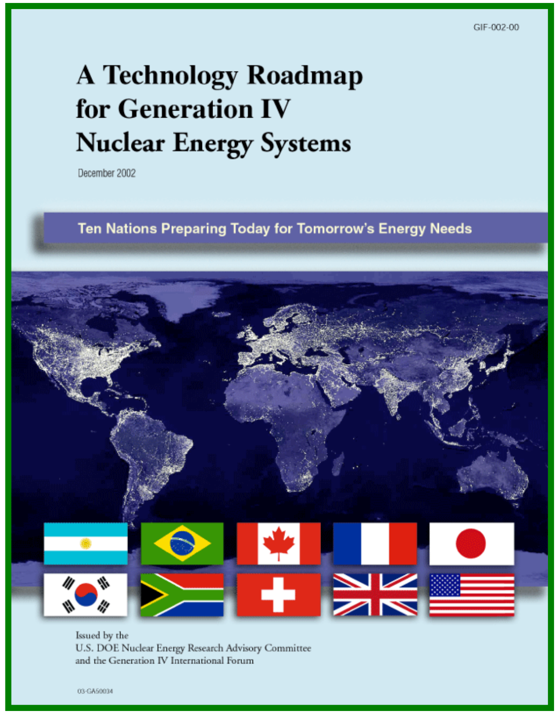
Table based on ICAPP 2011, Paper 11465
Effect of Potential Energy Stored in Reactor Facility Coolant on NPP Safety and Economic Parameters
G.I. Toshinsky, O.G. Komlev, I.V. Tormyshev

The Generation IV International Forum

“Since the year 2001, under US initiative, a group of countries have recognised the need of alternative nuclear technologies and joined together to form the Generation IV International Forum (GIF) to develop future-generation nuclear energy systems”.
Other countries joined later.

Generation IV Systems	***Acronym***
Gas-Cooled **F**ast **R**eactor	**GFR**
Lead-Cooled **F**ast **R**eactor	**LFR**
Molten **S**alt **R**eactor	**MSR**
Sodium-Cooled **F**ast **R**eactor	**SFR**
Super**c**ritical **W**ater-Cooled **R**eactor	**SCWR**
Very-**H**igh-**T**emperature **R**eactor	**VHTR**

Note: Three out of the six systems selected by GIF (GFR, LFR and SFR) are fast reactors. Others (i.e., MSR and SCWR have fast spectrum options).


GIF-002-00

A Technology Roadmap for Generation IV Nuclear Energy Systems

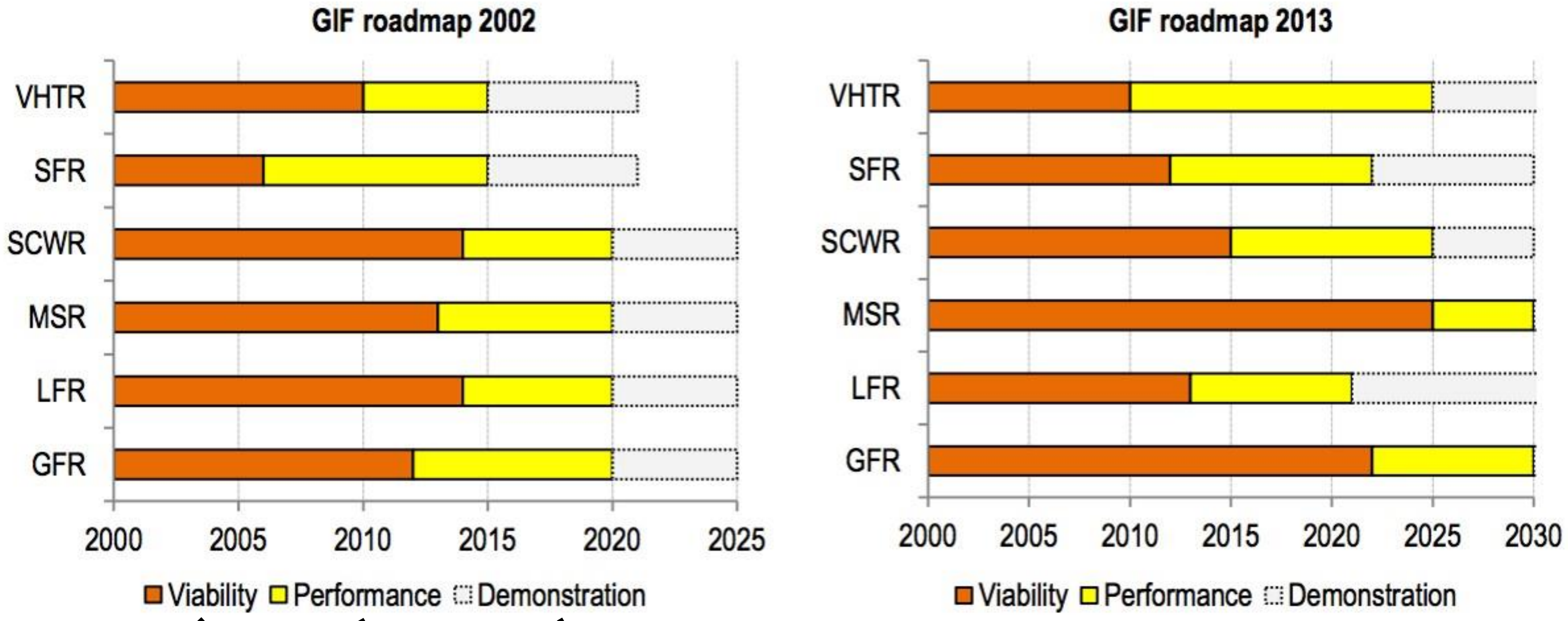
December 2002

Ten Nations Preparing Today for Tomorrow's Energy Needs

Issued by the U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum

Gen IV Roadmap Update (2014) Comparison of system timelines

Figure ES.2: System development timelines as defined in the original 2002 Roadmap (left) and in the 2013 update[4]



No showstoppers

Testing

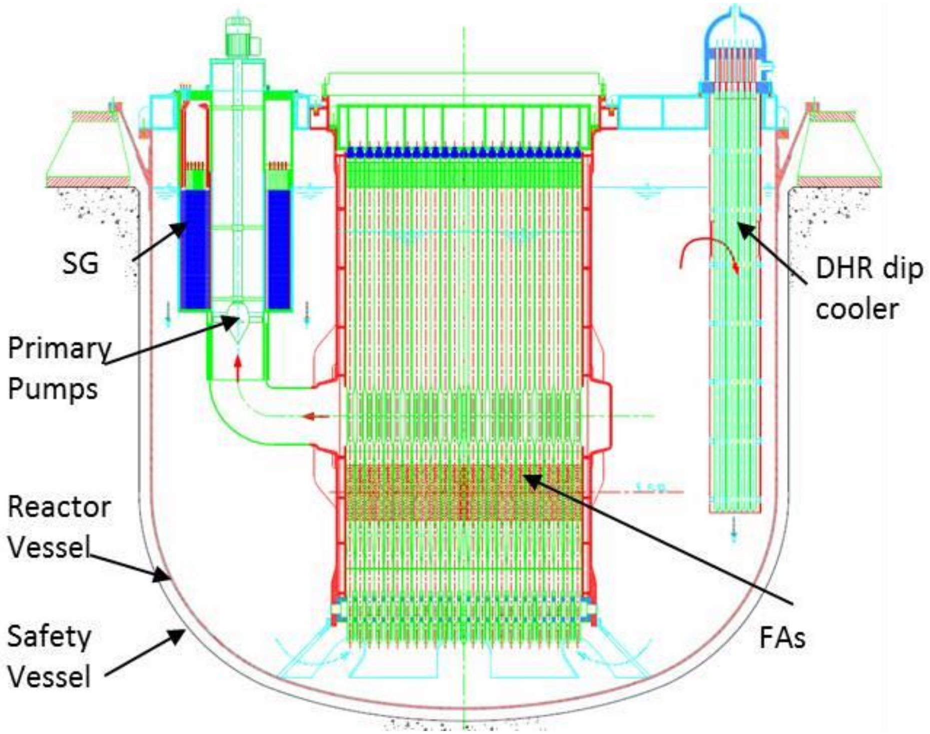
Detailed design complete

LFR technology readiness is higher than generally thought

Gen-IV International Forum (GIF):
Current Status with regard to LFR

- Provisional System Steering Committee (pSSC) formed in 2005
  - Members included EU, US, Japan and Korea
  - Prepared initial draft LFR System Research Plan (LFR-SRP)
- GOF-LFR Memorandum of Understanding (MOU):
  - In 2010, an MOU was signed between EU and Japan formalizing the pSSC
  - In 2011, the Russian Federation added its signature to the MOU resulting in a revision/augmentation of the SRP
  - In 2015, Korea became a full member by signing the MOU.
- The US and China participate in observer status
- The reference systems adopted by the pSSC include:
  - ELFR (600 MWe)
  - BREST-OD-300 (300 MWe)
  - SSTAR (20 MWe)

Primary System Configuration and Selected Parameters of ELFR



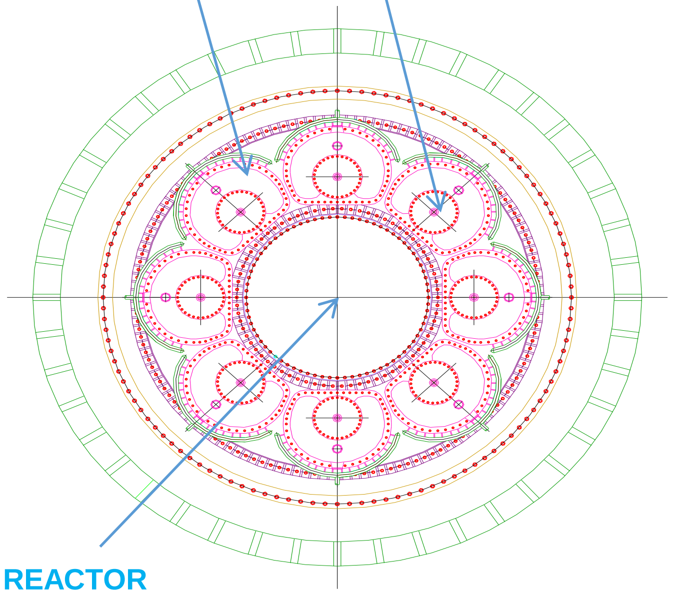
Item	Option
Electrical Power (MWe)	600
Primary Coolant / System	Pure Lead – Pool type – no intermediate circuit
Primary circulation	Forced - Natural (in DHR mode)
Primary Pumps	Mechanical in the hot collector - removable
Core Inlet / outlet T °C	400 / 480 °C
Steam Generators	8 SGs – Spiral tubes
Power conversion efficiency	~ 42 %
Reactor / Safety Vessel	Austenitic SS, Hung / Anchored to reactor pit
Fuel Assembly / Fuel type	Hexagonal wrapped / MOX
Fuel Cladding material	15-15 Ti coated (T91 coated as an option)
Refuelling /residence time	2 / 5 years
Seismic damping devices	2-D isolators below reactor building

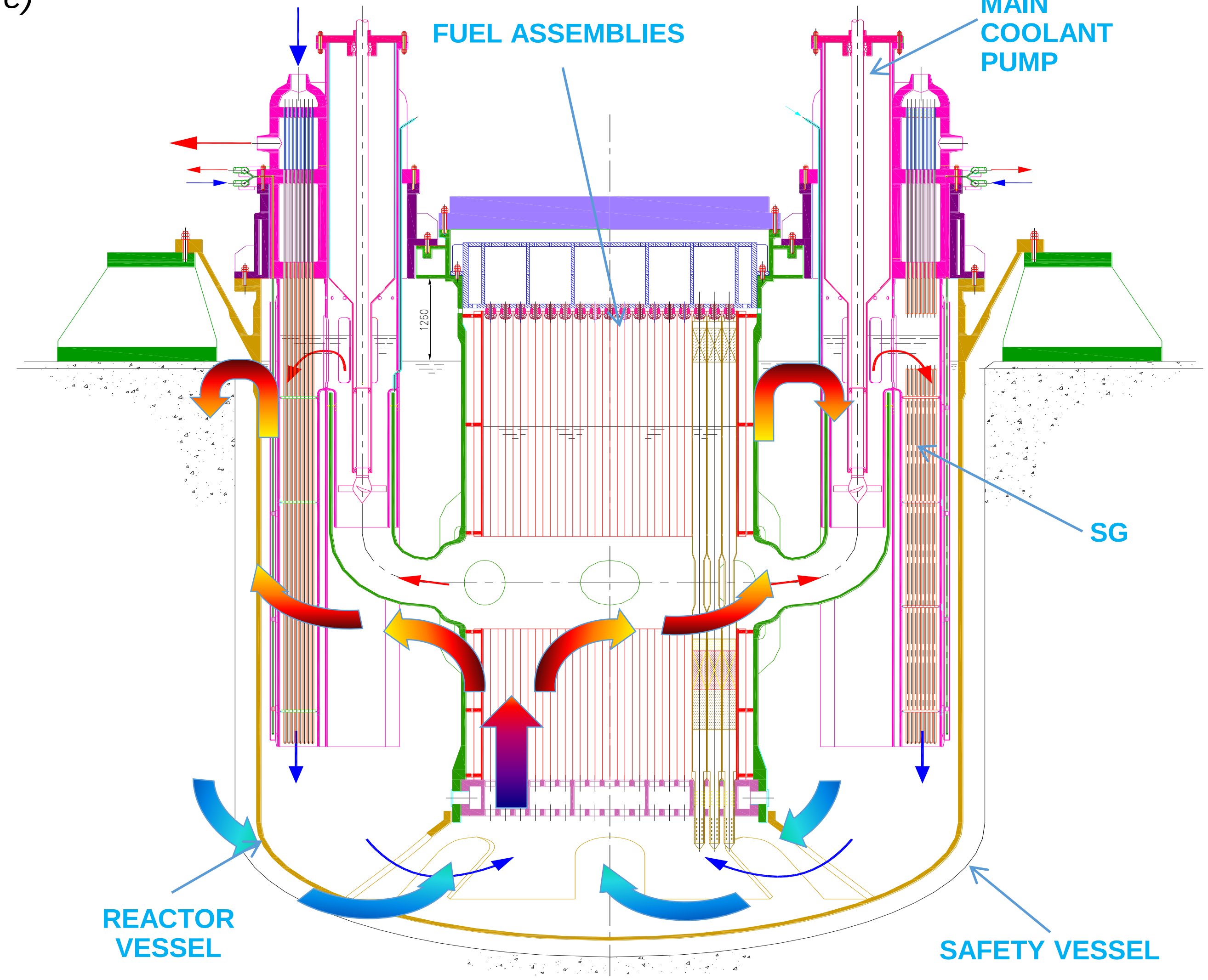
Note: Associated with ELFR is a smaller demonstration reactor known as ALFRED (125 MWe)

ALFRED – Advanced LFR European Demonstrator

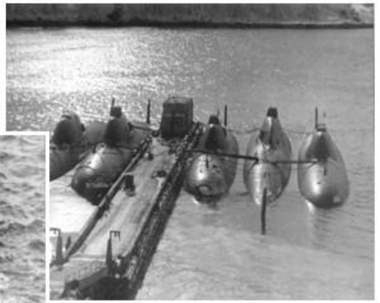
Design solutions scaled down with respect to ELFR

Power:	*300 MWth (125 MWe)*
Primary cycle:	*400 – 480ºC*
Secondary cycle:	*335 – 450ºC*
Secondary Side Pressure	*180 bar*
Steam cycle efficiency	*above 40%*





Russian Military Applications Led to Its Current Civilian LFR Developments



Nuclear submarine-
705 seris
(1976-1996)

Nuclear submarine-
705
demo (1971)

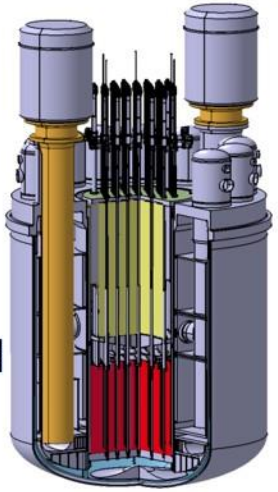
Prototype nuclear
submarine
Project 645
(1963)

Pb-Bi setup (1951)

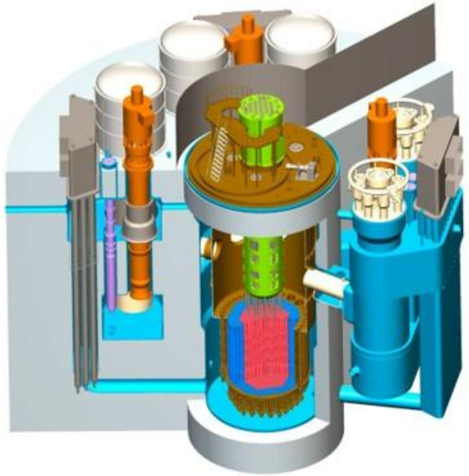
- 4 reactor cores (73MW) in prototype submarine (P-645)
- 7 “Alpha Class” subs (155 MWt) +1 replaced reactor
- 15 cores total, including 3 cores in 2 on-shore reactors
- ~80 reactor-years experience – with lessons learned

The ongoing development

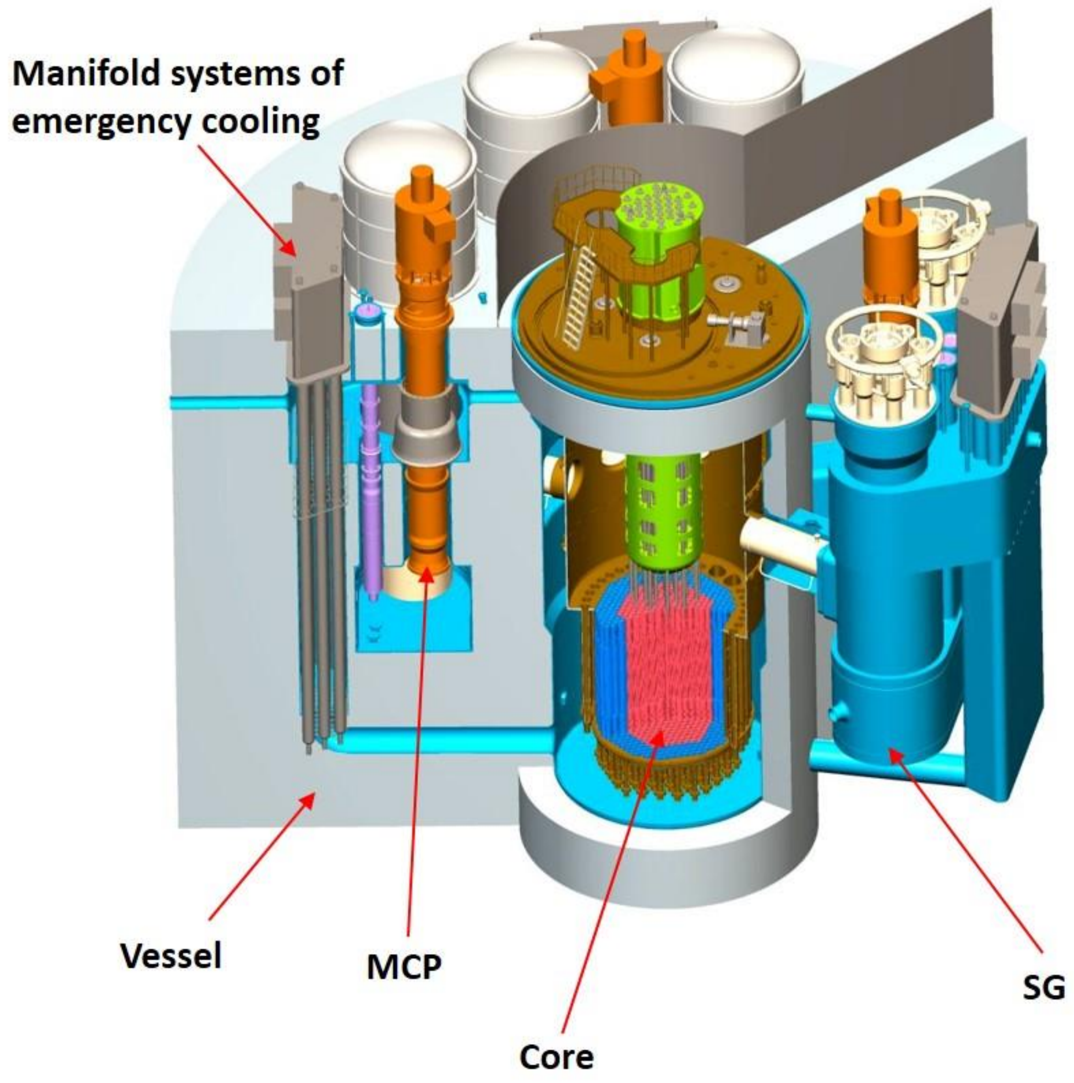
SVBR-100
LBE-cooled



BREST-OD-300
Lead-cooled

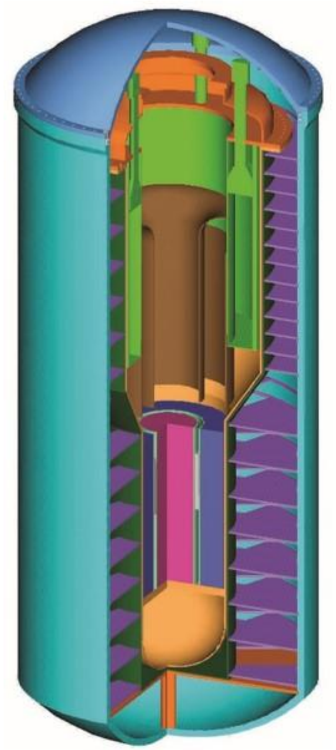


BREST-OD-300 Prototype for a Commercial Reactor. Sketch and System Characteristics



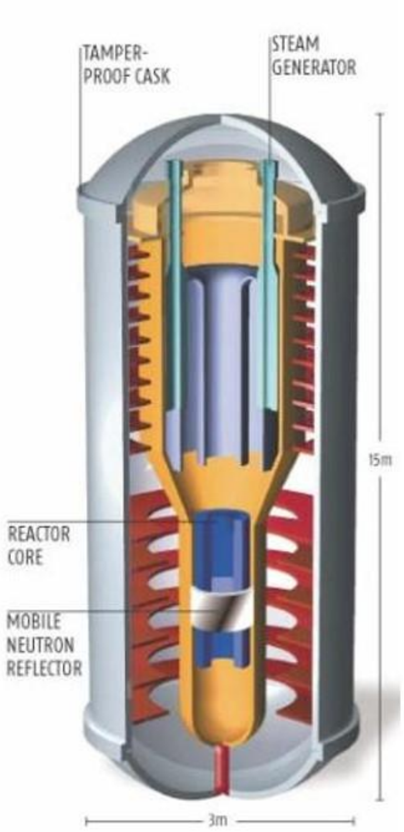
Thermal power, MWth	700
Electric power, MWe	300
Primary coolant	lead
Number of loops	4
Average temperature of lead coolant at the entrance/exit of the core, °C	420/535
Fuel Material	U-Pu Nitride
Number of fuel assemblies	169
Fuel charge, t	20.6
Power Conversion Efficiency, %	43.5

One of the first concepts for a SMR is the Small Secure Transportable Autonomous Reactor (SSTAR)



Nuclear Energy to Go: A Self-Contained, Portable Reactor
July/August 2004 article in *Science and Technology Review*

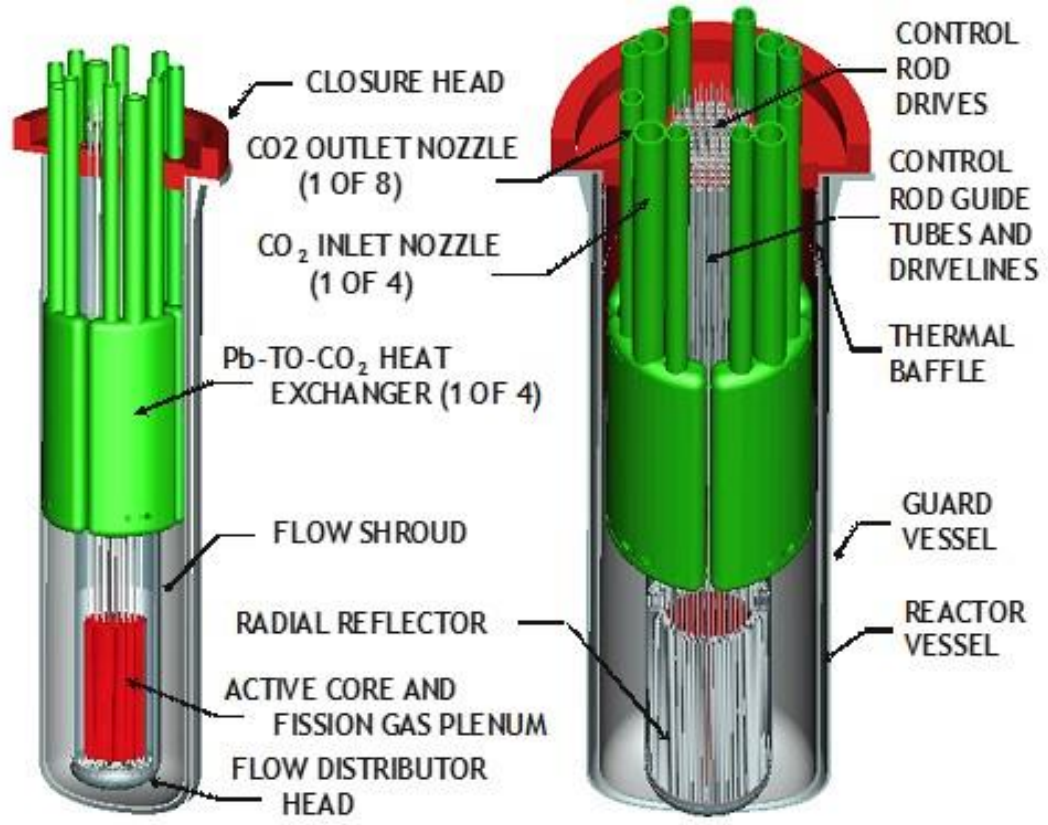
Nuclear's Model T
Feature article in July 2009 Issue of *Mechanical Engineering*



"Reactor in a Box" - The sealed reactor could give access to nuclear energy without the risk of the fuel being used to make nuclear weapons

US plans portable nuclear power plants
Article in New Scientist – Daily News, 3 Sept 2004

Sketch and Parameter Summary - SSTAR



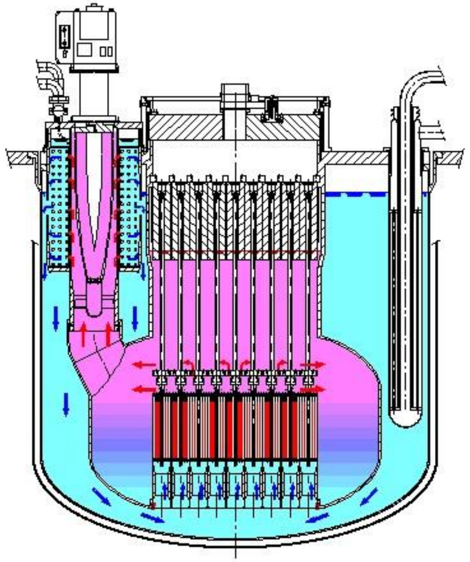
Coolant	Lead
Fuel	Transuranic Nitride enriched in N_{15}
Core lifetime, years	20-30
Core inlet/outlet temperature, °C	420/567
Coolant circulation	Natural convection
Power conversion	S-CO_2 Brayton Cycle
Power conversion efficiency, %	44

Key attributes include the use of lead (Pb) as coolant, reliance on natural circulation cooling, supercritical CO_2 power conversion, and a long-life sealed core in a small, transportable system.

Recap of Design Parameters of Gen IV Reference LFR Concepts

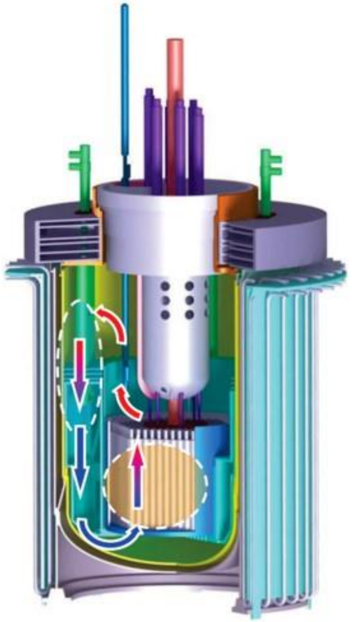
Parameter	ELFR	BREST-OD-300	SSTAR
Core power (MW_{th})	1500	700	45
Electrical power (MW_e)	600	300	20
Primary system type	Pool	Pool/loop	Pool
Core inlet T (°C)	400	420	420
Core outlet T (°C)	480	535	567
Secondary cycle	Superheated steam	Superheated steam	S-CO_2
Net efficiency (%)	42	43.5	44

Current active initiatives – Beyond the GIF Reference Systems

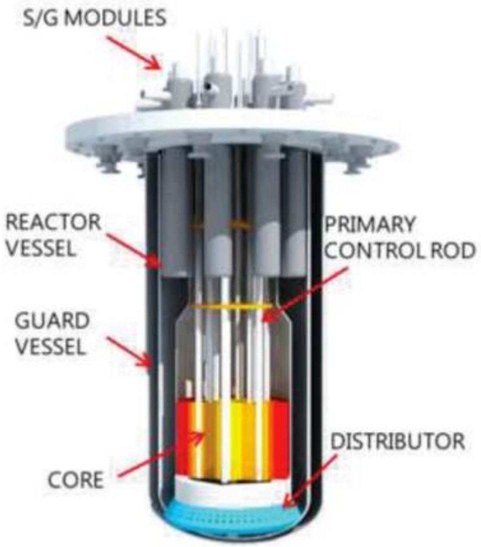


Hydromine AS-200
(200 MWe, USA)

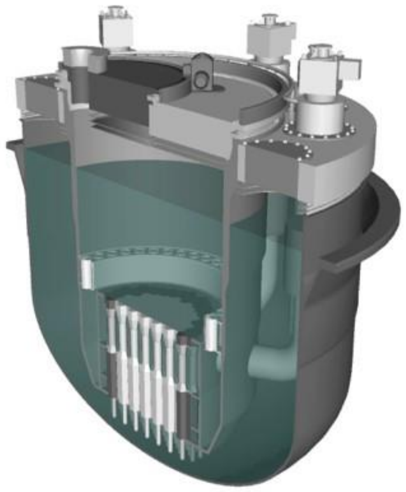
LeadCold SEALER
(1-10 MWe, Sweden)



CLEAR-1
(10 MWth, China)

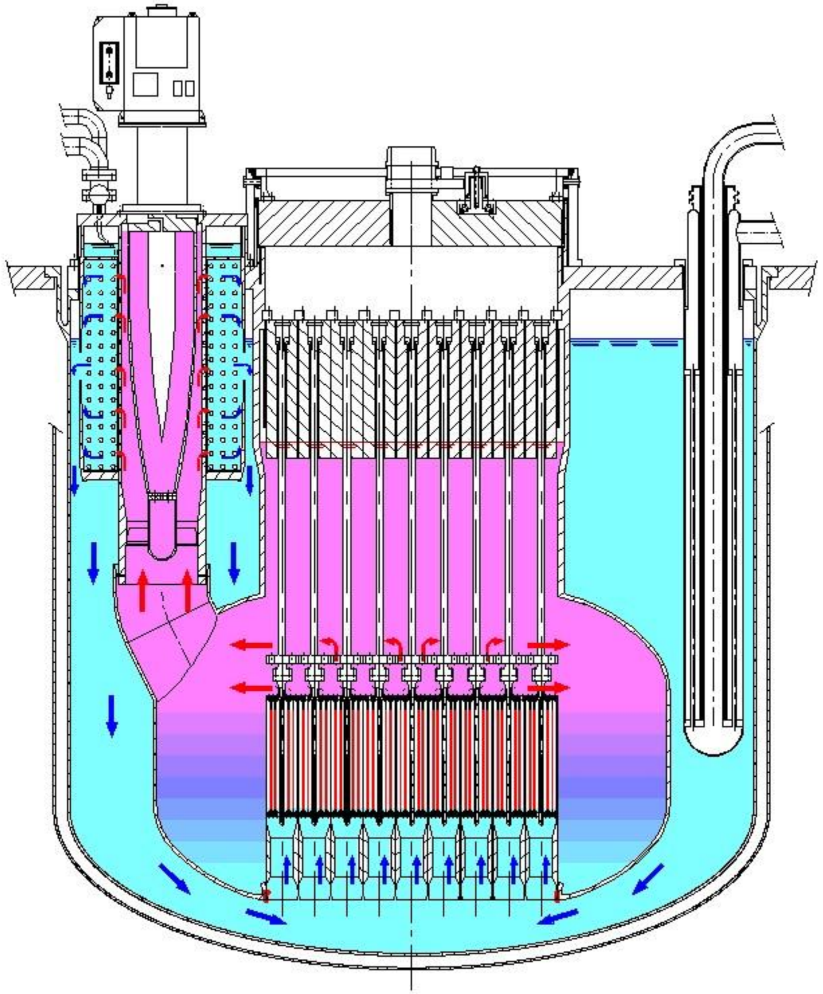


URANUS
(50MWe, Korea)



Westinghouse LFR
(power: undisclosed, USA)

Hydromine AS-200



The Hydromine AS-200 concept is a highly compact 200 MWe LFR:

- achieved by elimination of components
- ~ 4 times more compact than the Superphenix (SPX-1) SFR
- ~ 2-3 times more compact than than the best SFR projects
- ~ 3-5 times more compact than than previous LFR projects

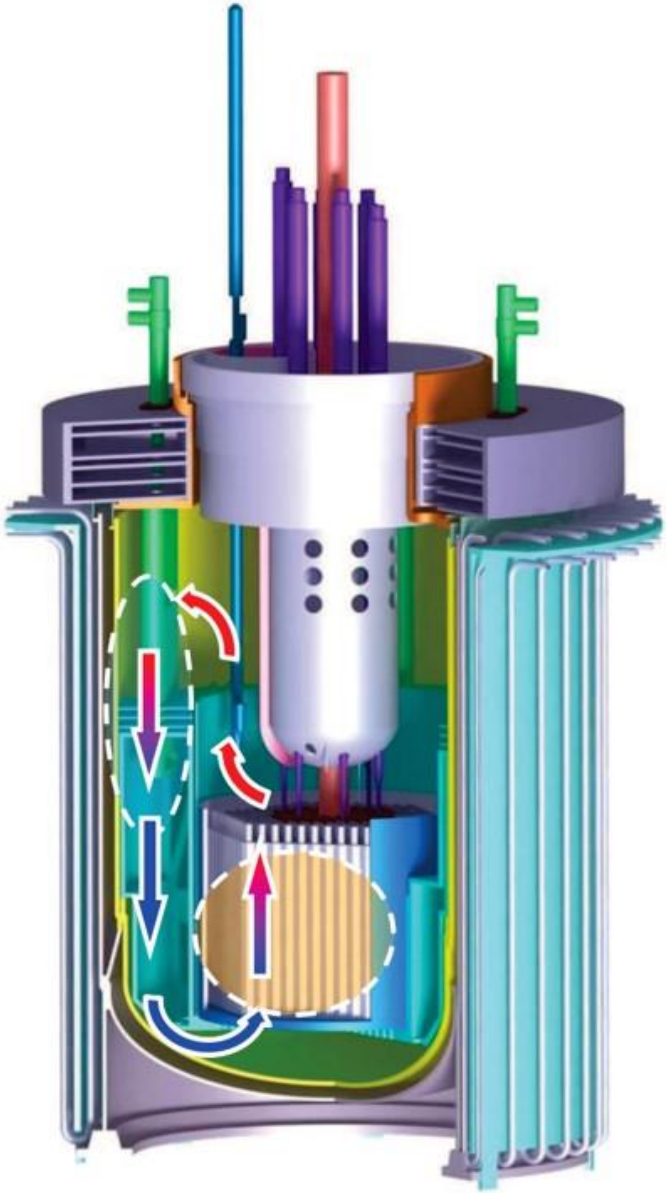
Core power (MWth)	480
Electrical power (MWe)	200
Coolant	Lead
Core inlet/outlet T (°C)	420/530
Primary loop pressure loss (bar)	1.3
Secondary cycle	Superheated steam
Fuel	U or mixed oxide

Lead Cold SEALER

SEALER stands for "Swedish Advanced Lead Reactor". It also means, "Person providing a stamp of quality."

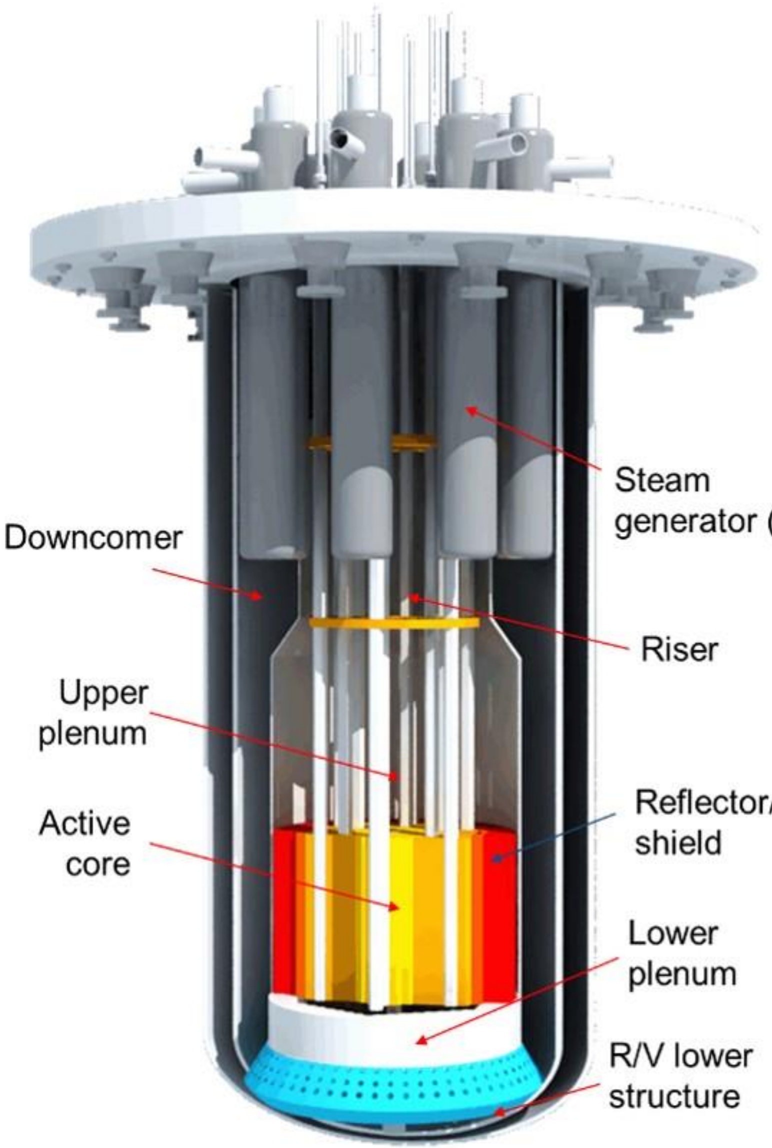
- –Very small (3-10 Mwe) reactor
- –LBE-cooled
- –19.75% enriched UO_2-fuel
- –3-10 MW electric
- –Core life: 10-30 years
- –Reactor vessel: 2.7 x 6.0 m
- –Transportable to/from site
- –Fuel cladding remains below 450°C

China's CLEAR-I Reactor



Parameters	Value
Thermal power	10 MW
Primary coolant	LBE
Fission fuel	UO_2(19.75%)
Driven force	Natural circulation
Subcritical mode k_{eff}	0.98
Primary coolant inventory	~700 t
Reactor core inlet/outlet temperature	260℃/390℃
Circulation height	2 m
Secondary coolant	Water
Secondary coolant pressure	4 MPa
Secondary coolant temperature	215℃/230℃
Primary heat exchanger	4 (2 independent loops)
Main vessel height	6300 mm
Main vessel diameter	4650 mm

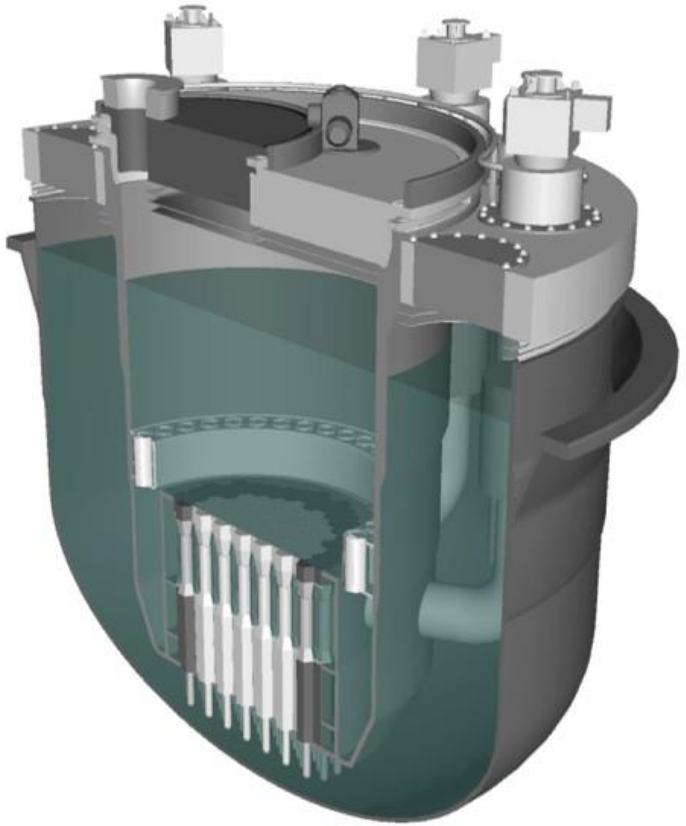
Korea's URANUS Reactor



Key parameter	Value
Core power during normal operation	125 MWth (50 MWe)
Primary coolant	Lead
Nuclear fuel (zone: enrichment)	UO_2 (inner: 9.55%, outer: 17.09%)
Core cooling mechanism	Natural circulation
Lead coolant inlet/outlet temperature	400/520 ^{o}C

Westinghouse LFR

- The Westinghouse LFR is under active development with multiple concepts/design options being considered
- The initiative originated to address the key hurdle of nuclear power: *economic competitiveness*
- Westinghouse independently evaluated multiple advanced technologies and selected LFR as the technology with best potential to meet key requirements: safety, economics and marketability
  - Also considered sustainability and technology readiness
  - Clean sheet approach: no legacy from the past
- Features of LFR technology that played very favorably in Westinghouse's assessment:
  - Plant simplification (atmospheric pressure operation; no significant sources for containment pressurization; no boiling concerns)
  - Strong safety case, addressing post-Fukushima considerations
  - Sufficient technology readiness thanks to multiple international programs including extensive experimental activities



Favorable Economic Indicators from Enhanced Safety

GEN IV International Forum[SM]

- Reduced capital cost from plant simplification
  - Reduced number of components from primary system operating at atmospheric pressure
  - Potential elimination of intermediate circuit
  - Small and easier/faster to build containment due to the lack of significant sources of pressurization
  - No need for special provisions, systems and components to protect the plant from coolant leakages and coolant-water/air interactions
- High plant efficiency
  - Large margin to boiling makes LFR efficiency dependent on progress in materials rather than on coolant boiling concerns
- High power density from the use of a liquid metal coolant
- Strong case for reducing Emergency Planning Zone
  - Advantages from large margin to boiling, high thermal capacity, reduced likelihood for LOCA and benign coolant coupled with lead's radionuclide retention capability result in reduced source term

Conclusion

There is growing international interest in LFR technology.

- Excellent sustainability from full utilization of uranium resources
- Reduced nuclear waste concerns due to the ability to consume minor actinides and utilize accumulated Plutonium as fuel
- Outstanding safety case
- Promising economics from lead’s inherent attributes combined with proper design

These are among the main drivers of this international interest.

Overall Summary of LFR Operating Conditions

Parameter		Typical value	Notes
Power-related characteristics			
Electric power range, MWe		20-600	Designs developed as low as 1 MWe, and as high as 1200 MWe
Power conversion		Superheated steam	S-CO2; Supercritical steam also possible, especially at higher temperatures
Plant's efficiency		40-44	Upper 40s with progress in materials. Current LWR efficiencies are 33-35%
Thermal-hydraulics characteristics			
Primary pressure, MPa		Near atmospheric	
Coolant temperature, °C	Core in	400-420	Temperature cycle can be reduced for LBE-cooled reactors
	Core out	480-567	Depending on materials used. Can be higher pending materials demonstration
Coolant velocity in the core, m/s		1-2	Can be higher pending materials' performance demonstration to higher velocities
Materials			
Fuel lattice		Hex or square	Wire wraps or grids to support fuel rods
Fuel		UO_2, UN	May include U, Mixed U-Pu and fuels with minor actinides added. Metal fuel may also be explored
Fuel rod cladding		Steel (e.g., 15-15Ti)	Al- and Si-enhanced steels, coatings, Functionally Grade Composites, SiC/SiC composite also considered for higher performance LFRs
Structural materials		Steels	Conventional steels such as SS316 for components at T≤480°C. Oxygen control and/or corrosion resistant material for higher temperatures

Some Selected References

1. OECD, Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies, NEA No 7268, 2015.
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