Lead-cooled reactors

Lead-cooled reactors would provide the following advantages:

- Low pressure system
- No exothermic reaction with structural materials nor water
- Very high boiling temperature: No loss of coolant
- Passive decay heat removal by natural convection in a highly compact design
- Retention of volatile fission products: Source term limited to noble gases
- Gamma shield: minimises concrete inventory, simplifies core melt management

Lead-cooled reactor issues

The following issues need to be managed:

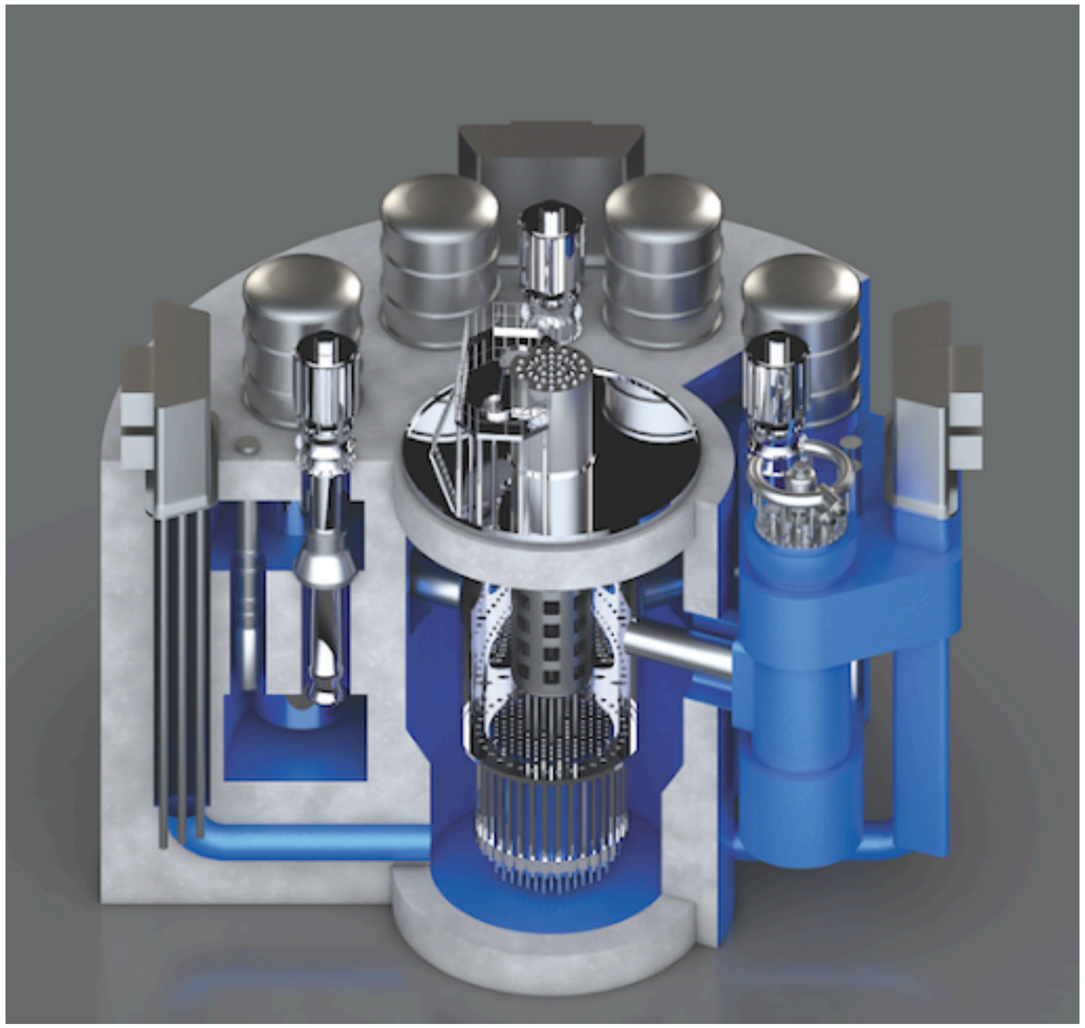
- Corrosion and erosion of steel in lead
- Freezing of lead (T_{melt} = 327°C)
- Maintenance at high temperature
- Inspection of welds and components in opaque coolant
- High density leads to high weight of the primary system.

Commercialisation of LFRs

The following reactor vendors are intending to commercialise LFRs:

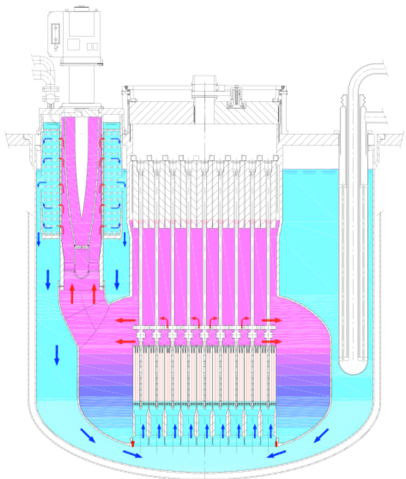
- Rosatom (Russia)
- AKME (Russia)
- Westinghouse (US)
- China General Nuclear (Biggest vendor in China)
- State Power Investment Corporation (Chinese vendor building AP1000)
- LeadCold Reactors (Sweden, KTH start-up company)
- NewCleo (Italian start-up company)
- Ansaldo Nucleare (Italy)
- GMET (UK)

First LFR under construction: BREST-300

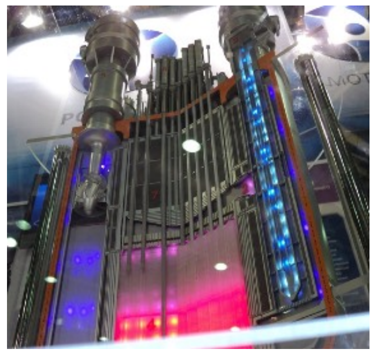


- Commercial lead-cooled reactor prototype
- Designed by NIKIET
- 300 MWe
- Uses Fe-12Cr-1Si corrosion tolerant steel
- Uses (U,Pu)N fuel
- Funded by Rosatom
- Reactor under construction in Seversk, Tomsk region
- Planned to operate in 2026.

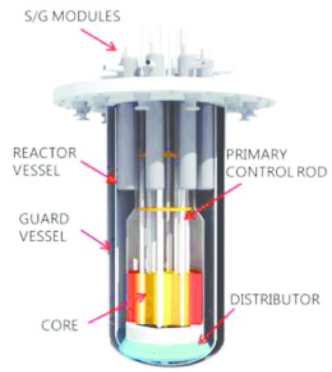
Small LFR designs currently under development



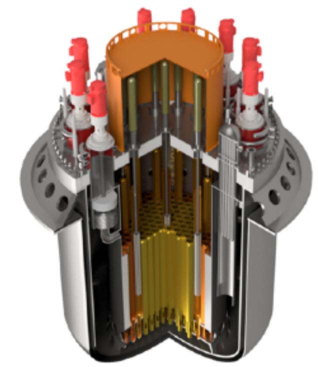
Small-LFR
200 MWe
NewCleo, Italy



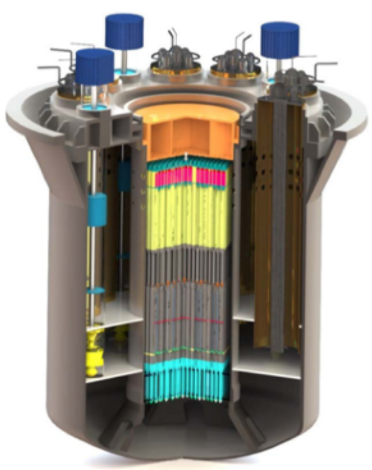
SVBR
100 MWe
AKME, Russia



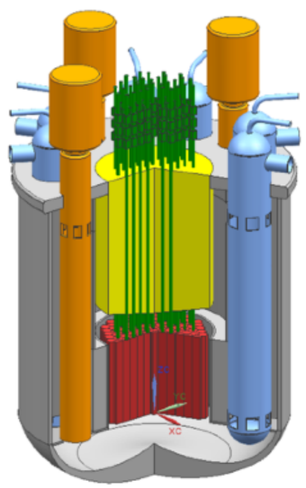
URANUS
40 MWe
SNU, Korea



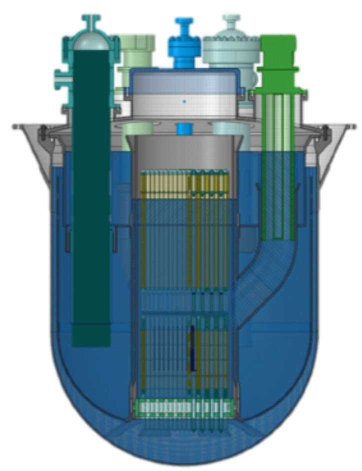
SEALER
3-55 MWe
LeadCold, Sweden



BLESS
120 MWe
SPIC, China



CLFR
300 MWe
CGN, China



ALFRED
125 MWe
Ansaldo, Italy

Fuel economy of lead-cooled reactors

Velocity of lead coolant limited to about 2 m/s

- Coolant flow area must be larger than for sodium cooled reactors
- In-core breeding ratio < 1 for UO_2 fuelled reactors without breeding blanket
- Fuel burnup limited by reactivity loss (similar to LWRs)

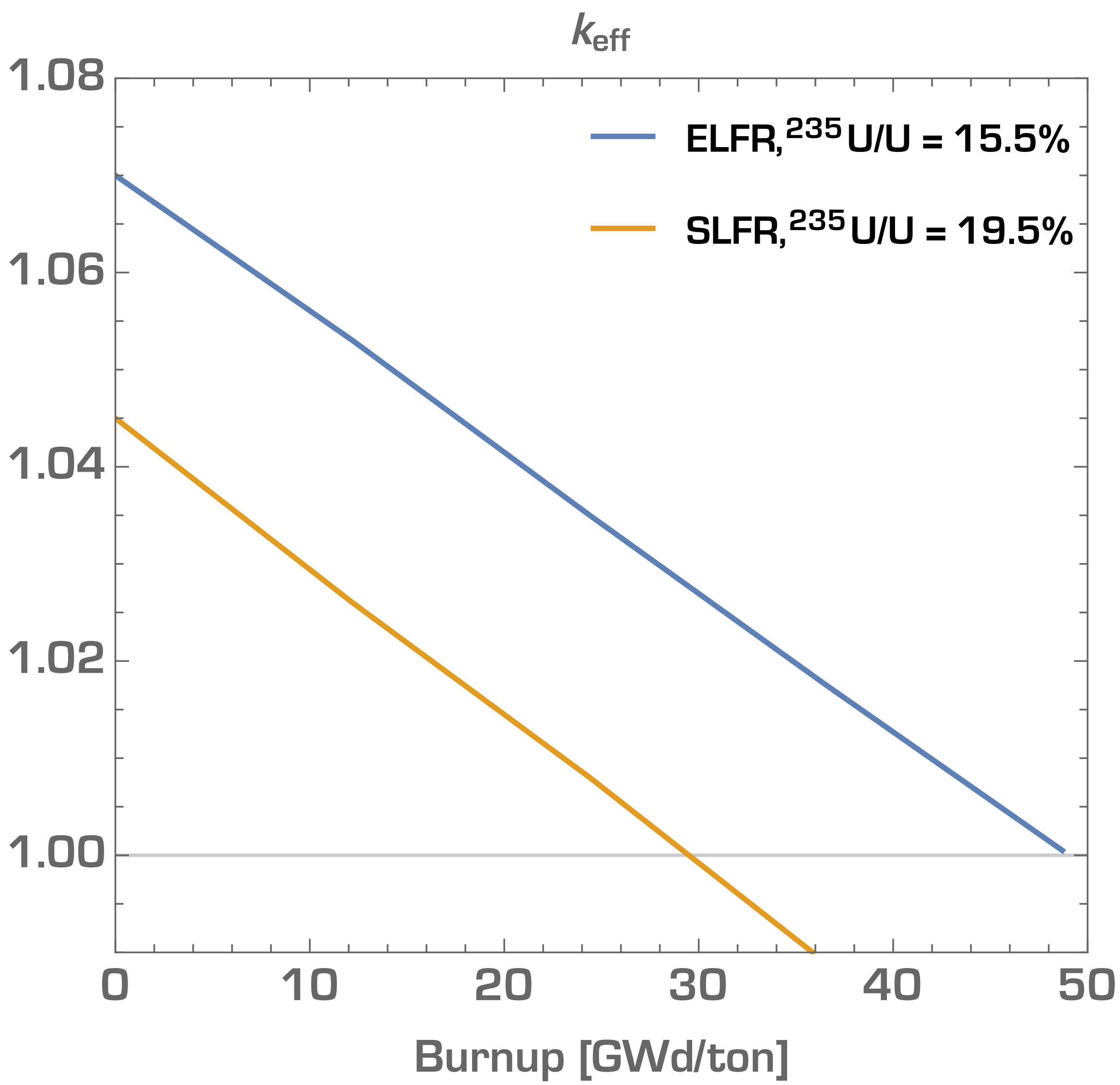
ELFR: 600 MWe

Item	Value
Fuel rods/SA	169
No of SA	433
Fuel height	1400 mm

SLFR:100 MWe

Item	Value
Fuel rods/SA	169
No of SA	151
Fuel height	700 mm

Reactivity loss and burn-up



ELFR enrichment (15.5%) adjusted to reach 50 GWd/t burnup, in parity with PWR.

SLFR: maximum permitted enrichment in commercial reactors: 19.5%

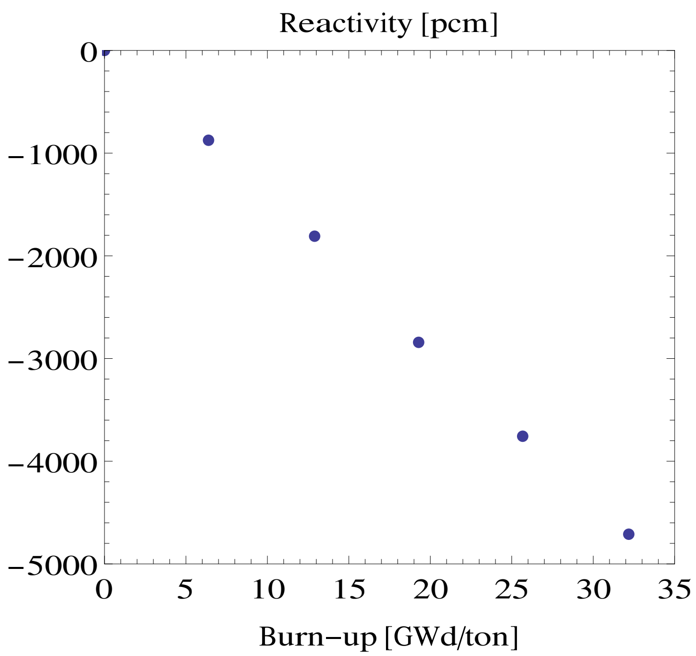
SLFR burnup limited to 36 GWd/ton.

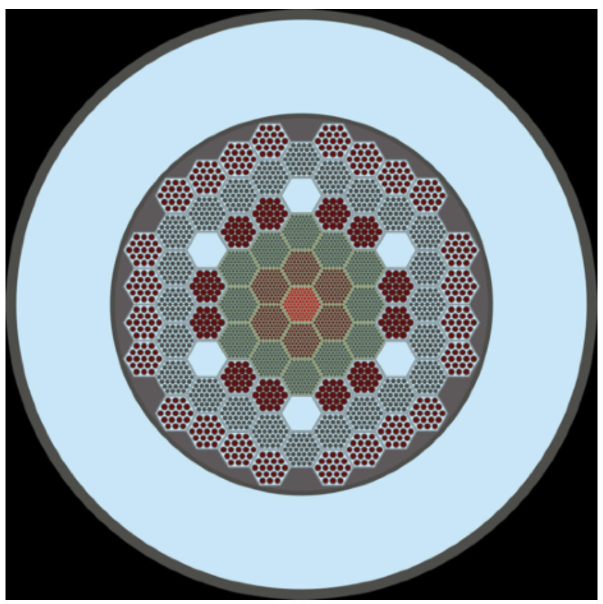
SEALER: smallest possible LFR with low enriched UO_2 fuel

Designed by LeadCold for commercial power production in off-grid applications.

- 19.75% enriched UO_2 fuel
- Vessel dimensions: 2.7 x 6.0 m.
- Core fuel inventory: 2.4 tons
- Core power: 3-10 MWe
- Core life: 9 - 30 years.
- Average fuel burnup: 3.3 %.
- Reactivity loss: 1400 pcm per % burnup

SEALER: Control rod requirement

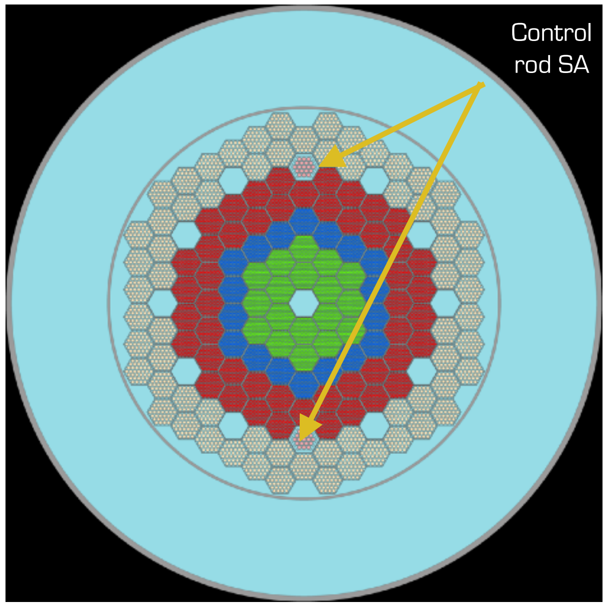


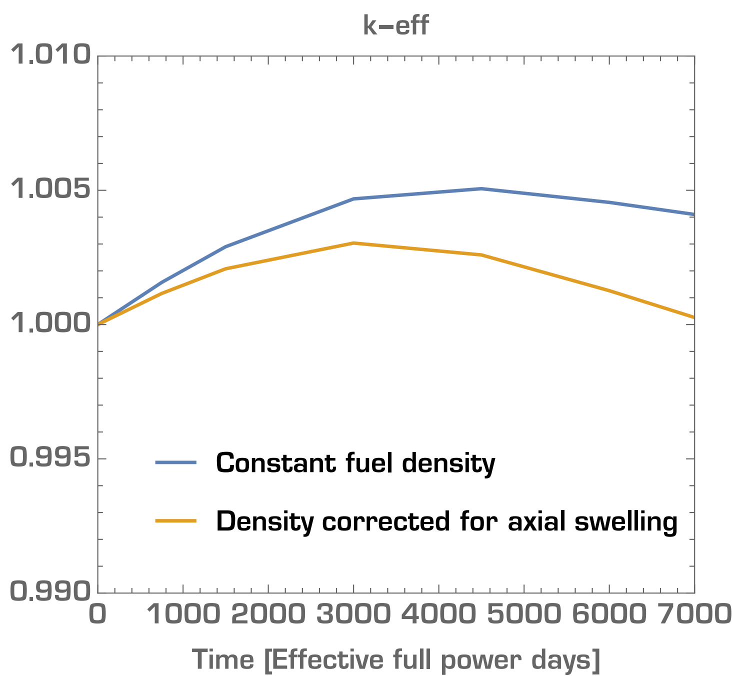


Large reactivity loss – no efficient option for burnable poisons in fast neutron spectrum.

- Maximum control sub-assembly (SA) worth: 0.5 dollars (see safety analysis later in course)
- 1 dollar in SEALER @ BoL ≈ 700 pcm
- Control SA located at periphery of core.
- Single control SA worth 280 pcm
- No of control sub-assemblies required to compensate for 4500 pcm reactivity loss: 12 (non-linear, explain why!)

A small LFR with minimum reactivity swing: SEALER-55





55 MWe reactor designed by LeadCold

With UN fuel, 12% enrichment yields core with a reactivity swing of ≈ 300 pcm for an average burnup of 60 GWd/t

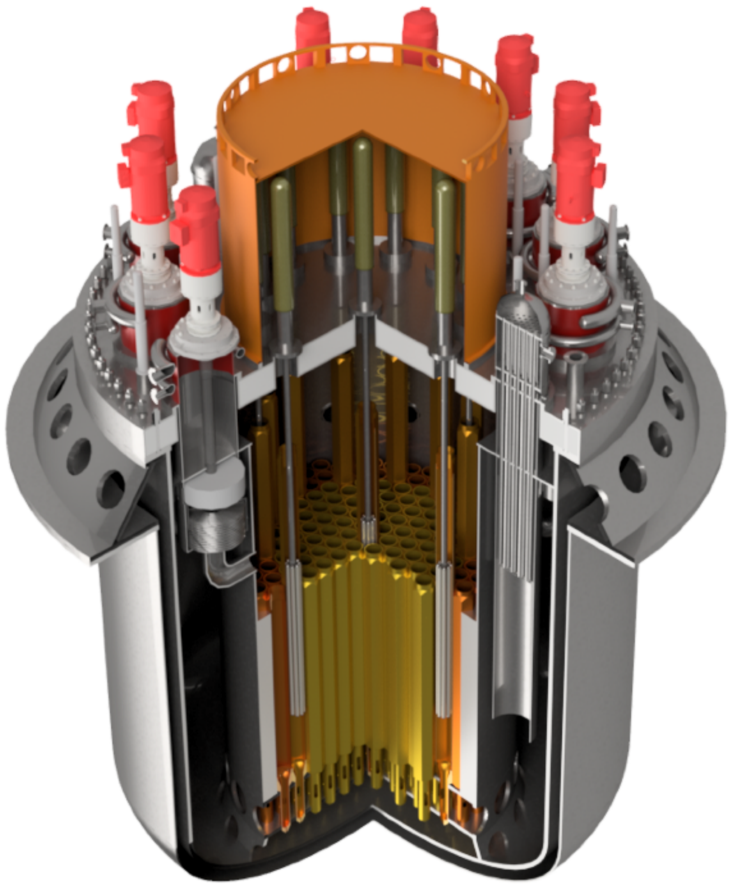
β_{eff} ≈ 600 pcm @ MoL

Number of required control assemblies = 2 (!)

Potential for reactivity insertion is minimised.

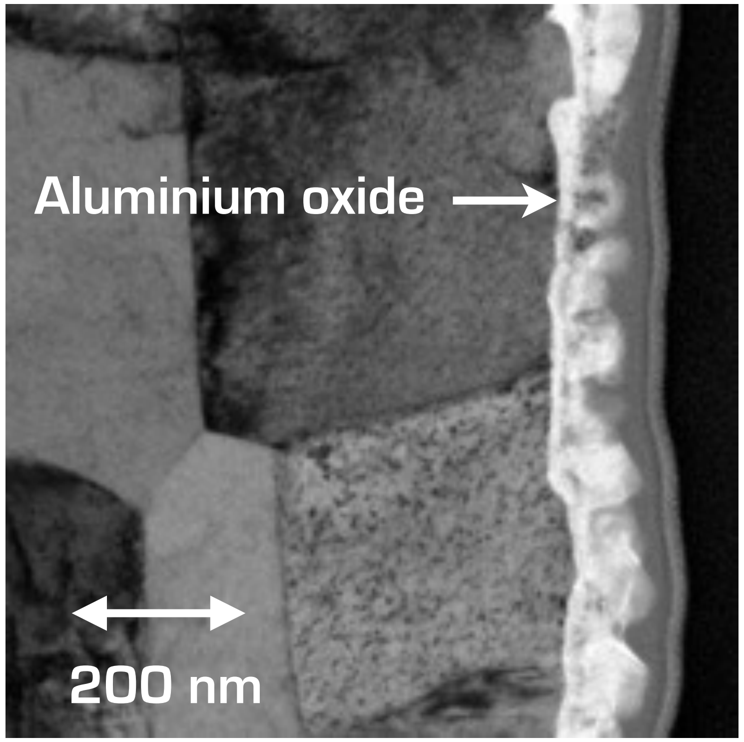
Core cannot go prompt critical!

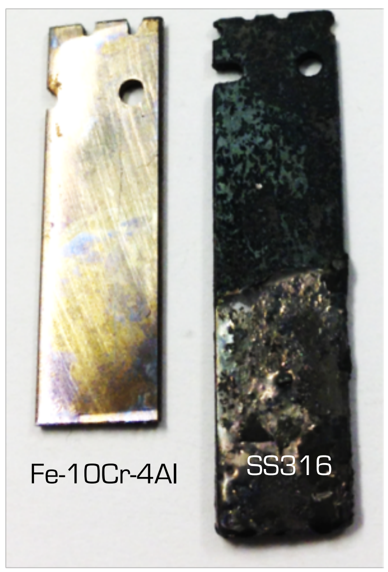
SEALER-55 design parameters



Item	Value
Thermal/electric power	140 MW_{th}/55 MW_e
Core inlet/outlet temperature	420/550 °C
Operating pressure	0.1 MPa
Primary system coolant flow rate	7400 kg/s
No of fuel assemblies	84
Active fuel length	1.3 m
Rod length	1.8 m
Fuel mass	21 ton $U^{15}N$
Fuel average/peak burn-up	60/90 MWd/kg
Fuel life	25 full power years
Reactor vessel height	5.5 m
Reactor vessel diameter	4.8 m

A solution to the corrosion problem

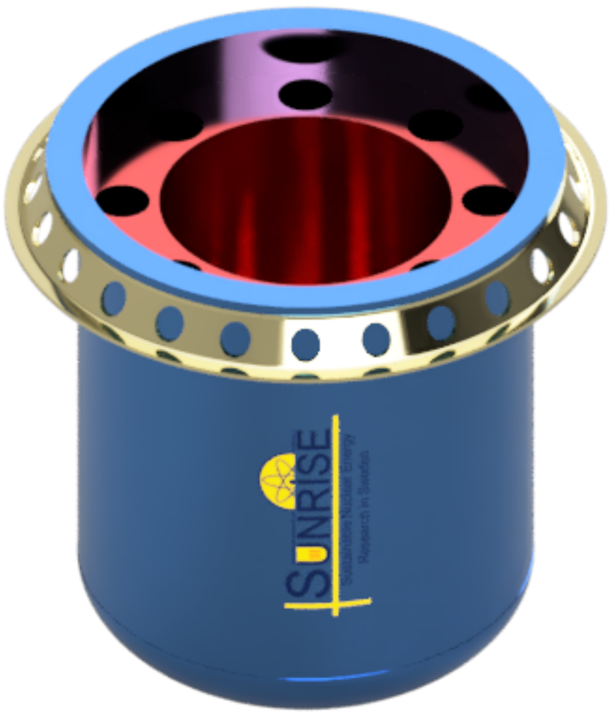




- Stainless steel corrodes rapidly in lead at T > 420°C, irrespective of oxygen control.
- Russian solution (Fe-12Cr-2Si) forms protective oxide, but is strongly embrittled by neutron irradiation at T < 420°C.
- FeCrAl steels form thin aluminium oxide scale on surface.
- Cr content must be ≤ 10% to avoid irradiation embrittlement.
- Reactive elements (Ti, Nb, Zr) added to ensure formation of high quality oxide scale
- Fe-10Cr-4Al-RE alloys developed at KTH successfully tested in stagnant lead for 2 years at 550° and 10 weeks at 850°.
- Kanthal has manufactured 10 ton batch.

SUNRISE

SUNRISE
Sustainable Nuclear Energy Research in Sweden



- 50 MSEK grant from Swedish Strategic Research Foundation (SSF) to KTH, UU and LUT.
- Design of lead-cooled research reactor, intended for operation in Oskarshamn by 2030.
- Includes pump test facility at KTH and qualification of laser welding of alumina forming steels in Luleå

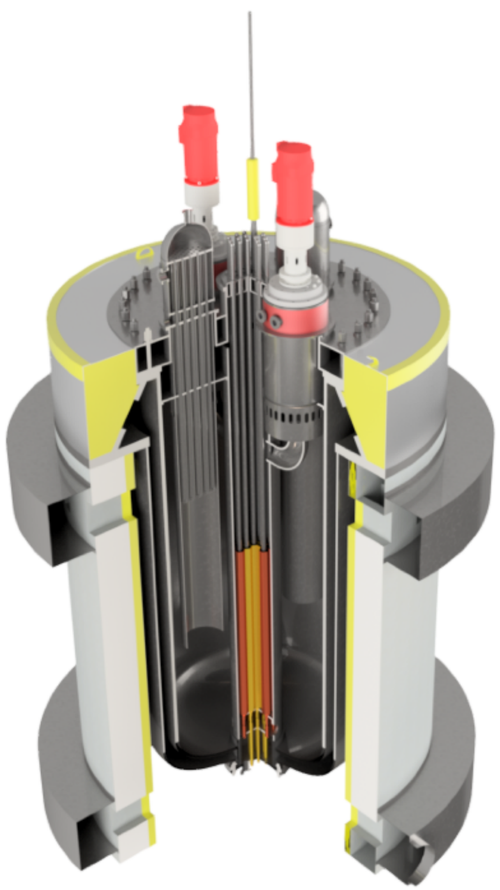
Item	Value
Thermal power	80 MW_{th}
Core inlet/outlet temperature	420/550 °C
No of fuel assemblies	54
Fuel	UO_2 (1st core) and UN
Fuel average burn-up	45 MWd/kg
Fuel life	15 full power years

Stakeholders

uniper
outokumpu
Oskarshamns kommun
Strålsäkerhetsmyndigheten
UNSW
Westinghouse
Jernkontoret
LeadCold
Bangor University
PROMATION nuclear
KANTHAL
Safetech
VATTENFALL
MIT

SEALER-E

- 3.3 MW electrically heated LFR mockup
- Funded with 10 M€ by Swedish Energy Agency
- To be constructed on OKG's site in Oskarshamn
- Intended for operation in 2025



Item	Value
Electrical power	3.3 MW
Core inlet/outlet temperature	420/550 °C
No of heated rod assemblies	7
No of rods/assembly	37
No of pumps	2
No of steam generators	2
No of shut-down assemblies	2
Vessel height	5.5 m
Vessel diameter	2.0 m

Summary & discussion