On going issues on structural materials of LFR

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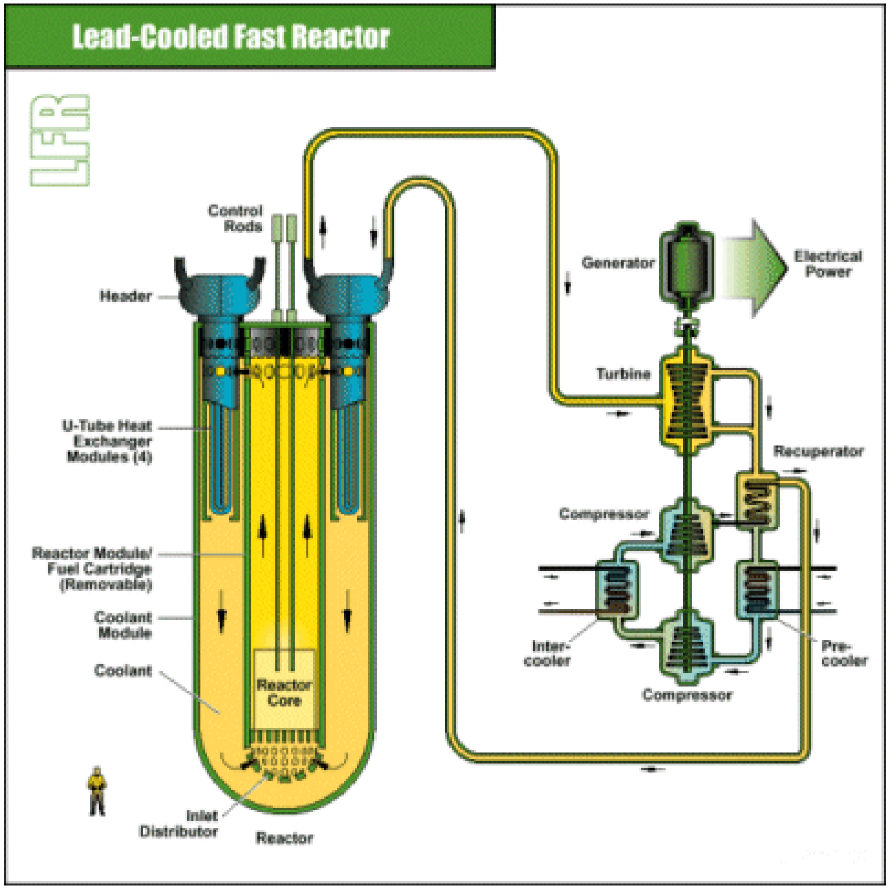
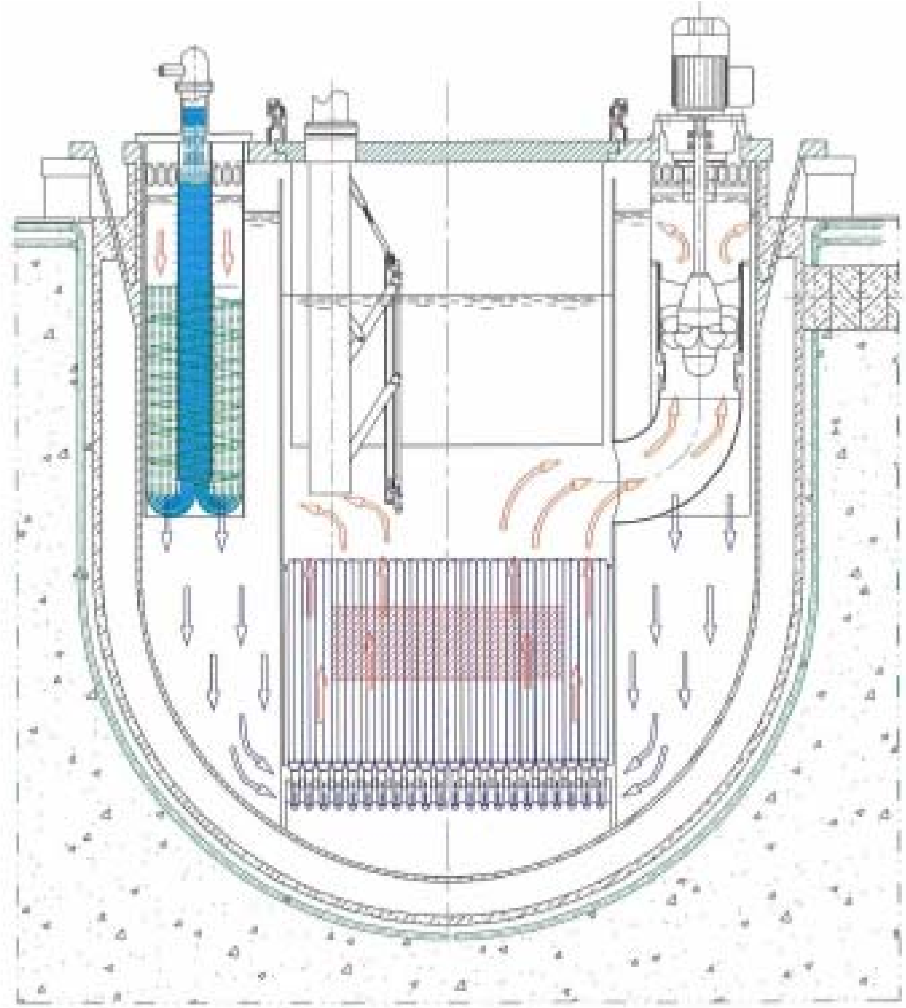


- GEN IV
- Fast Reactor concepts
- LFR – GEN IV
- Design features
- System
- Issues
- Pb/materials issues
- Comparison with SFR
- Conclusions

GEN IV – main goals

Safety & Reliability
Sustainability
Economics
Proliferation resistant & physical protection



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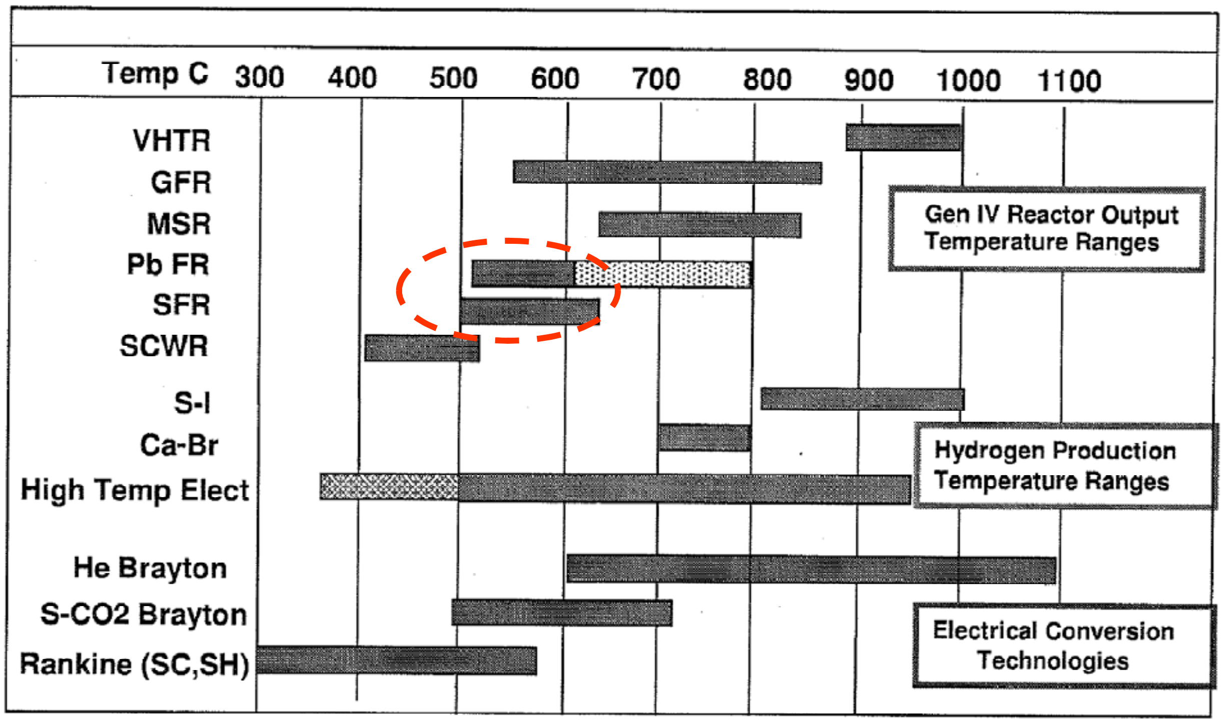
LFR; FR concepts within GEN IV

- **Fuel** as metal or nitride-based
  - containing fertile U & transuranics, full actinide recycle cycle
- Cooled by **lead** by natural convection (high T erosion-corrosion)
- Possibility to **progressively increase the outlet temperature** (800!)
  - as soon as advanced materials become available after qualification work…
  - higher temperatures interesting for efficiency purposes
  - also enables the production of H by thermo-chemical processes



Generation IV energy conversion (from Picard, 2004)

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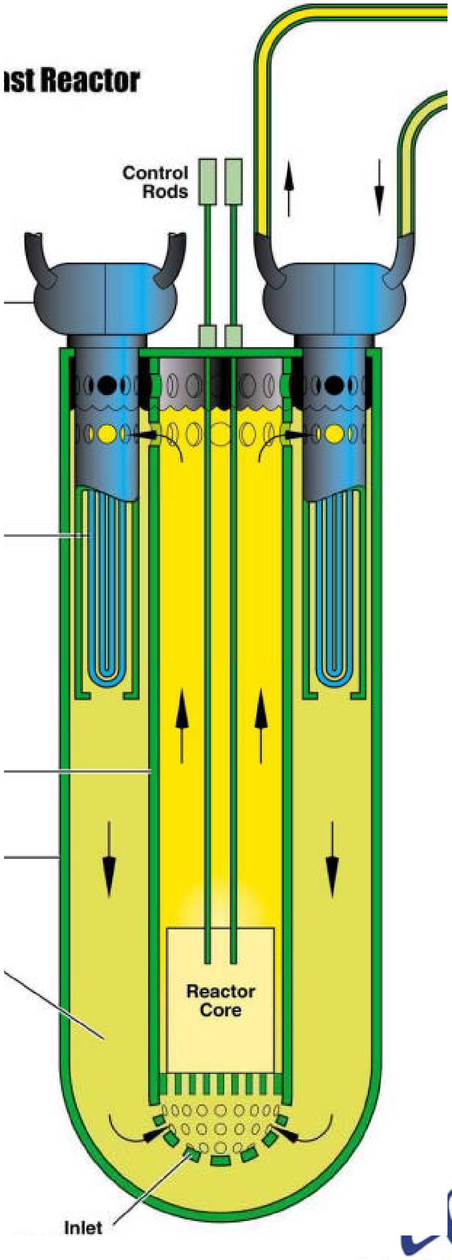
Lead-Cooled Fast Reactor (LFR) system

- **Safety** enhanced by a relatively inert coolant

- Specifically designed for distributed generation of electricity & other energy products (including hydrogen and potable water)

- Top-ranked in **sustainability** (closed fuel cycle) and in proliferation resistance and physical protection (e.g. long-life core)

- Rated good in safety and **economics**



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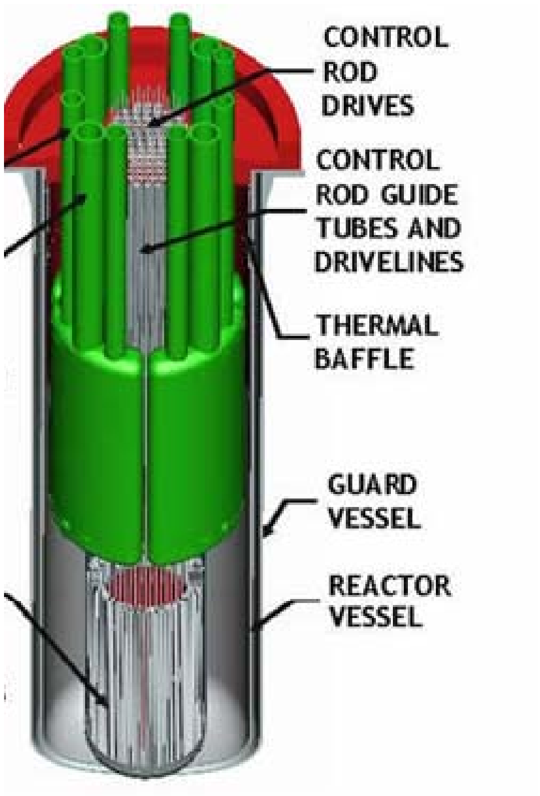
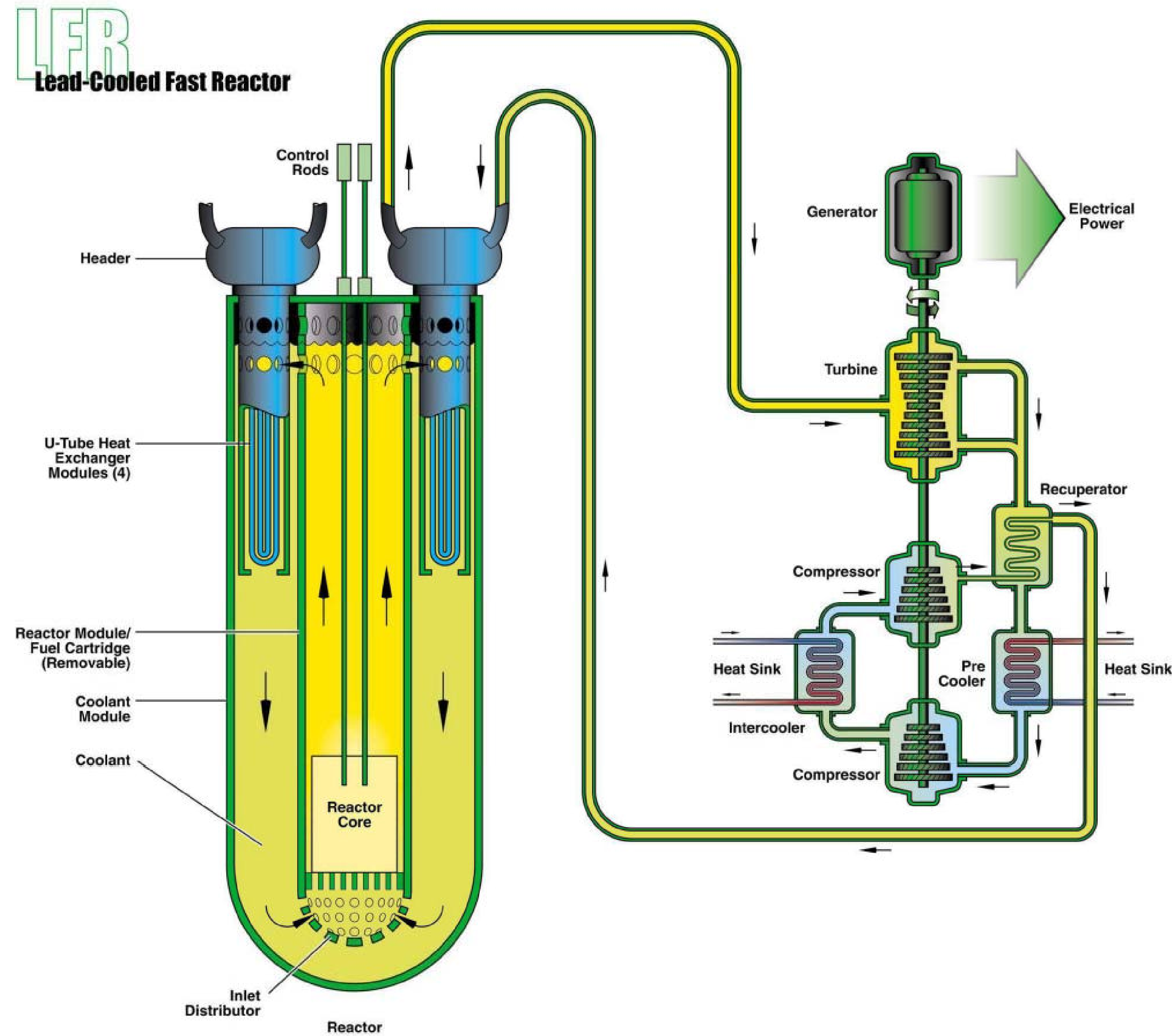
Lead-Cooled Fast Reactor (LFR) system

- Fast-neutron spectrum - closed fuel cycle
- Efficient conversion of fertile U + management of actinides
- Full actinide recycle fuel cycle (central or regional fuel cycle facilities)
- LFR uses lead or lead/bismuth eutectic as coolant

- range of plant ratings
- 50-150 MWe (very long refuelling interval)
- modular system at 300- 400MWe
- large monolithic plant option at 1200 MWe





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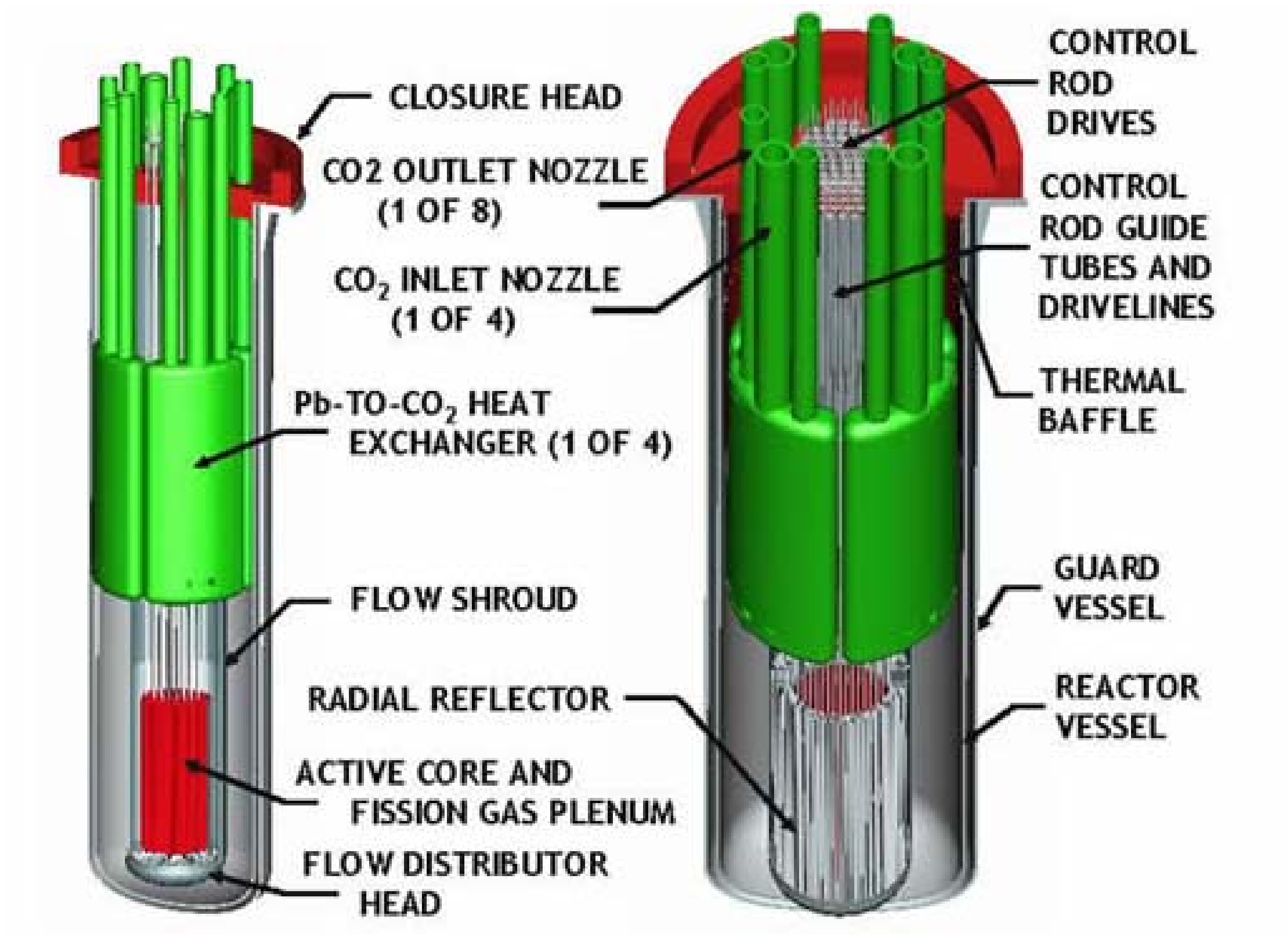
Conceptual 20 MWe (45 MWt) SSTAR system



Key Design data of GIF LFR concepts

	SSTAR	ELSY
Power [MWe]	19,8	600
Converstion Ratio	~1	~1
Thermal efficiency [%]	44	42
Primary coolant	Lead	Lead
Primary coolant circulation (at power)	Natural	Forced
Primary coolant circulation for Decay Heat Removal (DHR)	Natural	Natural
Core inlet temperature [°C]	420	400
Core outlet temperature [°C]	567	480
Fuel	Nitrides	MOX (Nitrides)
Fuel cladding material	Si-Enhanced Ferretic/Martensitic Stainless Steel	T91 (aluminized)
Peak cladding temperature [°C]	650	550
Fuel pin diameter [mm]	25	10,5
Active core dimensions Heigh/equivalent diameter [m]	0.976/1.22	0.9/4.32
Primary pumps	-	N°8, mechanical, integrated in the SG
Working fluid	Supercritical CO2 at 20 MPa, 552°C	Water-superheated steam at 18 MPa, 450°C
Primary/secondary heat transfer system	N°4 Pb-to-CO2 HXs	N°8 Pb-to-H2 O SGs
DHR	Reactor Vessel Air Cooling System + Multilple Direct Reactor Cooling Systems	Reactor Vessel Air Cooling System + Four Direct Reactor Cooling Systems Four Secondary Loops Cooling Systems

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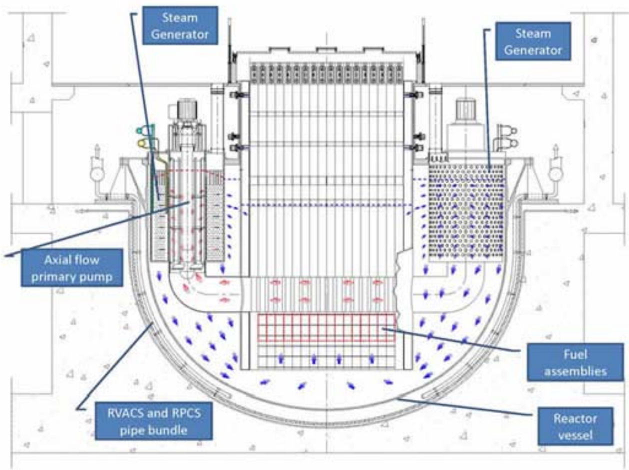
‘Battery’ concept option

- Pb/Bi battery
- small size core (metal or nitride-based fuel)
- reactor module is designed to be factory-fabricated
- containing fertile uranium and transuranics
- transported to the plant site
- very long core life (10-30 year)
- cooled by natural convection
- sized between 120-400 MW_{th}
- reactor outlet temperature of 550 ºC
- possibly ranging up to 800 ºC
- **depending upon the success of the materials R&D !**



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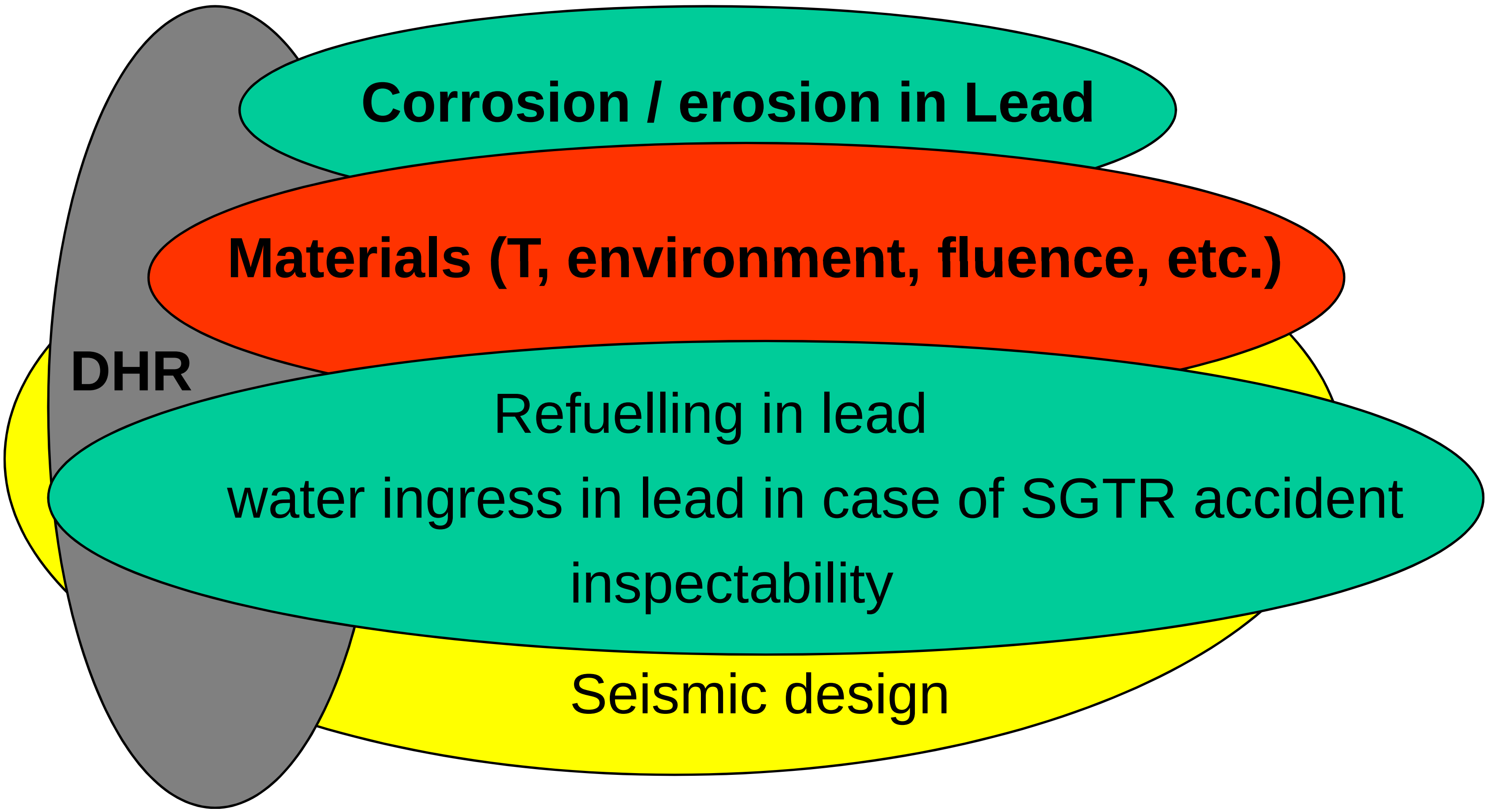
key challenges for the LFR



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Materials Issues

- **Pb and LBE corrosion environment**
- **Oxygen control**
- **Erosion** (m/s range)
- **High fast neutron fluences (4 10^{23} n/cm^2 limit)**
- **Known materials up to 500 ºC (or slightly more)**
- **Evolutionary or new materials to be qualified!**
- **Especially for higher temperatures**
- **Long-core life (corrosion, creep, TF, etc.)**
- **High reliability (limited inspection, core battery)**
- *Low pressure is an advantage*

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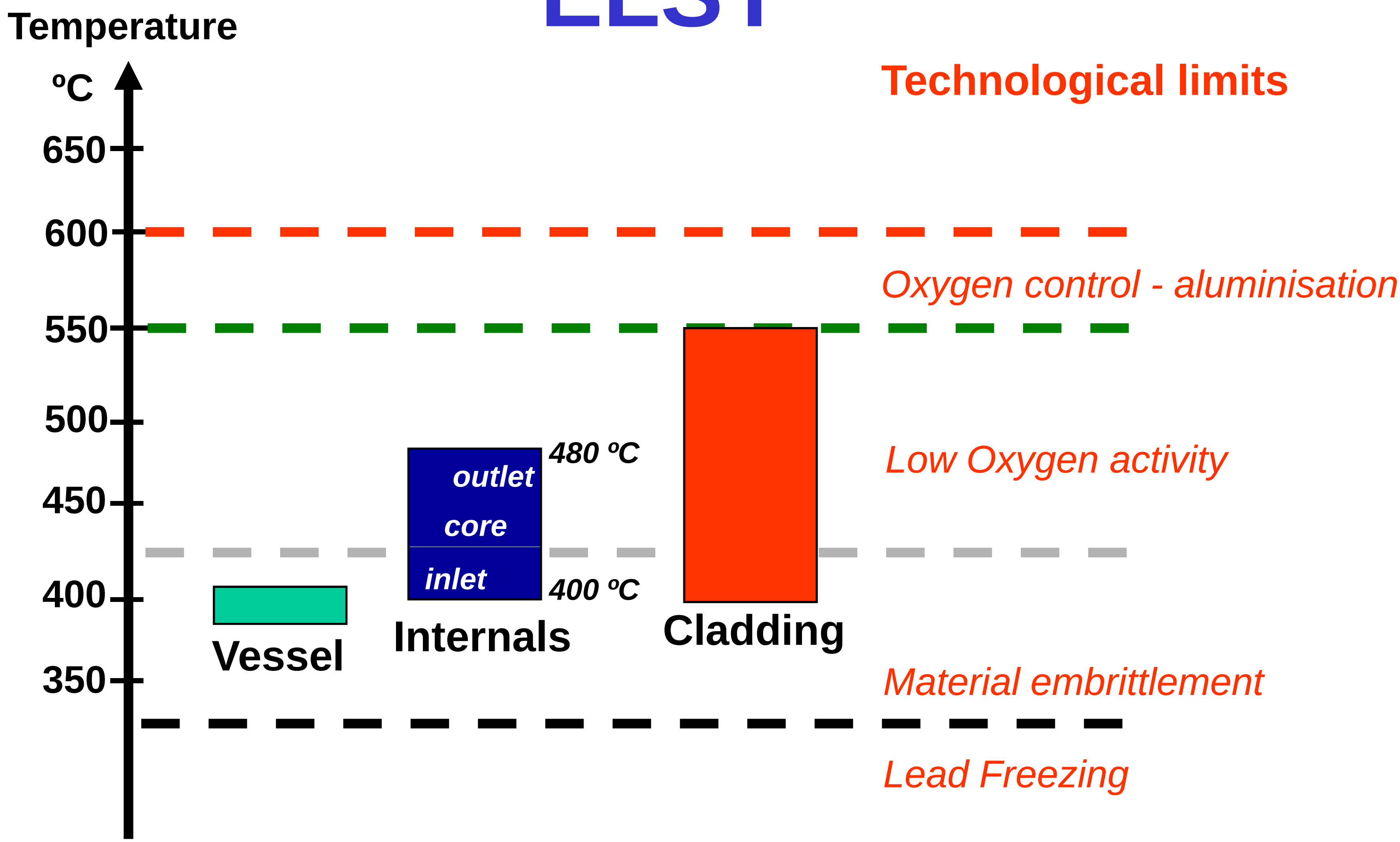
ELSY


Temperature
ºC
650
600
550
500
450
400
350
outlet
core
inlet
480 ºC
400 ºC
Vessel
Internals
Cladding
Technological limits
Oxygen control - aluminisation
Low Oxygen activity
Material embrittlement
Lead Freezing

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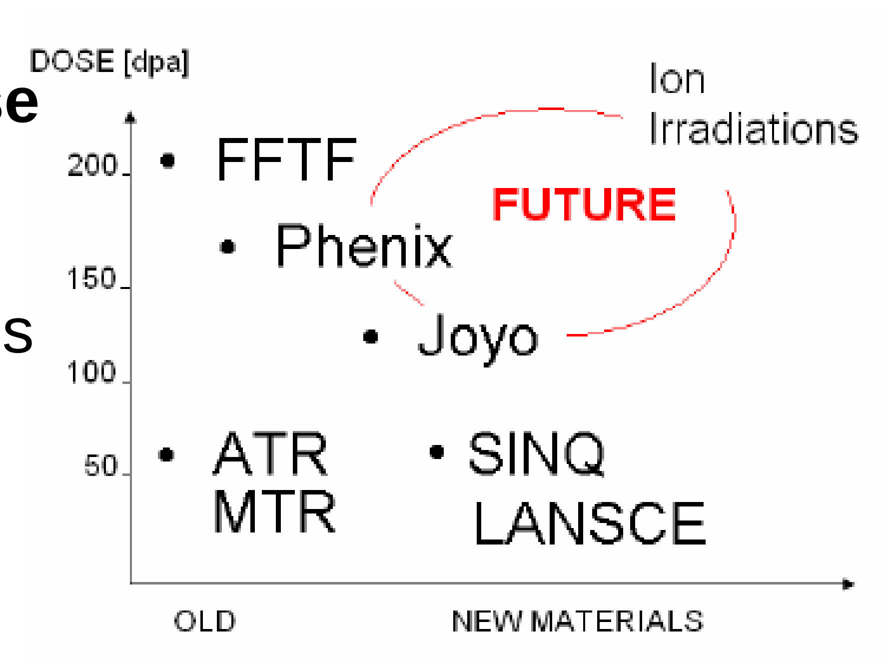
LFR fast neutron fluence

- **Only some dedicated data available**
- **Few data at limit dose**
- **Materials not optimised for Pb corrosion** (T91, MA957, HT9)
- **New evolutionary materials (ODS, Si- Al-enhanced, etc.)**
- **Limited testing facilities**
- **Ion Irradiations for high dose**
- **Medium doses in FR**
  - but limited temperatures
  - or no Pb realistic conditions



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Steels and other metals

- **Ferritic-martensitic** as fuel cladding and structures at high n-flux
- Corrosion tests ongoing (e.g. ADS activity in Europe); stagnant and flowing LBE under different oxygen activities
- Pb is less corrosive than LBE (at same T and coolant speed)
- Preliminary results: corrosion rate negligible < 400°C

- **Austenitic steels** (e.g. AISI 316L) with the appropriate oxygen activity; up 500 °C (large d-base available, especially those of low-carbon grade). Vessel.

-**Martensitic steels** (e.g. T91) probably up to 550 °C, but for limited time (high oxidation rate)

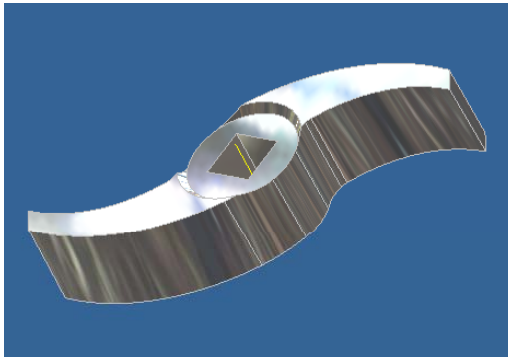
Development of new materials is a very time consuming process
Use as much as possible of available materials
Limiting the qualification work in the new environment

- **FeAl coating** acts as an effective corrosion barrier at temperatures up to 600 °C (controlled oxygen activity)

- Other materials are required for special parts; e.g. components of a mechanical pump

Example:
ADVANCED ALLOYS FOR CORROSION RESISTANCE

Maxthal: **Ti_3SiC_2**



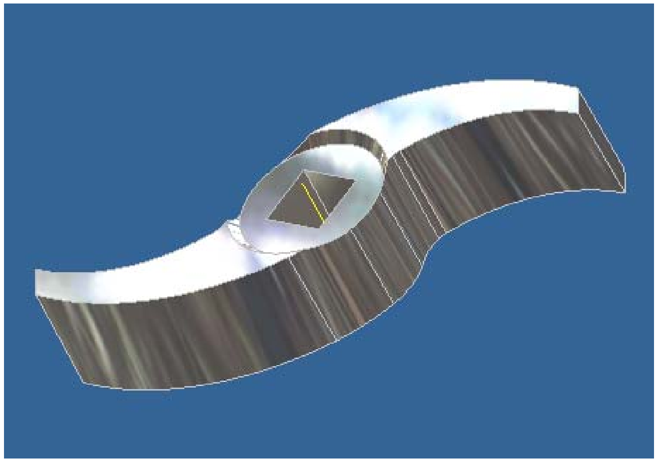
ADVANCED ALLOYS FOR CORROSION RESISTANCE

Example: Impellers (550 °C and Pb relative velocity up to 20 m/s)

Tests at COSTA facility at different temperatures and different oxygen activities, up to 4000h

Materials that "survived" the screening tests 4000h in Pb with an oxygen content of 10^{-8} und 10^{-6} wt % at 550 and 600°C

Maxthal: **Ti3SiC2**



Other options considered:
SiSiC,
Noriloy (KSB): 25Cr, 2Mo, 1.7C, 1Mn, 1Si
Chromium cast steel (KSB): 13Cr, 1.5Ni, 1Mn, 1Si
Martensitic cast steel (KSB): 13Cr, 4Ni, 1Mn, 1Si

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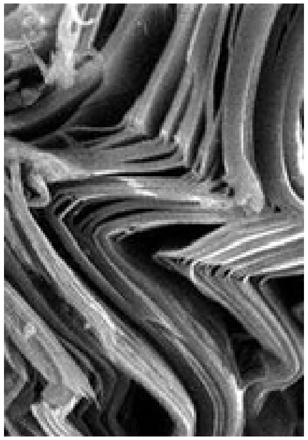
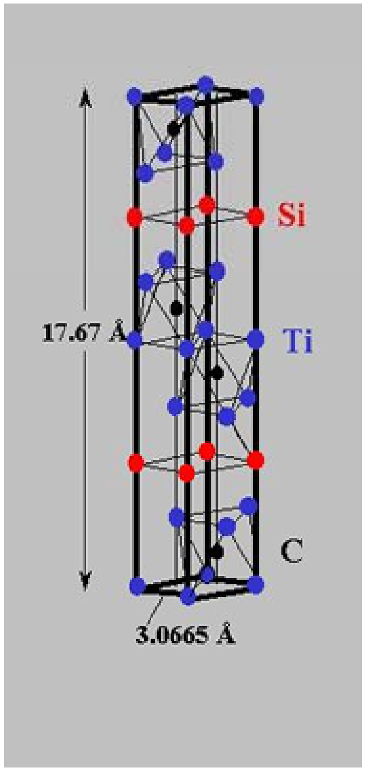
MAXTHAL (Ti_3SiC_2) is a ternary compound. Can be considered as a nano-laminar composites with a layered microstructure where mono-atomic Si-element sheets are interleaved with Ti_3C_2 -layers

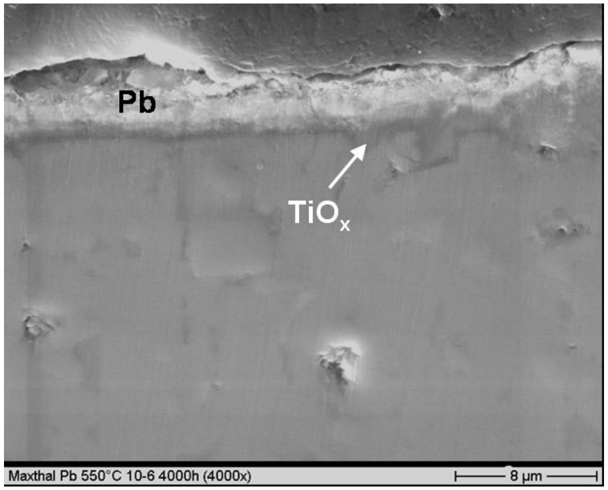
Combines some of the most attractive proprieties of ceramics with those of metals:

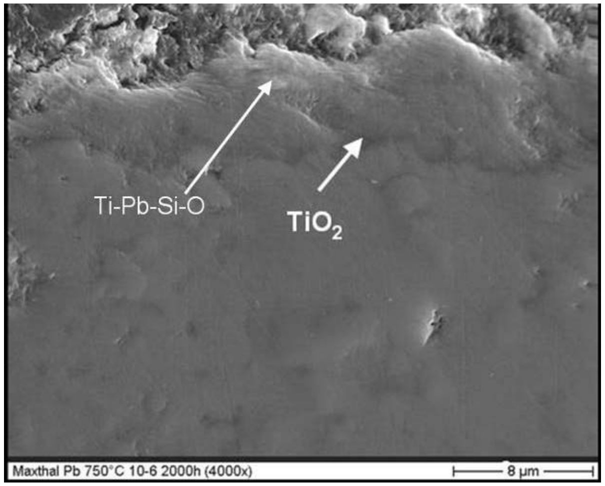
Metals proprieties:
- machineable,
- thermally and electrically conductive,
- resistant to thermal shock,
- deforms plastically at elevated temperatures.

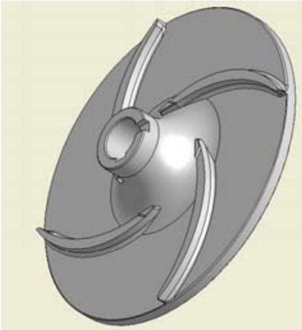
Ceramics proprieties:
- refractory
- oxidation resistant.











Ti_3SiC_2 4000h at 550°C
Oxide scale about 1 µm

Ti_3SiC_2 2000h at 750°C
Oxide scale about 7 µm

Both surfaces are coved by a thin TiO_2 layer
close to the surface Pb inclusions or a compound of Ti-Pb-Si-O.

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LFR vs sodium reactor

- **lead is chemically safer** (no fast reaction with water or air like sodium)
- **LFR requires only two circuits!**
- **Lowers initial investment and increased thermal efficiency**
- **lead is more corrosive to steels than sodium**
- **limited velocities, temperatures allowed** **(2-2.5 m/s and 893 K are feasible)**

- LFR can be started-up and operated in both self-breeder and burner mode, incinerating transuranic wastes from about 2 LWRs of the same power output.

- ***The performance of the SFR can be improved if the primary circuit is pressurized, but that raises other safety concerns, e.g how to contain the sodium in case of leakage.***

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LFR vs sodium reactor

Properties of sodium and lead

Coolant	Na	Pb
ρ [g/cm^3]	0.847	10.48
T_m [K]	371	601
T_b [K]	1156	2023
c_p [kJ/kg×K]	1.3	0.15
$\rho \cdot c_p$[J/m^3/K]	**$1.1 \cdot 10^6$**	**$1.6 \cdot 10^6$**
k [W/m×K]	70	16
v [m/s]	10	2.5

- Grace times longer for LFR (volumetric heat capacity is 50 % larger and higher boiling point higher)

- ULOF accident. LFR safer due to its superior natural circulation and the higher boiling temperature of lead

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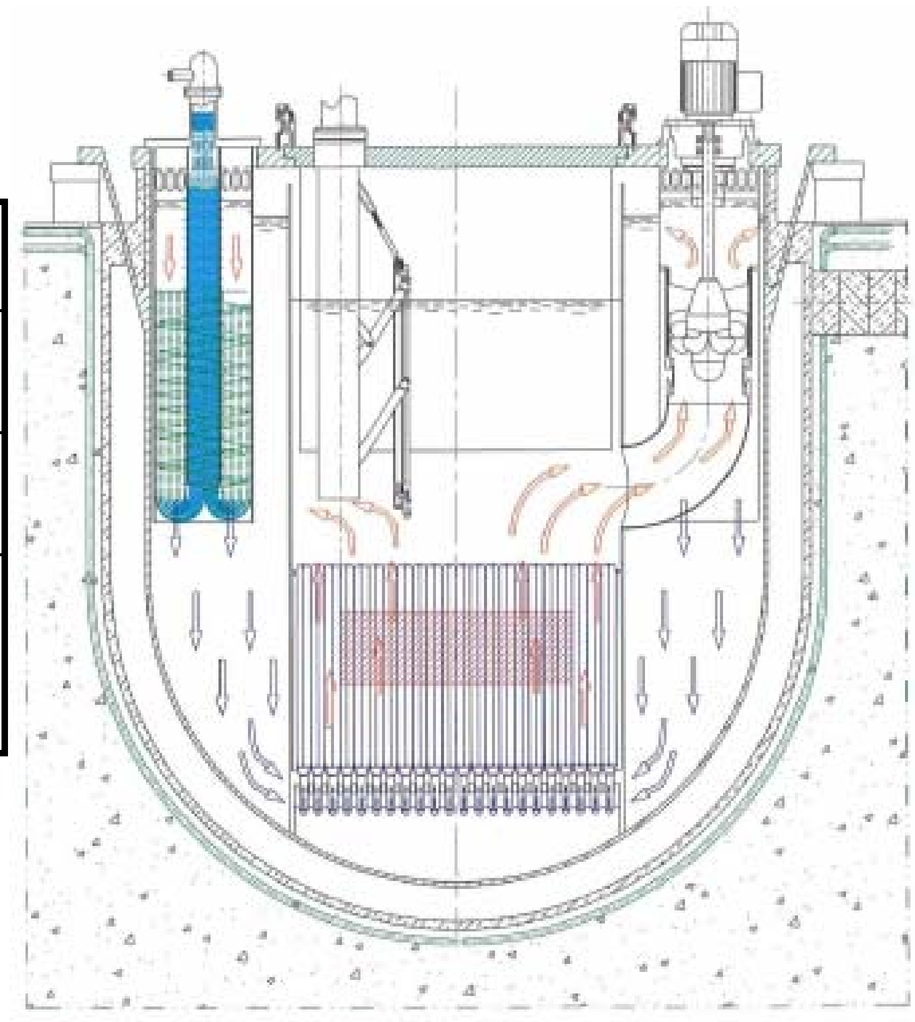
GEN IV – main goals

Safety & Reliability
Sustainability
Economics
Proliferation resistant & physical protection



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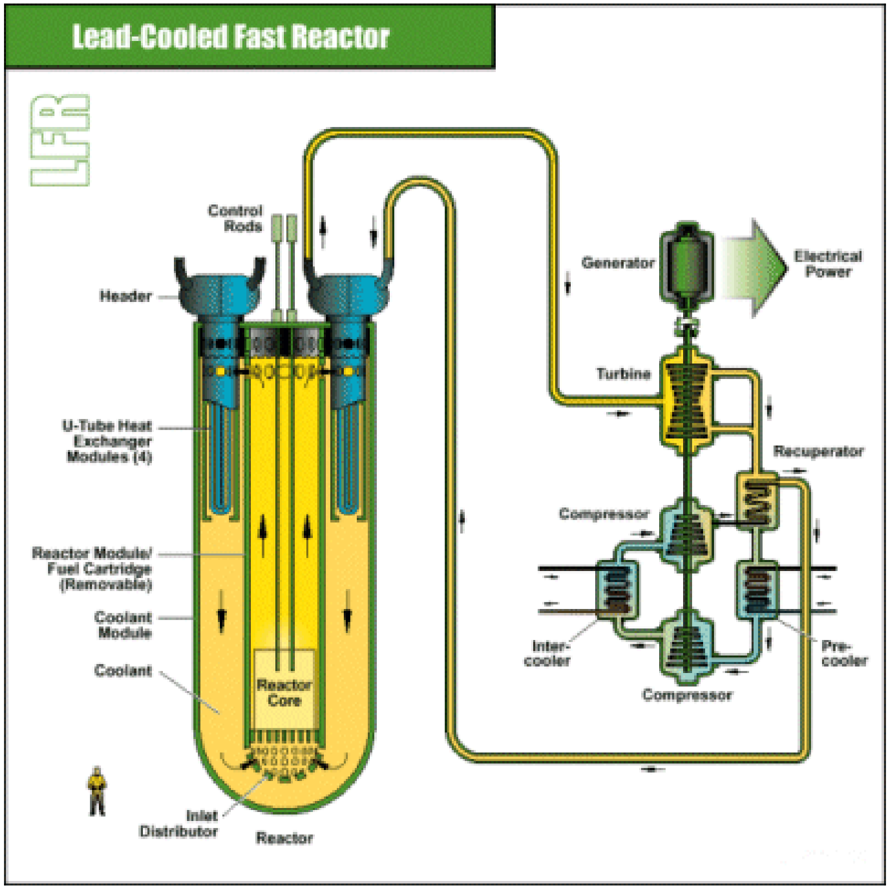

- **GEN IV**
- **Fast Reactor concepts**
- **LFR – GEN IV**
- **Design features**
- **System**
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RESERVES

Safety and reliability are essential priorities in the development and operation of nuclear energy systems. Nuclear energy systems must be designed so that during normal operation or anticipated transients, safety margins are adequate, accidents are prevented, and off-normal situations do not deteriorate into severe accidents. At the same time, competitiveness requires a very high level of reliability and performance. There has been a definite trend over the years to improve the safety and reliability of nuclear power plants, reduce the frequency and degree of off-site radioactive releases, and reduce the possibility of significant plant damage. Looking ahead, Generation IV systems will face new challenges to their reliability at higher temperatures and other anticipated conditions. Generation IV systems have goals to achieve high levels of safety and reliability through further improvements. The three safety and reliability goals continue the past trend and seek simplified designs that are safe and further reduce the potential for severe accidents and minimize their consequences. The achievement of these ambitious goals cannot rely only upon technical improvements, but will also require systematic consideration of human performance as a major contributor to the plant availability, reliability, inspectability and maintainability.

Proliferation resistance and physical protection are also essential priorities in the expanding role of nuclear energy systems. The safeguards provided by the Nuclear Nonproliferation Treaty have been highly successful in preventing the use of civilian nuclear energy systems for nuclear weapons proliferation. This goal applies to all inventories of nuclear materials (both source materials and special fissionable materials) in the system involved in enrichment, conversion, fabrication, power production, recycling, and waste disposal. In addition, existing nuclear plants are highly secure and designed to withstand external events such as earthquakes, floods, tornadoes, plane crashes and fires. Their many protective features considerably reduce the impact of external or internal threats through the redundancy, diversity and independence of the safety systems. This goal points out the need to increase public confidence in the security of nuclear energy facilities against terrorist attacks. Advanced systems need to be designed from the start with improved physical protection against acts of terrorism, to a level commensurate with the protection of other critical systems and infrastructure.

Sustainability is the ability to meet the needs of present generations while enhancing and not jeopardizing the ability of future generations to meet society's needs indefinitely into the future. There is a growing desire in society for the production of energy in accordance with sustainability principles. Sustainability requires the conservation of resources, protection of the environment, preservation of the ability of future generations to meet their own needs, and the avoidance of placing unjustified burdens upon them. Existing and future nuclear power plants meet current and increasingly stringent clean air objectives, since their energy is produced without combustion processes. The two sustainability goals encompass the interrelated needs of improved waste management, minimal environmental impacts, effective fuel utilization, and development of new energy products that can expand nuclear energy's benefits beyond electrical generation.

Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems. In today's environment, nuclear power plants are primarily baseload units that were purchased and operated by regulated public and private utilities. A transition is taking place worldwide from regulated to deregulated energy markets, which will increase the number of independent power producers and merchant power plant owner/operators. Future nuclear energy systems should accommodate a range of plant ownership options and anticipate a wider array of potential roles and options for deploying nuclear power plants, including load following and smaller units. While it is anticipated that Generation IV nuclear energy systems will primarily produce electricity, they will also help meet anticipated future needs for a broader range of energy products beyond electricity. For example, hydrogen, process heat, district heating and potable water will likely be needed to keep up with increasing worldwide demands and long-term changes in energy use. Generation IV systems have goals to ensure that they are economically attractive while meeting changing energy needs

Tentative parameters of ELSY (L.Cinotti)

PLANT CHARACTERISTIC	TENTATIVE PLANT PARAMETERS
Power	600MWe
Thermal efficiency	40 %
Primary coolant	Pure lead
Primary system	Pool type, compact
Primary coolant circulation (at power)	Forced
Primary coolant circulation for DHR	Natural circulation + Pony motors
Core inlet temperature	~ 400°C
Core outlet temperature	~ 480°C
Fuel	MOX with consideration also of nitrides and dispersed minor actinides
Fuel handling	ELSY will seek innovative solutions
Main vessel	Austenitic stainless steel, hanging, short-height
Safety Vessel	Anchored to the reactor pit
Steam Generators	Integrated in the main vessel
Secondary cycle	Water-supercritical steam
Primary Pumps	Mechanical, in the hot collector
Internals	Removable to the greatest possible extent, (objective: all removable)
Inner Vessel	Cylindrical
Hot collector	Small-volume, above the core
Cold collector	Annular, outside the Inner Vessel, free level higher than free level of hot collector
DHR coolers	Immersed in the cold collector
Seismic design	2D isolators supporting the main vessel