Hydromine
Nuclear Energy

LFR-SMR: affordable solutions for all needs

September 24-27, 2019

Milano

PREPARED FOR PRESENTATION TO

Technical Meeting on the Benefits and Challenges of Fast Reactors of the SMR Type

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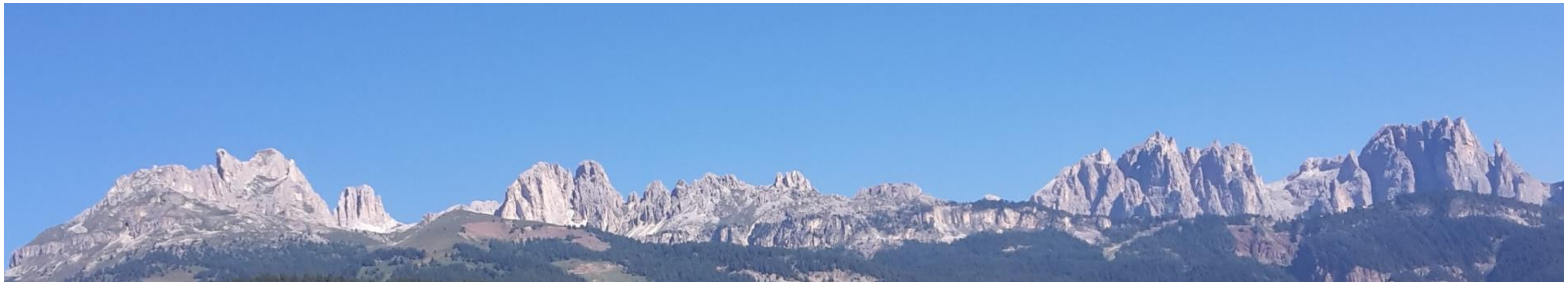
Personal experience of climate changing

For 36 years I have been spending the August holidays in Moena in the Dolomites, UNESCO World Heritage.

- **Several glaciers have disappeared and according to a study of the Italian Consiglio Nazionale delle Ricerche the glaciers below 3,500 meters, are destined to disappear within 20-30 years.**



Personal experience of climate changing

- **An unprecedented windstorm with gusts up to over 190 km / h, on October 27-29, 2018 brought down millions of trees in the woods which had been used by the Republic of Venice to build ships.** The felled trees have saturated the timber market in Italy, and Austria and are also being exported to China!
- **Several resonance trees used by luthiers have also fallen.**
- **Several paths opened by Italian or Austrian soldiers during the First World War are still blocked by fallen trees.**

United Nations Climate Action Summit

To day, the United Nations Secretary-General, António Guterres, hosts the 2019 Climate Action Summit to accelerate actions to implement the Paris Agreement on Climate Change.

Nuclear energy could greatly contribute to the solution of changing climate .

↓

It is our task to provide convincing solutions.

↓

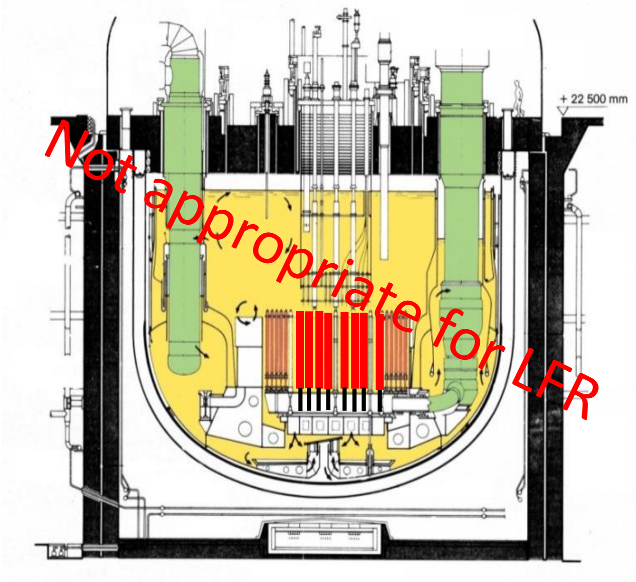
Fast reactors in a closed fuel cycle are a convincing solution:
Each industrial sector is increasingly driven to recycling,
why in nuclear power it should be otherwise!

The use of SFR experience for LFR development

- There has been huge investment in development of SFR, but a very limited deployment: SFR have turned out to be expensive.

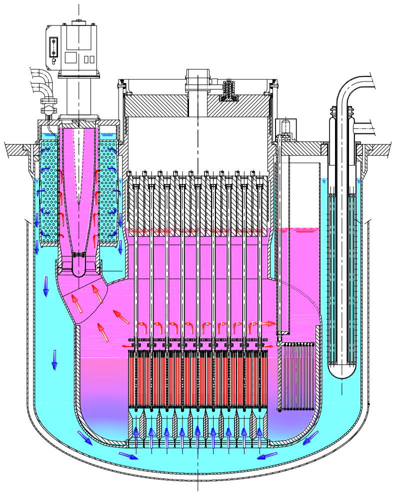
- Fortunately all experience acquired with SFR can be almost entirely used for the development of the LFR, which uses the same fuel; behaves functionally similar; presents similar thermal-hydraulic and mechanical aspects but seems to be more promising in term of cost and safety.

- In a LFR, it is possible to eliminate the intermediate loop and to design a more compact primary system, thanks to innovative components in an appropriate configuration.



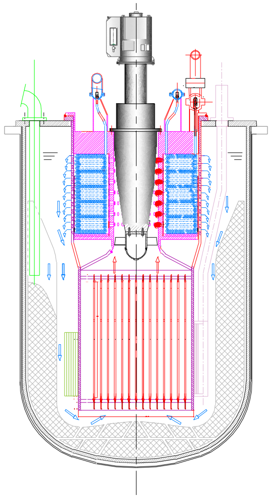
SPX1-sodium cooled

New proposed configurations



LFR-AS-200

AS stands for Amphora Shaped referring to the shape of the inner vessel.



LFR-TL-5

TL stands for Transportable reactor and Long-life core.

New configuration of LFR-AS-200

Economics

Compact primary system

< $1 m^3$/MWe !!

(~ 4 times less than SPX1, 2-3 times less than integrated PWRs)

- Elimination of components no more needed
- Innovative components
- Reversal of traditional engineering solutions

Compact reactor building

- No intermediate loops
- Compact primary system
- No risk of LOCA

Resistance to seismic loads

Short reactor vessel: only 6,2 m

Safety

New steam generator to minimize the effect of the steam generator rupture accident

Availability

No in-vessel refueling machine

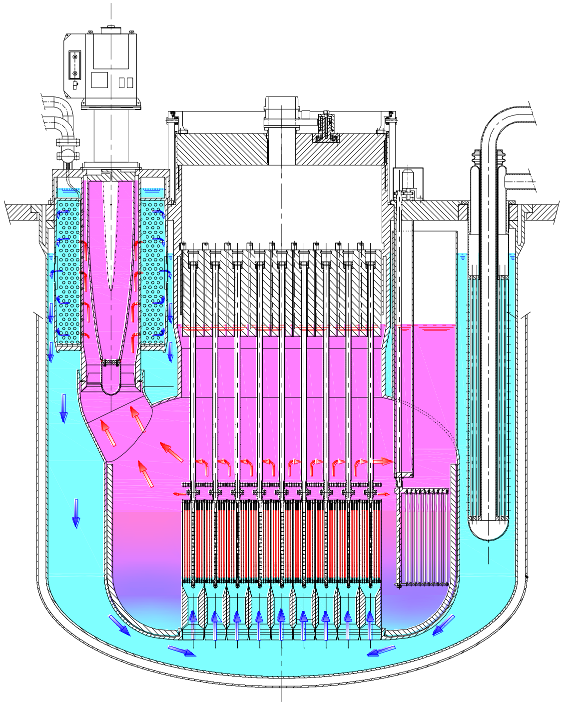
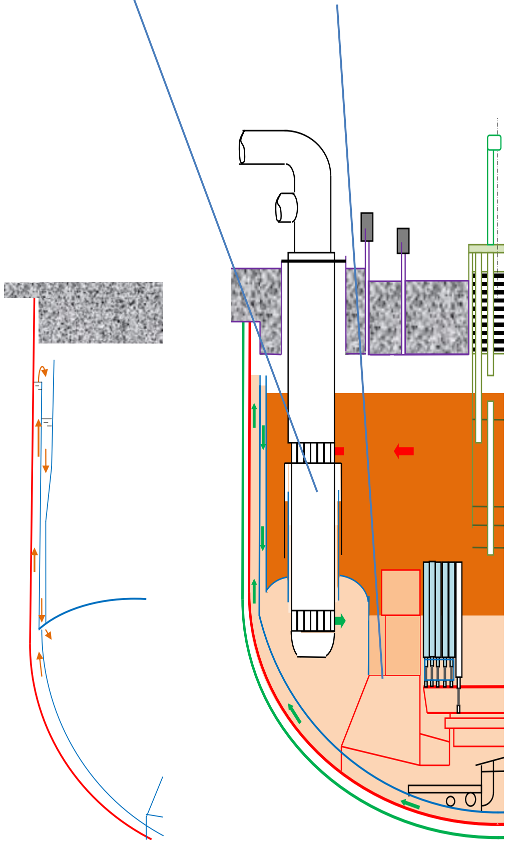


Table1: Main design parameters of LFR-AS-200

Core power (MWth)	480
Electrical power (MWe)	200
Core inlet/outlet T (°C)	420/530
Primary loop pressure loss (bar)	1,3
Secondary cycle	Superheated steam
Turbine inlet pressure (bar)	180
Feed water /steam temperature (°C)	340/500

The compact Spiral-Tube SG

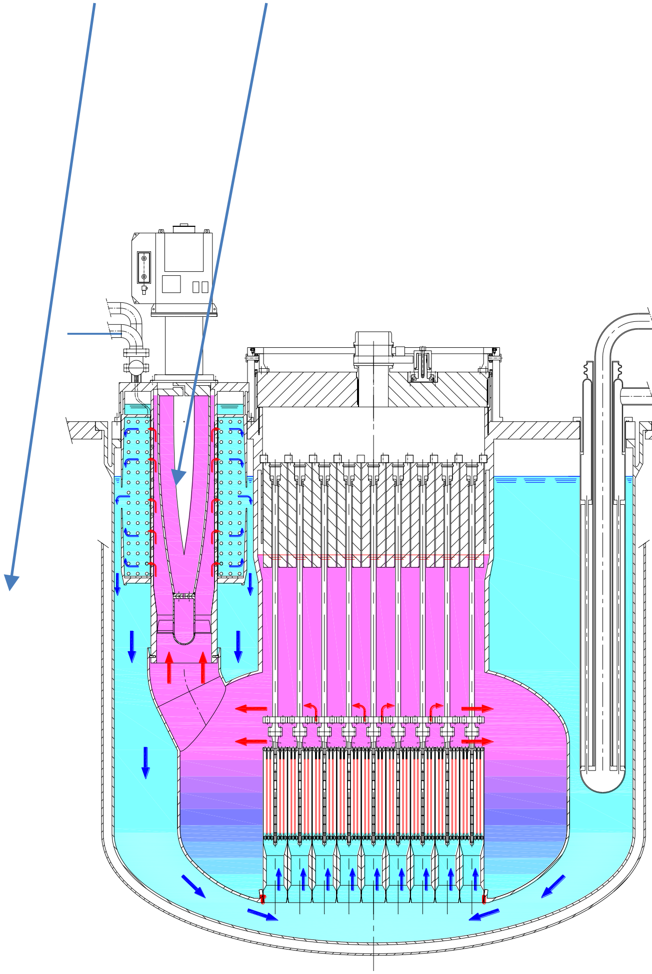
From:
long IHX with top inlet window
and bottom outlet window.



To:
short Spiral-tube SG with bottom inlet and top outlet.

Advantages:

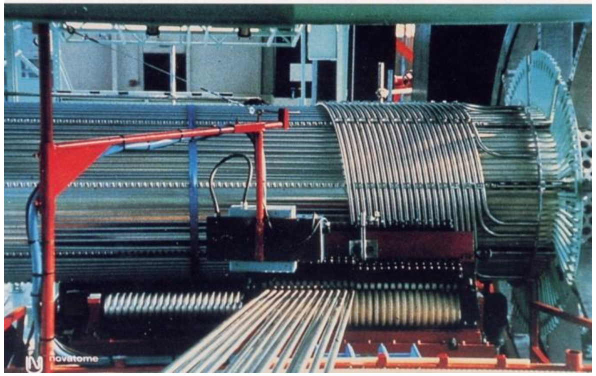
- No collectors inside the vessel
- Short, compact SG,
  reduced RV height.
- No "Deversoir",
  reduced RV diameter.
- No risk of steam release
  deep in the melt and
  large lead displacement.
- No risk of cover gas
  entrance into the core.



The Spiral-Tube SG

The Spiral-tube SG (STSG) is mechanically forgiving as the Helical-tube SG (HTSG), but more compact and of easier manufacturing.

LFR-AS-200 MAIN SG PARAMETERS	
Number of SGs and Pumps	6
Outer diameter of tubes [mm]	18
Number of tubes	100
SG shell-side pressure loss [bar]	0.2
Active length of the tubes [m]	34

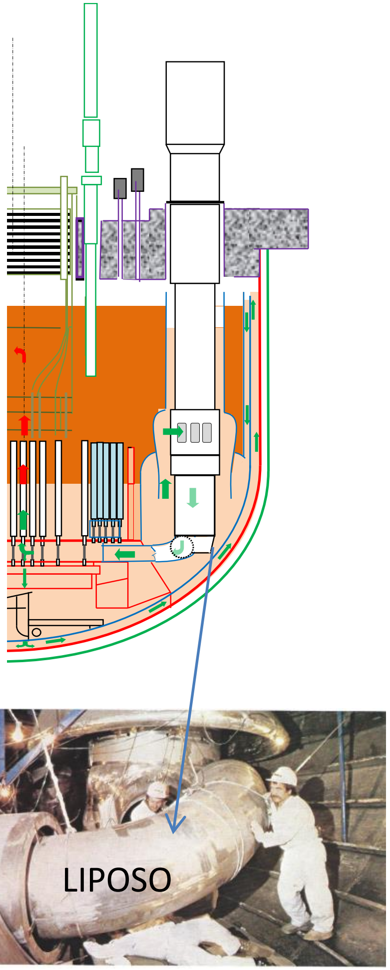


Manufacturing of the SPX1 SG

Mock up of a STSG after testing at Saluggia ENEA lab.

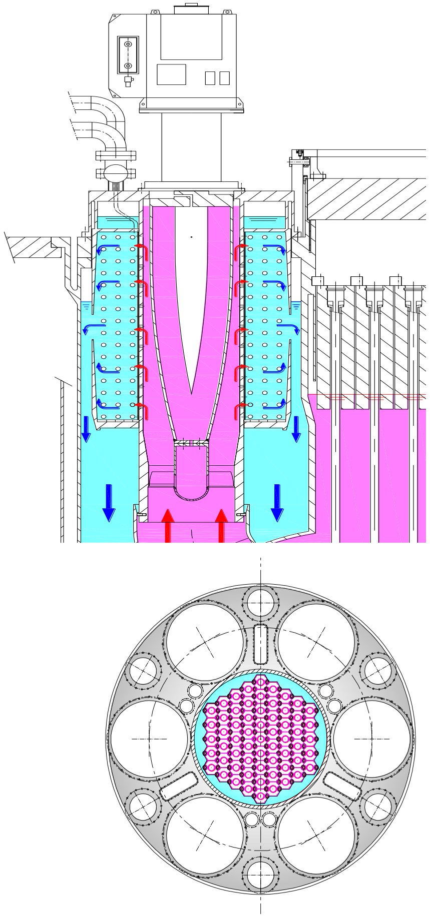
The STSG-Pump assembly, the key for compactness

From:
Pumps in the cold collector, in-between the SGs, with long shafts and in-melt bearings.



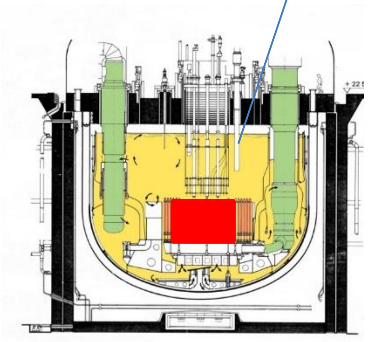
To:
Pump in the hot collector, integrated in each SG to feed the SG, with large hollow shaft filled with lead, and no in-melt bearings.

Advantages:
- Use of available space inside the SG, reduced RV diameter.
- No bearings in lead.
- High mechanical inertia for mild transients from forced to natural circulation.
- Core fed by the hydrostatic head Δh between cold and hot collector, no "LIPOSO"



The Fuel Assembly with extended stem

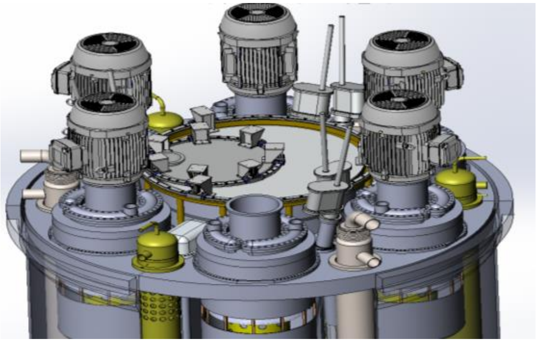
From:
Fuel Assemblies immersed in the melt handled by an in-vessel + ex-vessel Refueling Machine.

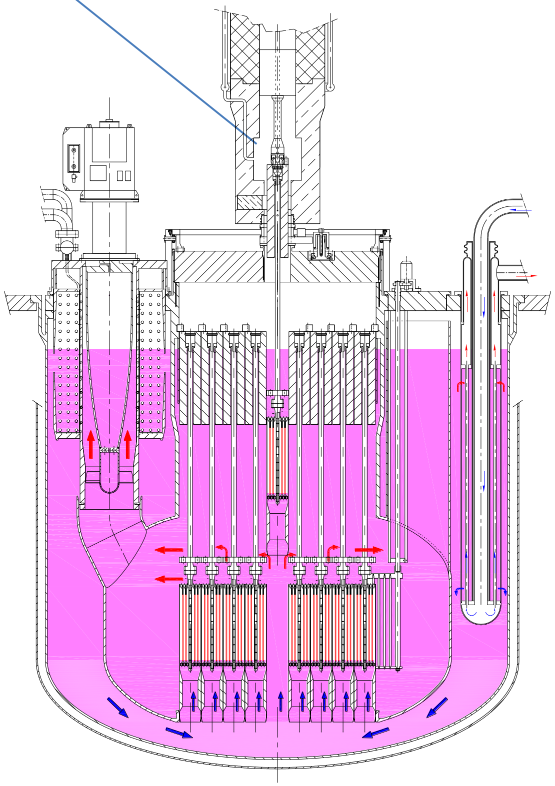


To:
Fuel Assemblies with stem extended above the lead free level handled by an ex-vessel Refueling Machine.

Advantages:

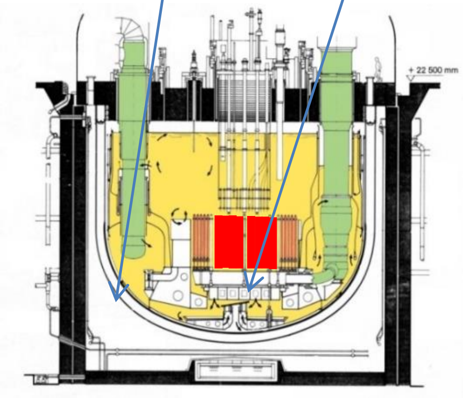
- No in-vessel Refueling Machine, increased reliability.
- No Above Core Structure, reduced RV diameter.
- Buoyance compensated by the emerged portion of the stem.





The self-sustaining core

From:
Fuel Assemblies (FA) supported
in lead at the bottom by Diagrid
and Strongback.

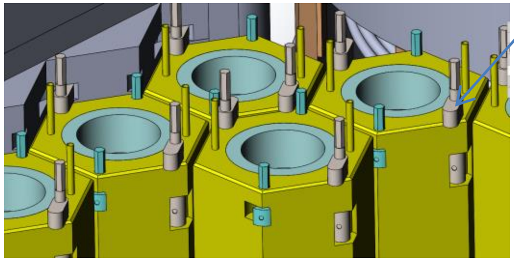


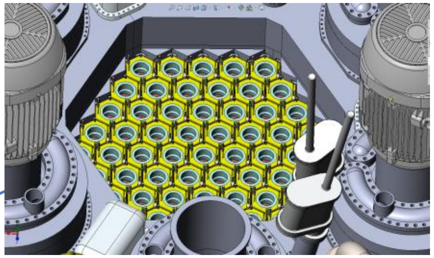
To:
Core anchored at the top to a barrel
in gas space.

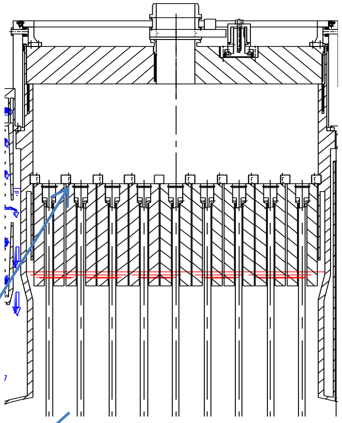
Advantages:

- No Diagrid.
- No Strongback.
- FA vertical loads are supported by structures not subject to thermal transients and neutron damage.

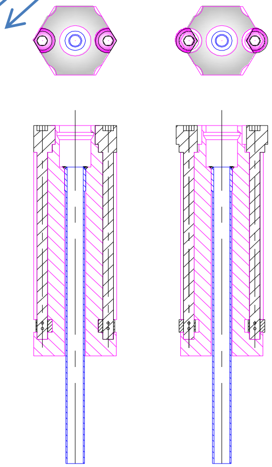
  (barrel, reactor roof, vessel flange, reactor pit).
- No need of disconnecting all FAs instrumentation at refueling.





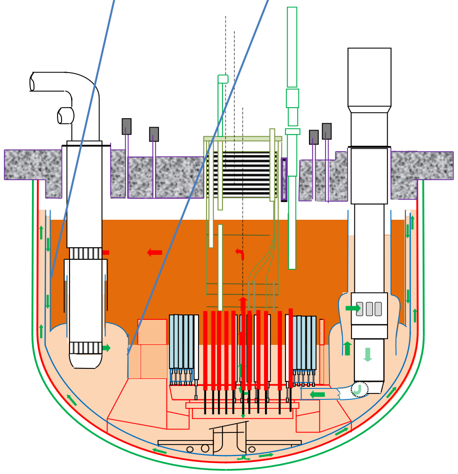


Cams

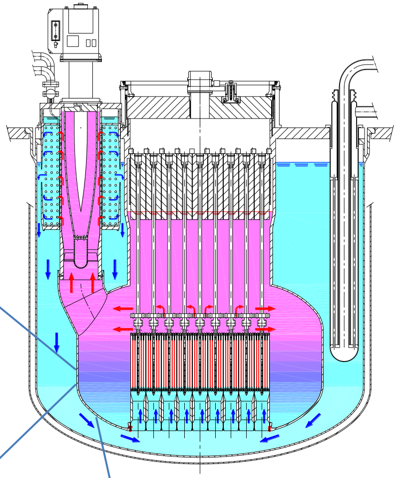


The Amphora-Shaped Inner Vessel

From:
Inner Vessel, large at top and smaller at bottom, containing Shielding Assemblies (and Breeding Assemblies).

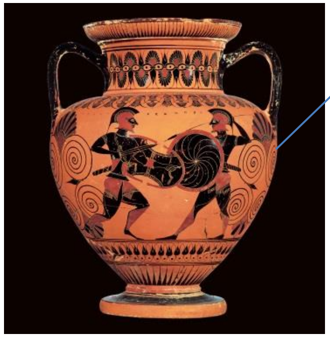


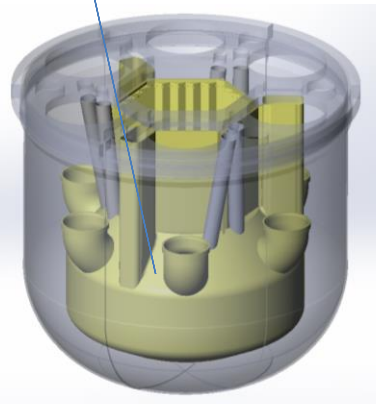
To:
Amphora-Shaped Inner Vessel, no Shielding Assemblies (and no Breeding Assemblies).



Advantages:

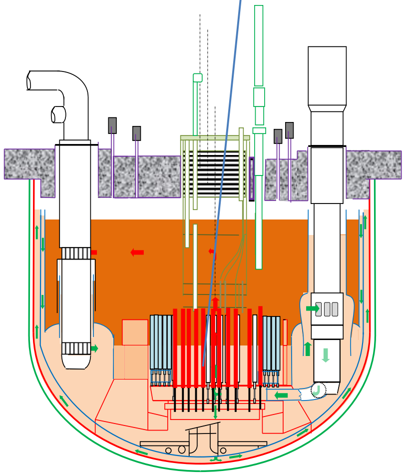
- No Shielding Assemblies.
- Reduced RV diameter,
- Increased availability.
- Reduced waste inventory.



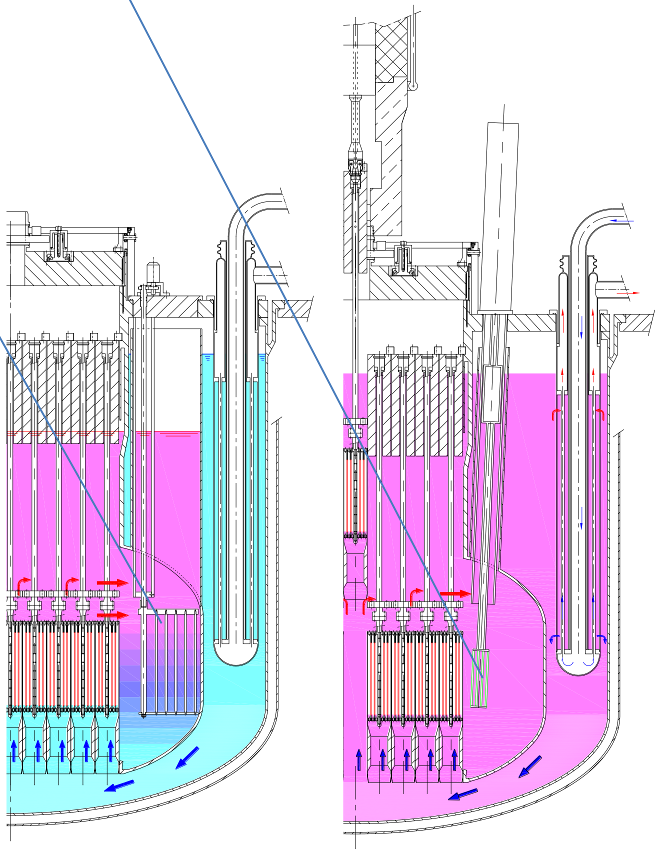


The ex-core control rods

From:
In-core control and shut down rods.



To:
Ex-core control and shut down rods.

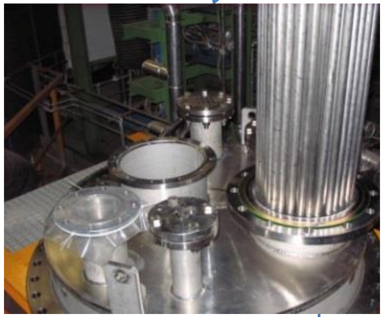


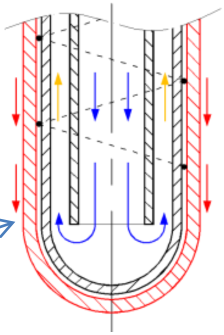
Advantages:

- Reduced core dimensions.
- No disconnection of rod drives for refueling.

Passive DHR systems for safety and resistance to cyber attacks

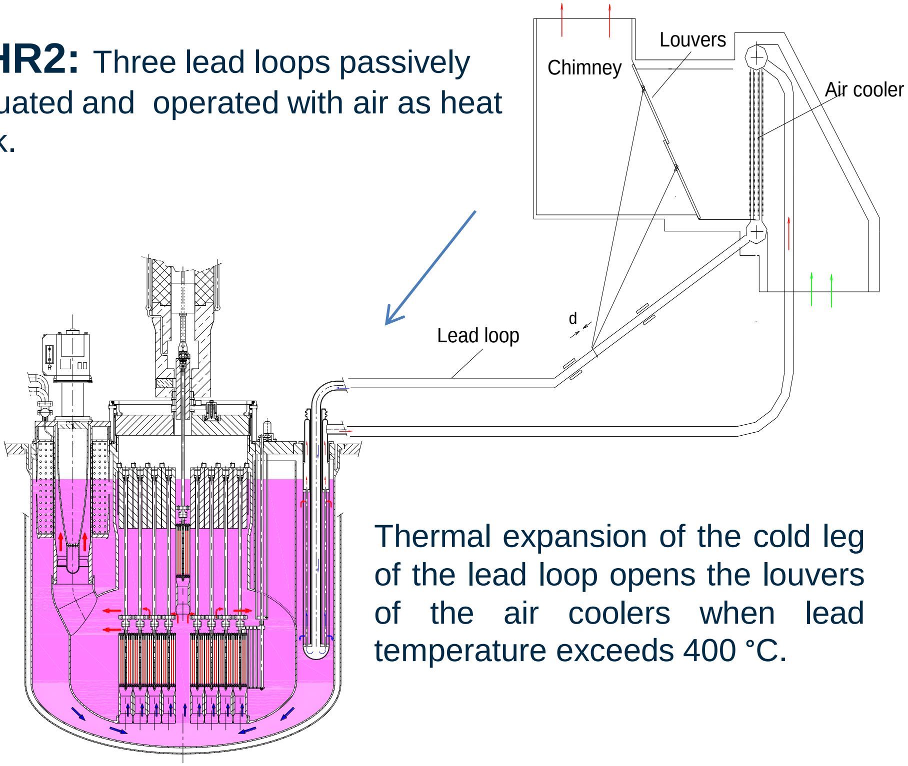
DHR1: Three water-steam loops passively operated with water as heat sink.





Lead-water, double-wall bayonet-tube bundle heat exchanger at Brasimone site.

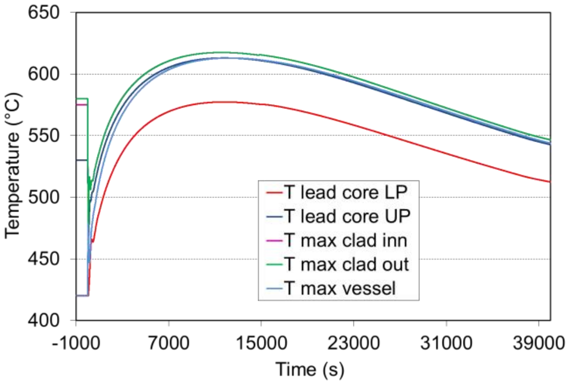
DHR2: Three lead loops passively actuated and operated with air as heat sink.



Thermal expansion of the cold leg of the lead loop opens the louvers of the air coolers when lead temperature exceeds 400 °C.

Fukushima-like accident (complete station blackout, no active systems available)

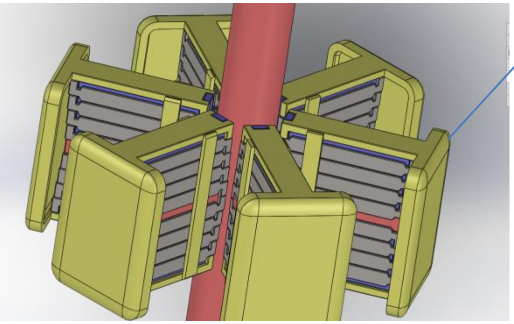
- reactor properly shut-down
- proper passive cooling
- structural integrity ensured



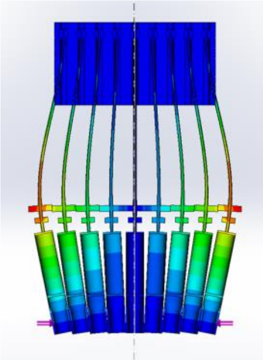
Passive shut down for safety and resistance to cyber attacks

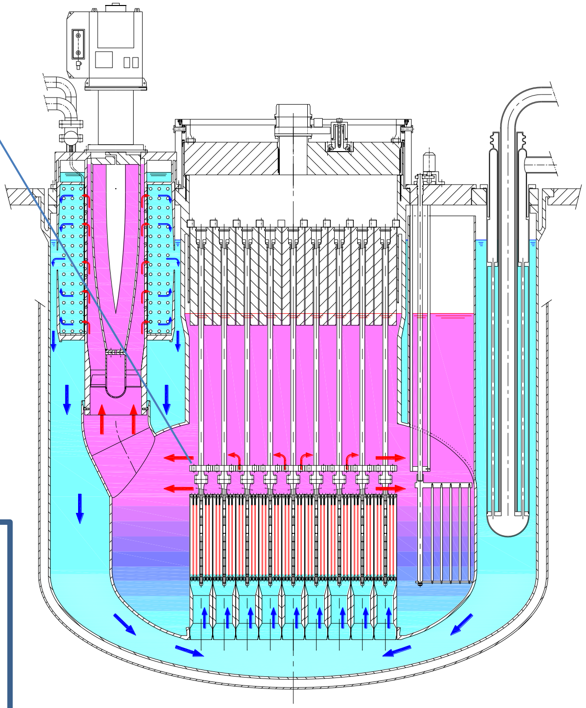
Logics and operators backed up by passively actuated systems to shut down the reactor.

In a LFR there is a margin of hundreds K between the operating temperature and the safety limit, hence, e.g., thermal expansion can be used to open the core and shut down the reactor in case of failure of logics or of operator intervention.

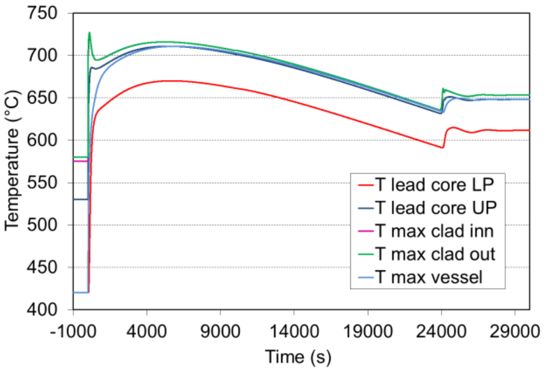


Bi-metallic expansors open and shut down the core when temperature exceeds normal operating limits.





Passive shut down and passive DHR systems to face the Unprotected Loss Of Offsite Power (ULOOP).



Simplicity of the LFR-AS-200

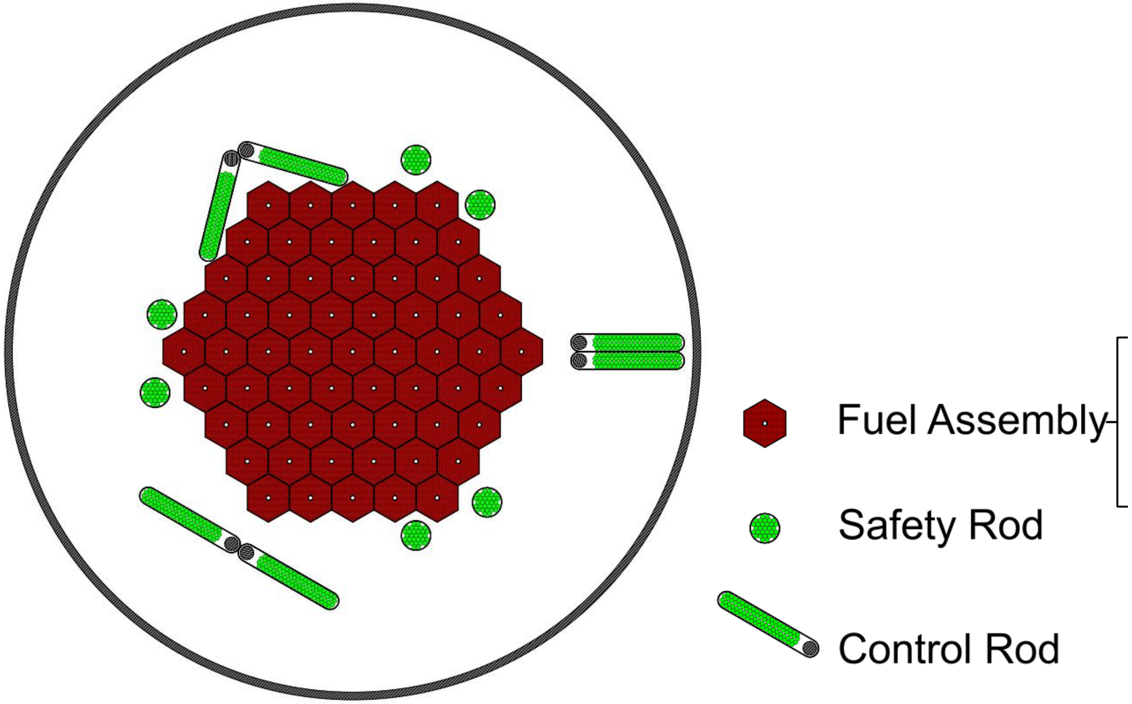
LFR-AS-200 enhances safety while dispensing of hitherto classical critical components

Components/systems no more needed	Rationale for elimination	Impact
Intermediate loop	Lead properties.	Compact Reactor Building, easy operation, cost reduction (about 30% of the cost of NSSS in a SFR).
Above core structure	Use of FAs with extended stem.	Reduced diameter of the RV, no need of its displacement for refuelling.
In-vessel refuelling machine	Use of FAs with extended stem.	Elimination of a mechanically critical component to be operated in opaque medium.
“Deversoir “ or equivalent component	SG-outlet window at top of the SG.	Reduced diameter of the RV, reduced vibration risk.
Diagrid	Self-sustaining core.	No need of a component difficult to inspect.
Strongback	Core supported by the roof via the barrel.	No need of a component difficult to inspect. No structure fixed to the RV
“LIPOSO” , hydraulic connection pump to diagrid	Pumps in the hot collector.	Elimination of a mechanically critical component.
Pump bearings in lead	Low required NPSH for the pumps.	Elimination of a mechanically critical component.
Flywheel on the pump system	Use of rotating lead inertia.	Smaller footprint on the reactor roof.
Core shielding assemblies	Use of the ASIV.	Reduced diameter of the RV, simplicity.
Blanket assemblies	No net Pu generation.	Reduced diameter of the RV, simplicity, increased proliferation

LFR-AS-200 (nearly) self sufficient in Pu

- large negative reactivity feedbacks
- control from outside
- shielding by lead

The design of the core has been oriented towards a system nearly self-sufficient in plutonium. A conversion ratio of about 0.9 is obtained without blankets. In the absence of fertile FA, a larger core would be necessary for complete autonomy in Pu, which is not a main objective of the project, given the surfeit of Pu available worldwide.



Inner enrichment = 14.6 wt.%

Outer enrichment = 23.2 wt.%
20.4 wt.%

The LFR-AS-200 burner

An added value of the LFR-AS-200 could be the capability to burn Pu in Countries which have long been producing nuclear energy to reduce the inventory of available plutonium.

A new configuration has been identified in order to maximize plutonium burning (LFR-AS-200 Burner), while maintaining all the main plant characteristics.

Parameter	Value of the self-sustaining core	Value of the core burner
Fuel rods diameter/ lattice pitch (hex) [mm]	10,5/13.5	7/10,5
Active height [cm]	85.0	60
Number of FAs	61	127
Coolant flow velocity [m/s]	1.54	1.55
Average linear power rating [W/cm]	225	214
Fuel mass [t]	12.8	6.3
U mass [t_{HM}]	9.14	3.9
Pu mass [t_{HM}]	2.15	1.65
In-pile residence time [days]	2400	1080
Cycles	5	2
Criticality swing [pcm]	1340	2180

Pu balance for the self-sustaining and the burner cores

	Self-sustaining core		Core burner	
	U (kg)	Pu (kg)	U (kg)	Pu (kg)
Initial inventory	9139	2148	3900	1651
Final inventory	8063	2028	3606	1412
Balance	-1076	-120	-294	-239

The Hydromine's new development strategy

- ➢ The LFR-AS-200 has demonstrated the potential of the LFR.

- ➢ Despite its potential , political/financial conditions for completion of the R&D and the construction of the first of a kind LFR-AS-200 (~ 1B€) have not yet matured.

- ➢ Having found it impossible to proceed with the development / realization of the LFR-AS-200 in the short term, taking into account that:
  - historically the development of nuclear power began with the construction of small plants.
  - that there is a potential market for micro reactors,

Hydromine will concentrate its short-term activity on the development of the micro LFR-TL-X

The LFR-TL-5 conceptual design

Matrioska-type configuration, in which the upper part of the shroud, which supports the core, contains the Spiral-Tube Steam Generator, that in turn contains the circulation Pump.

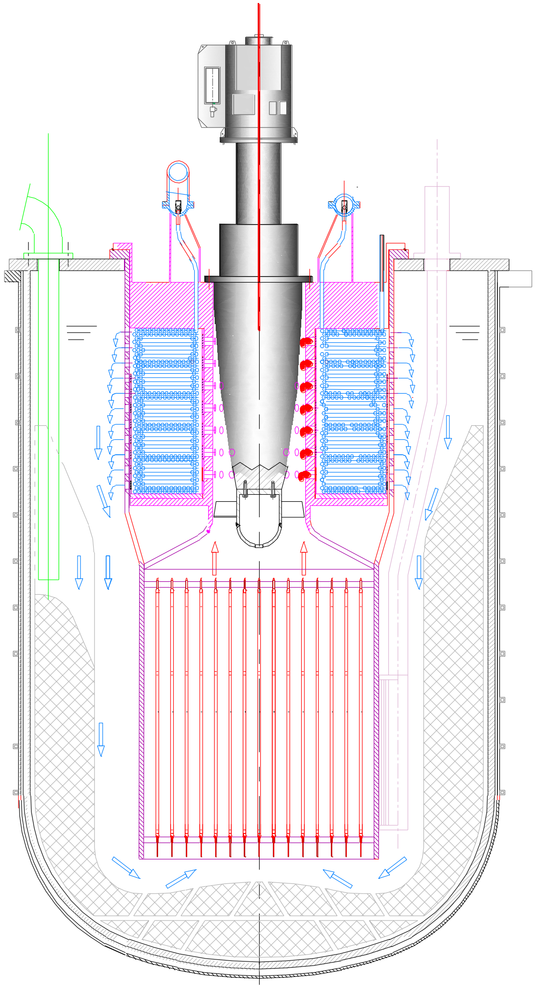
Control and Shut-down rods located outside the core.

The LFR-5 compactness is the condition for transport, and long-life-core for refueling in a few nuclear facilities, (i) without exacerbating the proliferation issue and (ii) avoiding the on site expensive fuel handling equipment.

The LFR-5 could be deployed in the short-term, owing to: the lower operating temperature and the use of steels already qualified in the nuclear field.

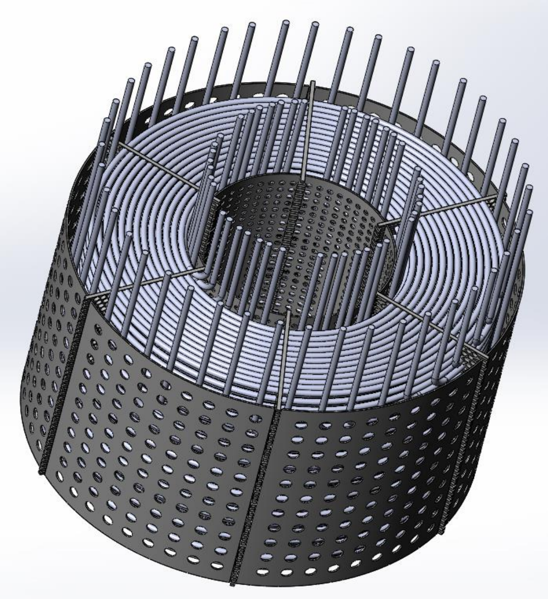
The LFR-TL-5 could be used for:

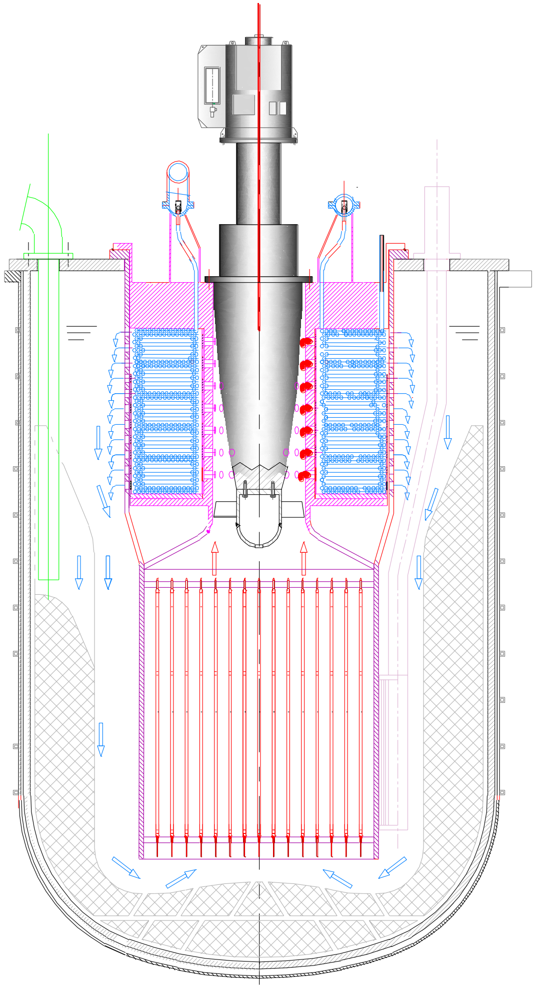
- qualification of advanced structural steels for use in the LFR-AS-200;
- sites without interconnected grids;
- offshore oil platforms;
- mines;
- islands;
- naval propulsion.



The LFR-TL-5 conceptual design

Compactness of the LFR-TL-5 results from the use of the above-core volume to install a single pump and a Spiral-Tube Steam Generator (STSG)





Number of tubes	42	Radial pitch (mm)	18,5
Tube active length (m)	32	Axial pitch (mm)	17
Tube OD (mm)	16	Feedwater/steam temperature (°C)	330/400
Tube ID (mm)	14	Steam pressure (bar)	130

Basic parameters of the LFR-5

Power	15 MWth, 5MWe
Core life-time	15 years
Primary coolant	Pure lead
Primary system	Pool type, compact
Primary coolant circulation (at power)	Forced
Primary coolant circulation for DHR	Natural circulation
Core inlet/outlet temperature	360°C; 420°C
Feed water temperature	330°C
Feed water pressure	130 bar
Fuel	UO_2 (19,75% enriched U)
Primary side pressure loss	0,4 bar
Steam	Superheated at 400°C and 130 bar
Fuel handling	The whole reactor is sent back to the factory for refuel
Main vessel/Safety Vessel	Austenitic stainless steel, hung, short-height.
Steam Generator	Spiral tube, integrated in the main vessel above the core
Primary Pump	Mechanical, vertical in the hot collector above the core
Inner Vessel	Cylindrical
Hot collector	Small-volume above the core
Cold collector	Annular, outside the core.
DHR Systems	Passive, diverse, redundant
Reactor outline dimensions	Diameter 2 m; height 3 m

Canada and Alaska: opportunity for micro-reactors

Summary Report

PERSPECTIVES ON CANADA'S SMR OPPORTUNITY
Summary Report: Request for Expressions of Interest—
CNL's Small Modular Reactor Strategy

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Canada was a world leader in nuclear technology. With this government and its

priorities, the environment, reducing GHG's, support for science and innovation, investing in northern and remote communities paired with strong federal provincial relations, we have an enormous opportunity in Canada to develop this technology and establish ourselves again as a world leader. If we do not seize this opportunity it would be lost for a generation.

Vic Pakalnis, P. Eng,. MBA. M. Eng.
President and Chief Executive Officer MIRARCO Mining Innovation

In rural Alaska:
- Electric power: 0.50-1.50 $/kWh
- Heating fuel: 3.50-10.00 $/gallon

Mining sites?

User Needs – Alaska

GAIN – EPRI – NEI - US NIC
Micro-reactor Workshop
Idaho Falls, ID // 18 June 2019
George Roe
Alaska Center for Energy and Power

Merchant ship propulsion: opportunity for micro-reactors

Merchant ship propulsion is again in the agenda of the ship companies because of the programs of decarbonization and because future environmental regulations concerning fossil fuel emissions place constraints on the types of fuels ships can burn .

The steady decline of polar sea ice over the last few decades has led to predictions that the North Polar regions will be open to regular marine traffic by at least the middle of the century.The production of soot from oil and gas burning engines will be caught in the circumpolar winds of the Arctic atmosphere and eventually be deposited on the snow and ice (Femenia, 2008).

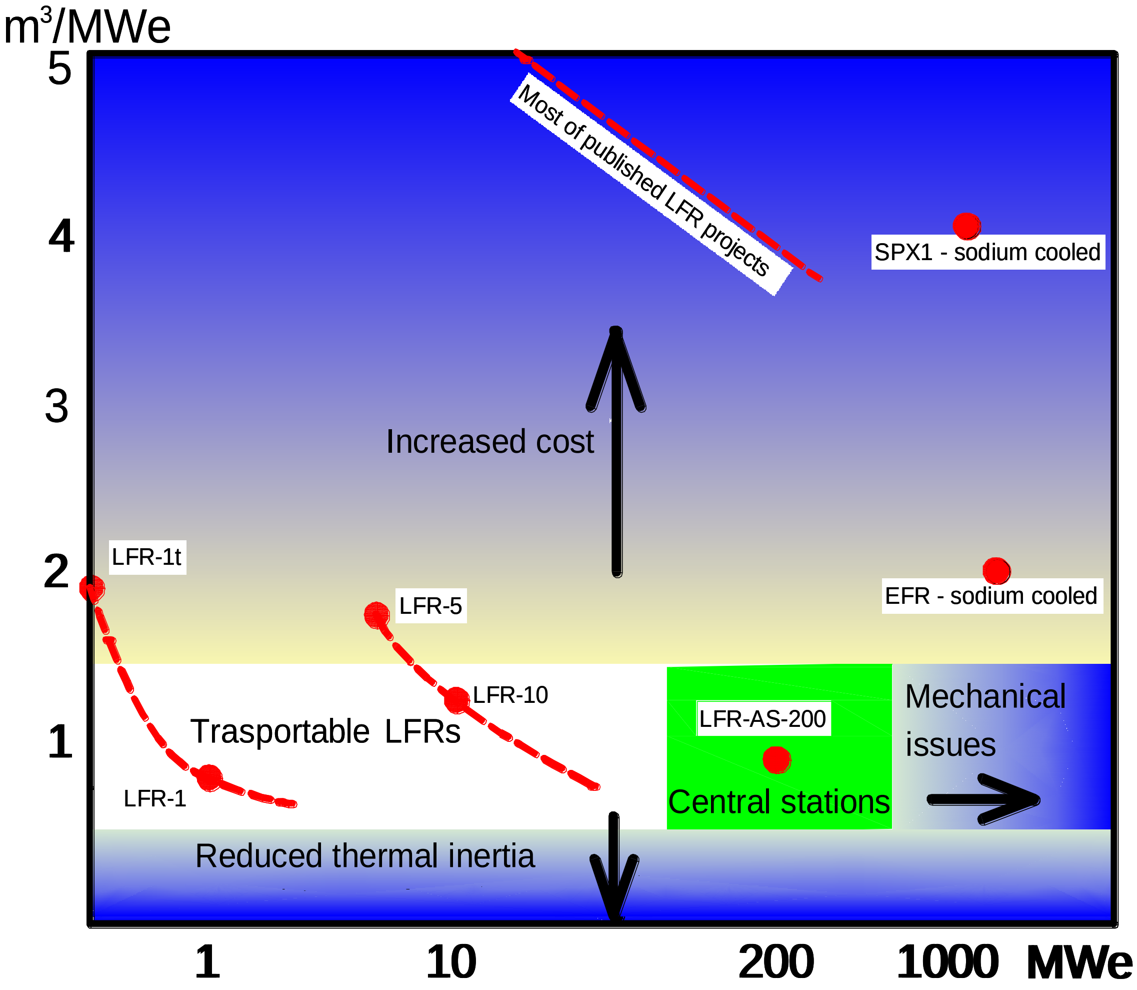
The presence of hundreds, if not thousands of hydrocarbon burning vessels in the Arctic region would lead to substantial ice loss **independent from concerns regarding anthropogenic CO2 emissions.** (Arctic Marine Shipping Assessment, 2009; Strategies for the Success of Nuclear Powered Commercial Shipping By Benjamin S. Haas).

Desired Feature / Characteristic	***HNE LFR-TL-X and LFR-AS-200***	***Implications for shipping***
Passive safety/simplified design	LFR systems feature a high level of passive safety • relative chemical inertness of lead • high boiling temperature • ability to operate at atmospheric conditions • favorable thermo-hydraulic properties that support natural circulation heat removal.	Simplified design and operation result in high reliability, low maintenance operations over very long time frames.
Safety in the event of catastrophic occurrence	In the event of catastrophic occurrence, core becomes encapsulated in frozen lead coolant and prevents release of significant radioactivity.	Eliminates the potential for environmental dispersion of contaminants in the event of otherwise catastrophic conditions.
Compactness	LFR designs are very compact.	Reduced volume frees up cargo capacity.
Very Long refueling interval/sealed system	These systems can operate for 15-20 years without refueling.	Eliminates service outages/routing restrictions for refueling; eliminates safety issues with fuel transfer operations.

Potential LFR deployment

LFR-1t, LFR-1 and LFR-AS-200
are fuelled with MOX

LFR-5 and LFR-10
are fuelled with Enriched U



Potential deployment of LFRs at different power level

Conclusion

According to Hydromine,

the LFR-TL-X:

- could be deployed in the short term because of the availability of qualified steels for its low operating temperature;
- thanks to its compactness has market opportunities for deployment in remote areas and for ship propulsion;
- its core can be provided with a central channel used to qualify steels for the LFR-AS-200 operating at higher temperature;

the LFR-AS-200:

- is outstanding safe because of the fully exploited lead properties and the design provisions.
- can economically compete in mid-term for electric energy generation in a scenario of revival of nuclear energy in a closed fuel cycle or as Pu burner.