Simplification, the *atout* of LFR-AS-200

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Abstract. LFR-AS-200 is under development by Hydromine in cooperation with ENEA. LFR stands for Lead-cooled Fast Reactor, AS stands for Amphora-Shaped, referring to the shape of the inner vessel and 200 is the electrical power in MW. The project has been carried out by a team of engineers, who had participated to the construction of SPX1.

The strengths of the LFR-AS-200 are safety, simplicity, and eventually kWh cost-competitiveness.

Safety relies on lead properties and is enhanced by innovative solutions including passively actuated and operated decay heat removal systems, a core with enhanced temperature negative reactivity feedback and a Steam Generator (GV) featuring a spiral-tube bundle, partially raised above the free level of the cold collector.

The SG features a lower inlet window and an upper outlet window in correspondence of the lead free level, in order to drastically reduce the mass of displaced lead in case of SGTR.

LFR-AS-200 dispenses with several components, which are hitherto typical of fast reactors, and achieves a specific volume of the primary system of less than 1 m^3/MWe, i.e. about 4 times less than that of the SPX1 Sodium-cooled Fast Reactor (SFR), and also several times less than of other international LFR projects, a key-factor for cost competition.

The smaller size has been achieved through design simplification, that did mainly consist in the elimination, besides of the intermediate circuits (feature common to any other LFR project), of several components typical of SFRs and also of previous LFRs, namely (i) the in-vessel refueling machine, (ii) the above-core structure, (iii) the diagrid, (iv) the strongback, (v) the shielding elements, (vi) in-lead bearings of the pumps, (vii) the "LIPOSO" or equivalent tubular hydraulic connection between the pumps and the core and (viii) the "Deversoir" or equivalent system aimed at keeping the reactor vessel at the temperature of the cold collector.

Several operational benefits pertaining to the proposed LFR-AS-200 technology are the result of insightful choices, typically the adoption of Fuel Assemblies (FAs) with a stem that extends above the lead free surface, and hung by a support system which is integral part of the FA's head, i.e. located in the gas plenum and therefore visible by the operators. This keeps the support system free from neutron damage and thermal loads and strongly reduces the burden of in-service inspection of the primary system.

Because of the project's sound design and brilliance, the designers are confident that the transition from concept to commercialization could occur over a fairly short year period, provided that investment be timely granted and the relevant regulatory reform addressed.

Key Words: LFR-AS-200, Amphora-Shaped Inner Vessel (ASIV), Spiral-Tube Steam Generator (STSG), FA with extended stem.

1. Background of the LFR-AS-200 development

The LFR-AS-200 is a fast reactor cooled by pure lead and therefore it implements one of the six nuclear system concepts selected for further development by the Generation IV International Forum (GIF) [1].

The LFR presents the sustainability advantage of fast reactors in term of reduced consumption of natural uranium and waste management and is characterized by recognized outstanding safety. In fact the LFR is by its nature safer than reactors which operate with coolant at high pressure and, therefore, are subject to the risk of the Loss Of Coolant Accident.

Dramatic events, such as Chernobyl or Fukushima, have demonstrated that nuclear risks shall by no means be cumulated with chemical risks, owing to coolants or moderators capable to generate large amount of energy by chemical reaction and hence worsen the nuclear accident or else hinder mitigation measures. These risks are represented, e.g., by sodium that explosively reacts with water and self-ignites in air; by graphite that did result in fire at Chernobyl; even by water, that at Fukushima did generate hydrogen and hence the subsequent explosions. The LFR does not present any of these risks.

Also, the LFR benefits from the notable thermal capacity of the coolant for smoothing power transients. To this regard, LFR can achieve unparalleled safety through natural mechanisms and simple systems, thanks to lead's high boiling point. In fact, differently from the LWR, it is possible to accept an important transient of temperature increase of the coolant with respect to normal operating condition and to exploit it for reactivity feedback, actuation of passive shut down systems, and actuation and operation of passive decay heat removal systems in order to become a walk-away reactor.

In spite of its recognized safety features, the LFR has not received enough international consideration until recent years have shown a large acceleration of LFR programs in Russia, Europe and China. The result is that LFR is the only Generation IV reactor which meets the expected development time as it appears from the comparison of the original 2002 Roadmap with the 2013 update (see *FIG.1.*) [2].

The initial limited LFR progress is related to the inertia of the international nuclear community, that discourages innovation, and to the over-estimation of the difficulties and inconveniences related to the lead technology and the perception that the LFR had no particular economic advantages over more traditional technologies such as SFR.

The recent acceleration of development programs is favored by the increasing degree of safety required for nuclear power, especially after the Fukushima accident and to the fact that some initial technical issues have been proved unfounded and others have been solved or are in the process of being solved.

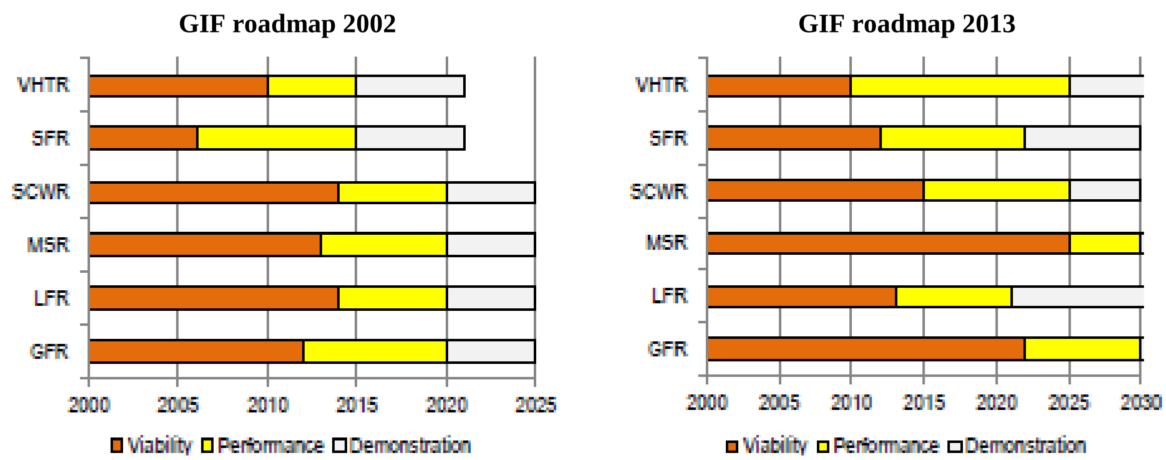

FIG. 1. Generation IV 2002 Roadmap (left) and the 2013 update (right).

A typical unfounded issue is the high pumping power expected for LFR because of the high density of lead, when, instead, the pumping power is much lower than that for sodium in the SFR, because of the elimination of the intermediate loops and of the reduction of the speed of lead and resulting pressure loss of the primary system. The reduced speed of lead is the result of the larger flow path inside the core, because the fuel rods are spaced farther apart, a feature possible owing to the lower neutron absorption and the reduced moderation properties of lead.

An important drawback of lead is its corrosive behavior of the structural steels significantly higher than that of sodium, but decisive progress in this respect have been obtained in various international laboratories, both in the development of new materials and in the development of protective coatings.

The Hydromine activities, as described in the following chapters, have been focused on the design aspects to improve at the same time safety, and feasibility, to facilitate operation and to reduce the costs drastically.

2. Design objectives of the LFR-AS-200

The LFR-AS-200 project is the result of ten years activities carried out by a small team of engineers, in the following called “design team”, who had participated to the construction of SPX1 and are aware of the need to reduce complexity to make the LFR competitive with the LWR.

During the first phase of the activity, the effort of the design team has been devoted to explore various solutions to address the critical design issues of the LFR. Recently, the activity of the design team, since 2013 Hydromine’s design team, has been focused on assembling the most promising innovations in a consistent design: the LFR-AS-200.

The LFR-AS-200 (Lead Fast Reactor - Amphora Shaped) is a 200 MWe reactor under development in cooperation with ENEA. It was disclosed for the first time during an international symposium at the Imperial College in London in July 2016, with audience participation from nuclear industrial companies, R&D organizations, universities, officials of the British government, and representatives of embassies.

Currently, the LFR-AS-200 project is included in the list of SMRs being evaluated by the British government and is also being evaluated by nuclear companies for potential collaboration.

Since the beginning, the large mass of lead of the primary system appeared as an important design issue to be solved. The large mass of lead results from the great density of lead emphasized by the large volume of the primary system, consequent to the low lead speed to reduce the erosion effects of lead. In the Russian BREST design this issue has been solved with a concrete vessel, in the US only very small module have been proposed and in Japan the JAEA had expressed concern for excessive earthquake loads of their LBE-cooled FR 750MWe design.

In conclusion, the large mass of lead is such an important drawback for feasibility and for cost, that the large volume of the primary system, in addition to casting doubts on the feasibility of plants of a reasonable power, could erase the potential economic advantage, compared to SFR, resulting from the suppression of the intermediate loops.

Moreover, Hydromine’s design team had the perception that additional critical issues had been undervalued in most of the disclosed international projects and that innovative solutions were required to avoid or at least to strongly mitigate these issues.

Careful attention has been given by the design team to attenuate the effects of the Steam Generator Tube Rupture (SFTR) accident, considering inacceptable the feature of a long steam generator with coolant outlet port close to the core level. In fact, the release of steam and/or water at high pressure deeply inside the Reactor Vessel and its expansion and flow towards the lead free level would displace a large mass of lead with associated large mechanical loads upon the structures of the primary system.

An additional concern of the design team has been the design of the In-Vessel Refueling Machine (IVRM). The design team was aware that refueling is difficult in sodium, which is opaque, to the point that both Jōyō and Monju in Japan are at shutdown because of handling accidents. In lead, refueling is even much more complicate than in sodium because lead is opaque as sodium, but refueling in lead takes place at higher temperature and the Fuel Assemblies (FA) are subjected to high buoyancy. One known solution to overcome buoyancy and to keep the FA connected to the diagrid is the addition to the FA of mechanical devices to be actuated by the refueling machine. This solution would have, however, complicated the design of the FA and of the refueling machine and in addition increased the risk of blockages between FAs and diagrid, and has been disregarded.

The solutions of all these issues has engaged the design team over the last ten years and the publication of the LFR-AS-200 reference conceptual design has been postponed till July 2016 when the identified solutions have been considered adequate on the base of the team experience.

3. Description of the LFR-AS-200

The LFR-AS-200 is an integrated reactor, which means that all the primary components are installed in a single vessel, among them the key-components: the Amphora-Shaped Inner Vessel (ASIV), the Core, the Spiral-Tube Steam Generators (STSG), the Dip Coolers of the Decay Heat Removal Systems (DHR) and the Recirculation Pumps (see *FIG.2.*).

The (superheated) steam is generated at relatively high pressure (180 bar) and temperature (500 °C) to guarantee a thermal cycle net efficiency of 42% (see Table I).

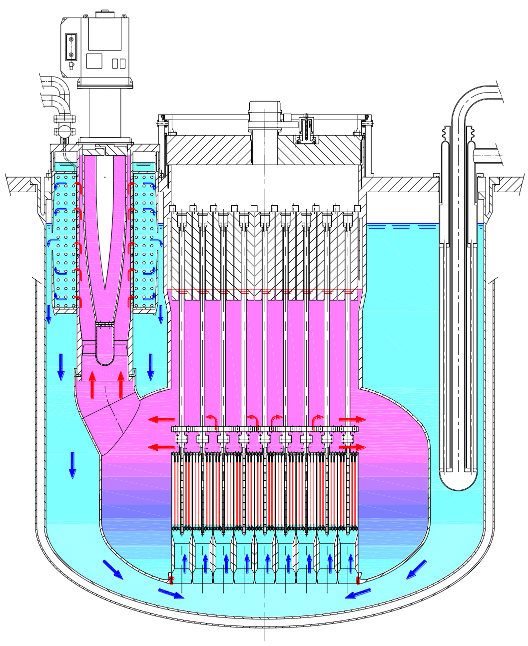

FIG. 2. LFR-AS-200 – Reactor assembly scheme.

TABLE I: MAIN DESIGN PARAMETERS OF LFR-AS-200.

Core power [MWth]	480	Primary side pressure loss [bar]	1.3
Electrical power [MWe]	200	Net efficiency [%]	42
Primary system type	Pool-type	Turbine inlet pressure [bar]	180
Primary coolant	Lead	Feed water temperature [°C]	340
Core inlet/outlet temperature [°C]	420/530	Turbine inlet temperature [°C]	500
Primary coolant flow rate [m3/s]	2.86	Reactor vessel height [m]	6.2
Secondary cycle	Superheated steam	Reactor vessel diameter, current/at support flange [m]	6/6.5

3.1.The Reactor Vessel and the internals

The reactor vessel is shaped as a cylindrical vessel with flat roof. The lead free surface is kept sufficiently below the roof to allow for a gentle thermal gradient between the vessel in contact with lead and the colder roof. The reactor vessel is supported by a forged Y-piece, the outer leg of which is welded to a ring beam anchored to the reactor pit, and the inner leg supports the roof.

The gas plenum above the lead free level is argon cover gas.

The roof is made of an annular thick plate with penetrations for components of the primary system and a large-diameter, central opening, the edge of which supports the ASIV (see *FIG.3*.).

The ASIV is a mechanical structure that in the upper part accommodates the heads of the Fuel Assemblies (FAs) and in the lower, larger part, their active section. A large pool of lead protects the ASIV from neutron irradiation and thus allows the elimination of the shielding elements normally required in a fast reactor.

The ASIV separates the hot collector from the cold collector and is provided with ducts branching out from its bottom part, each duct feeding hot lead to one SG.

To be removable, the internals are hung from, and supported by, the reactor roof. The penetrations through the reactor roof are gas tight-sealed because reactor roof and reactor vessel constitute the primary containment. No internal component is connected to the Reactor Vessel.

3.2.The core

The core (see Table II) consists of 61 wrapped, hexagonal FAs, each containing fuel pins laid out on triangular pitch.

Power shaping or flattening has been achieved through the use of zones with different levels of Pu-enrichment [3].

The FAs, the weight of which is supported by buoyancy, present stems extended up to above the lead free level, i.e. in gas space. Their heads can be interconnected, and the outer heads fixed also to the ASIV, by means of cams, which are integral part of each head. The result is a self-sustaining core anchored to the inner profile of the ASIV, that acts as the core barrel in gas space.

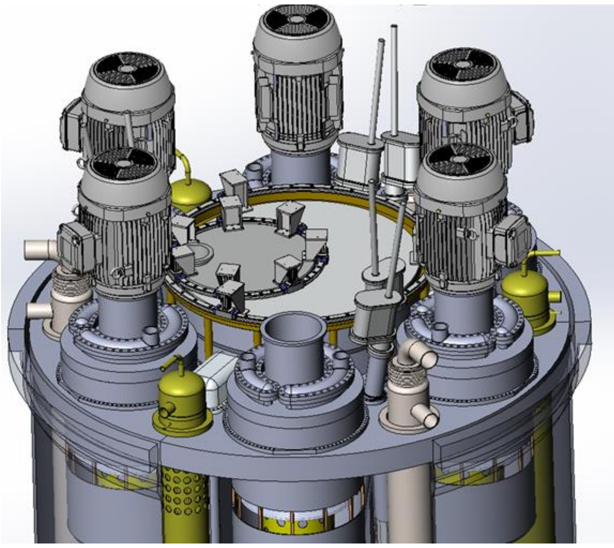

FIG. 3. Reactor roof main components layout.

The lower part of each FA consists of a bundle of the fuel pins vented, through the FA stem toward a vessel located outside the Reactor Vessel.

The FA foot is free from mechanical supports (no core grid of classical design) except for the radial touching with adjacent FAs, which are brought into contact to create a packed bundle, bounded on the lower end by the profile of the bottom port of the ASIV.

The stem of the FAs is peculiar to this novel design, because the FAs heads are directly accessible for handling with an ex-vessel refueling machine operating in gas space under visual control in conjunction with rotating plugs of classical design.

Core reactivity is controlled by ex-core rods, installed in the lead pool between the core and the ASIV. Ultimate reactor shutdown is guaranteed by core expanders placed on the FAs stems.

3.3.The Spiral-Tube Steam Generator and Recirculation Pump assembly

The Spiral-Tube Steam Generator (STSG) is an innovative SG conceived for compactness and because it offers several advantages in term of reactor cost, safety and reactor operability and simplicity of the lead flow path (see Table III). The SG tube bundle, partially raised above the lead free level, is composed of a stack of spiral-wound tubes.

The inlet and outlet ends of each tube are connected to the feed water header and steam header, respectively, both arranged above the reactor roof.

TABLE II: LFR-AS-200 MAIN CORE PARAMETERS.

Number of FAs	61	Clad thickness [mm]	0.6
Number of pins/FA	390	Pellet outer diameter [mm]	9
Active height [cm]	85	Pellet inner diameter [mm]	2
Pins pitch (triangular) [mm]	13.6	Coolant velocity [m/s]	1.58
FA pitch (triangular) [mm]	280	Mass of fuel [t]	12.8
Clad outer diameter [mm]	10.5	Core pressure loss [bar]	0.9

TABLE III: LFR-AS-200 MAIN SG PARAMETERS.

Number of SGs and Pumps	6	Outer diameter of tubes [mm]	18
Outer diameter of SG outer shell [m]	1.3	Tube-bundle height [m]	1.82
Number of tubes	100	SG shell-side pressure loss [bar]	0.2
Active length of the tubes [m]	34		

The tube spirals, one spiral for each tube, are arranged one above the other and equally spaced.

The SG is fed from the bottom and hot lead flows radially through the perforated inner shell and, once past the tube spirals, is released in the cold collector through a circumferential window located just below the lead free level.

The vertical axial-flow pump is integrated inside the SG; the pump rests on, and is connected to, the upper support plate of the SG by means of a flange which closes the pump's shaft penetration through the reactor roof and supports the variable-speed electric motor of the pump.

The pump is characterized by a short, large-diameter, hollow shaft containing lead brought in rotation by the shaft itself, in order to increase the mechanical inertia of the pump. There are no in-lead pump bearings.

3.4.The safety-related DHR system

DHR is performed by means of two diverse, redundant systems, each consisting of three identical loops, each loop rated 2.5 MW. Two loops are sufficient to remove the decay heat.

The loops of the first system are filled with lead. Each loop consists of a lead-lead dip cooler and of a lead-air cooler with interconnecting piping, and is passively operated and also passively actuated thanks to the thermal expansion of the cold branch of the loop, which actuates the louvers of the air cooler when its temperature exceeds 400°C.

Each loop of the second system consists of a lead-boiling-water dip cooler (2,5 MW nominal power), of a vessel with storage water, of interconnecting piping and of a (1 MW) steam condenser installed in order to reduce the storage water consumption and to operate the system for unlimited time without need of make-up water. It is passively operated and actively actuated.

4. Advantages of LFR-AS-200 innovations in term of cost, feasibility and operation[1]

The resulting volume of the primary system of the LFR-AS-200 is about **1 m^3/MWe which is about 4 time less than that of SPX1** and most of the previous LFR projects!

[1] All the innovations presented in this document have been conceived by Hydromine's design team and are certified by 12 application for patent of Hydromine property. Additional innovations not described in this document are under development, mainly for safety improvements.

TABLE IV: COMPONENTS NO LONGER NEEDED ELIMINATED FOR SIMPLICITY AND ECONOMIC.

Systems/Components eliminated	Rationale for elimination	Impact
Intermediate loop.	Lead properties.	Compact Reactor Building, easy operation, cost reduction.
Above core structure.	Use of FAs with extended stem.	Reduced diameter of the RV, easier refueling.
In-vessel refueling machine.	Use of FAs with extended stem.	Elimination of a mechanically critical component.
"Deversoir" or equivalent system.	SG-outlet window at free level of lead in the cold collector.	Reduced diameter of the RV, reduced vibration risk.
Diagrid.	Self-supporting 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.
"LIPOSO", hydraulic connection pump to Diagrid.	Pumps in the hot collector.	Elimination of mechanically critical components.
Pump bearings in lead.	Short shaft of the pump; low required NPSH for the pumps.	Elimination of mechanically critical components.
Core shielding assemblies.	Wide shielding lead mass in the ASIV.	Reduced diameter of the RV, simplicity.
Blanket assemblies.	No high breeding ratio required.	Reduced diameter of the RV, simplicity, increased proliferation resistance.

This exceptional compactness coupled with the elimination of several components no more needed (see Table IV.) and the elimination of the intermediate loops, which are peculiar to SFR, **can now eliminate residual doubts on economics**. The compactness is due (i) to the innovative STSG, positioned high in the reactor vessel, which keeps cool the reactor vessel without additional provisions, (ii) to the integration of the recirculation pumps inside the STSGs, (iii) to the elimination of the in-vessel FA storage[2], (iv) to the elimination of the IVRM and (v) to the elimination of the shielding assemblies.

Most of the volume reduction is obtained from the reduction of the height of the reactor vessel to about 6 m, from typical 10-20 m of previous designs, thanks to the short, raised STSG. **The short vessel** is the key to assure also the primary system robustness against seismic loads.

Differently from traditional solutions, the FA presents a stem that extends up to above the lead free level, allowing the elimination of the Above Core Structure and the **elimination of the in-lead IVRM**, which is a critical component at the limit of the technical feasibility.

[2] Refueling in gas after about ten days cooling is possible thanks to the specific FA design and cooling system.

Opposite from traditional solutions, the FAs are supported from the top with a support structure which is integral part of the FA itself, allowing the **elimination of the diagrid and the strongback**, which are critical components in term of ISI.

5. Advantages of LFR-AS-200 innovations in term of cost, feasibility and operation

Differently from traditional solutions, the primary pumps are installed in the hot collector and feed from the bottom the raised STSG with outlet window at lead free level. This design feature **avoids displacement of a large mass of lead and the associated large mechanical loads** on the primary system structures in case of the SGTR accident.

Differently from traditional solutions, the primary pumps have no bearing in the melt, feature a short, hollow shaft of large diameter full of lead for a **reliable large pump inertia** and the elimination of mechanical flywheels[3].

Differently from other reactors, in a reactor cooled by lead there is a margin of hundreds K between the operating temperature and the safety limit and LFR-AS-200 exploits this margin for actuation of passive shutdown and passive decay heat removal systems, which do not need power sources, operator intervention and logics, and hence are also **free from cyber-attacks**.

Passive shutdown takes place, in fact, by expansors installed on the FA stems, which amplify the radial thermal expansion of the core. Decay heat removal of the lead loops is initiated by opening louvers of the air coolers, triggered by the thermal expansion of the cold leg of the loop connecting the air cooler with the dip cooler.

Lead has also good retention capability of volatile fission products and in extreme conditions can be directly cooled by jets of water, as done at Fukushima, with the further advantage that frozen lead builds its own sarcophagus and stops additional radionuclide dispersion.

6. Conclusion

In the last 40-50 years great progress has occurred in various areas of technology, particularly in the automotive, aeronautic, and electronic fields, whereas the nuclear companies continue to offer systems with higher output power, but essentially based on the same technology, with the same low thermal efficiency and limited progress in reducing nuclear waste.

With the LFR-AS-200, Hydromine demonstrates that, even in the nuclear field there is the possibility of great innovation and simplification resulting in improvements both in cost reduction and added safety.

The LFR-AS-200 project shows, in particular, that with the use of lead as coolant, in addition to eliminating the intermediate circuit typical of the SFR reactor, it is also possible to reduce the volume of the primary system per unit power of about a factor 4 when compared to SPX1 and most of the disclosed LFR projects.

Lead has properties favorable to safety, such as the compatibility with air and water, and the high boiling point, that allows to operate at ambient pressure. While in case of extreme accidents in some other reactors, typically in the SFR, there would no longer remain credible means of accident mitigation, in the case of lead it would still be possible direct core cooling with water as done at Fukushima, with the further advantage that lead has also large retention

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[3] A large pump inertia is necessary for mild transients from forced to natural circulation. As an example, in SPX1 the inertia is provided by flywheels installed upstream of the electric generators, which power the motors of the primary pumps.

capability of volatile fission products and frozen lead can build its own sarcophagus, thereby avoiding additional radionuclide dispersion.

Hydromine has recently started to present the LFR-AS-200 to the international nuclear community with the intention to move from the conceptual design, carried out by its small design team, to the phase of detailed design, for which the involvement of large companies and the relevant regulatory reform are essential steps.

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