The Core of the LFR-AS-200: Robustness for Safety

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Abstract. The LFR-AS-200 is a 200 MW(e) Lead Fast Reactor (LFR) standing on simplicity to target the objective of representing a commercially viable option for an innovative Small Modular Reactor (SMR). To fulfil its envisaged role, which is particularly meaningful for multi-units sites, the design has to enhance the safety performances; this is achieved by exploiting the relevant favorable intrinsic properties of lead, and by implementing engineered features, passively operating to permit a robust response of the system even in challenging beyond-design accidental conditions resulting as a consequence of multiple failures of the reference lines of defense. The design of the core is here presented with a particular emphasis on the encompassed safety provisions, both intrinsic and engineered. Notably, the largely negative reactivity coefficients of the core will be presented along with a passive provision enhancing the flowering of the core, thereby the anti-reactivity insertion upon transients resulting in an increase of the core outlet temperature. The performances of the system in one of the main unprotected transients – a combined loss of flow-loss of heat sink – are finally presented. The results prove the effectiveness of the design to withstand such challenging conditions and to ensure extremely large grace times for actuating countermeasures without incurring in the failure of any of the first two engineered barriers for the confinement of radioactivity – the fuel cladding and the primary circuit boundary – thereby protecting not only the environment and the population, but also the investment itself.

Key Words: LFR, SMR, core design, safety by design.

1. Introduction

The ambition for extending the role of nuclear as a reliable, secure, safe and sustainable energy source in the long-term implies that innovative systems being developed also have to top score in economics. Under these assumptions, Lead-cooled Fast Reactors (LFRs), excelling in safety and sustainability, are more and more acknowledged as promising solutions, gathering interest worldwide at industrial and governmental level.

Moreover, in a perspective of exploiting all market segments so as to allow nuclear playing the envisaged role, next generation nuclear systems have to match economic competitiveness both as large and small-medium power stations. Again, the LFR – thanks to the favorable features of lead cooling – has the potential for pursuing system simplification, to the benefit of both construction and operation costs reduction.

The LFR-AS-200, standing on simplicity, emerges among the candidate innovative Small Modular Reactor (SMR) systems as a very promising solution in terms of competitiveness [1]. In the present paper, an accent on the safety performances of the LFR-AS-200 is put by introducing the design of the core along with the rationales that drove the definition of the reference configuration so as to target safety and operation flexibility. Results of the system behavior under challenging accidental conditions (notably an unprotected transient) are also shown to prove the effectiveness of the design, thus the unparalleled safety performances of this system.

2. The LFR-AS-200 core

In order to target the aimed 480 MW_t ($\approx$200 MW_e) core configuration top scoring in safety performances, the rationale driving the design was to exploit inherent lead properties to the largest extent, and to adopt the simplest possible solutions to increase robustness and promote economic competitiveness.

In doing so, a comprehensive design approach [2] was adopted, allowing at once i) to integrate technological and safety constraints, and design objectives, from the very beginning of the design procedure, thereby defining a viability region in the reactor space domain, and ii) to drive the selection of the optimal configuration among the ones lying in the viability domain.

2.1.Reference configuration

At the end of the design process, the configuration shown in the left frame of *FIG. 1* was obtained, made of 61 hexagonal Fuel Assemblies (FAs) organized in a triangular lattice of 4 complete rings around the central position. Each FA is made of 390 fuel pins arranged as well in a triangular lattice of 13.6 mm pitch (right frame of *FIG. 1*) and enclosed in an hexagonal steel wrapper 3.0 mm thick; the 7 positions – the central ones – remaining to complete a full hexagonal scheme are replaced by a structural beam tube with hexagonal cross section, used to provide an additional support to the grids forming the pins bundle, thereby increasing the stiffness of the FA. The outer flat-to-flat dimension of a FA is 278.4 mm, thus leaving a small clearance to by-pass lead within the core cell of 282.0 mm pitch. The wrapper and the beam tube are also machined, close to the corners, to modulate the coolant flow area so as to avoid an excessive overheating of the adjacent fuel pins.

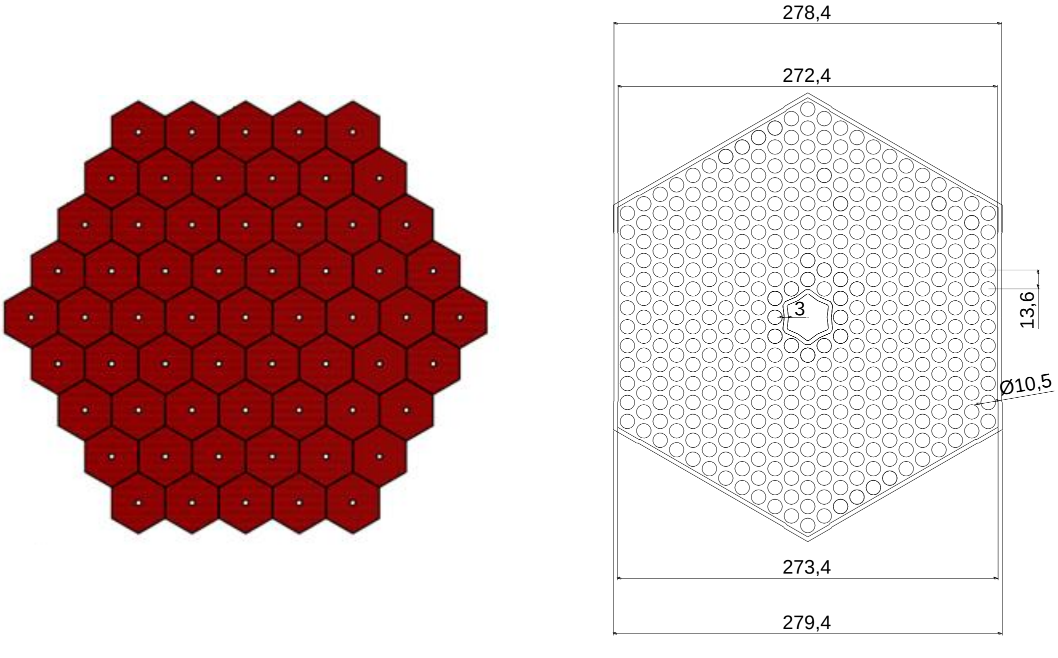

FIG. 1. Horizontal cross-section views of the LFR-AS-200 core (left) and Fuel Assembly (right).

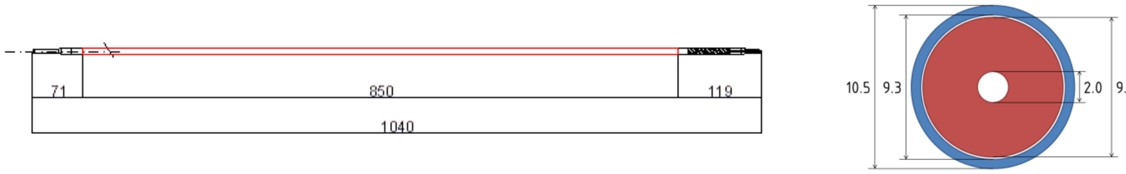

FIG. 2. Vertical (left) and horizontal (right) cross-section views of the LFR-AS-200 fuel pin.

The fuel pins are rather thick, with an outer diameter of 10.5 mm and an overall length of 1040 mm (left frame of *FIG. 2*). The horizontal cross-section of the fuel pin is shown in the right frame of *FIG. 2*. The clad tube, 0.6 mm thick, encloses the stack of fuel pellets, 9.0 mm in diameter and with a hollow (2.0 mm in diameter) to permit achieving the target average burnup of 100 MW·d/kg$_{HM}$ with limited Pellet-Clad Mechanical Interaction (PCMI) and to reduce the peak temperature, thereby providing a relevant margin against fuel melting during Unprotected Transients of Over-Power (UTOP). At both ends of the fuel column, an insulator pellet is foreseen to thermally protect the structures. At the lower end, right after the insulating pellet, the clad is welded to the lower cap which mounts on one of the racks forming the lower grid defining the bundle. At the upper end, above the insulator, a spring is inserted to accommodate differential expansions between the fuel and the clad; the spring insists at its top on the upper cap which seals the cladding. No plenum is foreseen to accommodate the gaseous fission products as the fuel pins are vented through the upper cap, the upper grid holding the pins and the structural stem of the FA; the fission gas is in this way piped to a tank, relieving the pin from internal pressure and thereby opening to the possibility to achieve, in perspective, very high burnups. The short length of the fuel pins is also beneficial both for the vertical compaction of the system, and for the onset of natural circulation, by reducing the pressure drops through the core: in fact, the nominal primary system temperatures (420/530 °C at core inlet/outlet) are attained with an average coolant flow velocity of 1.54 m/s, to which correspond about 0.9 bar only of core pressure drops.

The fuel pellets are made of Mixed Oxide (MOX). Three different uranium-plutonium blends are chosen to flatten the power distribution throughout the core:

- all the fuel pins in the outer 24 FAs have 23.2 wt.% plutonium enrichment;
- the fuel pins belonging to the remaining 37 FAs are made of three axial sections:
    - the central one, 55 cm tall, has fuel enriched to 14.6 wt.% with plutonium,
    - the two, equal, external sections have a plutonium enrichment of 20.4 wt.%.

The fuel clad, all other elements of the pin and the main structural parts of the FA are made of a low-swelling austenitic stainless steel of class 15-15Ti; the whole pin is also externally coated with alumina by Pulsed Laser Deposition (PLD) [3] to enhance corrosion resistance and proof the pins against the migration of tritium into the primary system.

2.2. Control and safety systems

Thanks to the rather small dimensions of the core, the control of the reactivity can be performed from the outside, thus leveraging on the neutron leakage from the active region.

Three different systems are foreseen (see *FIG. 3*):

- a bank of six “flags”, each rotating around its vertical axis to approach or move away from the multiplying region;
- two banks, of three rods each, actuated by buoyancy (first bank) or by gravity (second bank).

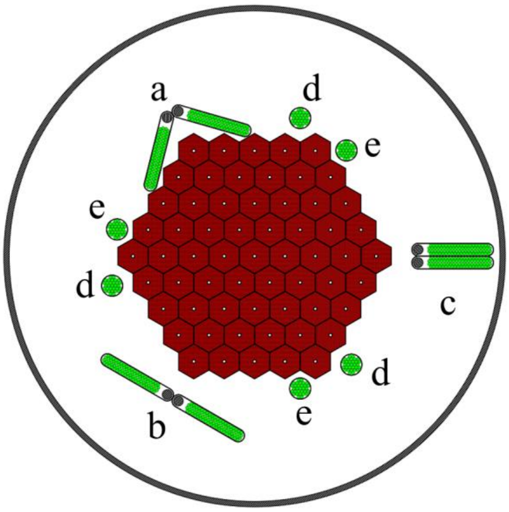

FIG. 3. Control and safety systems in the LFR-AS-200: "flags" in operating (a), partially withdrawn (b) and withdrawn (c) positions; safety rods operating by buoyancy (d) and by gravity (e).

The first bank, made of the six flags, is envisioned for the control of the system, hence on one hand for the compensation of the reactivity change from cold shutdown to full-power and the criticality swing during burnup, and for commanding power excursions on the other.

The other two banks, redundant and diverse, are only devoted to the emergency shutdown of the system (SCRAM).

The flags and the rods are all made of bundles of pins filled by enriched boron carbide as neutron-absorbing material (green parts in *FIG. 3*).

2.3.Neutronic performances

The fuel inventory in the core is of 12.8 t, out of which 2.15 t and 9.15 t are of plutonium and uranium, respectively. The aimed burnup is achieved with 2400 EFPDs (Equivalent Full-Power Days) fuel residence time in the core, corresponding to about 80 months of full-power irradiation.

In order to reduce the reactivity swing during burnup, and in consideration of the outages that are to be foreseen for periodic inspections and normal maintenance, the management of the fuel is based on a 5-batches strategy that is: every 16 months one fifth of the fuel (which has reached the limit of in-pile residence) is discharged and replaced with fresh fuel. The resulting criticality swing during an irradiation sub-cycle is 1340 pcm, which can be effectively compensated by the control flags.

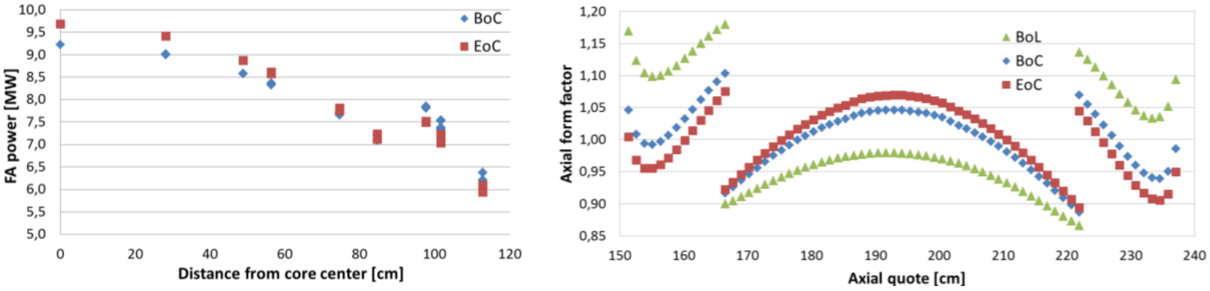

FIG. 4. Power distribution per FA at Beginning and End of Cycle as a function of the radial distance from core center (left) and axial power distribution factor at Beginning of Life, Beginning and End of Cycle for a fuel pin in the central FA (right).

TABLE I: POWER DISTRIBUTION FACTORS FOR INNER AND OUTER CORE AT BEGINNING AND END OF CYCLE: AMONG THE FAS AT CORE LEVEL (ff_{core}), AMONG THE PINS AT THE LEVEL OF THE HOTTEST FA (ff_{FA}), ALONG THE AXIAL FUEL LENGTH IN THE HOTTEST PIN (ff_{ax}), AND THEIR COMBINATION ($ff_{tot} = ff_{core} \cdot ff_{FA} \cdot ff_{ax}$).

Case	**MAX ff_{core}**		**MAX ff_{FA}**		**MAX ff_{ax}**		**MAX ff_{tot}**	
	INN	**OUT**	**INN**	**OUT**	**INN**	**OUT**	**INN**	**OUT**
BoC	1.1870	1.0100	1.0033	1.1902	1.1029	1.1328	**1.3135**	**1.3617**
EoC	1.2462	0.9676	1.0040	1.2087	1.0746	1.1289	**1.3445**	**1.3203**

The adopted enrichments cope with the aims of flattening the power distribution not only axially within the fuel pins of the FAs belonging to the inner core region (right frame of *FIG. 4*), but also among all the FAs at the level of the whole core (left frame of *FIG. 4*). To this end it is worth recalling that – due to the technological constraint of lead corrosion limiting the peak cladding temperature facing the coolant – the flattening has to be pursued at the level of hot spot, thereby including in the computation also the internal power distribution among the pins of the hottest FAs and the axial power distribution along the fuel in the hottest pin. Referring to distribution factors (i.e. local-to-average ratios) as shown in Table I, it can be seen that the proposed scheme fulfills the flattening between the two fuel regions throughout the whole length of an irradiation sub-cycle. All the presented results were obtained by combining ERANOS [4] and MCNP6 [5] results, both used in combination with the JEFF3.1 [6] nuclear data library.

2.4.Feedback reactivity coefficients

In order to perform the transient analysis required to stress the LFR-AS-200 in safety-challenging conditions, a complete set of reactivity coefficients was retrieved by evaluating the impact on criticality of a series of elementary changes in some core parameters such as the fuel temperature (at the level of nuclear cross-sections only), height and density, the cladding radius and density, etc.

Combining then these elementary results according to some defined scenarios, and linking the so retrieved results to the related coefficients of thermal expansion, the set of reactivity coefficients shown in Table II was obtained.

TABLE II: REACTIVITY COEFFICIENTS FOR THE LFR-AS-200.

Coefficient	**Value [pcm/K]**
Doppler effect	-0.737
Axial core expansion (not linked/linked)	-0.205 / -0.268
Radial diagrid expansion (below/above T_c)	-0.308 / -0.378
Radial pads expansion (below/above T_c)	-0.648 / -2.309
Coolant expansion in active region	0.366
Coolant expansion (below/above/aside core)	-0.107 / -0.109 / -0.404

It is worth highlighting the magnification effect that the expansors placed atop the core on the stem holding each FA [1] have on the radial core expansion coefficient: when the core outlet temperature exceeds the critical value $T_c = 560$ °C at which the expansors enter in contact, their dilation – ruled by a huge coefficient of thermal expansion – forces the FAs to space apart much faster than normally due to the expansion of the wrappers, enhancing the loss of criticality by increase of the neutron leakage and by the ingress of more lead in the by-passes between adjacent FAs. Under such conditions, this coefficient becomes by far the largest, thereby assuming the leading role in every transient.

3. Safety performances in Design Extension Conditions

LFRs are acknowledged to excel in safety, even in extreme conditions, leveraging mainly on the huge thermal inertia of the primary system, the large margins offered by the high boiling point of the coolant and the combination of the large absolute thermal expansion of lead with a design promoting natural circulation. This typically translates in the capability of withstanding – with no damage to the system – all accidents occurring in protected conditions, i.e. upon proper intervention of the Reactor Protection System (RPS) in shutting down the reactor. Even when the RPS fails to shut the reactor down (unprotected conditions), the inherent response of the system is able to bring the system to a new equilibrium condition which still allows for huge grace times before the protection of the investment is challenged.

In order to verify the safety performances of the LFR-AS-200, one of the major unprotected accidents has been investigated: an Unprotected Loss Of Offsite Power (ULOOP).

3.1.System nodalization

A complete model of the LFR-AS-200 has been developed with RELAP [7], taking care of reproducing all the volumes, connections, heating structures and free levels so as to correctly catch the system behavior in nominal and transient conditions. The scheme of the resulting nodalization is shown in *FIG. 5*.

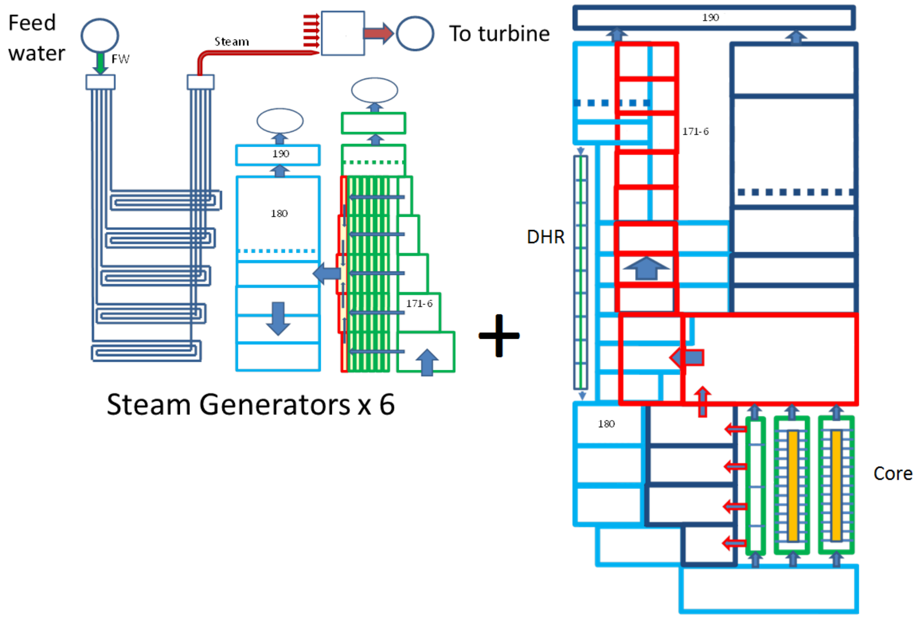

FIG. 5. RELAP nodalization of the LFR-AS-200: primary system (right part) and steam generators (left part).

3.2. Unprotected Loss Of Offsite Power (ULOOP)

The main conditions against which the LFR-AS-200 is challenged are those determined by an ULOOP accident. Such conditions may result from the complete loss of power to the plant and the contextual failure of the RPS to actuate SCRAM: in practice, the simulated accident is alike the one occurred at the Fukushima-Daiichi nuclear power plant, but further complicated by the unsuccessful shutdown of the core. Under these conditions, all the Primary Pumps (PPs) are arrested and the Steam Generators (SGs) unavailable while the core continues to produce its nominal, full-rated power. For conservativeness, only one of the two Decay Heat Removal (DHR) systems [1] is supposed to work, but with only two out of the three loops in operation (single failure assumption).

During the first phases of the accident, the response of the system is driven by the initial undershot in the coolant flow rate, partially smoothed by the inertia of the PPs (top-left frame of *FIG. 6*). The sudden reduction of the coolant flow rate and the lack of the main heat sink result in a steady increase of all system temperatures (top-right frame of *FIG. 6*). The increase of system temperatures triggers and progressively enhances the feedback responses of the core (bottom-left frame of *FIG. 6*) which in turn determine the reduction of the system power (bottom-right frame of *FIG. 6*).

As can be seen, the strong negative feedback due to radial core expansion – magnified by the expansors placed atop the active region – quickly reduces the core power to levels that are comparable with those of the DHR system in operation. The inherent shutdown of the core is so fast to induce some fluctuations after the first equalization of the core and DHR powers; however, in less than 8 hours after the beginning of the accident, the transient is concluded and the system stabilized to a new equilibrium condition.

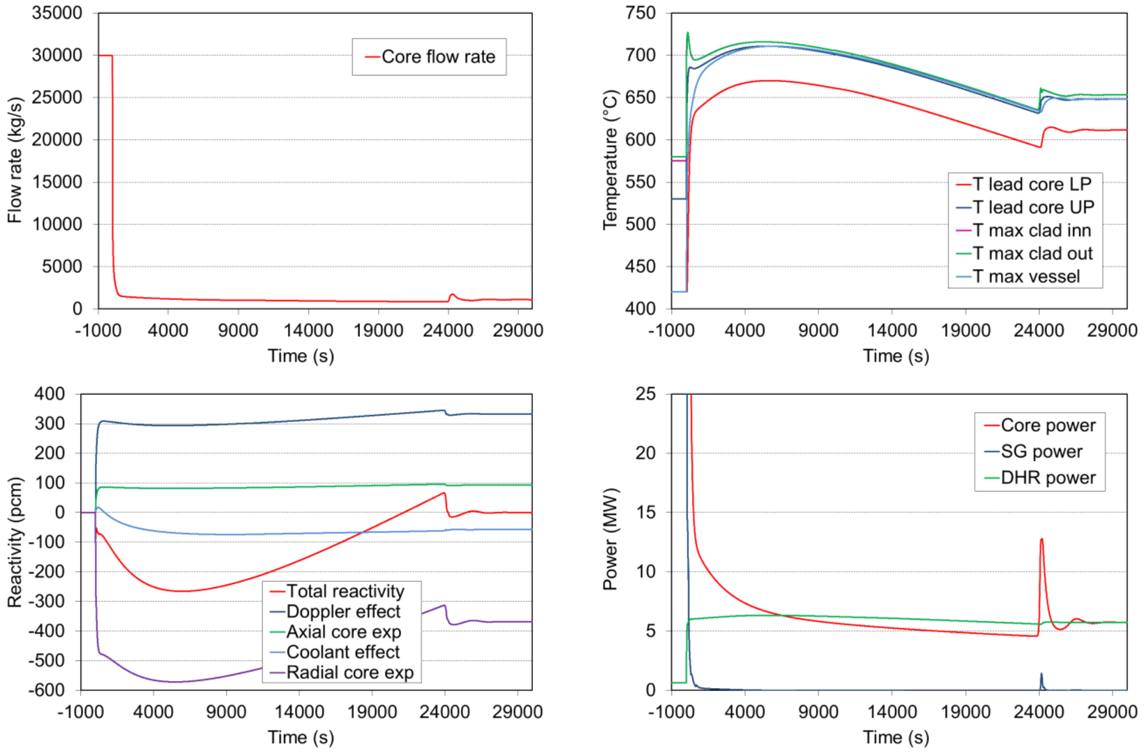

FIG. 6. Power distribution per FA at Beginning and End of Cycle as a function of the radial distance from core center (left) and axial power distribution factor at Beginning of Life, Beginning and End of Cycle for a fuel pin in the central FA (right).

Apart from the initial temperature peak – notably for the cladding, at about 730 °C – due to the flow undershot following the arrest of the PPs, all system temperatures stabilize at about 650 °C. In these conditions, and considering the loads to which the structures are subject, no failure is to be expected in the short- (due to the initial peak) nor in the long-term (at the final stationary regime), thereby proving the complete protection of the investment even in these conditions. Notably, it is worth stressing that nor for the fuel claddings nor for the main vessel – which are the first two engineering barriers against the release of radioactivity inventory – are expected to fail in such challenging conditions.

4. Conclusions

The LFR-AS-200 has been conceived to provide a credible option for an innovative SMR integrating the safety and sustainability performances that are proper of LFRs with the economic competitiveness that is required to compete in this emerging market segment.

In this paper, the design of the core of the LFR-AS-200 has been presented, introducing the rationales and discussing the key performances that can be expected once in operation. The system is able to achieve 10% of fuel utilization, delivering 200 MW_e for 5 cycles 16 months each long.

A complete set of reactivity coefficients was also retrieved to permit the analysis of the behavior of the system against extremely challenging conditions. To this end, an Unprotected Loss Of Offsite Power accident was selected, representing the extreme scenario (due to the failure of the RPS in shutting the reactor down) of the condition that affected the Fukushima-Daiichi nuclear power plant.

Thanks to the favorable lead properties, the robust core and plant design and the introduction of expansors magnifying core flowering, thus the associated inherent feedback reactivity response, the LFR-AS-200 has shown the capability to preserve the integrity of the whole system, with no failures up to the achievement of a new stable condition to which extremely long grace times (weeks) are associated. The obtained results have shown that the system poses no threat not only to people and the environment, but also to the protection of the investment.

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