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GEN-IV LFR development: Status & perspectives☆

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ABSTRACT

Since Lead-cooled Fast Reactors (LFR) have been conceptualized in the frame of Generation IV International Forum (GIF), great interest has focused on the development and testing of new technologies related to Heavy Liquid Metal (HLM) nuclear reactors. In this frame, ENEA developed one of the larger European experimental fleet of experimental facilities aiming at investigating HLM thermal-hydraulics, coolant chemistry control, corrosion behavior for structural materials, and at developing components, instrumentations and innovative systems, supported by experiments and numerical tools.

The present work aims at highlighting the capabilities and competencies developed by ENEA so far in the frame of the liquid metal technologies for GEN-IV LFR.

In particular, an overview on the ongoing R&D experimental program will be depicted considering the actual fleet of facilities: CIRCE, NACIE-UP, LIFUS5, LECOR and HELENA.

CIRCE (CIRColazione Eutettico) is the largest HLM pool facility presently in operation worldwide. Full scale component tests, thermal stratification studies, operational and accidental transients and integral tests for the nuclear safety and SGTR (Steam Generator Tube Rupture) events in a large pool system can be studied.

NACIE-UP (NAtural CIrculation Experiment-UPgraded) is a loop with a HLM primary and pressurized water secondary side and a 250 kW power Fuel Pin Simulator working in natural and mixed convection.

LIFUS5 (lithium for fusion) is a separated effect facility devoted to the HLM/Water interaction. HELENA (HEavy Liquid metal Experimental loop for advanced Nuclear Applications) is a pure lead loop with a mechanical pump for high flow rates experiments. LECOR (LEad CORrosion) is a corrosion loop facility with oxygen control system installed.

All the experiment actually ongoing on these facilities are described in the paper, depicting their role in the context of GEN-IV LFR development.

1. Introduction

The LFR are considered the most promising technologies to meet the requirements introduced for GEN IV nuclear plants and they are being studied worldwide (USDOE & GIF, 2002), (USDOE & GIF, 2014). Their main characteristics are listed below:

Sustainability - the very low neutron absorption cross section and poor moderating power, allows to design fast-neutron spectrum with geometries characterized by a high coolant/fuel ratio and fuel bundle with high pitch to diameter ratio. The fast neutron spectrum and the breeding ration about 1 make possible an efficient utilization of excess neutrons and reduction of uranium consumptions with a reduction of the high radiotoxic waste thanks to a close fuel cycle.

Safety and Reliability - the coolant high molten point and the low vapor pressure allows a primary loop operating at atmospheric pressure and low temperatures; moreover, the high shielding capability against gamma radiation offers a great protection to the workers with very low doses. The good thermo-physical properties allow to design cores with a high pitch/diameter ratio with low pressure drops and consequently low power requested for pumping. In terms of passive safety, with an effective configuration it is possible to increase the system capability to remove the decay power in natural circulation regime with a consequent reduction of the active safety systems. The high density can avoid the risk of fuel compaction and subsequent achievement of critical conditions in case of core melting, promoting the dispersion phenomena, moreover, in case of breakage of the steam generator tubes, the high density of coolant reduces the risk of steam inlet inside the core. Finally, in case of loss of flow accident in the primary loop, the

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	TRL	TRL Function	Generic Definition	Phase
achieved	1	Technology Down-Selection	•Basic principles definition	Screening
	2		•Technology concepts and applications definition	
Ongoing	3		•Demonstration of critical function •Proof of concept	Pre-qualification
	4	Final Process Selections & integration	•Lab-scale component validation	
	5		•Component validation in a relevant environment	Qualification
Further Development	6	Full-scale integrated testing	•System/subsystem model or prototype demonstration in relevant environment	
	7		•System prototype demonstration in prototypic environment	Demo
	8	Full-scale demo	•Actual system completed and qualified through test and demonstration	
	9		•Actual system proven through successful operations	

Fig. 1. LFR Technology Development Overview according to the TRL approach.

leaked lead will solidify in a very short time without significant chemical reactions, avoiding further loss of coolant and protecting the nearby structures and equipment.

Resistance to the Proliferation and Physical Protection - The MOX (Mixed Oxide Fuel) used contains actinides and it makes these systems unattractive for the extraction of weapon-usable materials. After all, the nuclear properties of the coolant can allow the realization of cores with a long life and not useful for the production of weapon-grade plutonium. The physical protection to the public and to the environment is assured by the coolant, which does not react with air and water at low pressure and reduces need for strong protection against the risk of catastrophic events deriving from natural causes or acts of sabotage, avoiding the chance of significant containment pressurization. Furthermore, the absence of inflammable substances reduces the risk of fire propagation.

Economy - The simple design reduces the building time, the capital cost and the operation and maintenance cost in order to offer a competitive price of the electricity generated. This is possible thanks to the favorable characteristics of the coolant chosen which allows the realization of low-pressure system with a steam generator integrated in the primary loop with a less complexity and dimension of systems. The absence of an intermediate loop makes possible thermal cycles characterized by a very high efficiency.

Research activities related to the lead and Lead-Bismuth Eutectic (LBE) technology development are ongoing in EU, with the design of two main systems: MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), a subcritical research reactor using LBE as coolant and ALFRED (Advanced Lead Fast Reactor European Demonstrator). The extensive R&D (Research and Development) efforts undertaken are necessary in order to improve the knowledge and the experience performed in terms of design, operations, maintenance and materials for components. The LFR/ADS (Accelerator Driven System) technological issues concern the following main topics (P. Agostini et al., 2014).

- *Material studies and physical-chemistry coolant characterization* – it is necessary to assess the phenomena in which the lead and LBE are involved in LFR/ADS. The contamination of the lead by metal oxide and the corrosion of structural materials is the main issue in these systems. The long term exposure to liquid metal leads to embrittlement and degradation of structures and primary system components as vessel, internals, heat exchangers, fuel cladding.
- *Irradiation studies* – The activities focus on structural materials subject to fast neutron fluxes defining their resistance for thermal stresses and dpa (displacements per atom) and determining whether or not irradiation promotes embrittlement and corrosion attack by HLM. The main issues on the performance of materials are due to the corrosion on HML under irradiation, irradiation embrittlement, as well as neutron irradiation induced effects such as creep and swelling.
- *Thermal-hydraulic properties* – the relevant issues of the HLM thermal-hydraulics research are related to:
  - HLM pool thermal-hydraulics which identifies as main topics the study of forced convection flow (mixing, stratification, stagnant zones, surface level oscillations), natural convection flow (pressure drops, surface level oscillations), transition to buoyancy driven flow, fluid structure interaction and system response to seismic events.
  - Fuel Assembly thermal-hydraulics, with the main scope to define the assembly geometries to achieve optimal conditions for heat transfer between fuel rods and coolant in forced and natural circulation, also demonstrating the capability to maintain the geometrical features, withstanding to irradiation effects, high temperatures, mechanical loads and corrosion. Other issues which need investigation are: the sub-channel flow distribution, the cladding temperature profile and hot spot, the pressure drops, the vibrations induced by flow, the fluid structure interaction, consequence of a hypothetic core damage. The study of these topics is actually performed in ENEA (CIRCE, NACIE and HELENA facilities).

The collection of experimental data aims to improve the knowledge of phenomena and processes, and to create a database for the validation of computer codes for the prediction of phenomena and processes relevant for design and safety.

- *Instrumentation* – the suitable instrumentation for LFR/ADS is an important challenge due to the high thermal loads, high temperatures, the corrosive environment, the fast neutron spectrum and the non-transparency of the coolant. The research activities aim to develop instrumentation capable to withstand the operating conditions of the (Heavy Liquid Metal Reactors) HLMRs and to maintain the reliability of the measurements for a long time.