ESFR-SIMPLE: new HORIZON-EURATOM project on SFR safety

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Abstract – *Following several previous European projects (EFR, CP-ESFR and ESFR-SMART), a new project ESFR-SIMPLE has been proposed in response to the HORIZON-EURATOM call on "Safety of advanced and innovative nuclear designs and fuels". The new project aims at challenging the Generation IV ESFR (European Sodium Fast Reactor) designed in the ESFR-SMART project, to improve its safety and economics thanks to innovative technologies. The project high-level objectives and actions are:*
1) Challenge the ESFR design to simplify the reactor, through reducing its size, which could allow taking advantage of SMRs (Small Modular Reactors) in terms of transportability, modularization, standardization, flexible operation and machine learning, all ultimately leading to improved economics.
2) Propose, develop and assess advanced methods of monitoring and processing operational data using Artificial Intelligence, e.g., to optimize fault detection in the steam generators at an early stage.
3) Produce new experimental data in order to support calibration and validation of the computational tools such as properties measurements of irradiated and non-irradiated MOX fuel including fuel with optimized micro-structures, and to assist in qualification of innovative components, such as expansion bellows, thermo-electric pumps and accident tolerant core-catcher.
4) Assess alternative technologies, such as the use of metallic fuel and compact secondary system design, for the large-size ESFR to improve the economics and safety.
5) Ensure that the knowledge generated in the project will be shared not only among the project partner institutions, but also among as wide a range of stakeholders as possible in Europe and internationally.
The project relies on a consortium of 16 partners and will benefit from different skills and experiments available in Europe and in the US. It started in October 2022 and will end in September 2026. In addition to the technical details, this paper also briefly outlines the organization of the project.

I. INTRODUCTION

For 20 years, the Generation IV International Forum (GIF) [1] has proposed and defined a series of ambitious objectives for future nuclear reactors, including resource sustainability, safety, economics and non-proliferation. Among the six reactor technologies selected, a Sodium Fast Reactor (SFR) has already demonstrated its strong potential through decades of operation of reactors of various power levels. In parallel, the European Sustainable Nuclear Industrial Initiative (ESNII) [2] of Sustainable Nuclear Energy Technology Platform (SNE-TP) [3] places a strong emphasis on fast neutron reactors for sustainable nuclear energy production in Europe. Among the proposed concepts, the SFR stands out from two other fast-spectrum Generation-IV systems (Gas and Lead Fast Reactors) by its maturity and its experience feedback. The 3600 MWth European Sodium Fast Reactor (ESFR) concept has been developed for more than 10 years by 25 countries in two European projects (FP7 CP-ESFR [4] and H2020 ESFR-SMART [5]). In this context, ESFR has already closely approached the GIF goals and was identified as a part of the roadmap of ESNII.

While environmental issues are becoming more and more important in the energy debate, the 17 sustainable development goals proposed by the United Nations [6] are becoming more influential in the choice of future energy generation technologies. Providing clean energy at an affordable cost, which would help addressing the Climate Change, is a strong advantage of the future SFR.

Building on the advances made by the FP7 CP-ESFR and H2020 ESFR-SMART projects on the ESFR high-power reactor, a new European project on reactor safety is proposed in line with the ESNII roadmap guidelines and with the aim of best meeting GIF objectives through focused innovation and advanced technologies. The ESFR-SIMPLE project (European Sodium Fast Reactor - Safety by Innovative Monitoring, Power Level flexibility and Experimental research) brings together a consortium of research centres, industries, universities, Technical Safety Organisations (TSOs) and Small and Medium Enterprise (SME) with the aim of improving the attractiveness and safety of future SFRs. The consortium is presented on the Fig. 1. The project is coordinated by the CEA.

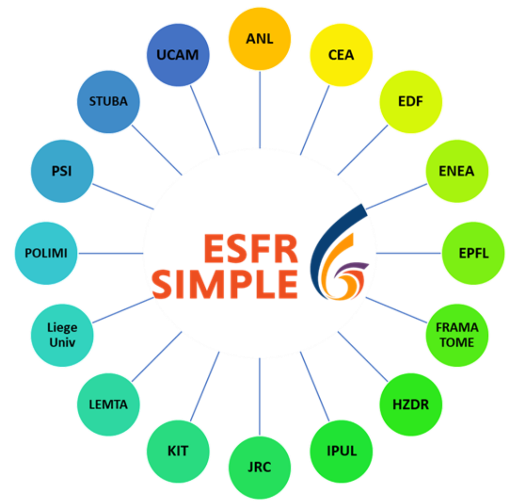

Fig. 1. Consortium of the ESFR-SIMPLE project.

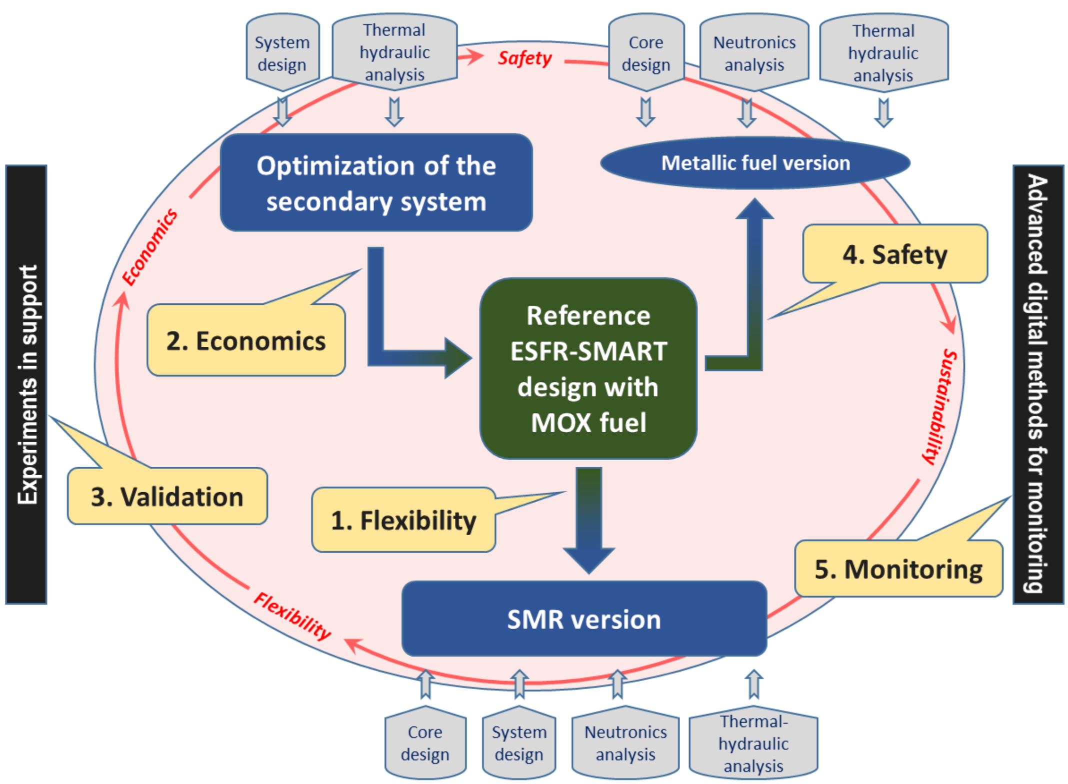

Fig. 2. Main project activities related to the reference ESFR design.

II. OBJECTIVES OF THE PROJECT

The safety measures implemented in CP-ESFR and ESFR-SMART have allowed a significant design simplification and advances in meeting the GIF goals. In order to take a further step towards the GIF goals, the ESFR-SIMPLE project will explore the impact of the new safety measures on the GIF goal metrics (Fig. 2). The new safety measures include development and assessment of

1) a new design of the 3600 MWth core based on a metallic fuel;
2) a simplified secondary circuit design;
3) passive pumps for improvement of Decay Heat Removal (DHR);
4) Artificial Intelligence (AI) to support monitoring of selected reactor components, in particular, Steam Generator (SG) tube rupture;
5) a small power MOX core and correspondingly simplified reactor systems, including a dedicated heat storage for improved flexibility.

The last activity will result in a Small Modular Reactor (SMR) [7] version of ESFR, referred to as ESFR-SMR. Several experimental programs detailed below will support development and assessment of these safety measures.

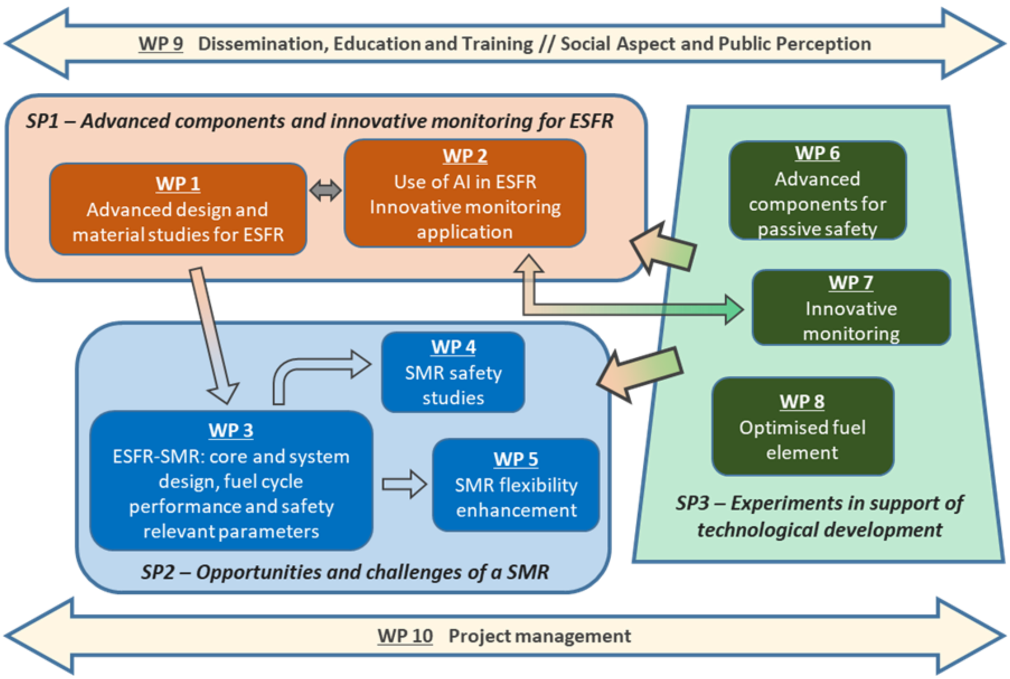

Fig. 3. PERT.

The goals of this project can be presented as the following five High Level Objectives (HLO) subdivided further into specific objectives.

HLO1. Challenge the high power ESFR design on the safety and economics by down-sizing
   a. Design an ESFR-SMR, improve its safety and compare its key performance characteristics with reference ESFR
   b. Evaluate the ESFR-SMR competitiveness for a future energy system in terms of reactor flexibility, network integration and Generation IV targets.

HLO2. Design, test and implement innovative technologies
   a. Design and assess an innovative core based on metallic fuel, in relation to GIF criteria
   b. Define and assess advanced mitigation measures for severe accidents
   c. Strengthen and optimise decay heat removal systems

HLO3. Improve the safety and monitoring by using advanced digital technologies
   a. Improve accuracy and confidence in the SFR modelling tools and perform their experimental validation
   b. Develop a data analysis tool to monitor system operation status
   c. Evaluate the possibility of the use of AI to support monitoring and components failure detection

HLO4. Produce and analyse new experimental data
   a. Obtain new experimental data on innovative oxide fuel pellets to improve performance and fuel performance modelling
   b. Explore core catcher improvement measures for mitigating consequences of severe accidents

c. Develop and assess an innovative passively driven pump to simplify and improve reliability of decay heat removal safety function
d. Qualify advanced sensors for detection of gas bubbles in liquid metal to mitigate SG tube rupture accidents
e. Assess the behaviour of innovative expansion bellows to simplify and reduce footprint of secondary system

HLO5. Perform a survey on public and expectations regarding Generation-IV reactor systems as future energy source in Europe
a. Develop a series of questions on the directions and priorities for development of nuclear technologies
b. Conduct survey and process answers from project stakeholders and general public
c. Evaluate in an iterative manner the public and stakeholders' opinion and its possible influence on the design for public acceptability
d. Propose recommendations for the implementation of innovative nuclear technologies in Europe, which are viewed more favourably by the public.

III. Structure of the project

To achieve its objectives, the ESFR-SIMPLE project is comprised of 10 work packages (WPs) grouped in four subprojects (SP), as clarified in Fig. 3. The first three SPs comprise technical WPs, while the fourth one deals with dissemination, education & training, as well as social aspects and project management. SPs, WPs and tasks have strong links between them. The PERT chart and the Fig. 12 aim to showcase these links.

Subproject 1 is devoted to the improvement of the safety and of the economics. As these developments need an advanced design to be assessed, they are applied on the ESFR with the objective to improve its attractivity. Composed of two WPs, it is in strong relation with Subproject3 and coordinates several experimental tasks.

Work Package 1 is devoted to two main tasks. The first one aims at designing and assessing a new secondary system (Fig. 4). The work will be focused on the reduced pipe-length design, on the new steam generator design, on the new passive pumps and on the safety assessment of this new secondary loop. For this purpose, it will be in direct relations with WP6 and WP7 concerning the tests on sodium expansion bellows and TESP, and the implementation of an advanced monitoring for bubble detection in the design of a new steam generator. The second task is devoted to the design of ESFR version with metallic fuel (Fig. 5). Based on the US and UK experience, the fuel type will be selected. Then the work will focus on the design of a fuel rod, a fuel assembly and a core. Neutronics calculation will allow the evaluation of performance and safety parameters, the fuel behaviour will be evaluated in transients and accident analysis will be realized. A summary will present the pros and cons of the use of a metallic fuel in ESFR.

Work Package 2 is devoted to the development of a demonstrator of machine learning system devoted to safety improvement. The R&D activities, suggested here for ESFR innovative monitoring, have the following objectives to define specifications, use case and experimental conditions for the development of an AI (Artificial Intelligence) engine dedicated to preventive maintenance for a sodium fast reactor. The studied case corresponds to gas leakage detection in a steam generator (Fig. 6) and will be devoted to detect with an improved robustness millimetric bubbles in sodium to allow fault detection. A strong relation exists with WP7 that will produce experimental data. The work done in WP2 will deliver information for WP7 and WP1 regarding the design of a new SGU (Steam Generator Unit) and the associated monitoring implementation.

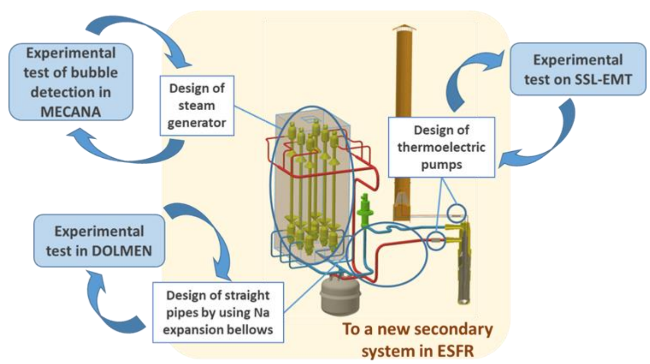

Fig. 4. Three R&D activities on the secondary system aiming at improving the economics.

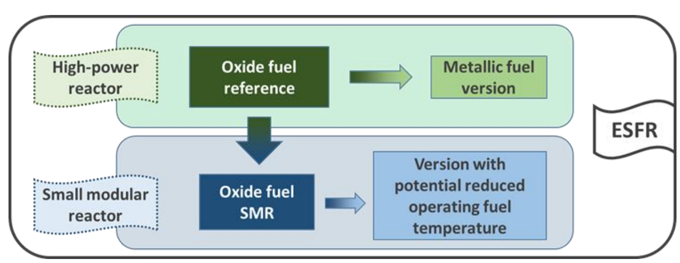

Fig. 5. Methodology of the oxide and metallic fuel options development in the project.

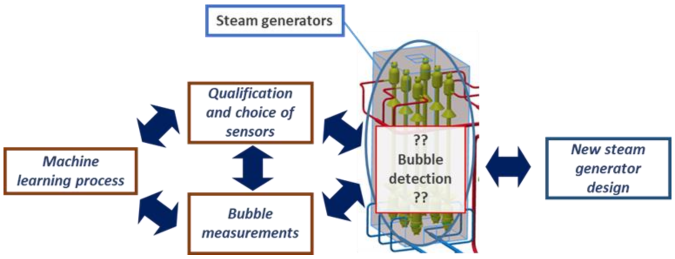

Fig. 6. Methodology applied on the new steam generator and bubble detection system.

Subproject 2 will be based on a work with an iterative process between system and core design and with preliminary safety assessments along this process, aiming at preparation of a SMR (Fig. 7). A strict coordination is needed in the whole subproject that will be eased by the fact that the lead of the different tasks is mainly done by experts who have experienced it in the past in the ESNII+ and ESFR-SMART projects.

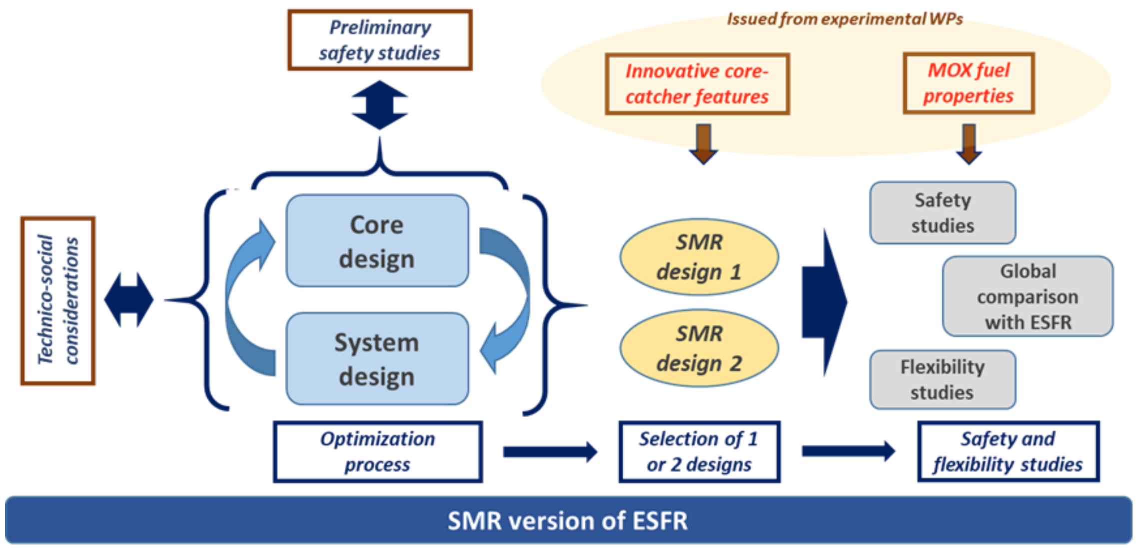

Fig. 7. Methodology of the ESFR-SMR development.

Work Package 3 will design a SMR based on two main tasks concerning the core and the system. A similar optimization that was done in ESFR-SMART is proposed, but with different objectives: formulate design criteria for ESFR-SMR in terms of safety, economics, and fuel cycle; propose a few ESFR-SMR designs that could potentially meet the specified criteria; assess fuel cycle and safety performance of the selected designs and compare ESFR and ESFR-SMR in terms of safety, economics, and fuel cycle. WP1 and WP6 will deliver data for the system design. One or two designs will be evaluated and WP3 deliver parameters to WP4 and WP5 for transient assessments. The comparison between ESFR and ESFR-SMR will be done based on results from WP3, WP4 and WP5.

Work Package 4 will assess the SMR safety analysis, based on the core and system design, as well as neutronics data coming from WP3, WP1 and WP6. Therefore, the real work to produce results can only begin in M26. Task 4.1 and 4.2 will deal with accident prevention analyses. Task 4.1 will focus on the investigation of transition from forced to natural circulation, analyze decay heat removal capabilities using DHR system(s) and evaluate the possibility of sodium boiling in the core, while task 4.2 will investigate sodium boiling and in-pin fuel melting phenomena in SMR, also their effect on the selected transients. Task 4.3 and Task 4.4 will deal with accident mitigation studies. Task 4.3 will study the effect of core safety measures on thermal energy release potential, molten fuel relocation and re-criticality potential after a hypothetical accident, while task 4.4 will analyze the thermal-to-mechanical energy conversion in such situation.

Work Package 5 will deal with flexibility studies. The objective of this WP is to identify, and to preliminary design and demonstrate the additional benefits of a flexible SMR-SFR based on a thermoelectric solar pump (TES) coupled to the secondary loop. Flexibility assessments will be realized at different timescales.

Subproject 3 is based on three WPs aiming at testing innovative components, advanced monitoring and improving MOX knowledge.

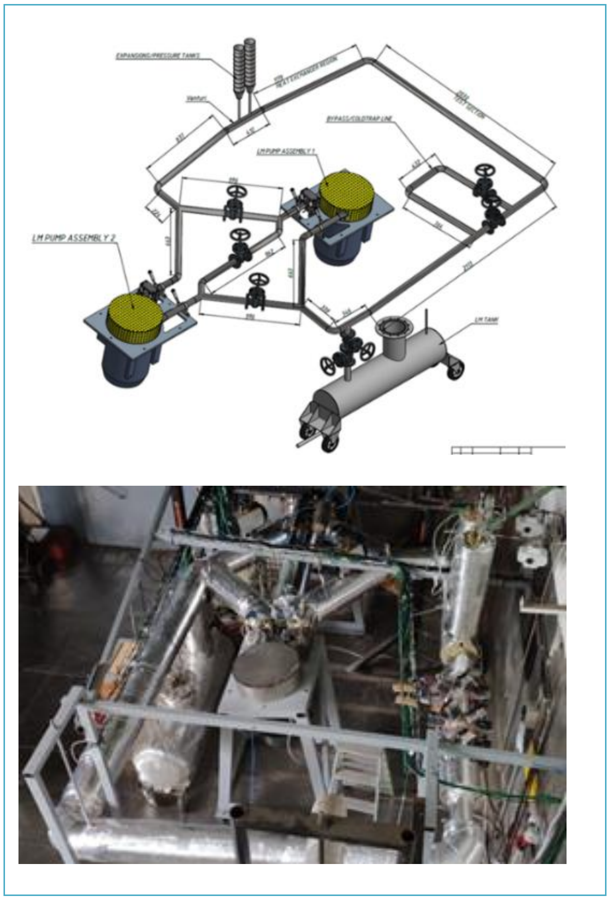

Fig. 8. SSL-EMT loop drawing and photo.

Fig. 9. A bellow tested on Superphenix heat exchanger.

Work Package 6 is devoted to the design and test of innovative components related with reactor passive safety. Task 6.1 deals with the design and test of an innovative passive driven thermoelectric pump and its system based on thermal alimentation. Tests will be realized at the IPUL facility (Fig. 8). Task 6.2 will design and characterize with the improved design feature of core catcher provide the resilience against both jet ablation and long-term ablation by a molten pool. Experiments will be done on the HANSOLO facility (Fig. 10) and on LIVE-CC facility (Fig. 11). Task 6.3 will focus on the design and testing of Na expansion bellows mock-up representative of a ESFR concept to reduce the second loop (Fig. 9). The tests will be realized at the MECANA facility.

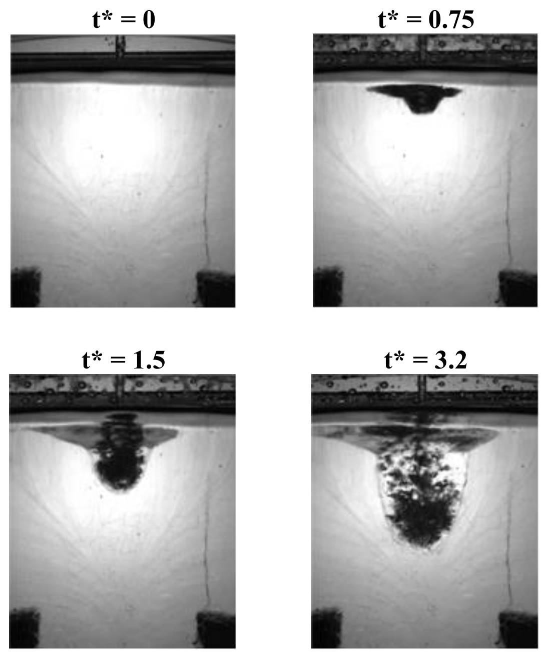

Fig. 10. Sequences of the ablation for jet temperature of 50°C, Djet=6mm, Rejet=24000, Prjet=3.6 (t*=t/tpe where tpe is the time of transition to pool effect).

Work Package 7 is devoted to the development and test of various measuring techniques for the detection and characterization of gas bubbles in sodium. The focus will be on inductive bubble measurements as it is a fully contactless approach. In a benchmark experiment, this technique will be compared to ultrasonic, eddy-current flowmeter and accelerometers antenna-based measurements. The contactless inductive bubble measurements will be validated by comparison with full bubble measurements using an available ultrafast electron beam X-ray tomography scanner. WP7 will deliver data to WP2 for the experimental testing of advanced monitoring. WP7 will deliver to WP1 the possibility to integrate such system on the new SGU designed in WP1.

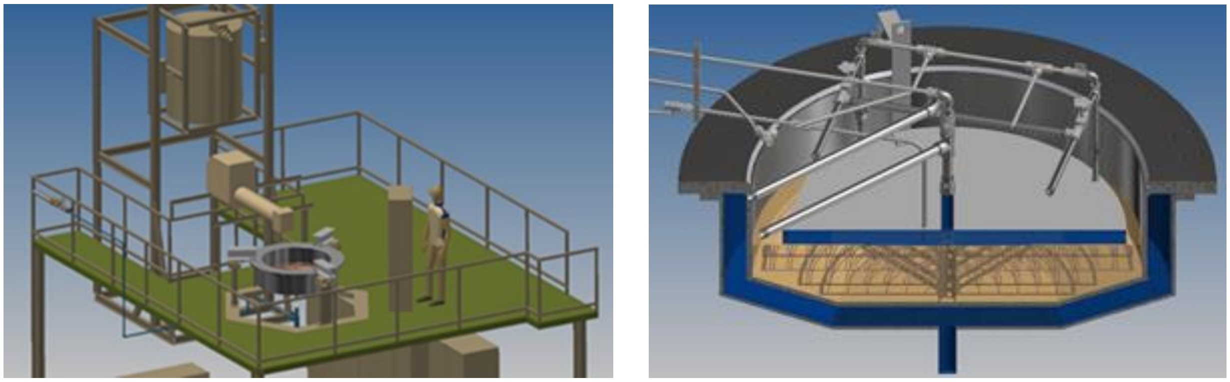

Fig. 11. LIVE-CC test facility at KIT (l*eft*: LIVE experimental platform; *right*: LIVE-CC test vessel with all boundary cooling system).

Work Package 8 is devoted to the optimization of the MOX fuel element with two main objectives. A parametric study of the behavior of MOX pins during the transients considered in SFR (UTOP and ULOF) will be realized. The associated objective is to assess the impact of each of the parameters (pin design, irradiation conditions, characteristics of the transients). This will orient the design choices in support of the ESFR-SMR. In parallel, the fuel characteristics will be evaluated through their impact on the fuel properties at very high temperature (expected during transients): electronic and radiative contribution to thermal conductivity, effect of porosity on thermal properties to better control the fuel uncertainties (TABLE I). Fabrication and tests of these fuel pellets will be realized at CEA and JRC facilities.

TABLE I

Qualification base for MOX fuel characterized during EU collaborative projects

Fresh Fuel	**Pu content (w%)**		24.5	28.4	32.7	40	45	65-70-75	100
	Density = 95-98%		Phenix Inner zone	Phenix CAMP99	CAPRA4	TRABANT2	TRABANT2	Fabricated in ATALANTE	JRC and CEA samples
	Density = 80%			New fabrication in ATALANTE					
	Density = 70 %			New fabrication in ATALANTE					
Irradiated Fuel	**Pu content (w%)**	19.8	23.3	28.4			45		
		NESTOR (Phenix)	PAVIX-155 (Phenix)	MYOSOTIS-12 (Phenix)			TRABANT 1 (HFR) CAPRIX (Phenix)		
	Burn-up	8 & 13 at%	13 at%	15 at%			9.5 & 11.7 at%		
	with only fission products under oxide and fuel phases	SIMFUEL - equivalent to NESTOR 13 at%							
		ESNII+ (2013-2017)		ESFR-SMART (2017-2021)		PUMMA (2020-2026)		ESFR-SIMPLE	

Subproject 4 is devoted to the transversal activities.

Work Package 9 will deal with the Dissemination, Education & Training activities. The main objectives are: develop new SFR computer simulator specifically for education and training purposes; compile, review and adapt a series of computational benchmarks to be used for education and training of young professionals on best practices and techniques of SFR modelling and design; organize and conduct a series of SFR technology-focused workshops and a Summer School to ensure information exchange and disseminate knowledge generated in the project; share the findings of ESFR-SIMPLE project with international organizations such as GIF; engage with general public through social media and other channels to disseminate knowledge and ideas created in the project; understand the public and stakeholder perceptions and needs for advanced reactor technology to inform the reactor design community decisions.

Work Package 10 will ensure timely delivery of quality project results to reach the objectives and contractual commitments. It covers consortium coordination, decision-making and conflict resolution, quality assurance, and management of administrative, financial and legal matters.

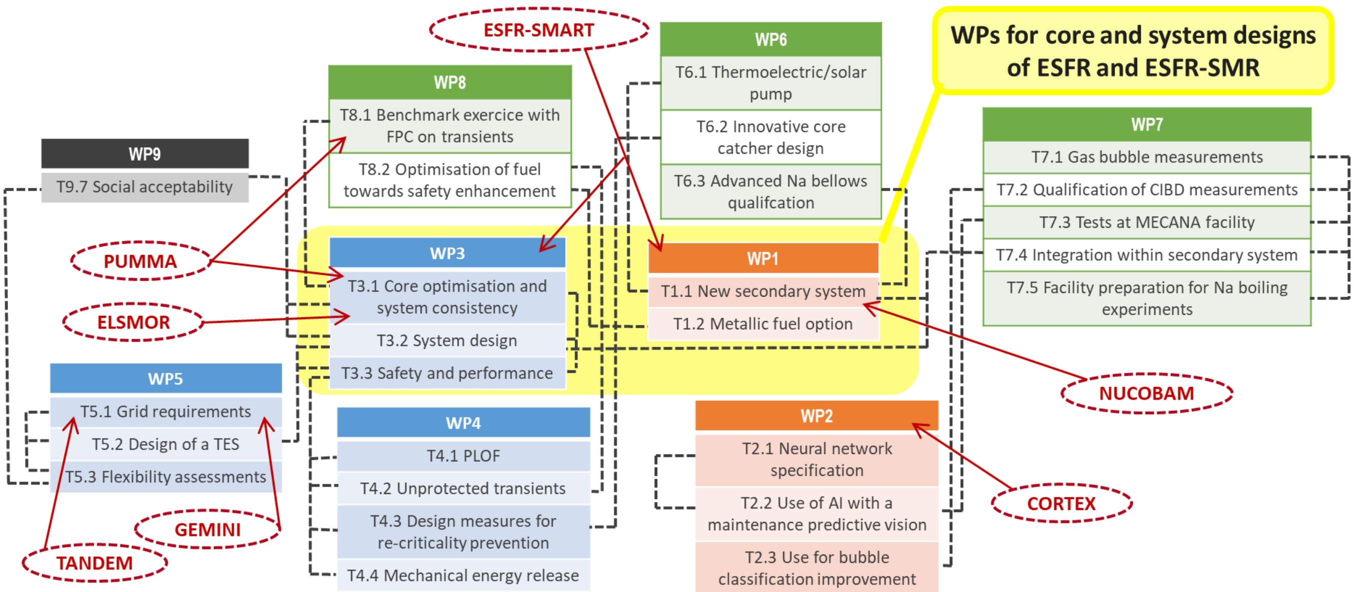

Fig. 12. Technical work packages - interrelations and relations with other projects.

IV. CONCLUSIONS

Based on a large consortium, the ESFR-SIMPLE aims at challenging the previous design of the EURATOM ESFR-SMART project. Five high level objectives have been defined to ensure a good consistency of the whole. Started in October 2022, it will end in September 2026.

Specific work will be carried out on the design of a small reactor to try to fill the gaps identified in terms of attractiveness, sustainability, flexibility with the objective of simplifying the design.

As a continuation of the ESFR-SMART project, experiments will be carried out to capitalize on the EURATOM investment made in the past in order to obtain valuable experimental data concerning severe accidents, innovative components such as thermoelectric pumps and sodium bellows, and the qualification of advanced MOX fuel.

A first step is proposed to demonstrate the possibility and interest of using advanced digital methods to improve safety and operation support.

The Project will provide added value to the European energy landscape by integrating industry input, international safety requirements, sustainable development goals and public perception into the new ESFR designs and by disseminating knowledge and results in Europe.

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NOMENCLATURE

ESFR: European Sodium Fast Reactor
ESFR-SIMPLE: European Sodium-Fast Reactor - Safety by Innovative Monitoring, Power Level flexibility and Experimental research
ESFR-SMART: European Sodium-Fast Reactor - Safety Measures Assessment and Research Tools
MOX: Mixed Oxides
SGU: Steam Generator Unit
SMR: Small Modular Reactor
SP: SubProject
TES: ThermoElectric Solar pump
ULOF: Unprotected Loss Of Flow
UTOP: Unprotected Transient Over Power
WP: Work Package

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