ESFR-SMART: new Horizon-2020 project on SFR safety

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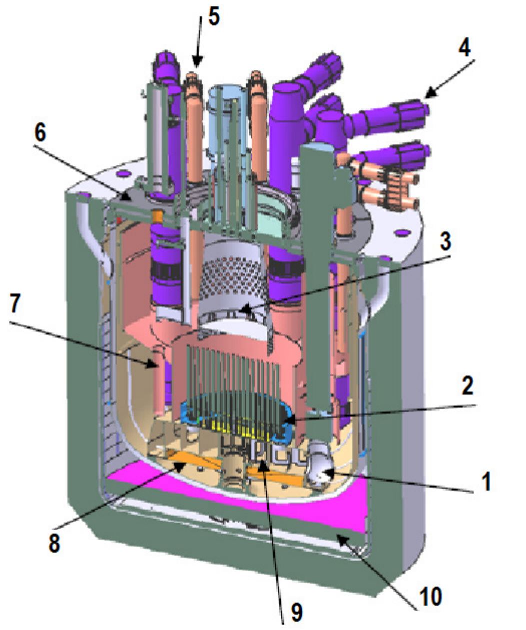
Abstract. To improve the public acceptance of the future nuclear power in Europe we have to demonstrate that the new reactors have significantly higher safety level compared to traditional reactors. The ESFR-SMART project (European Sodium Fast Reactor Safety Measures Assessment and Research Tools) aims at enhancing further the safety of Generation-IV SFRs and in particular of the commercial-size European Sodium Fast Reactor (ESFR) in accordance with the European Sustainable Nuclear Industrial Initiative (ESNII) roadmap and in close cooperation with the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) program. The project aims at 5 specific objectives: 1) Produce new experimental data in order to support calibration and validation of the computational tools for each defence-in-depth level. 2) Test and qualify new instrumentations in order to support their utilization in the reactor protection system. 3) Perform further calibration and validation of the computational tools for each defence-in-depth level in order to support safety assessments of Generation-IV SFRs, using the data produced in the project as well as selected legacy data. 4) Select, implement and assess new safety measures for the commercial-size ESFR, using the GIF methodologies, the FP7 CP-ESFR project legacy, the calibrated and validated codes and being in accordance with the update of the European and international safety frameworks taking into account the Fukushima accident. 5) Strengthen and link together new networks, in particular, the network of the European sodium facilities and the network of the European students working on the SFR technology. Close interactions with the main European and international SFR stakeholders—Generation-IV International Forum (GIF), ASTRID Research and Development Cooperation (ARDECo), ESNII and IAEA—via the Advisory Review Panel will enable reviews and recommendations on the project's progress as well as dissemination of the new knowledge created by the project. By addressing the industry, policy makers and general public, the project is expected to make a meaningful impact on economics, environment, EU policy and society.

Key Words: Sodium fast reactor, safety, Horizon-2020

1. Introduction

A concept of the European Sodium Fast Reactor of large power (1500MWe / 3600 MWt) was born in 1990s as a successor of the French SPX2 project. The name of the project was EFR: European Fast Reactor. Both the SPX2 and EFR projects aimed at the high breeding ratios, made use of the operational experience of the Superphenix reactor SPX1 of 3000 MWt and relied on the wide European cooperation. For a number of reasons (first of all, public opposition after the Chernobyl accident) the EFR project was stopped in late 90s. The renewed interest in the large-power SFR in the first decade of the 21st century was partly invoked by establishment of the Generation-IV International Forum in 2000 and resulted in the FP7 CP-ESFR project (2009 – 2013) [1], see the ESFR primary system layout in *FIG. 1*.



1 – primary pump
2 – diagrid
3 – above-core structures
4 – IHX (6)
5 – DHR loops (6)
6 – reactor roof
7 – fuel handling station
8 – space for internal core catcher
9 – strongback
10 – space for external core catcher

FIG. 1. ESFR primary system layout [1]

Logically following the FP7 CP-ESFR project (as well as a number of other projects: SARGEN_IV, JASMIN , ESNII Plus) and focusing on the safety-related GIF goals, the new EU project on Generation-IV SFR safety is proposed under Horizon-2020 in accordance with the ESNII roadmap [2] and in close cooperation with the French ASTRID program [3]. The ESFR-SMART project (European Sodium Fast Reactor Safety Measures Assessment and Research Tools) gathers a consortium of research centres, industries, universities, Technical and Scientific Support Organizations (TSOs) as well as Small to Medium Enterprise (SME) aiming at enhancing further the safety of Generation-IV SFRs and in particular of the commercial-size European Sodium Fast Reactor (ESFR). The partners and areas of their expertise related to the project area are schematically shown in *FIG. 2*.

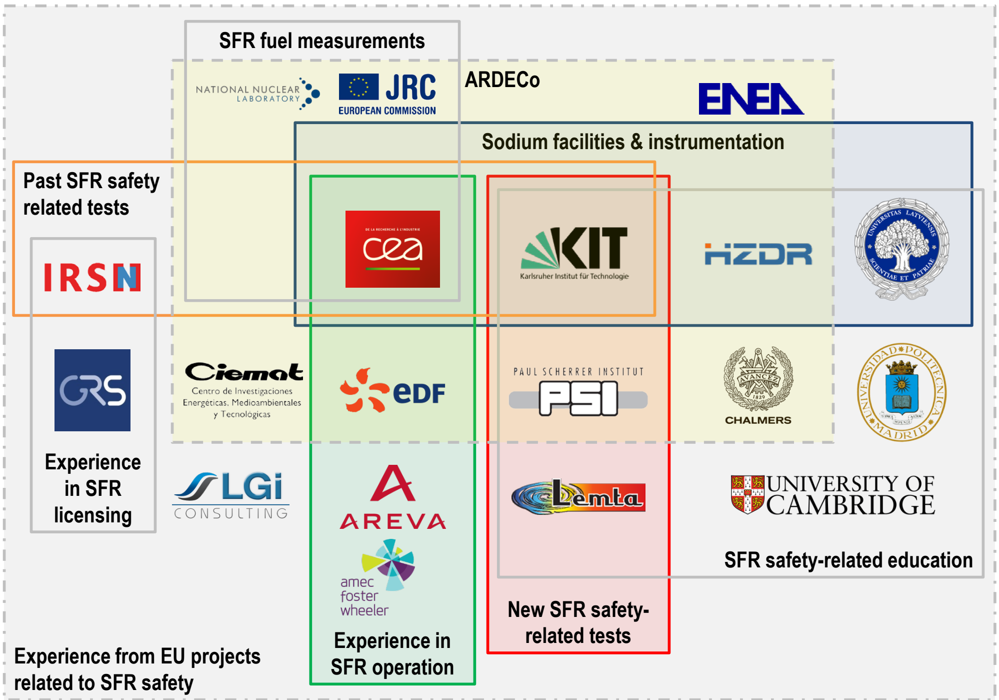


FIG. 2. ESFR-SMART partners: areas of expertise related to the project

2. Objectives of the project

The ESFR-SMART project relates to Topic NFRP 2: "Research on safety of fast neutron Generation-IV reactors" identified under Section A "Support Safe Operation of Nuclear Systems" of the Euratom Work Programme 2016-2017 and aims at 5 specific objectives:

1) Produce **new experimental data** in order to support calibration and validation of the computational tools for each defence-in-depth level:
   - selected safety-relevant fresh and burnt MOX fuel properties will be measured, using experience gained in the ESNII Plus project [4], in order to fill few gaps in the current knowledge;
   - forced-to-natural convection transition will be studied, using the KASOLA sodium loop [5], including conditions simulating the channel blockage (*FIG. 3*);
   - stabilized and/or chugging sodium boiling conditions will be studied with the new test section of the SOLTEC sodium facility [6] (*FIG. 4*);
   - chugging boiling regime conditions will be studied for the specific geometry of the low-void SFR core, using the new two-phase water facility CHUG (*FIG. 5*), see a similar approach *e.g.* [7];
   - interaction of corium jet with core catcher will be simulated using an ice-water analogy at the JOLO device (*FIG. 6*), see *e.g.* [8];
   - corium behaviour on the core catcher will be studied using the LIVE facility [9] (*FIG. 7*);
   - interaction of the corium jet with the concrete will be studied, using the MOCKA facility [9] (*FIG. 8*).
2) Test and qualify **new instrumentations** in order to support their utilization in the reactor protection system:
   - an advanced concept of the eddy-current flowmeter aimed at the detection of the channel blockage will be developed and tested, see *e.g.* [10];
3) Perform **further calibration and validation** of the computational tools for each defence-in-depth level in order to support safety assessments of Generation-IV SFRs, using selected data produced in the project as well as legacy experiments and SFR operational experience:
   - selected legacy Superphenix SFR core measurements and start-up tests [11] to calibrate and validate static and transient neutronic and thermal-hydraulic codes (*FIG. 9*);
   - new data from the KASOLA, SOLTEC and CHUG tests produced in the project as well as legacy data from the KNS-37 experiments [12] (*FIG. 10*) to calibrate and validate single- and two-phase sodium flow thermal-hydraulic models;
   - selected legacy CABRI test data of the molten fuel ejection from the fuel pin to calibrate and validate models of the fuel-coolant interaction (*FIG. 11*);
   - selected legacy SCARABEE-N test data of the molten pool behaviour to calibrate and validate models of the radial heat transfer in the molten pool in the fuel rod bundle (*FIG. 12*);
   - new LIVE test data produced in the project to calibrate and validate models of the melt pool coolability and refractory material dissolution;
   - selected legacy data to calibrate and validate models of release and behaviour of aerosols in the containment in sodium vapour atmosphere (FAUST and NALA programs) and from the sodium pool fires (FANAL program) (*FIG. 13*).
4) Select, implement and assess **new safety measures** for the commercial-size ESFR, using the GIF methodologies, the FP7 CP-ESFR project legacy, the calibrated and validated

codes and being in accordance with the update of the European and international safety frameworks taking into account the Fukushima accident [13], in order to demonstrate that

- the iso-breeding properties of the new core meet the GIF requirements;
- passive decay heat removal capability is improved compared to traditional LWRs (*e.g.*, no core melt down and hydrogen explosions in a Fukushima-like accident);
- the grace time between the sodium boiling onset and the core melting start is significantly increasing (at least for several minutes) compared to traditional SFRs, which will allow the activation of passive mitigation dispositions;
- mechanical energy release challenging vessel integrity in case of a hypothetical severe accident is significantly decreasing compared to traditional SFRs.

5) Strengthen and link together **new networks**, in particular, the network of the European sodium facilities (*FIG. 14*) and the network of the European students working on the SFR technology in order to support the new data acquisition as well as the SFR-related education and training:
    - the PhD students will be supported by the mobility grants to let them make internships at the facilities;
    - series of workshops and a summer school will be organized at different organizations with technical visits to the facilities when possible.

The project's outcome is expected to be exploited by the key SFR stakeholders, and particularly by ARDECo, ESNII and to some extend by GIF and IAEA Technical Working Group on Fast Reactors (TWG-FR).

3. Structure of the project

To achieve the objectives described in Section 2, the ESFR-SMART project is structured in twelve work packages (WPs) grouped in three subprojects (SP) as clarified in *FIG. 15*. The first two SPs comprise five technical WPs each, while the third SP deals with dissemination, education & training as well as project management.

2.1. Subproject 1 "Selection and assessment of innovative safety measures for the ESFR concept"

Subproject 1 is devoted to the next phase of the ESFR concept development with a focus on safety enhancement compared to the current light-water reactors and to the traditional sodium fast reactors. The objective of SP1 is to select and assess new safety measures in accordance with the update of the European and international safety frameworks taking into account the Fukushima accident. The work packages are structured according to the defence-in-depth strategy.

Work Package 1.1 will start with the ESFR specifications from the FP7 CP-ESFR project to provide by the end of the first year a consistent set of new safety measures to be assessed in WPs 1.2 – 1.5. These safety measures will relate to the core and to the primary system. WP 1.1 will monitor the consistency of different R&D studies during the whole project duration. The GIF Integrated Safety Assessment Methodology will be used to deliver the guidelines for the whole SP1. The new safety measures will take into account the approaches considered for the ASTRID SFR and where relevant for the other Generation-IV (ESNII) systems, including

- passively activated core shutdown system;
- heterogeneous core design characterized by low total sodium reactivity effect;
- primary pumps with improved coast-down characteristics;
- primary system with improved natural circulation characteristics;

- passive decay heat removal systems resilient against common mode failure, using natural circulation and atmospheric air as a final heat sink;
- corium discharge tubes connecting the core with the core catcher;
- passively activated introduction of absorber into the core under severe accident conditions.

The important milestone for the whole SP1 will be the core and system specification for the upgraded ESFR design.

Work Package 1.2 will assess the impact of the new reactor safety measures, provided by WP1.1, on the normal operation in terms of the fuel cycle performance in order to confirm that this impact is favourable or neutral (otherwise the iteration will be done with WP1.1 to correct the selected measures). The work package will show that the new safety parameters are mainly improved compared to the CP-ESFR core and will deliver them to WP1.3, WP1.4, and WP1.5 for the subsequent safety analysis. The work in WP1.2 will be supported by calibration and validation of codes in WP2.1 as shown in TABLE 1)

Work Package 1.3 will assess the performance of primary pumps, decay heat removal system, reactor passive shutdown systems and the primary system as a whole under selected accident conditions. The provisions to avoid sodium boiling will be determined. The work in WP1.3 will be supported by new experiments in WP2.2 and by calibration and validation of codes in WP2.1 as shown in TABLE 1). The final milestone of the work package is to conclude on the passive decay heat removal capability of the new reactor in Fukushima-like scenarios to demonstrate the safety enhancement of the new reactor compared to the traditional LWRs.

Work Package 1.4 will deal with evaluation of the low-void effect core capability to avoid severe consequences of the loss of flow or blackout events (*i.e.* deterioration of the heat removal from the core) when the reactor scram failed and the chain reaction is not stopped. Three innovative analytical studies will be done with significant contributions from the PhD students in order to: 1) explore under which conditions the chugging boiling regime can establish in the core and whether a sudden vapour bubble collapses can cause high pressure pulses (this study will be supported by the experimental work performed in WP2.2 and the validation work in WP2.1 as shown in TABLE 1); 2) investigate how the pressure pulse inside the subassembly could dynamically deform the subassembly wrapper tube and/or the core support structure (diagrid) and how this geometry perturbations propagate through the core; 3) analyse how these geometry perturbations (or perturbations of other natures) could impact the dynamic reactivity and power of the core. The final milestone of the work package is to conclude on the grace time between the sodium boiling onset and the severe accident start to demonstrate the safety enhancement of the new reactor compared to the traditional SFRs.

Work Package 1.5 will deal with the mitigation of severe accidents focusing on the core behaviour during the transitional and expansion phases as well as with the special measures to insert additional absorber in the core during the severe accident. The analytical work on the initial phases of the severe accidents will be supported and supplemented (for later phases of the severe accidents) by the validation studies in WP2.1 and by the new experiments in WP2.2 as shown in TABLE 1). The final milestone of WP1.5 is to conclude on mechanical energy release challenging vessel integrity in case of a hypothetical severe accident to demonstrate the safety enhancement of the new reactor compared to the traditional SFRs.

2.2. Subproject 2 “Support and development of the new research tools related to SFR safety”

Subproject 2 assumes under the term “*research tools*” calculational codes, new experimental data and sodium facilities and, correspondingly, is devoted to producing new data and instrumentation, method developments and codes calibration and validation.

Work package 2.1 will deal with the calibration and validation of the existing computational tools for each defence-in-depth level: using new and available SFR safety-related data to support and link the two subprojects (SP1 and SP2) and to provide at the end of the project the computational tools validated for the SFR safety analysis to the other SFR-related programs[1].

Work package 2.2 will create new experimental data (listed in Paragraph 1 of Section 2) to calibrate and validate the computational tools for each defence-in-depth level. At the end of the ESFR-SMART these data will be made available for the other SFR-related programs[1], according to the Grant Agreement.

Work package 2.3 will focus on the improvement and strengthening of the network between European sodium facilities to contribute to the future experimental support of the other SFR-related programs[1]. One of the ideas of the ESFR-SMART project is to connect the network of the European sodium facilities and the pool of the PhD and MS students working on different aspects of the SFR safety and with the help of the students mobility program organized by WP3.1 let the students to make part of their studies at one of the European sodium facilities doing an experiment or supporting the experiment with an analytical work (*e.g.* the CFD calculations).

Work package 2.4 will deal with improved monitoring of the processes in the reactor and the auxiliary systems, in particular, the work package will focus on the qualification of eddy-current flow meters (ECFM) to further develop such sensors for a positioning above the fuel subassemblies in a sodium cooled fast reactor in order to detect possible blockages of the sodium flow along the multitude of subassemblies. The ECFM developed at HZDR will be tested at the SOLTEC facility at KIT under temperature conditions similar to the ESFR-SMART core outlet conditions. The reliable flowmeter working in sodium environment is needed by all SFR-related programs[1].

Work package 2.5 is devoted to the new campaign on measurements of fresh and burnt MOX fuel properties. This cross-cutting activity follows up WP7 “Fuel safety” of the FP7 ESNII Plus project and will be used at the end of the project by not only SFR-related programs (ARDECo), but by all fast reactor projects relying on the use of the MOX fuel, *e.g.* the other ESNII systems: MYRRHA, ALFRED, ALLEGRO.

2.3. Subproject 3 “Management and interaction”

In addition to the project management the subprojects focuses on dissemination, education and training.

Work package 3.1 will improve educational tools and learning methodologies; will organise workshops for PhD students, post-docs, designers, stakeholder, etc. highlighting the safety issues related to the development of Sodium Fast Reactors and in particular operation of sodium facilities; will support doctoral dissertations, related to SFR safety; will favour

[1] In particular: ARDECo, ESNII, GIF, IAEA TWG-FR

mobility of PhD students and post-docs; will communicate with external organizations (ESNII, GIF, etc.); and will manage project website.

Work package 3.2 will provide overall technical, legal, contractual, administrative and financial management of the project, to ensure timely delivery of quality project results to reach the objectives and contractual commitments.

FIG. 3. KASOLA facility to study sodium transitional flow

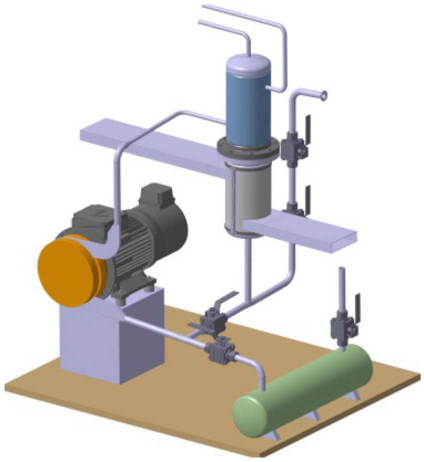


FIG. 4. 3D sketch of the SOLTEC facility presently under construction at KIT

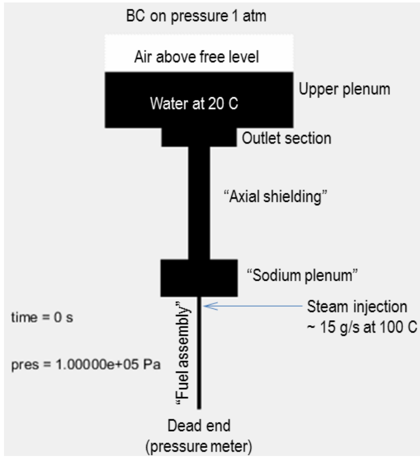


FIG. 5. 2D sketch of the CHUG facility to be built at PSI

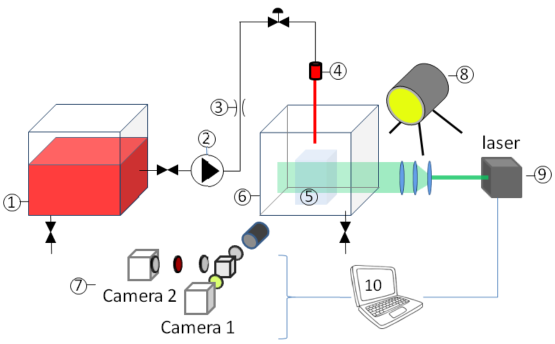
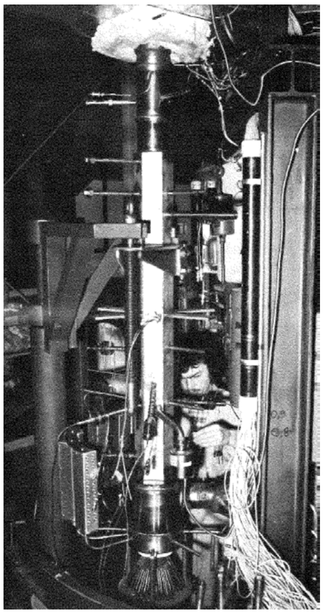


FIG. 6. Diagram of JOLO at LEMTA

1 – main tank at controlled temperature;
2 – pump;
3 – mass flowmeter;
4 – nozzle;
5 – sacrificial material;
6 – vessel;
7 – camera (PLIF, PIV, high speed video);
8 – back light illumination;
9 – laser source;
10 – system control

FIG. 7. LIVE facility at KIT [8]

FIG. 8. Cross section of MOCKA crucible at KIT [8]



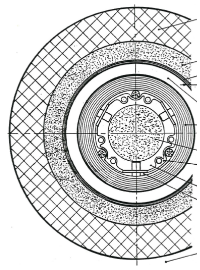


FIG. 11. CABRI single-pin test section

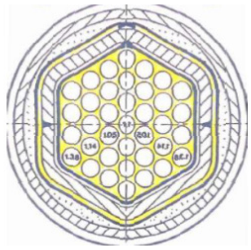
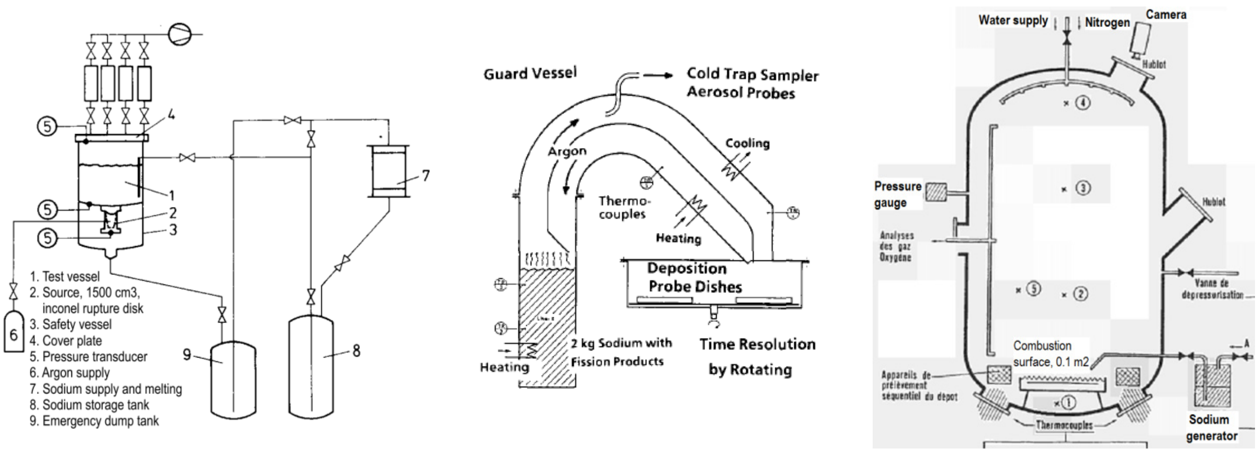


FIG. 9. Superphenix (SPX1) SFR

FIG. 10. KNS test section

FIG. 12. SCARABEE 37-pin bundle



a) [14] b) [14] c) [15]

FIG. 13. Diagrams of a) FAUST at FzK; b) NALA at FzK; c) FANAL at Cadarache CEA

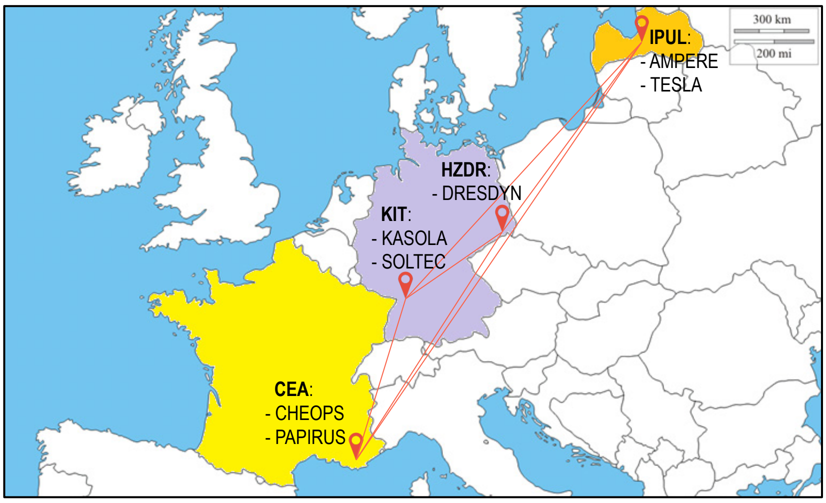


FIG. 14. Network of European sodium facilities

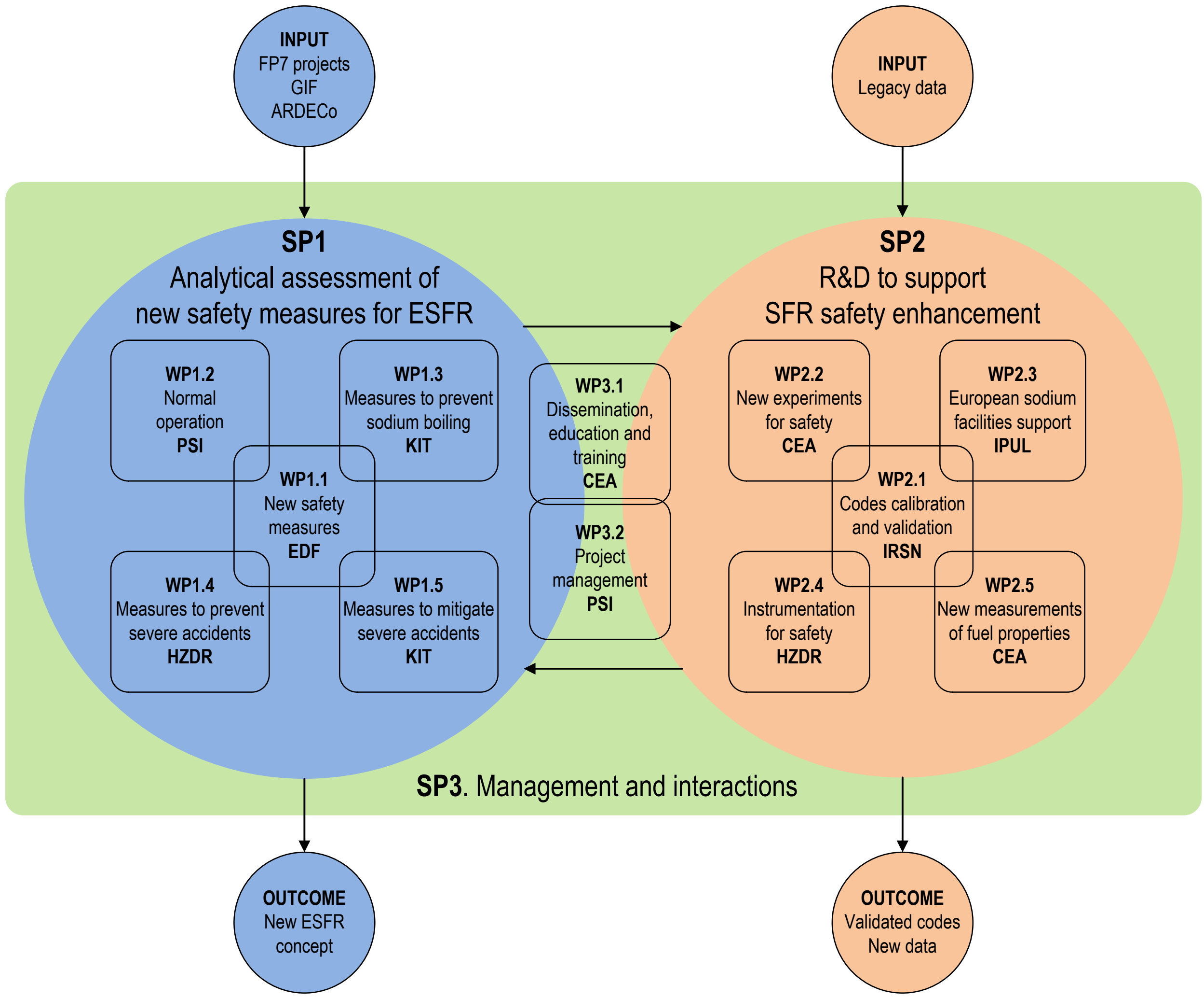


FIG. 15. Organizational structure of the ESFR-SMART project, showing the relationship between the work packages as well as the main input information and the main outcomes of the project.

TABLE I: INTERNAL LINKS BETWEEN DATA ACQUISITION, VALIDATION OF CODES AND SAFETY ASSESSMENTS IN ESFR-SMART.

DiD	Legacy data used in the project & New data produced in the project (WP)		New validation of codes using the data (WP)		New assessment for ESFR using the codes (WP)
1	SPX1: neutronic tests at start-up	→	Static neutronics modeling (**2.1**)	→	Performance of low-void core in commercial-size SFR (**1.1**), (**1.2**)
2	SPX1: reactor operational transients	→	Modeling of operational transients, thermal expansion effects (**2.1**)	→	Safety assessment of natural convection performance, DHRS*, pumps, PCSS** (**1.3**)
3	KASOLA: transitional flow (**2.2**)	→	Heat exchange at forced-to-natural convection transition (**2.1**)	→	
4	KNS: sodium boiling	→	2D sodium boiling modeling (**2.1**)	→	Coupled thermal-hydraulic/ neutronic behaviour of low-void core under ULOF conditions (**1.4**)
	CHUG: chugging boiling (**2.2**)	→	Chugging boiling modeling (**2.2**)	→	
	SCARABEE-N: fuel bundle melting	→	Radial heat transfer in molten bundle (**2.1**)	→	Transition and expansion phases of severe accidents (**1.5**)
	JOLO: corium jet-catcher interaction (**2.2**) LIVE: corium behaviour on catcher (**2.2**) MOCKA: corium-concrete interaction (**2.2**)	→	Corium jet impingement modeling (**2.1**)		
	FAUST, NALA, FANAL: aerosols behaviour	→	Source term calculations (**2.1**)		

*DHRS – decay heat removal system
**PCSS – passive core shutdown system

4. Summary

The 4-year Horizon-2020 ESFR-SMART project (European Sodium Fast Reactor Safety Measures Assessment and Research Tools) gathers 19 European partners aiming at enhancing further the safety of Generation-IV SFRs and in particular of the commercial-size European Sodium Fast Reactor (ESFR).

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