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HORIZON-2020 ESFR-SMART PROJECT ON SODIUM FAST REACTOR SAFETY: STATUS AFTER FIRST 15 MONTHS

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ABSTRACT

Devoted to the Generation-IV European Sodium Fast Reactor safety, the Horizon-2020 ESFR-SMART project was launched in September 2017. Selected results and milestones achieved during the first fifteen months of the project are briefly reviewed in the paper, including 1) proposal of new safety measures for ESFR; 2) evaluation of ESFR core performance; 3) benchmarking of codes; 4) experimental programs; and 5) education and training.

1. INTRODUCTION

Following the FP7 EU CP-ESFR project and focusing on the safety-related Generation-IV International Forum (GIF) goals, the new EU Horizon-2020 ESFR-SMART project (European Sodium Fast Reactor Safety Measures Assessment and Research Tools) (Mikityuk et al., 2017) was launched in September 2017 by a consortium of 19 European organizations (see Fig. 1) aiming at enhancing further Generation-IV SFR safety and in particular of the commercial-size European SFR (ESFR) initially defined during the CP ESFR project. The project logo continues the tradition of using a Phenix bird image as a symbol of Sodium Fast Reactor (Fig. 2). Selected achievements reached during the first 15 months of the project are briefly overviewed.

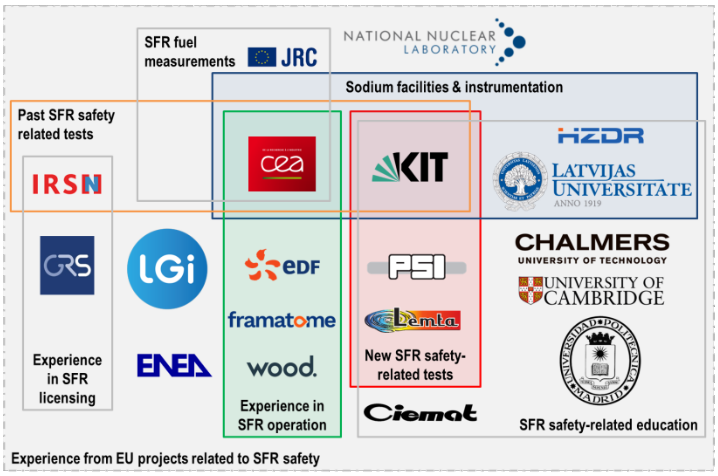


Fig. 1 ESFR-SMART project consortium

Fig. 2 ESFR-SMART project logo

2. PROPOSAL OF NEW SAFETY MEASURES

The key idea of the project is to make a next step in developing the large-power (1500 MWe/3600 MWt) SFR concept, following up the “line” of the Superphenix 2 (SPX2), European Fast Reactor (EFR) and ESFR designs and using the set of the GIF objectives as a target. Compared to the traditional LWRs and SFRs, the new reactor should **not only** be able to reprocess its own and legacy waste, exclude fuel enrichment, be more reliable in operation, friendlier to the environment, more affordable, better protected against proliferation, **but also** be safer. Using the CP-ESFR (Collaborative Project for ESFR) legacy as a starting point, we select novel safety measures and technically assess their impact on the ESFR defence-in-depth levels.

2.1. Definition of safety requirements

The main objective of this activity is to provide ambitious guidelines to support the definition of innovative design options for SFR. This is the opportunity to assess and possibly to adapt for this purpose the methodology recommended by GIF RSWG, 2011 (Fig. 3). The methodology provides a view of safety functions implementation in accordance with defence-in-depth principle as it is defined by Western European Nuclear Regulators’ Association (WENRA). A specific approach relying on confinement barriers is proposed for the confinement function. The application allows missing equipment identification. Safety features to prevent/overcome mechanisms likely to degrade equipment ensuring safety functions are investigated, in particular common cause failures with other level provisions (*e.g.* diversity of equipment with regard to manufacturing defects or design failure).

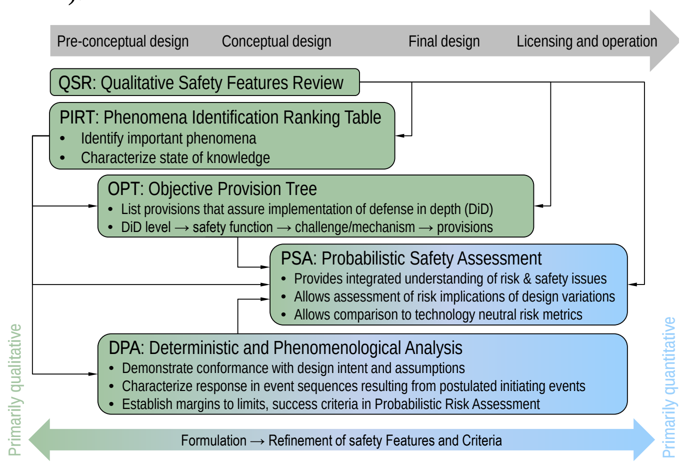


Fig. 3 Flowchart of GIF Integrated Safety Assessment Methodology

2.2. New core safety measures

The ESFR core design modifications were aimed at improving the core map symmetry; optimizing the void effect; and facilitating the corium relocation toward the corium catcher. Based on the previous experience the conceptual core configuration was proposed featuring the sodium plenum above the fuel to reduce the void effect; two radial zones with the same plutonium content and different fissile heights to flatten the radial power distribution; mixed six-batch reloading scheme with internal spent fuel storage to optimize the reloading procedure. The exact core design was defined by optimizing neutronics, thermal-hydraulic and fuel performance using multi-physics and multi-objective optimization tool (see Fig. 4). Rineiski, et al., 2018 reports the details of the proposed design and of the optimization procedure. A detailed analysis of the neutronics, thermal-hydraulic and fuel performance of the proposed core is currently under way (see Section 3).

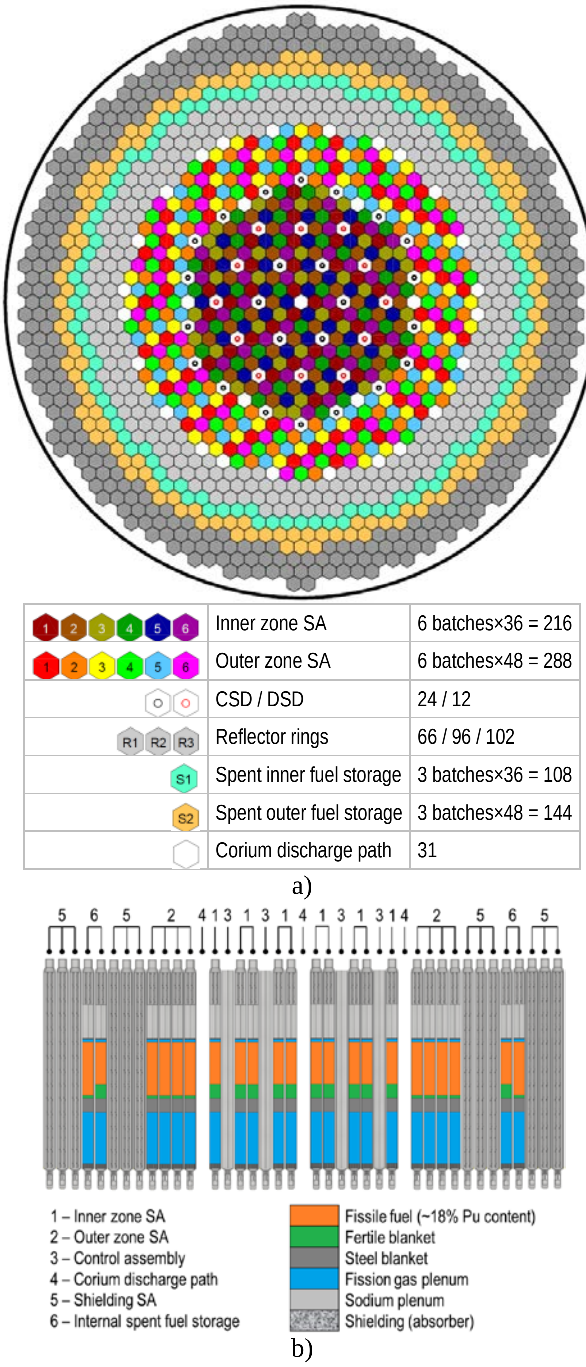
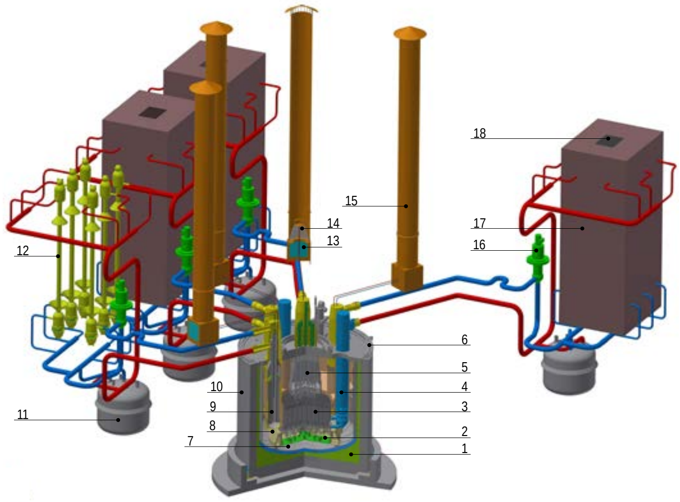


Fig. 4 Core radial (a) and axial maps (b)

2.3. New system safety measures

The ESFR system modifications were aimed at simplifying the overall design (see Fig. 5) and improving the safety functions: control of reactivity, heat removal from fuel, and confinement of the radioactive materials. The measures related to the reactivity control improvement are listed in Section 2.2. The measures related to the heat removal improvement include new Decay Heat Removal systems (DHRS). In particular, 1) DHRS-1 loop is proposed to be connected to the secondary side of Intermediate Heat Exchanger (IHX) in parallel to the main secondary loop providing the secondary sodium circulation through the sodium-air heat exchanger under natural convection assisted at the sodium side by the thermoelectricity-driven passive pumps and at the atmospheric air side by the air chimney, 2) six steam generators (SGs) of one secondary loop are enclosed in a casing with windows to promote the atmospheric air natural convection removing heat from the SG surfaces; 3) two active (oil and water) systems for the reactor pit concrete cooling are considered also available for the DHR. Improvement of the confinement function is proposed to be reached by simplifying the reactor pit and roof designs. In particular, the safety vessel used in the previous ESFR design has been replaced by a metallic liner on the surface of the reactor pit. The reactor roof is designed as a solid and heavy metallic structure with a minimum number of penetrations, which leak tightness is given either by freezing seals or by temporary welding. Due to these measures the reactor dome above the roof is proposed to be suppressed simplifying the design and improving the economics. More details about new safety measures implemented in the ESFR design could be found in Guidez, et al., 2018.



1: Insulation with steel liner
2: Core catcher
3: Core
4: Primary pump
5: Above-core structure
6: Pit cooling system (DHRS-3)
7: Main vessel
8: Strongback
9: IHX
10: Reactor pit
11: Secondary sodium tank
12: Steam generator
13: Window for air circulation (DHRS-1)
14: Sodium-air HX (DHRS-1)
15: Air chimney (DHRS-1)
16: Secondary pump
17: Casing of SGs (DHRS-2)
18: Window for air circulation (DHRS-2)

Fig. 5 General view of ESFR systems with proposed modifications

3. EVALUATION OF CORE PERFORMANCE

After the new core design (see Fig. 4) was proposed the studies were launched to check how this core design will influence the neutronics and fuel performance.

3.1. Core neutronics performance

As a first step, fresh-core and once-through burnup calculations were performed by several teams using both deterministic and stochastic codes. After identifying and solving several problems, a reasonable agreement was obtained between different codes. As a second step, realistic six-batch burnup calculations were performed using a Monte Carlo code (see Fig. 6) and the core state specification at the End of Equilibrium Cycle were defined, including the 3D isotopic composition in the core for the subsequent calculation of the reactivity coefficients and kinetics parameters as well as the 3D power distribution for the following-up thermal-hydraulic analysis.

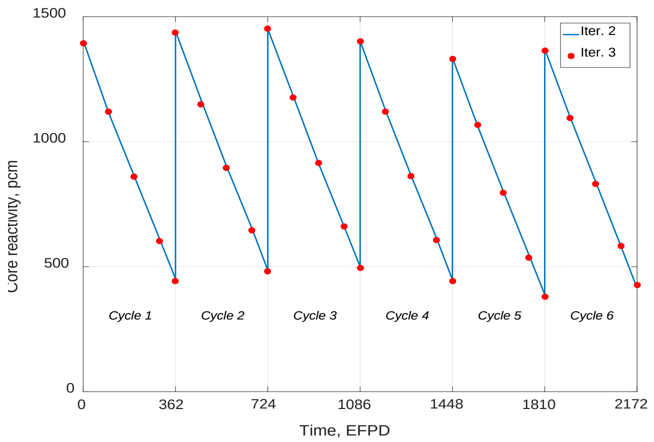


Fig. 6 Reference solution for core reactivity versus time for six equilibrium fuel cycles

3.2. Fuel base irradiation performance

The objectives of the analysis are to evaluate the fuel performance of the new core design for a typical cycle and to derive the correlation for the gas gap heat conductance to be used in the subsequent steady-state and transient thermal-hydraulic analyses. The evolution of the axial power profiles for representative fuel rods from the inner and outer zones were provided by the neutronics analysis. Seven codes are currently used to evaluate fuel performance and prepare the input for correlating the gap heat conductance with respect to local power rating and fuel burnup. The example of the axial profile of the gap heat conductance in a representative fuel rod of the inner zone at the very beginning of the base irradiation is shown in Fig. 7.

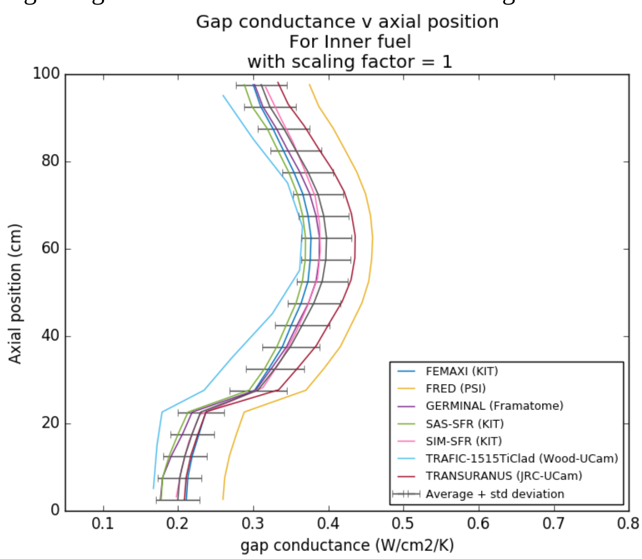


Fig. 7 Axial profile of gap conductance at 1 EFPD as predicted by different fuel performance codes

4. BENCHMARKING OF CODES

One of the specific objectives of the project is to 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. Two examples of these activities are given in this Section.

4.1. Benchmark on Superphenix SFR start-up core neutronics

In support to the neutronics analysis (see Section 3) a new calculational benchmark has been proposed for the startup core of the Superphénix (SPX) Sodium Fast Reactor based on open publications (Ponomarev et al., 2018). A detailed core specification was prepared (see Fig. 8) and the available measurements were collected to compare with calculational results. Six solutions are obtained with different stochastic and deterministic codes and good agreement was reached between codes and available measurements (see the comparison of multiplication factor in Fig. 9). At the second phase of the benchmark the calculated reactivity coefficients will be used in simulation of the SPX start-up transient tests using the system codes.

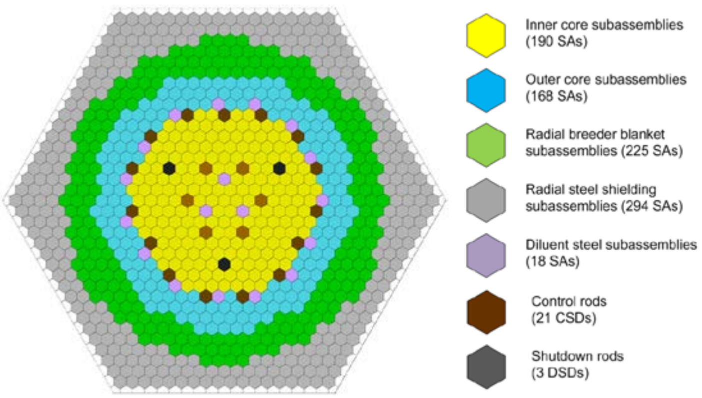
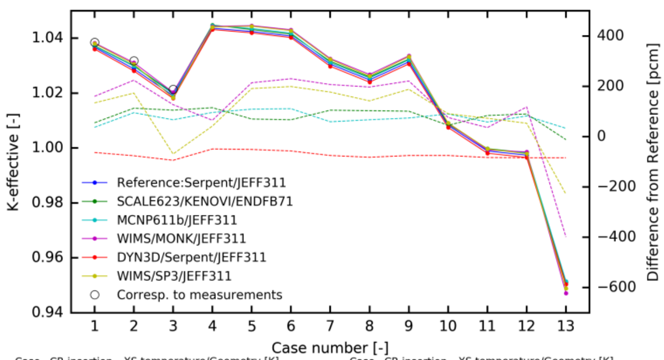


Fig. 8 Superphenix startup core map (Ponomarev et al., 2018)



Case	CR insertion [cm]	XS temperature/Geometry [K] Fissile	Fertile	Others	Case	CR insertion [cm]	XS temperature/Geometry [K] Fissile	Fertile	Others
1	0	453/453	453/453	453/453	8	0	900/673	900/673	900/673
2	0	673/673	673/673	673/673	9	0	600/673	600/673	300/673
3	0	1500/1500	900/900	673/673	10	40	300/673	300/673	300/673
4	0	300/300	300/300	300/300	11	40	600/673	600/673	600/673
5	0	300/453	300/453	300/453	12	40	673/673	673/673	673/673
6	0	300/673	300/673	300/673	13	100	453/453	453/453	453/453
7	0	600/673	600/673	600/673					

Fig. 9 Multiplication factor calculated for 13 different states of Superphenix start-up core

4.2. Benchmark on sodium boiling in ULOF conditions (KNS-37)

In preparation to the safety analysis to be done for ESFR, a computational exercise on sodium boiling modeling was organized among seven partners using seven different codes. This exercise is based on a KNS-37 sodium loop experiment performed in Germany in 80s to study sodium boiling in pin-bundle geometries (Bottoni et al, 1990). Since the Unprotected Loss Of Flow (ULOF) analysis is planned to be performed later for ESFR, the KNS-37 L22 test was selected for modeling, because in this test typical ULOF conditions were reproduced. The analysis of the computational results in comparison with the measured data is currently under way and, as an example, the boiling front evolution is shown in Fig. 11. After completion of the L22 test analysis, other KNS-37 ULOF tests with different power levels, flow rates and coast down halving times are foreseen to be simulated.

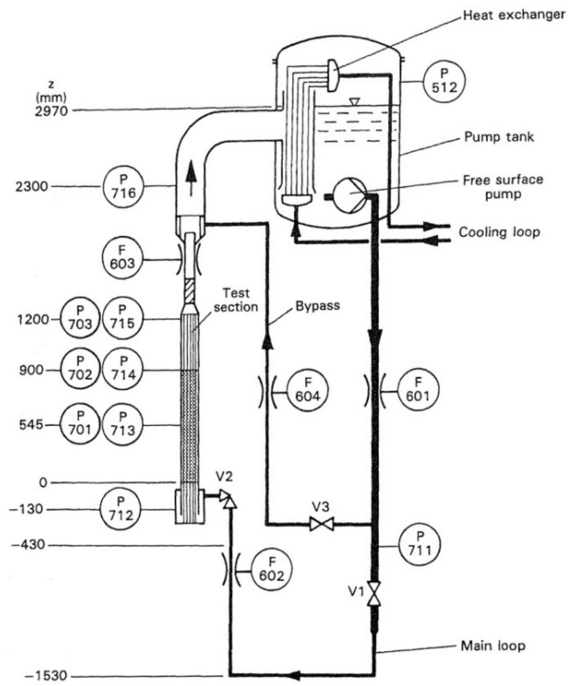


Fig. 10 Simplified diagram of the KNS-37 sodium loop

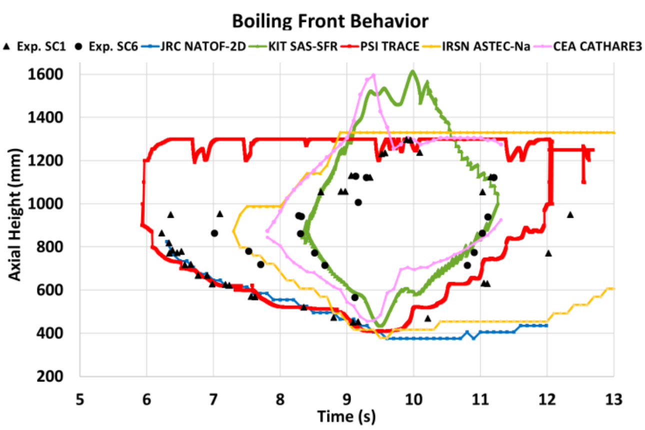


Fig. 11 Evolution of the boiling front in KNS-37 L22 test: comparison of measured data with code predictions

5. EXPERIMENTAL PROGRAMS

Two specific objectives of the project address new experiments:

– to produce new experimental data in order to support calibration and validation of the computational tools for each defence-in-depth level;
– to test and qualify new instrumentations in order to support their utilization in the reactor protection system.

Few selected examples of the achievements are shown in this section.

5.1. New test on chugging boiling regime (CHUG)

This test was design in support of the computational activities on analysis of the ESFR behaviour under sodium boiling conditions. The CHUG test section (Fig. 12) consists of a vertical pipe of few-centimetre diameter filled with light water at ambient temperature and atmospheric pressure. High-pressure steam is injected in upward direction through the injection pipe hosted in the bottom lid. Pressure at the bottom of the section and the axial stratification of the water temperature are tracked through the use of appropriate sensors.

One of main goals of the CHUG facility is application of a transparent acryl glass test section and a high speed camera in order to track and analyse the void pattern and steam condensation phenomena characterised by condensation-induced pressure waves (see the first images in Fig. 13).

Additionally, analytical simulations of the experiment are conducted applying the thermal-hydraulics code TRACE to assess the validity of the code for the chugging boiling simulation. Moreover, the behaviour of high-pressure steam bubbles in cold water is to be investigated through the CFD code PSI-BOIL, highlighting the presence of inertia-driven bubble collapse and the partial suitability of water as sodium simulant. (Mambelli, 2018).

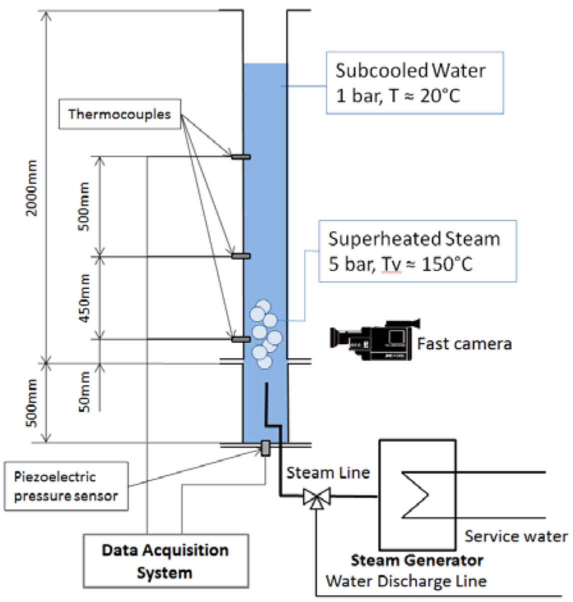
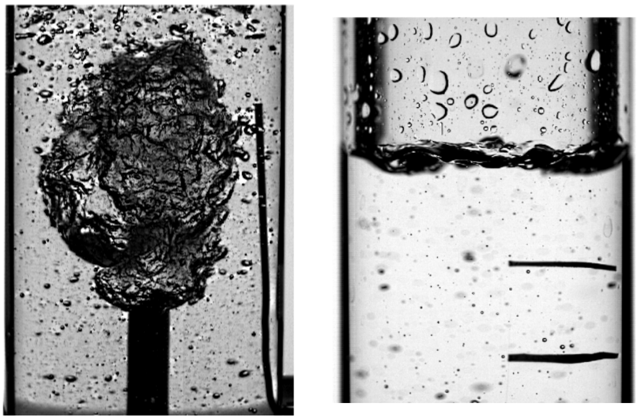


Fig. 12 Diagram of the CHUG experiment

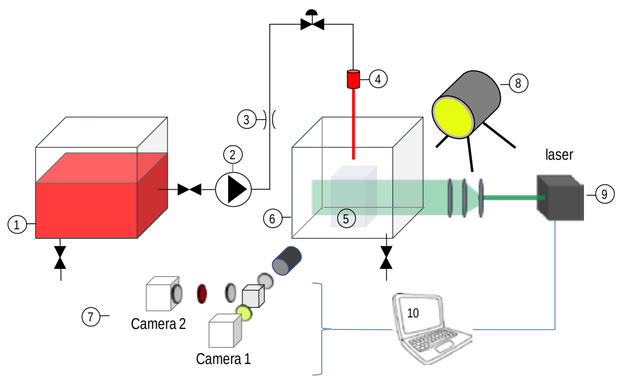


a) b)

Fig. 13 Fast camera images of (a) steam bubble in the subcooled liquid and (b) free level of subcooled liquid

5.2. New test on corium jet impingement (HAnSOLO)

The first set of tests on corium jet impingement was started at University of Lorraine, using a water-ice system as a model of the corium-catcher system. The HAnSoLO[1] experimental set up aims to observe the ablation front formed by the impingement of a hot water jet on a transparent dice ice, Fig. 14. It should be noted that we are not strictly in the case of “two immiscible media” but this kind of tests will be further done using thermite jets at KIT (Germany). For the tests presented below, the diameter of the nozzle is 1 mm or 1.2 mm, the jet temperature is set at 30°C, 50°C and 70°C, and the velocities of the jet VJ are between 2.5 and 11 m/s. For now, three different regimes have been observed: an impact regime with the formation of a liquid film, the splashing corresponding to the beginning of the formation of the cavity, then the “pool effect” which starts when the liquid cannot escape from the cavity. An illustration of these regimes is given in Fig. 15 and more details can be found in Zacharie et al., 2018. Note that it is not possible, for the moment, to measure thickness, velocity or temperature of the liquid film.



1: Main tank at controlled temperature
2: Pump
3: Mass flowmeter
4: Nozzle
5: Sacrificial material (ice)
6: Vessel
7: Cameras
8: Back light illumination
9: Laser source
10: System control

Fig. 14 Diagram of the HAnSoLO experiment

[1] **H**ot **A**blatio**N** of **SO**lid by **L**iquid jet - **O**bservations

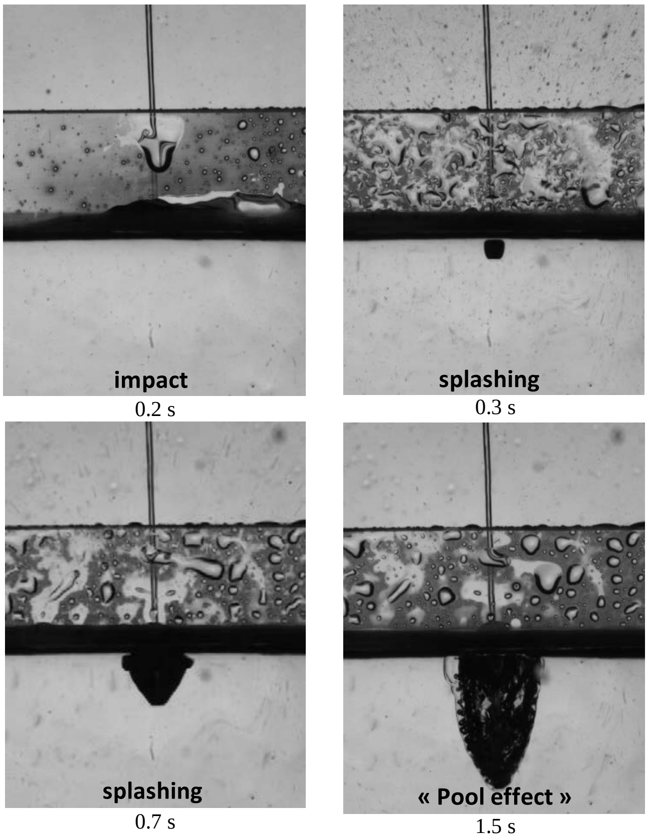


Fig. 15 Cavity formation - T_J=70°C, V_J=4,8m/s, D_J=1mm

5.3. Design guidelines for sodium loops

There are four laboratories in Europe where sodium loops are operated: one in France, one in Latvia and two in Germany (see Fig. 16). Based on the operating experience, the safety rules were formulated to be taken into account while designing a new high-temperature sodium facility, including recommendations for storage, filling, draining, isolation and connection, pre-heating, cleaning, and circulation of sodium as well as for cover gas system; guidelines are also provided for arrangements of general and building layouts (Ayrault et al., 2018).

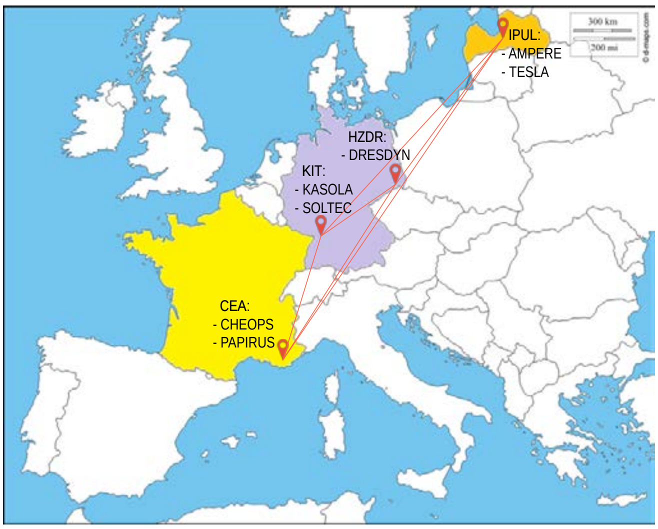


Fig. 16 European sodium facilities (Mikityuk et al., 2017)

5.4. ECFM qualification by means of model experiments

The goal of the activities consists in the qualification of eddy-current flow meters (ECFM) for a positioning above the fuel assemblies in order to detect possible blockages of the sodium flow. For that purpose, model experiments using the room-temperature melt GaInSn, tests in available sodium flows, high-temperature tests in sodium as well as the preparation of a new mock-up for tests under relevant sodium conditions are planned by HZDR, CEA and KIT. Successful tests of a traditional ECFM (consisting of one emitter and two receiver for the measuring electromagnetic field, see Fig. 17) in sodium flows up to 240°C and comparisons with ultrasonic velocity measurements were recently reported (Krauter et al., 2017). In parallel, the new measuring principle of a transient ECFM, *i.e.* a TECFM, based on two transmitter and two receiver coils was developed and successfully tested in a GaInSn flow (Krauter & Stefani, 2017). The key advantage of TECFM compared to the traditional ECFM consists in absolute velocity measurements without any need for sensor calibration.

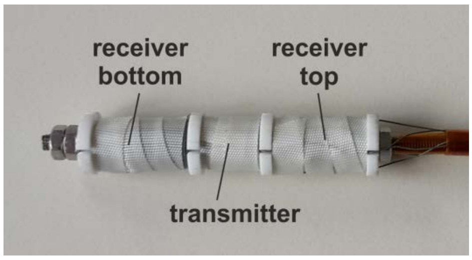


Fig. 17 Photo of ECFM coils to be encapsulated into a cylindrical stainless steel thimble

5.5. Preparation for measurement of MOX fuel properties

In frame of the work package on new measurements of thermal-physical properties of the mixed oxide fuel (MOX), few MOX fuel pellet irradiated at Phénix SFR were transported from CEA Cadarache to JRC Karlsruhe where measurements will be done, using the IR100 transportation cask (Fig. 18). The characteristics of the irradiated fuels to be used for measuring the properties are detailed in Table 1.

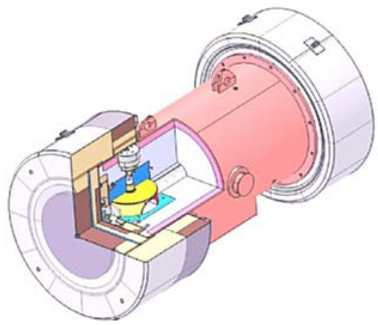


Fig. 18 Transportation cask IR100 (Tcherkoff, 2010)

Table 1. Characteristics of MOX fuel irradiated at Phenix

Irradiation name	$Pu/(U,Pu)O_2$, %	$PuO_2/(U,Pu)O_2$, %	Density, g/cm^3	Porosity, %	Burnup, MWd/t
PAVIX Capsule : DCI 1812	20.61	23.316	10.499	4.63	126200
MYOSOTIS, Capsule 0207	24.92	28.25	10.36	6	140606

6. EDUCATION AND TRAINING

One more specific objective of the project is to strengthen and link together new networks, in particular, the network of the European sodium facilities (see Fig. 16) 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. Few respective highlights are listed below.

6.1. Workshop

Organised by ENEA and dedicated to sodium facilities design and safe operation, the first ESFR-SMART workshop took place in Rome, from May 22 to 24, 2018 (Fig. 19). To perform research and development activities (such as the validation of codes or the qualification of systems and components), it is necessary to operate experimental facilities. The workshop aimed at establishing guidelines and good practices for facilities design and operation, and more particularly safety issues related to sodium induced by its chemical reactivity. A specific focus had been on the instrumentation required for safe operation. As the main topic proposed to the students, functional analysis methodology was also addressed for several selected facilities.

Fig. 19 Participants of the first ESFR-SMART workshop

6.2. Student projects

Nine PhD projects are integrated in ESFR-SMART. The topics are listed below:

- Modeling and assessment of new safety measures for Generation-IV European Sodium Fast Reactor (PSI/EPFL).
- Development and Application of a Coarse-mesh Methodology for the Treatment of Two-phase Flows in Sodium Fast Reactors (EPFL).
- Understanding of a melt mixture in presence of an injected liquid, solid or gaseous phase and convective heat transfer associated to these phenomena (CEA).
- Development and validation of improved methodology for Gen-IV SFR transient analysis using Serpent/DYN3D/ATHLET code system (HZDR).
- Theoretical and experimental research of annular linear induction type electromagnetic pump stability (University of Latvia).
- Assessment of thermal hydraulics behaviour under backward facing step conditions under LOF conditions (KIT).
- Experimental ablation of a thick sacrificial material plate by jet of liquid - application to the ESFR severe accident (University of Lorraine).
- Developing a new method for capturing multiphysics interactions in safety analysis of sodium-cooled fast reactors (University of Cambridge).
- Sensitivity and uncertainty analysis of spatial-dependent voiding and Doppler effects to nuclear data in Sodium Fast Reactor (Technical University of Madrid).

7. CONCLUSIONS

The achievements of the ESFR-SMART project after the first year were reviewed during the progress meeting hold at University of Latvia in Riga in September 2018 (Fig. 20) where the progress of the consortium was evaluated by the Advisory Review Panel. Some of the highlights reviewed at this meeting are presented in the paper. All in all, the project is successfully progressing according to the work program.

Fig. 20 Participants of the ESFR-SMART progress meeting in Riga, Latvia (September 2018)

ACKNOWLEDGMENTS

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