GEN IV International Forum℠

EUROPEAN SODIUM FAST REACTOR: AN INTRODUCTION

Dr. Konstantin Mikityuk

Paul Scherrer Institute, Switzerland

15 April 2019

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Meet the presenter

Since graduating from Moscow Engineering Physics Institute in 1992, Dr. Konstantin Mikityuk has been involved in research of safety-related aspects of various nuclear reactors with fast neutron spectrum: first at the Russian Research Centre “Kurchatov Institute” and then at the Paul Scherrer Institute (PSI).

His current interests are safety analysis of sodium-cooled fast reactor, in particular neutronics and thermal-hydraulic aspects of sodium boiling.

Dr. Mikityuk is a Group leader at PSI, Maître d'enseignement et de recherche at Ecole Polytechnique Federale de Lausanne (EPFL), Lecturer at the Eidgenössische Technische Hochschule Zürich (ETHZ). He is also the coordinator of the Horizon-2020 ESFR-SMART project.

He is the co-chair of the Gen IV International Forum (GIF) Education and Training Task Force.

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Goals of the webinar

1. Present a brief history of the conceptual development of a large-power (3600 MWth) European Sodium Fast Reactor (ESFR)

2. Discuss the status of the current R&D activities on Generation-IV ESFR safety enhancements of the Horison-2020 ESFR-SMART project

3. Provide an overview of new safety measures proposed for improvement of the three safety functions: reactivity control, heat removal and radioactivity containment

4. Introduce experimental programs currently on-going in Europe in support of the ESFR R&D

5. Summarize the activities to be performed during the next phase of the project

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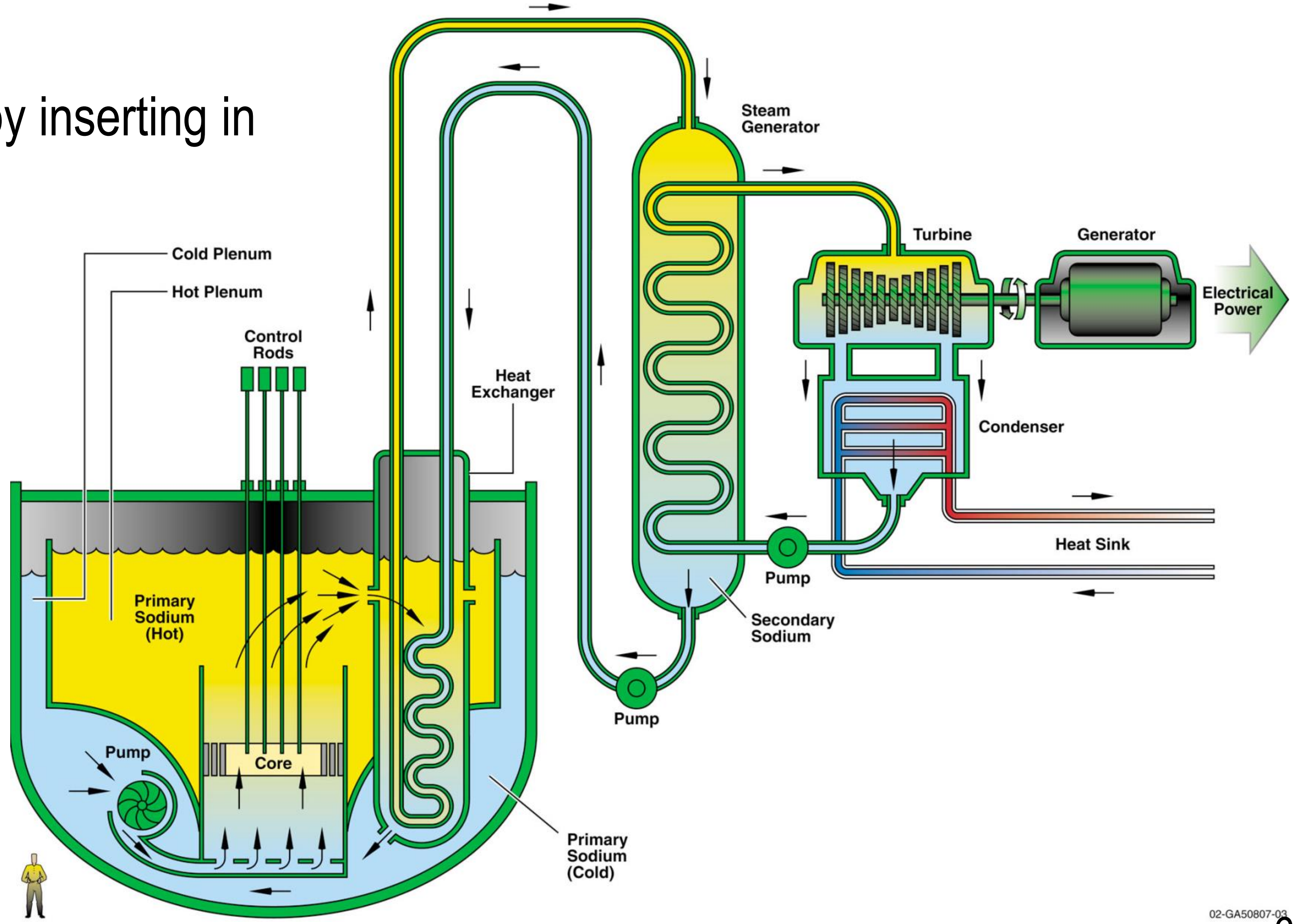
Sodium Fast Reactor: concept

- Thermal power generated in the core due to fission of heavy metal nuclei by fast neutrons
- The fission chain reaction is controlled by inserting in the core the rods absorbing neutrons
- The core is located in the pool of liquid sodium at ~500ºC
- This sodium circulates through the core (T↑) and Heat eXchangers (T↓) by means of Primary Pumps
- Secondary sodium loop includes Steam Generators
- The steam drives turbines generating electric power



Sodium Fast Reactor: concept

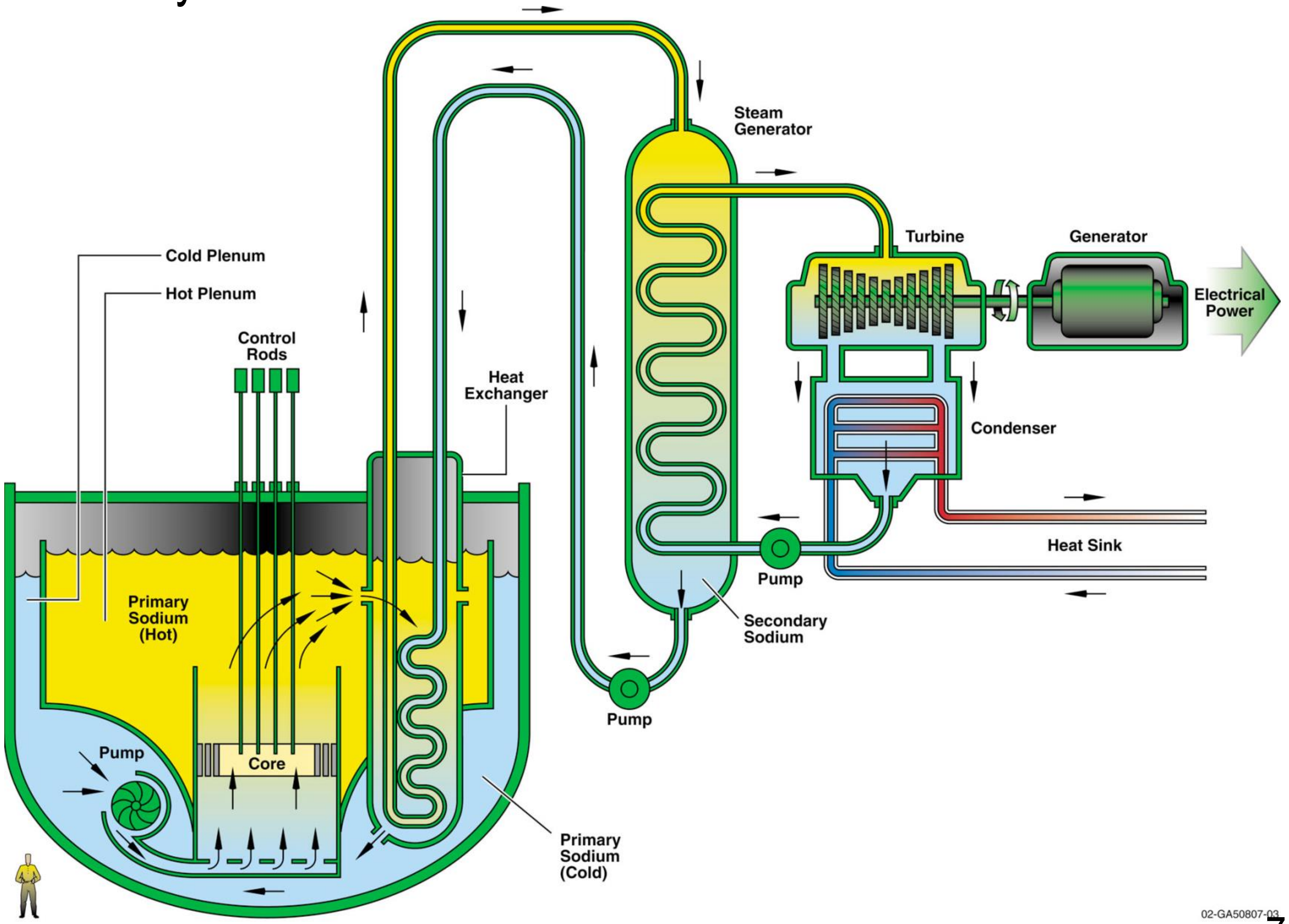
The basic safety functions should be fulfilled in every reactor state:

1. control of reactivity
2. removal of heat* from the fuel
3. confinement of radioactive materials

Below we will use the following symbols
to remind about the three safety functions:

1 2 3

**Note that even when the chain reaction is stopped there is residual heat generation in fuel due to decay of radioactive isotopes (Decay Heat)*



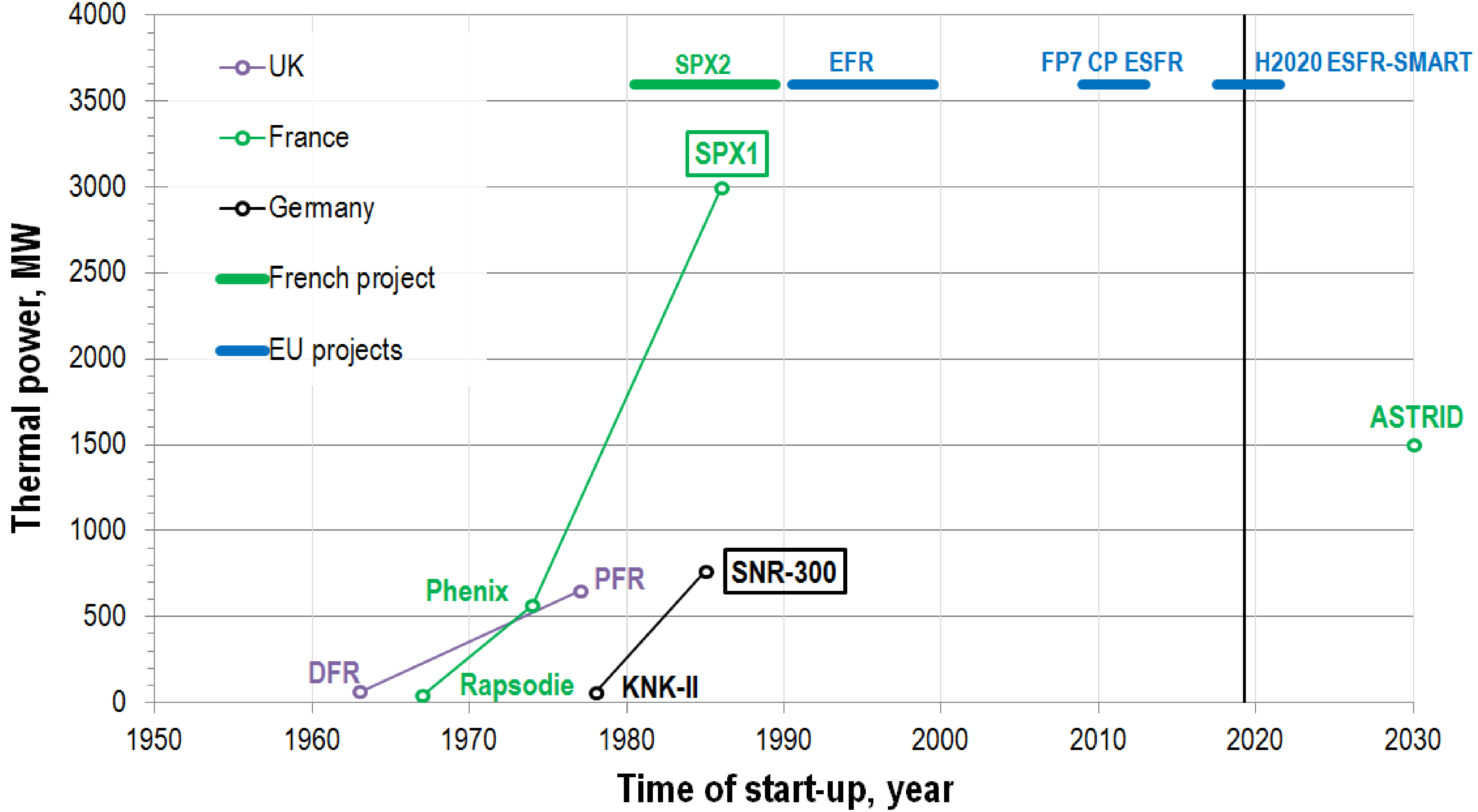
Sodium Fast Reactor: concept

- **Advantages**
  - Potential for new fissile fuel breeding due to fast neutron spectrum
  - Excellent thermal conductivity of sodium → very efficient cooling 2
  - Large margin to boiling → no pressurization required 3
  - Significant operational experience (300+ reactor-years)

- **Challenges**
  - Sodium is chemically active in contact with water or air → intermediate circuit needed 3
  - Sodium has significant neutron scattering cross section → spectrum hardening when sodium removed → positive reactivity effect → special safety measures needed 1

- **Reactors under operation**
  - BOR-60, BN-600, BN-800 (all Russia), CEFR (China)

European Sodium Fast Reactor: brief history

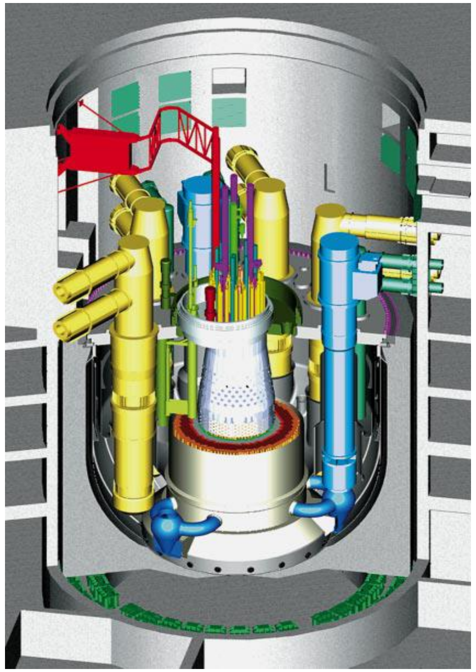


European Sodium Fast Reactor: brief history

Main goals of the projects:

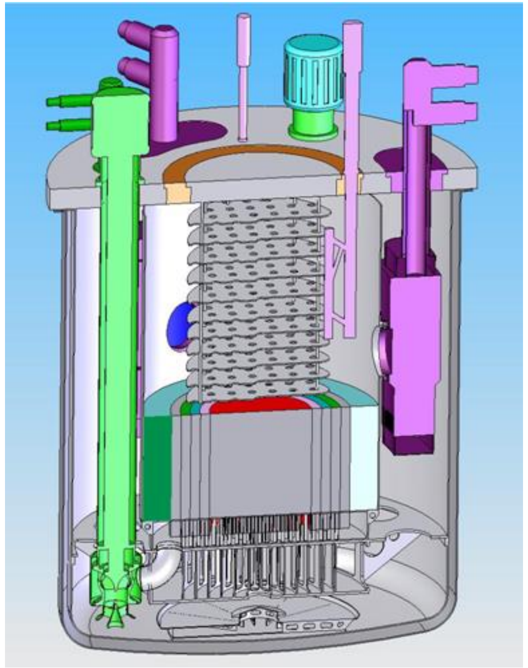
– Improve safety
– Improve economics E
– Improve management of nuclear materials

1990



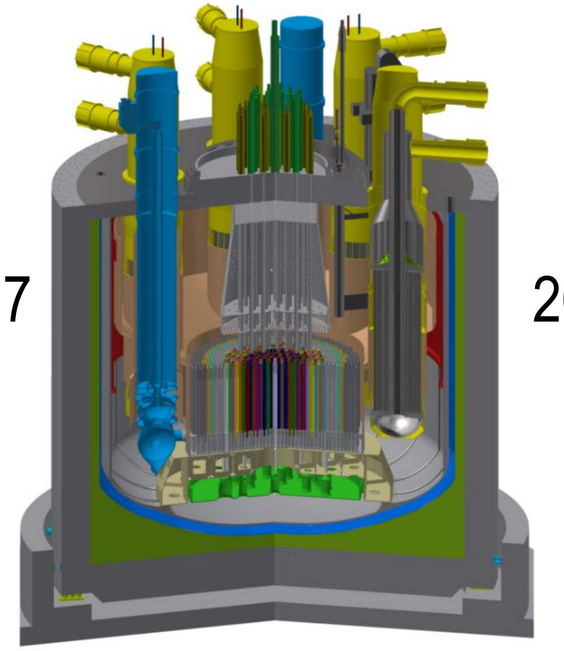
EFR

2000 ... 2008



CP ESFR

2012 ... 2017



ESFR-SMART

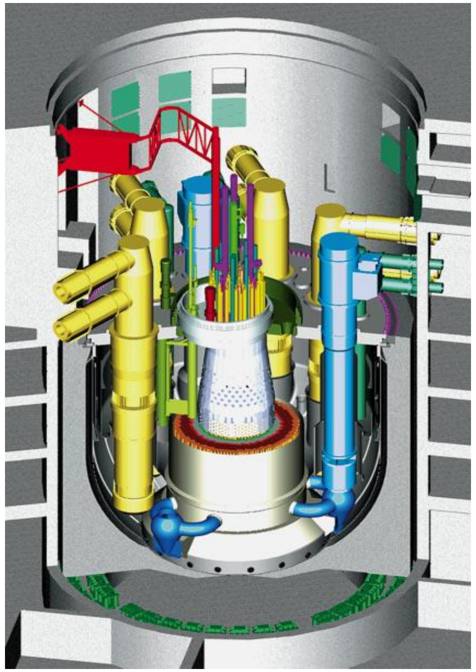
2021

European Sodium Fast Reactor: brief history

The reactor design has been developed taking into account SFR operation experience and multiple experiments:

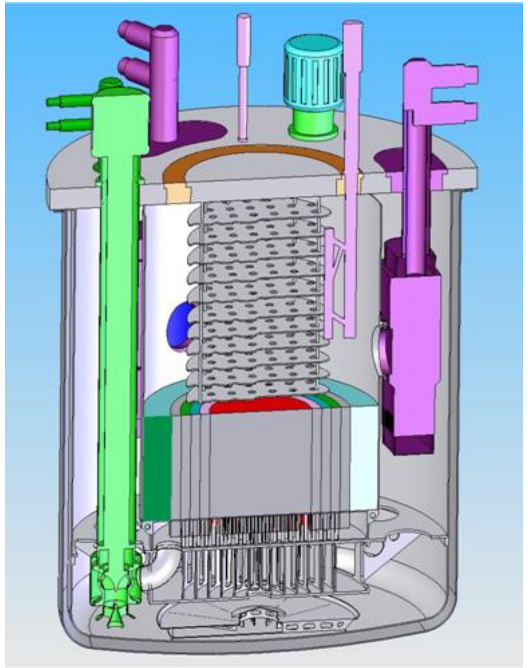
– Thermal / electrical power 3600 / 1500 MW
– Mass of sodium in the primary pool ~2500 t
– Primary sodium temperature 395ºC – 545ºC
– 6 Heat eXchangers, 3 Primary Pumps, 36 Steam Generators

1990



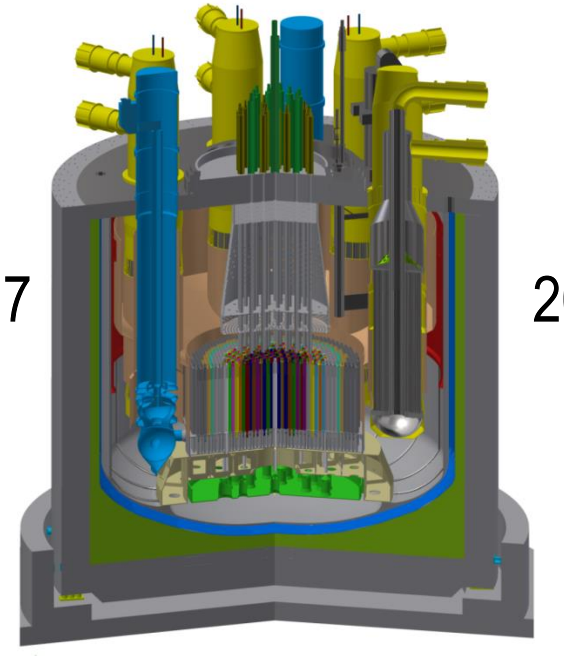
EFR

2000 ... 2008



CP ESFR

2012 ... 2017



ESFR-SMART

2021

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ESFR-SMART: project in a nutshell

GEN IV International Forum

Name:

– ESFR-SMART: European Sodium Fast Reactor Safety Measures Assessment and Research Tools

Goals:

– Select and assess innovative safety measures for European SFR concept

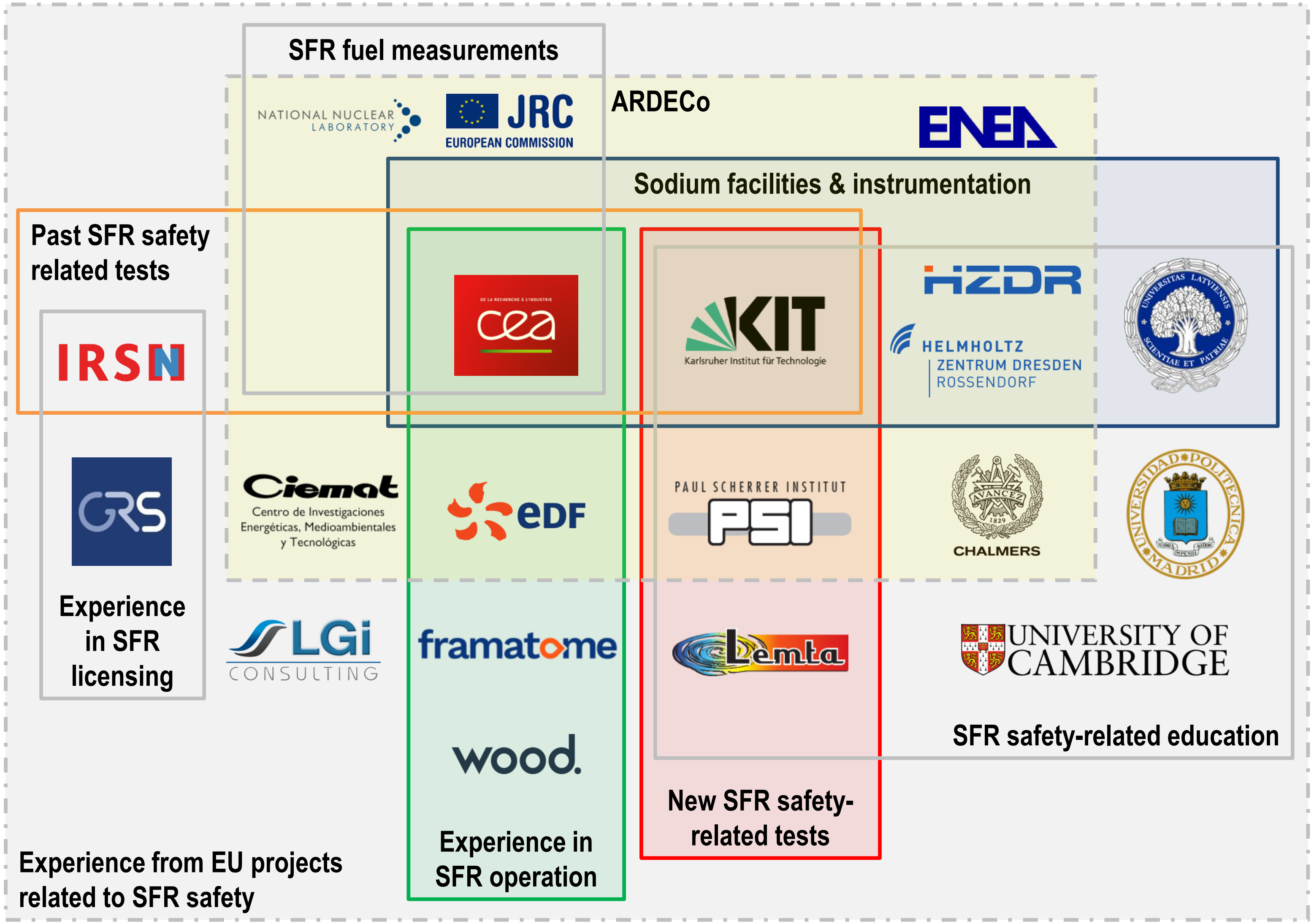
– Develop new research tools related to SFR safety (calculational codes, experimental data and facilities)

Budget: 5 MEUR of Euratom contribution + ~5 MEUR of consortium's own contribution

Timeframe: 01.09.2017 – 31.08.2021

ESFR-SMART
sodium fast reactor safety

ESFR-SMART: consortium



Work Package and Task Leaders

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F. Payot (PSI)
C. Latge (CEA)
E. Girardi (EDF)
E. Fridman (HZDR)
G. Gerbeth (HZDR)
L. Buligins (IPUL)
N. Girault (IRSN)
E. Bubelis (KIT)
A . Rineiski (KIT)
S. Ehster Vignoud (Framatome)
J. Guidez (CEA)
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C. Collignon (Framatome)
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C. Collignon (ENEA)
W. Pfrang (KIT)
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S. Eskert (HZDR)
E. Sanseigne (CEA)
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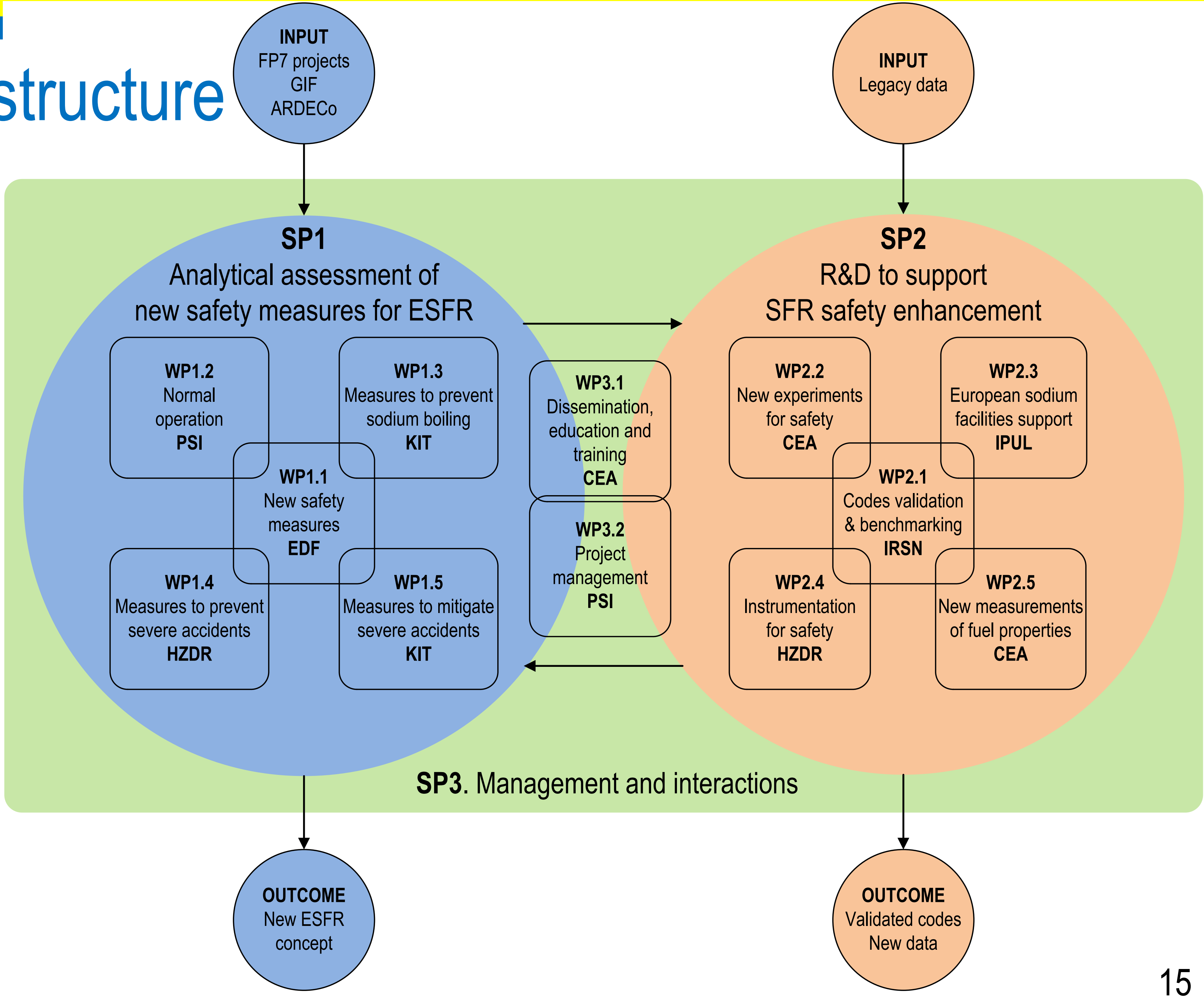
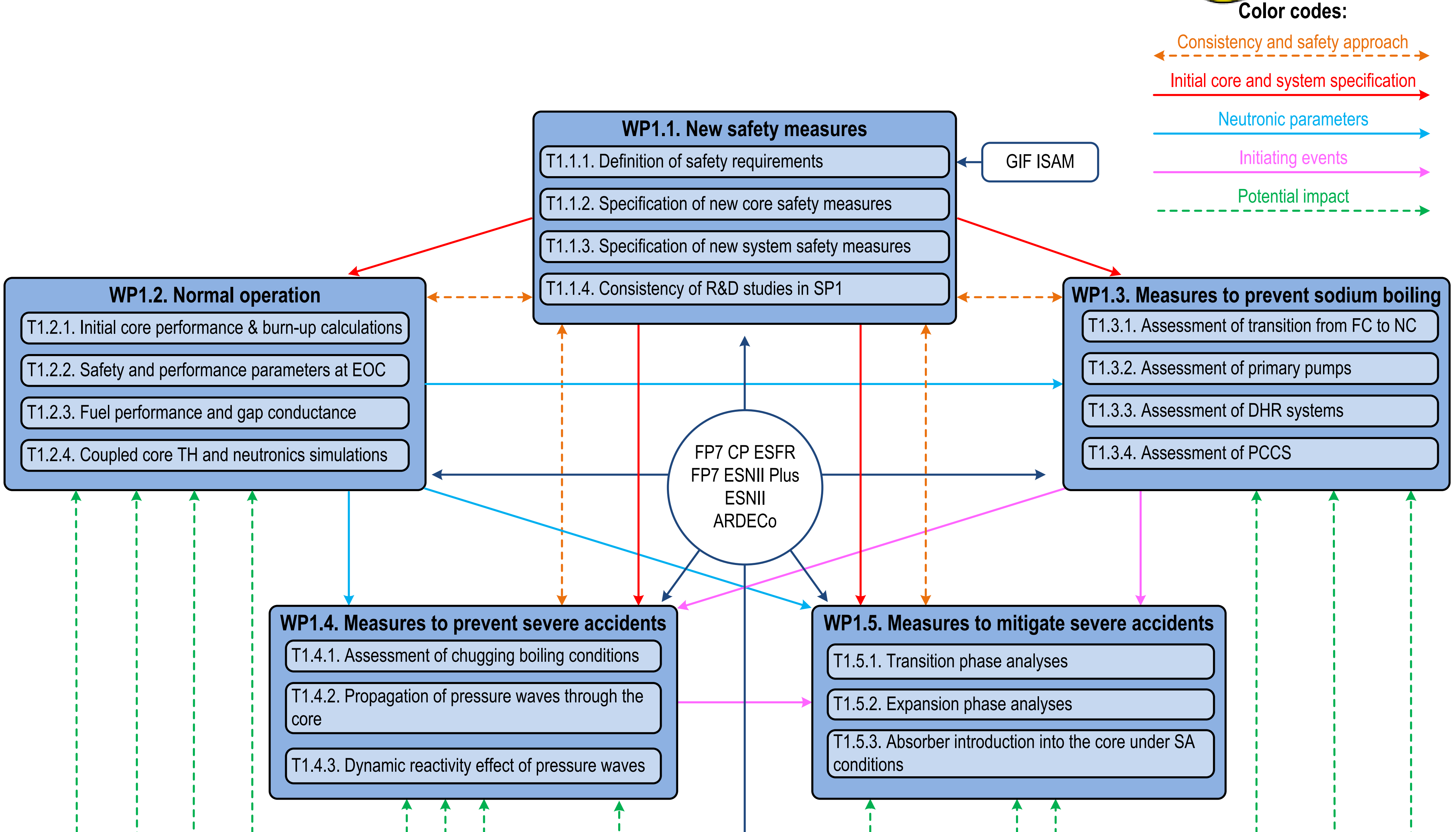
D. Staicu (JRC)
C. Demaziere (CHALMERS)
N. Garcia Herranz (UPM)
H. Tsige-Tamirat (JRC)
M. Bazin-Retours (LGI)

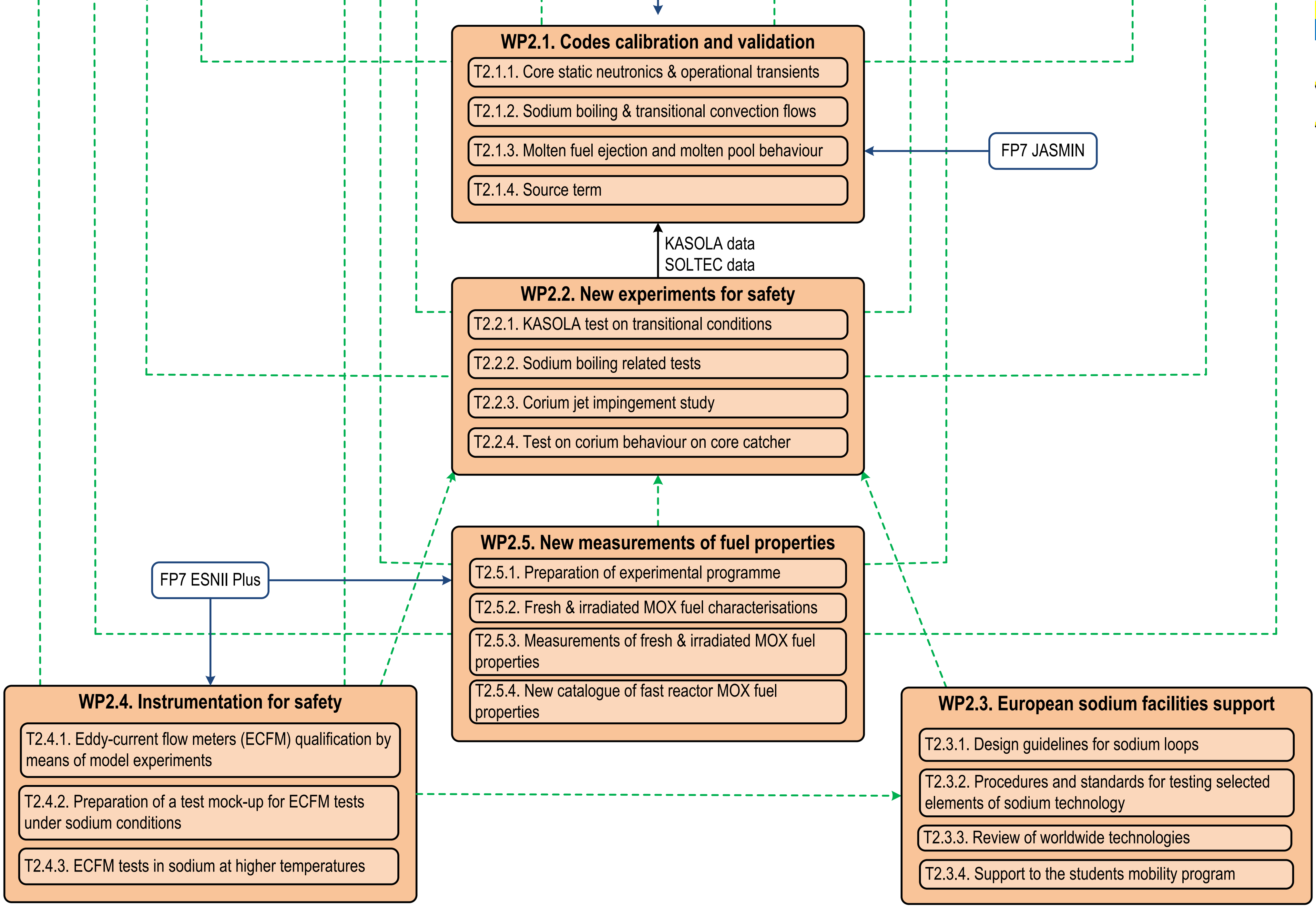
ESFR-SMART: structure

– 3 Subprojects
– 12 Work Packages
– 47 Tasks



ESFR-SMART: structure





WP2.1. Codes calibration and validation
T2.1.1. Core static neutronics & operational transients
T2.1.2. Sodium boiling & transitional convection flows
T2.1.3. Molten fuel ejection and molten pool behaviour
T2.1.4. Source term
FP7 JASMIN
KASOLA data
SOLTEC data
WP2.2. New experiments for safety
T2.2.1. KASOLA test on transitional conditions
T2.2.2. Sodium boiling related tests
T2.2.3. Corium jet impingement study
T2.2.4. Test on corium behaviour on core catcher
WP2.5. New measurements of fuel properties
T2.5.1. Preparation of experimental programme
T2.5.2. Fresh & irradiated MOX fuel characterisations
T2.5.3. Measurements of fresh & irradiated MOX fuel properties
T2.5.4. New catalogue of fast reactor MOX fuel properties
FP7 ESNII Plus
WP2.4. Instrumentation for safety
T2.4.1. Eddy-current flow meters (ECFM) qualification by means of model experiments
T2.4.2. Preparation of a test mock-up for ECFM tests under sodium conditions
T2.4.3. ECFM tests in sodium at higher temperatures
WP2.3. European sodium facilities support
T2.3.1. Design guidelines for sodium loops
T2.3.2. Procedures and standards for testing selected elements of sodium technology
T2.3.3. Review of worldwide technologies
T2.3.4. Support to the students mobility program

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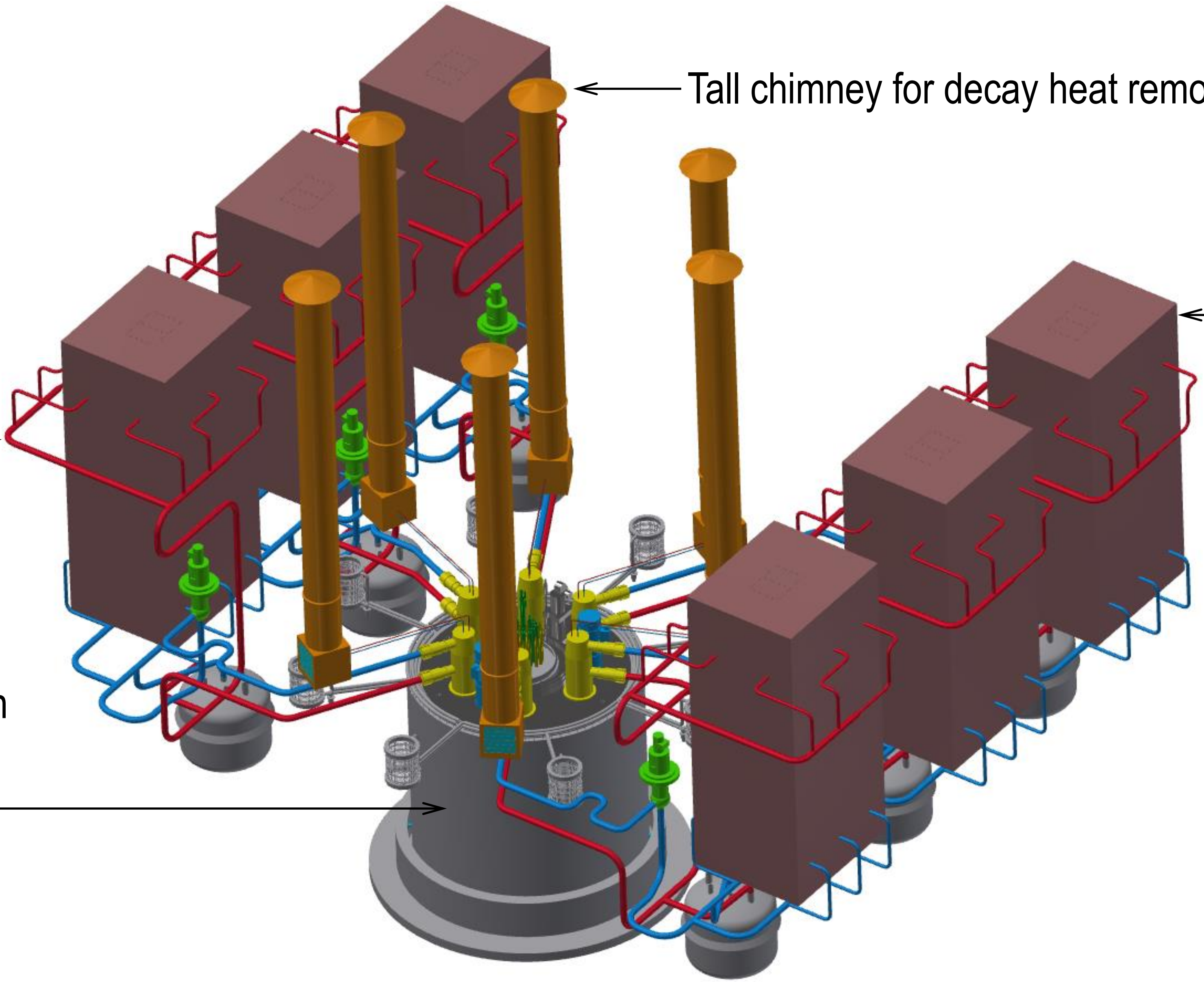
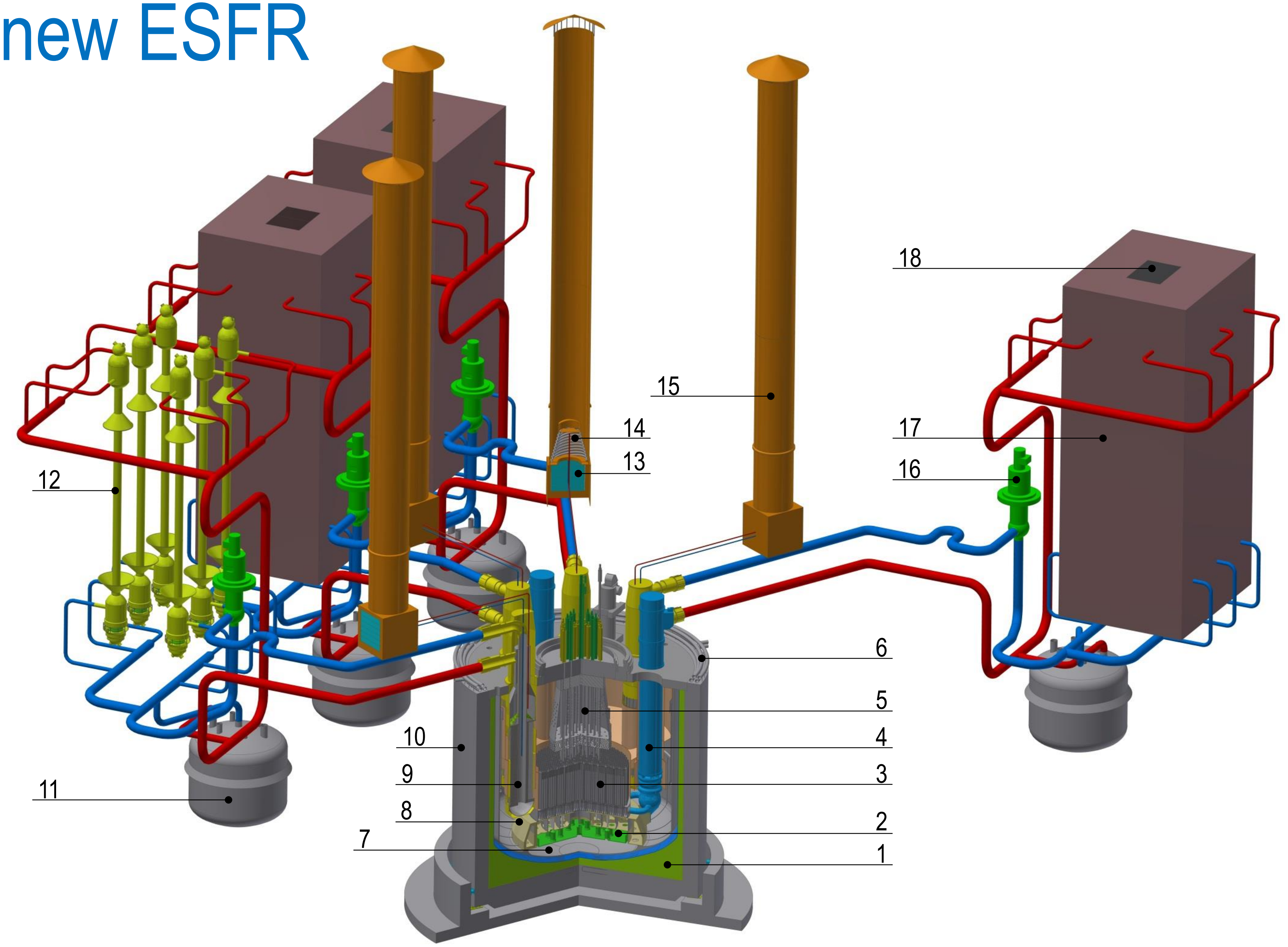
Overall view of new ESFR



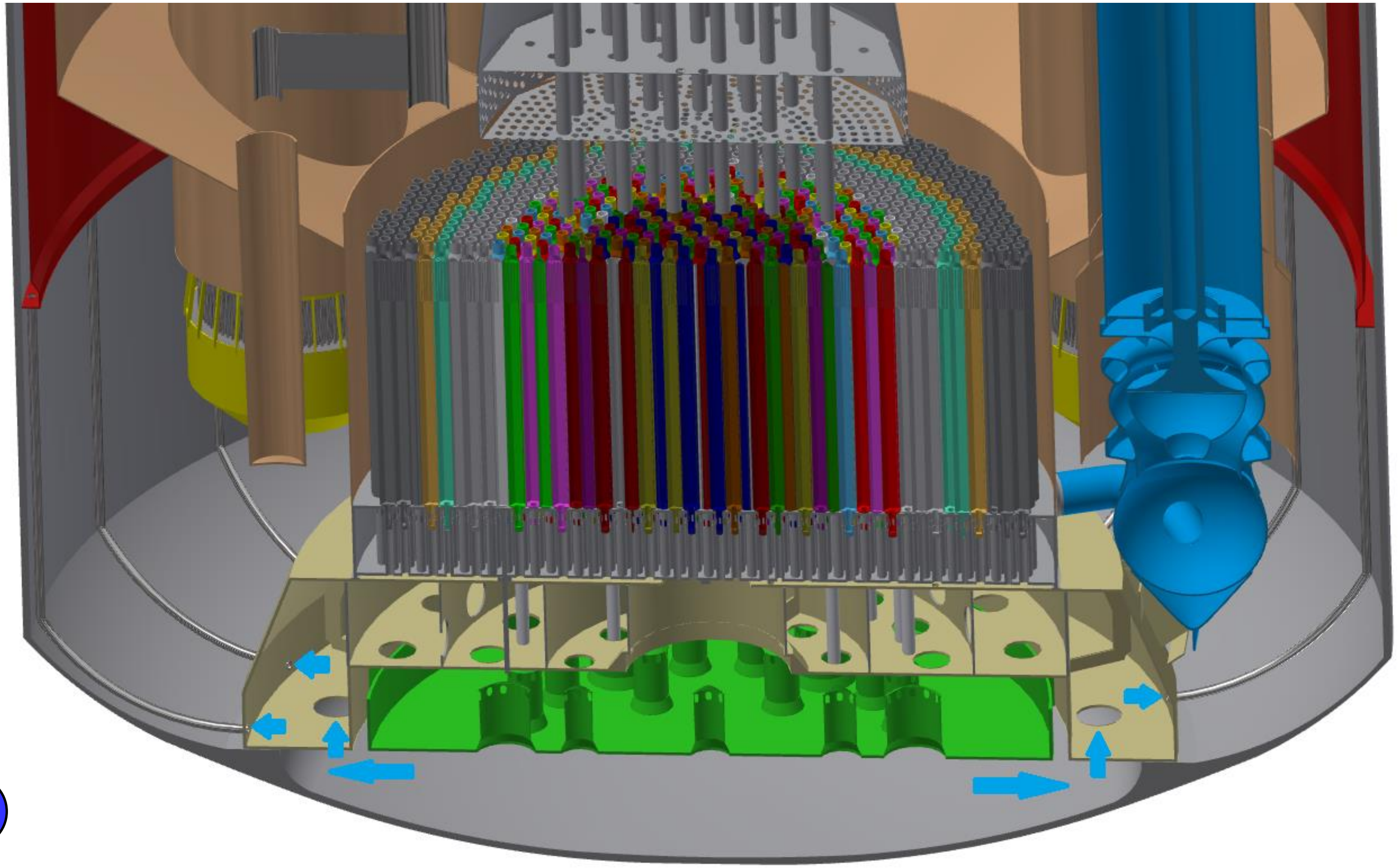
Overall view of new ESFR

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)



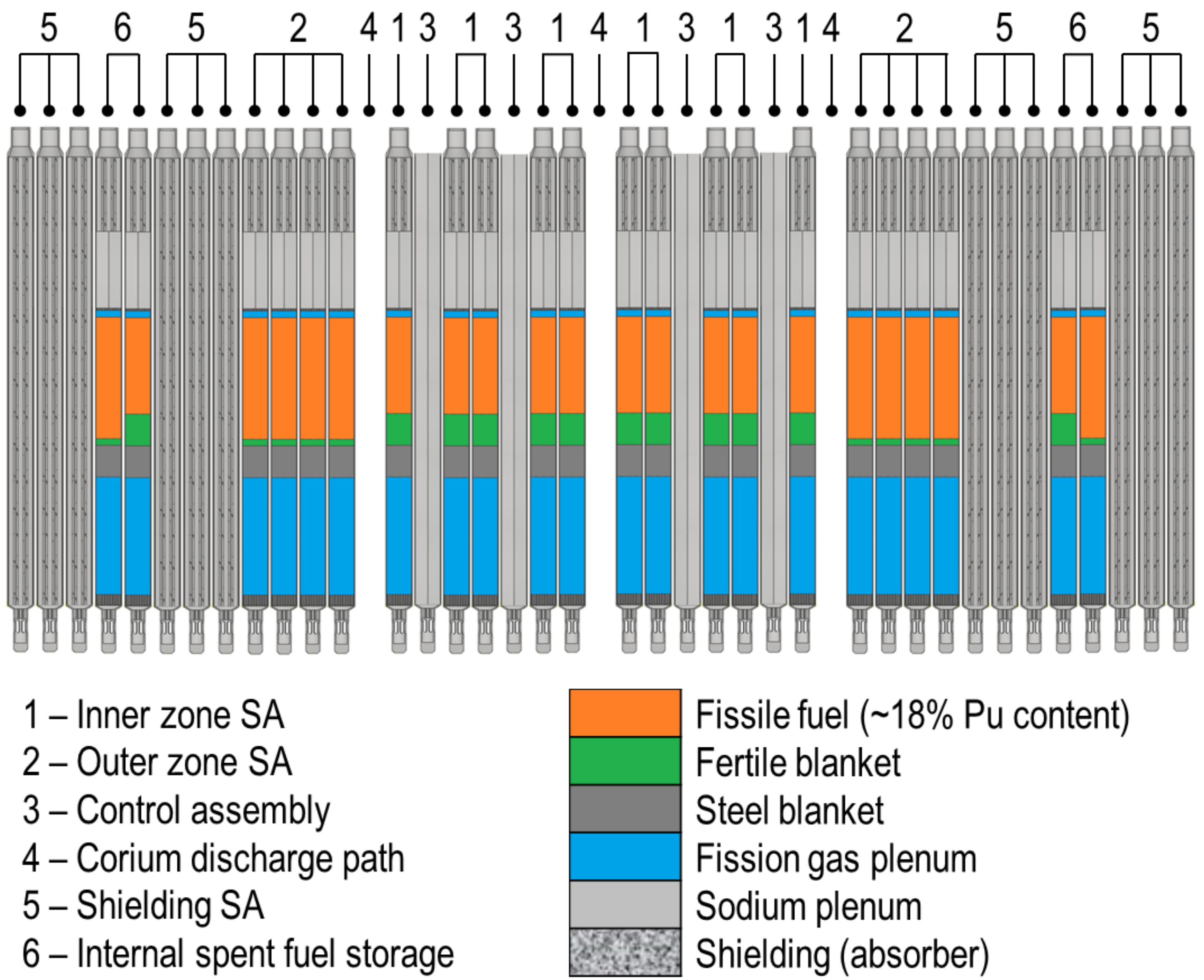
New design of core region

- Low-void effect core 1
- Control rods (DSD) passively activated: Curie temperature 1
- Internal spent fuel storage for 50% of core loading 3
- Corium discharge channels and core catcher 1 2 3
- Hydraulic diodes at the pump outlet 2



New core design: axial map

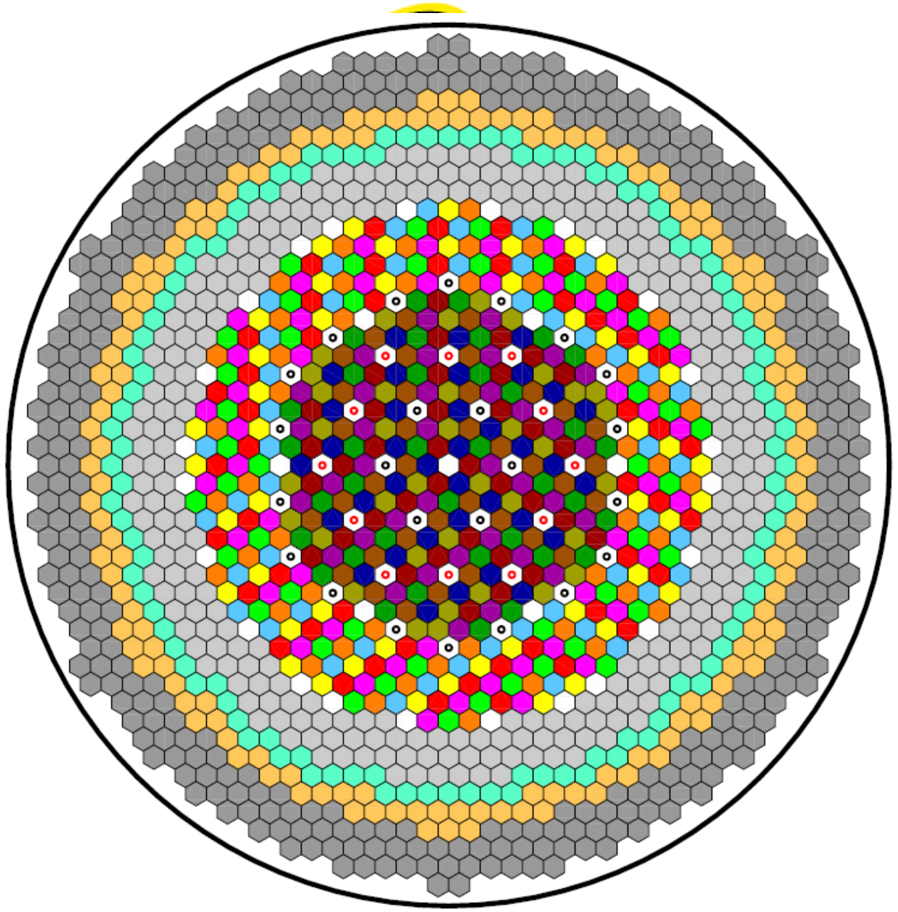
- The same initial plutonium content in the whole core
- The radial power profile is flattened by using different fuel height in inner and outer zones
- Passive protections against power excursion in case of sodium boiling:
  - —Sodium plenum is a layer above fuel which reflects neutrons down, when liquid, and lets them fly up towards neutron absorber when voided 1



ESFR-SMART

New core design: radial map

- Perfectly symmetric
- 6 batches = 6-year fuel cycle
- Mixed scheme (no reshuffling)
- Internal storage for 50% of core loading 3
- All safety (DSD) rods equipped with passively-activated Curie-point locks 1
- Corium discharge channels to facilitate the corium relocation in the core catcher in a very low-probability event of a core meltdown 1 2 3

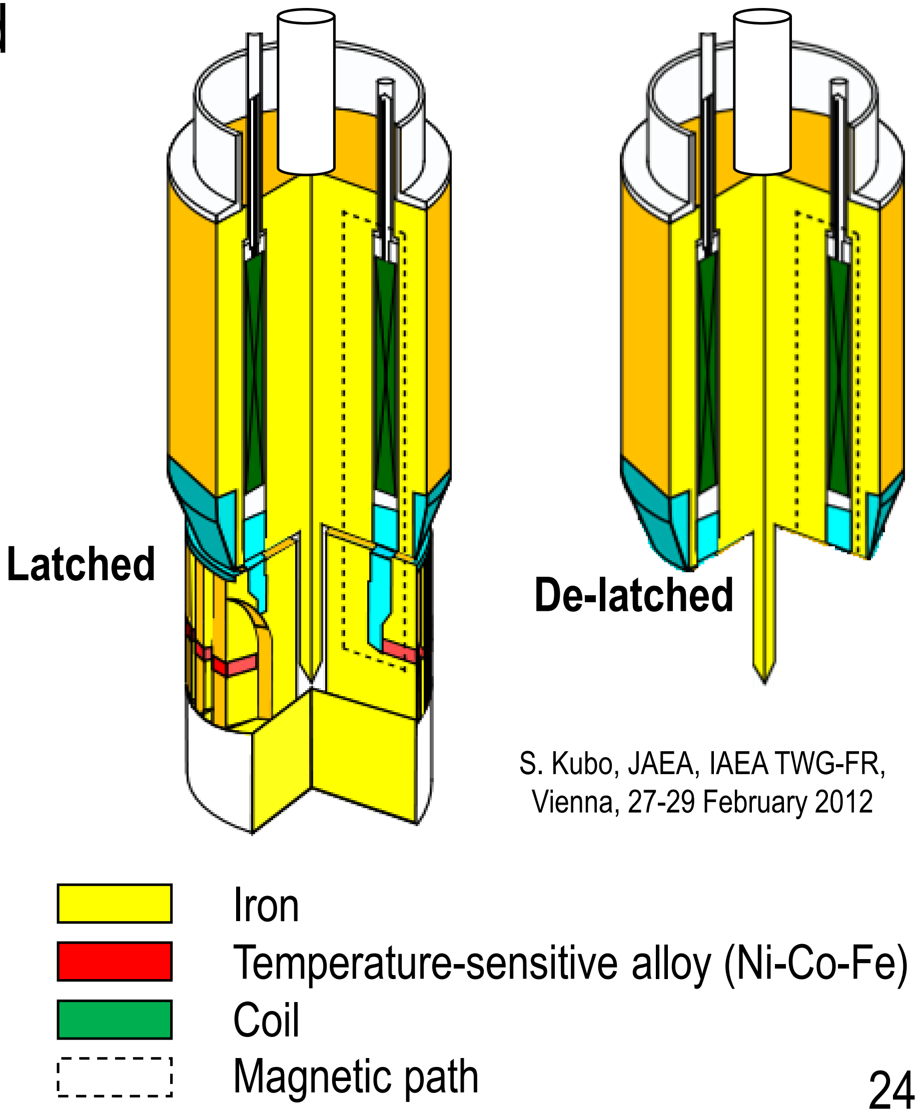


1 2 3 4 5 6	Inner zone SA	6 batches×36 = 216
1 2 3 4 5 6	Outer zone SA	6 batches×48 = 288
	CSD / DSD	24 / 12
R1 R2 R3	Reflector rings	66 / 96 / 102
S1	Spent inner fuel storage	3 batches×36 = 108
S2	Spent outer fuel storage	3 batches×48 = 144
	Corium discharge path	31

New core design: passive control rods [1]

- The safety control rod drivelines are proposed to be equipped with a Curie point magnetic latch device.
- This device releases the absorber rods downward into the core if either
  - — holding coil current is lost, or
  - — the coolant temperature rises beyond the Curie point of the temperature-sensitive alloy
- Activation is therefore provided both in response to
  - — a scram signal
  - — off-normal core conditions

JAEA SASS concept



S. Kubo, JAEA, IAEA TWG-FR, Vienna, 27-29 February 2012

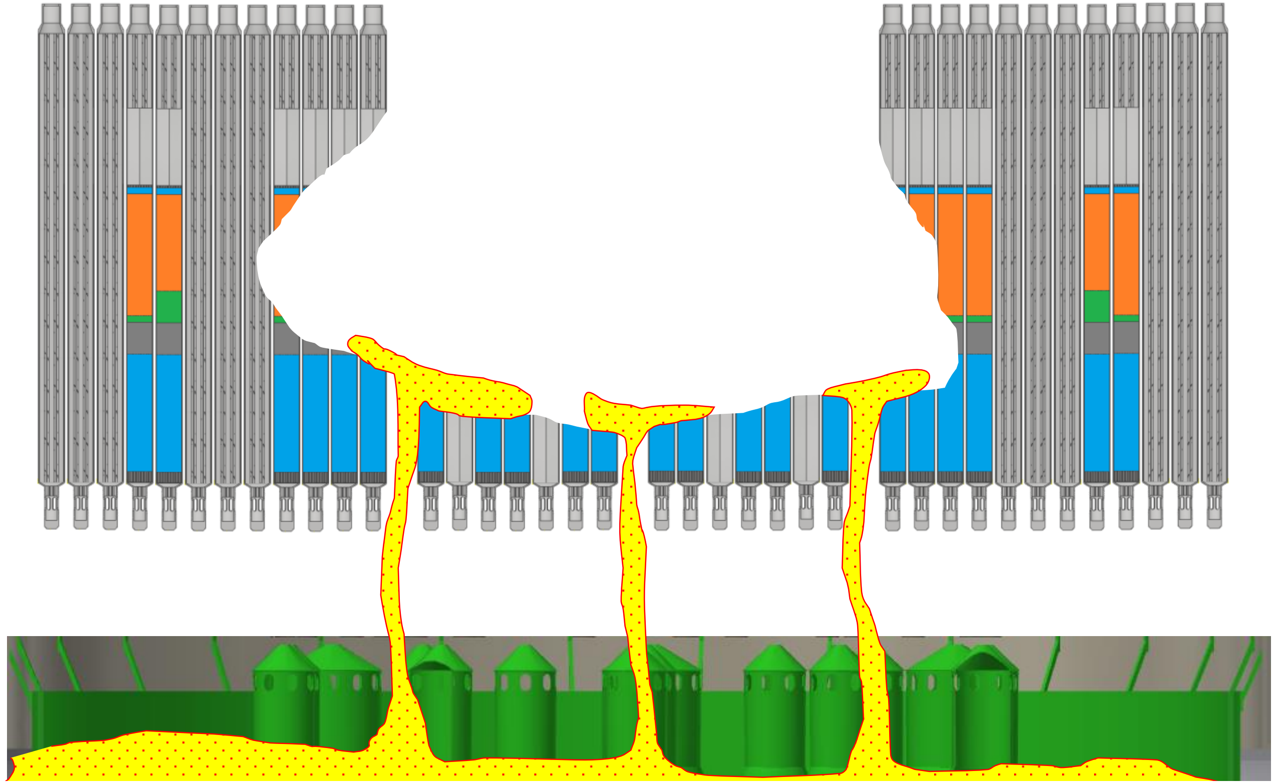
New core design: path for corium

In case of very low probability core meltdown event, the corium discharge channel helps

— To avoid re-criticality 1

— To promote transfer of the corium to the core catcher 3

— To efficiently remove decay heat 2

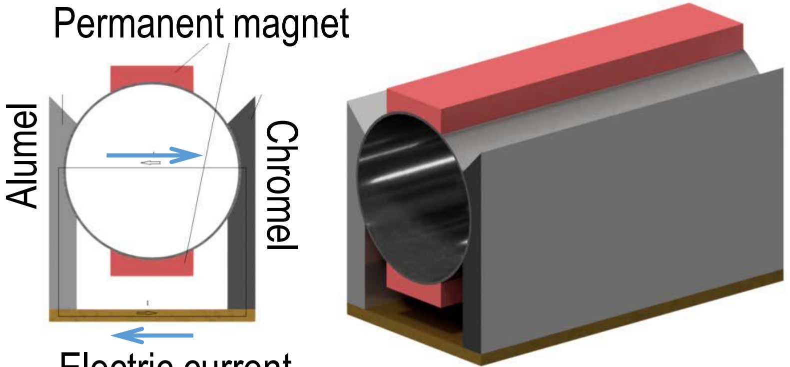


New system design: DHRS-1 and -2 2

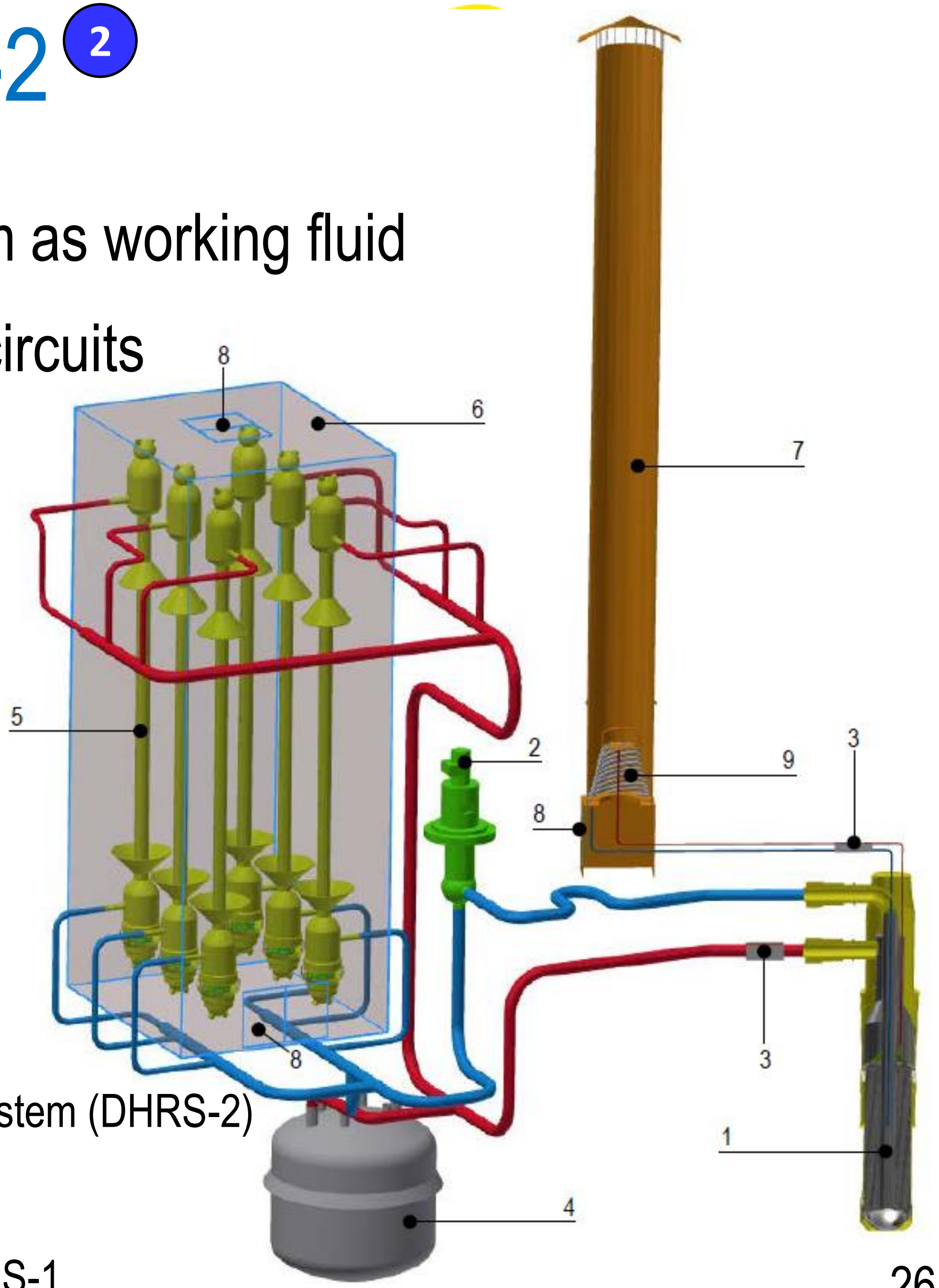
Decay Heat Removal System

- DHRS-1 connected to the IHX and using secondary sodium as working fluid
- Use of passive thermal pumps in secondary and DHRS-1 circuits
- Secondary pumps at lowest position
- DHRS-2 uses air circulation through the openings in the SG casing and heat removal from the SG surfaces

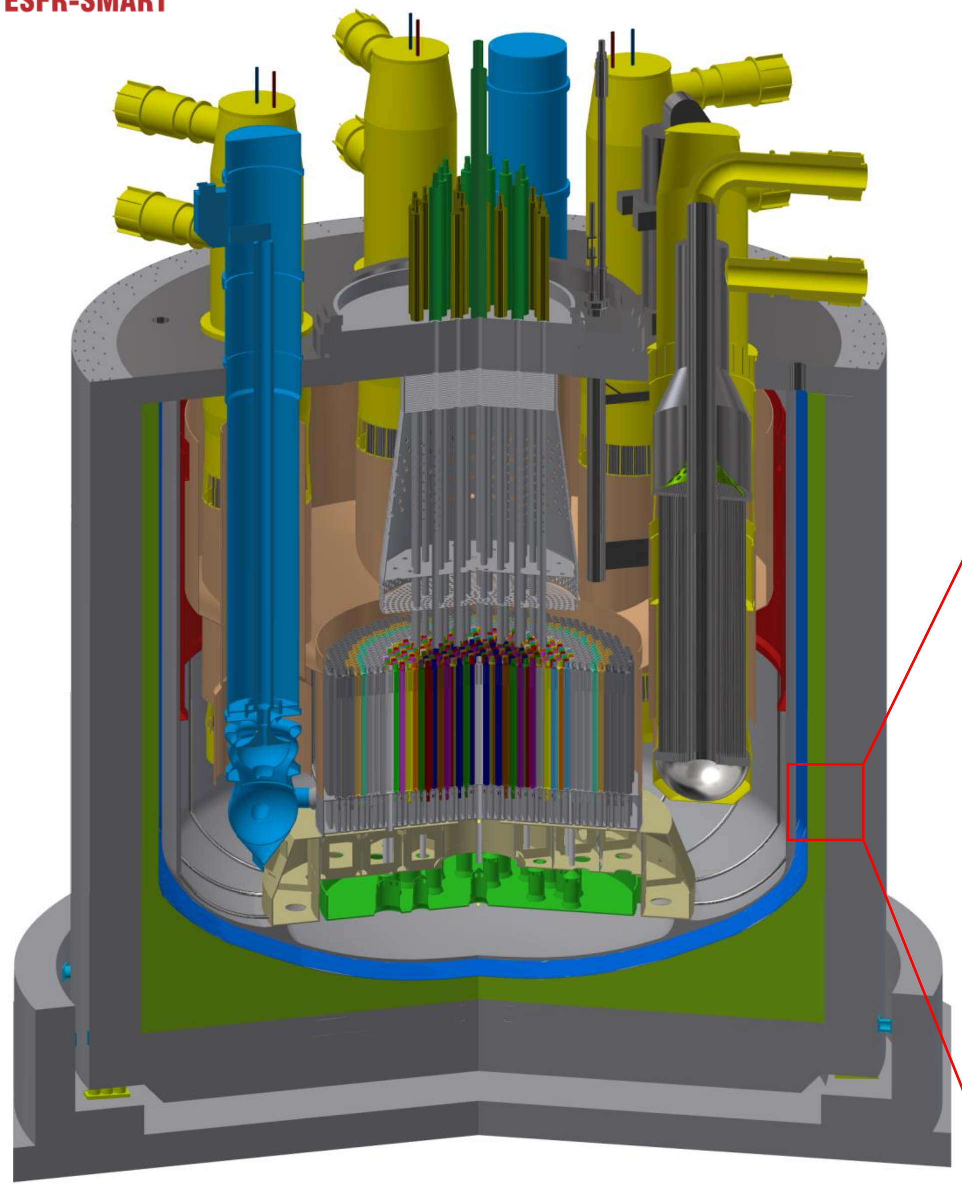
Thermal pump concept



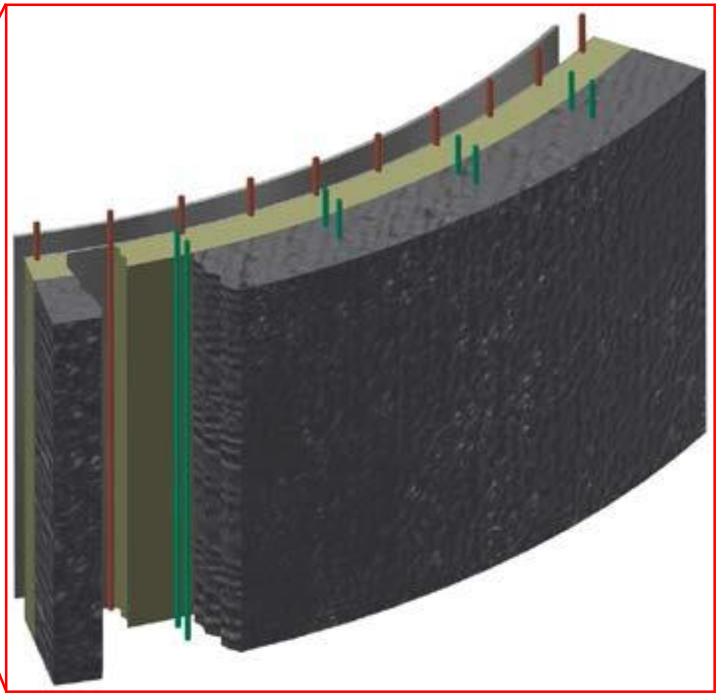
1 – Intermediate heat exchanger
2 – Secondary pump
3 – Thermal pumps
4 – Sodium storage tank
5 – Steam generator
6 – Casing of Decay Heat Removal System (DHRS-2)
7 – Air stack of DHRS-1
8 – Openings for air circulation
9 – Sodium-air heat exchanger of DHRS-1



New system design: pit and DHRS-3



- Elimination of reactor dome and of safety vessel E
- Minimization of the reactor vessel-pit gap, still large enough for inspection (shown in blue) 2
- Insulation (shown in green) with metallic liner on it 3



- Two reactor pit concrete cooling systems (oil and water) suitable for decay heat removal (DHRS-3) 2

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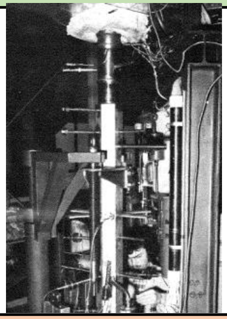
ESFR-SMART: past and ongoing tests

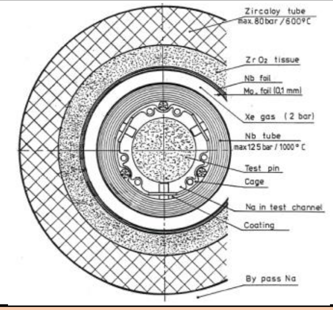
Normal operation | Sodium boiling | Severe accident (SA) management | SA mitigation

Superphenix

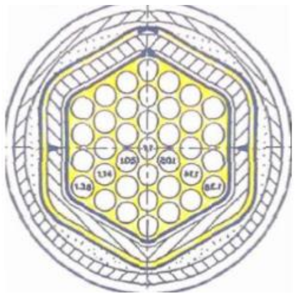
KNS-37



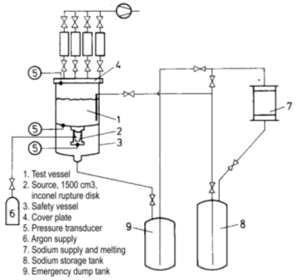
CABRI



SCARABEE

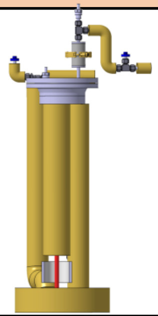


FAUST



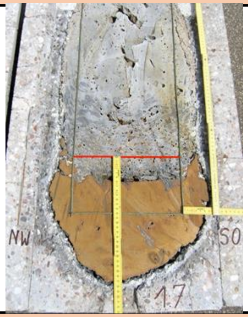
KASOLA

KARIFA

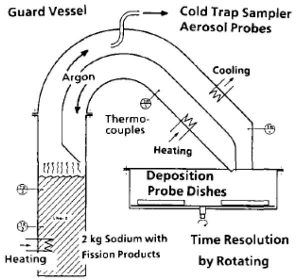


LIVE

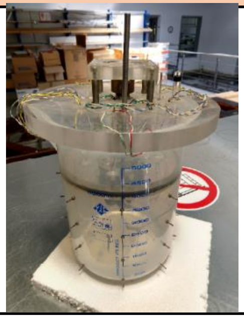
JIMEC



NALA

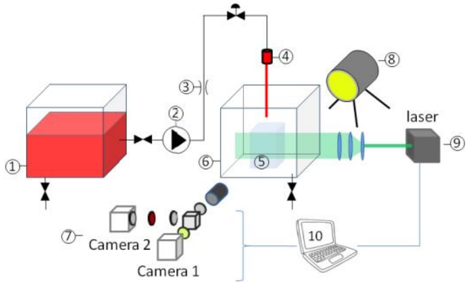


ECFM

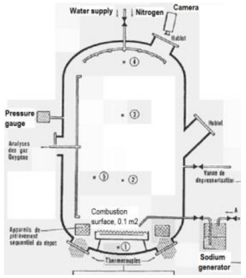


CHUG

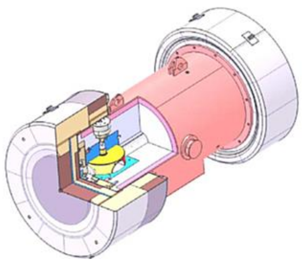
HAnSOLO and JEDI



FANAL



MOX fuel measurements



ESFR-SMART: past and ongoing tests

Normal operation

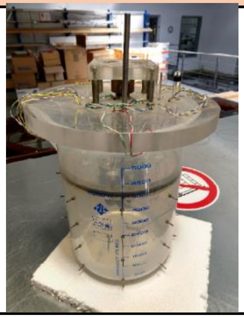
Superphenix

The openly available legacy data obtained during the start-up tests at **Superphenix Sodium Fast Reactor** operated in France are used for validation of computer codes for coupled neutronic and thermal-hydraulic calculations.

KASOLA

The **new sodium loop** is currently under commissioning at Karlsruhe Institute of Technology. The thermal-hydraulic data will be used for validation of Computational Fluid Dynamics codes.

ECFM

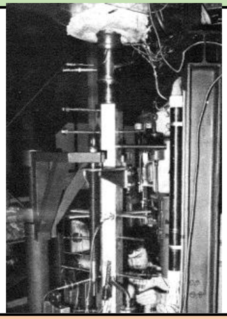


The new **Eddy Current Flowmeter** is under development at Helmholtz-Zentrum Dresden Rossendorf to measure sodium flowrate at the fuel subassembly outlet.

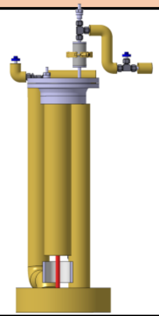
ESFR-SMART: past and ongoing tests

Sodium boiling

KNS-37



KARIFA



CHUG

The legacy data obtained at KNS-37 **sodium boiling loop** at Forschungszentrum Karlsruhe are used for validation of computer codes for dynamic thermal-hydraulic calculations of sodium boiling.

A new compact **sodium boiling facility** with pulse laser heating is under development at Karlsruhe Institute of Technology to gain experience with two-phase sodium flow experiments and to provide data for validation of thermal-hydraulic codes.

A new **water-steam facility** was built at Paul Scherrer Institute to study chugging boiling conditions as a first step toward experimental study of the sodium vapour condensation and to provide data for validation of thermal-hydraulic codes.

ESFR-SMART: past and ongoing tests

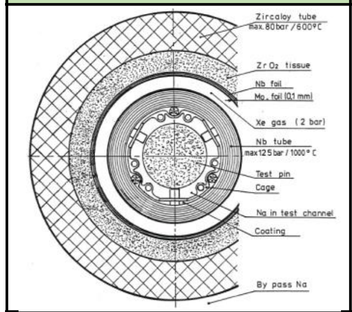
Legacy data on **molten fuel ejection** in the sodium channel obtained at CABRI reactor at Cadarache centre is used for validation of severe accident codes.

The new LIVE facility is designed at Karlsruhe Institute of Technology to study interaction of molten **corium simulant with core catcher**.

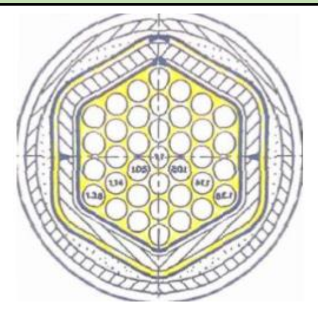
The new facilities are designed at University of Lorraine to simulate with ice-water jet system interaction of molten **corium jet with core catcher**.

Severe accident (SA) management

CABRI

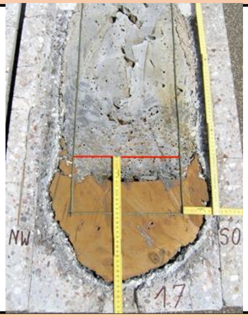


SCARABEE

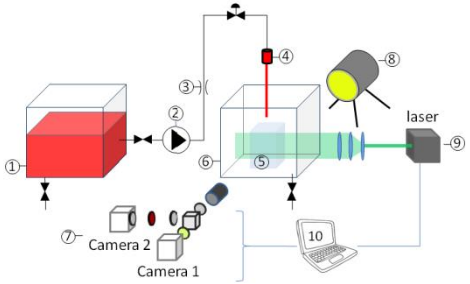


LIVE

JIMEC



HAnSOLO and JEDI



Legacy data on **melt propagation** into the bundle obtained at SCARABEE reactor at Cadarache centre is used for validation of severe accident codes.

The new JIMEC facility is designed at Karlsruhe Institute of Technology to study interaction of molten **corium simulant with concrete**.

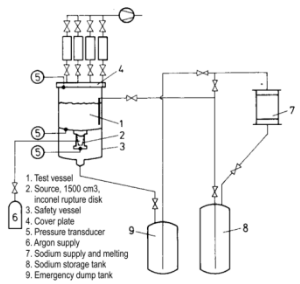
ESFR-SMART: past and ongoing tests

Legacy data obtained at small-scale FAUST and NALA facilities at Forschungszentrum Karlsruhe on hot sodium evaporation rate, release and **behaviour of aerosols** in sodium vapour atmosphere will be used for validation of severe accident codes.

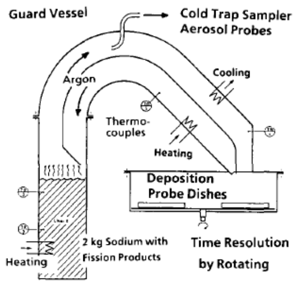
Legacy data on kinetics of aerosols release from sodium **pool fires** conducted at CEA Cadarache centre (France) will be used for validation of severe accident codes.

SA mitigation

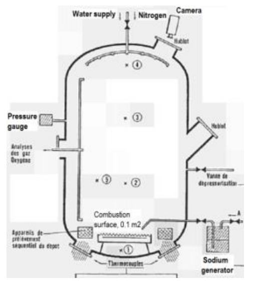
FAUST



NALA



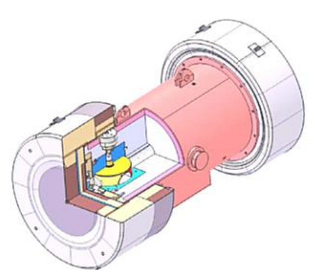
FANAL



ESFR-SMART: past and ongoing tests

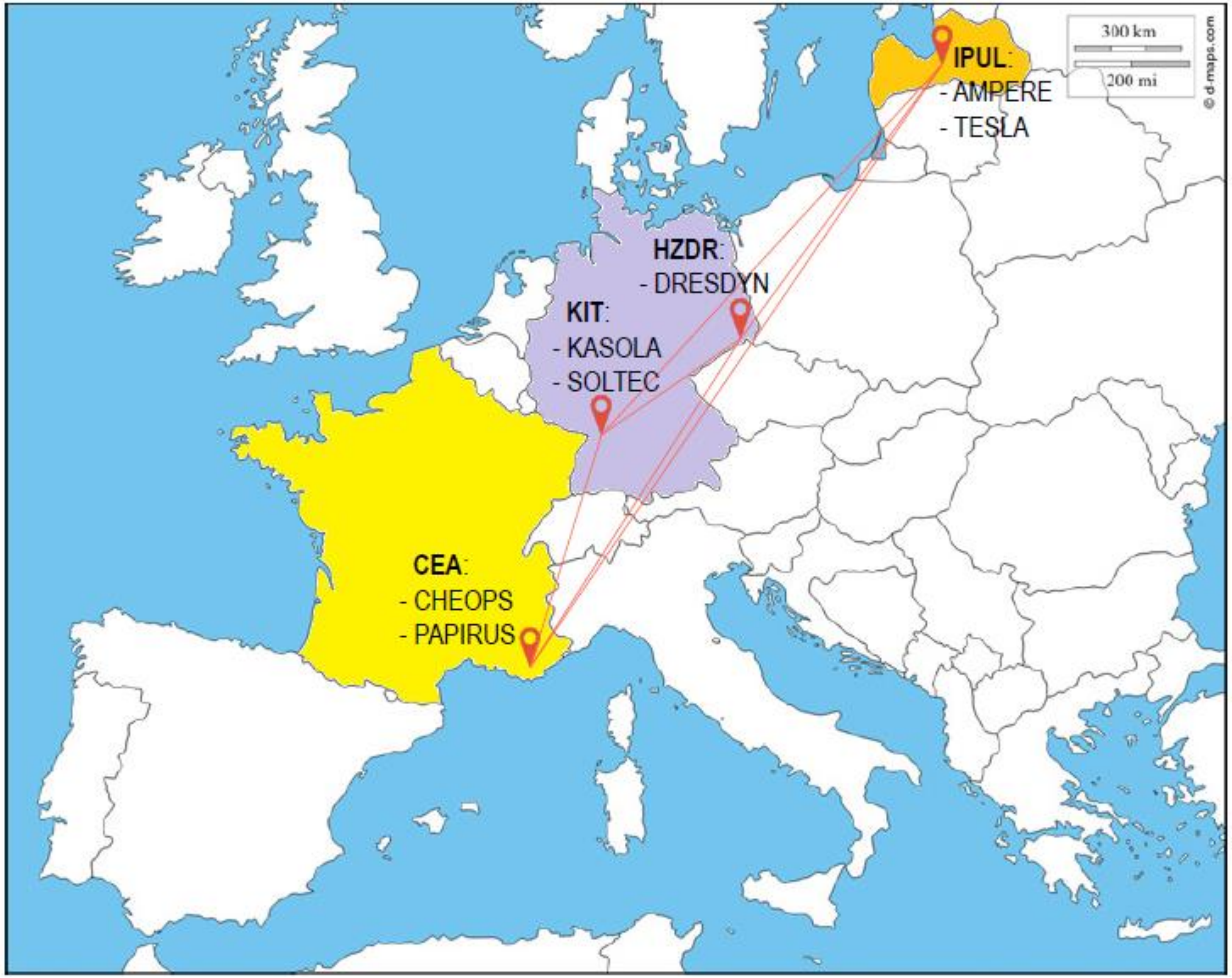
New data on fresh and burned mixed uranium-plutonium oxide **fuel thermal-physical properties** will be obtained for the use in computer simulations.

MOX fuel measurements



EU network of sodium facilities

In addition, attachments of students working in the project to the European sodium facilities will be supported by dedicated mobility grants



Goals of the webinar

1. Present a brief history of the conceptual development of a large-power (3600 MWth) European Sodium Fast Reactor (ESFR)

2. Discuss the status of the current R&D activities on Generation-IV ESFR safety enhancements of the Horison-2020 ESFR-SMART project

3. Provide an overview of new safety measures proposed for improvement of the three safety functions: reactivity control, heat removal and radioactivity containment

4. Introduce experimental programs currently on-going in Europe in support of the ESFR R&D

5. Summarize the activities to be performed during the next phase of the project

Summary

Current achievements of the ESFR-SMART project:

- A number of design modifications aimed at ESFR design simplification and safety enhancement were selected and specified (including design drawings).
- The new ESFR core neutronics performance in normal operation was evaluated.
- A number of benchmarks and new experiments started.
- The burned fuel samples were prepared for measurements of thermal properties.

Next phases of the project:

- The new ESFR core and system performance will be evaluated in normal and accidental conditions.
- New benchmarks and new experiments will be continued.
- The thermal properties of fresh and burned fuel samples will be measured.

Thank you!

Visit us at http://esfr-smart.eu/

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Upcoming Webinars

22 May 2019	Formulation of Alternative Cement Matrix for Solidification/Stabilization of Nuclear Waste	Mr. Matthieu De Campos, University Lille 1, France
19 June 2019	Interaction JOG/Sodium in Case of a Clad Breach in a Sodium Fast Reactor	Mr. Guilhem Kauric, CEA, France
31 July 2019	Security Study of Sodium-Gas Heat Exchangers in frame of Sodium-cooled Fast Reactors	Dr. Fang Chen, CEA, France