H2020 ESFR-SMART project

Konstantin Mikityuk
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SNETP Forum 2021, February 2-4, 2021

European Sodium Fast Reactor: background

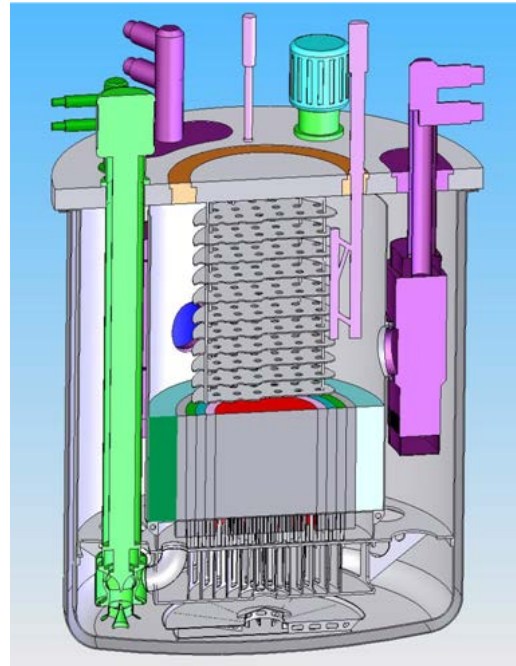The reactor design has been developed taking into account SFR operation experience and multiple experiments:
– Thermal / electrical power 3600 / 1500 MW
– Mass of sodium in the primary pool ~2500 t
– Primary sodium temperature 395ºC – 545ºC
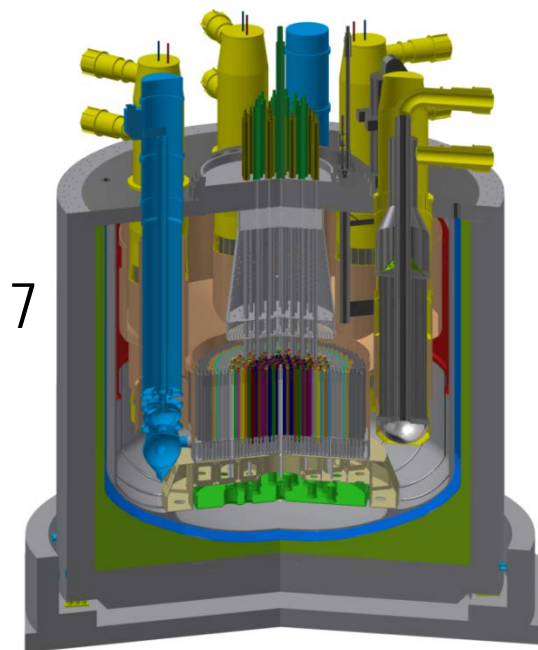– 6 Heat eXchangers, 3 Primary Pumps, 36 Steam Generators
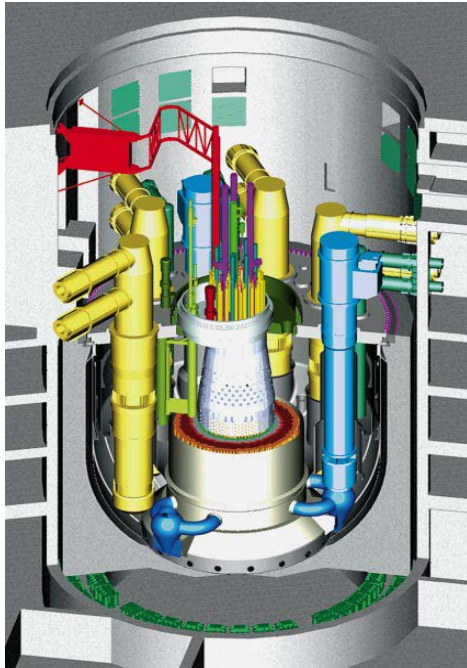
1990   2000 ... 2008   2012 ... 2017   2021
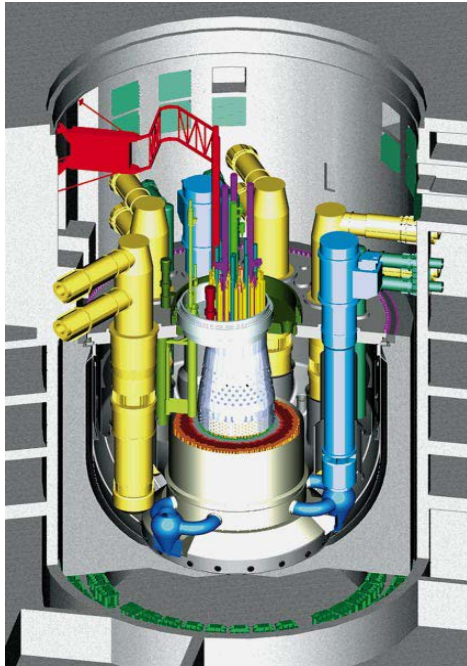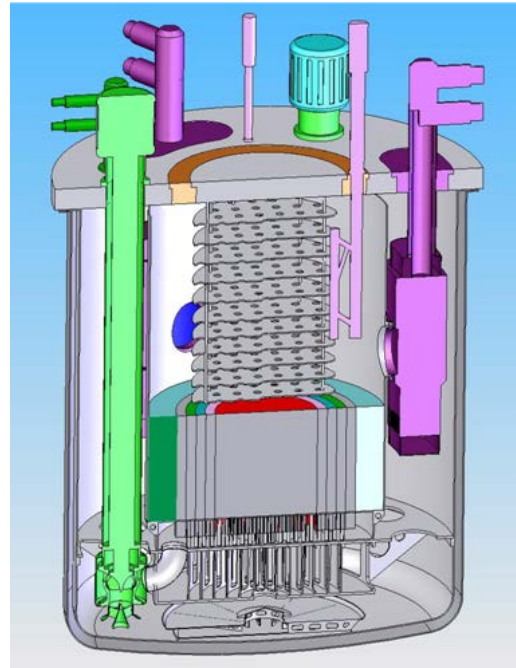
EFR   **CP ESFR**   **ESFR-SMART**

Main goals of the projects:
– Improve safety
– Improve economics
– Improve management of nuclear materials

1990

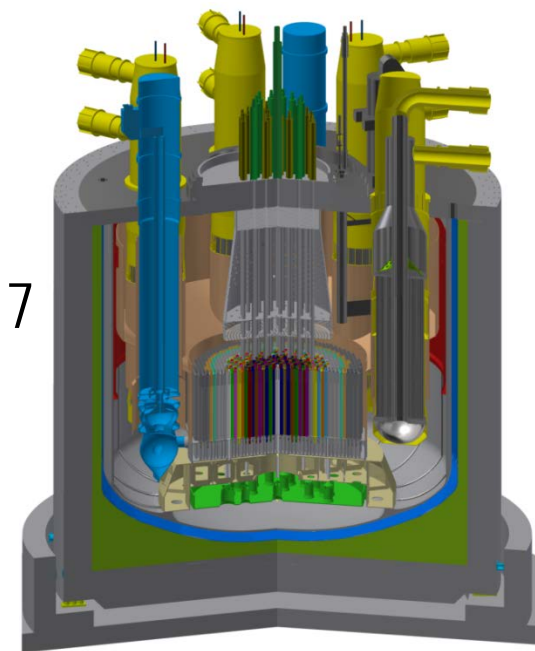2000 ... 2008

2012 ... 2017

2021

EFR

CP ESFR

ESFR-SMART

3

ESFR-SMART: project in a nutshell

Name:

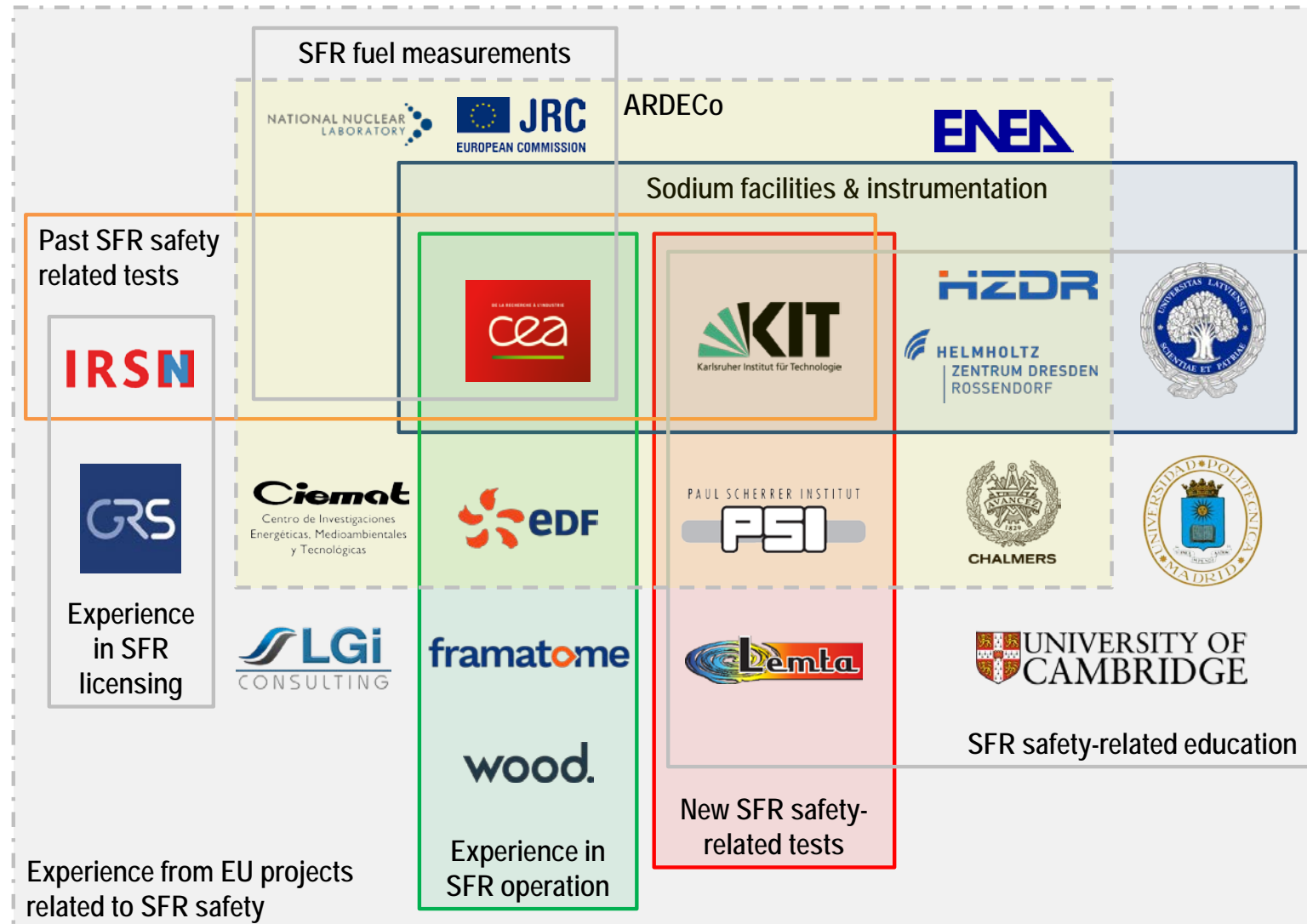– ESFR-SMART: European Sodium Fast Reactor Safety Measures Assessment and Research Tools

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: consortium

SFR fuel measurements

ARDECo

Sodium facilities & instrumentation

Past SFR safety related tests

Experience in SFR licensing

Experience from EU projects related to SFR safety

Experience in SFR operation

New SFR safety-related tests

SFR safety-related education

Work Package and Task Leaders

K. Mikityuk (PSI)	L. Andriolo (EDF)
J. Krepel (PSI)	A. Ponomarev (PSI)
N. Chauvin (CEA)	S. Perez Martin (KIT)
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E. Girardi (EDF)	C. Demaziere (CHALMERS)
E. Fridman (HZDR)	S. Poumerouly (EDF)
G. Gerbeth (HZDR)	C. Collignon (ENEA)
L. Buligins (IPUL)	W. Pfrang (KIT)
N. Girault (IRSN)	M. Gradeck (LEMTA)
E. Bubelis (KIT)	X. Gaus-Liu (KIT)
A . Rineiski (KIT)	L. Ayrault (CEA)
S. Ehster Vignoud (Framatome)	S. Eskert (HZDR)
J. Guidez (CEA)	E. Sanseigne (CEA)
E. Schwageraus (UCAM)	W. Jager (KIT)
B. Lindley (WOOD)	D. Staicu (JRC)
L. Ammirabile (JRC)	C. Demaziere (CHALMERS)
C. Lombardo (ENEA)	N. Garcia Herranz (UPM)
A. Seubert (GRS)	H. Tsige-Tamirat (JRC)
C. Collignon (Framatome)	M. Bazin-Retours (LGI)
M. Flad (KIT)	

ESFR-SMART: structure

- 3 Subprojects
- 12 Work Packages
- 47 Tasks

INPUT
FP7 projects
GIF
ARDECo

INPUT
Legacy data

SP1
Analytical assessment of new safety measures for ESFR

SP2
R&D to support SFR safety enhancement

WP1.2
Normal operation
PSI

WP1.3
Measures to prevent sodium boiling
KIT

WP1.1
New safety measures
EDF

WP1.4
Measures to prevent severe accidents
HZDR

WP1.5
Measures to mitigate severe accidents
KIT

WP3.1
Dissemination, education and training
CEA

WP3.2
Project management
PSI

WP2.2
New experiments for safety
CEA

WP2.3
European sodium facilities support
IPUL

WP2.1
Codes validation & benchmarking
IRSN

WP2.4
Instrumentation for safety
HZDR

WP2.5
New measurements of fuel properties
CEA

SP3. Management and interactions

OUTCOME
New ESFR concept

OUTCOME
Validated codes
New data

ESFR-SMART: structure

Color codes:
- Consistency and safety approach
- Initial core and system specification
- Neutronic parameters
- Initiating events
- Potential impact

WP1.1. New safety measures
- T1.1.1. Definition of safety requirements
- T1.1.2. Specification of new core safety measures
- T1.1.3. Specification of new system safety measures
- T1.1.4. Consistency of R&D studies in SP1

GIF ISAM

WP1.2. Normal operation
- T1.2.1. Initial core performance & burn-up calculations
- T1.2.2. Safety and performance parameters at EOC
- T1.2.3. Fuel performance and gap conductance
- T1.2.4. Coupled core TH and neutronics simulations

WP1.3. Measures to prevent sodium boiling
- T1.3.1. Assessment of transition from FC to NC
- T1.3.2. Assessment of primary pumps
- T1.3.3. Assessment of DHR systems
- T1.3.4. Assessment of PCCS

FP7 CP ESFR
FP7 ESNII Plus
ESNII
ARDECo

WP1.4. Measures to prevent severe accidents
- T1.4.1. Assessment of chugging boiling conditions
- T1.4.2. Propagation of pressure waves through the core
- T1.4.3. Dynamic reactivity effect of pressure waves

WP1.5. Measures to mitigate severe accidents
- T1.5.1. Transition phase analyses
- T1.5.2. Expansion phase analyses
- T1.5.3. Absorber introduction into the core under SA conditions

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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

ESFR-SMART

NETP
ble Nuclear Energy
ogy Platform

8

Tall chimney for decay heat removal

Six steam generators are inside this box

One of six secondary loops

The primary sodium pool (~20 m high) with core, 3 pumps and 6 heat exchangers

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
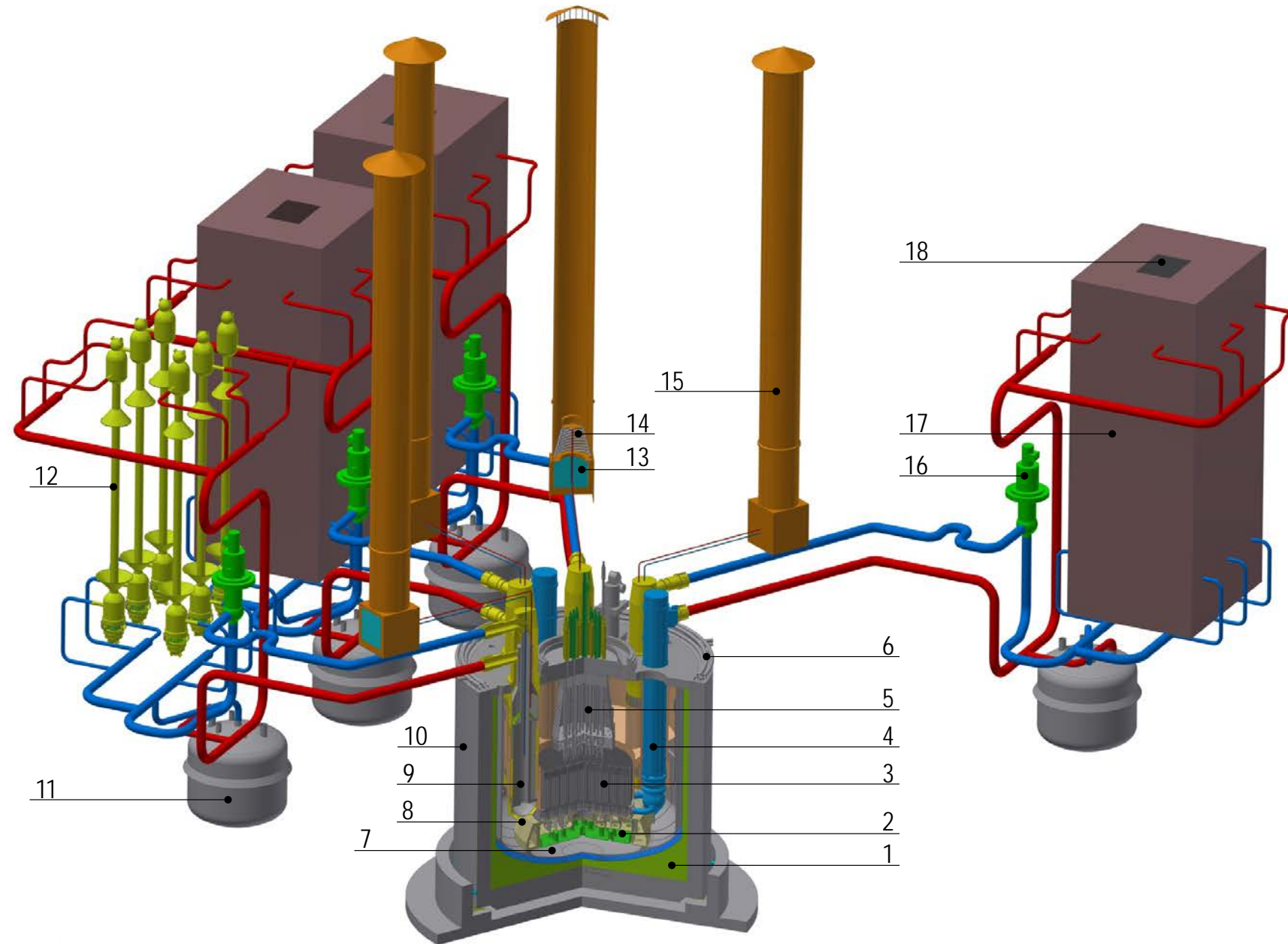
- Low-void effect core

- Control rods (DSD) passively activated: Curie temperature

- Internal spent fuel storage for 50% of core loading

- Corium discharge channels and core catcher

- Hydraulic diodes at the pump outlet
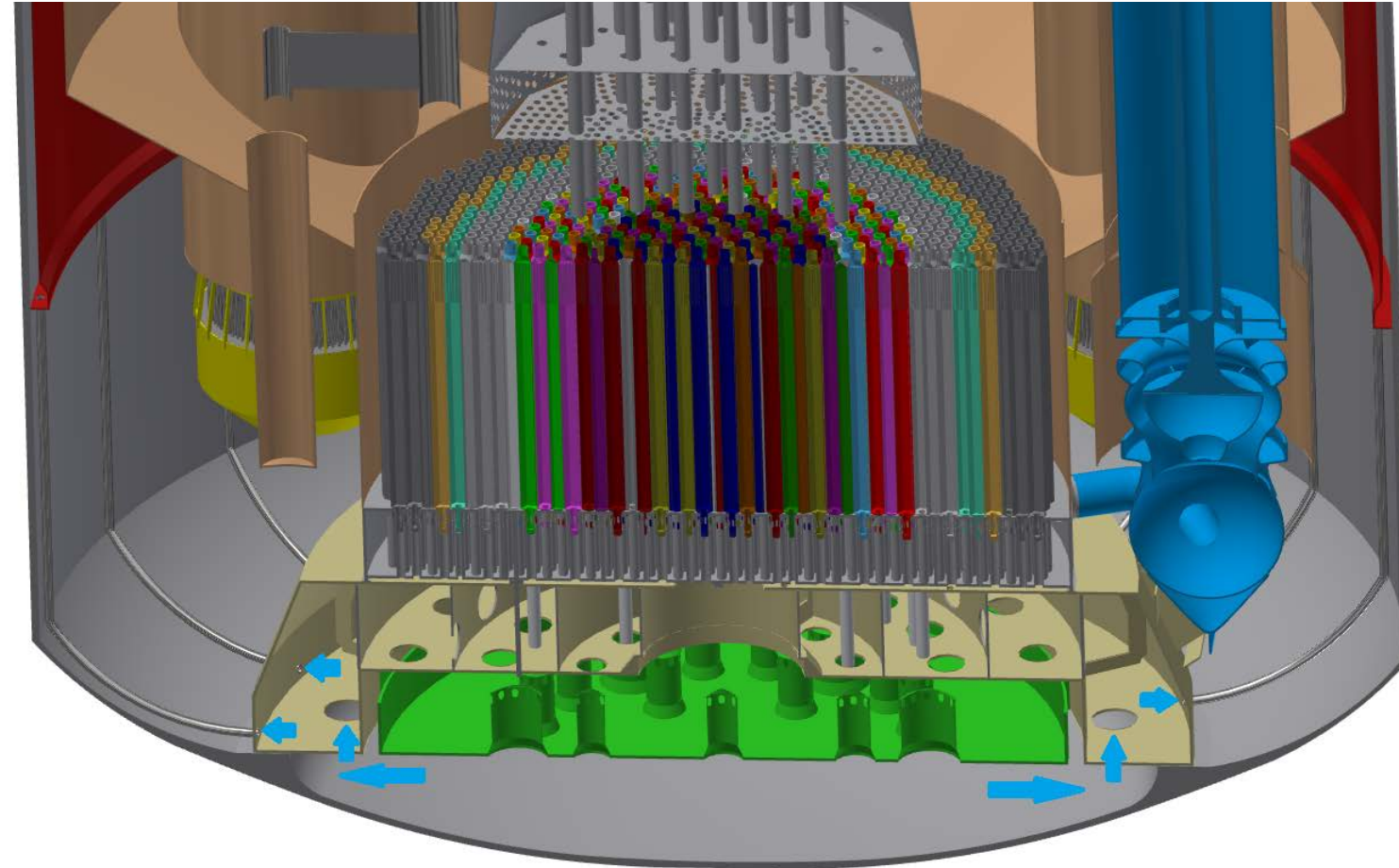
- The same initial plutonium content in the whole core

- 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 – Inner zone SA
2 – Outer zone SA
3 – Control assembly
4 – Corium discharge path
5 – Shielding SA
6 – Internal spent fuel storage

Fissile fuel (~18% Pu content)
Fertile blanket
Steel blanket
Fission gas plenum
Sodium plenum
Shielding (absorber)

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New core design: radial map
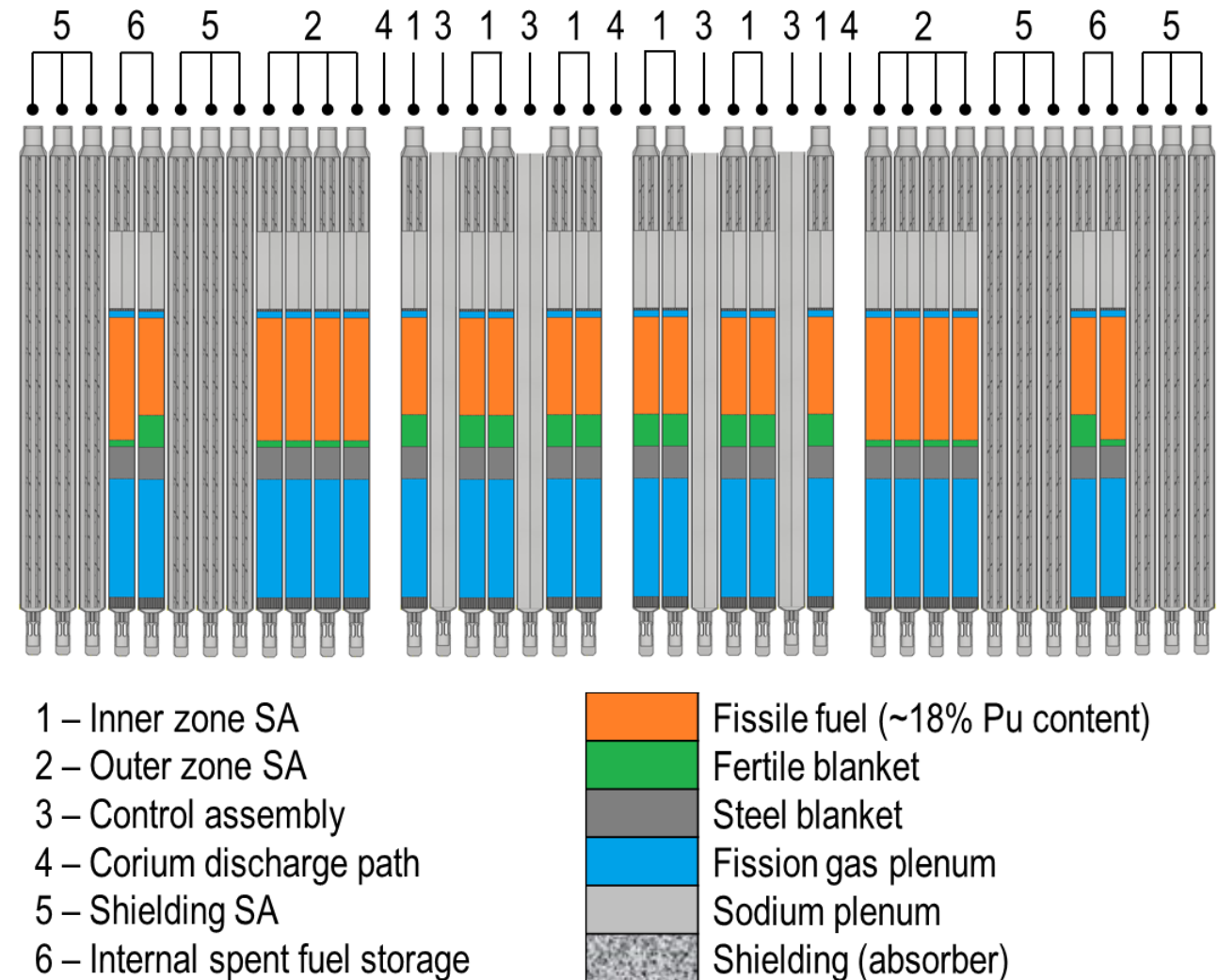
- Perfectly symmetric

- 6 batches = 6-year fuel cycle

- Mixed scheme (no reshuffling)

- Internal storage for 50% of core loading

- All safety (DSD) rods equipped with passively-activated Curie-point locks
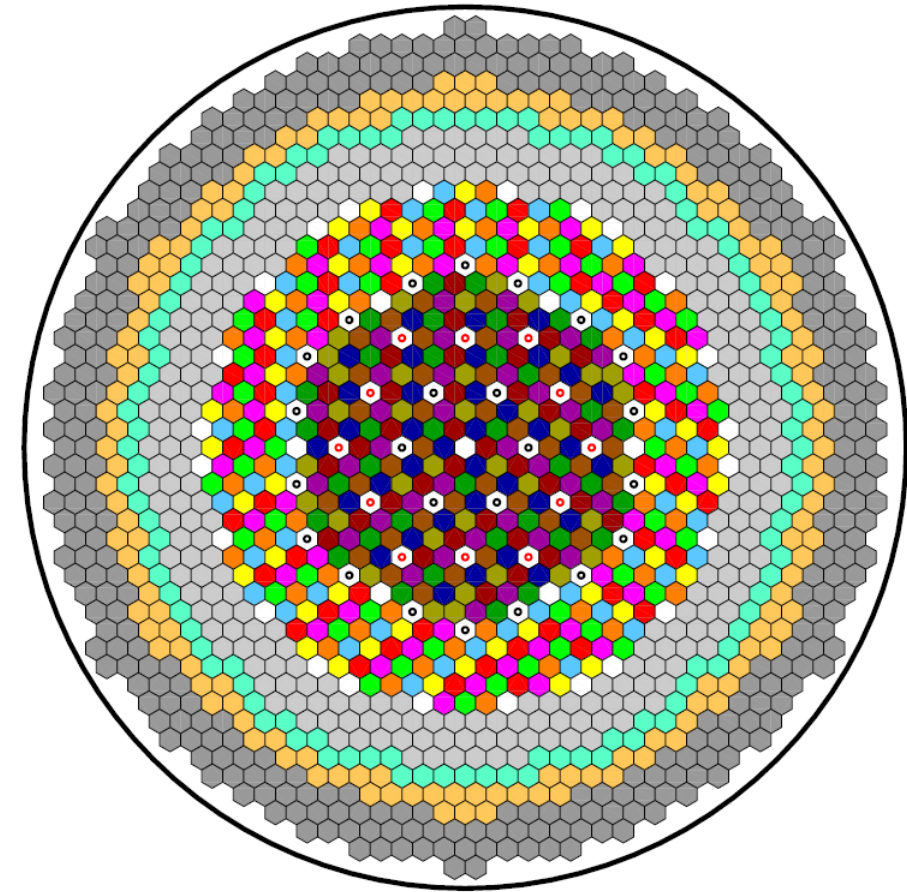
1	2	3	4	5	6	Inner zone SA	6 batches×36 = 216
1	2	3	4	5	6	Outer zone SA	6 batches×48 = 288
○	○					CSD / DSD	24 / 12
R1	R2	R3				Reflector rings	66 / 96 / 102
S1						Spent inner fuel storage	3 batches×36 = 108
S2						Spent outer fuel storage	3 batches×48 = 144
						Corium discharge path	31

New core design: passive control rods

- 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

Latched   De-latched

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

- Iron
- Temperature-sensitive alloy (Ni-Co-Fe)
- Coil
- Magnetic path

New core design: path for corium
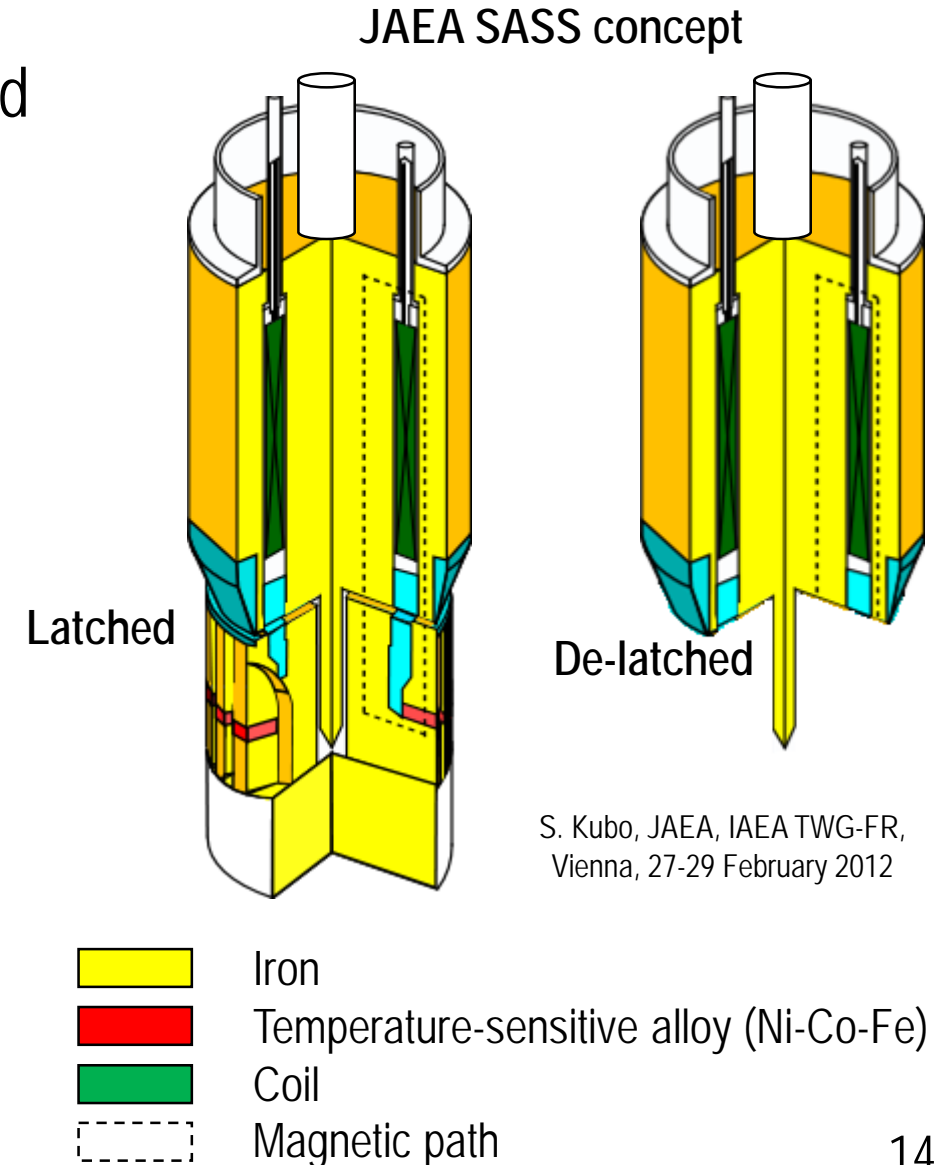
In case of very low probability core meltdown event, the corium discharge channel helps
— To avoid re-criticality
— To promote transfer of the corium to the core catcher
— To efficiently remove decay heat

New system design: DHRS-1 and -2

Decay Heat Removal System
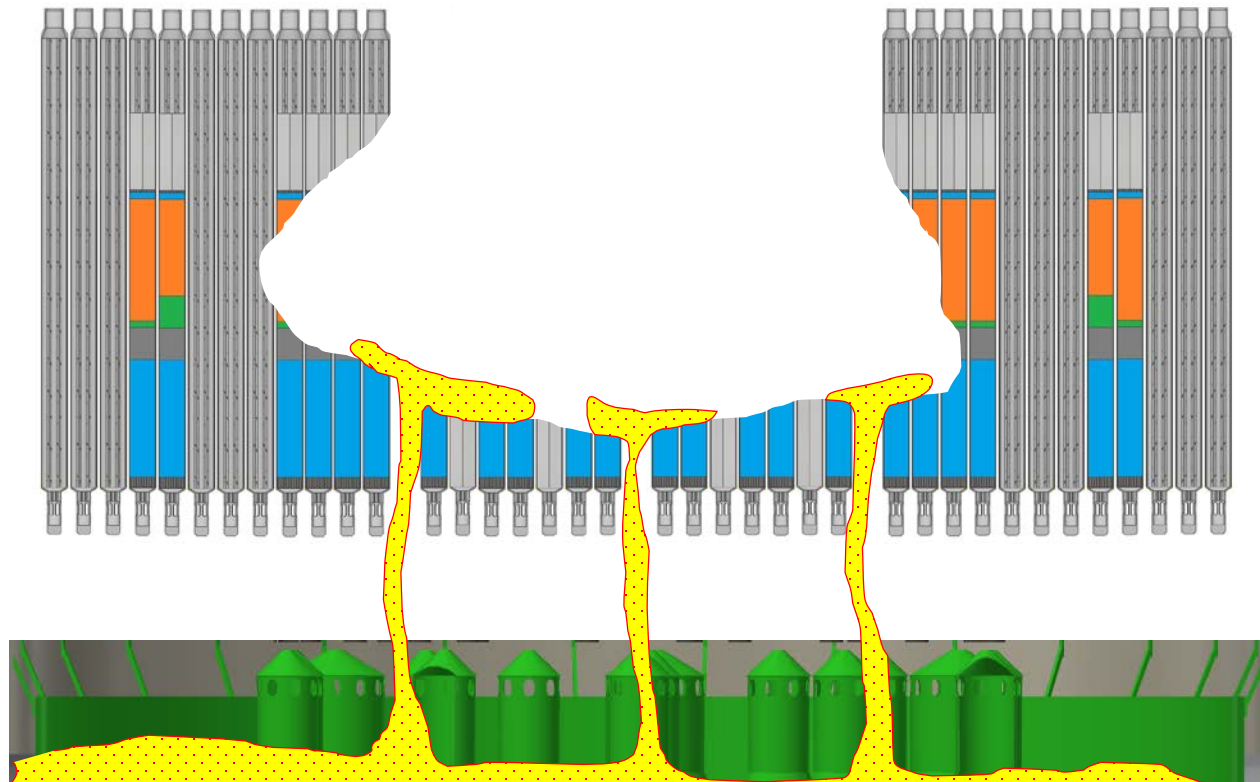
- DHRS-1 connected to the IHX and using secondary sodium as working fluid

- Use of passive thermal pumps in secondary and DHRS-1 circuits

- DHRS-2 uses air circulation through the openings
  in the SG casing and heat removal from the SG surfaces

Thermal pump concept

Permanent magnet

Alumel

Chromel

Electric current
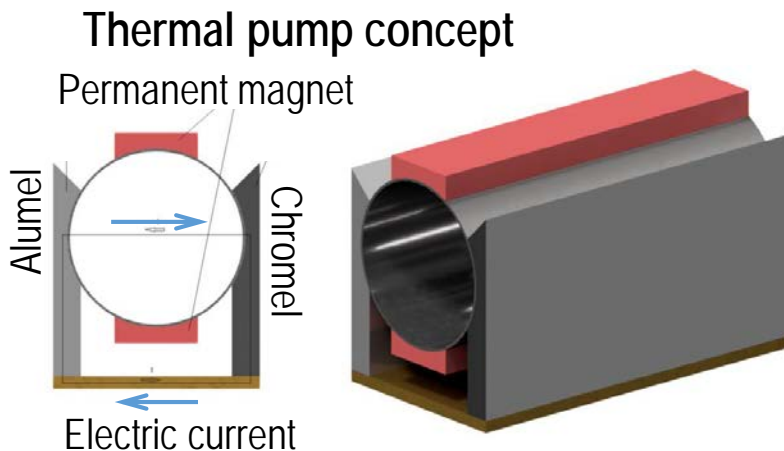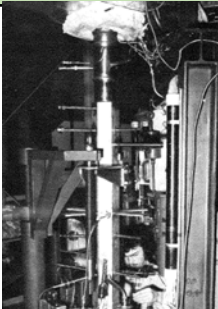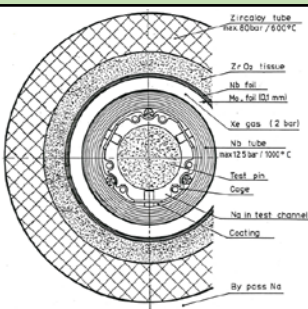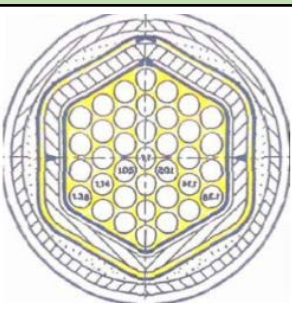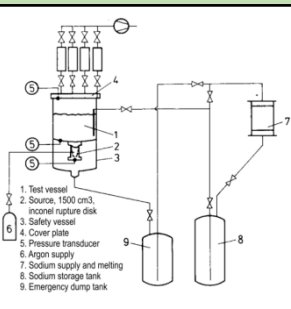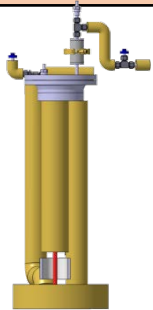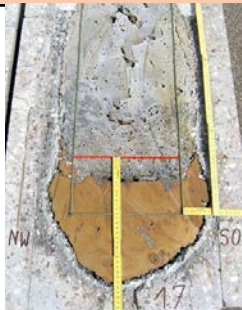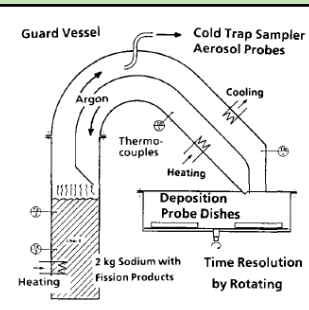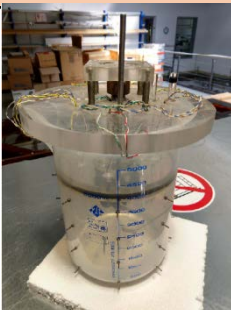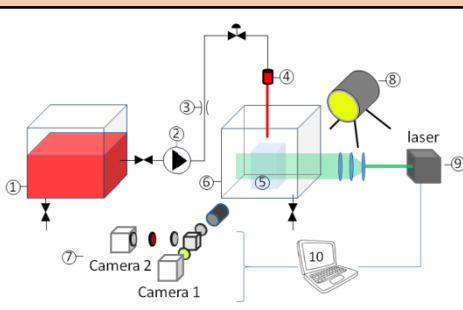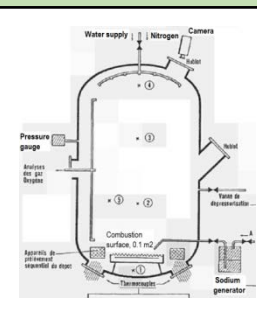
1 – Intermediate heat exchanger
2 – Secondary pump
3 – Thermal pumps
4 – Sodium storage tank
5 – Steam generator
6 – Casing of Decay Heat Removal System (DHRS-2)
7 – Air stack of DHRS-1
8 – Openings for air circulation
9 – Sodium-air heat exchanger of DHRS-1
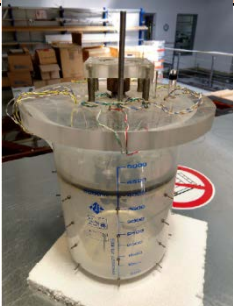
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New system design: pit and DHRS-3
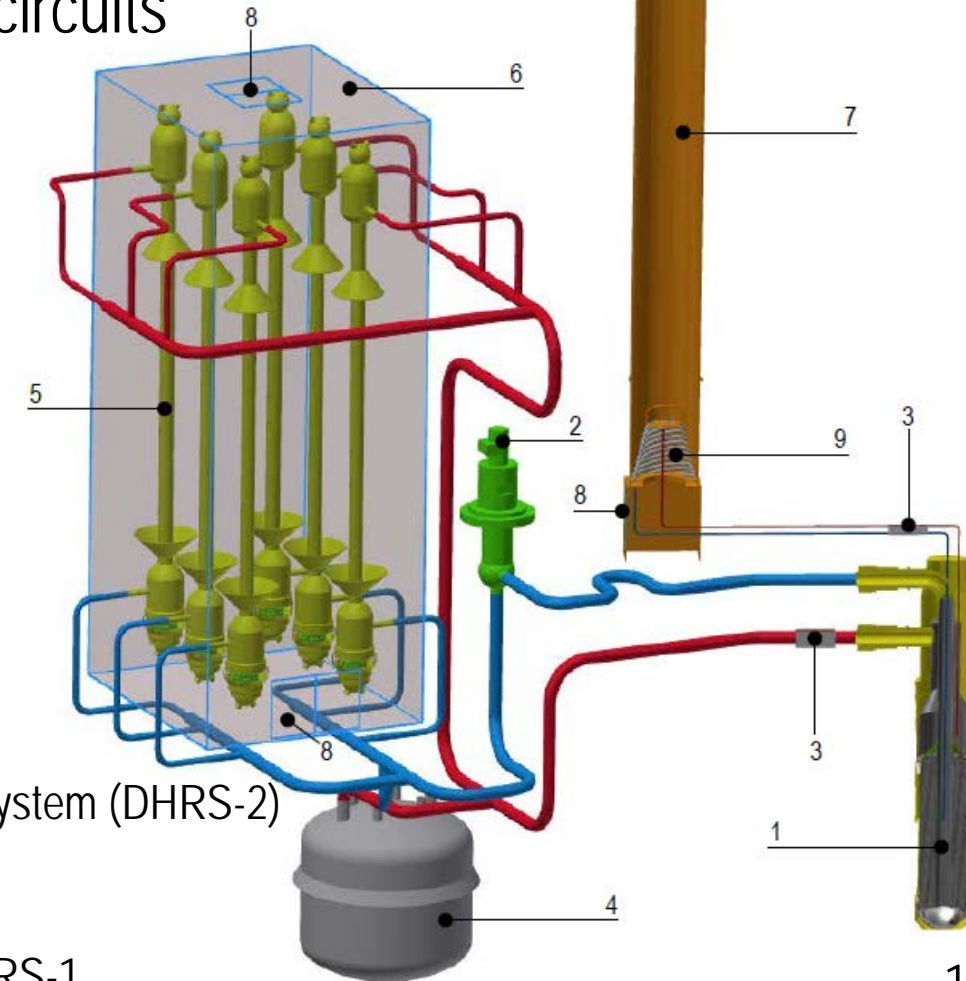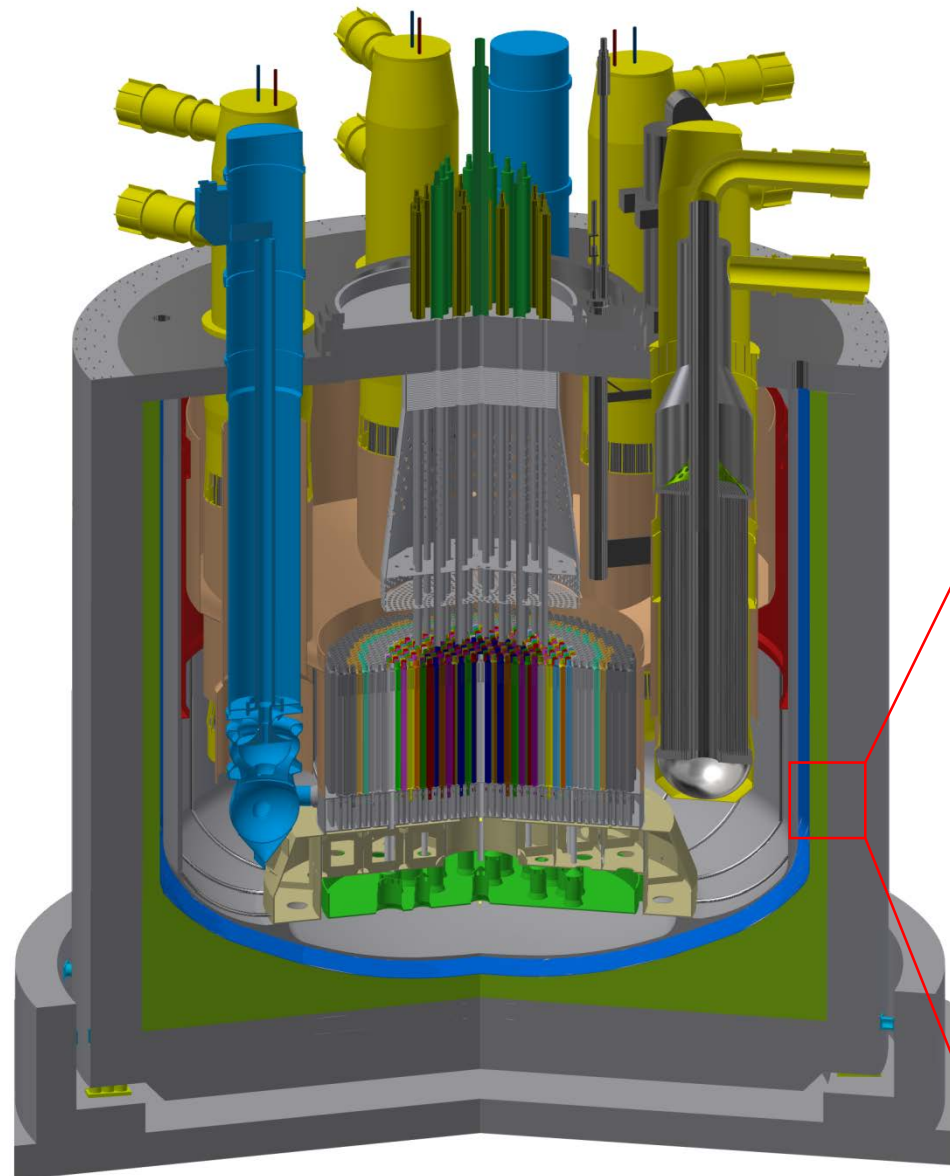
- Elimination of reactor dome and of safety vessel

- Minimization of the reactor vessel-pit gap, still large enough for inspection (shown in blue)

- Insulation (shown in green) with metallic liner on it

- Two reactor pit concrete cooling systems (oil and water) suitable for decay heat removal (DHRS-3)
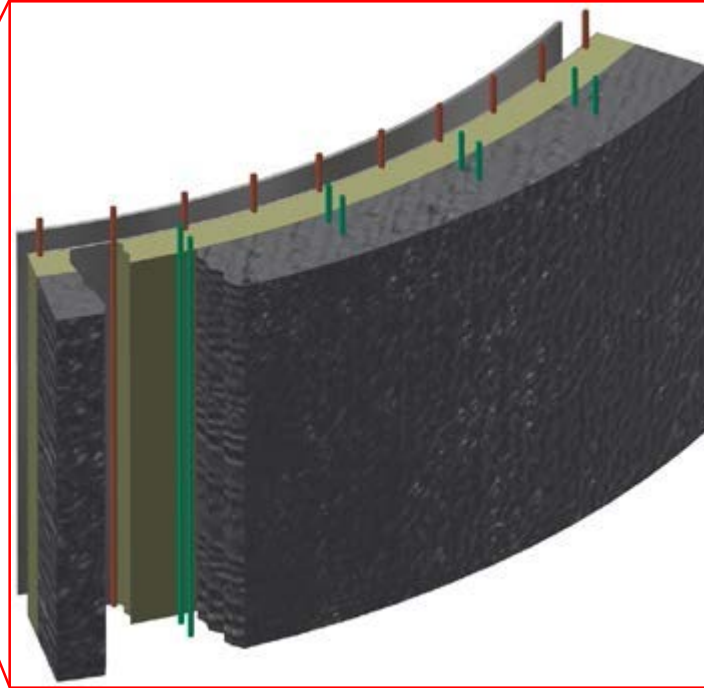
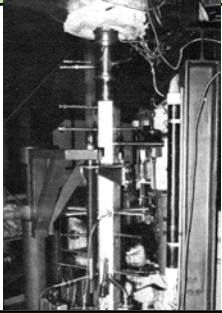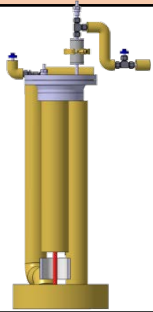| Normal operation	Sodium boiling	Severe accident (SA) management		SA mitigation
Superphenix	KNS-37	CABRI	SCARABEE	FAUST
KASOLA	KARIFA	LIVE	JIMEC	NALA
ECFM	CHUG	HAnSOLO and JEDI		FANAL

MOX fuel measurements
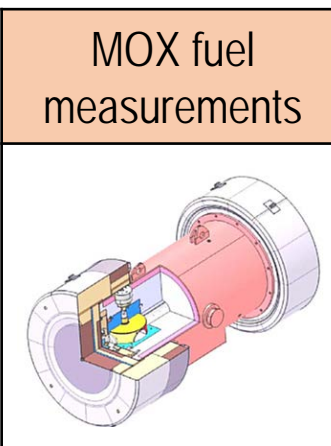
Normal operation

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.

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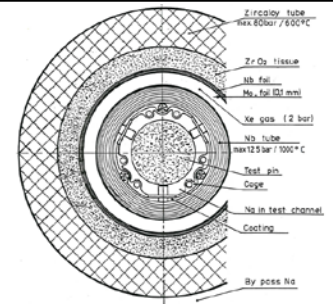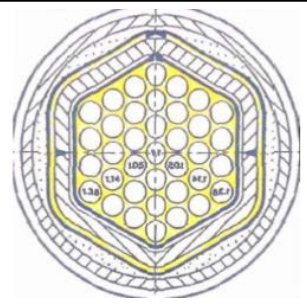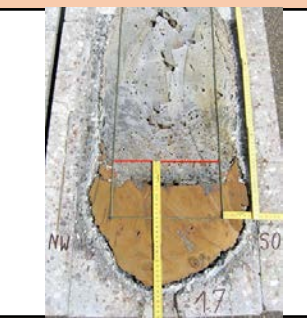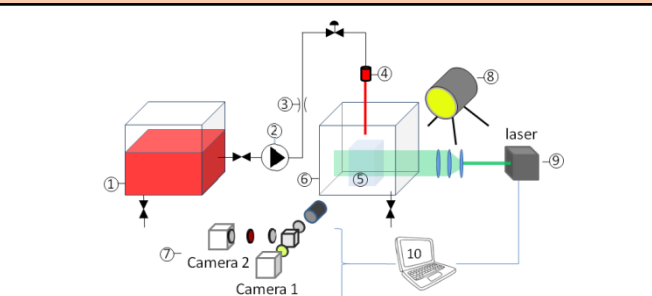
A new compact **sodium boiling facility** with pulse laser heating is under development at Karlsruhe Institute of Technology to gain experience with two-phase sodium flow experiments and to provide data for validation of thermal-hydraulic codes.

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**.

| SA mitigation |
| --- |
| FAUST |
| |
| NALA |
| |
| FANAL |
| |

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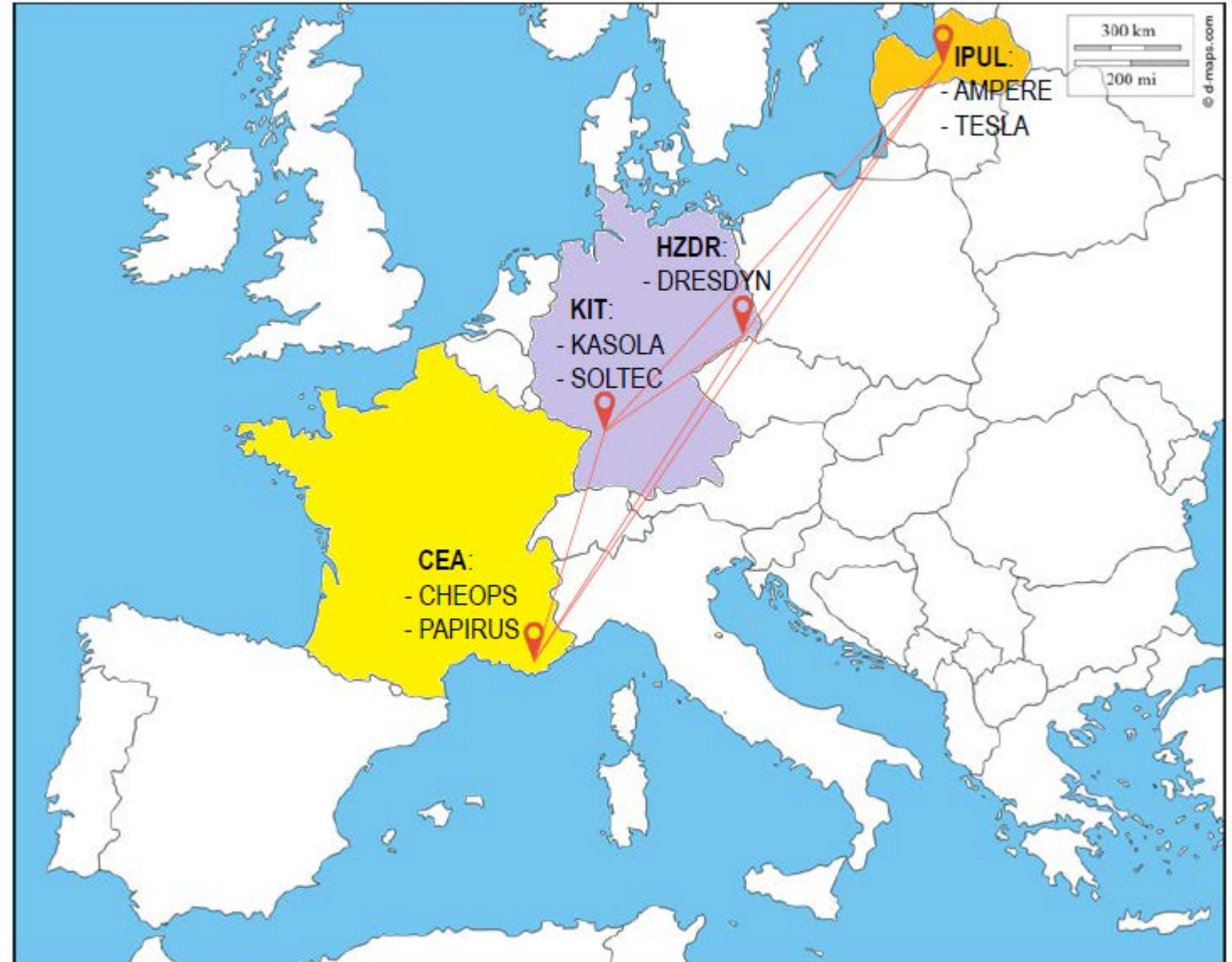
MOX fuel measurements
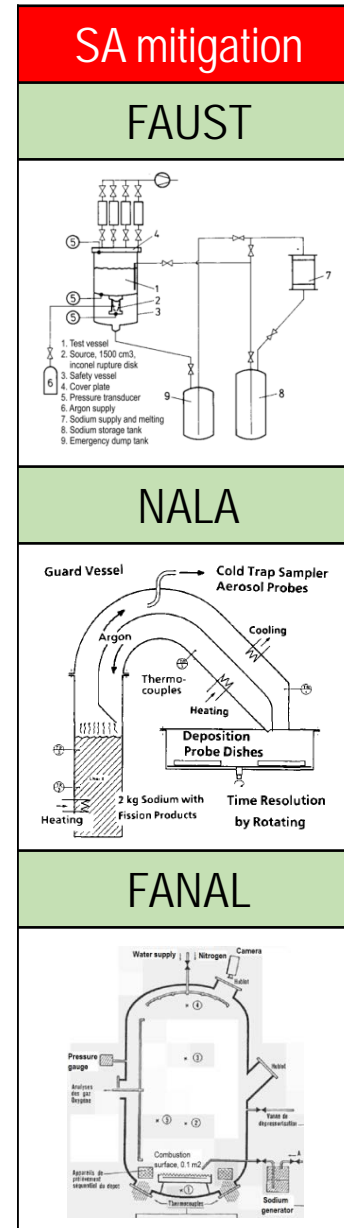
New data on fresh and burned mixed uranium-plutonium oxide **fuel thermal-physical properties** will be obtained for the use in computer simulations.

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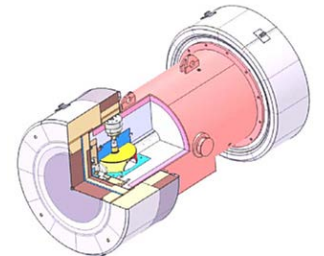
In addition, attachments of students working in the project to the European sodium facilities will be supported by dedicated mobility grants

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 and system performance is evaluated in normal and accidental conditions. Advantages and shortcomings are identified.

- A number of calculational benchmarks and new experiments conducted.

- The fresh and irradiated MOX fuel samples were prepared for measurements of thermal properties.

Next steps:

- Ongoing benchmarks and experiments will be completed.

- The thermal properties of fresh and burned fuel samples will be measured.

- Main results of the project will be published in a Special Issue of Journal of Nuclear Engineering and Radiation Science

Thank you!

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