EUROPEAN SODIUM FAST REACTOR: AN INTRODUCTION

Dr. Konstantin Mikityuk
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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 ~500°C
- 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
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 $\rightarrow$ very efficient cooling
  - Large margin to boiling $\rightarrow$ no pressurization required
  - Significant operational experience (300+ reactor-years)

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

- **Reactors under operation**
  - BOR-60, BN-600, BN-800 (all Russia), CEFR (China)
European Sodium Fast Reactor: brief history

- SPX2
- EFR
- FP7 CP ESFR
- H2020 ESFR-SMART

**Thermal power, MW**

- UK
- France
- Germany
- French project
- EU projects

**Time of start-up, year**

- Phenix
- PFR
- SNR-300
- ASTRID

- DFR
- Rapsodie
- KNK-II

- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030
Main goals of the projects:
- Improve safety
- Improve economics
- Improve management of nuclear materials
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 395°C – 545°C
- 6 Heat eXchangers, 3 Primary Pumps, 36 Steam Generators
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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

Work Package and Task Leaders

K. Mikityuk (PSI)  L. Andriolo (EDF)
J. Krepel (PSI)  A. Ponomarev (PSI)
N. Chauvin (CEA)  S. Perez Martin (KIT)
F. Payot (PSI)  E. Dufour (CEA)
C. Latge (CEA)  L. E. Herranz Puebla (CIEMAT)
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

SP1
Analytical assessment of new safety measures for ESFR

WP1.1
New safety measures EDF

WP1.2
Normal operation PSI

WP1.3
Measures to prevent sodium boiling KIT

WP1.4
Measures to prevent severe accidents HZDR

WP1.5
Measures to mitigate severe accidents KIT

SP2
R&D to support SFR safety enhancement

WP2.1
Codes validation & benchmarking IRSN

WP2.2
New experiments for safety CEA

WP2.3
European sodium facilities support IPUL

WP2.4
Instrumentation for safety HZDR

WP2.5
New measurements of fuel properties CEA

SP3. Management and interactions

WP3.1
Dissemination, education and training CEA

WP3.2
Project management PSI

WP3.3
New ESFR concept IRSN

INPUT
Legacy data

OUTCOME
Validated codes
New data

INPUT
FP7 projects GIF ARDECo
ESFR-SMART: structure

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

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

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

Color codes:
- Consistency and safety approach
- Initial core and system specification
- Neutronic parameters
- Initiating events
- Potential impact
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One of six secondary loops

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

Tall chimney for decay heat removal

Six steam generators are inside this box
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

Diagram:

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)
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
- Corium discharge channels to facilitate the corium relocation in the core catcher in a very low-probability event of a core meltdown
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

S. Kubo, JAEA, IAEA TWG-FR, Vienna, 27-29 February 2012
In case of very low probability core meltdown event, the corium discharge channel helps:

1. To avoid re-criticality
2. To promote transfer of the corium to the core catcher
3. To efficiently remove decay heat
New system design: DHRS-1 and -2

- 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

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

Thermal pump concept

Permanent magnet
Electric current
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)
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## ESFR-SMART: past and ongoing tests

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<thead>
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<th>Sodium boiling</th>
<th>Severe accident (SA) management</th>
<th>SA mitigation</th>
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<td>KNS-37</td>
<td>CABRI</td>
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<td>ECFM</td>
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**MOX fuel measurements**

**GENIV** International Forum

- CABRI
- SCARABEE
- FAUST
- KNS-37
- Superphenix

- LIVE
- JIMEC
- NALA
- KARIFA
- KASOLA

- ECFM
- CHUG
- HAnSOLO and JEDI
- FANAL
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.

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.

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

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**.
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.
New data on fresh and burned mixed uranium-plutonium oxide fuel thermal-physical properties will be obtained for the use in computer simulations.
In addition, attachments of students working in the project to the European sodium facilities will be supported by dedicated mobility grants.
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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/

The ESFR-SMART project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754501
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