IAEA
International Atomic Energy Agency

"Atoms for Peace and Development"

Technical Meeting on
Safety Approach for Liquid Metal Cooled Fast Reactors and Analysis and Modelling of Severe Accidents
13 - 17 March 2023 , IAEA, Austria

IAEA Activities on Fast Reactor Technology

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Fast Reactor Technology Development Team
Nuclear Power technology Development Section
Division of Nuclear Power
Department of Nuclear Energy
International Atomic Energy Agency

https://www.iaea.org/topics/fast-reactors

email: FR@IAEA.ORG

Fast Reactors in Operation, and under Construction and Decommissioning

Country		Type	coolant	Purpose	Power (th/e) MW	Year (Op.)	Status
Russia	BOR-60	SFR	sodium	experimental	60/10	1969	operating
	BN-600	SFR	sodium	prototype	1470/600	1980	operating
	BN-800	SFR	sodium	industrial	2100/880	2015	operating
	MBIR	SFR	sodium	experimental	150/50	~2028	construction
	BREST-OD-300	LFR	lead	Gen-IV, demonstrator	700/300	~2026	construction
China	CEFR	SFR	sodium	prototype	80/20	2011	operating
	CFR600 x2	SFR	sodium	prototype	1500/600	~2025	construction (2 units)
India	FBTR	SFR	sodium	experimental	40/-	1985	operating
	PFBR	SFR	sodium	demonstrator	1250/500	?2024	comissioning
Japan	MONJU	SFR	sodium	prototype	714/280	1994	decomissioning
	JOYO	SFR	sodium	experimental	140/--	1978	license renew

Fast Reactors under Developing and Design

Country	Name	Type	coolant	Purpose	Power (th/e), MW	Status
Russia	**BN-1200**	SFR	sodium	Gen-IV, industrial	2900/1220	design
	SVBR-100	LFR	LBE	prototype	280/100	design
	MOSART	MSR	molten salt	prototype	2400/	concept
China	**CFR1000**	SFR	sodium	Gen-IV, industrial	2512/1000	design
	CLFR-300	LFR	LBE/lead	demonstrator	740/300	concept
	CLEAR-M10a	LFR	LBE	experimental	10/1-3	concept
	CLEAR-I	LFR	LBE	experimental	10/-	design
	CLEAR-M10d	LFR	lead	demonstrator	25/10	concept
EU	ALFRED	LFR	lead	Gen-IV, prototype	300/120	design
	ALLEGRO	GFR	helium	Gen-IV, demonstrator	75/-	design
	MSFR	MSR	molten salt (LiF-AFn)	Gen-IV, prototype	3000/	concept
Belgium	MYRRHA	LFR ADS	LBE	experimental	100/-	design
France	ASTRID	SFR	sodium	demonstrator	1500/600	suspended
Italy	newcleo LFR-AS-30/200	LFR	lead	experimental/prototype	/30 or /200	concept
R. of Korea	KALIMER-600	SFR	sodium	GEN-IV, prototype	1523/600	design
	PGSFR	SFR	sodium	GEN-IV, demonstrator	400/150	suspended
Sweden	**SEALER-55**	LFR	lead	demonstrator	140/55	design
UK	**Westinghouse LFR**	LFR	lead	demonstrator	950/450	design
USA	**Westinghouse LFR**	LFR	lead	demonstrator	950/450	design
	NATRIUM	SFR	sodium	demonstrator	1000/345-500	design
	VTR	SFR	sodium	experimental	300/-	design
	SSTAR	LFR	lead	experimental	45/20	supended
	MCFR	MSR	chloride salt	experimental	1800/800	design
	EM2	GFR	helium	demonstrator	500/265	concept
	KP-FHR	MSR	fluoride salt	demonstrator	310/140	concept
	PRISM	SFR	sodium	demonstrator	840/311	concept
	LLC ARC-100	SFR	sodium	demonstrator	260/110	concept

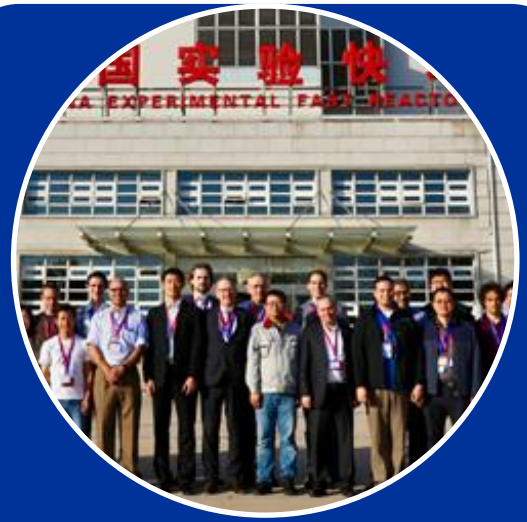
Main IAEA Activities on Fast Reactor Technology

Knowledge Sharing

Publications

Conferences

TMs



Technology Development

Coordinated Research Projects (CRPs)

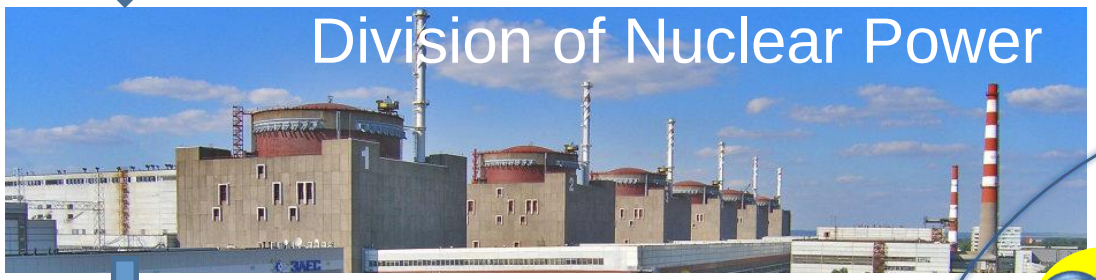
Capacity Building

Training Courses

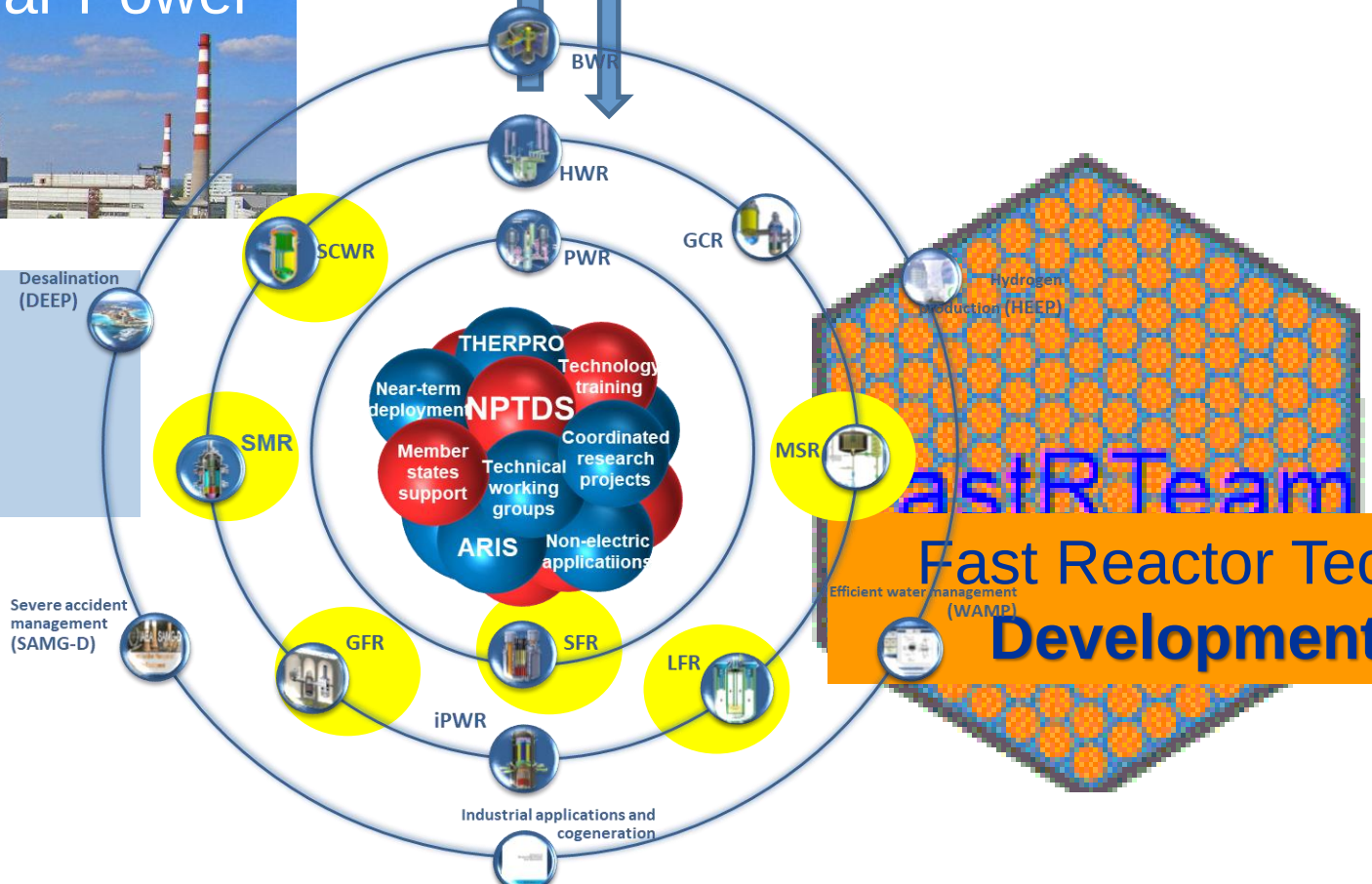
Workshops

TECDOCs

Fast Reactor Technology Development Team



NPTDS:
Nuclear Power Technology Development Section



Fast Reactor Technology **Development** Team

IAEA Technical Working Group on Fast Reactors (TWG-FR)
New Term: 2022 - 2025

- Provide advice and guidance
- Forum for information exchange and knowledge sharing
- Link between IAEA activities and national communities
- Provide advice in planning and implementing of CRPs
- Develop and review selected documents
- Contribute to status report, technical meetings, topical conferences
- Identify important topics for SAGNE
- Encourage participation of young professionals in IAEA activities

Members of the IAEA Technical Working Group on Fast Reactors

Members

Argentina	**Belgium**
China	**Czech Republic**
France	Germany
India	Italy
Japan	Kazakhstan
Korea, republic of	Mexico
Netherlands	Romania
Russian Federation	Sweden
Switzerland	UK
Ukraine	USA

Observers

European Commission/JRC

OECD/NEA

Generation-IV International Forum (GIF)

From 2022: MSs as members; IOs as observers

53rd TWG-FR Meeting: **17-20 Nov 2020 (virtual)**

54th TWG-FR Meeting: **22-25 June 2021 (virtual)**

55th TWG-FR Meeting: **23-27 May 2022 (Hybrid)**

IAEA Conference on Fast Reactors and Related Fuel Cycles **FR22**

Vienna
19-22 April 2022

Track 1. Innovative fast reactor designs
Track 2. Fast reactor safety
Track 3. Fuels, fuel cycles and waste management
Track 4. Fast reactor coolants, structures, and components
Track 5. Test facilities and experiments
Track 6. Modelling, simulations and digitalization
Track 7. Sustainability: Economics, environment and proliferation
Track 8. Commissioning, Operation and Decommissioning
Track 9. Education, professional development and knowledge management

and Special Session on IAEA ongoing CRPs

FR22: 365 Contributions
680 Registered participants
~120 in-person

FR22 Proceedings in preparation, expected Q2 2023

IAEA Coordinated Research Projects on FRs

The IAEA encourages and assists research on and development and practical use of atomic energy and its applications for peaceful purposes throughout the world. It brings together research institutions from its developing and developed Member States to collaborate on research projects of common interest, so-called **Coordinated Research Projects** (**CRPs**).

Completed CRPs

- **PHENIX** – EOL Tests
- **MONJU** – Na Natural Convection
- Analytical and Experimental Benchmark Analysis of **ADS**
- **EBR-II** Shutdown Heat Removal Tests
- **PSFR Source Term** – Radioactive Release Under Severe Accident Conditions

CRPs on Fast Reactors Technology

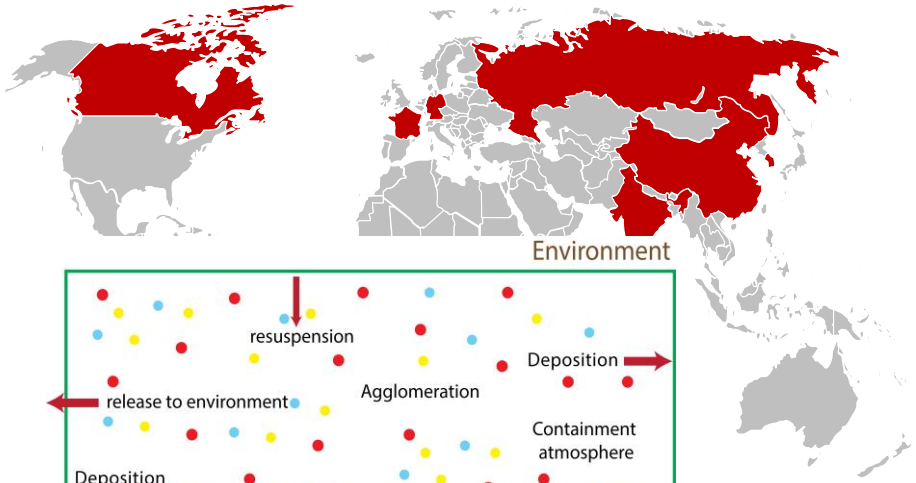
On-going CRPs

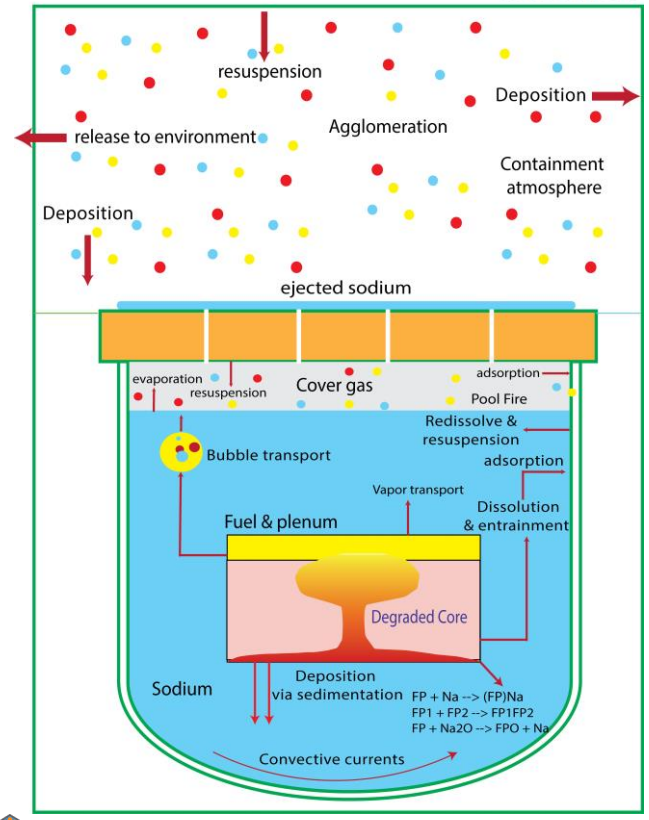
- **NAPRO** – Na Properties and Safe Operations of Exp. Facilities
  Ended in Sept 2018
  2 TECDOCs in Publishing
- Neutronics Benchmark of **CEFR** Start-Up Tests
- Benchmark Analysis of **FFTF** Loss of Flow Without Scram Test
- Natural Circulation in LBE Sub/Assembly: **NACIE** Tests

New Proposals

- Total Instantaneous Blockage of SFR Fuel Assembly
- Simulation of **CLEAR-S** Loss-of-Flow Experiment
- Benchmark Analysis of **STELLA-2** LOHS/LOF Tests
- **PLANDTL**: Decay Heat Removal Thermal Hydraulics Tests

CRP on Radioactive Release from Prototype SFR under Severe Accident Conditions (2016-2020): Summary





Reference design for the safety analysis:
500 MW(e) pool type **PFBR**

CRP on "Radioactive Release from the PSFR under Severe Accident Conditions"	
~~*Canada (UOIT)*~~	China (*CIAE*, *NCEPU, XJTU)*
France (~~IRSN~~, CEA)	~~Germany, (KIT)~~
India, IGCAR	Korea, Republic of, KAERI
Russia (~~IPPE~~, IBRAE)	Spain (CIEMAT)
Japan (~~NRA~~, JAEA)	US (*TerraPower)*

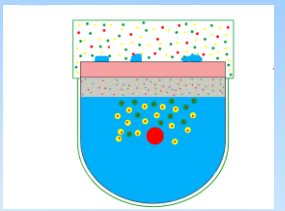
* Japan JAEA joined in 2019 (SIMMER-IV code)

- 1st RCM: Vienna, May 2016
- 2nd RCM: IGCAR, November 2017
- 3rd RCM: Vienna, April 2019
- 4th RCM: Vienna, February 2020

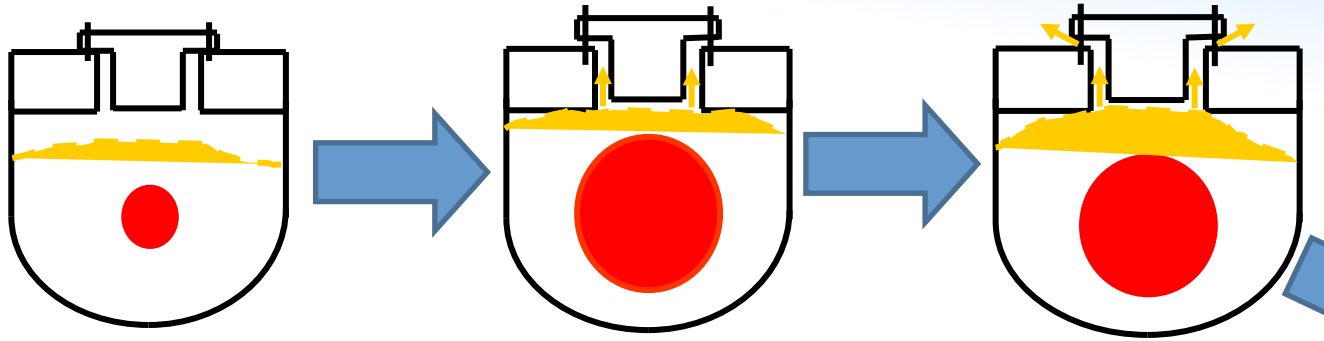
- CRP is completed
- TECDOC is published:

https://www-pub.iaea.org/MTCD/publications/PDF/TE-2006web.pdf

CRP on Radioactive Release from Prototype SFR under Severe Accident Conditions (2016- 2020)



CDA development and propagation in pool type SFR

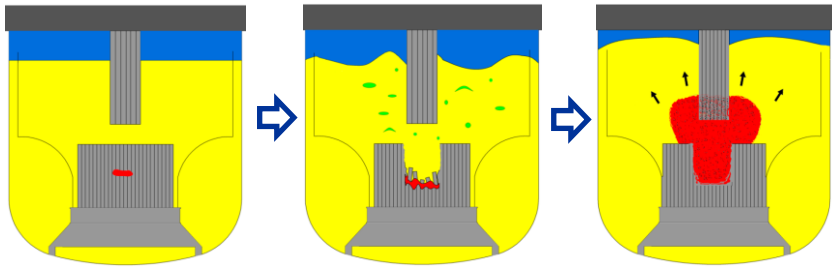


Initiation *(neutronics), and* ***Transition*** *(fuel relocation) Phases*

Core Melt/Bubble is formed

I. *Expansion Phase*

Core bubble expands in sub-cooled sodium



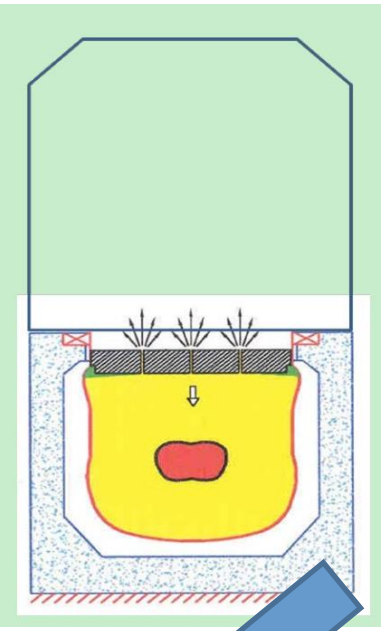
Incipient melting and early relocation

Extended relocation and core compaction

Rapid fuel vapor bubble expansion

II. *Quasi-static Phase*

Release of sodium to the Reactor Containment Building (RCB)



Reference design for the safety analysis:
500 MWe pool type PFBR

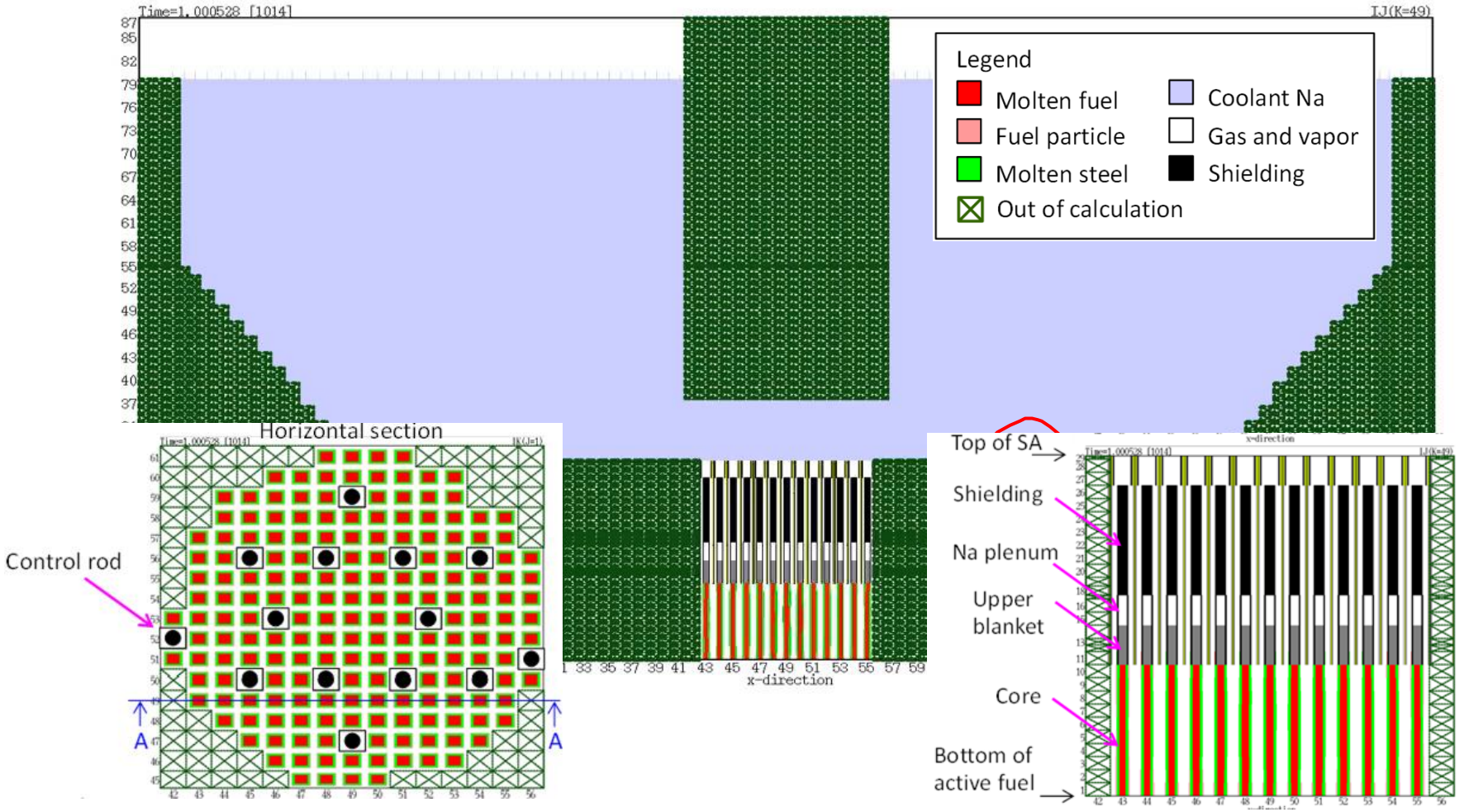
Very complicated multi-physics phenomenon
Can be a Standard Benchmark for Verification of Safety Analysis Codes and Models

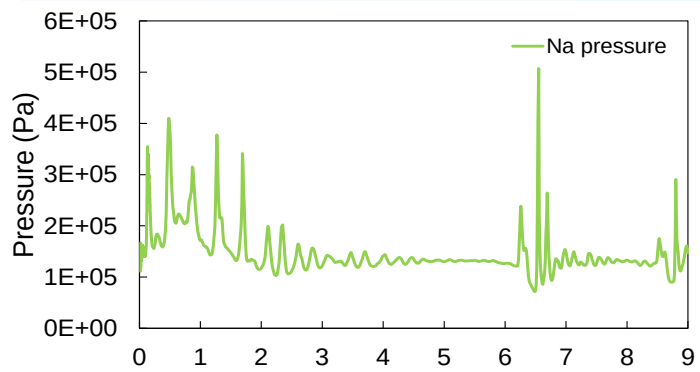
III. *Containment Source Term*

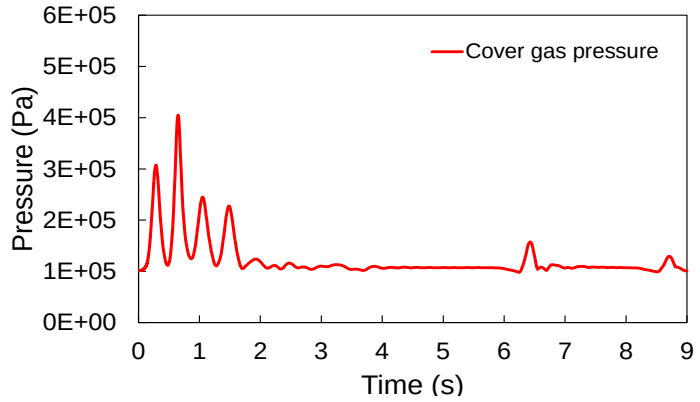
- Evaluation of multi-component aerosol evolution is required
- Two typical sodium fire accidents:
- *sodium pool fire accident*
- *sodium spray fire accident*

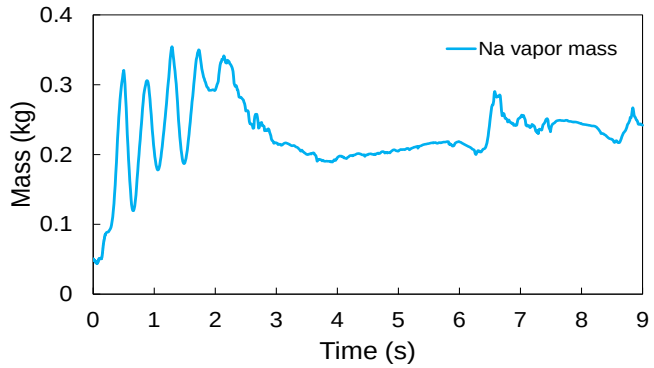
CRP on Radioactive Release from Prototype SFR under Severe Accident Conditions (2016- 2020): Expansion Phase

Click to play SIMMER-IV Video
(provided by JAEA)







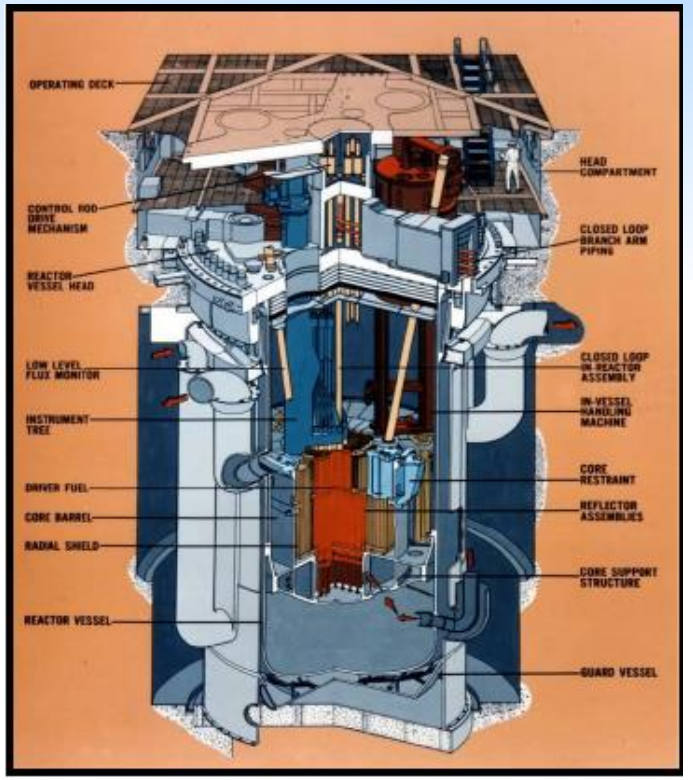


WP-1. *Sodium Bubble Expansion Phase*

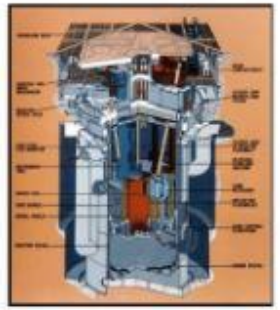
CRP: **Benchmark Analysis of FFTF Loss of Flow Without Scram Test**

- FFTF (Fast Flux Test Facility) Reactor:
  - 400 MW_{th} sodium cooled fast test reactor
  - Mixed UO_2-PuO_2 (MOX) fuel
  - Loop type plant, axial and radial reflectors
  - Prototypic size
    - ~1m^3 core volume
    - ~91 cm high, ~120 cm diameter
  - Built to assist development and testing of advanced fuels and materials for fast breeder reactors
  - Series of Passive Safety Tests performed in 1986
    - Unprotected transients including 13 Loss of Flow without scram tests
    - Demonstrated passive safety of SFRs
    - Demonstrated efficacy of negative reactivity insertion safety devises (Gas expansion modules - GEMs)
  - This Benchmark analysis is based on the Test number 13, which was initiated at 50 % power and 100 % flow.

24 Participating Organizations from 13 Countries

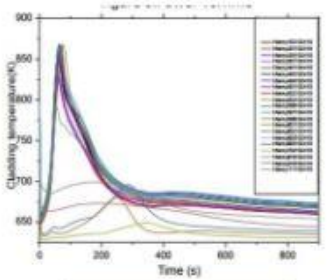


CRP: **Benchmark Analysis of FFTF Loss of Flow Without Scram Test**

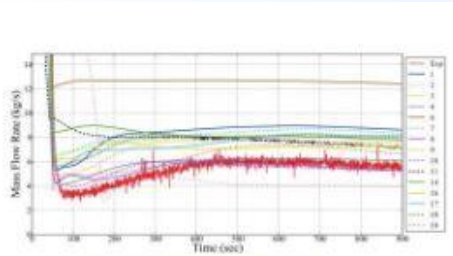


Plant Data

Modelling



Simulations



Benchmark

Kick Off: 1st RCM: October 2018, Vienna

Blind Phase Results Submissions, March 2020

Refined Simulation Submissions, November 2021

Final Simulation Results, June 2022

IAEA TECDOC Draft December 2022

Benchmark Specifications | Individual Simulations | Sharing of results and comparison with Experimental Data | Publication

1st Virtual Informal OM: October 2019, Vienna

2nd Virtual Informal OM: October 2020, Vienna

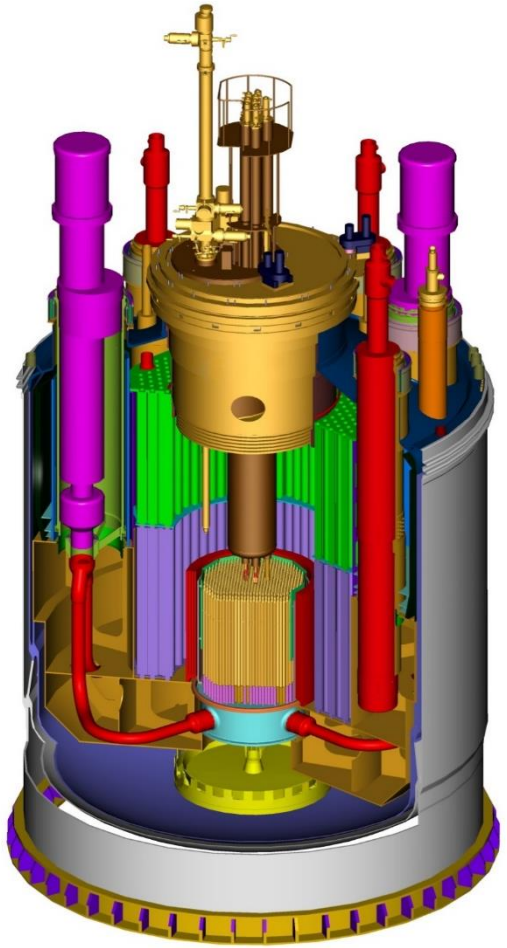
2nd RCM: December 2021, (virtual)

3rd RCM: November 2022, Italy

CRP: Neutronics Benchmark of CEFR Start-Up Tests

CEFR (China Experimental Fast Reactor)

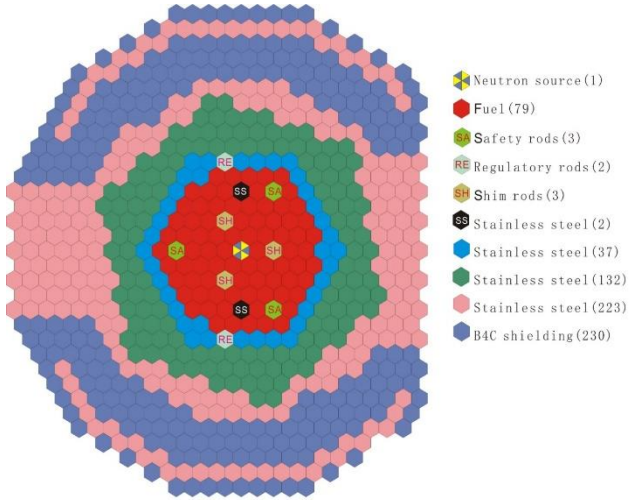
- Located in China Institute of Atomic Energy
- 65MWt (20MWe) sodium cooled fast reactor with a high neutron leakage core fuelled with uranium oxide and stainless-steel radial reflector.
- The primary system is a pool-type design, liquid sodium working fluid for the primary and secondary circuits.
- In 2010, CEFR went into first criticality.
- A series of start-up experiments were carried out to measure reactor physics and kinetics parameters.
- **6 experiments were selected for benchmark analysis**
  - evaluations of the criticality, control rod worth, sodium void worth, temperature effect reactivity, and various reaction rates.
- This CRP provides an excellent opportunity to the member states for validation of the physical models and neutronics simulation codes by comparing the calculated results to the recorded experimental data from the CEFR start-up tests.



CEFR Reactor Block

中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

China Experimental Fast Reactor Plant



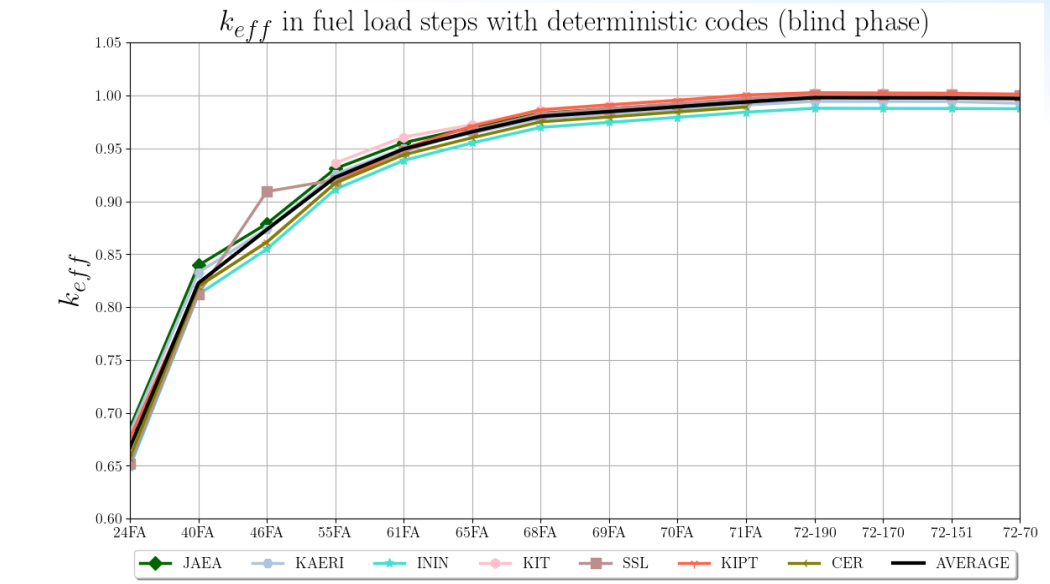
Core layout of the CEFR First Loading

CRP: Neutronics Benchmark of CEFR Start-Up Tests

WP1	Net criticality
WP2	Control Rod Worth
WP3	Temperature reactivity coefficient
WP4	Sodium void reactivity effect
WP5	Core S/A exchange reactivity effect
WP6	Reaction rate distribution
WP7	Reactivity coefficients and kinetic parameter
WP8	Analysis of Uncertainties

Separate TECDOC

WP1. Net criticality

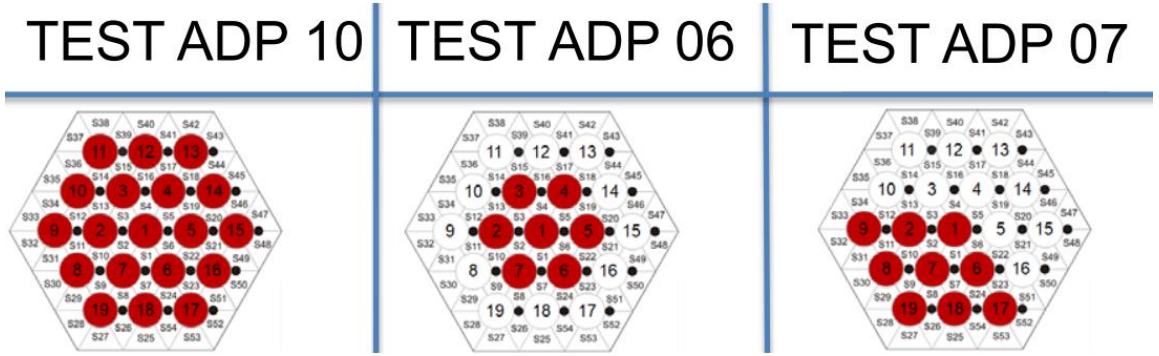


Country	Organization
Belgium	SCK•CEN
China	CIAE
China	INEST (FDS)
China	~~SNERDI~~
China	XJTU
Finland	VTT
France	CEA
Germany	HZDR
Germany	GRS
Germany	KIT
Hungary	~~BME~~
Hungary	CER
India	IGCAR
Italy	NINE
Italy	UNIPI
Japan	JAEA
Korea, Rep. of	KAERI
Korea, Rep. of	UNIST
Mexico	ININ
Romania	RATEN-ICN
Russia	~~IBRAE~~
Russia	IPPE
Russia	SSL
Russia	Kurchatov Ins. (NRCKI)
Slovakia	VUJE
Switzerland	PSI
Ukraine	KIPT
UK	Un. of Cambridge
United States	ANL
United States	NRC

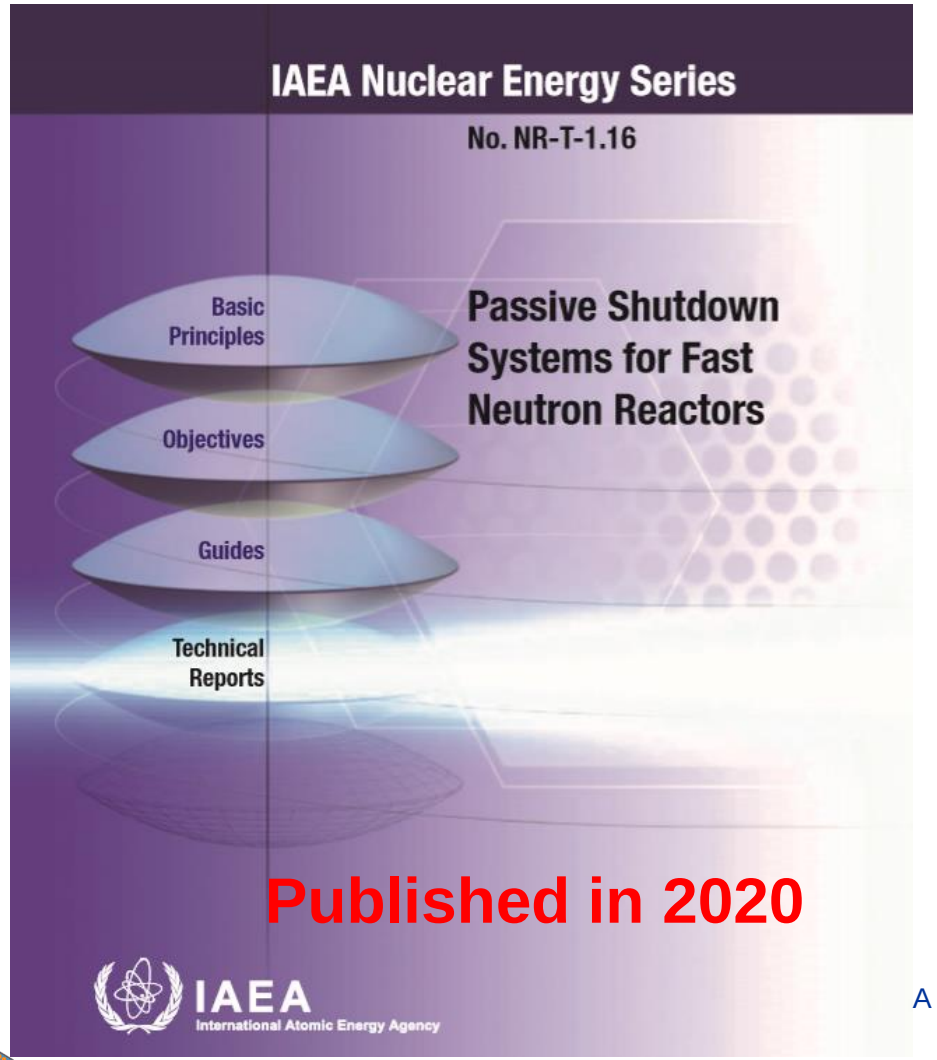
30 Participating Organizations from 18 Countries

CRP: **Benchmark of Transition from Forced to Natural Circulation Experiment with Heavy Liquid Metal Loop**

- The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) proposed this CRP to TWG-FR 2020. ENEA operates the Natural Circulation Experiment Upgrade (NACIE-UP) facility:
  - Rectangular LBE flow loop
  - Containing a wire spaced 19 pin fuel pin simulator
  - Operating up to 250 kW for qualification and instrumentation testing.
- **Objective**: Validation of computational fluid dynamics (CFD), subchannel, and system analysis codes for heavy liquid metal systems.
- 22 proposals received
- **1st RCM 12-15 July 2022**
- **TECDOC publication – Mid 2025**



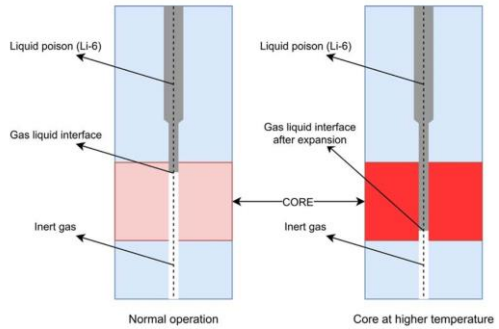
NES: Passive Shutdown Systems for Fast Neutron Reactors



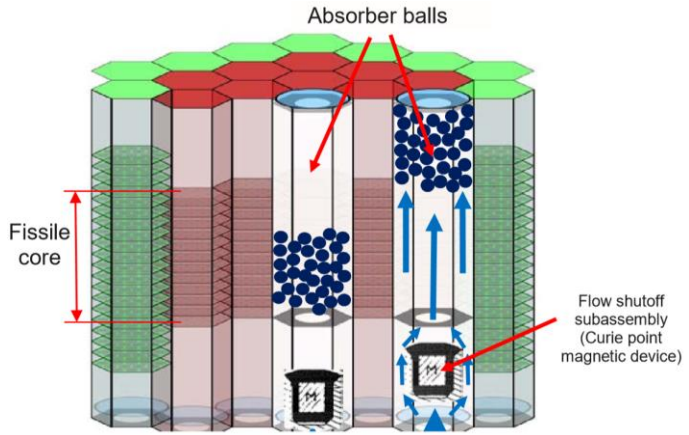
Published in 2020

Click to access: https://www.iaea.org/publications/13386/passive-shutdown-systems-for-fast-neutron-reactors

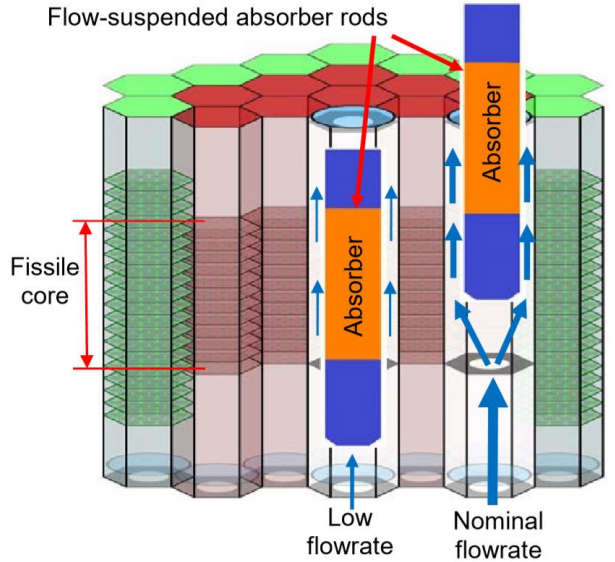
- Lithium expansion modules
- Lithium injection modules
- Curie point latches
- Thermostatic switches
- Lyophobic capillary porous systems
- Flow levitated absorbers
- Cartesian divers
- Levitated absorber particles
- Enhanced thermal elongation of control rod drivelines
- Gas expansion modules
- Autonomous reactivity controls
- Travelling wave reactor thermostats
- Thermo siphon based passive shutdown systems
- Static absorber feedback equipment



Lithium expansion module concept



A levitated absorber system for self-actuated shutdown system



Passive shutdown system with flow levitated rods for BN-800

TM on Benefits and Challenges of Fast SMRs

Country	Participants /Papers
Belgium	4/1
China	2/2
France	1/1
Germany	2/0
India	1/1
Italy	13/5
Japan	3/2
Korea, Rep. of	2/3
Luxembourg	1/1
Netherlands	1/1
Russia	3/2
Slovakia	1/0
Switzerland	1/1
Sweden	1/1
USA	1/1
EC/JRC	3/1
Total: 16	**40/23**

24-27 September 2019, Milan, Hosted by CIRTEN: Consortium of Italian Nuclear Universities

Six Technical Sessions:

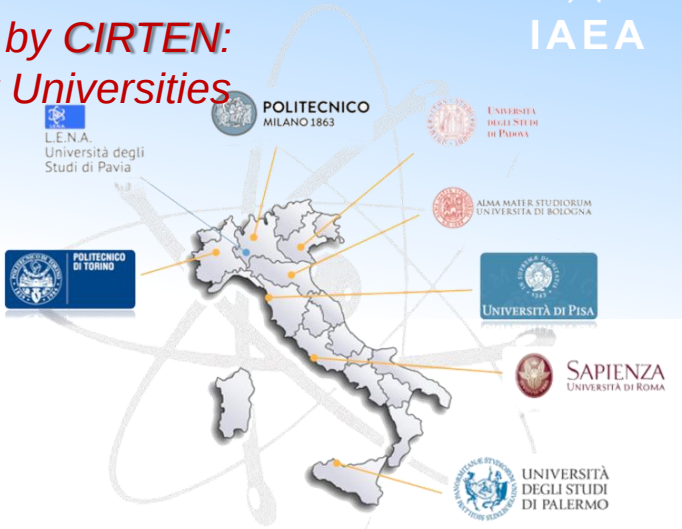
- Sodium Cooled Fast SMRs
- Heavy Liquid Metal Cooled Fast SMRs
- Safety Investigations
- Technology and Research in Support of Fast SMRs

Three Group Discussions:

- In-factory construction
- Benefits of Fast SMRs including market needs
- Technological Challenges

TECDOC Proceedings to be published in 2020

TECDOC published in 2021



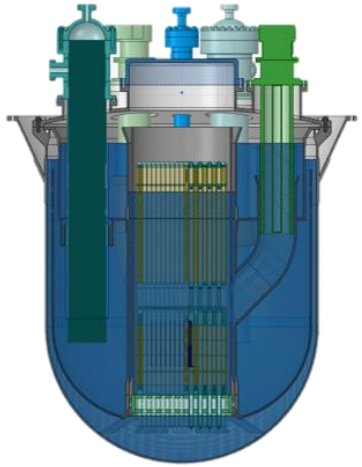
Thanks to advanced coolants, Fast SMRs can be safer and of simplified design

BUT:

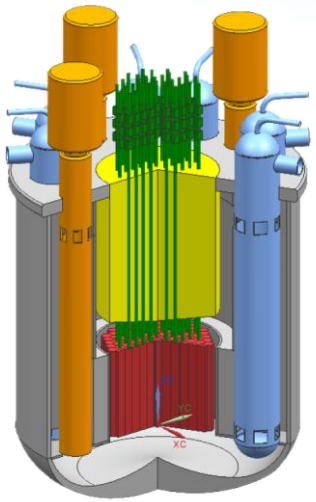
- Fast construction (in- factory) is required to win economic competition;
- Extended R&D are needed to fit technological gaps
- LFRs require more R&D to prove material compatibility and develop new materials
- Licensing challenges

Liquid Metal cooled Fast SMRs

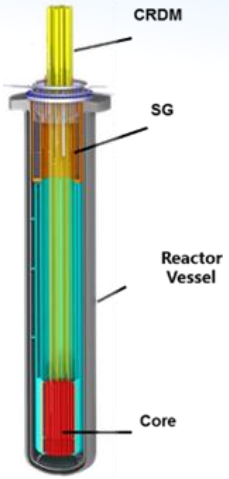
Latest reactor designs presented at TM on Fast SMRs in Milan, Sep 2019



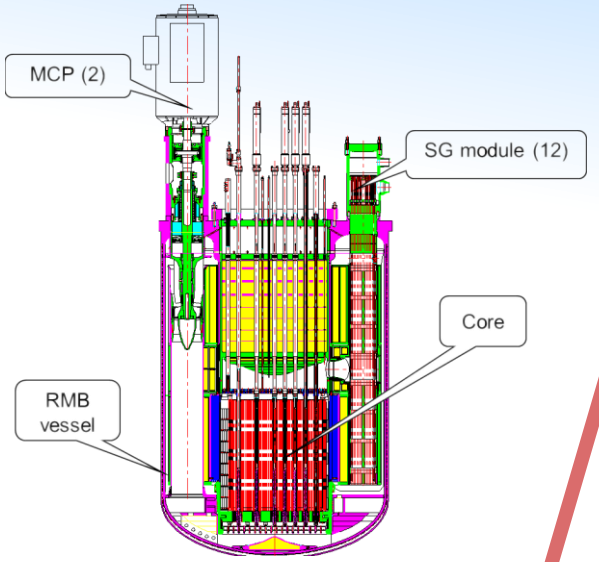
ALFRED
125-250 MW(e)
EU



CLFR-300
China

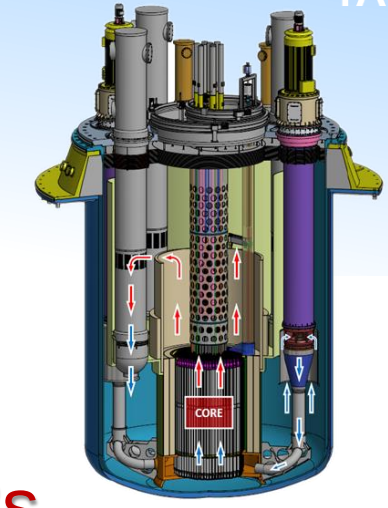


14 MW(e) CLEAR-M10d
China



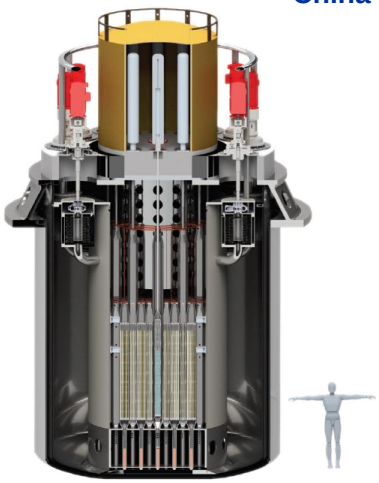
СВБР-100 (LBE)
Russia

SFRs

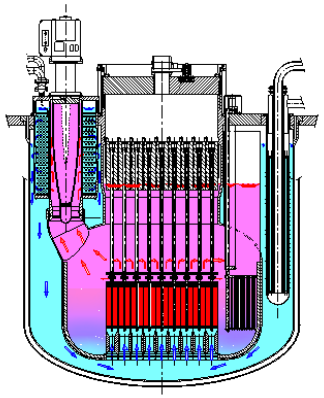


150 MW(e) PGSFR
Rep. of Korea

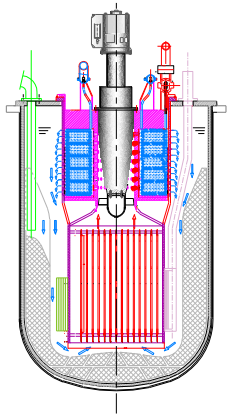
3-10 MW(e) SEALER
Sweden



55 MW(e) SEALER-UK
Sweden

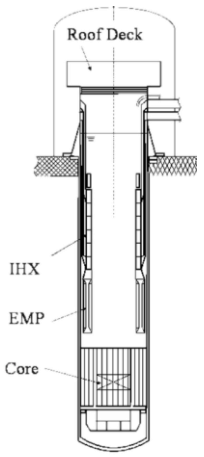


LFR-AS-200 MW(e)
Luxembourg

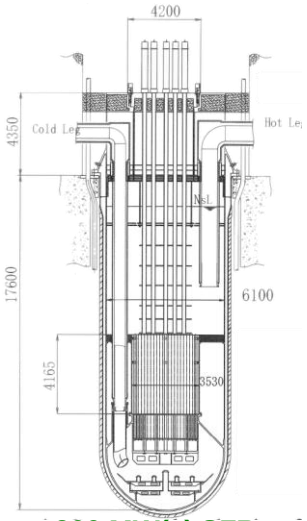


Transportable LFR-TL-5 MW(e)
Luxembourg

LFRs



50 MW(e) SMFR
Japan



300 MW(e) SFR
Japan

TM on Structural Materials for Heavy Liquid Metal Cooled Fast Reactors

Country	Participants /Papers
Belgium	2/1
China	7/4
Czech Rep.	3/1
Germany	1/1
Italy	5/3
Korea, Rep. of	4/1
Luxembourg	1/0
Netherlands	1/0
Romania	2/2
Russia	3/3
Slovakia	1/1
Sweden	2/1
UK	1/0
Ukraine	1/1
EC/JRC	1/1
Total: 14	**34/20**

Three Technical Sessions:

- HLM Compatibility with Structural Materials
- Corrosion Mitigation Measures
- Qualification Programmes of Structural Materials

Three Group Discussions:

- Outstanding Research Challenges
- New Materials and Coating Techniques
- Technology Readiness

15-17 October 2019, Vienna

TECDOC Proceedings published in September 2021

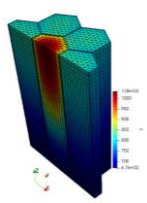
Free download

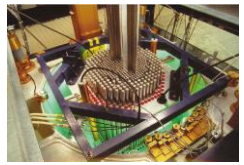
Technical Meetings on

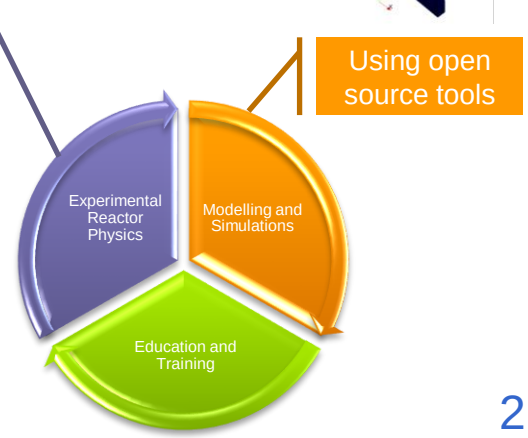
State-of-the-art Thermal Hydraulics of Fast Reactors
&
Development and Application of Open Source Modelling and Simulation Tools for Nuclear Reactors

26-30 September 2022
C.R. ENEA, Lago Brasimone, Italy

20-24 June 2022
Milano, Italy







Fast Reactors Safety: Joint GIF-IAEA Workshops on Safety of LMFRs

A decade of cooperation

1st : June 2010
2nd : Dec 2011
3rd : Feb. 2013
4th : June 2014
5th : June 2015
6th : Nov. 2016

7th Joint GIF-IAEA Workshop on LMFR Safety

March 2018

8th GIF-IAEA Workshop on LMFR Safety

20-22 March 2019

9th GIF-IAEA Workshop on LMFR Safety

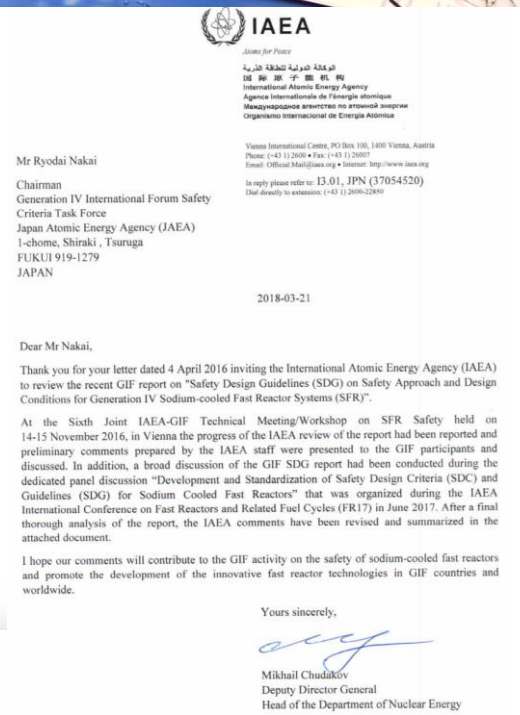
30 March - 01 April 2021

- Review of GIF Report on "Safety Design Guidelines on Structures, Systems and Components for Gen-IV SFRs"
  - Discussion of review comments

10th GIF-IAEA Workshop on LMFR Safety

28 June – 1 July 2022

- Organized by NSNI



IAEA

Atoms for Peace

Mr Ryodai Nakai

Chairman
Generation IV International Forum Safety
Criteria Task Force
Japan Atomic Energy Agency (JAEA)
1-chome, Shiraki , Tsuruga
FUKUI 919-1279
JAPAN

2018-03-21

Dear Mr Nakai,

Thank you for your letter dated 4 April 2016 inviting the International Atomic Energy Agency (IAEA) to review the recent GIF report on "Safety Design Guidelines (SDG) on Safety Approach and Design Conditions for Generation IV Sodium-cooled Fast Reactor Systems (SFR)".

At the Sixth Joint IAEA-GIF Technical Meeting/Workshop on SFR Safety held on 14-15 November 2016, in Vienna the progress of the IAEA review of the report had been reported and preliminary comments prepared by the IAEA staff were presented to the GIF participants and discussed. In addition, a broad discussion of the GIF SDG report had been conducted during the dedicated panel discussion "Development and Standardization of Safety Design Criteria (SDC) and Guidelines (SDG) for Sodium Cooled Fast Reactors" that was organized during the IAEA International Conference on Fast Reactors and Related Fuel Cycles (FR17) in June 2017. After a final thorough analysis of the report, the IAEA comments have been revised and summarized in the attached document.

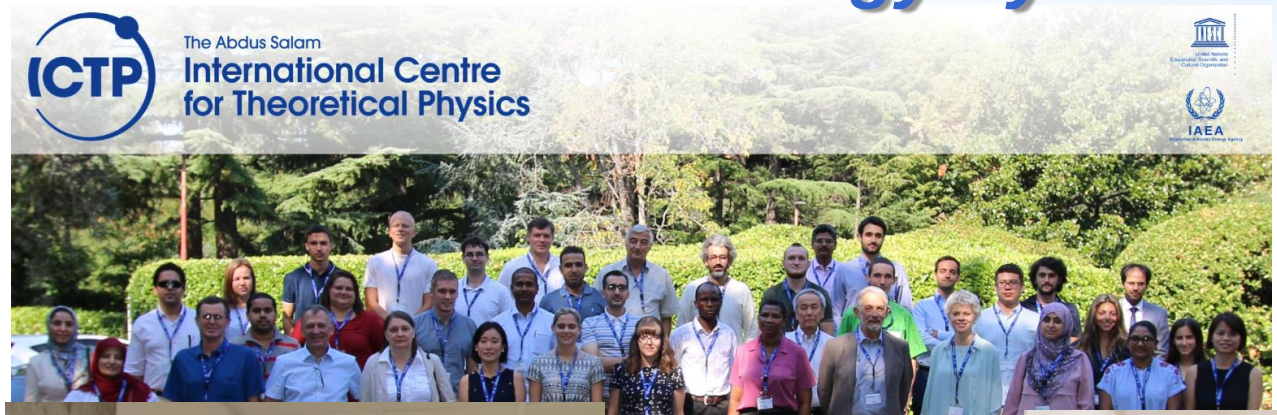
I hope our comments will contribute to the GIF activity on the safety of sodium-cooled fast reactors and promote the development of the innovative fast reactor technologies in GIF countries and worldwide.

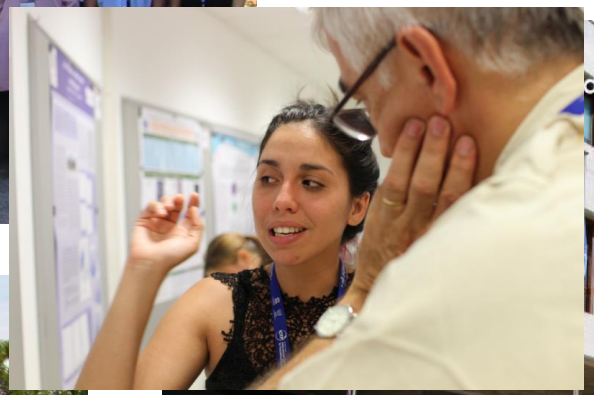
Yours sincerely,

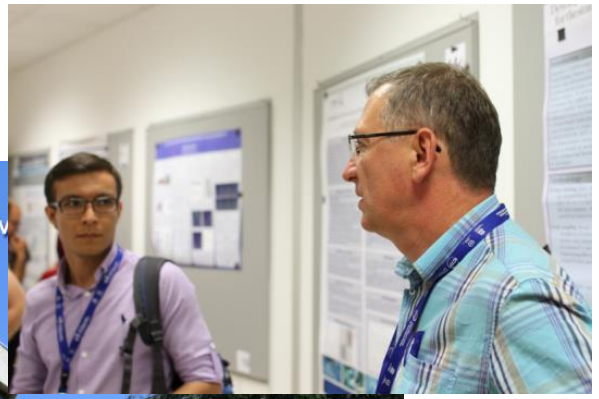
Mikhail Chudakov
Deputy Director General
Head of the Department of Nuclear Energy

Joint ICTP-IAEA Workshops on Innovative Nuclear Energy Systems

- In **2016, 2028 and 2022** in Trieste, Italy
- Contributed by NPTDS, INPRO, GIF, and other external experts



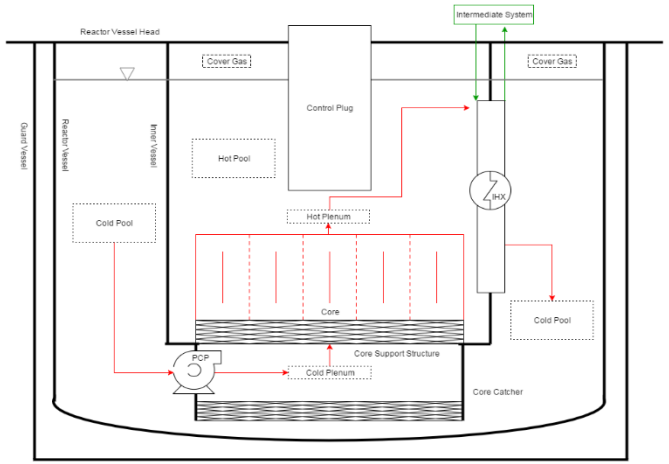


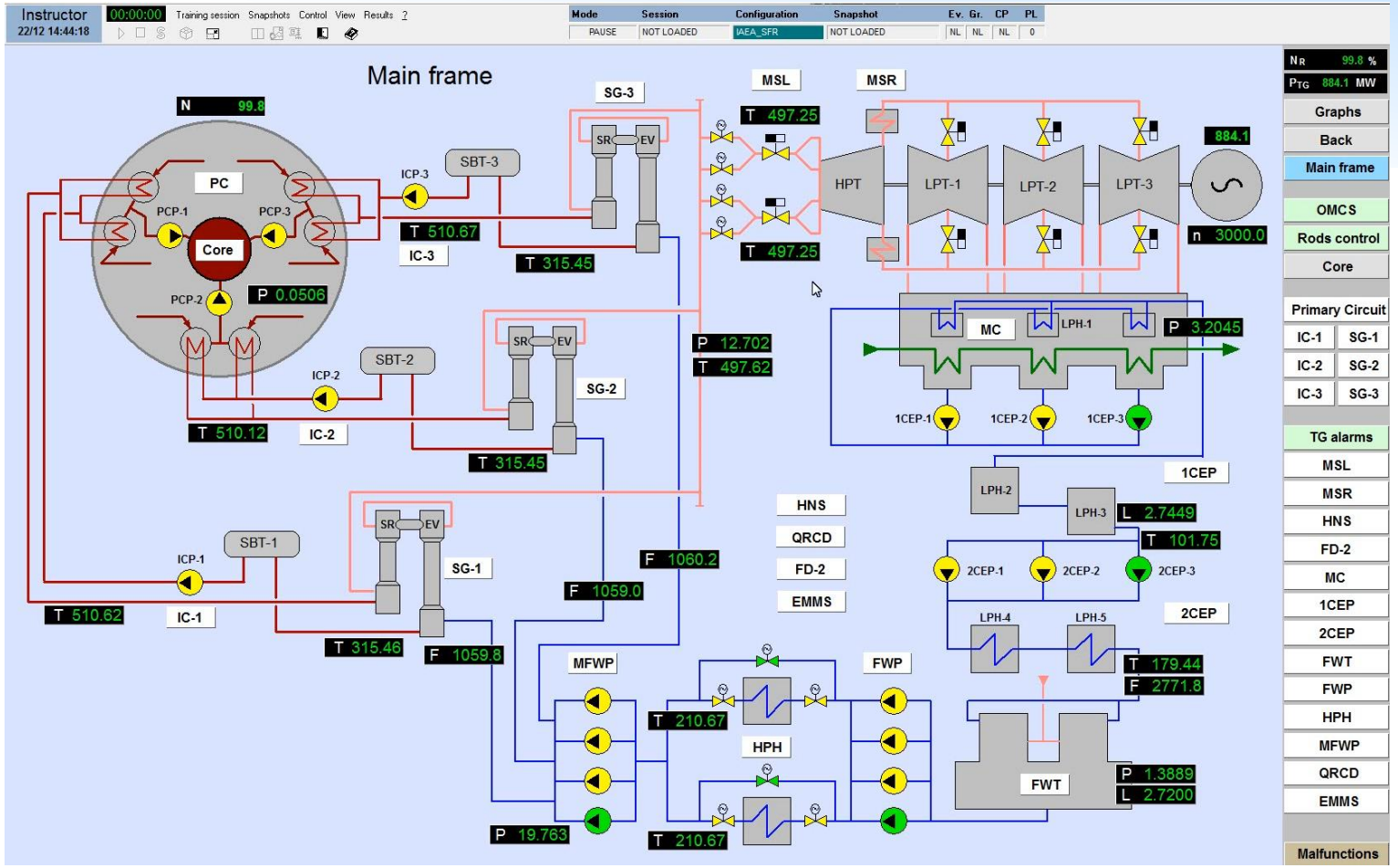


29 August - 2 September 2016
Miframare, Trieste

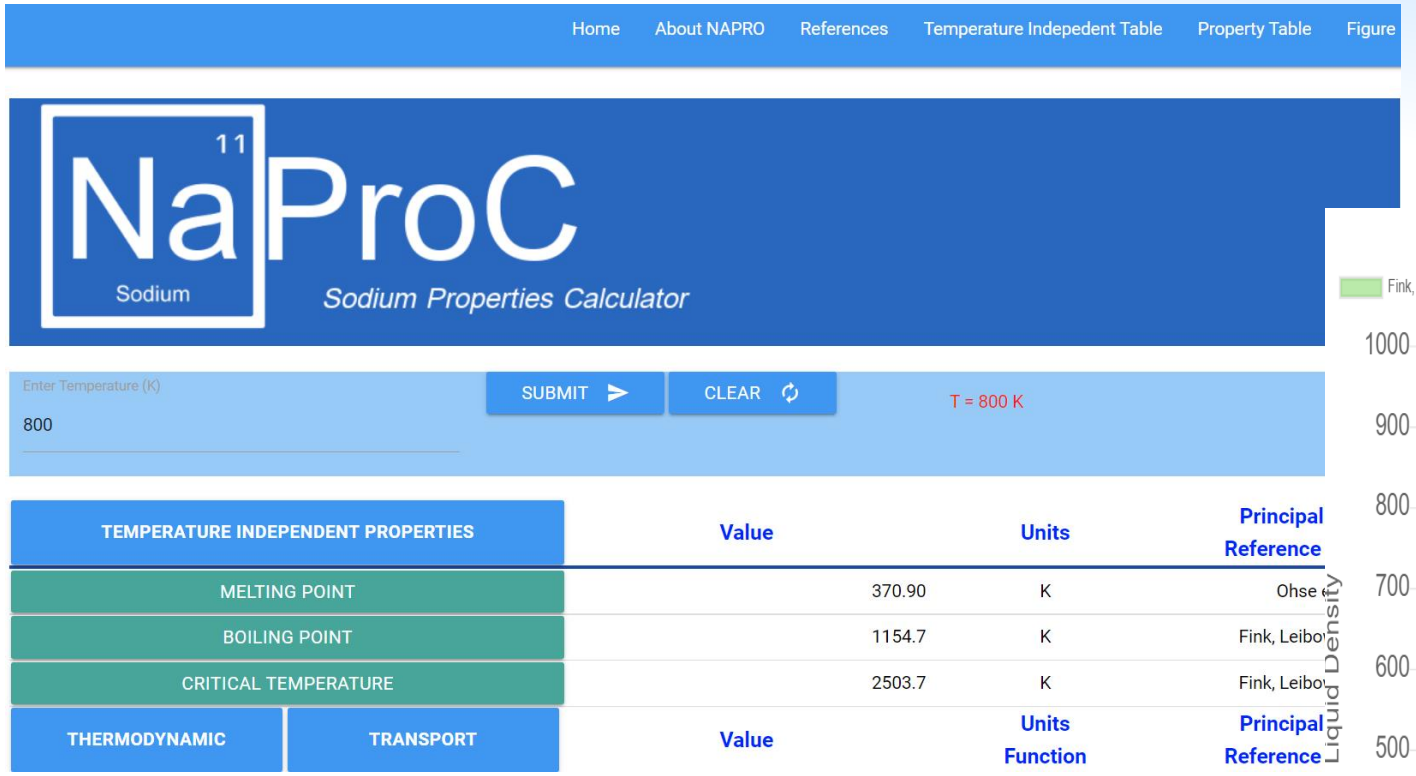
SFR Educational Simulator

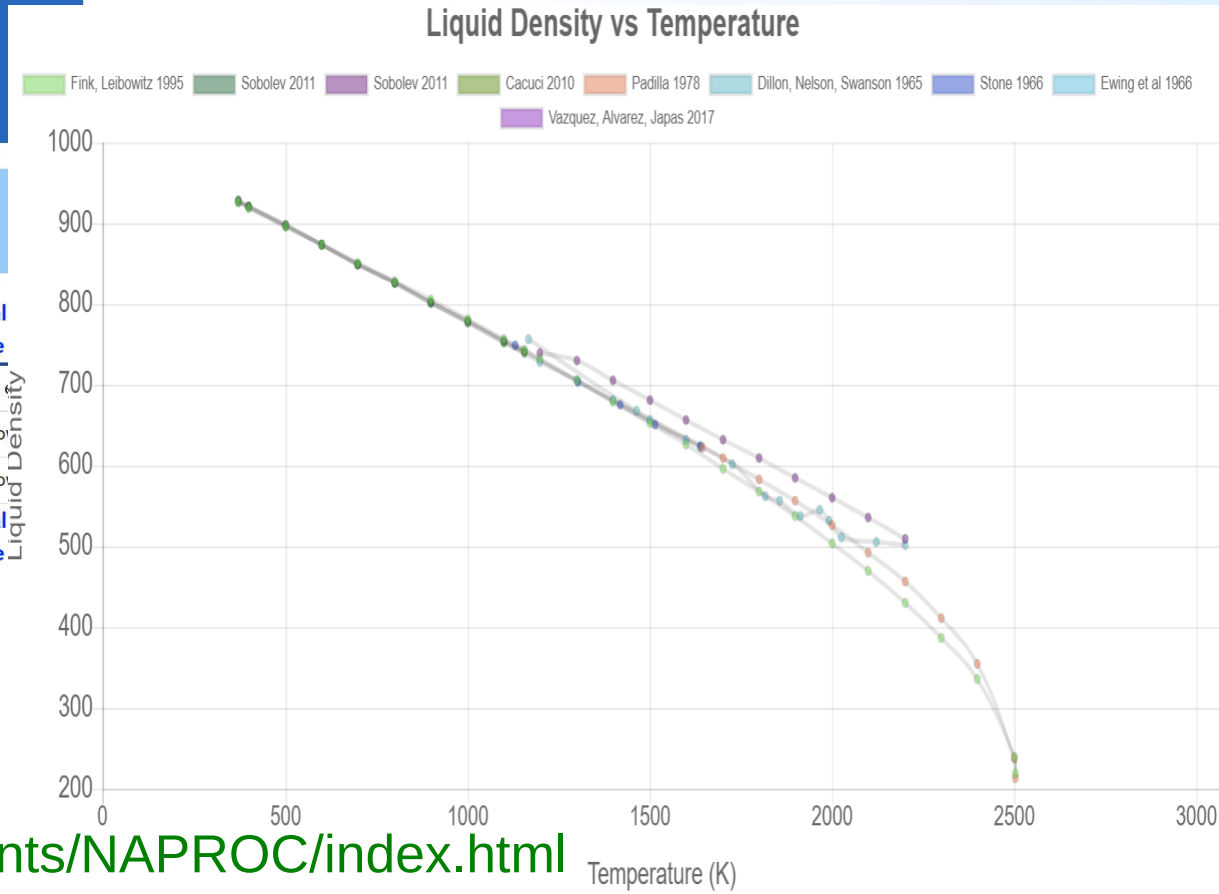
- Pool type sodium cooled fast reactor simulator for education and training
- February 2021: Factory Acceptance Tests
- January 2022: Site Acceptance Test
- **2023: Distribution to Member States**





NAPRO: Sodium Properties Calculator





https://nucleus.iaea.org/sites/fr/Shared%20Documents/NAPROC/index.html

Main IAEA Activities on Fast Reactor Technology in 2021 - 2022

- CRPs/Benchmarks/Studies
  - Completed
    - NAPRO (2013 – 2018, in publishing)
    - PSFR Source Term (2016 – 2020, just published)
  - 3 Ongoing CRPs:
    - CEFR Start-Up Tests (2018 - 2022)
    - FFTF ULOF Test (2018 - 2022)
    - NACIE (2022-2026): Benchmark of Transition from Forced to Natural Circulation Experiment with Heavy Liquid Metal Loop
  - New CRPs proposals (to start in 2023+):
    - PLANDTL: PLANt Dynamics Test Loop Decay Heat Removal Thermal Hydraulics Tests
    - Modelling of Total Instantaneous Blockage of SFR F/A (Delayed)
    - Benchmarking LOF transient test in CLEAR-S HML Pool Facility (Delayed)
    - Benchmark Analysis of **STELLA-2** LOHS/LOF Tests
    - Thermal-hydraulic simulations of a high temperature helium facility S-Allegro
  - Benefits and Challenges of Fast SMRs (published in 2021)
  - Structural Materials for HLM Reactors (published in 2021)
  - TM on Development and Application of Open-Source Modelling and Simulation Tools for nuclear Reactors in June 2022
  - TM on State-of-the-art Thermal Hydraulics of Fast Reactors: ENEA Brasimone in September 2022

- Technical Working Group on Fast Reactors
  - 54th TWG-FR Meeting (Virtual), June 2021
  - 55th TWG-FR Meeting (Hybrid), May 2022
- Joint IAEA-GIF Workshops on LMFR Safety
  - 9th GIF-IAEA Workshop on LMFR Safety (2021)
  - 10th GIF-IAEA Workshop on LMFR Safety (2022)
- Basic Principles SFR Simulator
  - Factory Acceptance Test: 2021
  - Site Factory Acceptance Test: Jan 2022
  - Distribution to Member States: 2023
  - Training Course: 2023
- Training Courses and Workshops
  - Joint ICTP-IAEA Workshops on the Physics and Technology of Innovative Nuclear Energy Systems Trieste; December 2022
  - Regional Workshop on Advances in Modelling & Simulation of Thermal Hydraulics in LMFRs, India, November 2022
- Webinars
  - Repurposing sites of retired fossil plants with advanced nuclear reactors for clean energy transition; May 2022, available online
  - Multi-physics modelling and simulation of nuclear reactors using OpenFOAM (12 Lectures), Aug-Oct 2022, available online

IAEA
International Atomic Energy Agency

Atoms for peace and Development…

Thank You!

email: FR@IAEA.ORG