Karlsruhe Institute of Technology

Research Activities on Advanced Nuclear Reactors at KIT

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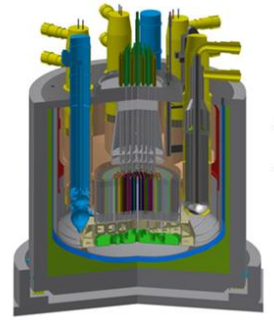
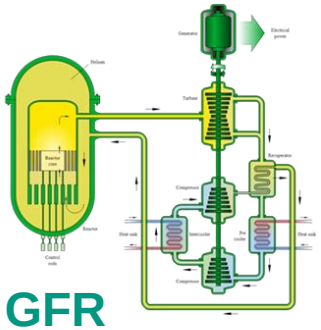
03.06.2025

Our Goal

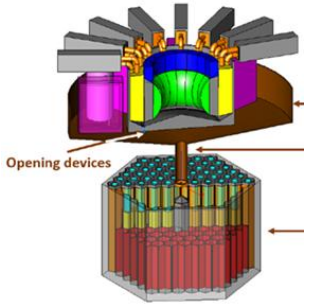
- Simulation tools to design and assess Advanced Nuclear Systems.
  - Understand the fundamental phenomena
  - Implement to correct mathematical formulations and numerical solutions.
  - Validate the simulation tools and models with qualified experimental data



SFR



GFR

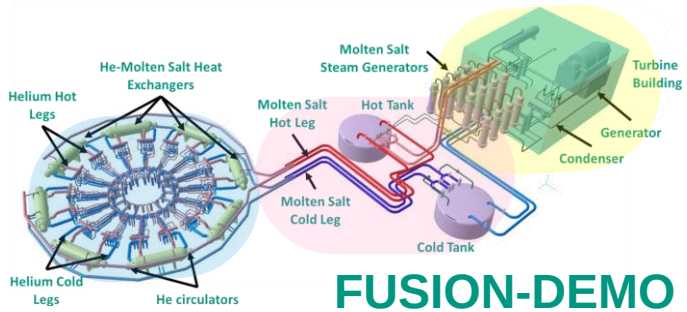


MSR

Outline

1. Basic research: experimental and theoretical research
2. Designers of experimental facilities: small, medium, large
3. Qualified experimental data to be used for code validation
4. Extension and validation of existing simulation codes.

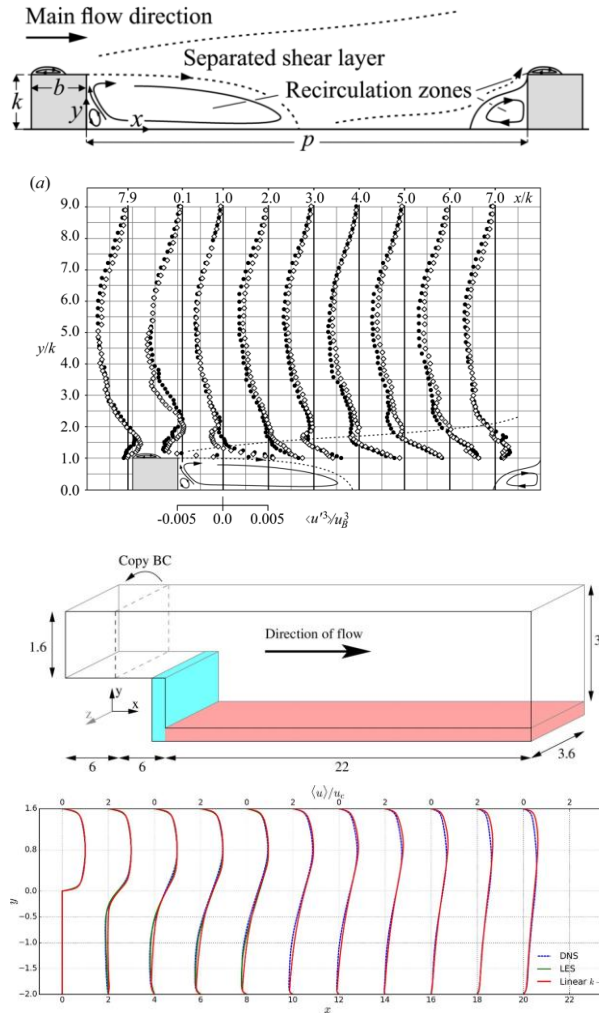
... All this applied to SFR, MSR, LFR, GFR, and FUSION PP.



FUSION-DEMO

Basic research: experimental and theoretical research

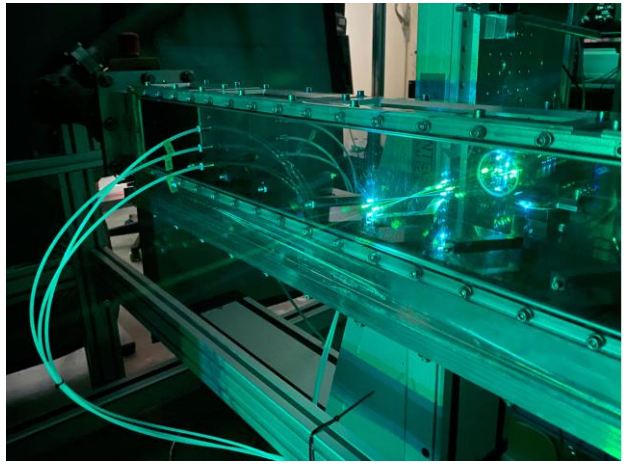
- KIT – The Research University in the German Helmholtz Association.
- Focusing not only on applications and technologies, but also on fundamental research.
- Thermal and Fluid Dynamics in liquid metals, gases and molten salts.
  - Flow characterization by means of velocity, pressure, density and temperature fields.
  - Flow interaction with structural materials at different temperatures.
- Structured surfaces subjected to high thermal loads (high heat flux densities & fluid temperatures) in cooling channels (Fusion FW/DIV), high-temperature reactor components, heat exchangers, gas-liquid recuperators, air-cooled gas turbine blades, solar receivers, etc.
- Experimental and numerical CFD-analysis of laminar and turbulent flows with heat transfer.



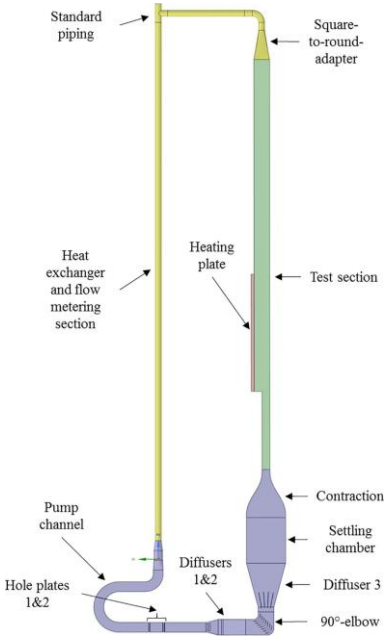
FW: First Wall; DIV: Divertor

Experimental facilities providing qualified experimental data

- Design, construction, conception and instrumentation of thermal-hydraulic test facilities with liquid metal, molten salt or conventional fluids as heat transfer medium.



AEROLAS Facility
Gas; room temperature
Laser-Doppler-Anemometry, hotwire flow velocity measurements
square channel rib-roughened by detached 60° V-shaped ribs



DITEFA 2 facility
Liquid Metal (GaInTn)
room temperature
Backward Facing Step

- Development and tests of large-scale thermal components and measurement equipment for loops with liquid sodium as heat transfer medium under high-temperature conditions, e.g. high-temperature thermal storages, CSP receivers, velocity sensors, ...

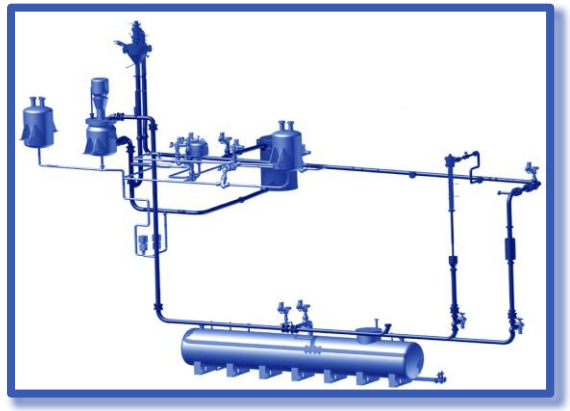
Small-scale experiments →Medium/Large-scale facilities

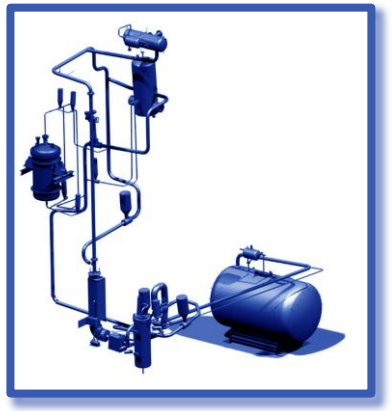
www.inr.kit.edu/english/238.php

Thermal Hydraulics and Materials Research

- Providing benchmark and reference data for CFD codes, system codes and licensing tools used for liquid metal cooled nuclear systems to the international scientific community.

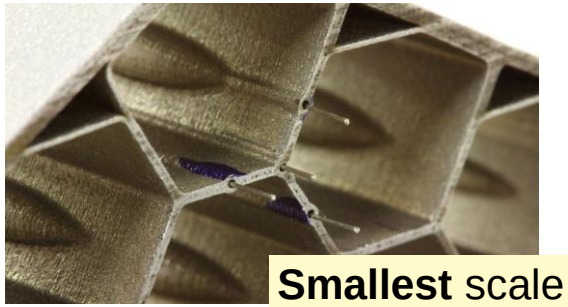
- Loop facilities
  - THEADES-KALLA: Lead Bismuth Eutectic (LBE)
  - KASOLA: Sodium
  - HELOKA-US: Molten Salt

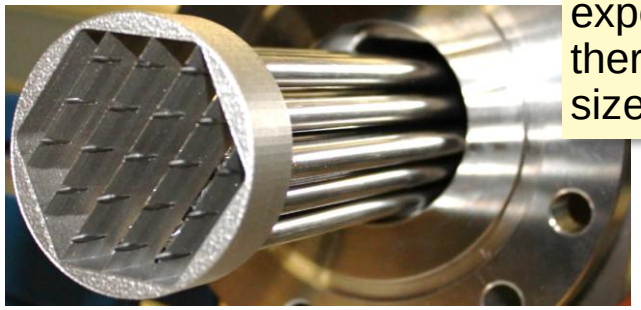




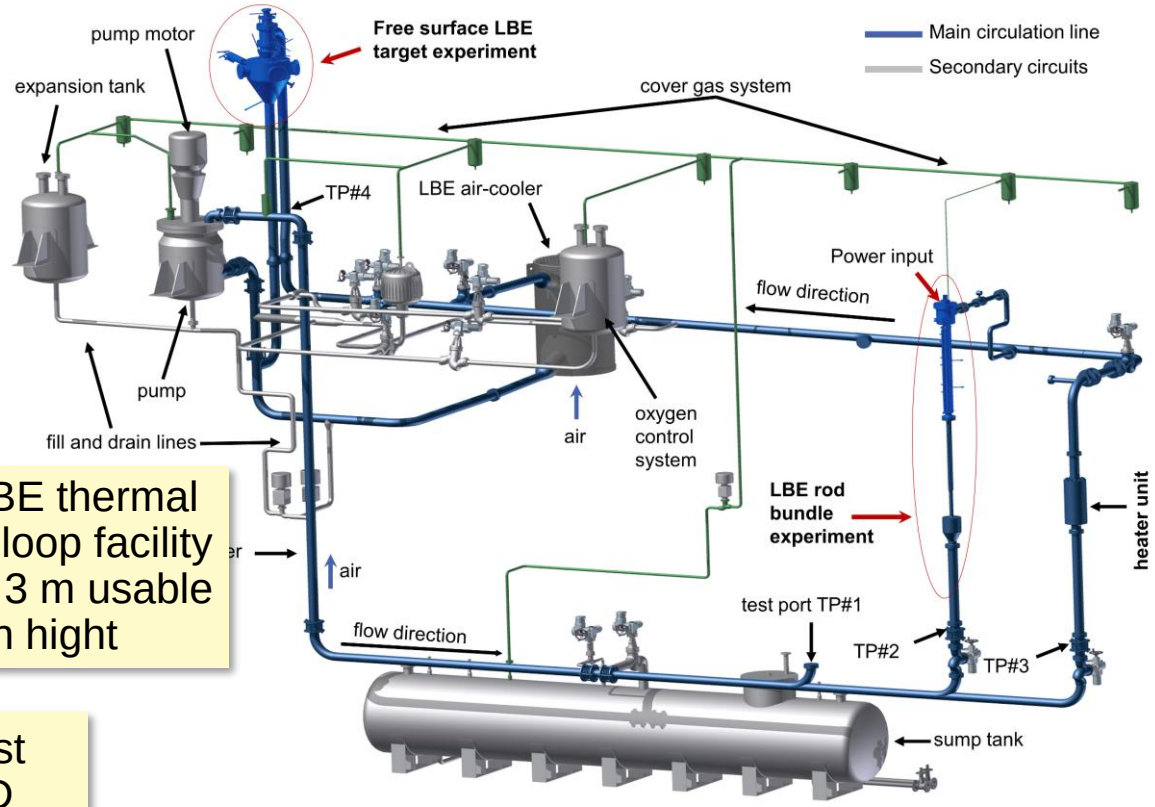
THEADES loop at Karlsruhe Liquid Metal Lab KALLA

- Inventory: 44 to Lead Bismuth Eutectic (LBE)
- Temperature: 180°C - 450°C
- Flow rate: 47 m³/h (136 kg/s) max.
- Heating power: 500 kW max.





Smallest scale in experimental setup: thermocouple tip size 0.25 mm

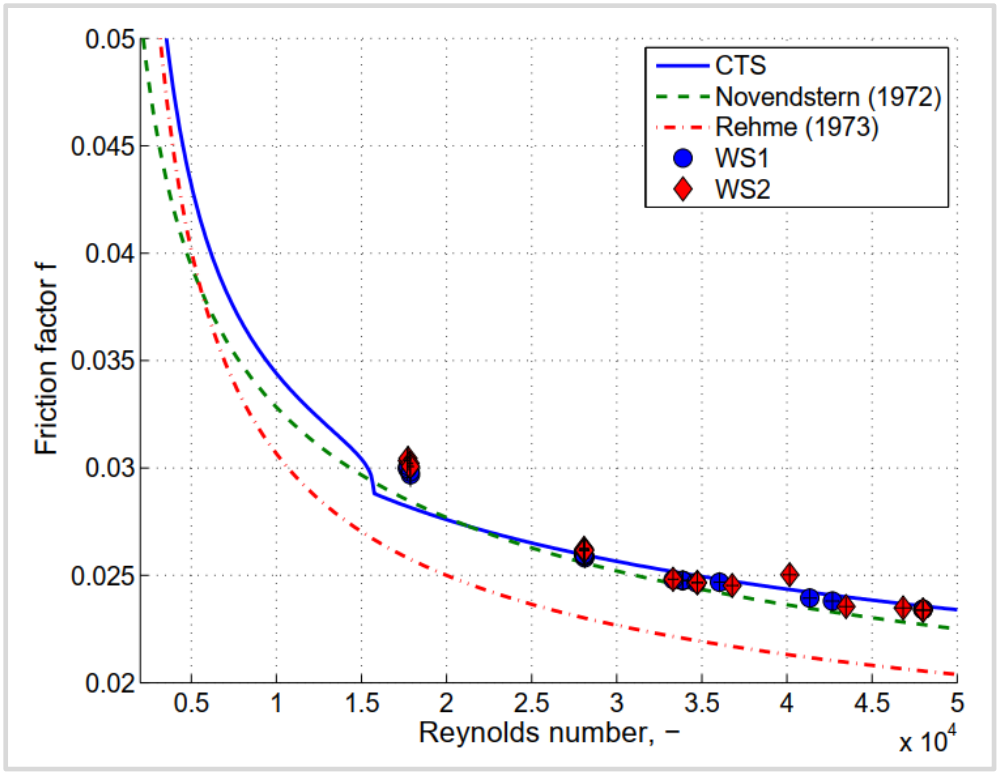


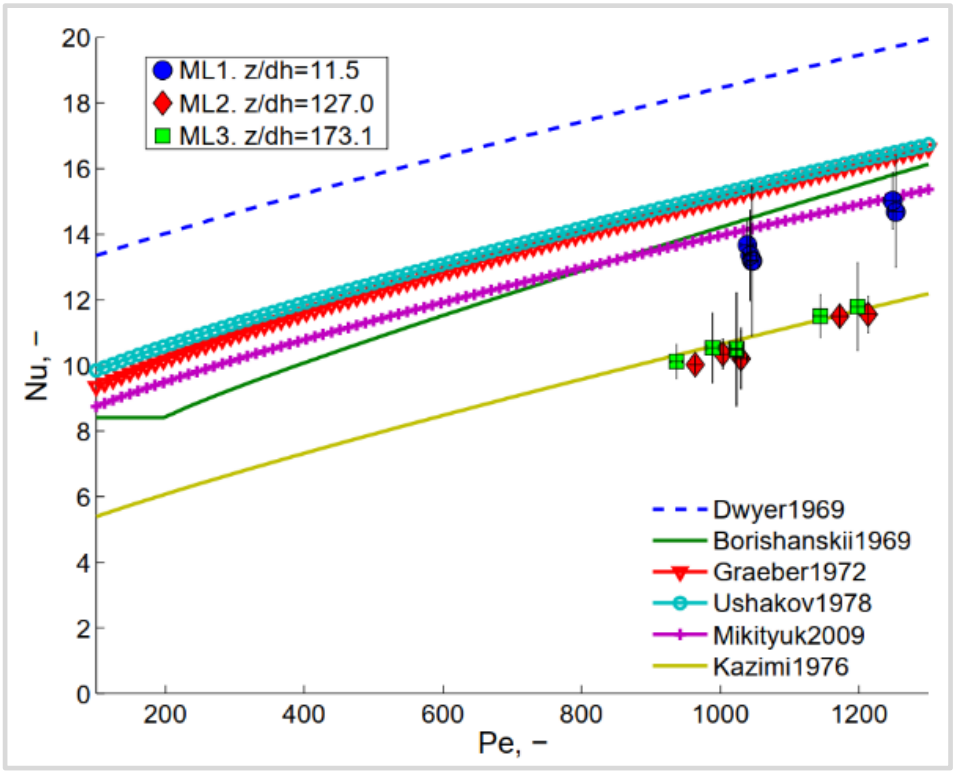
Largest LBE thermal hydraulics loop facility in Europe, 3 m usable test section hight

Prototypical test conditions AND highest precision combined.

Thermal hydraulics: LBE Wire wrapped 19 pin bundle

- Friction coefficient and Nusselt Number – Test and provision of correlations





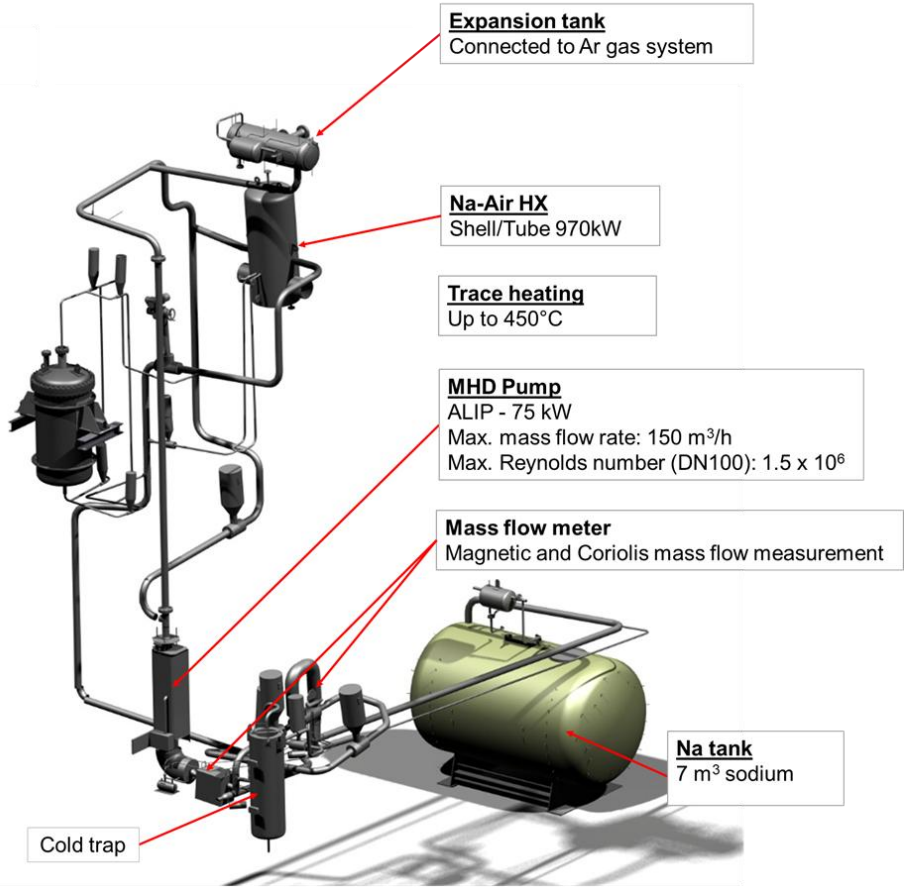
J. Pacio et al., Technical Report MAXSIMA Deliverable D3.4
J. Pacio et al., NED, https://doi.org/10.1016/j.nucengdes.2016.03.003
J. Pacio et al., NED, https://doi.org/10.1016/j.nucengdes.2018.01.034

Karlsruhe Sodium Lab KASOLA

- Inventory: 7 m³ Sodium
- Temperature: 150 - 450°C
- Flow rate: 150 m³/h
- Flexible test space: 6 x 2 x 2 m³
- Operational since: July 2024
- In-house facility and component design: Cold trap, expansion tank, sodium precipitators, plugging meter

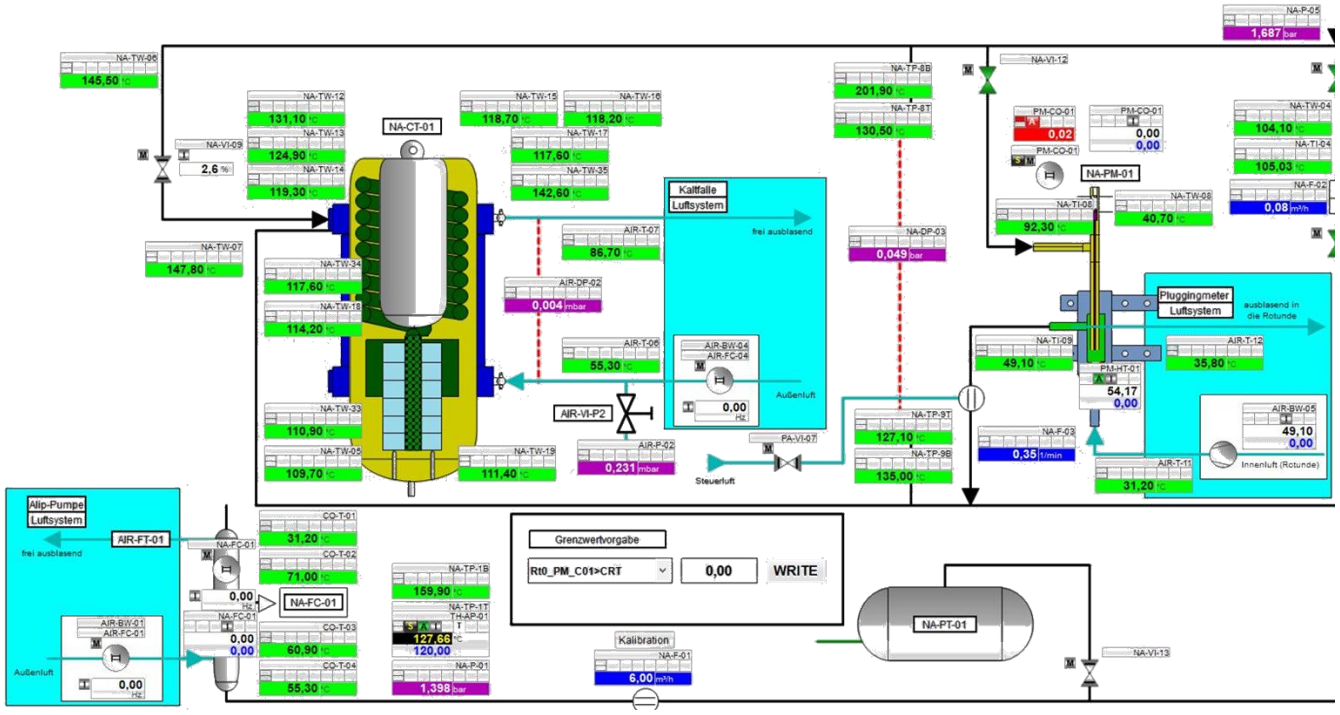
- Versatile platform: fundamental thermal hydraulic flow phenomena (forced, mixed and free convection) → qualification of instrumentation → prototypical component testing for Sodium Fast Reactor and Advanced Modular Reactor.

- Qualification, validation and improvement of turbulent liquid metal heat transfer models in CFD (Computational fluid dynamics) as well as reduced order models or system codes



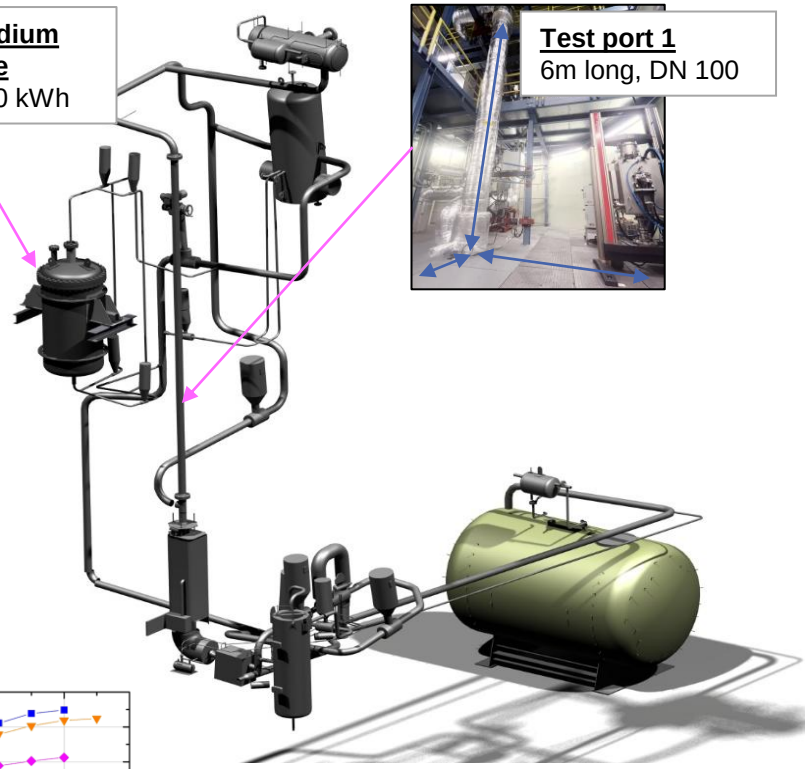
Karlsruhe Sodium Lab KASOLA

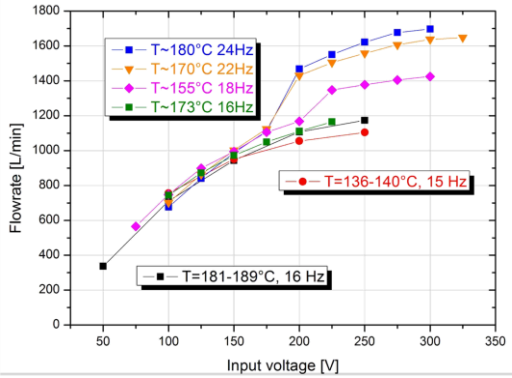
- Large flexible test ports
  - Port 1 (6 x 2 x 2 m³)
  - Port 2 (4 x 2 x 1.5 m³)
  - Port 3 (0.75 x 0.5 x 0.5 m³)



Test port 2: Sodium thermal storage
150–450 °C, 110 kWh

Test port 1
6m long, DN 100

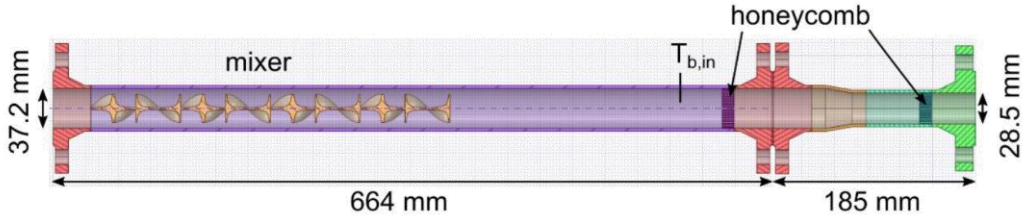




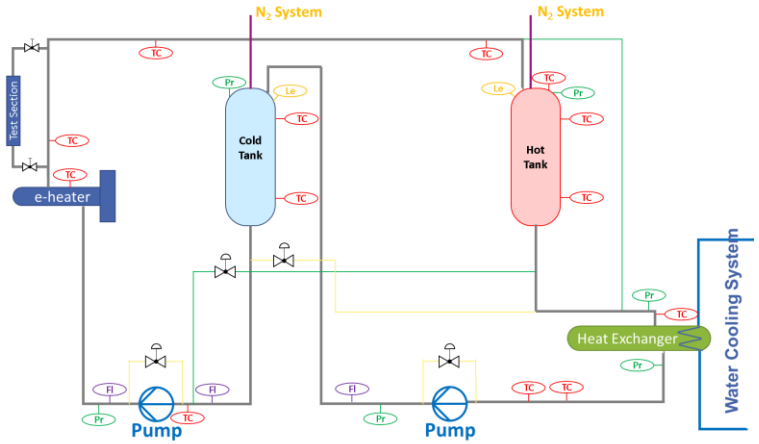
Na flow rate vs. pump input voltage at different pump frequencies and inlet temperatures.

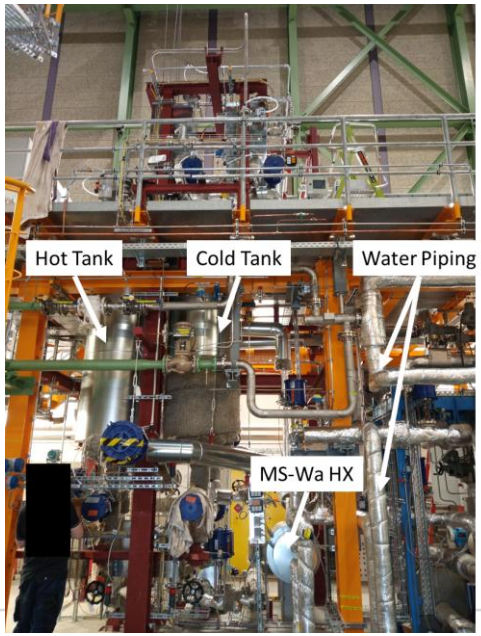
Molten Salt Loop: HELOKA-US

- Three coupled heat transfer loops, 260 kW thermal power:
  - Helium loop: 300-520°C, 80 bar
  - Molten salt loop: 270-465°C, 6 bar
  - Water cooling system: 160-220°C, 45 bar
- Molten Salt: HITEC eutectic mixture of potassium nitrate, sodium nitrite and sodium nitrate with large operational temperature range (149-593°C).
- Instrumentation: 16 x Thermocouples, 9 x Pressure Sensors, 3 x Flowmeters, 4 x Level Sensors
- Applications:
  - Heat transfer measurements in various flow conditions
  - Thermal Energy Storage: charging/discharging modes
  - Strategies for Control Systems in non-steady operations



Test Section Design (MS-side HX)

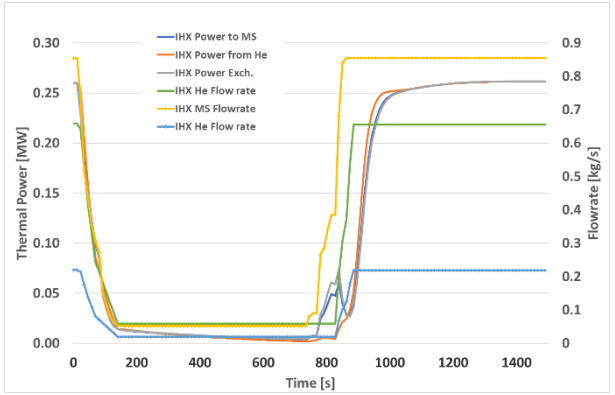


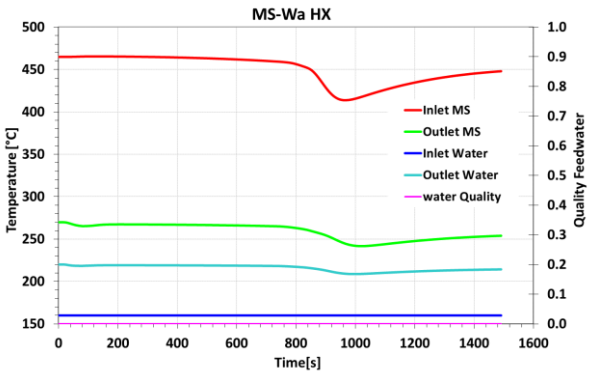


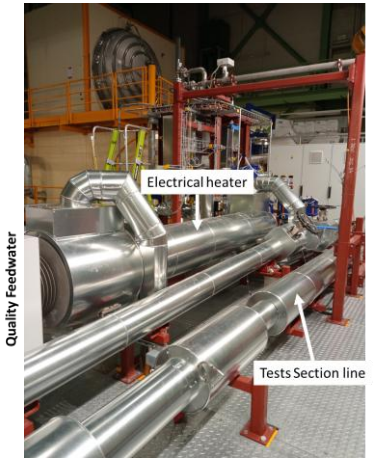
Molten Salt Loop: HELOKA-US

- Engineering Design and construction : completed
- Design, construction and integration of test section mimicking the MS-side of Helium-MS Heat Exchanger
- Commissioning Test: on-going
- Thermal-hydraulic numerical models

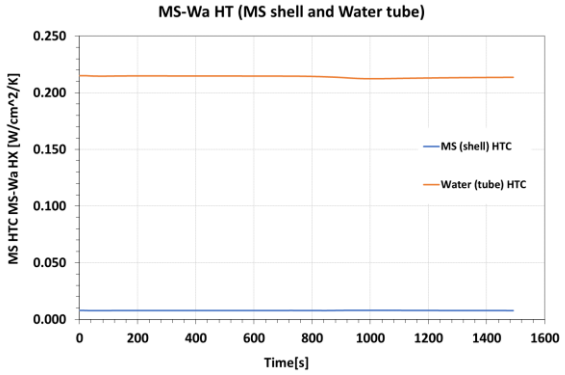
	High Power	Low Power
Thermal power (kW)	260	2.60
Duration (s)	7,200	600
MS IHX in / out temp. (°C)	270/465	270/299
MS SG in/out temp. (°C)	465/270	453/270
MS hot tank temp. (°C)	465	465
MS cold tank temp. (°C)	270	270
MS flow rate in charg. line (kg/s)	0.854	0.0581
MS velocity in charg. line (m/s)	0.452	0.031
MS flow rate in disch. line (kg/s)	0.789	0.727
MS velocity in disch. line (m/s)	0.417	0.385

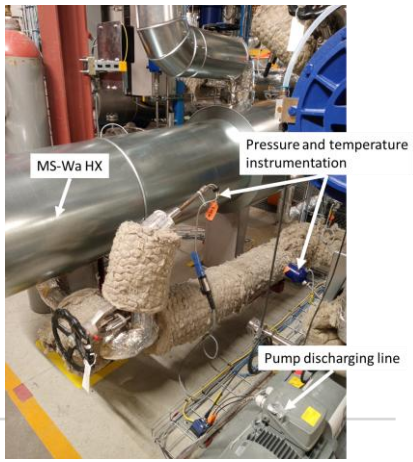






	Sodium	Helium	HITEC	Water
Cold temperature (°C)	300	300	270	160
Hot temperature (°C)	550	520	465	220
Average temperature (°C)	425	410	368	190
Pressure (bar)	6.0	80.0	6.0	45.0
Density at Ave. Temp. (kg/m3)	854.7	5.7	1811	876.0
Dyn. Viscosity at Ave. Temp. (Pa.s)	0.00029	0.00004	0.00184	0.00015
Th. Conduct. at Ave. Temp. (W/mK)	72.888	0.279	0.357	0.667
Heat Capacity at Ave. Temp. (J/kgK)	1276	5195	1562	4459





Outline

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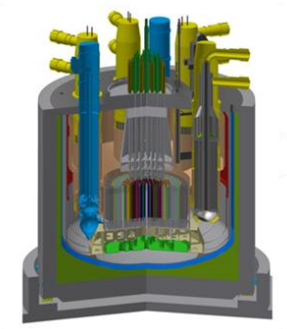
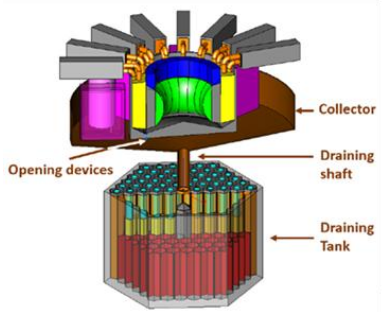
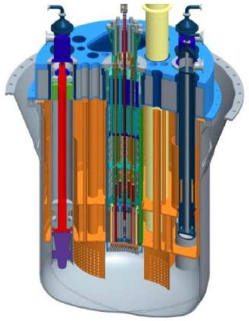


SFR



MSR



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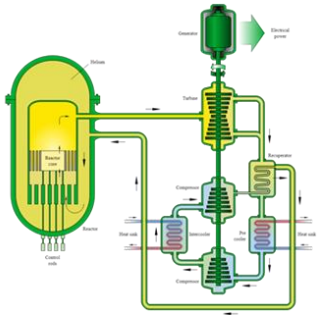

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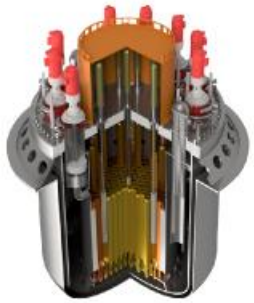

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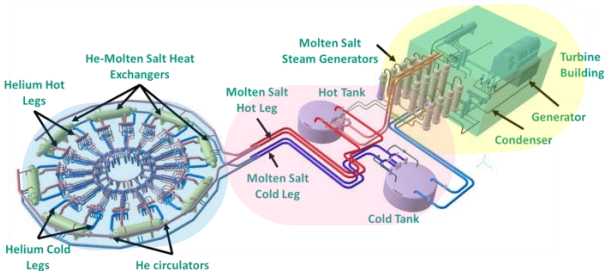
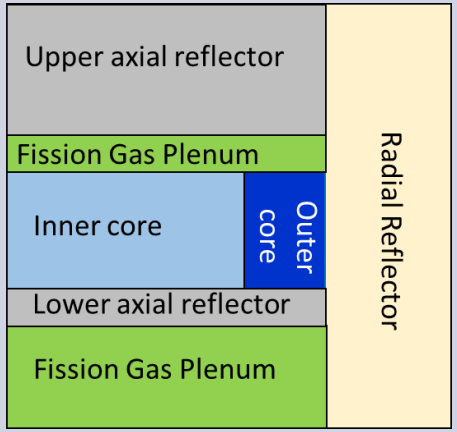
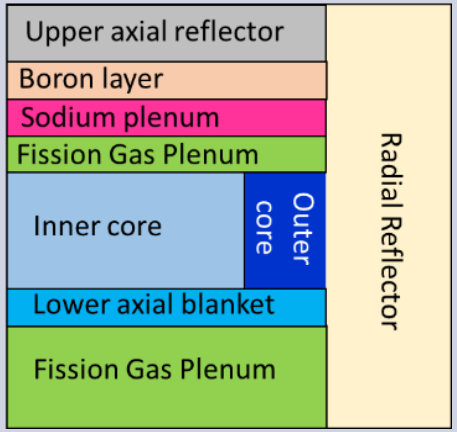
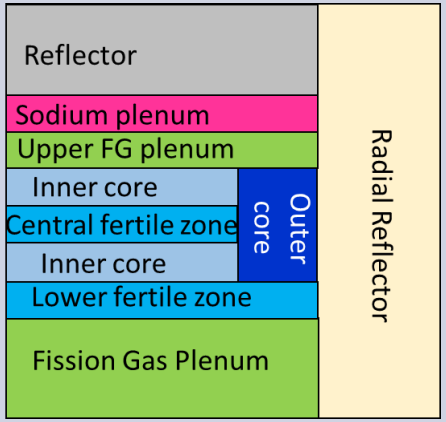
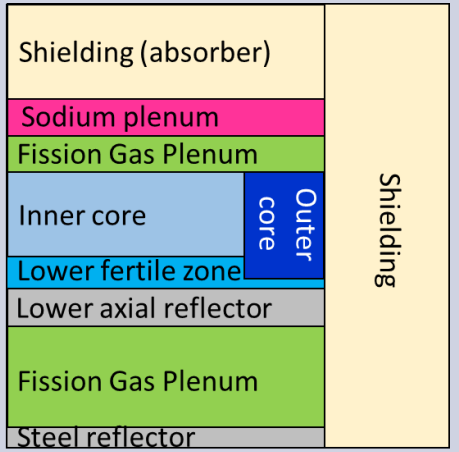
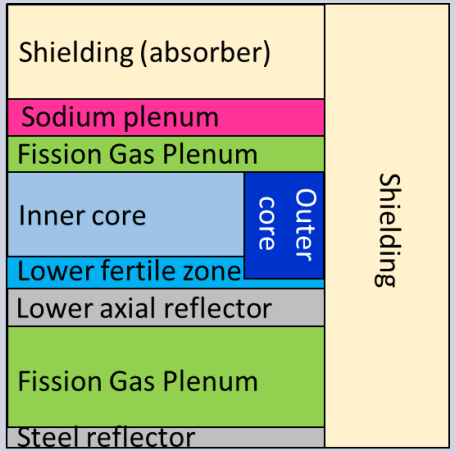


FUSION-DEMO

SFR reactor designs in EU projects

	CP-ESFR	ESNII+	ESFR-SMART	ESFR-SIMPLE
Time	2009-2012	2013-2017	2018-2022	2023-2027
Target	SFR	Gen-IV (SFR, LFR, GFR…)	SFR	SFR
Reactor power (MWth)	3600	1500	3600	3600 & SMR
Reactor performance	Minor Actinides transmutation	ASTRID	Improved CP-ESFR reactor	SMR design (oxide) Metal fuel (SFR)
Safety measures	decrease sodium void worth	negative sodium void worth	corium discharge tubes passive SR (Curie-point triggered)	Low void, small core

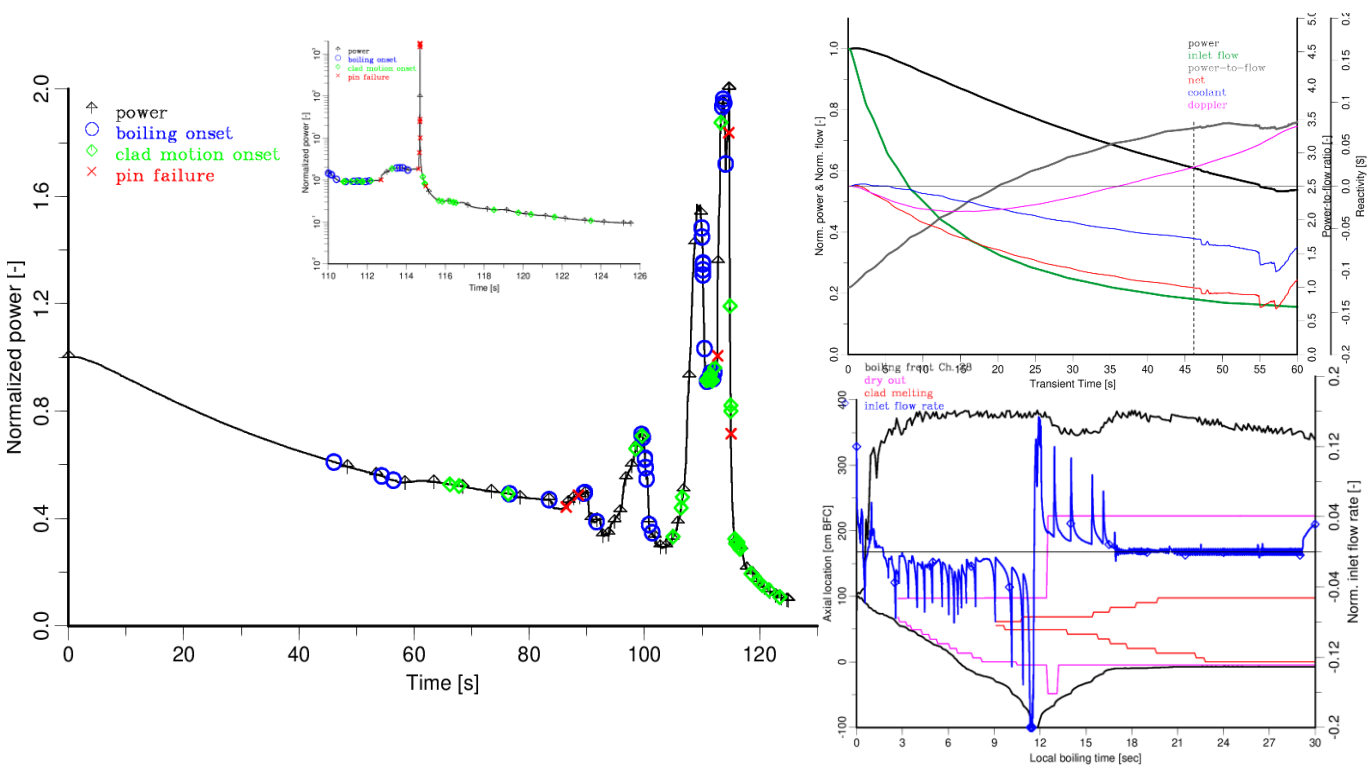
CP-ESFR Reference	CP-ESFR Optimized	ESNII+	ESFR-SMART	ESFR-SIMPLE
				

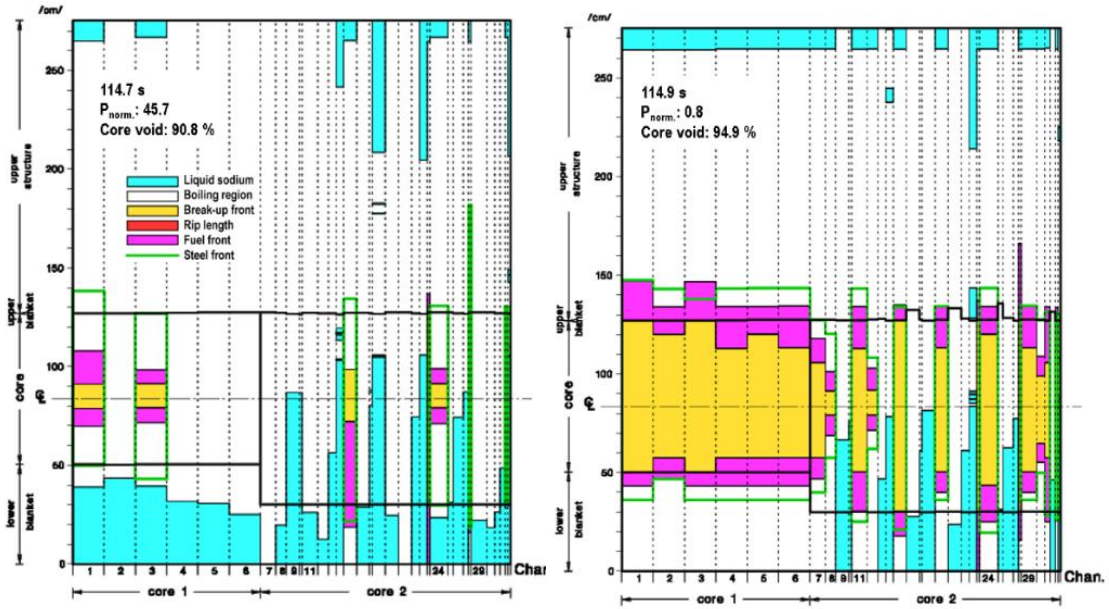
- KIT Calculation Platform: SAS-SFR, SIM-SFR, SIMMER, CONTAIN-LMR.

...not only user, but also code developers!

Initiation Phase of Accidental Transients

- SAS-SFR Code: Complete transient analysis including post-boiling and post-cladding failure phases up to hexcan integrity failure.
- EU Project ESFR-SMART Core Design ULOF Transient:





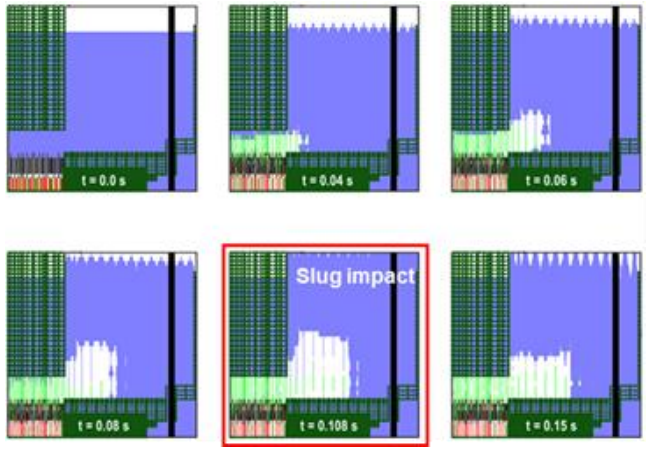
~ 17 % min. Flow rate to avoid pin failure.
... Now being applied to SMR (360 MWth) SFR

- Currently being extended to model metallic-fuel SFR core and validated against EBR-II and TREAT tests and code-to-code benchmarking with SAS4A code.
- SIM-Code: in-house code with similar capabilities.

Transition Phase of Accidental Transients

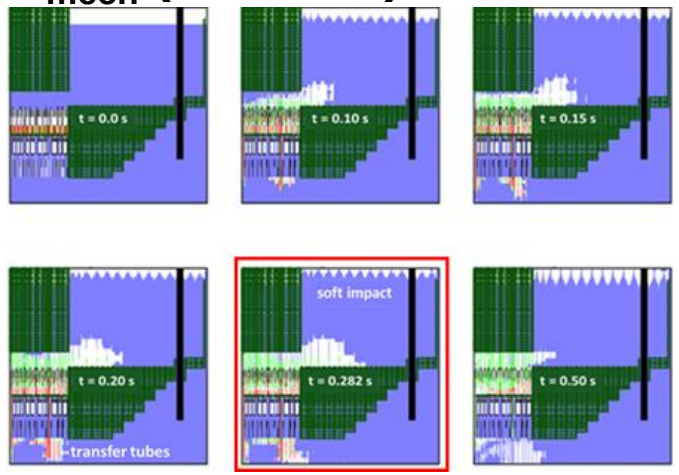
- SIMMER Code: developed by KIT, JAEA, and CEA extensively employed
- Reference code for CDA analyses in fast spectrum reactors (2D/3D fluid-dynamics+structure model+space-, time- and energy-dependent neutron dynamics). Originally developed for SFRs, extended at KIT also for LFRs, GFRs, MSRs
- Mechanical energy release after CDA in SFR

- CP-ESFR (2012) - Conventional SFR design
- **W_{mech} (SIMMER)= 794 MJ**



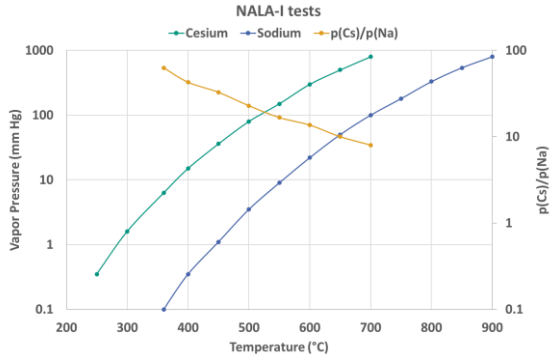
- **ESFR-SMART**
  - innovative SFR design
  - with sodium plenum
  - corium transfer tubes
  - passive safety devices

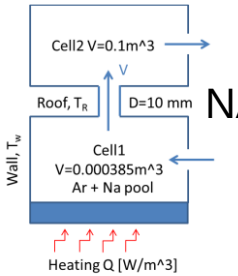
- ESFR-SMART
- **W_{mech} (SIMMER)= 396 MJ**



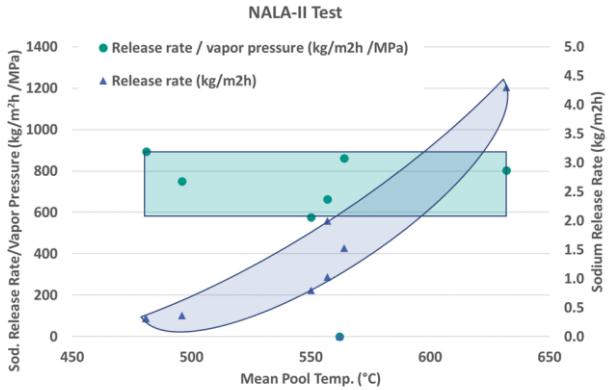
Source Term Evaluation in SFR SA

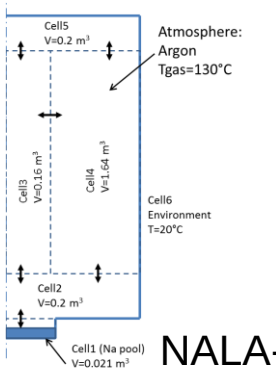
- CONTAIN-LMR Code: Validate against various experimental (KfK) programs FAUNA (Na fires), NALA (secondary source term), FAUST (primary source term).
- NALA Program: Laboratory- and technical-scale experiments at different Na temperature and Cs content conducted in an inert-gas atmosphere (Ar or N2).
- Results of NALA tests for assessing Fission Products Retention Factors



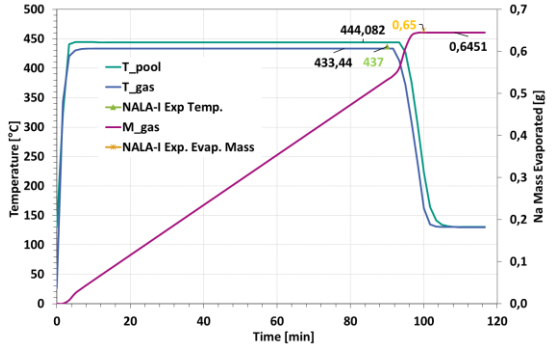


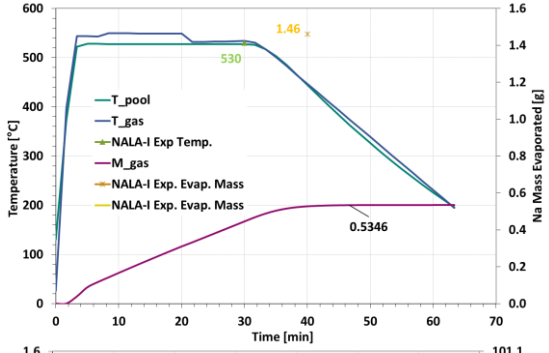
NALA-I

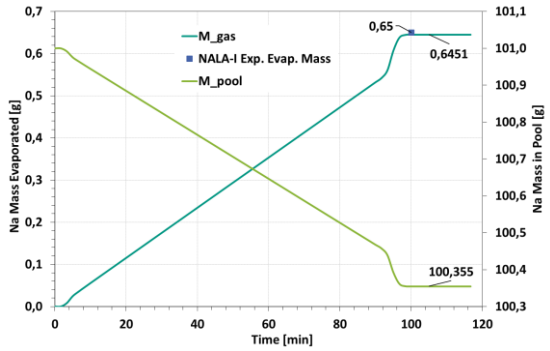


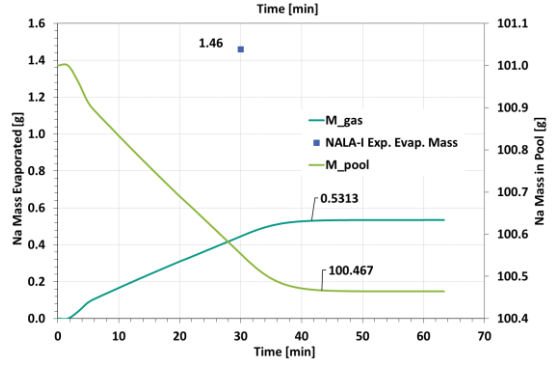


NALA-II





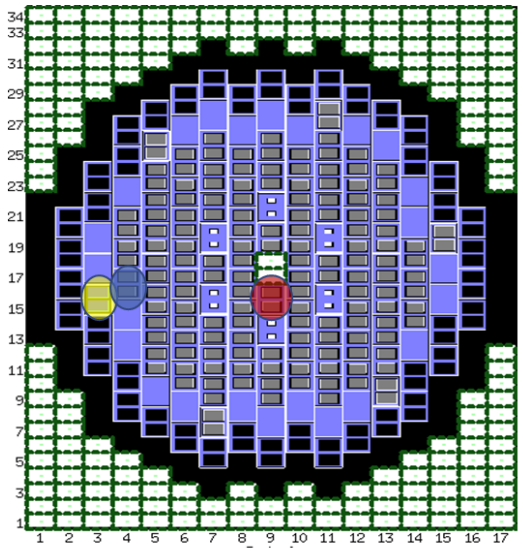




Benchmarking with MELCOR is very welcome!

... further Advanced Systems

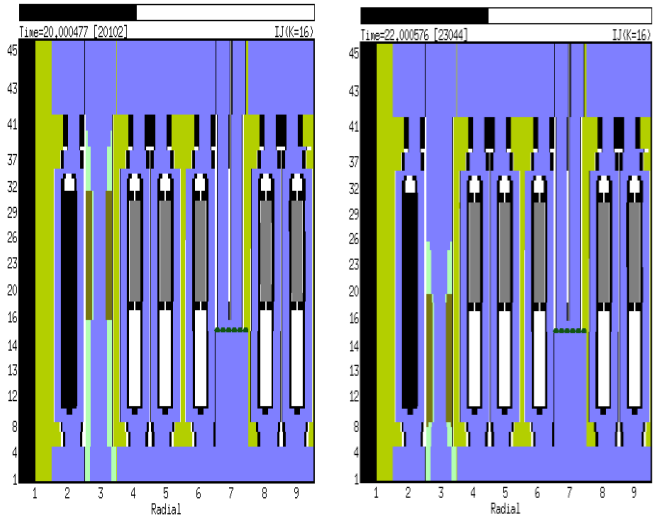
- MYRRHA-LFR (EU ANSELMUS Project)
- 3-D neutronics & fluid-dynamics coupled calculation on CR withdraw
- Supporting the validation of codes applied for LFR licensing, such as RELAP

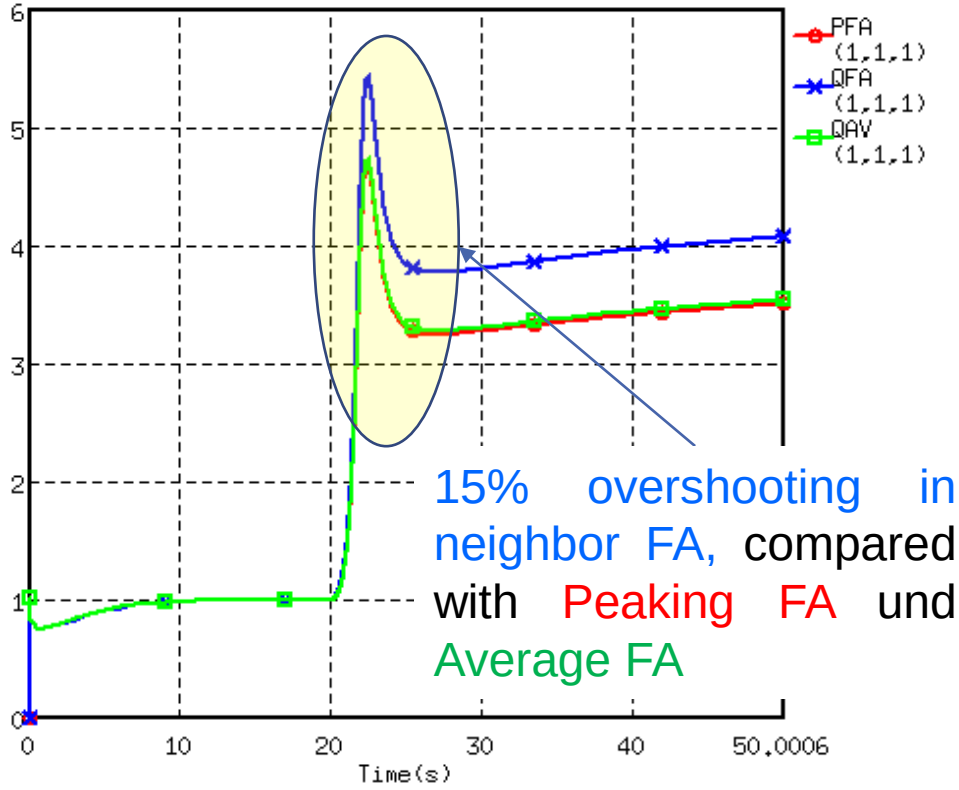


CR withdrawn

CR Neighboring FA

Peak Power Fuel Assembly (FA)





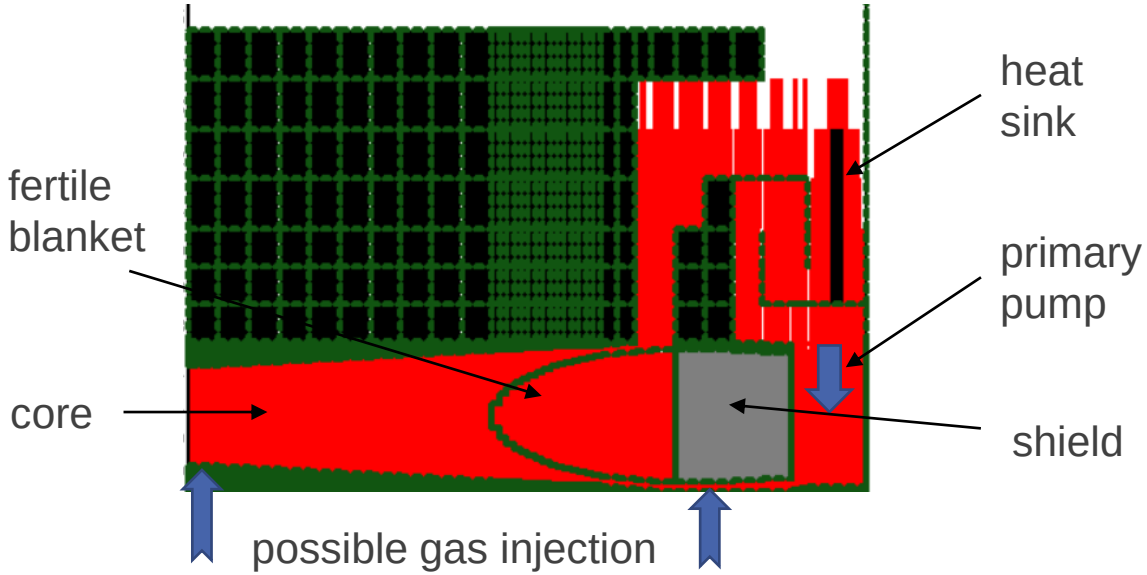
15% overshooting in neighbor FA, compared with Peaking FA und Average FA

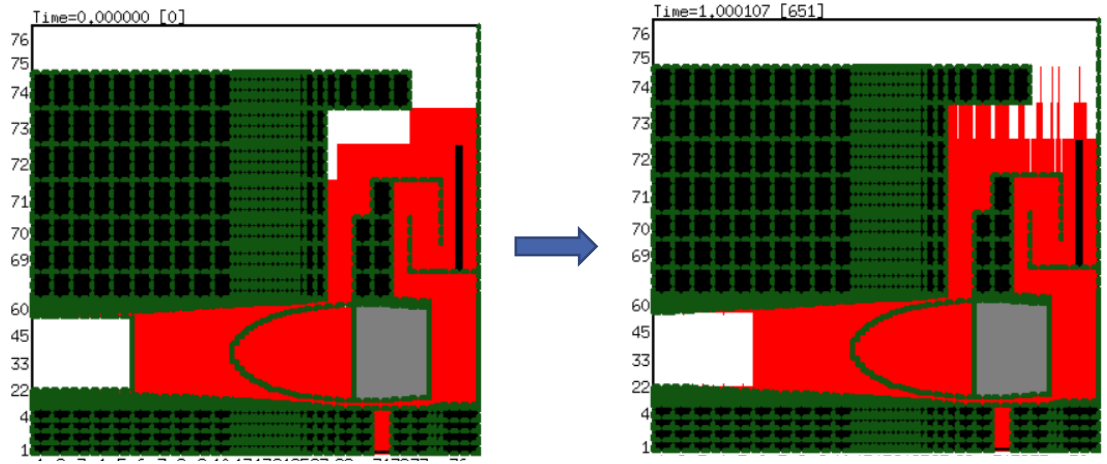
... further more

- Molten Salt Fast Reactor (3 GWth) with Flouride salt

- MSFR safety studies
  - Improved geometry of the primary system
  - Steady state and transient simulations
  - Verification against CFD tools

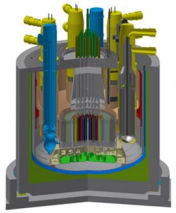
- Steady state achieved
  - Due to the fuel expansion, less fuel is in the core initially
  - The reactivity loss must be compensated by external reactivity
    - achieved by removing walls separating an initially empty zone

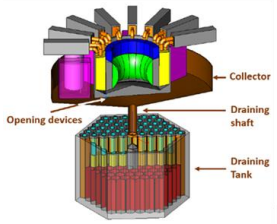


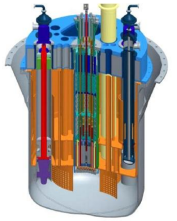


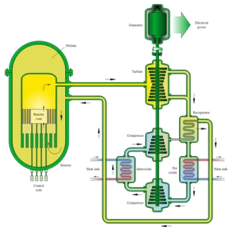
Summary

- KIT is very active in the field of Advanced Nuclear Systems both from the experimental and code simulation point of view.
- Experimental Facilities: small, medium and large-scale gas, liquid metal and molten salt loops
- Code developers: SIM-Code, SAS-SFR, SIMMER, CONTAIN-LMR, ...
- Topics: Thermal-hydraulics (single & two-phase), severe accidents (initiation and transition phase), sodium aerosols (inert/fires), vessel integrity, etc.









	SFR	MSR	LFR	GFR
Exp. Facilities	KASOLA, DITEFA	HELOKA-US	KALLA	AEROLAS
Simulation Codes	SAS-SFR, SIM-SFR, SIMMER, CONTAIN-LMR	SIM-MS, SIMMER	SAS-LFR, SIM-LFR, SIMMER	SIM-GFR
Current Projects	EU ESFR-SIMPLE	EU SAMOFER	ANSELMUS, MYRRHA	TREASURE, IAEA S-allegro