Regional Workshop on Advances in the Modelling and Simulation of Thermal Hydraulics in Liquid Metal Cooled Fast Reactors
GCNEP, India 28 Nov - 2 Dec 2022

Simulations and experiments with liquid metals at KIT

Research on Liquid Metal Thermal-hydraulics

Sara Perez-Martin

Outline

- SAS-SFR code
- Validation and SFR Simulations
  - CABRI tests
  - KNS-37 tests
  - EU-SFR designs
- LM facilities at KIT
  - DITEFA: GaInSn Loop
  - KASOLA: Large Sodium Loop

SAS4A Origin

- The code was designed to predict accident consequences focusing on the initiating phase of core disruptive accidents resulting from unprotected under-cooling or overpower conditions.

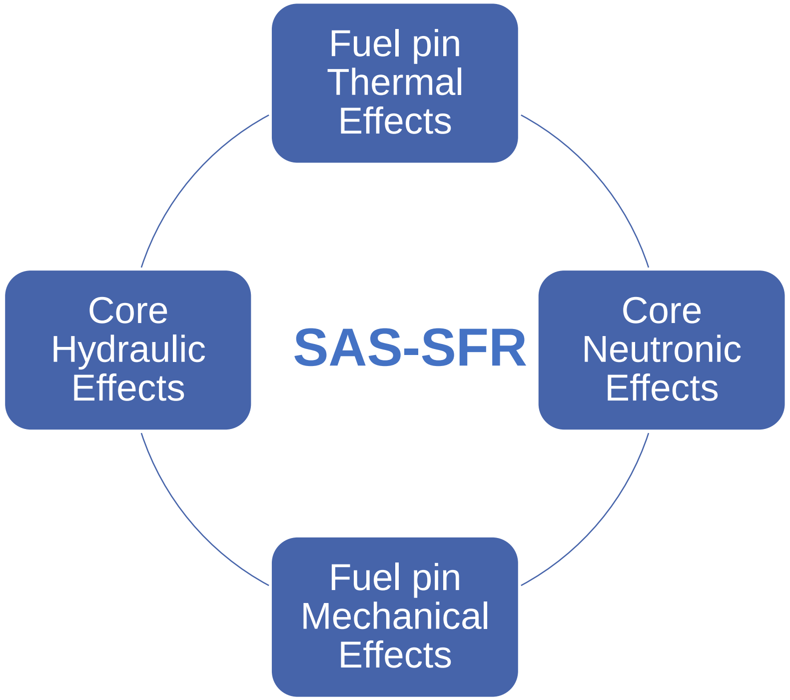
	1960-1970	1970	1980	1990	2000	2022
SAS1A, SAS2A, SAS3A, SAS3D						
SAS4A						
SAS4A/SAS-SYS						
SAS-SFR						

- SAS-SFR code is based on the SAS4A (**S**afety **A**nalyses System) code developed by Argonne National Laboratory (ANL).

- SAS-SFR development: i) Interpretation of CABRI experiments; ii) integral demonstration using the experimental findings

SAS-SFR Code Frame

- In the 1960s, limited computational resources (compared to today)
- Goal: to predict the transient power: Neutron Physics → Point Kinetics
- Point Kinetics: reactivity feedbacks
  - Doppler: Fuel temperature → fuel pellet thermo-mechanical model
  - Coolant: Na temperature and density → one & two-phase **sodium** TH
  - Fuel and cladding axial expansion → fuel pin thermo-mechanical model
  - Fuel and clad relocation → fuel pin failure model under single & two-phase coolant
  - Hexcan thermal expansion → structure mechanical model
  - Diagrid thermal expansion → special parametric model
  - Control Rod Guide tubes → special parametric model



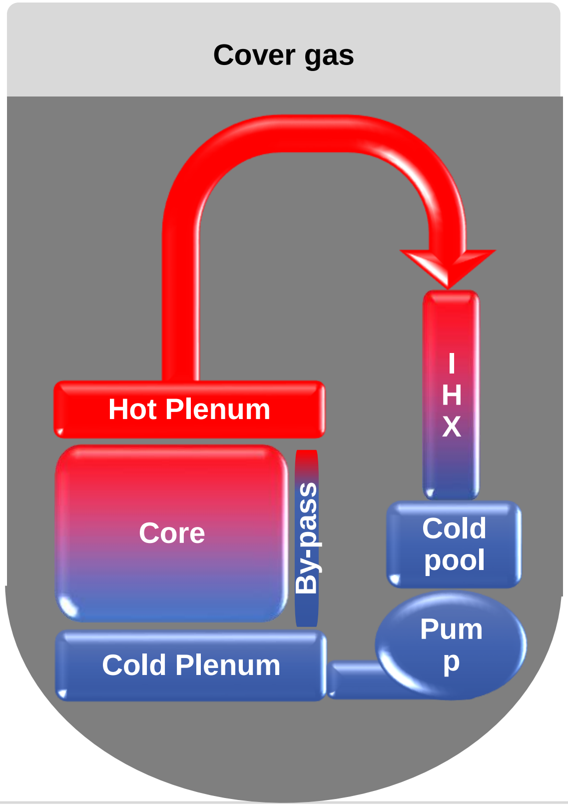
Outcome: code models limited to 1D phenomena → good compromise for events occurring up to hexcan integrity failure, core damage is limited to fuel assemblies and the motion of the failed fuel is uniformly controlled by the wrapper tube wall.

Sodium Primary Circuit

PRIMAR-4: Advanced Primary Loop Model

Thermal-hydraulic model for primary and intermediate loops

Volumes perfectly mixed, compressible liquid with/without cover gas

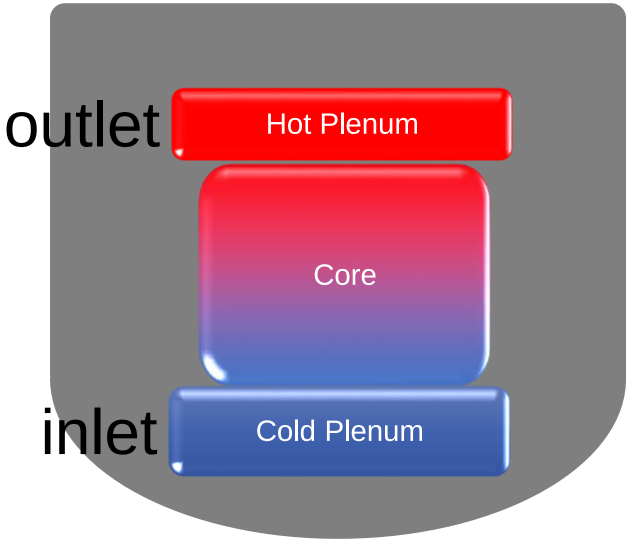


PRIMAR-1: Simple Primary Loop Model

Primary loop conditions given by the user: outlet plenum pressure $p_x(t)$ & inlet plenum temperature $T_{in}(t)$

$$p_{in}(t) = p_x + fp(t) + \Delta p_{grav}$$

$$\Delta p_{grav} = \rho_{hot} g\left(z_{p_{out}} - z_{p_{in}}\right) + \rho_{cold} g\left(z_{IHX} - z_{p_{in}}\right)$$



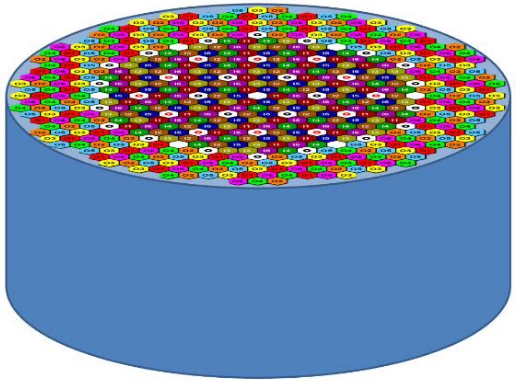
Core Model: Multiple SA Channels

- The core heat model: multi-channel approach grouping fuel subassemblies (SA) with similar nuclear and heat characteristics represented by a single pin.

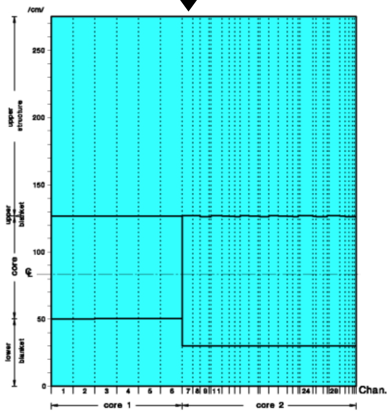
- Grouping criteria:
  - Number of batches in a multi-batch core load: 3 to 5 per enrichment zone
  - Number of cooling groups in a core load: up to 5
  - Peak linear rating differences between SA groups: < 5 - 10 %
  - Coolant outlet temperature differences between SA groups: < 15 K

- Pressure drop characteristics of coolant channels needed to determine the coolant mass flow (time-dependent inlet-to-outlet plena pressure)

- SA inlet gagging (orifice coef.) to establish coherent pressure conditions at channel outlet.



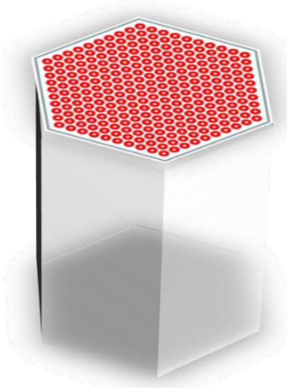
ESFR-SMART core



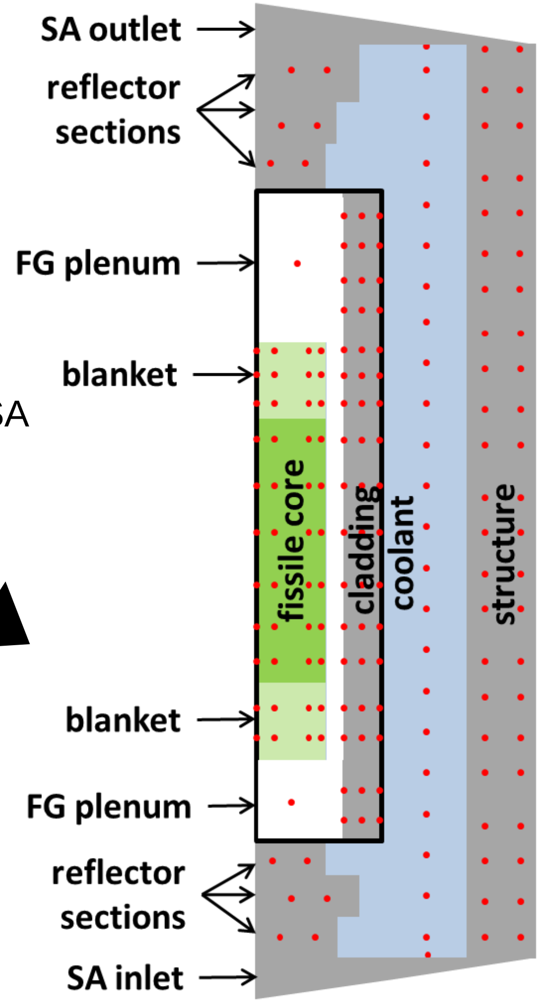
SAS-SFR representation with 34 SA channels

SA Model: single pin approach

- Power released in fissile and fertile regions
- Hydraulics:
  - SA inlet / outlet are represented by a singular pressure losses
  - Reflector sections represent zones with different hydraulic characteristics
  - Singular pressure drops at cross section changes between different axial segments representing the axially varying subassembly geometry
- The fraction of the lengths of two neighboring axial nodes should not exceed 1.5.



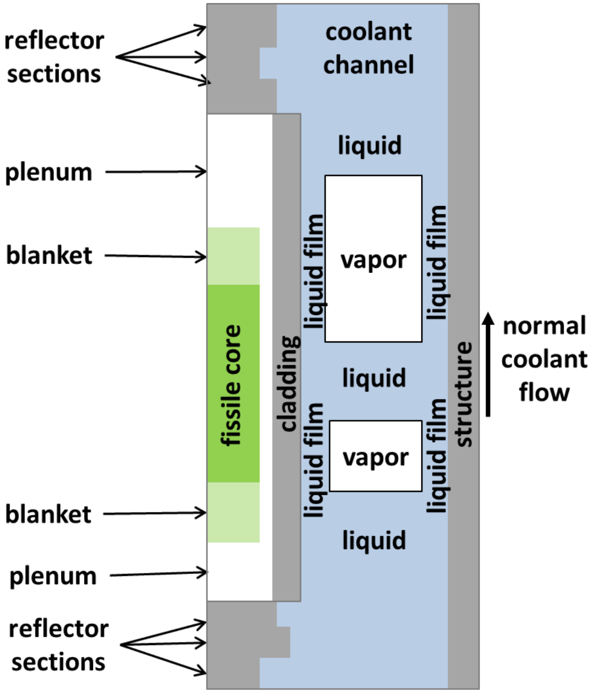
ESFR-SMART SA



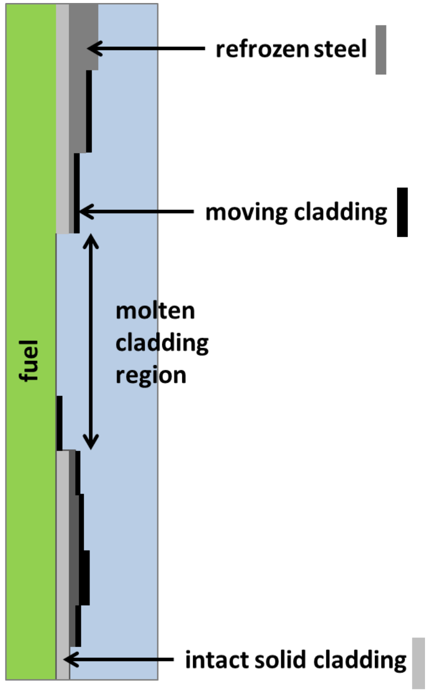
SAS-SFR axial nodes of a channel.
Red dots: heat transfer mesh

Multiple bubble/slug & Molten clad relocation

- Axial distribution of the voiding extent → **voiding reactivity feedback**
- Vapour flow rates driving **molten cladding motion**
- Finite number of bubbles separated by liquid slugs
- Voiding fills the whole coolant channel cross section except for a **liquid film**

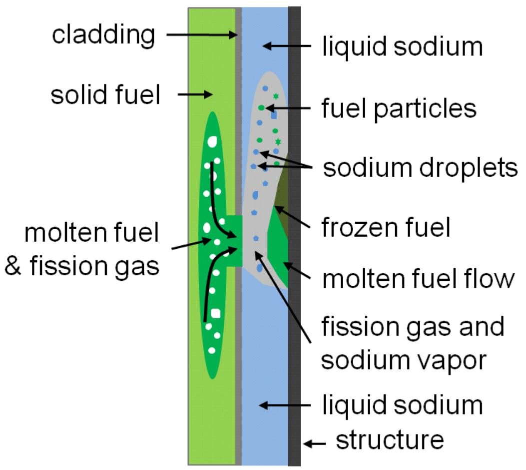


- Coolant voiding + pin dry-out → rapid heating + subsequent cladding melting → relocation of molten clad material along fuel pin structures.
- Molten cladding motion due to vapor flow (pressure gradient & shear forces) and gravity



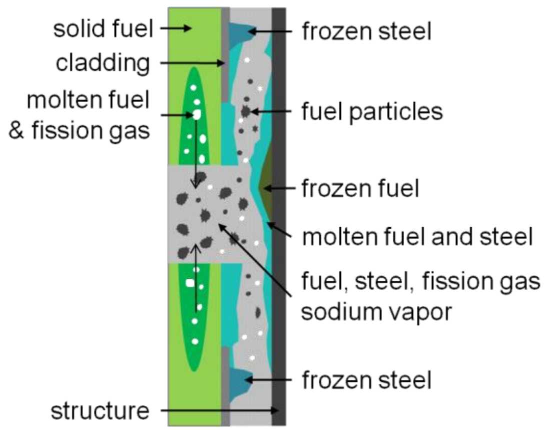
Fuel ejection into the coolant channel

- The PLUTO2 model addresses to the post pin-failure behaviour:
  1. in-pin fuel motion toward a cladding rupture (transiently varying pressurized cavity)
  2. fuel and gas ejection through the cladding rupture so that cavity pressure = coolant channel pressure
  3. multi-component, multi-phase hydrodynamics treatment in the coolant channel (1D, compressible two-fluid flow with variable flow cross section).
  4. crust formation on colder structures



PLUTO2

- Thermo-mechanical load to the fuel pin leading to a total fuel pin disintegration (fuel pin break-up).
- Liquid&solid fuel + fission gas + liquid&solid clad + potentially fuel&clad vapour into a voided coolant channel
- Thermal-hydraulic models:
  - Hydrodynamics of fuel cavity in stubs below and above broken-up region
  - Hydrodynamics of the multiphase mixture (crust formation on colder structures, clad melting and ablation) bounded by cladding surface and the hexcan wall.
  - Heat-transfer and melting/freezing response of the solid fuel pin stubs separating channel and inner cavity.



LEVITATE

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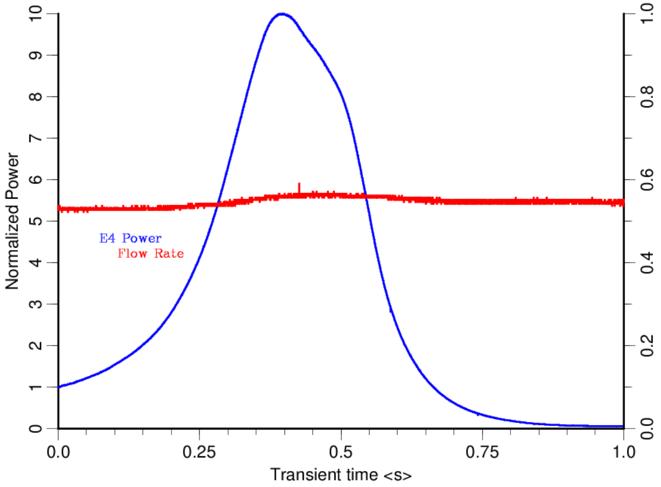
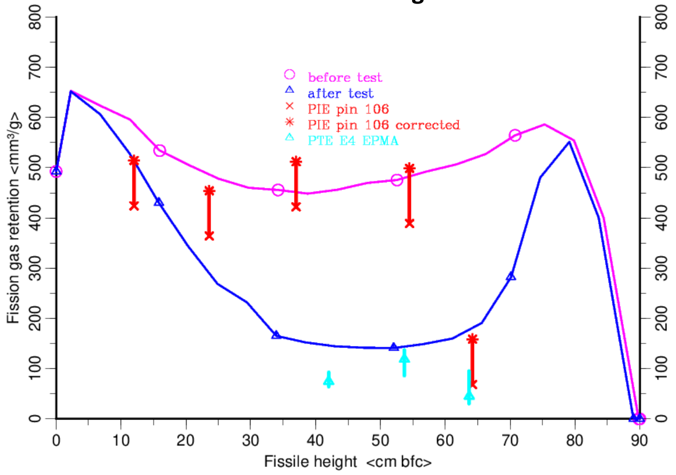
CABRI E4 thermal test

- E4 test: thermal calibration test of VIGGEN fuel pins → irradiated VIGGEN pin characteristics after CABRI steady-state conditions and light power increase.
- SAS-SFR simulation to verify irradiation in PHENIX reactor as well as the CABRI steady-state conditions

E4 power and flow rate

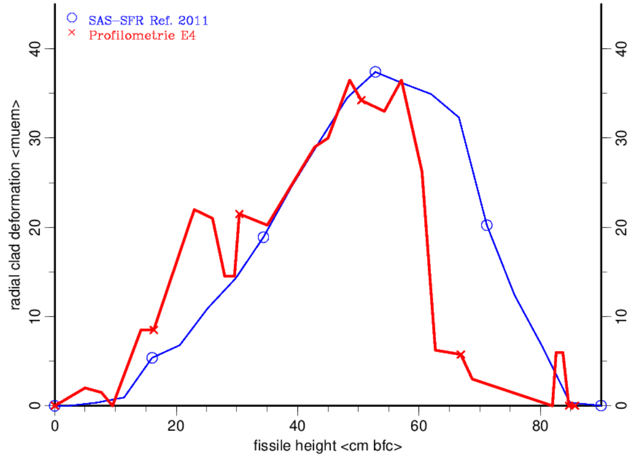


E4 fission gas retention

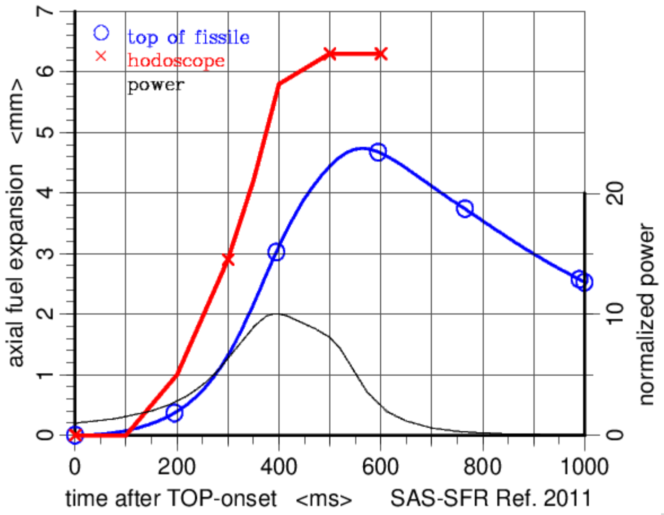


- Computational running time
  - 1 representative pin (so-called SA channel)
  - Fuel pin irradiation:
    - Real irradiation time: 2.2 y
    - Computing time: ~5 min.
  - E4 transient:
    - Real transient time: 10 s
    - Computing time: ~1 min.

E4 radial cladding deformation

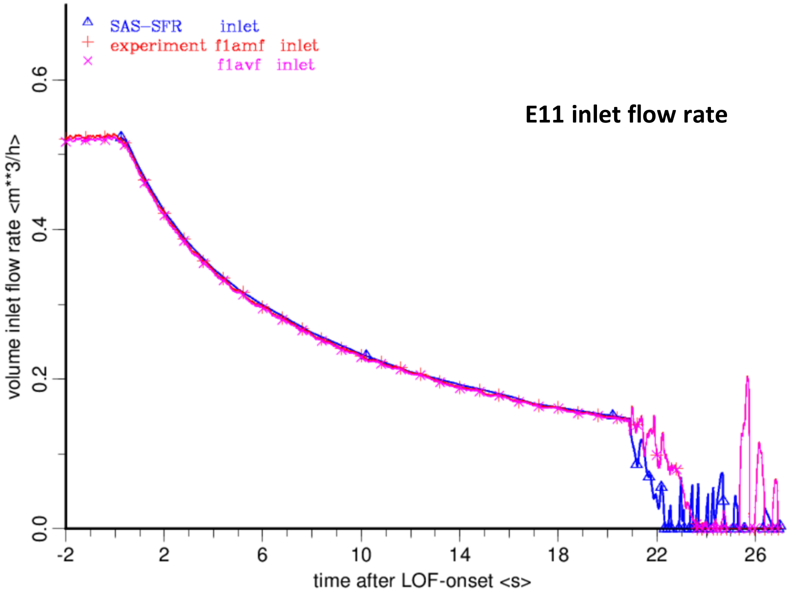


E4 axial fuel expansion

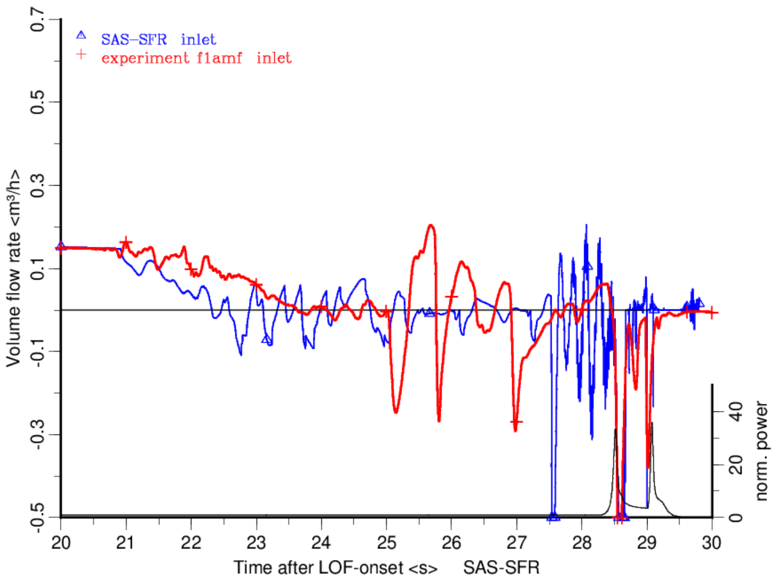


CABRI E11 TUCOP test

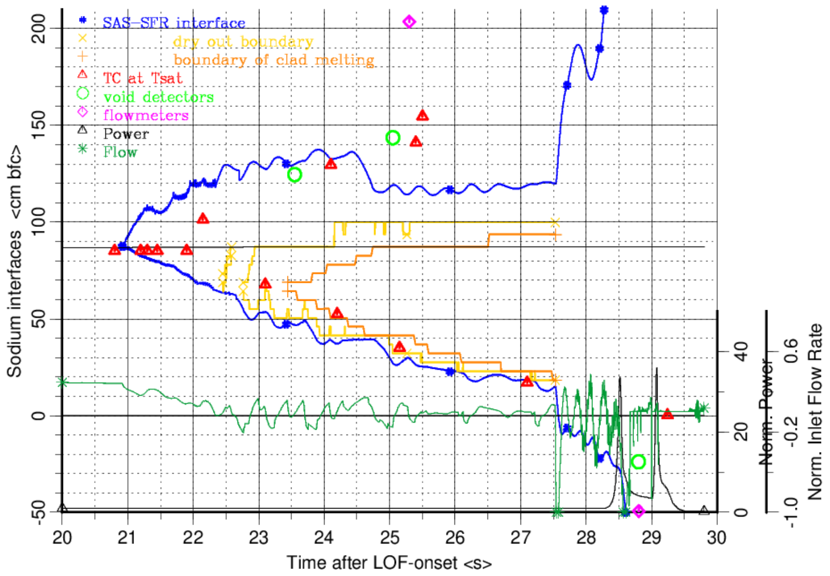
- TUCOP= LOF+TOP test



E11 inlet flow rate after boiling onset



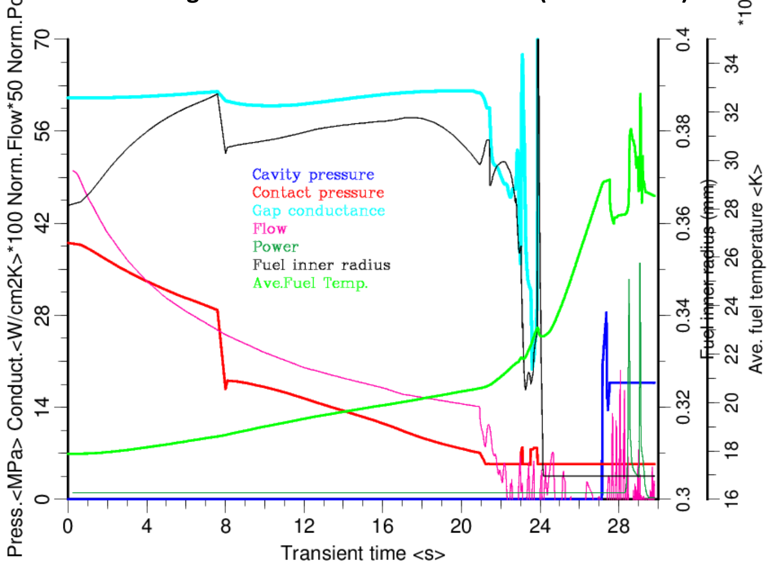
E11 coolant boiling behavior



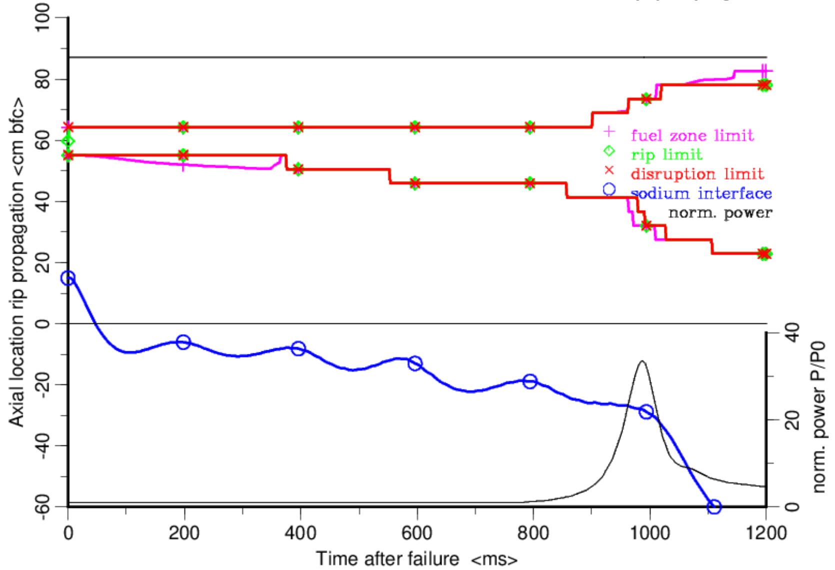
CABRI E11 TUCOP test

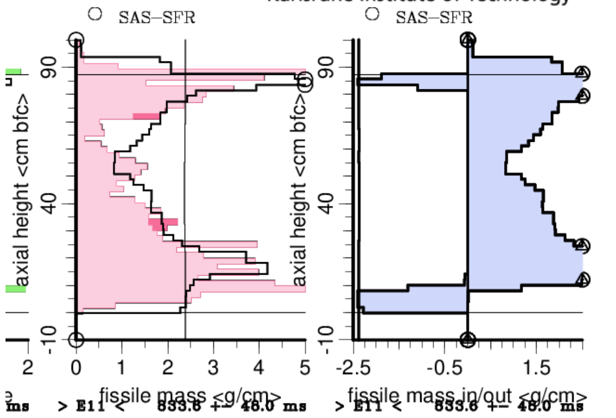
Fuel relocation took place in fully voided coolant channels.

E11 cladding conditions at the failure node (57.4 cm BFC)

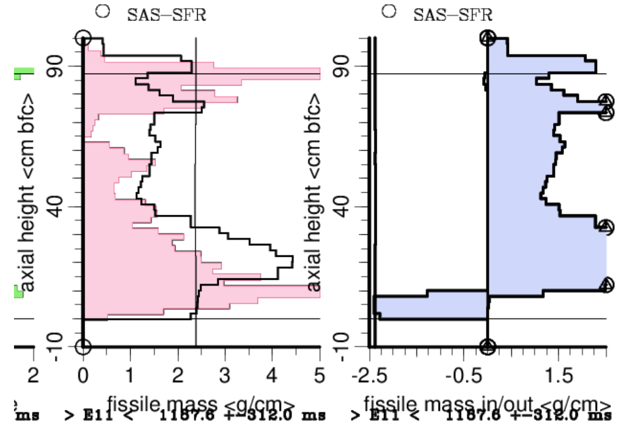


E11 axial location of rip propagation





Time averaged axial distributions



E11 axial profile of the fuel density distribution

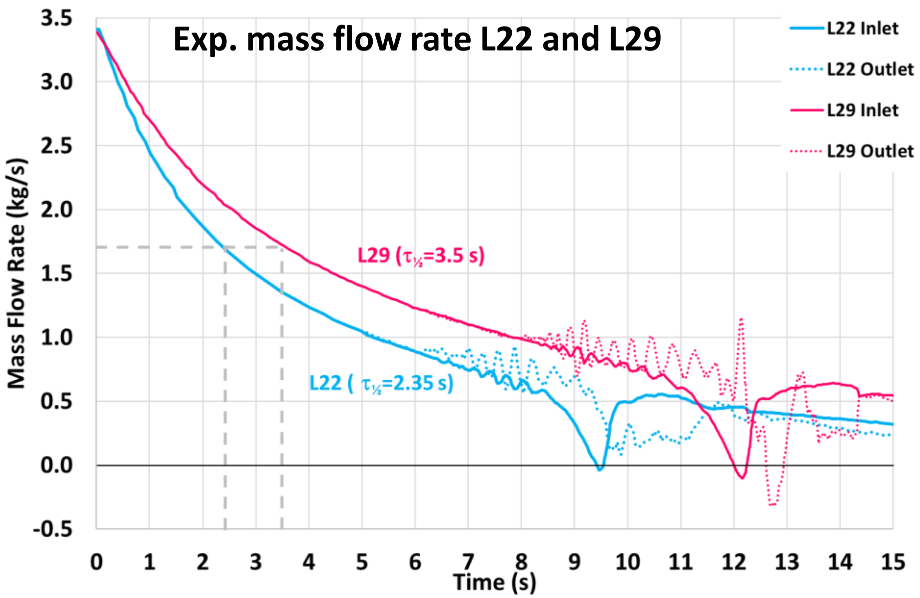
Pink: linear density profile of the fissile mass (2.5 g/cm ref. non-failure)
Black line: SAS-SFR calculation
Blue: SAS-SFR fissile density in pin (negative) and channel (positive)

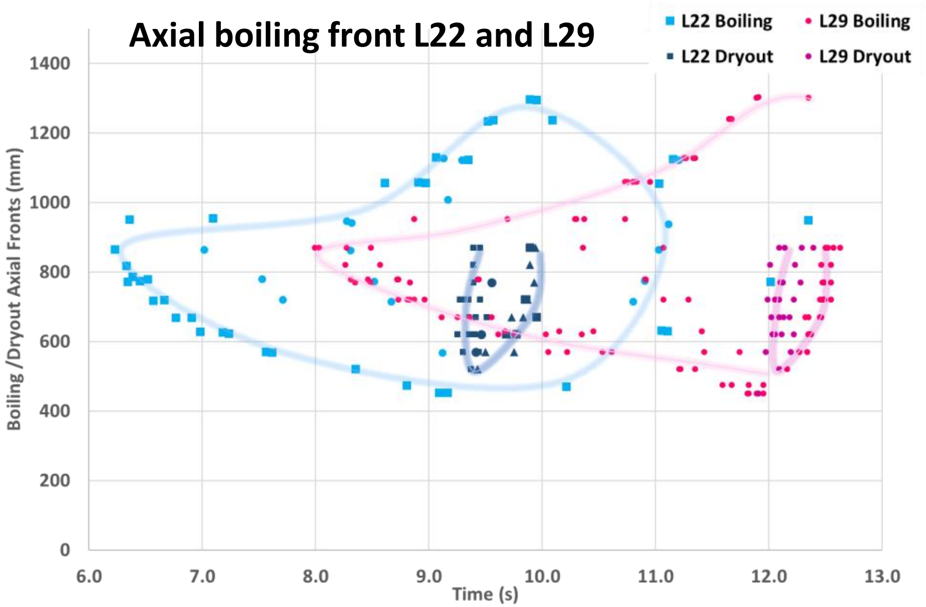
Computational running time

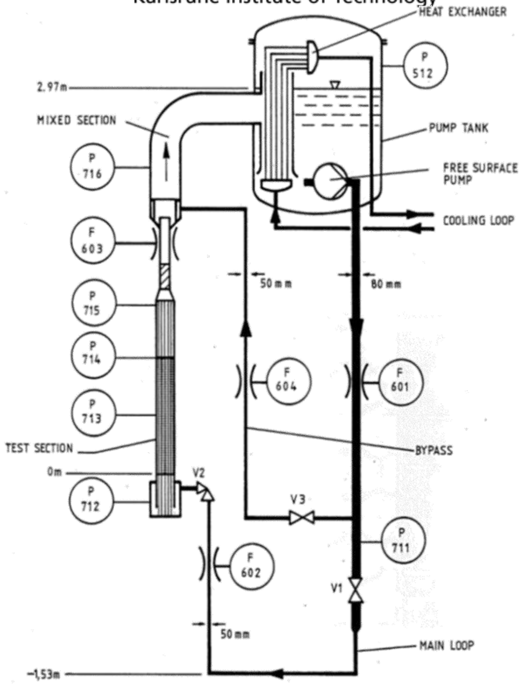
- 1 representative pin (so-called SA channel)
- Real transient time: 30 s
- Computing time: ~5 min.

KNS-37 LOF tests

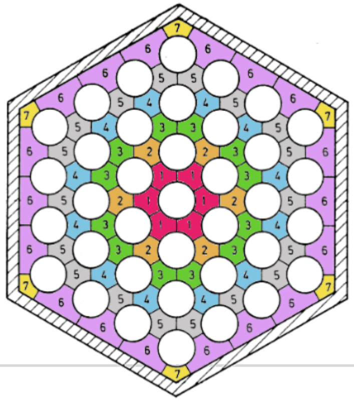
- Na boiling onset and behavior (onset location and axial/radial extension) and fuel pin dry-out in a 37 pin SA.
- Characterization of main physical events during the boiling phase (Na temp., press., inlet flow and vapor volume)







KNS-37 Sodium Boiling Loop



Characteristics		Load (W/cm)	Power Tilt (%)	Halving Time (s)	Flow Rate (kg/s)	Inlet Temp. (ºC)
L22	Reference LOF tests	215 (100%)	0	2.35	3.41	379
L29	As L22 with a slower pump coast down	216 (100%)	0	3.50	3.40	391

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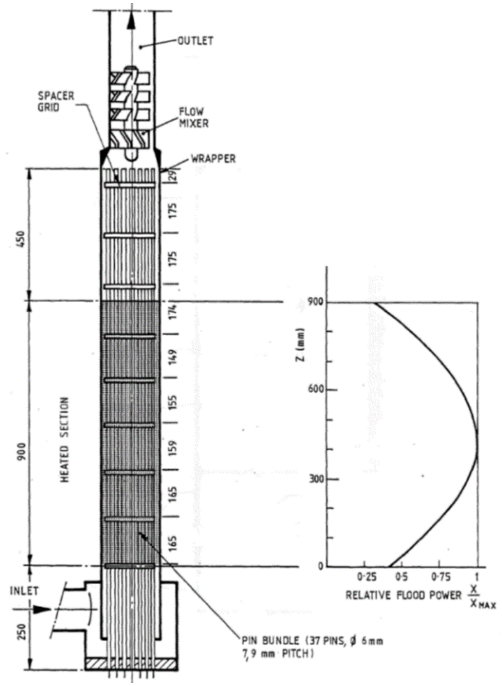
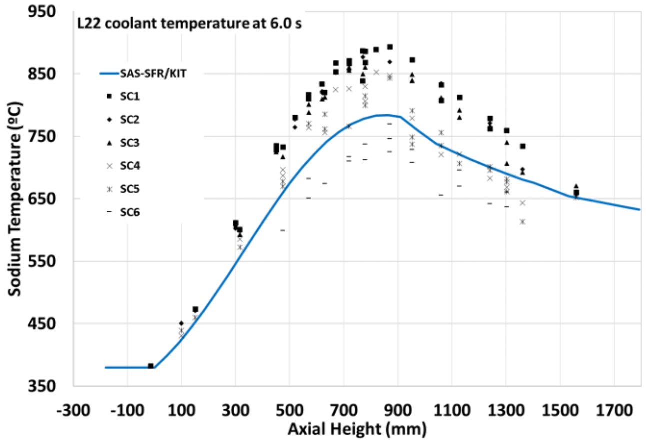
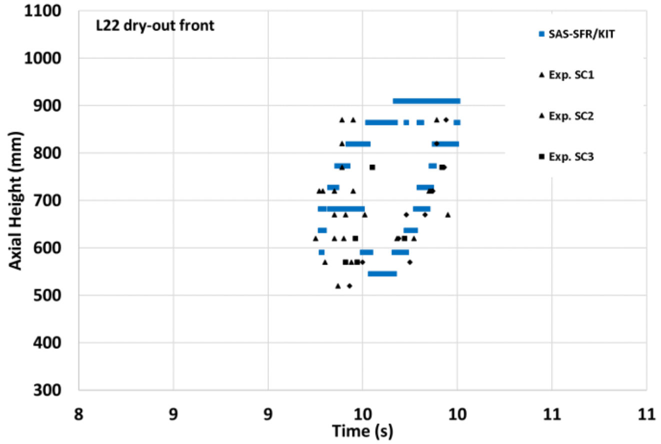
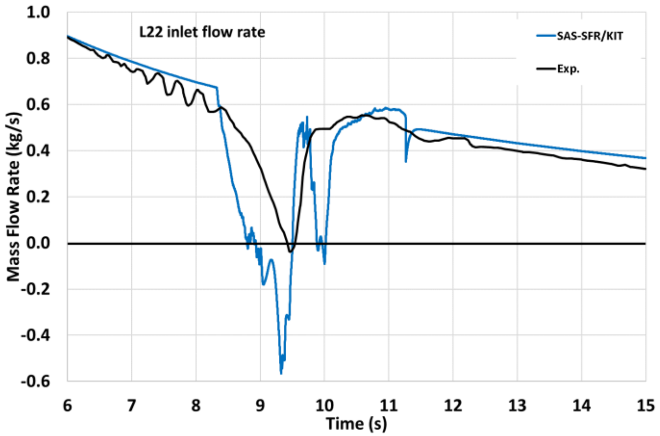
KNS-37 L22 LOF test

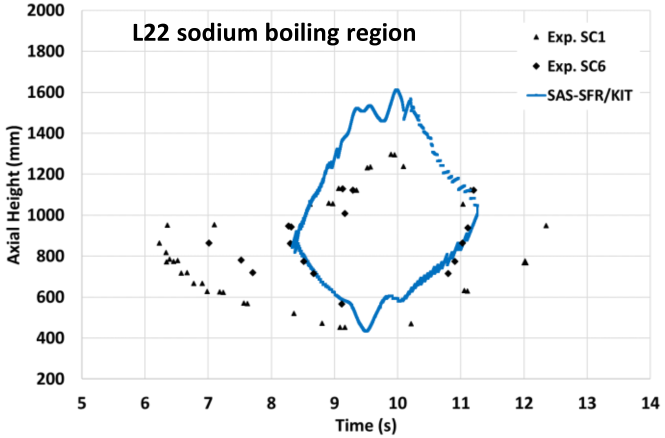
	Experiment	SAS-SFR
Total Power (kW)	717.41	690.13
Average Pin Power (W/cm)	215.44	205.01
Boiling onset (s)	6.11	8.33
Na velocity at boiling (m/s)	0.87	0.73
Dry-out onset (s)	9.25	9.28
Duration of two-phase flow (s)	6.20	2.94











Computational running time

- 1 representative pin (so-called SA channel)
- Real transient time: 15 s
- Computing time: 20 s

Perez-Martin, S., Anderhuber, M. et al. "Evaluation of Sodium Boiling Models Using KNS-37 Loss of Flow Experiments." ASME. *ASME J of Nuclear Rad Sci*. January 2022; 8(1): 011310 doi.org/10.1115/1.4050769

Review of sodium boiling models

- EU Project ESFR-SMART Task: review the models for sodium boiling implemented in the codes participating in our task:
  - SAS-SFR(KIT)
  - CATHARE (ENEA V2.5mod2.1, CEA CATHARE-3 V2.1.)
  - ASTEC-Na(IRSN)
  - NATOF-2D (JRC)
  - NEPTUNE_CFD(EDF), SATURNE/SYRTHES (EDF)
  - TRACE(PSI)

- The approach followed in the review is as follows:
  - code description of the physical basis and models
  - Information condensed and tabulated
  - advantages and limitations of the approaches implemented in the codes
  - recommendations for future improvements outlined

Tsige-Tamirat, H., Perez-Martin, S., et al. "A Review of Models for the Sodium Boiling Phenomena in Sodium-Cooled Fast Reactor Subassemblies." ASME. *ASME J of Nuclear Rad Sci*. January 2022; 8(1): 011305. doi.org/10.1115/1.4051066

SFR reactor designs in EU projects

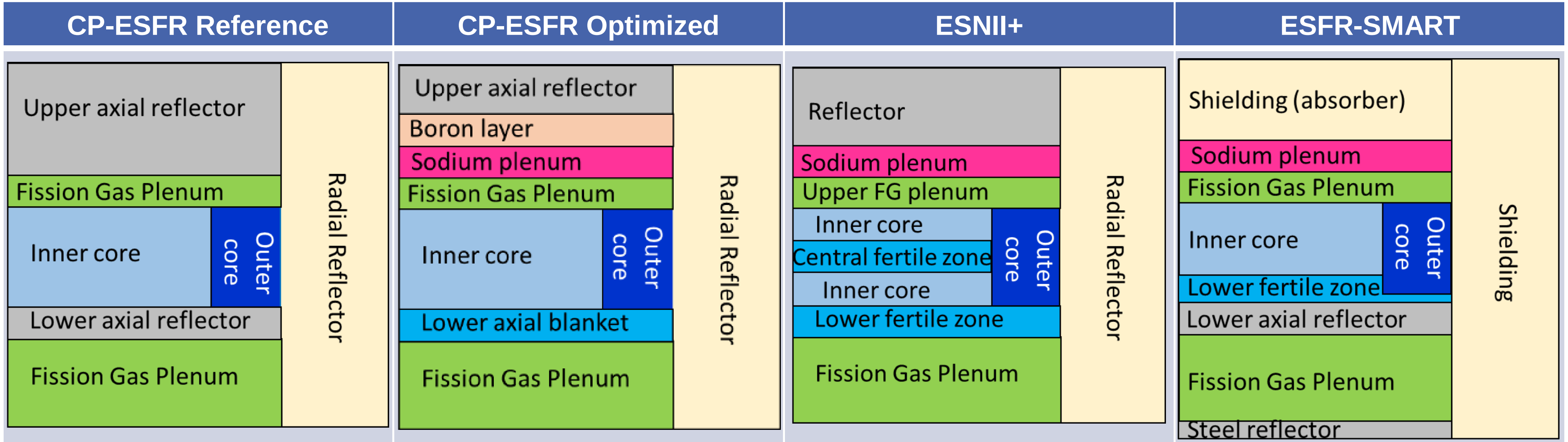
SFR Safety Analysis, ULOF importance:

- Potential to progress into the coolant boiling phase (and eventually into partial or even total core destruction).
- Detailed consideration of the particular effects of various specific design characteristics (e.g. upper sodium plenum, absorber layers, discharge tubes, etc.).

	CP-ESFR	ESNII+	ESFR-SMART
Time	2009-2012	2013-2017	2018-2022
Target	SFR	Gen-IV (SFR, LFR, GFR…)	SFR
Reactor power (MWth)	3600	1500	3600
Total number of SA	453	291	504
Number of pins per SA	271	217	271
Core inlet temp. (°C)	395	400	395
Core outlet temp. (°C)	545	550	545
Av. core structure temp. (°C)	470	475	470
Reactor performance	Minor Actinides transmutation	ASTRID	Improved CP-ESFR reactor
Safety measures	decrease sodium void worth	negative sodium void worth	corium discharge tubes passive SR (Curie-point triggered)

S. Perez-Martin, E. Bubelis, et al. On the Pursuing of Safety Enhancements in Sodium Fast Reactors. Proceeding of the 10th European Review Meeting on Severe Accident Research (ERMSAR2022) , Karlsruhe, Germany, May 16-19, 2022. doi.org/10.5445/IR/1000151444

SFR reactor designs in EU projects



Sodium void (density) reactivity:

- Less neutron capture (positive effect)
- Neutron spectrum hardening (positive effect)
- Larger mean free path: neutron leakage increase (negative effect)

Measures:

- a large sodium plenum at the top of the core (where neutron leakages are increased)
- axially heterogeneous fuel pins with a central fertile layer in IC (increasing neutron flux in the upper fissile layer)
- shortening of the fissile zone in the IC
- absorbing zone in upper shielding (reducing neutron reflection back to the fissile core during voiding)

ULOF transient

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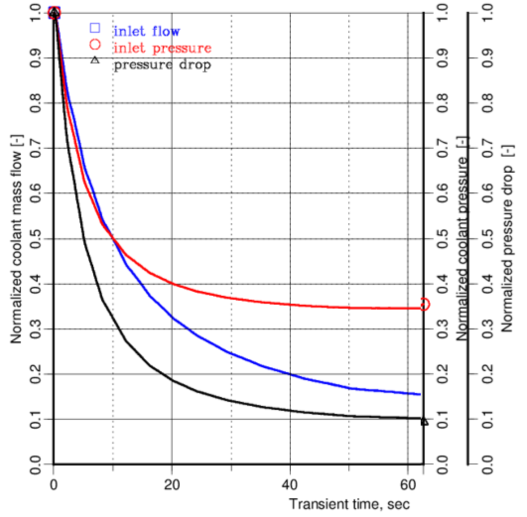
- Unintentional simultaneous coast-down of all primary pumps + failure of the reactor shut-down system.
- The primary mass flow rate:

$$\frac{\dot{m}(t)}{\dot{m}_0} = \frac{1}{1 + \frac{t}{\tau}}$$

- τ (halving time): 10 s, except for ESNII+ case which is 24 s.
- No pony motors or other devices maintaining coolant
- EOEC conditions (except for the CP-ESFR Opt. at BOL): degraded fuel & control rods withdrawn
- Reactivity feedbacks: Doppler, fuel cladding, sodium reactivity, control rods driveline thermal expan.



- CP-ESFR:
  - The optimized core improved the safety response by reducing peak temperatures and enlarging grace times.
  - Not sufficient to avoid a power excursion once sodium boiling commenced.

- ESNII+:
  - Upper sodium plenum provided only a small delay in boiling onset (void effect dominated by the fissile core voiding) → sodium plenum does not play a decisive role in improving total void effect
  - Transient progression beyond pin and hexcan failure, driven by cladding failure and relocation from the fissile core zone.
  - Optimization of the core neutron physics alone was not sufficient to avoid a power excursion during the ULOF transient.

SAS-SFR results for ESFR-SMART ULOF

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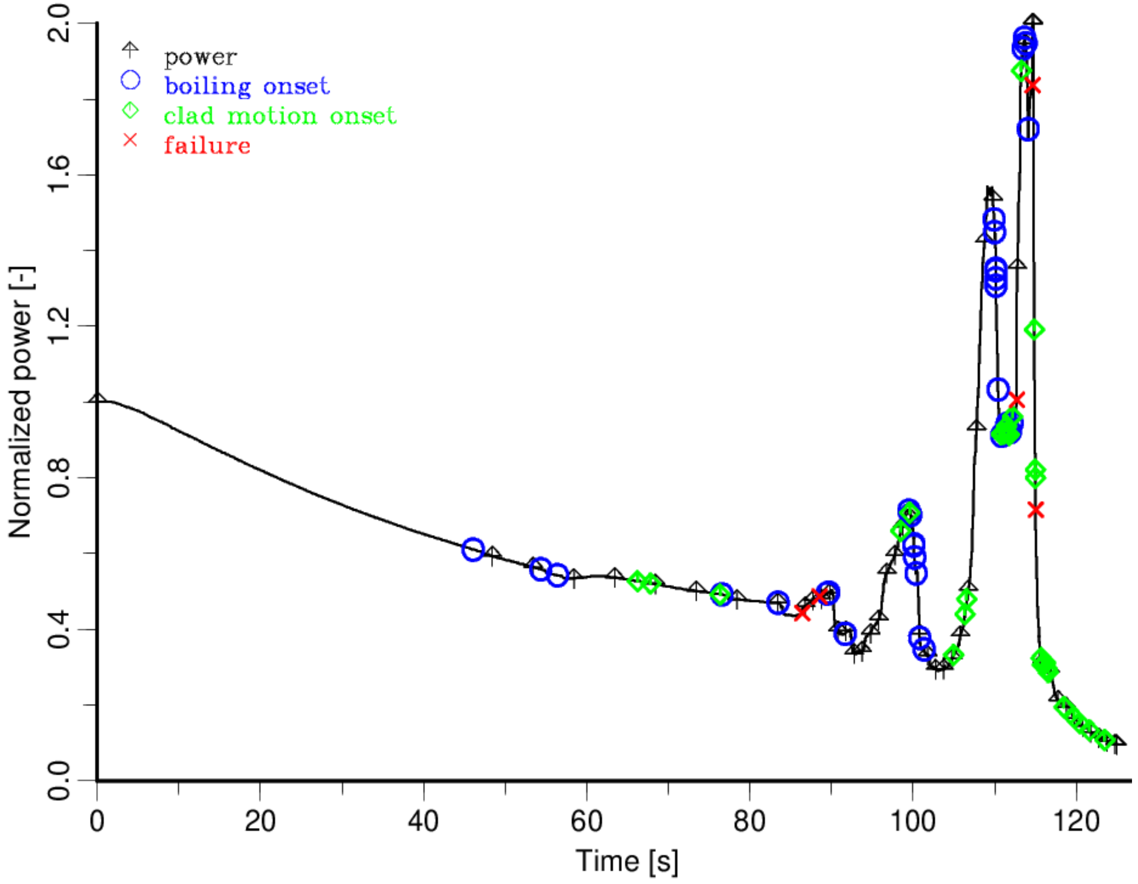
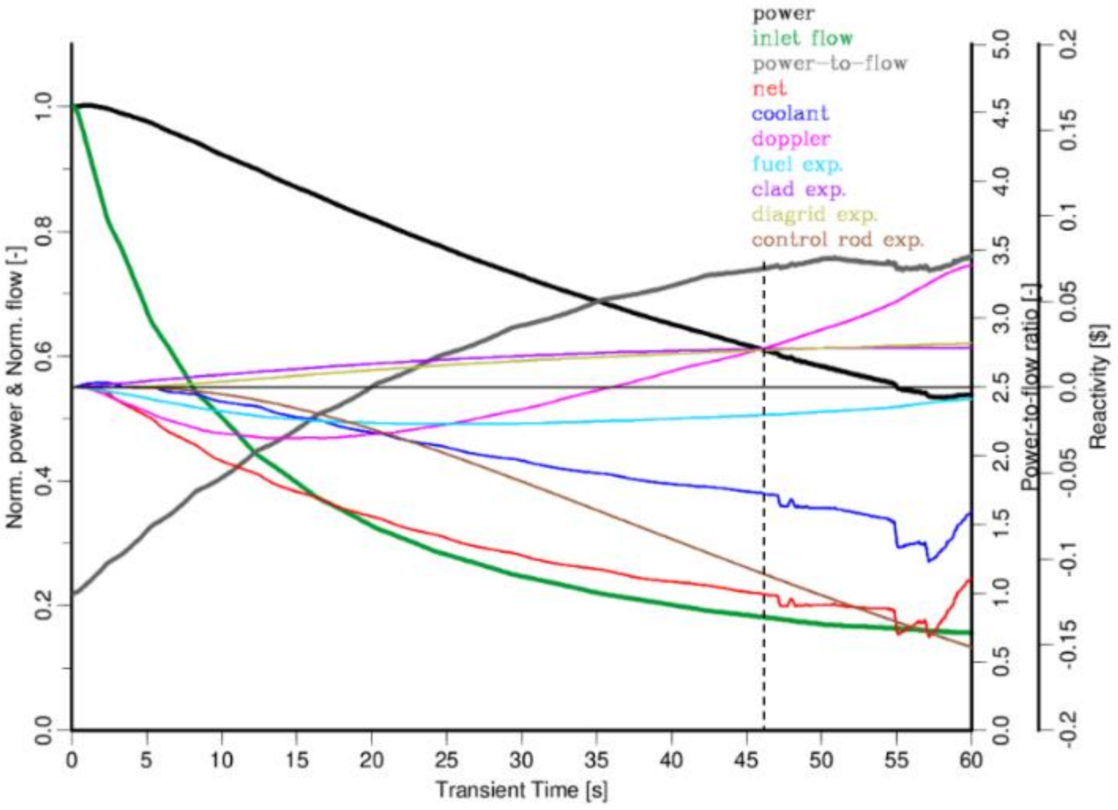
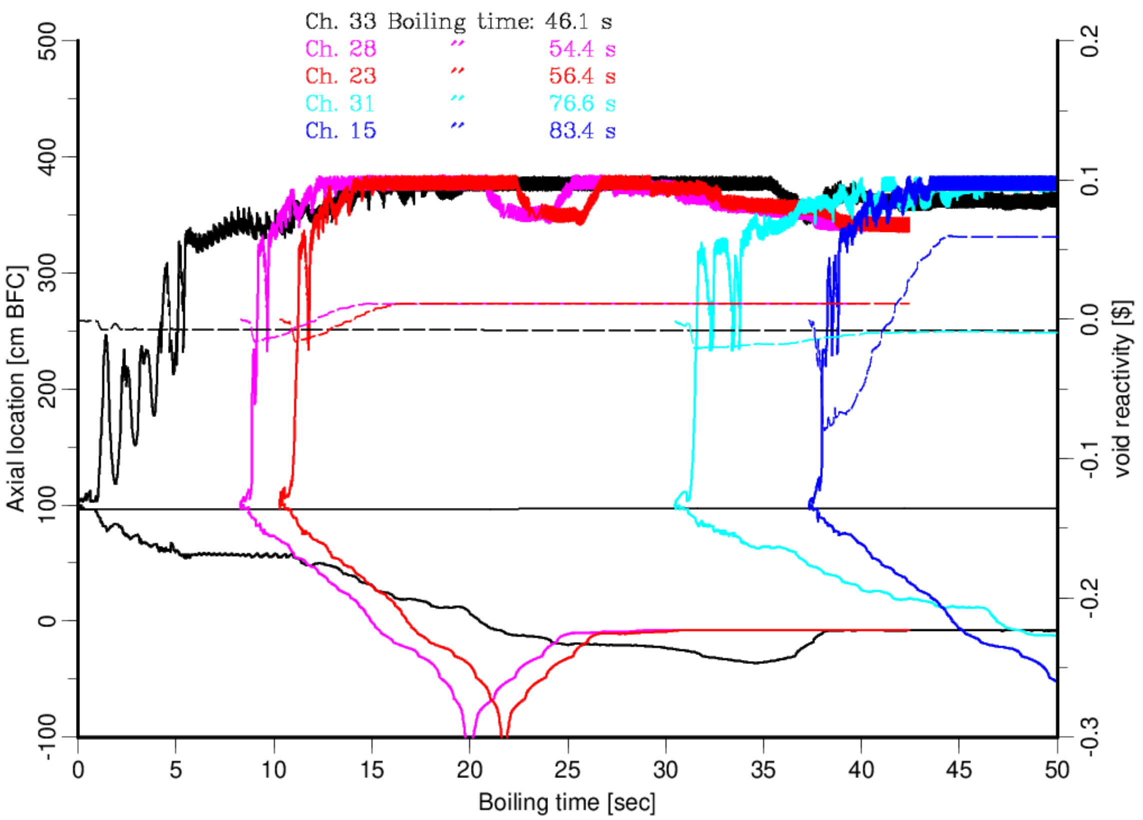
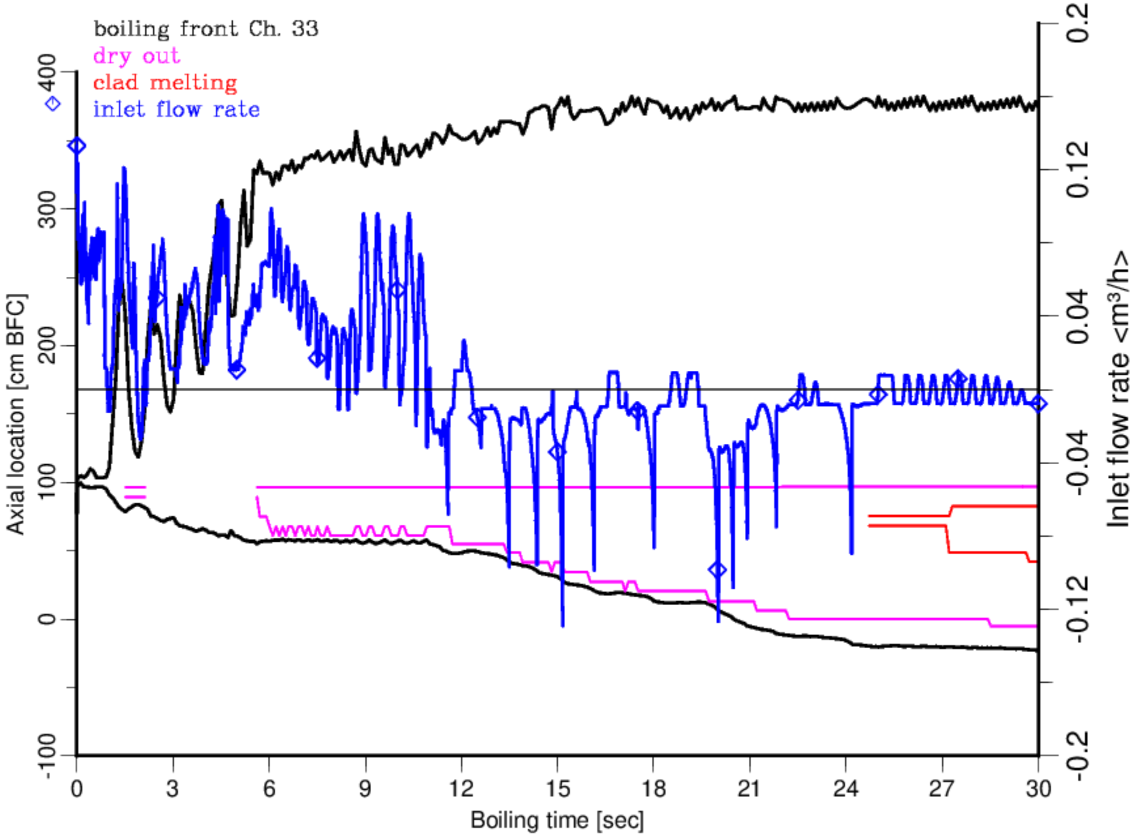
- Sodium boiling starts in ch. 33 (OC) at 46.1 s, nominal power is 0.61, net reactivity is -0.12 $.





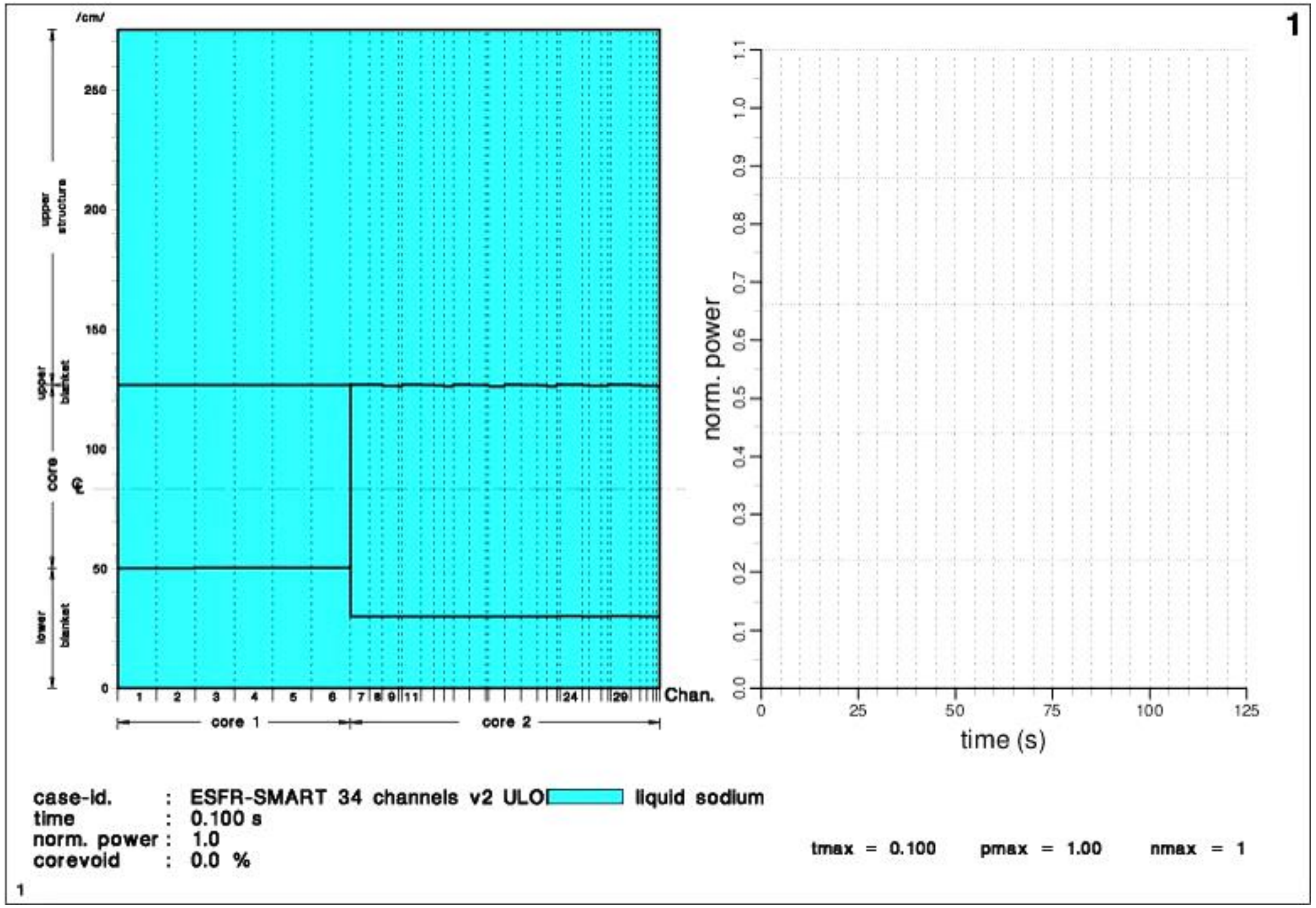
SAS-SFR results for ESFR-SMART ULOF

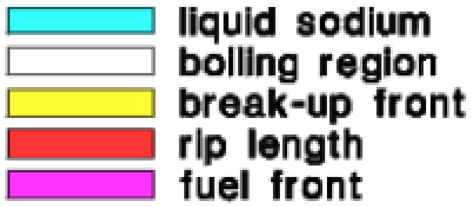




Fuel pin break-up failure mechanism: clad integrity compromised due to the high clad temperature and fuel pellet heat-up exceeds the melting limit and built-up cavity pressures.

SAS-SFR results for ESFR-SMART ULOF





Video

504 SAs with 271 pins per SA

Computational running time

- 36 representative pins (6 ch. inner core, 30 ch. outer core)
- Fuel pin irradiation:
  - Real irradiation time: 1800 d
  - Computing time: 38 min. total → ~1 min. per SA
- ULOF transient:
  - Real transient time: 125 s
  - Computing time: ~17 h total → 0.5 h per SA

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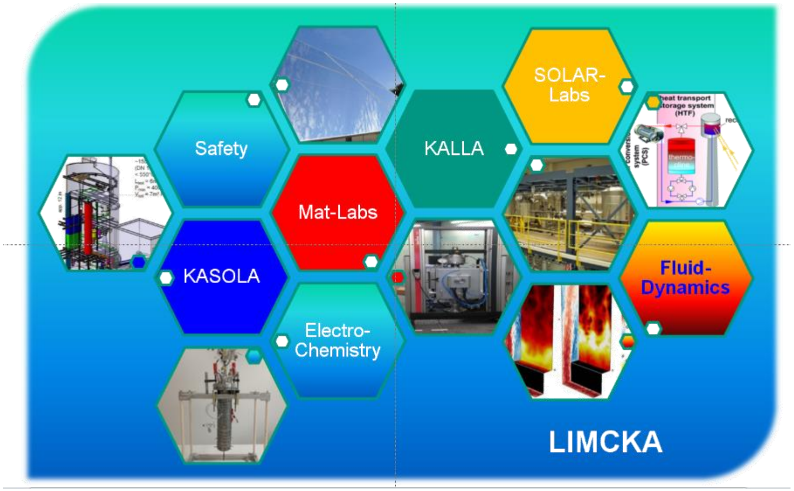
LIMCKA: LIquid Metal Competence center at KIT

- Energy and process technologies
- Combination scientific work on thermal hydraulics and technology development
- Application areas:
  - CSP – definition of key components and technologies
  - Medicine: providing cooling to high energy targets
  - Engineering: providing high heat load solutions for FUSION (Divertor, FW….)
  - Training including safety provisions and LM handling
- Competences:

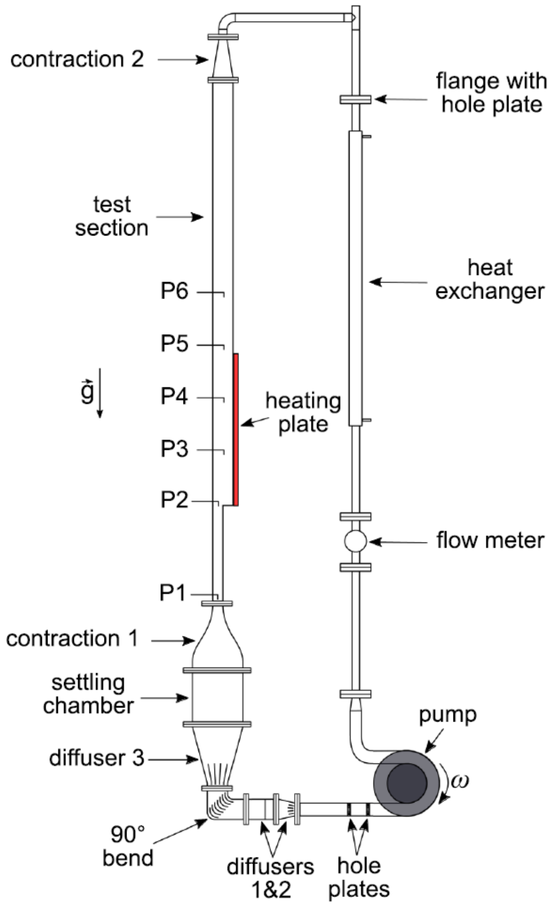


Material technology	Momentum/energy/mass transfer	Systems & components
Structural materials Functional materials Protective layers and surface alloys Material degradation Joints – heat treatment Fabrication Momentum transfer	Heat transfer Multi-phase flows Process design Fluid conditioning Thermo-electric conversion	System design Safety assessment Operational/loop analysis Instrumentation Component qualification Active liquid metal system units

Hering, W., Fuchs, J., et al. "Experiment and Codes to Support Safety Assessments for Sodium Fast Reactors (KASOLA, SOLTEC and KARIFA)." ASME. *ASME J of Nuclear Rad Sci*. January 2022; 8(1): 011324. doi.org/10.1115/1.4052642

DITEFA

- Multipurpose GaInSn test facility for TH investigations (~30 liters)
- Modular manufacturing concept allowing adaptation of future LM experiments
- First experiment: confined vertical Backward Facing Step.
- Intermediate step before the integration of a BFS-experiment in KASOLA
- Flow separation and its reattachment due to a sudden cross-section expansion of the duct.
- Experimental data on velocity profiles, temperature profiles, mean average reattachment point and turbulent heat flux:
  - Data to be used for CFD-code validation
  - Physical phenomena of fluid flow and convective HT regime transition
- Permanent magnet probes detecting very low mean-average velocities locally.
- Thermocouples (instead of copper electrodes) can measure local temperature fluctuations.



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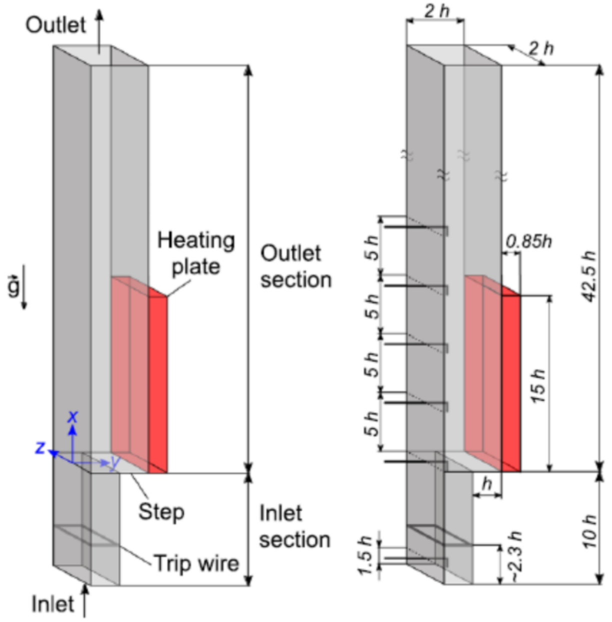
DITEFA Test Facility

DITEFA

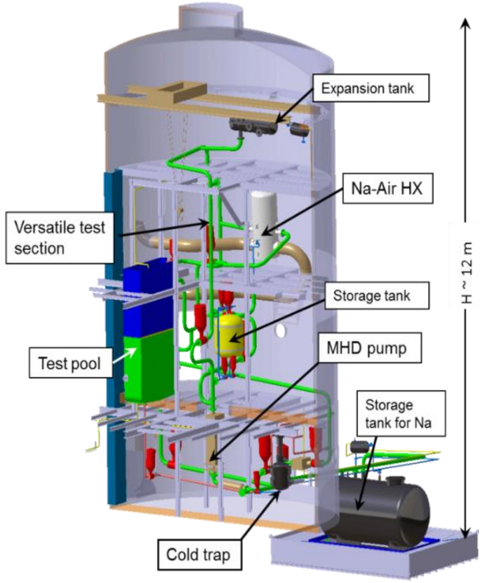
- Experiments conducted for different Reynolds and Richardson numbers (forced, mixed convection)
- Time-averaged velocity profiles measured at six streamwise position
- Local Nusselt number measured in stream- & spanwise directions along the heating plate
- RANS simulations: study the qualitative influence of assuming cte. heat flux condition
- Measured velocity profiles: expected behavior for both convection regimes
- Measured local Nu profiles not as expected (due to heating plate th. condition assumption).
- Estimation forced- to mixed convection trans. onset: good agreement with experiment but further measurements are needed to validate the estimated transition threshold.



- PhD Thomas Schaub „Experimental Analysis of a Turbulent Liquid Metal Flow in a Heated Vertical Confined Backward Facing Step“
- Schaub, T., et al. “Design and calibration of permanent magnet probes for the local measurement of velocity and temperature in a liquid metal backward facing step flow. Exp Fluids 62, 210 (2021). doi.org/10.1007/s00348-021-03293-6
- Schaub, T., Arbeiter, F., et al. Forced and mixed convection experiments in a confined vertical backward facing step at low-Prandtl number. Exp Fluids 63, 19 (2022). doi.org/10.1007/s00348-021-03363-9

KASOLA: KArlsruhe SOdium LAboratory

- Versatile experimental facility to investigate flow phenomena in sodium for solar and nuclear applications.
- Sodium inventory of 7 m³, and it can operate in the range of about 150–550 °C.
- A magneto-hydrodynamic pump provides a max. flow rate of 150 m³/h at a pressure head of 0.4 MPa.
- Three experimental ports for LM experimental investigations:
  - The primary test section ~ 6 m for developments and investigations of targets, component tests and experiments with high mass flow rates.
  - The second test port connects a direct thermal storage device foreseen to test the dynamic capabilities of a frozen thermocline storage tank (FlexStor).
  - Low temperature port separating experimental loops or devices, which can use the calibration and cleaning units of KASOLA can be connected.



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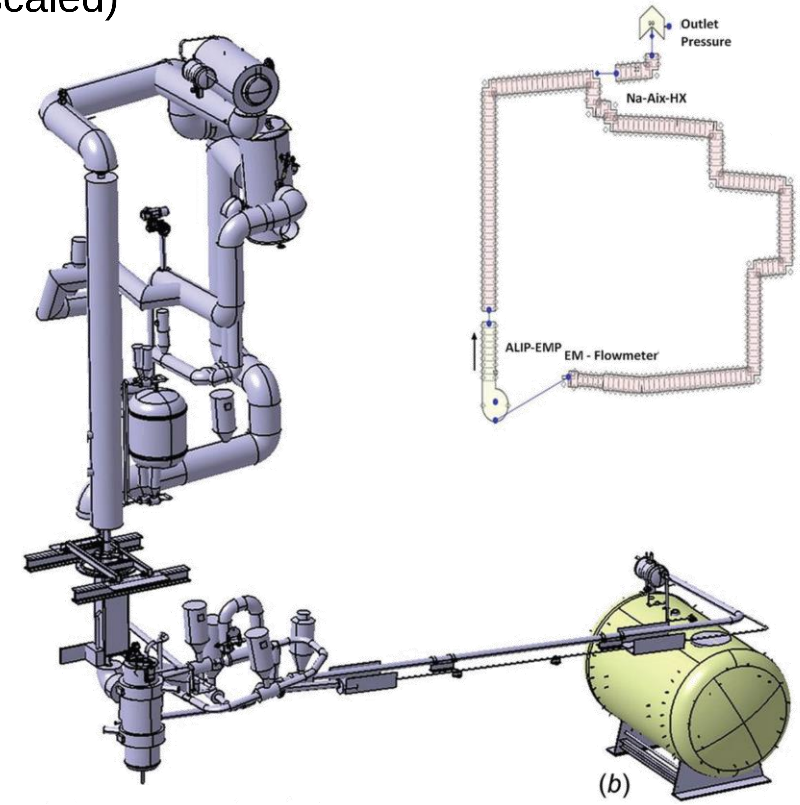
KASOLA

- Wide spectrum of TH experiments for solar and nuclear applications:
  - Qualification, validation and improvement of **turbulent LM HT models in CFD** and reduced order models
  - Development of **free surface liquid metal targets** for accelerator applications
  - Investigation of **transition in convective flow patterns** (forced, mixed and free convection)
  - TH investigations of flow patterns in bundles or pool configurations (prototypical/scaled)
  - Qualification of components and instrumentation for sodium applications in CSP

- Main Characteristics:
  - Temperature up to 550°C
  - Mass flow rate up to 150 m³/h
  - Pressure drop along the loop at full flow rate: 2.5 bar
  - Heat-Sink capability 400 kW
  - Base loop length ~37.7 m
  - Base loop volume 1-1.2 m³



KASOLA commissioning and qualification tests

	Tests
I&C tests	Thermal energy balance Test of control and safety limits (Overpressure, over-temp.) Test of interactivity between PLC-ISS and manual interaction Leak detection, video inspection, ISS actuation Test of air blower and air heater for AHX Check of sensitivity of fuse failure
	Valve operation and trace heating under any conditions Heat-up and Cool down tests (without HX) Heat-up by pump operation Emergency cases and operator reaction
Static tests	Test of level overflow
	Cool down test (HX activated) Calibration of EM flow meters Fill and normal drain / Fast drain (emergency) Convection assessment

	Tests
Flow control	Test of actuators and programs Pump curves and shut down/coarse down dynamics Cold trap and calibration loop test Emergency draining from 250°C
	Final test of warning and emergency signals (temp., level, press.) Check of sensitivity of fuse failure
Training	Training on sodium handling (component cleaning, glove box oper.) Training on sodium and lithium fires Fire brigade instruction and testing of extinguishing provisions
Safety	Check temperature at insulation outer skirts Check of argon injection in storage building
	Emergency draining from 250°C Check of remaining Na in case of emergency drain

CONCLUSIONS

- Assessment of SFR performance + verification & validation of computational tools

- Future R&D:
  - Sodium two-phase flow: large scale code validation comparisons based on experimental data sets (KNS-37 test)
  - New two-phase flow experimental tests reflecting the current trends in core designs.
  - Large scale clad relocation prevention: core and SA-design measures or min. flow rate (active/passive means, pony motor)
  - Assessment of SMRs based on SFR technology, where high benefits are expected in terms of safety and flexibility.
  - New code strategies to find the right compromise between:
    1. computing capabilities (new programming languages, parallelization, etc.)
    2. phenomena description (neutronics, thermal-hydraulics, pin thermal-mechanics, corium relocation, etc.)
    3. details of reactor description (pin-by pin level, core level or up to whole plant level).
    - Advantages for the safety analysis of advanced systems (Machine Learning, Digital Twins) compared to current Fortran-based codes
    - Attractive research to future nuclear engineers/scientist → costly person-intense requiring support of public and private stakeholders.