Karlsruhe Institute of Technology

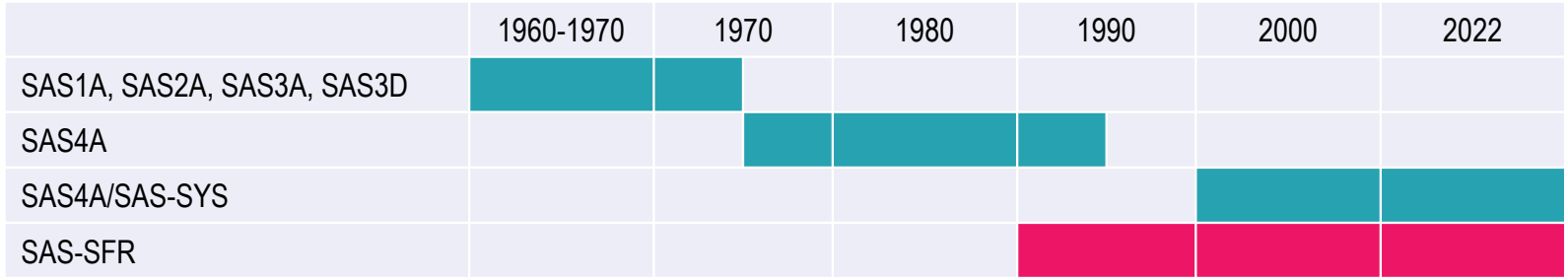
ESFR-SMART
sodium fast reactor safety

WP:	**WP3.1 “Dissemination, education and Training”**
Task:	3-1-3 Workshops and Summer School
Lecture :	***Mechanistic codes: SAS-SFR***
Speaker:	*Sara Perez-Martin*
Affiliation:	*Karlsruhe Institute of Technology*
Event:	Workshop N°7 Sodium-Cooled Fast Reactor Severe Accidents
When:	2022 April 5th-8th
Where:	Pertuis (France)

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754501.

SAS4A Origin

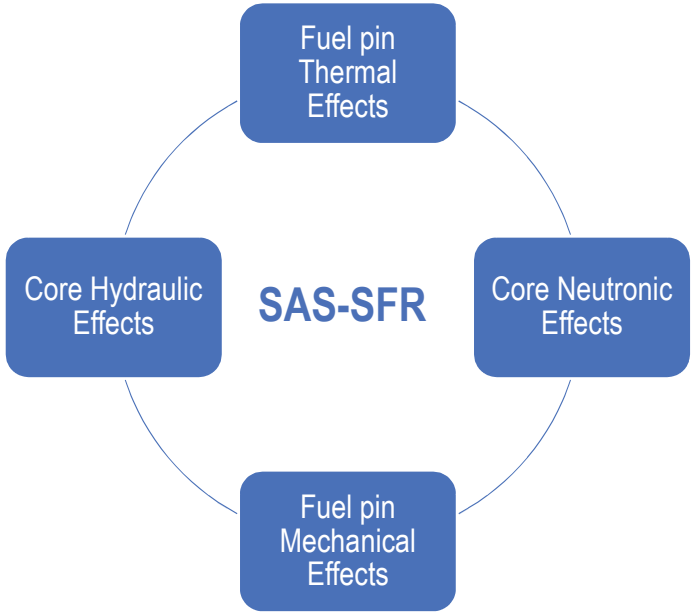
- The code was designed to predict accident consequences focusing on the initiating phase of core disruptive accidents resulting from unprotected under-cooling or overpower conditions.



- SAS-SFR code is based on the SAS4A (**S**afety **A**nalyses System) code developed by Argonne National Laboratory (ANL).
- SAS3A was used for licensing of Fast Flux Test Facility (FFTF) while SAS3D/SAS4A for Clinch River Breeder Reactor Project.
- FZK (KIT), CEA-IPSN (IRSN), and PNC (JAEA)-Oarai formed a consortium to further develop SAS4A accident oxide fuel models and SAS-SFR is the result of this fruitful cooperation over more than 20 years.
- SAS4/SAS-SYS documentation available https://wiki.anl.gov/sas (partly valid for SAS-SFR, though major parts were revised)
- 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



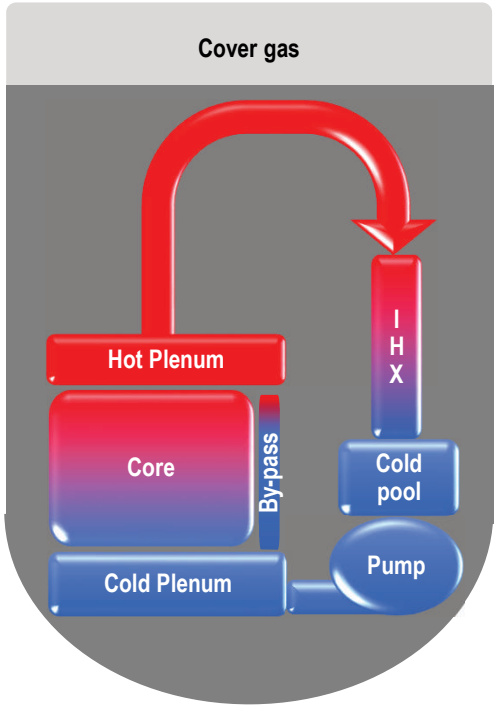
- Outcome: code models limited to 1D phenomena → good compromise for events occurring up to hexcan integrity failure, core damage is limited to fuel assemblies and the motion of the failed fuel is uniformly controlled by the wrapper tube wall.

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

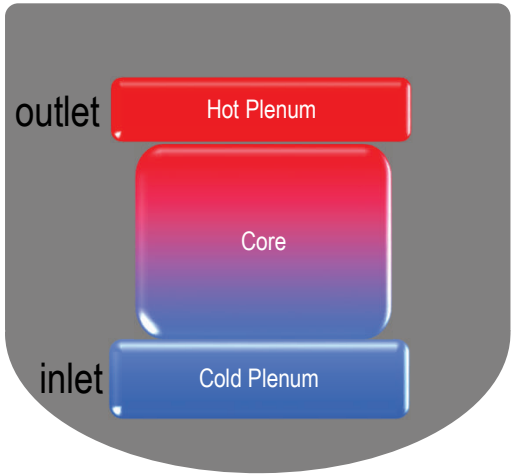


PRIMAR-1: Simple Primary Loop Model

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

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

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



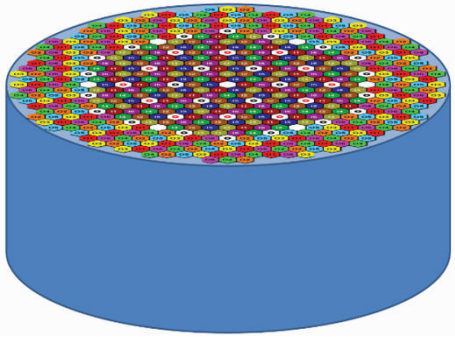
Core Model: Multiple SA Channels

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

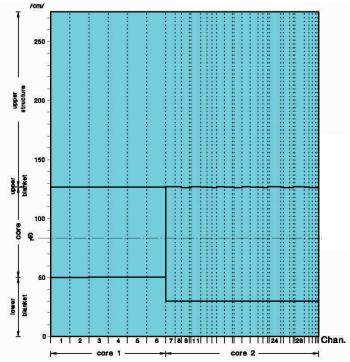
- Grouping criteria:
  - Number of batches in a multi-batch core load: 3 to 5 per enrichment zone
  - Number of cooling groups in a core load: up to 5
  - Peak linear rating differences between SA groups: < 5 - 10 %
  - Coolant outlet temperature differences between SA groups: < 15 K

- 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.



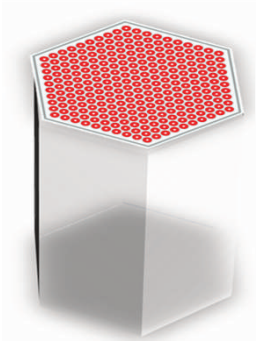
ESFR-SMART core



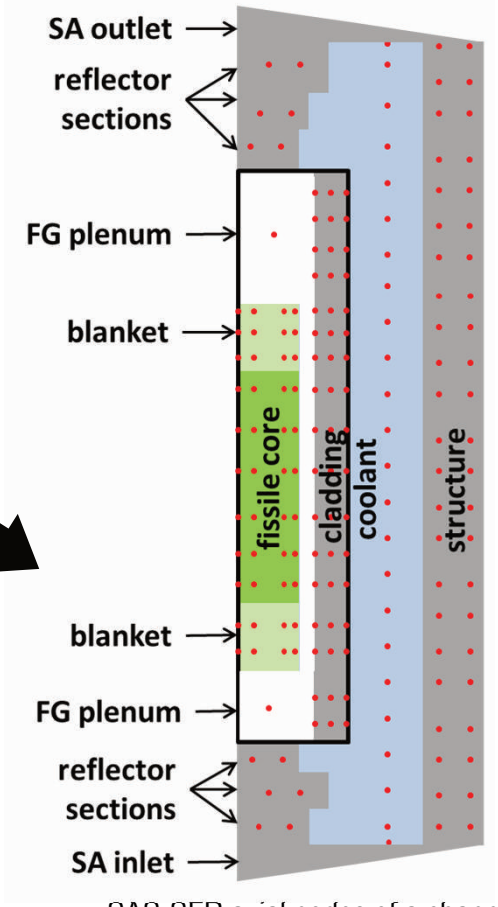
SAS-SFR representation with 34 SA channels

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

Point kinetics and reactivity feedback models

Fission flux amplitude is computed by a numerical solution of the point kinetics equations given the net reactivity computed as:

- programmed reactivity
- reactivity feedbacks due to reactor **materials density** and **temperature** changes
- radial core expansion due to structural material heating
- control rod insertion due to driveline thermal expansion

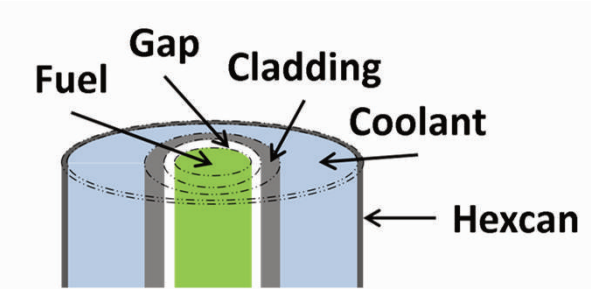
The **material density** reactivity feedbacks computed by first order perturbation theory $\alpha = \frac{\delta k}{\delta m}$ for:

- coolant (liquid heating and boiling)
- cladding (axial expansion in DEFORM, melting and relocation in CLAP, LEVITATE)
- fuel (axial expansion in DEFORM, melting and relocation in PLUTO and LEVITATE)

The **fuel temperature** Doppler reactivity feedback computed using the usual 1/T dependence $\frac{d(\delta k_D)}{T_f} = \frac{\alpha_D}{T}$

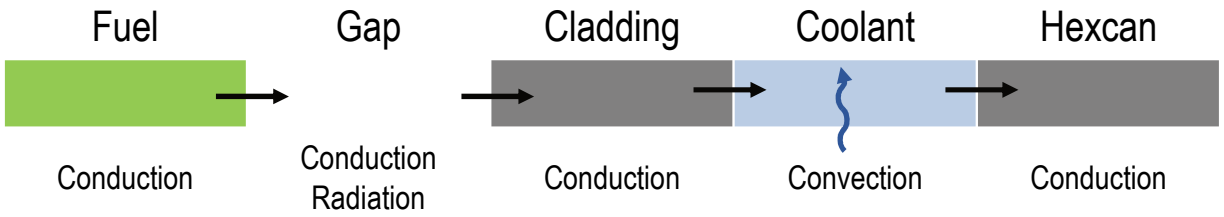
Fuel Pin Heat Transfer Model

- One-dimensional radial heat transfer at many axial nodes
  - Fuel thermal conductivity and other fuel properties
  - Fuel to clad heat transfer i.e. the URGAP model
  - Clad to coolant heat transfer
  - Coolant to structure heat transfer



- Heat conduction in reflectors and structures materials represented as two slab plate geometries.

- Clad to coolant heat transfer correlations for tube flows (Subbotin et al. for circular channels $Nu = 5.0 + 0.025\ Pe^{0.8}$)



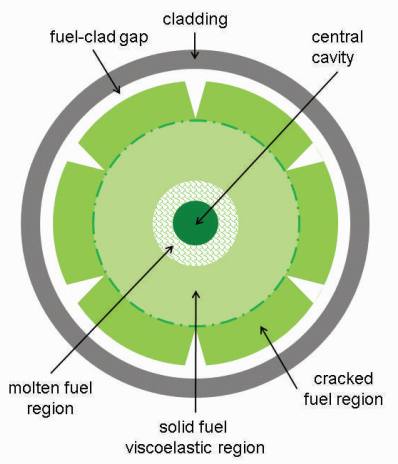
Fuel Pin Thermal-Mechanical Model

Gap conductance → fuel & cladding temperatures → swelling & thermal expansion of fuel and cladding

	HTC	fuel temperature	fuel swelling	thermal expansion	restructuring	FG release	stored energy
closed gap	↑	↓	↓	↓	↓	↓	↓
large open gap or low gas mixture conductivity	↓	↑	↑	↑	↑	↑	↑

- SAS-SFR has 3 gap conductance models, but the recommended one is the URGAP model:
  - radiation heat transfer between fuel and cladding surfaces h_{rad}
  - conduction through the gas between fuel and cladding h_{cond}
  - solid to solid heat transfer (contact pressure conditions and fuel & clad thermal state) h_{sol}
  - heat transfer modification due to JOG formation in the outer fuel rim h_{JOG}

$$h_G = \left[\frac{1}{h_{\mathrm{cond}} + h_{\mathrm{rad}} + h_{\mathrm{sol}}} + \frac{1}{h_{\mathrm{JOG}}}\right]^{-1}$$

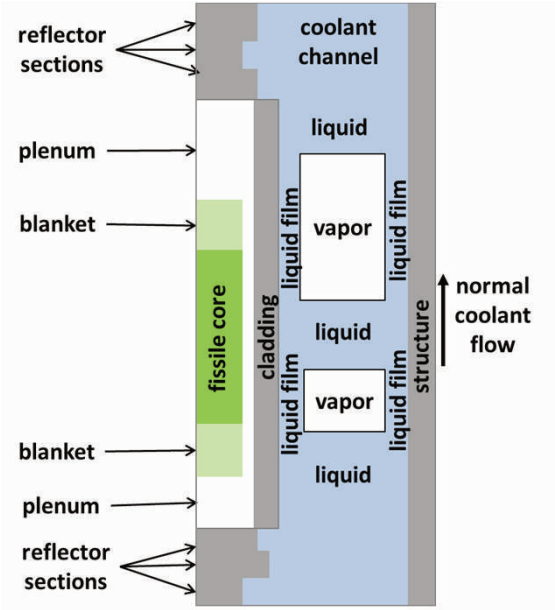


DEFORM-4C radial zones.

- Fuel pin failure criteria:
  - Mechanical failure: clad hoop stress $\sigma_H > \sigma_{cl}^{UTS}\left(T_{cl}^{mid}, \varepsilon_{cl}^{rate}, dpa\right)$ & clad plastic def. $\varepsilon_{cl} > \varepsilon_{cl}^{failure}\left(T_{cl}^{mid}, \varepsilon_{cl}^{rate}, dpa\right)$ failure strain.
  - Thermally induced break-up failure: when clad material loses its strength upon heat-up close to the melting temperature and when the fuel pellet heat-up exceeds the melting limit and built-up cavity pressures.

Multiple bubble/slug & Molten clad relocation

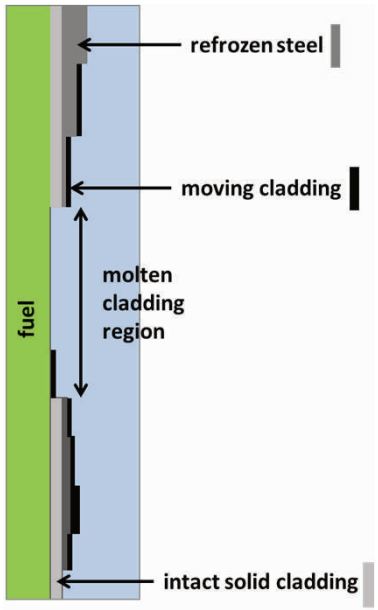
- Axial distribution of the voiding extent → **voiding reactivity feedback**
- Vapour flow rates that drive the **molten cladding motion**
- Finite number of bubbles separated by liquid slugs
- Voiding fills the whole cross section of the coolant channel except for a **liquid film** on cladding and structure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



- Coolant voiding + pin dry-out → rapid heating + subsequent cladding melting → relocation of molten clad material along fuel pin structures.

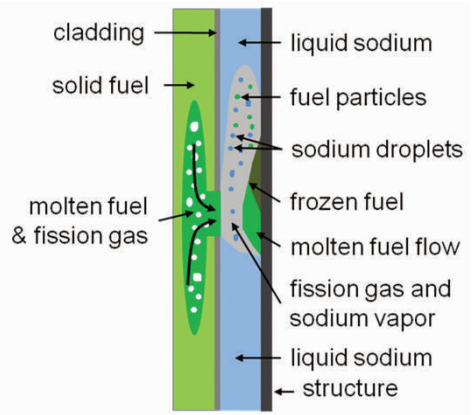
1. Molten cladding motion due to vapor flow (pressure gradient & shear forces) and gravity
2. Relocating molten cladding freezes in cooler structures.
3. Upper frozen cladding blockage

- From experimental clad relocation data: **effective viscosity** of the relocating molten cladding material plays a big role in the dynamics of the relocation process.



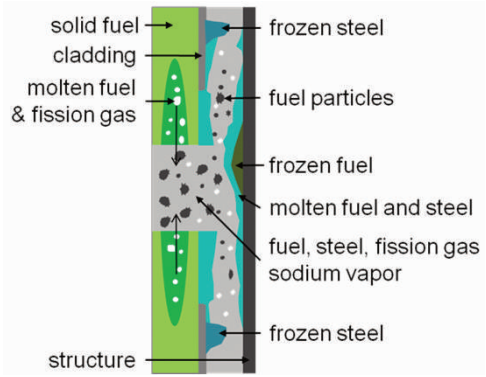
Fuel ejection into the coolant channel

- 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.



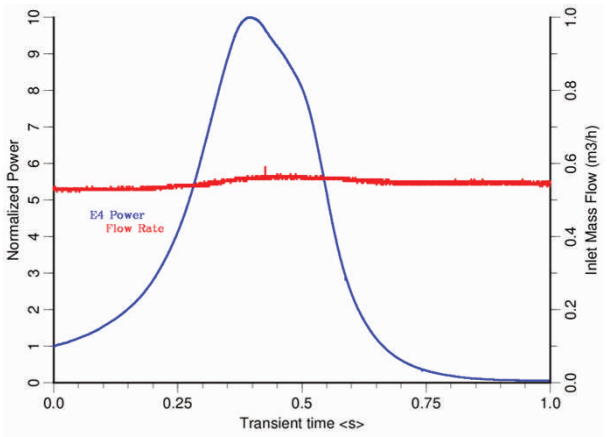
LEVITATE

CABRI E4 thermal test

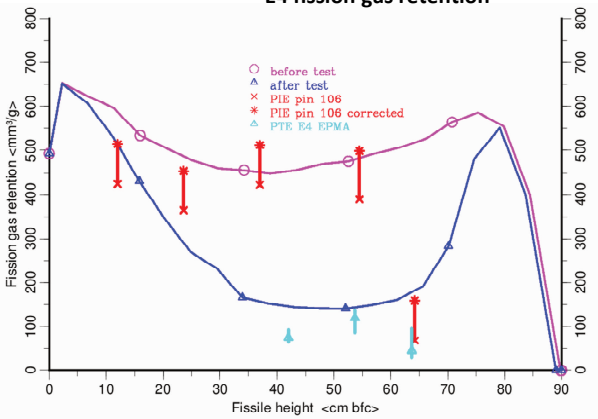
- E4 test: thermal calibration test of VIGGEN-4 fuel pins → insights to irradiated VIGGEN-4 pin characteristics after CABRI steady-state conditions and light power increase.
- SAS-SFR simulation to verify irradiation in PHENIX reactor as well as the CABRI steady-state conditions

- 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.

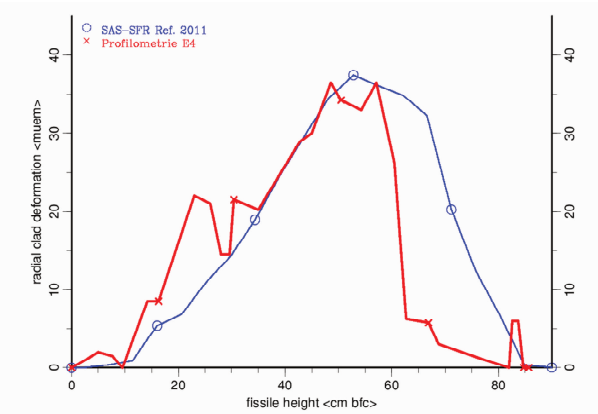
E4 power and flow rate



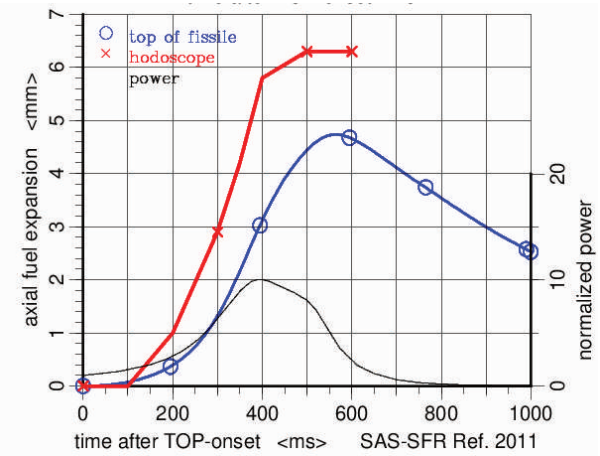
E4 fission gas retention



E4 radial cladding deformation

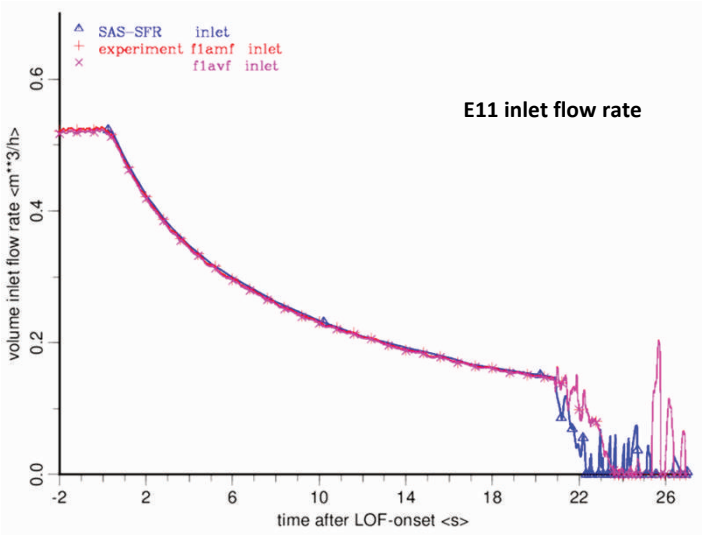


E4 axial fuel expansion



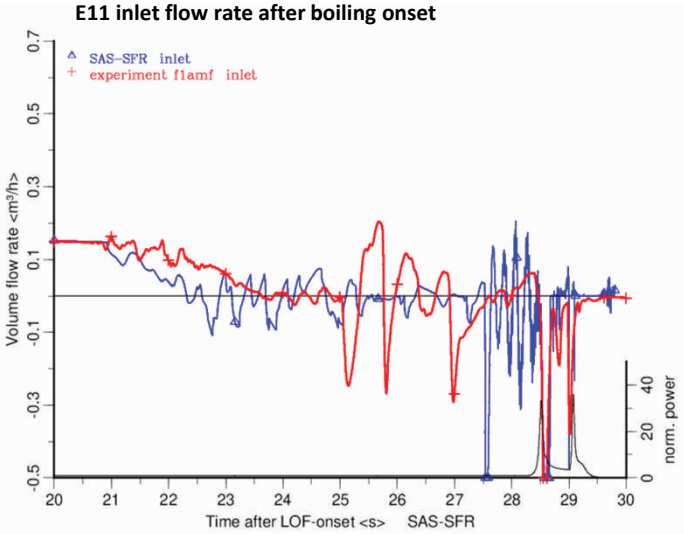
CABRI E11 TUCOP test

- TUCOP= LOF+TOP test

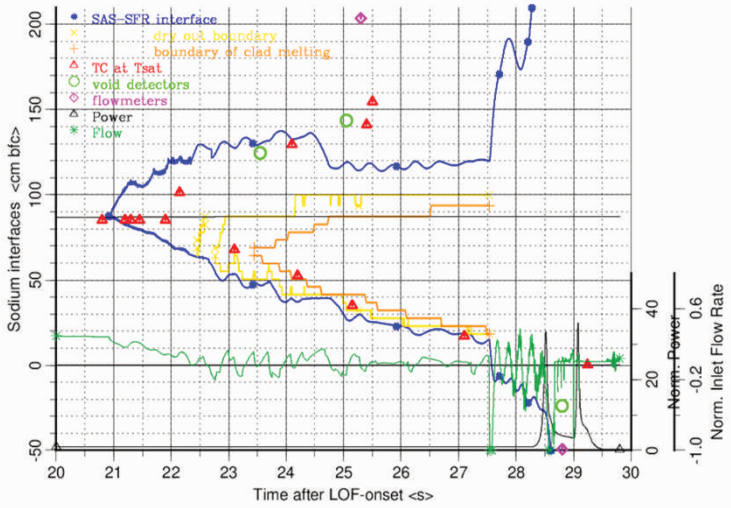


E11 inlet flow rate

E11 inlet flow rate after boiling onset



E11 coolant boiling behavior



CABRI E11 TUCOP test

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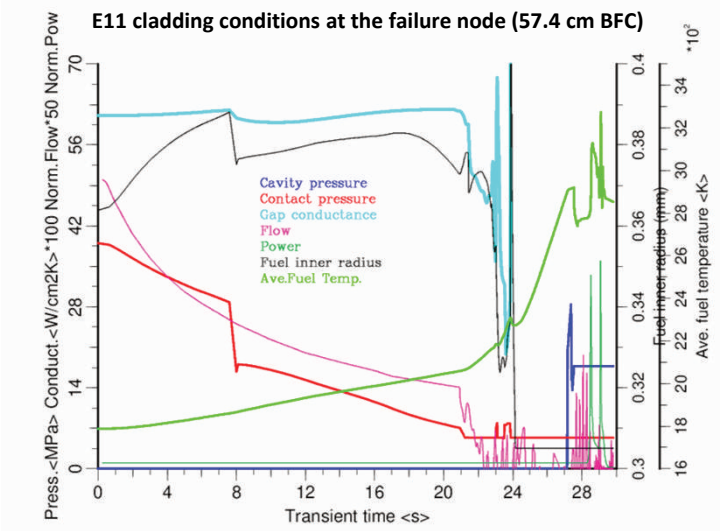
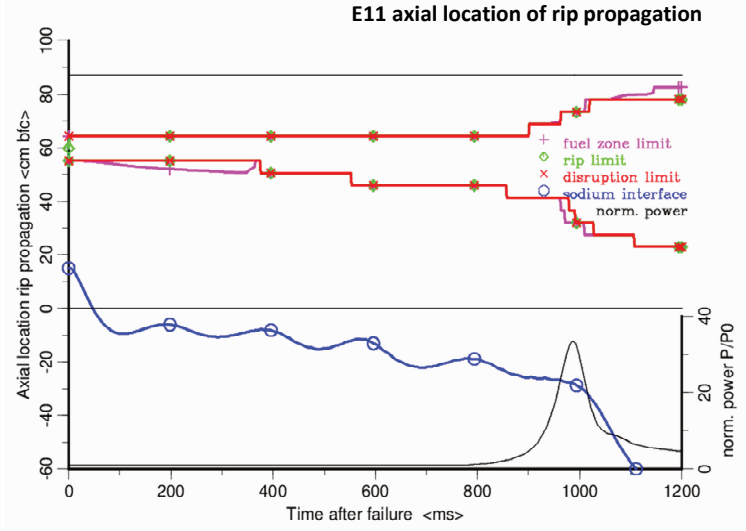
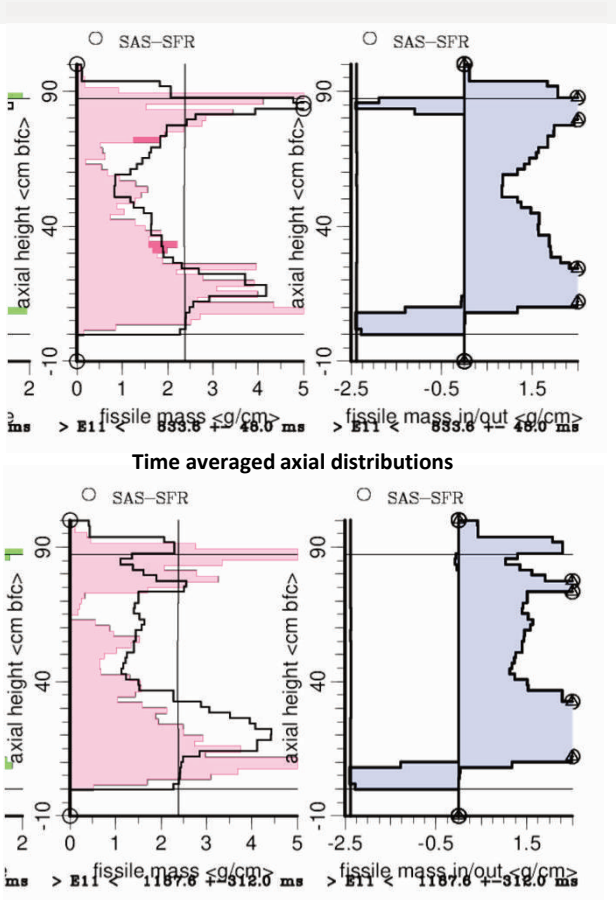
Fuel relocation took place in fully voided coolant channels.







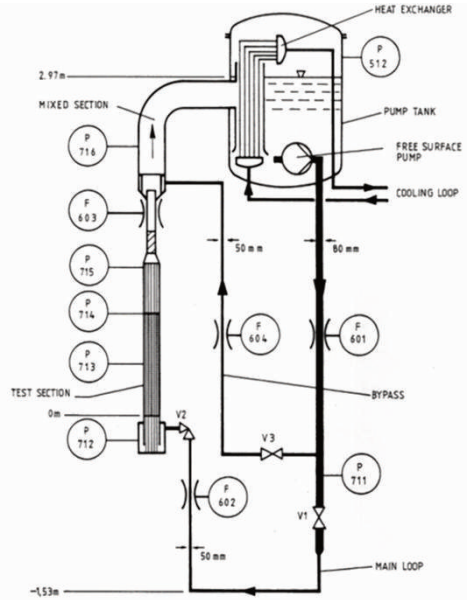
E11 axial profile of the fuel density distribution

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)

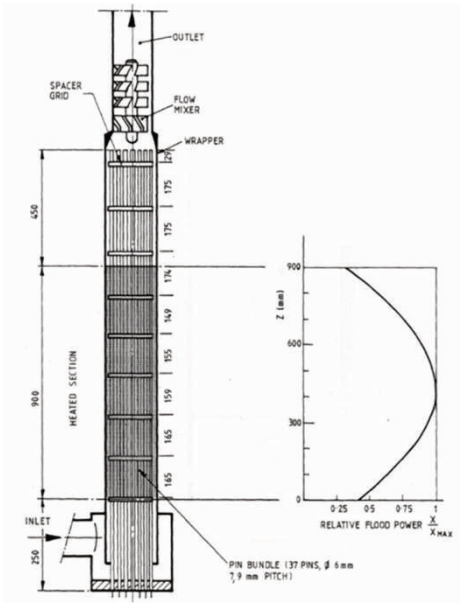
Computational running time
- 1 representative pin (so-called SA channel)
- Real transient time: 30 s
- Computing time: ~5 min.

KNS-37 L22 LOF test

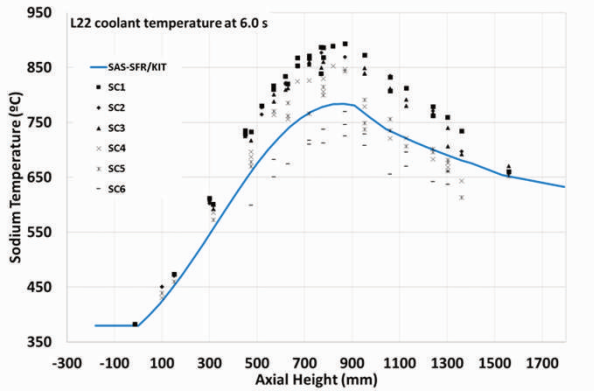
	Experiment	SAS-SFR
Total Power (kW)	717.41	690.13
Average Pin Power (W/cm)	215.44	205.01
Boiling onset (s)	6.11	8.33
Na velocity at boiling (m/s)	0.87	0.73
Dry-out onset (s)	9.25	9.28
Duration of two-phase flow (s)	6.20	2.94

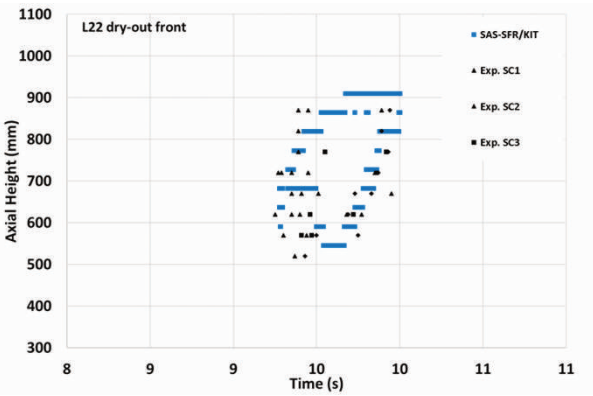


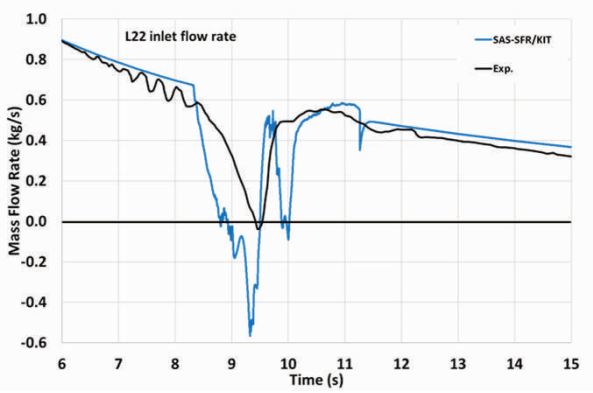
KNS-37 Sodium Boiling Loop

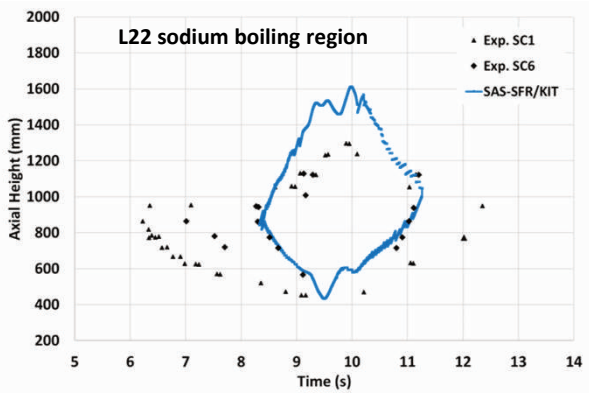


Schematic diagram of the KNS-37 pin bundle





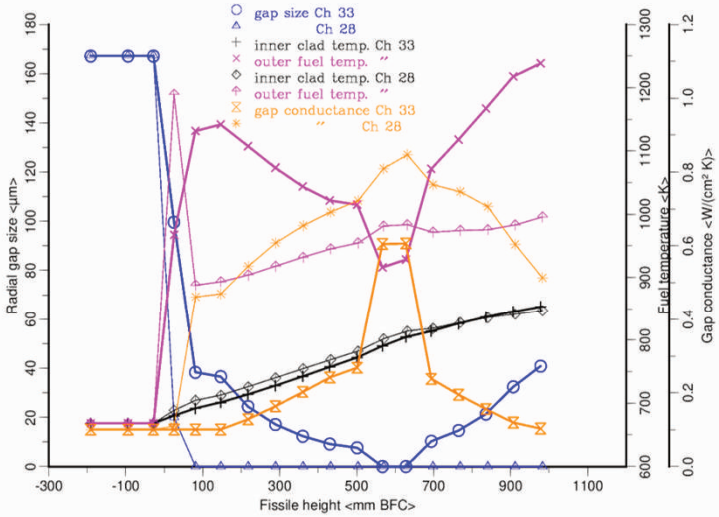


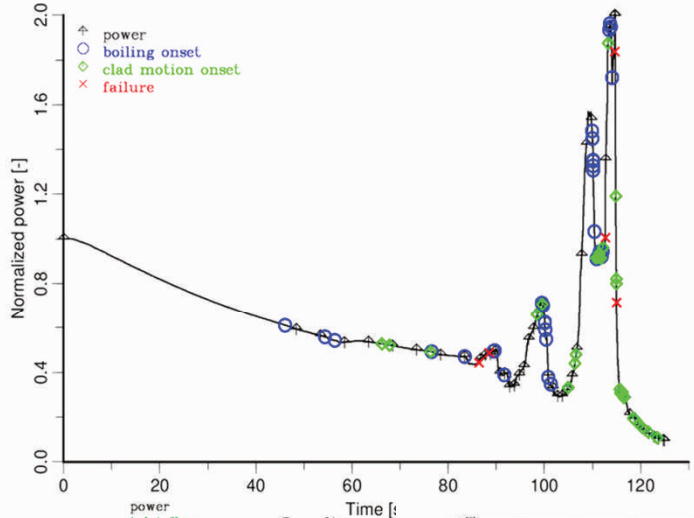


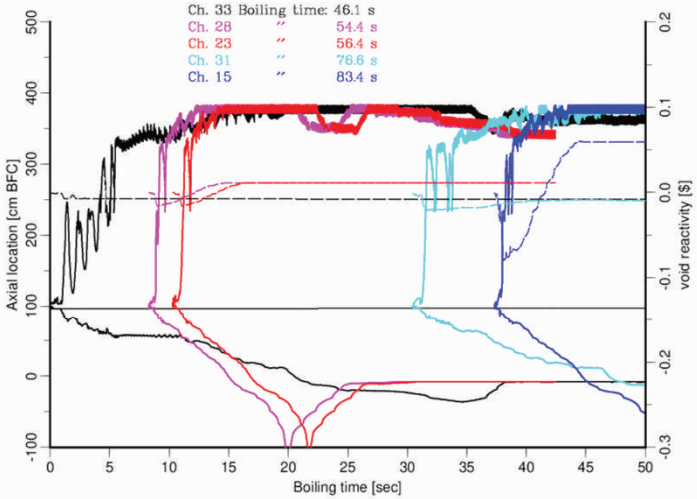
Computational running time

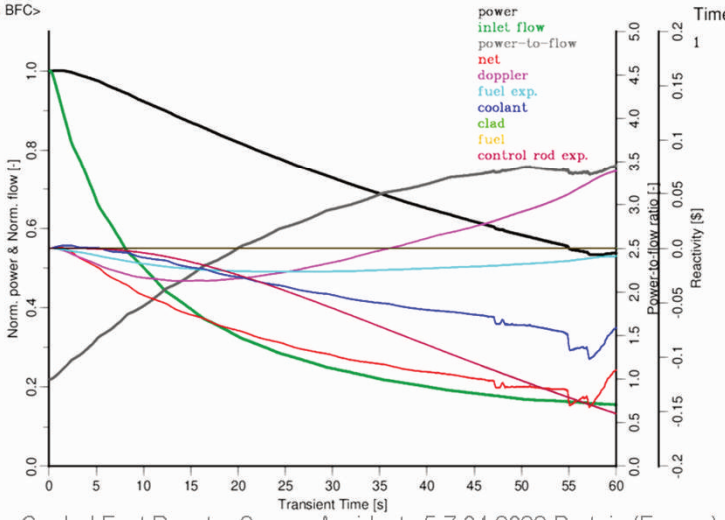
- 1 representative pin (so-called SA channel)
- Real transient time: 15 s
- Computing time: 20 s

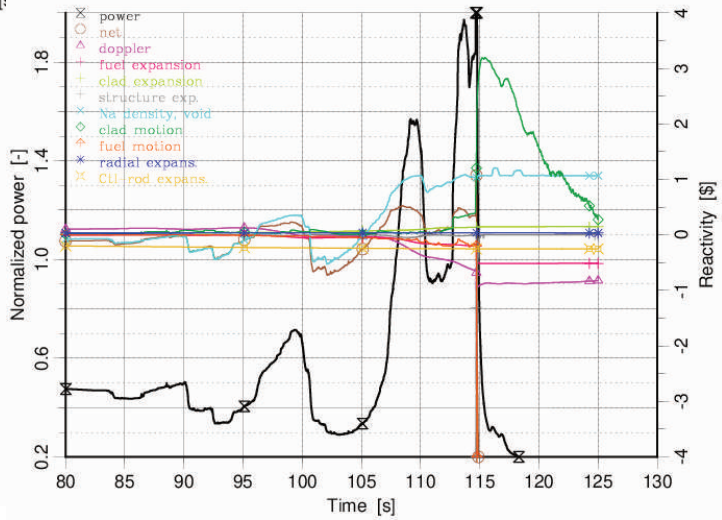
ESFR-SMART ULOF











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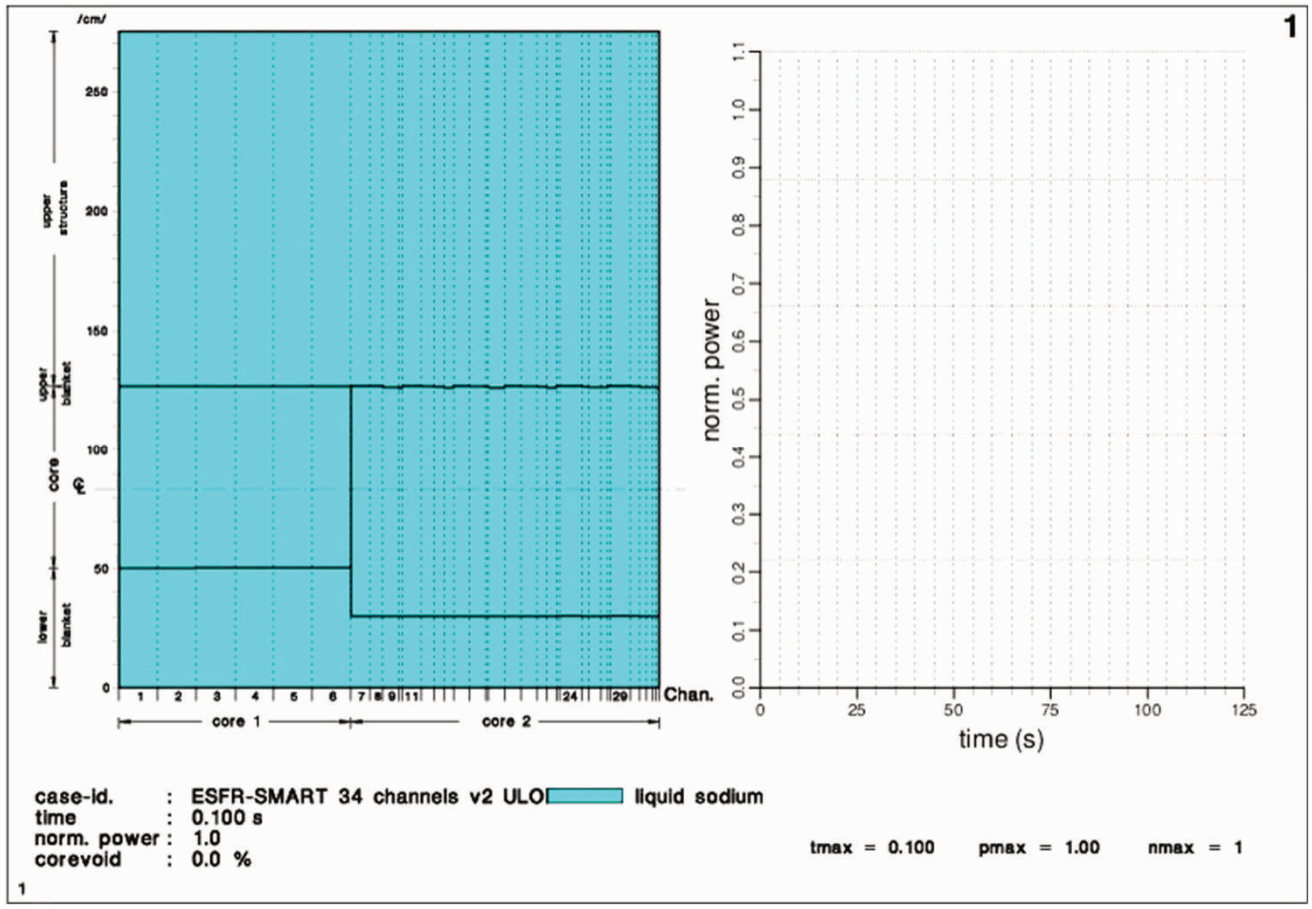
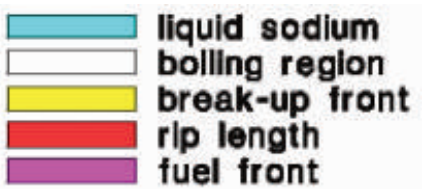


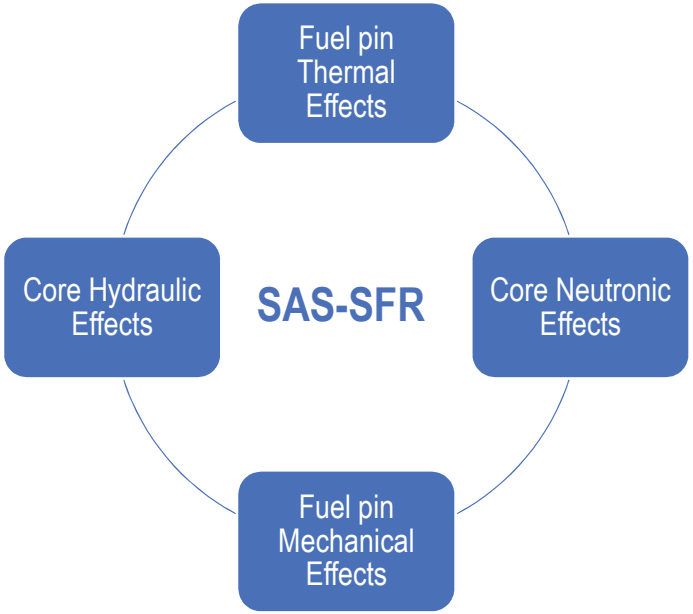


504 SAs with 271 pins per SA
Computational running time
- 36 representative pins (6 ch. inner core, 30 ch. outer core)
- Fuel pin irradiation:
  - Real irradiation time: 1800 d
  - Computing time: 38 min. total → ~1 min. per SA
- ULOF transient:
  - Real transient time: 125 s
  - Computing time: ~17 h total → 0.5 h per SA

Video

Conclusions

- SAS-SFR code provides a very good compromise in the description of the various physical phenomena taking place during the initiation phase of accidentals as well as the scope of those models and the computing resources needed.



- Improvements:
  - Point Kinetics
  - Further validation models (e.g. in-pin fuel motion, etc.)
  - Verification for advanced core designs, code-to-code comparisons