Sodium boiling: phenomena, models and tests
Transitional convection flows

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Motivation

Sodium boiling

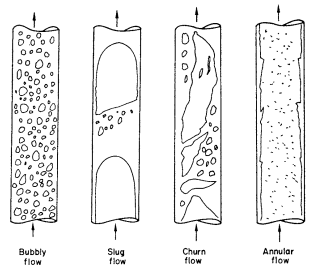
- an unavoidable consequence of ULOF transients in oxide core SFRs (except in RAPSODIE and FFTF)
- in traditional core designs (like PHENIX, SUPERPHENIX, EFR...): power excursion → severe accident (next talk!)
- in designs with above-core sodium plena (ASTRID, BN-1200) negative reactivity feedback → stable state, or maybe oscillations?

⇒ to predict it: models, codes and validation

Transition flows

- during all LOF transients: transition to natural convection
- in sodium, heat transfer remains good at low velocities, but:
  - heat transfer models are needed in system codes → Nusselt number
  - and turbulence models are needed in CFD codes!

Sodium boiling / Phenomena



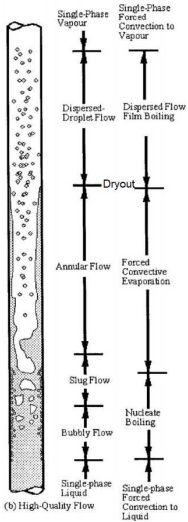
Momentum transfers

Physical properties of Na liquid/vapor in reactor conditons:

- $T_{sat} \sim 900°C$: high margin from normal operation but not far from clad degradation (1400°) once it starts!
- $\rho_l = 740 kg/m^3$, $\rho_g = 0.28\ kg/m^3 \rightarrow \rho_l/\rho_g \sim 2600$ $\rightarrow$ similar (even worse) than water at 1 atm :
  - high void fraction $\rightarrow$ annular flow
  - very high velocity differences : $v_l \sim 1$ m/s, $v_g > 10$ m/s common
  - droplet entrainment by gas
- viscosity: $\nu_{Na} \sim 0.7\nu_{H_2O}$
- surface tension: $\gamma_{Na} \sim 0.2\gamma_{H_2O}$

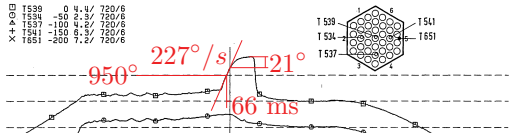
$\Rightarrow$ air/water or water/steam experiments at 1 atm relevant for some phenomena!

Sodium boiling / Phenomena



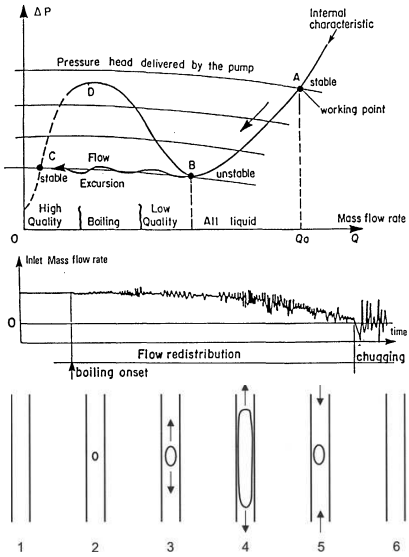
Heat transfers

- thermal conductivity : $k_l = 48$ W/m.K, $k_g = 0.045$ W/m.K
  - in liquid: $T_{wall} - T_{bulk} \sim 5°$
    → very fast vapor production once $T_{wall} > T_{sat}$
    → critical heat flux and DNB not an issue
  - instead, all the liquid boils... until dryout:
    - no heat removal by vapor → adiabatic heating (>200°/s)
    - rewetting within 1-2s → reversible
    - otherwise → cladding degradation or experimental damage!



⇒ no shortcuts for these phenomena: sodium tests are needed!

Sodium boiling / Phenomena



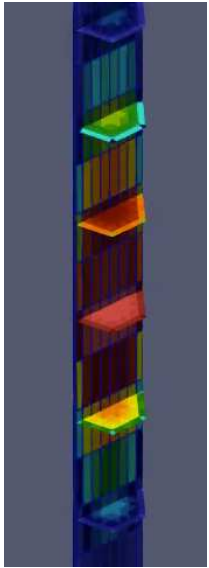
Instabilities

Because of the high ρ_l/ρ_g:

- vapor formation → higher velocity → more friction → lower flowrate → more vapor...
  ⇒ Ledinegg instability
- if flow is reduced slowly:
  quasi-static phenomenon → flow redistribution
- during a faster transient (e.g. loss of flow)
  → dynamic instabilities instead:
  - chugging: vapor growth → no heat transfer → bubble collapse → rewetting
  - or some less extreme oscillations
    → like BWR density-wave oscillations

In a real reactor, these would be coupled to neutronics!

Sodium boiling / Modelling



Two-phase equations

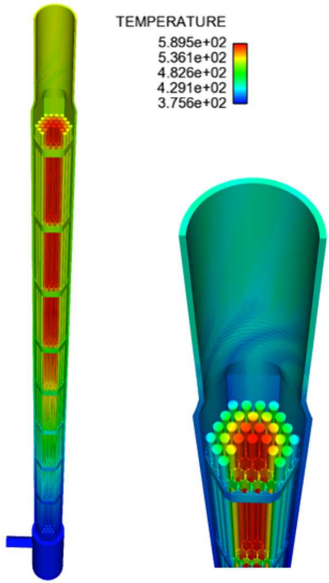
- strong velocity differences → two-fluid (Euler-Euler / 6 equations)
- but close to thermal equilibrium → almost 5 equations?
- possibility of entrainment → 3-field approach?

Physical models

- momentum exchanges (two-phase multiplier, interfacial friction)
  water similarity → use models from air/water experiments
- heat/mass transfers → no similarity, but no separate measurements!
  in general: start from single-phase Na + general models

⇒ then verify/adjust these models on sodium tests
(but somewhat hard to separate them)

Sodium boiling / Modelling

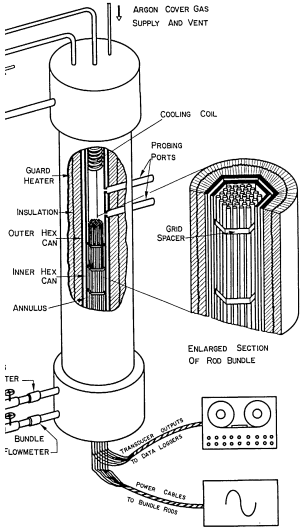


Modelling scales

- system scale (1D pipe per subassembly)
  → in ESFR-SMART: CATHARE (CEA), SAS-SFR (KIT)
- 2D per ring → to capture center/periphery differences
  up to 50°C in normal operation!
  → but stronger in experiments (7/19/37 pins)
  than in reactor (200+ pins)
  in E-S:TRACE (PSI), NATOF-2D (JRC), CESAR (IRSN)
- full subchannel → corner channels, better mixing models
  in E-S: TrioMC (CEA, not ready yet)
- two-phase CFD → better modelling, esp. above bundle
  in E-S: Neptune_CFD (EDF, two-phase difficulties)

⇒ overall: huge numerical challenge!

Sodium boiling / Validation

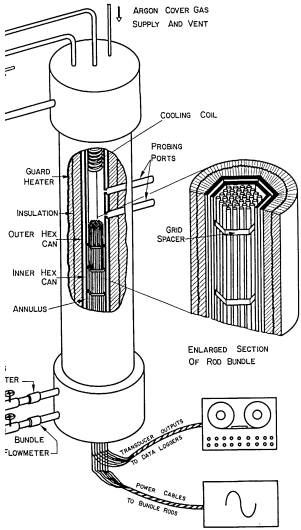


History

Many experiments in Europe, US and Japan in the '60s-'90s
$\rightarrow$ many shared in the Liquid Metal Boiling Working Group

- steady-states in forced convection
  $\rightarrow$ can (somewhat) isolate momentum models
  the best: ISPRA (JRC, 12 pins)
- fast transients (LOF or blockage):
  the best: KNS-37 (KfK/KIT, 37 pins)
- slow transients $\rightarrow$ flow redistribution:
  the best: GR19 (CEA), SIENA-37F (JAEA)
- two-phase natural convection:
  GR37 (CEA), KNS-37, SONACO (UKAEA)
- tests with 2 subassemblies:
  THORS-SHRS (ORNL), AR-1 (IPPE)
- in-pile tests in BR2, CABRI (SCARABEE)

Sodium boiling / Validation



Validation

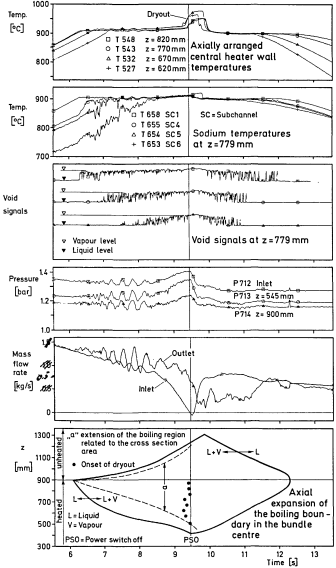
General approach:

- steady-states less sensitive to heat transfers
  $\rightarrow$ validate momentum transfer models
- then combined validation on representative tests
  $\rightarrow$ for instance LOF transients

Common difficulties:

- limited measurements (esp.: no average void fraction)
- data recovery issues
- differences with modern concepts:
  - small pins
  - no above-core sodium plenum

Sodium boiling / Validation



ESFR-SMART: KNS-37 benchmark

a 7-way benchmark on two KNS-37 tests:

- L22: fast LOF ($t_{1/2} = 2.35$s) at constant power
- L29: a bit slower ($t_{1/2} = 3.5$s)

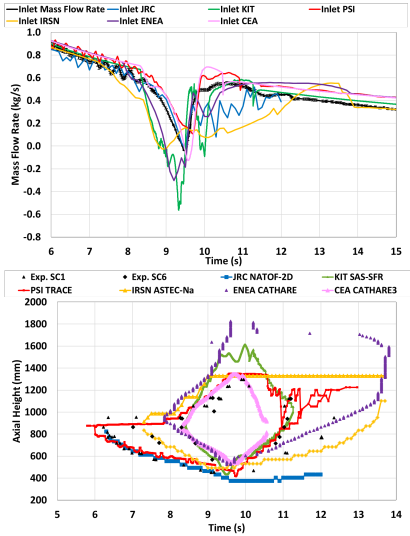
experimental data:

- thermocouples (around 200!)
- static pressures (4-5)
- local void sensors

7 participants:

- 1D: CEA, ENEA (CATHARE), KIT (SAS-SFR)
- 2D: PSI (TRACE), IRSN (CESAR), JRC (NATOF)
- CFD: EDF (Neptune_CFD)

Sodium boiling / Validation



ESFR-SMART: KNS-37 benchmark

Main events for L22 (fast):

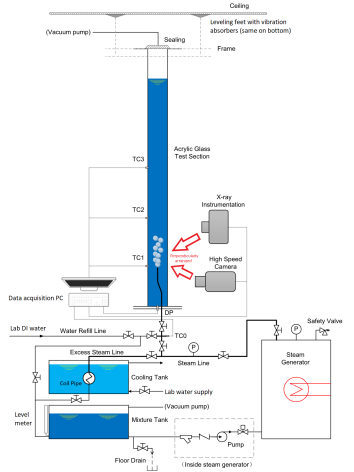
- $t = 0$s: transient start
- $t = 6$s: first vapor detected $\rightarrow$ local boiling: well-predicted by 2D codes, but not seen in 1D
- $t = 8$s : generalized boiling $\rightarrow$ seen in all codes
- $t = 9$s: flow redistribution $\rightarrow$ seen in all codes (+/- well captured)
- $t = 10$s: dryout + heater cut-off
- $t > 10$s: recondensation $\rightarrow$ not easy to predict!

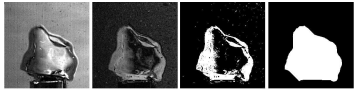
$\Rightarrow$ several potential improvements identified

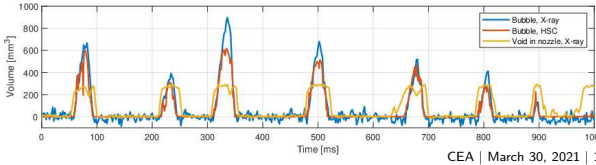
Sodium boiling / Validation

ESFR-SMART / CHUG

- during dynamics oscillations: recondensation + pressure peaks → not much data, even in water at 1 atm!
- new experiment at PSI/EPFL/ETHZ: CHUG: steam injection in water @ 20°
- instrumentation:
  - bubble size → high-speed camera
  - void fraction: X-ray radiography
  - pressure peaks → static pressure sensors
- early validation: TRACE

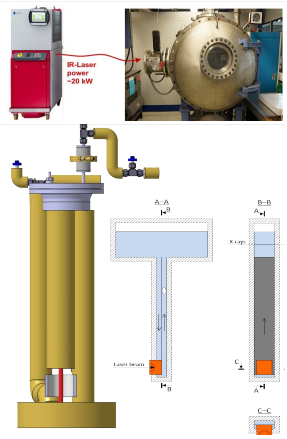






Sodium boiling / Validation

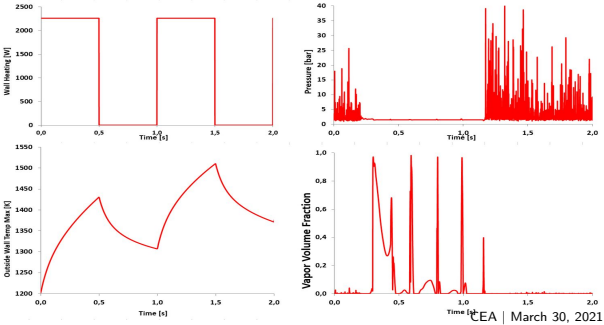
ESFR-SMART / KARIFA



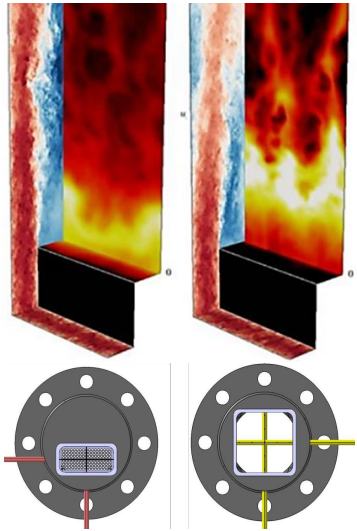
- Analytical test under development at KIT: vapor generation at laser-heated wall

⇒ better measurement of bubble formation and condensation

- pre-test CFD calculations:



Transition flows



ESFR-SMART / KASOLA → cf. tomorrow!

- RANS turbulence models for sodium flows:
  - momentum → water similarity: usual models OK
  - heat transfer → $Pr \ll 1$, large boundary layers
    → new models needed!
    especially at low velocity → transition flows
- new models require fine instrumentation ("CFD-grade") → difficult in sodium!
- new loop at KIT (same building as KNS-37): KASOLA → BFS test section:
  - backward facing step geometry (well-known flow)
  - all heating → boundary layer
  - moving probes → detailed temperature fields
- complementary to Hi2Lo approach (DNS/LES used as numerical experiment for RANS)

Conclusion

- despite its rich history, sodium boiling is probably the least mature field of SFR thermal-hydraulics!
  $\rightarrow$ and it is critical for low-void cores...
- main needs on the code side:
  - more robust solvers, especially for subchannel and CFD!
  - phenomena: condensation, droplet entrainment
- main needs on experimental side:
  - experiments for new designs ($\rightarrow$ sodium plena)
  - improved instrumentation to separate effects $\rightarrow$ esp. average void fraction
- at the reactor scale, multi-physics effects come into play:
  - neutronics : local effects on top of global power fluctuations
  - fuel: gap conductance variation $\rightarrow$ fuel temperature $\rightarrow$ Doppler feedback

  $\Rightarrow$ in practice, these effects are often stronger than T-H details!