# Some numerical achievements on Na boiling dynamics and next technical route

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# Numerical achievements from a Gen4 R&D initiative at CEA on Na boiling dynamics and next technical route

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## SUMMARY

*The paper proposes an overview of an R&D program for Gen4 Sodium Fast Reactors that was launched in 2012 at CEA to investigate Na boiling dynamics under an Unprotected Loss of Flow scenario. Part of the program motivation was an incident periodic two-phase flow pattern (limit cycle) along the transient that was calculated at first. If proven, such a stable phenomenology could indeed attractively improve reactor safety by providing a time-window for recovering pumping power. The paper is restricted to the thermal-hydraulic side of the R&D initiative that targeted to credit prediction of the boiling flow dynamics. First, the 1-D numerical achievements obtained by simulating with CATHARE3 thermal hydraulic code, some out-of-pile programs from the 70-80s, are detailed. The latter were indeed already very informative on two-phase flow stability scenarios, by so offering a first sound qualification basis. Related benefits allowed by a recent air-water experimental program that supported some modifications of wall and interfacial closure laws, are pointed out. The second part of the paper outlooks the next technical route and its early advances. Part of it, is 3-D simulation by subchannel code TrioMC which first application shows its added-value to perform a detailed analysis of a scaled experiment. Predictive capabilities of 3-D approach will be also central to credit a full-scale transposition. Progress on flow stability analysis, including subcooled condensation as well as connected channel reflooding and pressure wave aspects, could be as such expected from recent developments on CFD. Indeed, advances for an all flow regimes representation opportunely suit Na boiling physics. Bifurcation and stability analysis with the developed BACCARAT model is finally identified as providing a tailored mathematical approach to connect the periodic flow pattern with a Hopf bifurcation. Its ability to provide a mechanistic view of the scenarios shift on a natural convection test-case, is reported. On the experimental side, the scope of a new program planed with IPPE on a wire-spaced 19 pins bundle, is briefly introduced. HARIBO program suits some Gen4 hydraulic design specifics and targets CATHARE3 and TrioMC qualification.*

## Abbreviation

| | |
|---|---|
| **CEA** | Commissariat à l'Energie Atomique et aux Energies Alternatives (France) |
| **CHF** | Critical Heat Flux |
| **IPPE** | Institute of Physics and Power Engineering (State Atomic Energy Corporation Rosatom, Russia) |
| **LOF** | Loss Of Flow |
| **SFR** | Sodium Fast Reactor |
| **ULOF** | Unprotected Loss Of Flow |
| **VVUQ** | Verification, validation and uncertainties quantification |

## Nomenclature

| | | | |
|---|---|---|---|
| $J_l$ | Superficial liquid velocity, m/s | $\alpha$ | Void fraction, - |
| $J_v$ | Superficial vapor velocity, m/s | $\phi_l$ | Two-phase flow liquid friction multiplier, - |
| **T** | Temperature, °C | $\rho_l$ | Liquid density, kg/m$^3$ |
| $\Delta P$ | Pressure change, bar | $\rho_v$ | Vapor density, kg/m$^3$ |

**Keywords:** Boiling ; Sodium ; Stability ; Dry-out ; SFR ; HARIBO

## 1. INTRODUCTION

In the framework of Gen4 Sodium cooled Fast Reactors (SFRs) programs – such as BN1200 in Russia (Paramonov & Paramonova, 2016) or ASTRID in France (Gauche & Rouault, 2011) – nuclear cores have been designed to provide significant safety improvement in term of void neutronic feedback, compare to former generation. The point is to cope with the undesirable positive reactivity effects arising from neutron flux hardening in case of coolant density decrease. A main idea to achieve so consists in promoting neutrons leakage from the core through the implementation of a Na plenum at top of the fuel pins bundle (Volkov, Ashurko, Kuznetsov, & Burievskii, 2012). In ASTRID, this plenum is combined with a heterogeneous core design. The corresponding innovative arrangement for fertile and fissile zones (Beck, et al., 2017) provides a high neutron flux as an available leak source in case of coolant undue heat-up. Inline, negative void penalties have been designed in the upper parts of the fuel assemblies with such concepts (Sciora, et al., 2011). If one considers a complete core voiding as a base indicator to compare performance of the core design, a close to 0$ reactivity has been innovatively achieved with ASTRID compare to former SFRs generation, which was as high as 5$ (Varaine, et al., 2012).

In spite of these advances, Gen4 SFRs coolant boiling could not be discarded under some specific safety scenarios, such as an Unprotected Loss Of Flow transient (ULOF), (Chenaud, et al., 2013), if one supposes conservatively that passive safety devices are non-operant. Na boiling phenomenology understanding and modeling have therefore remained scientific targets to address in depth reactor safety, in addition to some monophasic important issues also considered (Tenchine, et al., 2012), such as stratification and decay heat removal under natural convection (Gerschenfeld, 2019). In line, an early European Gen4 initiative (Chenu, Mikityuk, & Chawla, 2009) was opportunely undertaken. This program led to the publication of stability studies along ULOF for innovative SFRs core designs (Sun, Chenu, Mikityuk, Krepel, & Chawla, 2012), including a patented design featuring openings in the hexagonal can to prevent from flow blockage. The same year, an R&D program on this specific topic has been reborn at CEA from the 70-80s. Na boiling had been indeed investigated intensively during the latter period in a couple of nuclearized countries from that time, among which Japan (Haga, 1983), United States of America (Gnadt, et al., 1984) and European partners (Kottowski-Dümenil, 1994). Two peculiarities make the work initiated in 2012 as likely informative compare to past findings. First, some thermal-hydraulic specifics could be expected from the large hydraulic diameter change between the fuel pins bundle (about 3.5mm) and the newly implemented Na plenum (about 16cm). Second, multi-physics coupling driven by the newly negative void neutronic feedback should obviously act in a different way.

A singular dynamic behavior has been actually calculated when simulating at first, with CATHARE2 and ERANOS, an ULOF transient performed on an ASTRID design (Alpy, et al., 2014). In this simulation, flow boiling at about 40% of nominal power (11kW/pin) onsets a limit cycle, corresponding to periodic changes from diphasic to monophasic states of the coolant as reported in Figure 1-Right. Importantly, (Alpy, et al., 2016) showed through a sensitivity calculation at zero void neutronic feedback, that thermal-hydraulic on its own could sustain the limit cycle mechanism within the two-phase flow subassemblies. It was analyzed as a chugging-like phenomena (Delhaye, 2008). Accordingly, the pins cladding temperatures remained close to the saturation temperature in this calculation (Figure 1-Left), instead of rising up to steel melting temperature as would have induced their dry-out. This phenomenology was identified as relevant – if proven – for reactor safety by providing a time-window for recovering pumping power, instead of shifting to a severe accident phase. Outside France, such a possibility for a stable periodic pattern under an ULOF was actually experienced earlier with another Gen4 concept in the framework of BN1200 R&D (Volkov, Ashurko, Kuznetsov, & Burievskii, 2012). With ASTRID design, it was next either disagreed (Kruessmann, et al., 2015) or instead again reported (Droin, Marie, Bachrata, Bertrand, Merle, & Seiler, 2017). One may expect the negative void neutronic feedback effect to promote stable boiling. (Pascal, et al., 2020) reports advanced CATHARE3-APOLLO3 coupled calculation for ASTRID that improves the multi-physics aspect of (Alpy, et al., 2016), outlining a possibility for stable boiling under

ULOF while power at boiling onset is as high as 60% of nominal one's (16kW/pin). Associated oscillations of power are large, rating 10 to 20% of nominal power and authors underline the need to investigate numerical stability while unstable flow can be also obtained depending on the modeling approach. Some advances about qualification of such multi-physics coupling simulation could be next expected from an ongoing Coordinated Research Project, CRP, organized by the IAEA (IAEA, 2018). This CRP is focusing on a benchmark analysis of one of the passive safety demonstration tests performed in the 80s at the Fast Flux Test Facility (FFTF). Indeed, a device called GEM (Gas Expansion Module) was invented in this 400 MWTh SFR to passively insert negative reactivity during a loss of flow event and a series of Loss of Flow Without Scram tests was accordingly performed to demonstrate their performance (Wootan, Omberg, & Grandy, 2017).

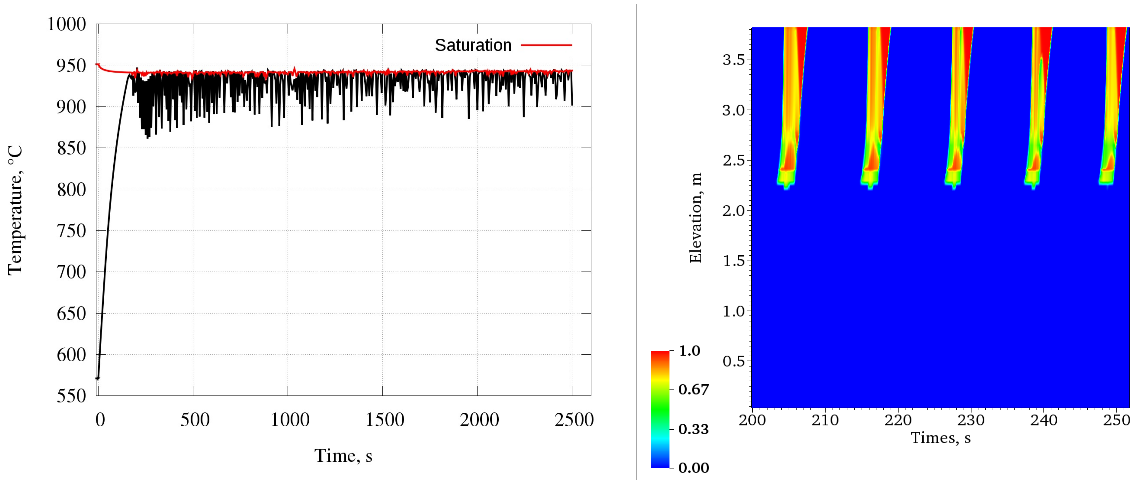


Figure 1. Left: stable boiling along a Gen4 SFR ULOF, CATHARE2-ERANOS.
Right: Void fraction profile showing the limit cycle in the hottest subassembly, CATHARE2 (Alpy, et al., 2016).

Facing such a singular behavior (limit cycle) questioned for sure, on what had been experienced in the 70-80s about Na boiling stability. The R&D work on liquid metal thermal-hydraulic that had been performed at that time is significant. A state of the art was opportunely compiled by European partners in (Kottowski-Dümenil, 1994), by so concluding 26 years of research since the first meeting of the international Liquid Metal Boiling Working Group (LMBWG) that had been held in 1966 in Aix en Provence. Inline, the expertise recovery which was the first initiative undertaken in 2012 could only be very partly performed, although supported by experts from this period to help selecting key points. Liquid superheating prior to boiling inception, flow stability and connected dry-out, are part of the key phenomenological points that were addressed by these pioneers. Below, only few points from this extensive work could be outlined. Note that wall and interfacial friction, heat and mass transfer were for sure addressed at that time and a comprehensive review is proposed in (Chenu, Mikityuk, & Chawla, 2009). Section 2.1 will better comment the matter in the framework of CATHARE code adaptation to Na two-phase flow.

Liquid metal has a marked propensity to incipient superheat due to its properties, eg. a surface tension at atmospheric pressure about ten times the one of water at 15MPa, while vapor density is lower and saturation temperature is higher, (Vanderhaegen & Le Belguet, 2014). This phenomenon is influenced by many parameters among which local ones on the cladding (eg. surface roughness, surface treatment, etc.) that are actually system-specifics. Helpfully, it was balanced that gas entrainment could overshadow other effects by efficiently providing nucleation sites. As such, (France & Carlson, 1974) reported that in a loop system with a gas buffer, hence prototypical of reactor configuration, long enough operation at steady state (few tens of hours) before boiling inception, allowed bulk superheat to be quite zero. While such a lesson was corroborated in France when performing the GR-19 program on Na boiling (Rameau & Seiler, 1982), one should keep in mind when considering a new campaign (see section 3) that peculiar conditions could revive the issue, such as operating to Na boiling too promptly after a long period with the liquid metal at rest.

Flow stability experimental analysis and dry-out had been in the 70-80s − and remain if one considers recent works by (Qiu, et al., 2015) and (Khafizov, et al., 2016) that recover technological skills on this ~ 900°C challenging field − central topics. In France, possibility for a stable Na boiling flow under natural circulation was demonstrated at 5kW/pin following a quasi-static approach (Rameau & Seiler, 1982) along the GR-19i campaign held at CEA Grenoble on a wire-wrapped 19 pins bundle. This showed that in spite of the 3-order magnitude between ρl and ρv that could raise concern about inlet cooling flow, dry-out in the two-phase was not an univocal ending to Na boiling onset, providing power was low enough. Noticeably, no periodic stable pattern was reported and the Ledinegg criteria (Ledinegg, 1938), which allows stating on static stability, was singly used at that time to analyze the whole program, including the static instability faced at 8kW/pin. This approach was later transposed in the ASTRID ULOF new framework, by so constituting a breakout effort to possibly value Na stable boiling skill for reactor safety (Seiler & Juhel, 2010).

Coming back to the 70-80s, possibility for Na boiling without definitive dry-out within a wire-wrapped pins bundle, was also experienced under natural circulation and decay heat removal power in the US on the SHRS 19 pins bundle (Levin, Carbajo, LLoyd, Montgomery, Rose, & Wantland, 1985) implemented on THORS facility (Gnadt, et al., 1984). This was repeated and extended to LOF in Japan (Haga, 1983) along SIENA-37 program (37 pins), providing again that power was low enough. In a distinct way from GR-19 program, US and Japanese programs exhibited a dynamic periodic behavior of the flow along stable boiling. The case will be better discussed in section 2, as part of CATHARE qualification on some data from the SIENA-37 program. (Yamaguchi, 1987) carried-out a comprehensive analysis of the latter and noticeably discussed stability and flow regimes complex coupling, outlining the efficiency of the slug regime compare to stable annular one's, for pins cooling. Slug regime was indeed connected to some dynamic processes such as falling of a liquid column from the unheated top part of the test section that offers extra-cooling. Temporary dry-outs were associated to short-term instabilities during transition from slug to annular flow or along stable annular flow. A criterion for permanent dry-out achievement (defined as triggering a 1000°C threshold) was defined based on flow regime transition from annular to annular-mist one's. It reduces in a thermodynamic title that exceeds 0.5 and recommended at least for low powers (decay-heat removal conditions). (Kottowski, Savatteri, & Hufschmidt, 1991) also investigated the CHF, but under forced convection, on a 19 pins bundle, grid and wire-spaced. They developed an empirical correlation that extends the modeling by (Gorlov, Rzayev, & Khudyakov, 1975) and takes into account subcooling of the inlet flow.

The above brief description of past experimental campaigns' outcomes on stability, highlights that they were informative. Inline, first point that was targeted by the technical group working on Na boiling in support to the ASTRID project, was to balance and further improve the ability of the CATHARE3 code (Emonot, Souyri, Gandrille, & Barré, 2011) to simulate some key tests from that time. The corresponding work is reported in section 2. One has to note that uncertainty quantification step of VVUQ methodology is out of the scope of the work, its first target being instead to model and analyze the rationale of the complex non-linear physics (materials still available from that time may whatever hardly allow for a consistent study on uncertainties). Section 3 outlines the next technical route that can be considered to achieve step-advances. Together with promising 3-D simulation, part of them should be a new IPPE-CEA experimental program, named HARIBO (Anderhuber, et al., 2019). The latter would noticeably be performed on a mock-up featuring some geometry specifics of a Gen4 SFRs subassembly design, which heterogeneous design is likely to impact flow regimes and stability, through a change of the forces balance. This point will be outlined by prior reporting of key results from a bifurcation and stability analysis for a two-phase flow under natural convection.

Note that only selected information about the R&D work that has been carried out since 2012 at CEA is provided in the paper, which first target is indeed to propose a synthetic overview of the program logic, key achievements and perspectives. The reader could refer to the provided references from authors for more detailed information.

## 2. 1-D CATHARE3 QUALIFICATION PROGRESS

### 2.1. Rationale for CATHARE adaptation to Na two-phase flow

CATHARE is a two-phase thermal hydraulic system code that has been developed since 1979 following an agreement between CEA, industrial partners and French public service expert in nuclear and radiation risks, IRSN (IRSN, 2020). It is duly qualified for PWRs geometries and safety scenarios through a methodology that coupled separated effect tests and integral loop ones, (Barre & Bernard, 1990). The code applies a 6 equations model which main closure laws have been described in (Bestion, 1990), according to an implicit numerical scheme for 0-D and 1-D modules. Along the last decade, version 3 of the code (Emonot, Souyri, Gandrille, & Barré, 2011) has been developed as part of the larger NEPTUNE multi-scale platform (Bestion & Guelfi, 2005).

The code has been extended to monophasic application for SFR's systems (Tenchine, et al., 2012). Extension of this capability to two-phase flow dynamics which is summarized in this paper, has been carried out according to the following considerations and approach:

- A comprehensive review of the closure laws that are available in the open literature for two-phase flow of a metal, has been carried out by (Chenu, Mikityuk, & Chawla, 2009) for their adaptation of version 5 of TRACE code to Na boiling. From qualification work, especially on a loss of flow test on a 37-pins bundle with spacer grids (Huber, Mattes, Peppler, Till, & Wall, 1982), they identified the laws from the latest version of the SABENA code (Ninokata & Okano, 1990) as the most predictive. However, one should note regarding these laws that no certitude can be pointed out and this has to be related to the limits of the instrumentation outlined in the introduction, which indeed make challenging to get an analytical knowledge of the two-phase flow mechanisms. As such within the set of SABENA's closure laws:
  - Interfacial friction reduces to an annular flow hypothesis. One may consider such a hypothesis as questionable within the 16cm hydraulic diameter plenum that has been reported as part of Gen4 subassembly design specifics. This will be confirmed in section 2.2.
  - Correlation from (Lottes & Flinn, 1956) is applied for two-phase flow wall friction multiplier. However, in (Kottowski-Dümenil, 1994) compilation, French experts who analyzed pressure drop measurements from the LMBWG (such as performed by (Kaiser & Peppler, 1977) within a 7-pins bundle), concluded instead that in regard of the work performed during twenty years with sodium boiling, no simple correlation which would be accurate for all performed experiments could be outlined. They finally identified the classical correlation from (Lockhart & Martinelli, 1949) as the best trade-off for a 1-D description, while over prediction at the pressure drop for quality below 1.7% was also noticed.
  - Heat transfer coefficient from liquid to interface which is used, features a parameter that introduces a large uncertainty, as pointed out by (Azad & Shirani, 2018), while vapor enthalpy simply reduces to saturation conditions.
- Instead, some capabilities of the CATHARE code, though initially developed for water-steam, have been considered as likely valuable for Na while CATHARE additionally benefits after several decades of development, from a numerical scheme that efficiently covers the whole monophasic to diphasic mechanisms.
- Accordingly, peculiar aspects of fluid mechanics modeling developed for water-steam in CATHARE have been identified as valuable: as such, original work performed on interfacial friction closure laws by (Bestion, 1990) corresponds to sound developments covering bubbly/slug/churn to annular flow patterns, depressurized situations (hence large density ratios) as well as a large scope of hydraulic diameters (from rod-bundle to pipe geometries). It does not

show any equivalent modeling for sodium and could advisably be extended to SFRs application. Some separated effects that address fluid mechanics have been however revised thanks to the SENSAS air-water program that is reported in section 2.2. Modifications of the closure laws addressed wall friction in the pins bundle in the low quality range (which uncertainty had been outlined by some pioneers, as reminded above) and interfacial friction in the plenum topping the bundle. Section 2.3 qualifies these modifications in a Na boiling test that was part of the GR-19 program in the 80s.

- Few other important changes, following expert judgment, have been introduced in CATHARE closure laws for Na boiling application. These address (Anderhuber, Perez, & Alpy, 2017):
  - Water-specific correlation from (Thom & Walker, 1965) for nucleate boiling has been removed. Instead, up to dry-out, heat transfer from the wall is supposed to be rated by the liquid metal which thermal exchange characteristics (Skupinski, Tortel, & Vautrey, 1965) is indeed already very efficient. Hence any further improvement by nucleate boiling, not measured for Na, is considered to make slight difference. Sub-cooled and nucleate boiling are additionally seen of much less importance sine annular flow should be predominant in the heated bundle so that heat transfer mechanism should mostly reduce to convection boiling.
  - The CHF for which water-specific look-up table from (Groeneveld, Cheng, & Doan, 1986) that describe DNB and transition regime, have been also removed. Therefore, the CHF only corresponds to dry-out which is the consistent phenomenology experienced (see section 1), in line with the large $\rho l/\rho v$ ratio. Criterion in CATHARE for its achievement has been unchanged, corresponding to a void fraction threshold of 0.99999. Criteria from (Yamaguchi, 1987) or (Kottowski, Savatteri, & Hufschmidt, 1991) were therefore not selected at first since considered as possibly presenting undesirable limitations (low power conditions applicability or forced convection regime, see section 1). Section 2.4 will balance the point.
  - Liquid to vapor heat exchange laws (and related interfacial mass transfer) have been kept unchanged. Indeed, reliability of the laws from the literature for Na application have been quoted as questionable so that if necessary, a parametric investigation of CATHARE original ones has been seen as a pragmatic approach.
  - Finally, liquid superheat is disregarded in the modeling, the reasons being already given in section 1.
- These changes have led to an updated version of CATHARE for Na two-phase flow, labeled CATHARE3_rev3. Integral validation of this version has been then undertaken through the simulation of stability scenarios, possibly leading to dry-out events, which indeed constitute the main part of the available experimental tests. Some tests from the SIENA-37 program have been selected to do so and results are reported in section 2.4. Results will be compared with an initial revision, labeled CATHARE3_rev1. Differences between both revisions are pointed out in Table 1.

Table 1: Some specifics of CATHARE3_rev1 and CATHARE3_rev3
(only differences from PWR's version are outlined)

| Physical revision | Fluid-mechanic | Thermal exchange |
|---|---|---|
| **rev1** | *Wall friction:*<br><br>Correlation from (Rehme, 1973) is made available for monophasic friction coefficient in a wire spaced pins bundle.<br><br>Two-phase flow multiplier for liquid wall friction applies the correlation from (Lockhart & Martinelli, 1949) following the recommendation from French experts in (Kottowski-Dümenil, 1994). | Wall to liquid heat transfer applies correlation from (Skupinski, Tortel, & Vautrey, 1965). |
| **rev3** | *Wall friction:*<br><br>Correlation from (Rehme, 1973) is made available for monophasic friction coefficient in a wire spaced pins bundle.<br><br>Two-phase flow multiplier for liquid wall friction applies SENSAS correlation (see section 2.2) up to liquid droplets entrainment onset. It is then shifted to (Lockhart & Martinelli, 1949) correlation.<br><br>*Interfacial friction:*<br><br>Law for pipe geometry has been modified following SENSAS program (see section 2.2) to describe properly the transition between bubbly to slug-churn flow patterns in the plenum of a Gen4 SFR subassembly. | Wall to liquid heat transfer applies correlation from (Skupinski, Tortel, & Vautrey, 1965).<br><br>*Nucleate boiling:*<br><br>Law from (Thom & Walker, 1965) has been removed. Instead, up to dry-out, heat transfer from the wall is supposed to be rated by the liquid metal according to (Skupinski, Tortel, & Vautrey, 1965).<br><br>*CHF:*<br><br>DNB and transition regime laws from (Groeneveld, Cheng, & Doan, 1986) have been removed. Dry-out is then only considered according to the criteria: $\alpha>0.99999$ |

## 2.2. Interfacial and wall friction closure laws modification: SENSAS program

SENSAS was a three years long air/water program under atmospheric pressure, started at CEA Grenoble in 2012. The experiment was considered to balance accurately – and not too costly – some two-phase flow aspects for fluid mechanics with regards to Gen4 SFRs specifics. To do so, pressure profiles were monitored with a high resolution (0.1 mbar for pressure sensor accuracy) along a scale 1:1 subassembly mockup exemplary of a Gen4 SFRs design so that scalability issue was opportunely discarded. Low values of (Jl, Jv) superficial velocities, respectively up to 0.5 and 1m/s, were investigated since this range had been identified as paramount for stability analysis (Seiler & Juhel, 2010) together with inaccurately modeled as explained in section 2.1. Table 2 compares some physical parameters between air/water and Na boiling for common liquid and gas superficial velocities of 0.14 m/s and 0.7 m/s. As commented in (Perez, Alpy, Juhel, & Bestion, 2015), the Laplace scale £ and therefore in a scale 1:1 geometry, the Bond number are only 32% lower in air–water. The air/water density ratio is twice less than the one in boiling Na, but remains a very large ratio. Liquid Reynolds numbers present significant differences, however a liquid turbulent regime was investigated throughout the SENSAS experimental grid. It was therefore expected that the very different Prandtl numbers between sodium and water would not distort too much the flow fluid-mechanics while allowing accurate measurements and visualizations that are not possible in

Na tests, together with much less expensive and simpler technology equipment. Qualification on Na boiling tests that is reported in section 2.3 and 2.4 led to some global check of the SENSAS models and credited the relevancy of these initial expectations owed to (Seiler & Juhel, 2010).

Table 2: Comparison of some air/water and liquid/vapor Na properties

| | P [Pa] x10[5] | T [°C] | $\mu$ [Pa s] x10[-3] | ρ [kg/m³] | $\rho_l/\rho_v$ | σ [N/m] | £ x10[-3] | Reynolds number Bundle x10[3] | Plenum x10[3] |
|---|---|---|---|---|---|---|---|---|---|
| **Water** | 1 | 13 | 1.2 | 999 | 819 | 0.075 | 2.77 | 1.4 | 19.3 |
| **Air** | | | 0.016 | 1.22 | | | | 0.6 | 8.8 |
| **Liq. Na** | 1.7 | 940 | 0.15 | 727 | 1652 | 0.12 | 4.06 | 7.1 | 111.1 |
| **Vap. Na** | | | 0.02 | 0.44 | | | | 0.16 | 2.5 |

(Perez, Alpy, Juhel, & Bestion, 2015) have detailed the modeling changes which were performed thanks to the SENSAS program. Closure laws modifications from SENSAS program, implemented in CATHARE3_rev3, address:

- Two-phase flow multiplier $\phi_l$ for wall friction contribution by the liquid within the 3.5mm hydraulic diameter of the 217 pins bundle for which monophasic friction coefficient from (Rehme, 1973) is used. $\phi_l$ reads:

$$\phi_l = \frac{1}{(1-\alpha)^2} \times \text{Min}\,[1\,;\ 1.4429(1-\alpha)^{0.6492}] \qquad \text{Eq. 1}$$

  In Eq. 1, the term $1/(1-\alpha)^2$ from (Lottes & Flinn, 1956) for an annular flow, is corrected to model scenarios in which the liquid is actually split in a low velocity field (film in contact with the wall) and a higher velocity liquid field (liquid structures far from the wall). Reduced friction are in such cases caused on the wall compare to average liquid velocity consideration, $J_l/(1-\alpha)$. Such a correction was already available for PWRs, but its expression made it non-operant for large ρl/ρv since $\phi_l$ was reading:

$$\phi_l = \frac{1}{(1-\alpha)^2} \times \frac{(1-\alpha)\rho_l}{\alpha\rho_g + (1-\alpha)\rho_l} \qquad \text{Eq. 2}$$

  Note that Eq. 1 is used up to liquid droplets entrainment onset, which is calculated according to the Wallis correlation (Wallis, 1969). Then it is shifted to (Lockhart & Martinelli, 1949) correlation.

- Non-linear change of interfacial friction (see Figure 2) from bubbly to slug-churn flow patterns within the 16cm hydraulic diameter plenum, topping the fuel bundle mock-up. This peculiar transition, was actually already observed by (Hewitt, 1986). It has been modeled in CATHARE by changing the expression of the vapor phase length scale that is involved in the drift velocity correlation, originally developed by (Bestion, 1990) for PWRs. This length was initially changing from the Laplace scale to the channel hydraulic diameter, following an α-based law. From SENSAS data, this law was reshaped according to a hyperbolic tangent function, with $J_l$ and $J_v$ as parameters. Note that values for drift velocity of gas phase, Vgj, and distribution parameter, Co, from (Bestion, 1990) have been instead unchanged for bubbly and slug-churn flows since SENSAS data confirmed their relevancy.

Figure 2, reports the connected improvements achieved with the CATHARE code for void fraction change along the 40cm high plenum (note that due to low wall friction in this part of the test-section, pressure drop reduces to change of buoyancy). By the way, SENSAS confirmed that an annular flow hypothesis within the plenum of a Gen4 SFR subassembly would be irrelevant.

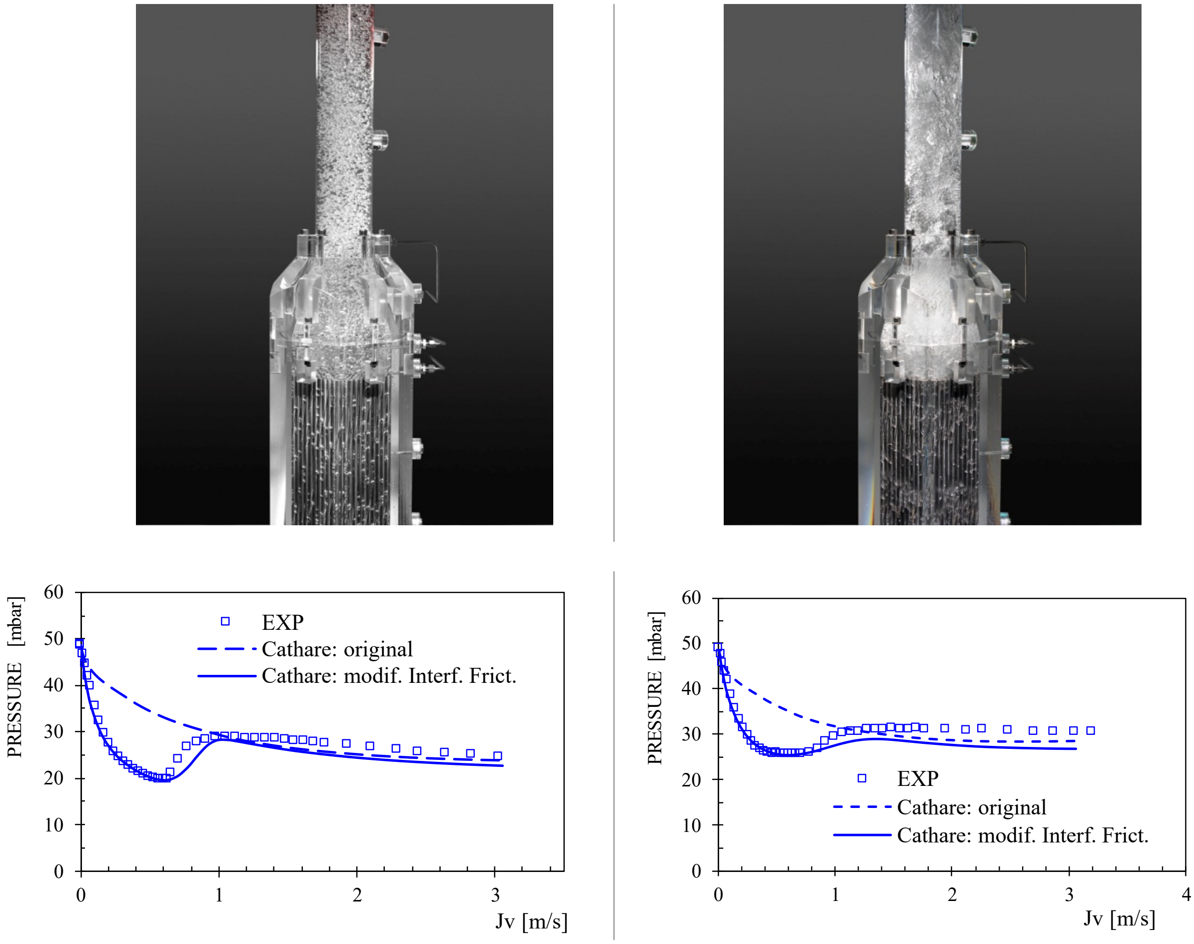


Figure 2. Top: bubbly and churn flow patterns in SENSAS, above the pins bundle.
Down: experimental and calculated pressure drop as a function of $J_v$ (left: $J_l$=0.1m/s; right: $J_l$=0.2m/s).

Three mains limitations of the program should be underlined:

- No investigation could be carried-out about flow patterns transition within the pins bundle since no void sensor was made available. This point remains therefore an open question, especially to bound onset of annular flow, which could be promoted by such a low hydraulic diameter configuration. Possible advance on the topic will be discussed as part of section 3.1.
- A limited range of $J_v/J_l$ was available so that effect of liquid droplets entrainment could not be investigated.
- At the bundle - plenum interface, featuring a large change of hydraulic diameters, separated effects causing local pressure drop could not be identified among dissipation by flow vortices and buoyancy change, the latter being driven by the progressive establishment of a new slip of the velocities. Mastering void fraction at this place seems actually paramount for multi-physics coupling since it drives neutron leakage from the fuel that is responsible for the negative void neutronic feedback.

### 2.3. Qualification under forced circulation: BP campaign of the GR-19 program

The BP campaign of the GR-19 80's program that was mentioned in section 1, was carried-out on a 19 pins bundle featuring a 60cm high electrically heated length, topped by a 48cm high unheated one's (see Figure 3). Noticeably, this campaign benefited from technological and scientific feedbacks of past campaigns. As such, and at contrary of GR-19i or other programs such as KNS-37 in Germany, the test-section bypass did not longer connect the upper part of the test-section, by so avoiding local chugging issues related to strong condensation events (see the 500°C difference when mixing the bypass flow with the ascending vapor). Additionally, extra buoyancy force from the upper subassembly part was interestingly made available for investigation, the latter being known as a key factor for flow stability (Fukuda & Kobori, 1978).

Figure 3 reports a comparison between CATHARE results and experimental data for pressure drop measurements along the bundle mock-up. Note that along the test, power was constant and Na flow rate at test-section inlet was varied following a quasi-static approach that matched the Ledinegg static stability criterion (Bouré, Bergles, & Tong, 1973) so that thermal equilibrium could be reached. The benefit from SENSAS program about two-phase flow wall friction multiplier that was reported in section 2.2, is noticeable in
Figure 3 when looking at CATHARE3_rev3 results compare to previous revision.

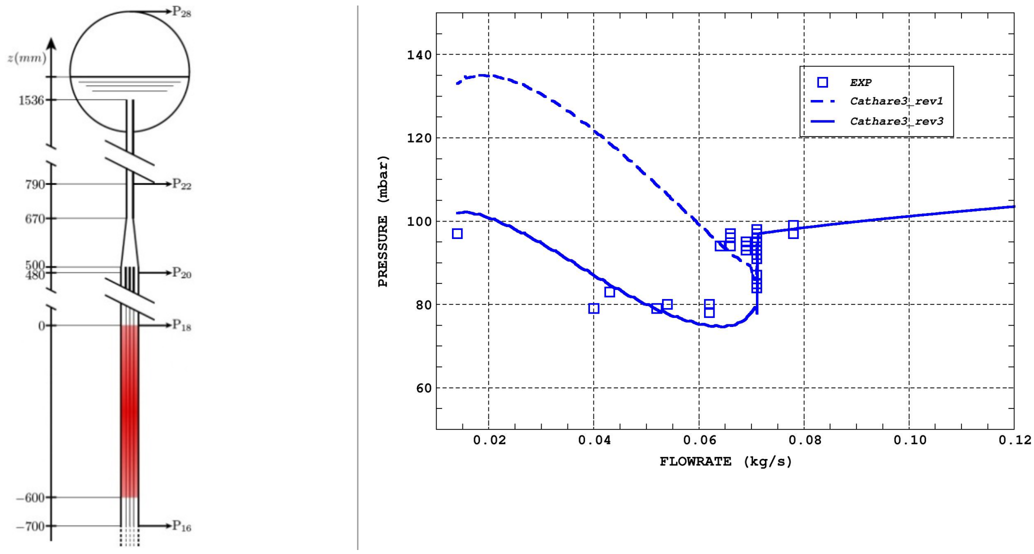


Figure 3. Left: schematic of GR-19 subassembly with pressure sensors label and elevation. Right: experimental and calculated P16-P20 pressure drop profile as a function of liquid Na inlet flow rate. GR-19BP test at 3kW/pin.

### 2.4. Qualification under natural circulation and loss of flow: SIENA-37 program

Na boiling dynamics with CATHARE3 is addressed below by focusing on the lessons learnt by comparing code results (Anderhuber, Perez, & Alpy, 2017) with some data of this Japanese program from the 80s (Ninokata, 1986). SIENA-37 test section consisted in a 37 pins bundle, featuring a 45cm heated length topped by a 71cm unheated one. Figure 4 reports two schematics of the test section so that thermocouples arrangement on plan G, which is located 1cm below the end of the bundle mock-up heated length.

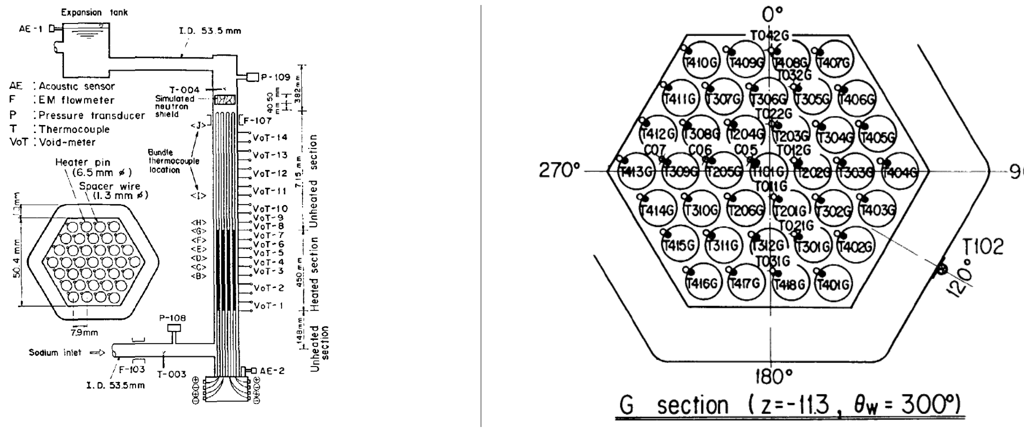


Figure 4. Left: SIENA-37 test section. Right: thermocouples on plan G.

*Natural circulation experiment – LHF-123 Test* (Haga, 1983)

Along the LHF-123 test, pins power was increased step by step while Na was at rest so that momentum was only provided by the buoyancy force. The two-phase flow stability boundary was opportunely crossed along this quasi-static process, allowing investigating both stability scenarios. Indeed, some last power steps outlined a dynamic but stable flow (Figure 5-Left) while final power step (Figure 5-Right) led to an unstable flow eventually causing pins wall dry-out (triggering the 1000°C threshold for pins power scram at about 2658s, see T204-G signal in Figure 7).

Comparison between CATHARE3_rev3 results and the experimental data, highlights that the code succeeds in capturing the flow stability change. Noticeably:

- Amplitude and shape-frequency of the dynamic but stable flow, which depends on the power step (3.97kW/pin from 2522s to 2568s, then 4.38kW/pin, up to 2612s) are well reproduced by the code. As such, experimental and calculated velocities reported in Figure 5 exhibit a very close dynamics. The phenomenology is actually similar to the one of the reactor case described in (Alpy, et al., 2016), by so providing some interesting qualification material. Its rationale can be summarized as follow, see Figure 6: after first deadened oscillations at boiling onset, significant expansion of vapor induces some two-phase flow bursts at channel exit. Increase of floatability provided by channel voiding causes a rise of the inlet velocity so that extra cooling is made available and onsets condensation. Condensation also takes place when the vapor phase reaches subcooled liquid at channel exit: the ascending two-phase flow experiences a loss of pressure due to condensation i.e. momentum and channel reflooding by liquid reverse flow from upper volumes, is calculated. Fall of the liquid column and final collapse of the condensation fronts eventually reverse the flow at test section inlet. Then the process repeats.
- Following the final 4.64kW/pin power step at 2612s, flow has dropt to zero in more than 45s (Figure 5-Right) along the test while CATHARE3 also calculates this loss of stability. However, this is achieved within 25s, hence following a shorter timeline, which could underline some limitations of the current modeling.

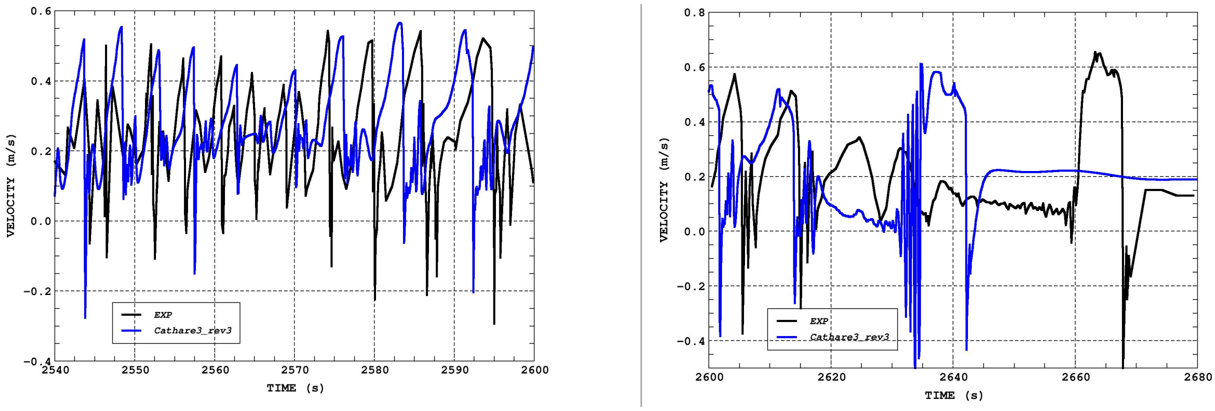

Figure 5. Experimental and calculated inlet flow velocity – LHF-123 test, SIENA-37.
Left: along the chugging (stable) flow. Right: from stable to unstable flow.

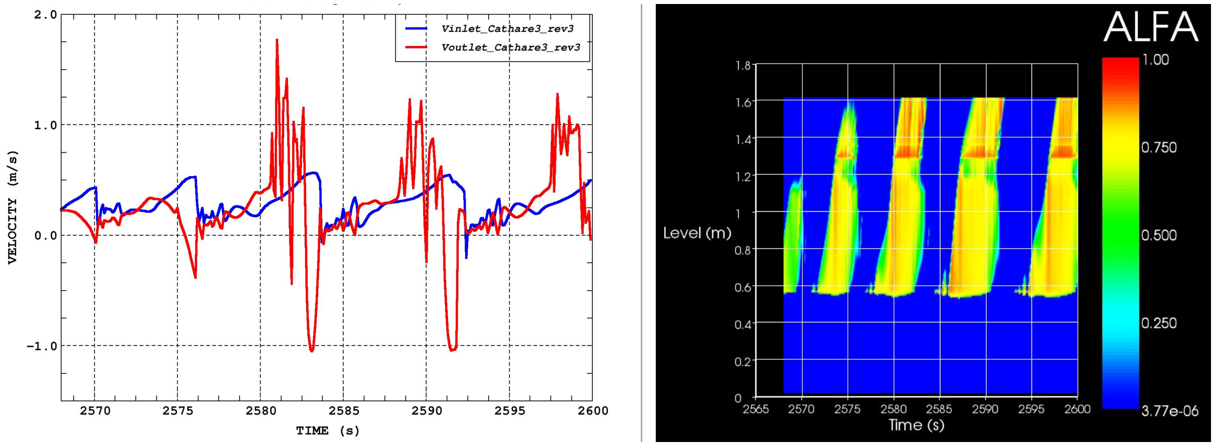

Figure 6: Left: calculated inlet and outlet liquid velocities along the chugging (stable) flow. Right: calculated void fraction axial profile (z=0.571 points the end of the heated part). LHF-123 test, SIENA-37.

Figure 7 reports the monitoring of three temperature sensors on pins wall at plan G, together with CATHARE3 results. It can be outlined that:

- CATHARE3_rev1 failed to simulate the flow stability, which is experimentally achieved until 2612s (green-line in Figure 7–Left points-out an early dry-out). As such, modifications implemented in CATHARE3_rev3 are shown as relevant since dry-out is duly triggered at the last power step (blue-line in Figure 7–Left).
- CATHARE3_rev3 calculates some subcooling events, which are indeed experienced locally, at the periphery of the bundle (blue and cyan lines in Figure 7–Left). These are the consequence of the described condensing fronts that transport cooler liquid metal. Vapor phase collapses also induce pressure peaks which are pointed-out by the ones of saturation temperature (red-line in Figure 7–Right). Such pressure peaks were indeed monitored during the campaign, as it will be seen below for FC34 test, which makes the phenomenology entering the field of condensation induced pressure waves.

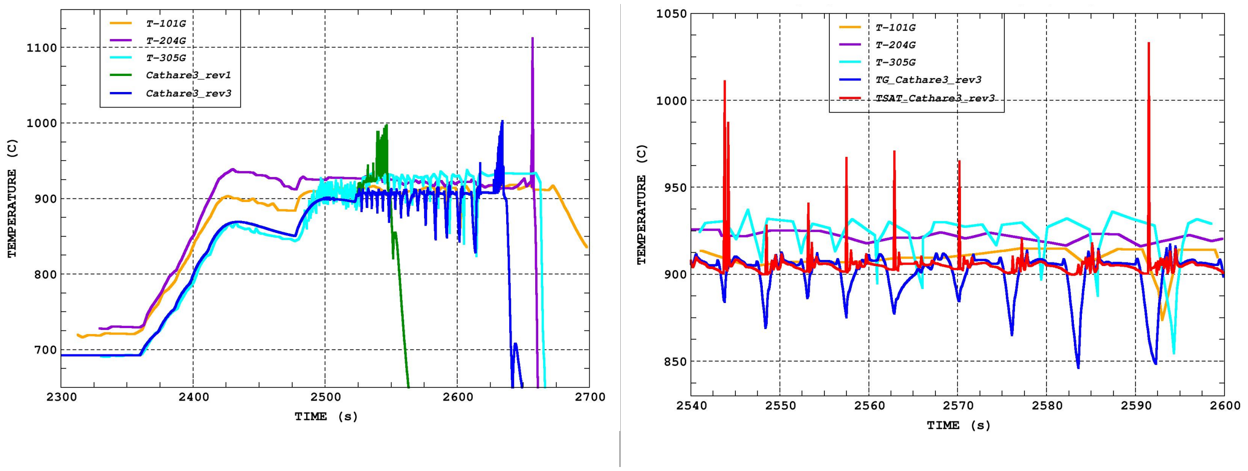


Figure 7. Left: experimental and calculated pins wall temperatures at plan G. Right: zoomed view.
LHF-123 test, SIENA-37.

*Loss of flow experiment – FC34 Test* (Haga, 1983)

The FC34 test was carried-out at a constant 8kW/pin electrical power which is significantly higher than for LHF-123. A loss of flow from forced circulation was mimicked, with a halving time around 3s. Figure 8 compares experimental and CATHARE3_rev3 flow rates together with pressure evolutions at test section inlet. Figure 9-Left compares some temperature at pins wall on plan G and reports saturation temperature calculated by CATHARE. Figure 9-Right provides the calculated void fraction evolution at plan G.

This experiment was stopped due to triggering of a temperature threshold on a pin wall. This final dry-out event, which concluded the flow instability, is also calculated by CATHARE at 1053.1s, which is about 1s earlier that during the test. This consistency constitutes a first qualification point.

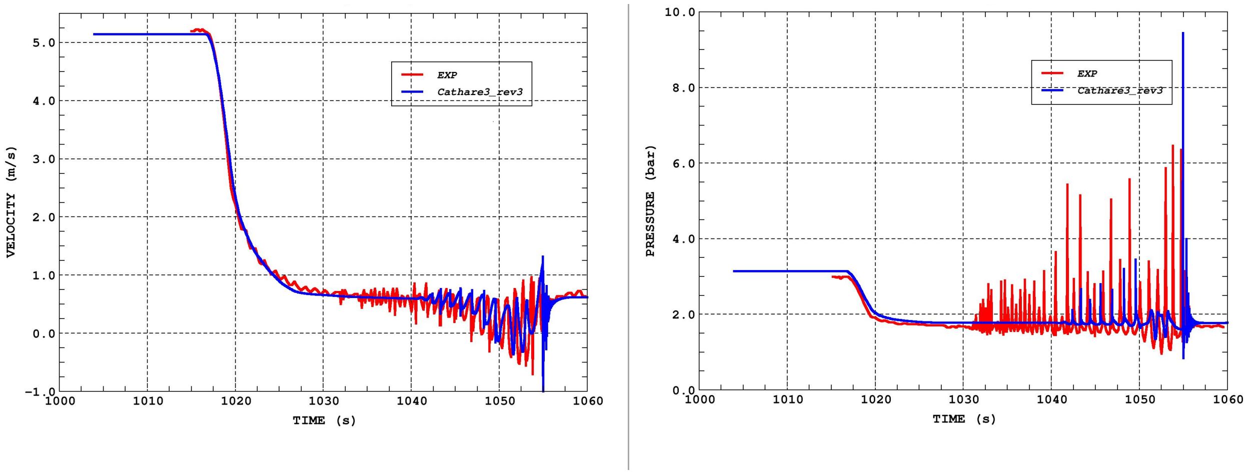


Figure 8. Left: experimental and calculated inlet flow rate. Right: experimental and calculated inlet pressure.
FC34 LOF test, SIENA-37.

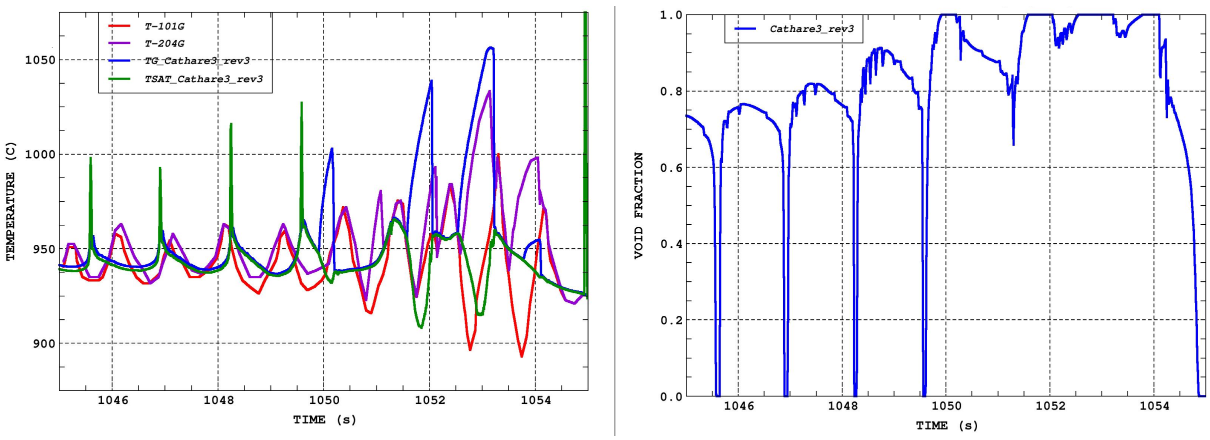

Figure 9. Left: experimental and calculated temperatures at plan G. Right: calculated void fraction at plan G. FC34 LOF test, SIENA-37.

From these figures, it comes out that:

- Due to its 1-D representation, local boiling is missed by CATHARE, which therefore calculates Na boiling onset with quite a 10s delay, at about 1041s.
- As for LHF-123 test, some chugging events of the flow are again experienced and calculated, but this time along a loss of stability. These are indeed outlined in Figure 8 by oscillations of the inlet flow rate (which eventually reverse) and pressure. The latter features some peaks following vapor phase collapses. Experimentally, they rated up to 6.5bar and CATHARE balances correctly this order of magnitude.
- The code reproduces consistently amplitude and frequency (0.5 to 1Hz) of the cyclic temperature peaks monitored by T204G sensor (blue and purple lines in Figure 9-Left), which is on a pin wall from the 3$^{rd}$ row (see Figure 4-Right). Changes of saturation temperature provided by CATHARE outline pressure changes from the chugging process, including some peaks that tag the strong condensation events. Interestingly, two-steps can be distinguished along the loss of flow stability:
    - Up to 1050s, both pins wall temperature evolutions which are reported (T101G being on the central pin) quite follow saturation conditions. As can be noticed in Figure 9-Right, volume fraction of the liquid metal is still at least above 10% and allows for an efficient cooling, resulting in a pins wall temperature always close to saturation value. The steep rises of the void fraction are due to the combined drops of the inlet flow and of the saturation temperature that indeed drives thermal disequilibrium of the liquid and rates vapor production to accommodate.
    - At ~1050s, void fraction finally reaches close to one. A dry-out event is therefore calculated. From that time, Na saturation temperature and wall temperature consistently evolve out of phase although punctually merging according to some few temporary rewettings of the wall that are calculated, again resulting from the chugging phenomenology. The close consistency between CATHARE results and the experimental data supports the choice of the unchanged dry-out criteria discussed in section 2.1.

Note finally about qualification materials got from the SIENA-37 program that two-phase flow stable periodic pattern of the FC21 LOF test (4.5kW/pin with a flow halving time of about 5s) was also consistently simulated with CATHARE (Anderhuber, Perez, & Alpy, 2017).

(Anderhuber, Gerschenfeld, Alpy, Perez, & Seiler, 2015) have comprehensively reported other qualification materials collected by simulating some natural circulation and LOF tests from the GR-19 program. The latter address consistency of calculated and experimental flow stability scenarios:

- Two-phase flow steady state or instead, pins wall dry-out are respectively achieved at 3kW/pin and 5kW/pin, if one shuts-off power of the electromagnetic pumps from forced circulation. In these LOF experiments, distinguishingly from a reactor LOF transient, no mechanical inertia from

the pumps rotors is available so that flowrate at test-section inlet first drops to quite zero before rising according to buoyancy force increase.
- As mentioned in section 1, static stability and instability of the flow are respectively achieved at 5kW/pin and 8kW/pin, providing power is decreased step by step from forced circulation down to natural circulation. Reliability of the simulations dynamics is however weakened by the lack of experimental data that are still available from that time. Especially, static solution given by CATHARE for the stable case can turn in a periodic one's (as shown above for the SIENA-37 program) and kinetic of the loss of flow for the instable case can be significantly accelerated, depending for instance on considered test-section heat losses, which are actually part of the calculation assumptions. This remark on missing data from GR-19 is actually a general weak point of the CATHARE qualification exercise credited in section 2.2. New HARIBO program will for sure allow discarding such an issue and its numerical monitoring will ease the analysis. Feedback has been also capitalized when building HARIBO about type, place and range of the sensors that could improve the reliability of a new Na boiling program analysis.

As a conclusion, one may consider the qualification of CATHARE3_rev3 on some stability scenarios as rather opportune since few adjustments of closure laws from the steam-water version have been performed (see Table 1), while they were decisive for a right prediction. While the qualification is still ongoing through the ESFR-SMART project (Mikityuk, Girardi, Krepel, & Bubelis, 2017), this achievement should not overshadow some likely limits. Note that some of them could hardly be addressed further through a 1-D representation. As such:

- Section 2.2 underlined that flow-patterns transition in the pins bundle would deserve to be investigated, together with liquid droplets entrainment from the wall. Importance of forces balance in the momentum conservation on stability scenario is further outlined in section 3.2.
- Missing local boiling rises some concerns to credit a full-scale transposition and this supports the development of more predictive 3-D approaches. 1-D qualification may also be riskier when performed on a pins inventory lower than SIENA-37 one's, such as in the HARIBO program which is foreseen.
- Along chugging mechanism, subcooled condensation aspect and connected channel reflooding by reverse flow from upper volumes, could depend very much on geometry characteristics. Transposition is also challenging on that point, which requires predictive capabilities.
- CATHARE occasionally faced some numerical instabilities when simulating final collapse of the condensation fronts. This is typically the case for high powers and/or when the bypass line connects directly the test-section (as in the KNS-37 program or GR-19i one's). While unchanged interfacial heat transfer laws (see Table 1) allowed from a right prediction of the stability scenarios for SIENA-37, the mentioned instability on other programs could point-out some weakness of the modeling. A refined description of the two-phase flow interface could help solving reliably-physically the issue.

## 3. NEXT TECHNICAL ROUTE

### 3.1. 3-D two-phase flow simulation with TrioMC

In the frame of the ASTRID program, the monophasic subchannel code TrioMC has been developed, e.g. to determine the maximum cladding temperature across the core under forced and natural circulations, hence covering reactor steady state and safety transients. The code is part, with TrioCFD and CATHARE, of the thermal hydraulic multiscale model of ASTRID's primary vessel, named MATHYS (Gerschenfeld, 2019) that has been already applied to address a comprehensive VVUQ analysis (Marie, 2020).

TrioMC modelling has been extended to a two-fluid, six-equation system, similarly to CATHARE, with a set of closure laws taken-back from SABENA code (Ninokata & Okano, 1990) that is indeed seen as a sound basis. While extension of the code's capability to two-phase flow is still in progress, simulations that have been yet performed with the current version, show how such a 3-D approach could be informative. As such, steady states of a 5kW/pin test from the BP campaign of GR-19 program (Anderhuber, Gerschenfeld, Alpy, Perez, & Seiler, 2015) have been simulated. Figure 10-Left reports the code-to-experiment comparison of in-bundle temperatures for a single-phase case that confirms the code's ability to predict correctly the temperature distribution within the bundle. This case shows also that scale-down experiments feature marked radial gradients of temperature so that the 3-D approach will be valuable to analyze reliably the new HARIBO program reported in section 3.3 that also features 19 pins. Indeed, such gradients drive local boiling and could induce bypass of the inlet flow through the still-monophasic subchannels, which offer less hydraulic resistance. This local phenomenology, to which a 1-D approach is blind, could onset an earlier dry-out.

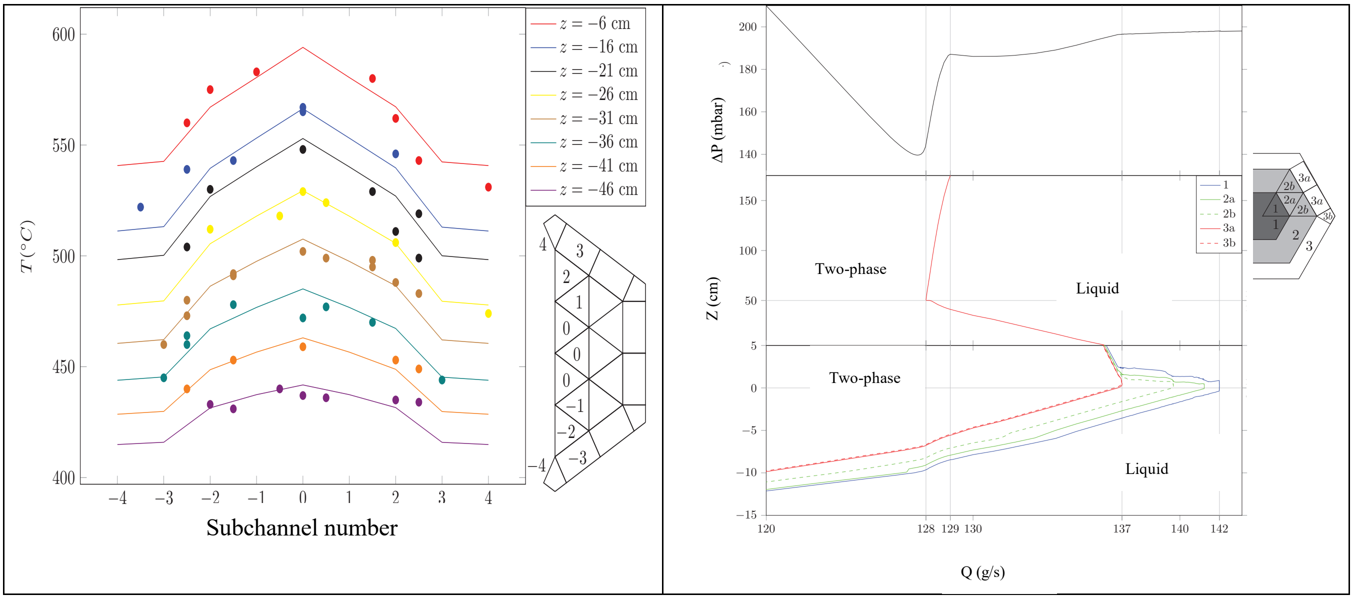


Figure 10: Left: experimental measurements (dots) and TrioMC simulation (lines) for in-bundle temperatures predicted at Q = 0.4 kg/s. Right: TrioMC simulation of boiling onset and generalization with decreasing flow: radial propagation of the boiling region (bottom) and overall pressure drop (top). GR-19BP test at 5kW/pin.

Figure 10-Right shows the influence of the 3-D extension of the boiling region on the bundle pressure drop, according to TrioMC:

- Local boiling (central subchannel #1 at first, then #2a and #2b subchannels) occurs at 137<Q< 142g/s, with only minor influence on the overall pressure drop (which cannot be caught experimentally due to sensor accuracy limitation);
- Boiling becomes generalized (#3 peripheral subchannels are also boiling) and propagates upwards in the bundle at 129<Q<137g/s;
- Around Q=129g/s, boiling by flash occurs along the low friction outlet channel (z >50cm), thereby providing extra floatability force to the flow momentum. This drives the noticeable drop of the pressure drop;
- Below Q=128g/s, the increasing void fraction and down-progression of the boiling front along the high friction pins bundle, results in a pressure drop increase.
- One can notice in Figure 10-Right a certain radial asymmetry of the temperature measurements that is not reproduced by the code. Complementary data would be required to balance the point such as uniformity of the electrical heating among the pins.

TrioMC (tagged by MC-Eb in Figure 11) was over predicting the two-phase pressure drop increase at low flow. Changing the two-phase flow wall friction correlation by the one’s coming-out from the SENSAS program (Eq. 1), results in an improved prediction (tagged by MC-TEb in Figure 11), as was the case for CATHARE (see section 2). Interestingly, between 0.13<Q<0.14 kg/s, TrioMC predicts unsteady boiling with periodic oscillations. Such a limit cycle at boiling onset, not reported by GR-19 experimentators but credited by other experimental results as was outlined, possibly constitutes an interesting point to be further investigated. From a mathematical point of view, this may be analyzed as a bifurcation of the solution and a connected R&D path to balance so, is addressed in section 3.2.

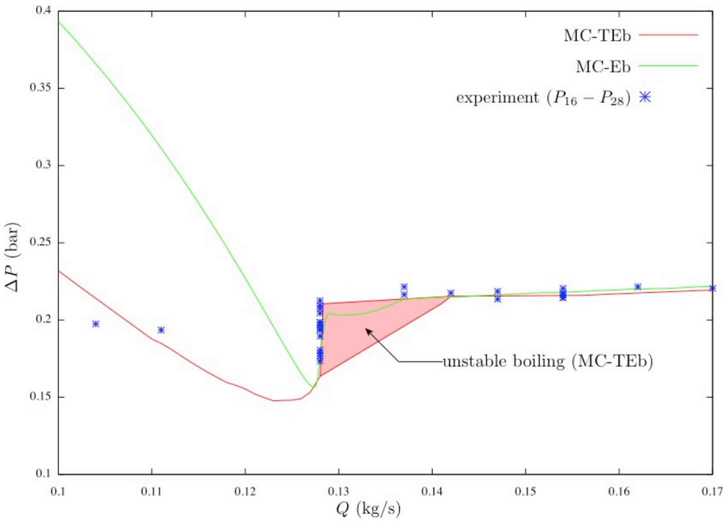


Figure 11: Predictions of the GR19-BP total internal characteristic (P16 - P28) at 5kW/pin by TrioMC.

Progress on TrioMC closure laws, among which slip of the phases, could be next expected from its qualification on the new HARIBO program. However, it will depend on sensors performance together with phenomenology complexity to be analyzed. Another promising route as regards progress on closure laws could consist in a numerical upscaling from CFD. Indeed, while pioneer CFD simulation of Na boiling applied a dispersed two-phase modeling (Mimouni, Guingo, & Lavieville, 2017), the challenging task for a two-phase CFD modelling of all flow regimes that better suits application to Na boiling physics, starts to produce relevant results and opens possibilities. As such, (Mimouni, Fleau, & Vincent, 2017) reports the ability of the NEPTUNE_CFD code to calculate a flow regime map for a horizontal flow of water. This is achieved thanks to a multi-fields approach following the recommendation by (Bestion, 2014) and includes the large interface model due to the breakout effort by (Coste, 2013). Note that some flow-regime maps for Na were dressed from past experimental programs, e.g. by (Yamaguchi, 1987), but they likely present some limitations, at least for Gen4 applications. These are connected to the available power range and to the methodology that was applied to identify the flow regime, based on observations about flow stability change. In SIENA-37 (see Figure 4), the test section resumed in the pins bundle. As was already commented, Gen4 design involves instead very heterogeneous hydraulic parts so that flow regime will change all-along and overall stability will result from the coupling. High fidelity simulations could also allow capturing local unsteadiness of the flow patterns or of their transition, which have been reported in the introduction as possibly interplaying on temporary dry-out achievements.
Benefits from CFD could additionally address simulation of subcooled condensation and connected channel reflooding by a condensing front from upper volumes, which interplay significantly on the phenomenology. Inline, experimental support from the Gen4 CHUG program (Mambelli, Ponomarev, Sato, & Mikityuk, 2019) should be relevant. To conclude let's mention some more incidental – but frequent – experimental recordings that could be typically highlighted by a 3-D approach: this addresses eccentricities of the slugs at high-flow which were experienced along the SIENA-37 program and attributed to effects of the wire-induced forced cross-flow.

### 3.2. Bifurcation and stability analysis

As part of the work undertaken by the technical group working on Na boiling in support to the ASTRID project, an innovative R&D path has been undertaken (Bissen, Alpy, & Medale, 2017) that addresses bifurcation theory and connected stability analysis (Seydel, 2010). Such an approach is new for SFRs but

has been actually applied for long in support to BWRs system (Rizwan-Uddin & Dorning, 1986) and allowed to draw stability maps (Lange, Hennig, & Hurtado, 2011). Interestingly, this field of R&D has outlined the role of HOPF bifurcation (Achard, Drew, & Lahey, 1985) as the reason for the onset of some periodic patterns of the two-phase flow. On this basis, (Bissen, Medale, & Alpy, 2018) has questioned whether the limit cycle calculated along ASTRID ULOF (see Figure 1) could be connected to such a bifurcation, which could ease the analysis of the flow stability by providing tailored mathematical tools.
As for 3-D simulation, the associated R&D work is still in progress but some promising results have already been obtained. As such, (Medale, Cochelin, Bissen, & Alpy, 2020) report the development of a 1-D numerical model named BACCARAT (which stands for Bifurcation Analysis in a vertiCal Channel by the Asymptotic numeRicAl meThod) that applies a full-range regime drift modelling of the two-phase flow, inspired from (Sonnenburg, 1989), and further allows for its linear stability study.

By this mean, a stability analysis of a water flow under natural convection at atmospheric pressure ($\rho l/\rho v$=1000) in a 1cm diameter, 1m long cylindrical channel was carried-out. HOPF bifurcations at low (boiling onset) and medium void fraction were outlined and connected to the relative weight of acceleration force compare to friction one's, as the balance to buoyancy. Importantly, as reported in Figure 12, this test-case shows the ability of a two-phase flow – featuring a three-order magnitude difference of the densities – to develop a periodic pattern following a static stability change, along a part of the solution branch that also presents other sections with a static stable pattern. This duality highlighted by BACCARAT could possibly conciliate two experimental observations from Na boiling past programs, since a periodic pattern is SIENA-37 like while a static stable pattern could be GR-19 like. Note also that such a topology agrees with the conclusions from (Levin, Carbajo, LLoyd, Montgomery, Rose, & Wantland, 1985), commenting Na boiling stability under natural circulation as a periodic pattern ended - for increased powers - by a final loss of stability of Ledinegg type. These authors also reported the analogy between their observations on the Na THORS facility and some steam –water tests they had performed, the latter being indeed the conditions of the BACCARAT test-case.

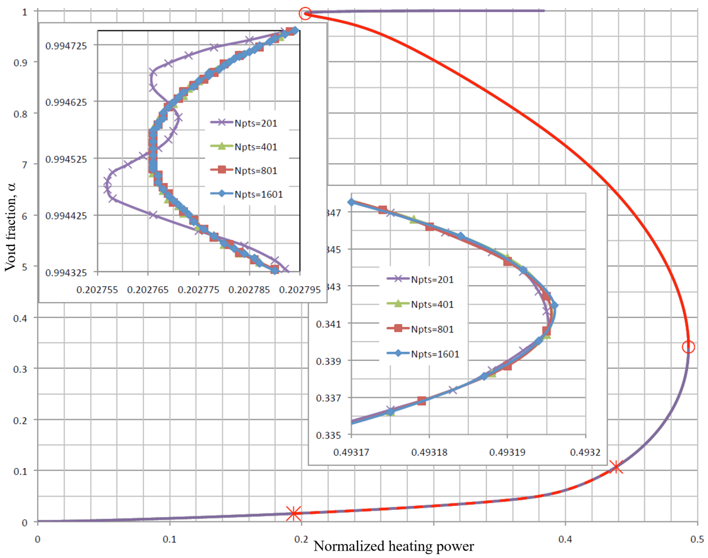


Figure 12: Steam volume fraction at the exit of a vertical channel under natural convection as a function of heating power (Medale, Cochelin, Bissen, & Alpy, 2020). The two-phase flow stability patterns are pointed-out: red-dots point a periodic flow (between two Hopf bifurcations, tagged by red-crosses) ; purple-lines point static stable flows (Ledinegg stability) ; red-line points static instability.

BACARRAT could be next used to review Na boiling flow stability and sensitivity for past out-of-pile experiments as well as to investigate impact of Gen4 design specifics which should modify the forces balance among buoyancy, friction and acceleration.

### 3.3. HARIBO program plan

A new experimental program, named HARIBO is planned in the frame of a collaboration between IPPE and CEA (Anderhuber, et al., 2019). This thermal hydraulic program targets to provide a database that suits the new Gen4 hydraulic design specifics for CATHARE and TrioMC qualification. To achieve so, a wire-spaced 19 pins bundle will be used, topped by a 40cm high Na cavity. Both items are reported in Figure 13-Left. The test-grid (about forty tests) will feature LOF, natural circulation and forced convection tests, combining the approaches that were used along past programs. Part of the parameters will be:

- Height of the Na plenum (pointed by Na cavity in Figure 13-Left) that could be increased up to a factor three. It will allow providing some insights on the forces balance impact onto flow pattern and possible stability gain, as outlined in the preceding section;
- Central pin power, which could be turn-off to change the temperature radial profile;
- Involvement of a bypass-line to mimic parallel subassemblies that would still be under monophasic state along a reactor transient.

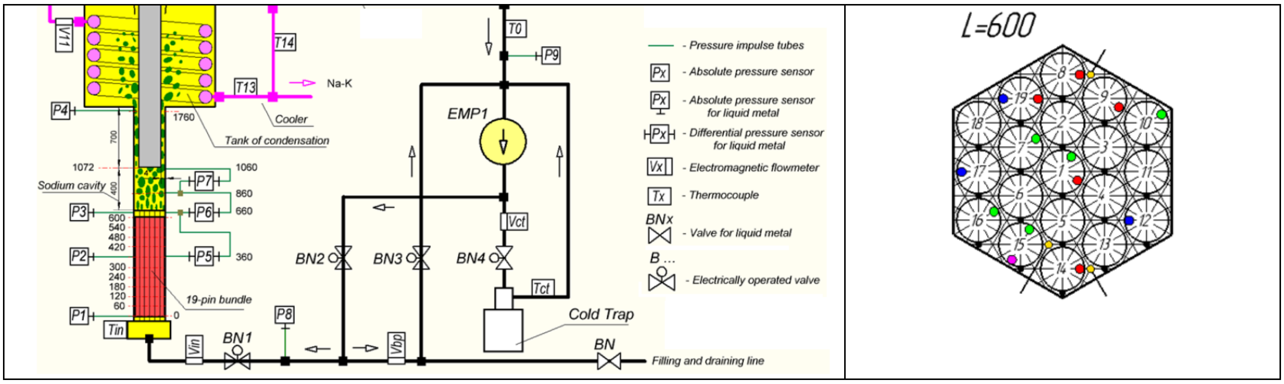


Figure 13: Left: Conceptual scheme of the facility for HARIBO program. Right: Temperature sensors at top of the bundle (sodium thermocouples in yellow, the rest are pins wall thermocouples), (Anderhuber, et al., 2019).

(Anderhuber, et al., 2019) reports that 1-D CATHARE and 3-D TrioMC calculations were carried-out as part of the preparatory work. They outlined the possibility to investigate a stable periodic pattern as well as an unstable one's under a LOF and supported the definition of sensors' location and range. Part of them are the differential pressure sensors P5, P6 and P7 (Figure 13-Left), which target an accurate monitoring of pressure changes. As highlighted through the SENSAS program (see section 2.1), P6 and P7 will interestingly allow balancing effect of entrance length on two-phase flow development; P7 will additionally allow balancing void fraction at low superficial velocities. Importantly, 76 pin wall thermocouples and 18 thermocouples within Na will be also implemented, distributed on 9 planes along the test section. Figure 13-Right maps these sensors at the 600mm elevation (hottest) plan and shows that any type of subchannel will be scrutinized. An accurate balance of heat losses will be made available, consistently with the lessons reported in section 2. Void and acoustic sensors will complete the monitoring. The later will innovatively target to support flow regimes identification.

## 4. CONCLUSION

An overview of the thermal-hydraulic side of an R&D program at CEA that has been run on Na boiling dynamics, as part of the ASTRID Gen4 SFR project, has been reported. Especially, a periodic stable pattern that was incidentally obtained when calculating at first an ULOF, motivated the initiative. If proven, such a phenomenology could indeed improve reactor safety by providing a time-window for recovering pumping power, instead of shifting to a severe accident phase. First, the 1-D numerical achievements obtained by simulating some out-of-pile programs from the 70-80s, have been detailed. The latter were indeed already very informative on two-phase flow stability scenarios, by so offering a first sound

qualification basis. Benefits for simulating Na boiling stability allowed by a recent air-water experimental program, have been inline highlighted. One may consider this qualification as rather opportune since only few adjustments of closure laws from the steam-water application have been performed but they were indeed decisive for a right prediction of the stability scenarios. However, these achievements should not overshadow some likely weakness, such as regarding the modeling of strong condensation events.
Then, the next technical route that is planned has been outlined, while pointing-out some of its early results. Part of them, is 3-D simulation by subchannel codes which added-value to perform a detailed analysis of scaled experiments, featuring steep radial gradients of temperature, has been illustrated. Indeed, these gradients drive local boiling and could induce bypass of the inlet flow through the still-monophasic subchannels, which offer less hydraulic resistance. This local phenomenology, to which a 1-D approach is blind, could onset earlier dry-outs. In the challenging context for the instrumentation raised by the high temperature and low hydraulic diameter pins bundle, capabilities of CFD should be precious to promote a numerical upscaling of the closure laws for the subchannel modeling and should be also central to credit a full-scale transposition. Progress on flow stability analysis, including two-phase flow patterns, subcooled condensation as well as connected channel reflooding and pressure wave aspects, could be as such expected from recent developments on CFD. Indeed, recent advances for an all flow regimes representation, featuring large interface modeling, opportunely suit Na boiling physics.
Bifurcation and stability analysis of the two-phase flow have been finally identified as providing a complementary tailored mathematical approach to connect the periodic flow pattern to a Hopf bifurcation and further balance stability of the associated mathematical solution (limit cycle). Conclusions from a test case withstand the ability of a two-phase flow – featuring a three-order magnitude difference of the densities – to develop a periodic pattern along a part of the solution branch that also presents another section with a static stable solution. This duality would possibly conciliate two experimental observations from Na boiling past programs. It is worth noticing that bifurcation and stability analysis could be relevantly extended to innovative safety passive systems that are considered for PWRs. Indeed, the mechanistic view that is provided, especially by connecting the consequences of a forces balance change on stability, should be valuable to support a safety demonstration.
On the experimental side, the scope of a new program planed on a wire-spaced 19 pins bundle, has been briefly introduced. HARIBO program suits some new Gen4 hydraulic design specifics and targets for sure codes qualification. Let's mention to conclude that thermal-hydraulic is only one side of the topic, which actually challengingly addresses various multiphysics aspects if one considers the reactor case.

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