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Next Generation Nuclear Systems: "The Force Awakens"

RESEARCH PROPOSAL

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Research topic/title

Stability and bifurcation analysis of sodium boiling in a GEN IV SFR reactor core

Introduction

Nuclear reactors of the fourth generation (GEN IV) are asked to meet a very high level of safety requirements [1]. In this context, it is crucial for Sodium Fast Reactors (SFRs) to study their behaviour in hypothetical singular situations, such as an Unprotected Loss Of Flow (ULOF), which might cause the liquid sodium to boil. This project aims to strengthen our knowledge on sodium boiling phenomenology, while important experimental lessons were get in the 80's thanks to international [2] and especially French programs [3]. A better understanding of such an event is indeed a helpful guide for a better, safer and more efficient design of the future reactors, typically for low void worth concepts such as the CFV designs [4]. To reach these new and stronger requirements, more detailed knowledge must be reached, which in turn demands to develop new study and validation tools, such as high-fidelity numerical simulations. Nevertheless, we should not forget that sodium boiling is a very dynamic two-phase flow phenomenon, and numerical tools such as system codes are challenging to set and validate for such circumstances.

Our research aims at developing an innovative methodology with respect to the nuclear safety context, based on stability and bifurcation analysis through a semi-analytical procedure. Thanks to such semi-analytical approach, one can expect to gain a more reliable understanding of boiling phenomenology in the reactor core and a better mastering of the non-chaotic side of these phenomena [5], which helps promoting safety. Since this method is new for SFRs, we also aim to provide innovative results, hence innovative design proposals. Helpfully, we can still capitalize on the R&D work on stability analysis that has already been developed for BWRs and on the some similar key-points and phenomena between BWRs and sodium boiling in SFRs, such as the nature of instabilities likely to appear for both types of reactors due to the aspects purely related to two-phase flow fluid dynamics [6]. Furthermore, such an analytical approach also helps cutting down on the limitations inherent to numerical modelling, which cannot be neglected in two-phase flows.

This project consolidates the SDG goal 7, as improvements to the safety of future nuclear reactors will help ensuring access to affordable and reliable energy for all. Moreover, it fits very well several of the theme tracks of this conference, as we are focusing on modelling and numerical simulations, with the necessary verification and validation of fundamental issues (topic 8) with a clear goal to improve safety by an innovative design approach (topic 4) and we want also our innovative approach to be a guide for innovative core design (topic 2).

Background/Problem Statement

Previous SFRs cores were characterized by a reactivity increase, hence a power excursion in case of an unprotected transient due to a positive void worth. Experiments have therefore been led to study boiling as a direct cause for a severe accident with core materials melting. On the contrary, recent SFRs designs, such as the CFV core, have been aimed at ensuring a negative reactivity by including an upper plenum above the core. The power therefore tends to decrease if the sodium starts to boil. This different geometry means also different nature and intensity of coupling phenomena as well as instabilities and non-linearities [7]. Moreover, as explained above, the new generation of reactors are being developed in a different context, which asks for higher safety requirements, hence the need for stricter validation.

In this section, we will succinctly analyze the efforts made at the CEA until now with this goal in mind. The main task recently has been to extend to codes from single-phase to two-phase thermal hydraulic studies: the CATHARE system code and MC_Teb subchannel code [8]. The first studies a sub-assembly and can couple a point-kinetics model to study the neutronics as well, therefore representing a complete primary circuit. On the other hand, a subchannel approach allows a study of boiling at a local level, hence showing the 3D effects within a sub-assembly. We shall here focus on the results obtained with CATHARE, as they are currently the most representative and complete.

CATHARE is a 2-fluid 6-equation thermal hydraulic code developed originally for the Pressurized Water Reactors, with a qualification grid that was also involving low pressure tests. Large void fraction aspect is reinforced for Na boiling which liquid and vapor densities differ from more than 3 orders of magnitude. Hence fluid-mechanics has been extended to SFRs, especially their new geometry, based on correlations extracted from air/water experimental studies, the SENSAS experimental campaign [9]. Regarding the thermal aspect, the complex steam/water grid [10] has been simplified [11] based on lessons from the 80's [3] which stated for instance that the liquid phase transfer performance could be considered as driving the wall heat transfer up to the dry-out phase (considering also instrumentation limit), hence neglecting the additional convection effects appearing when boiling starts as extensively studied on water two-phase flows [9]. CATHARE has been run in two main cases: firstly, using the geometry of the GR19 experiments to validate the code, secondly on a typical Gen IV SFR reactor case.

GR19 is a 19-pin, electrically heated test section built in Grenoble (France) at the end of the 70's and exploited during the 80's. The loop was designed to recreate the boiling conditions in the core of SUPERPHENIX reactor. The test section consists in a 19 pins rod bundle topped with a convergent plenum and a thick tube. The middle part of the rod bundle is the heated part to reach boiling.

The reason why GR19 experiments are stills so interesting today is because they showed that a stabilized boiling is possible under the right circumstances. Analyzing whether such a stabilized boiling could be possible for Gen IV SFRs is a very interesting scientific challenge and could promote safety [12]. Looking at Figures 1 and 2 below, which show the results of a reactor case [13], we can clearly see the calculated dynamic instabilities in the transient, shown with an oscillation in the sodium inlet flow rate and in the void fraction as well. We should note that these results have been obtained by considering no change of the problem's geometry.

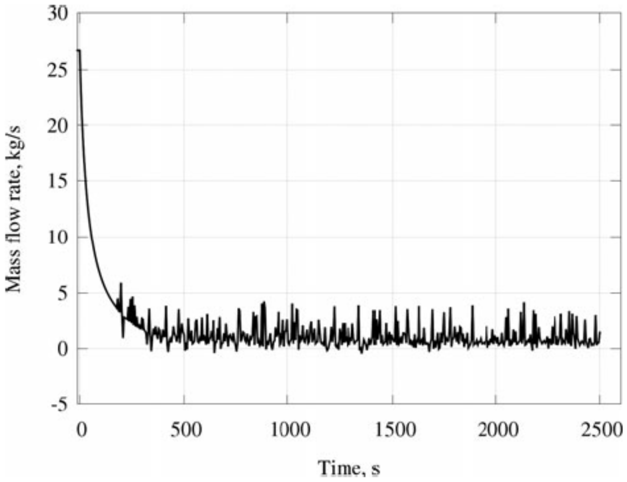


Figure 1 : Na inlet mass flow rate (hottest core subassembly)

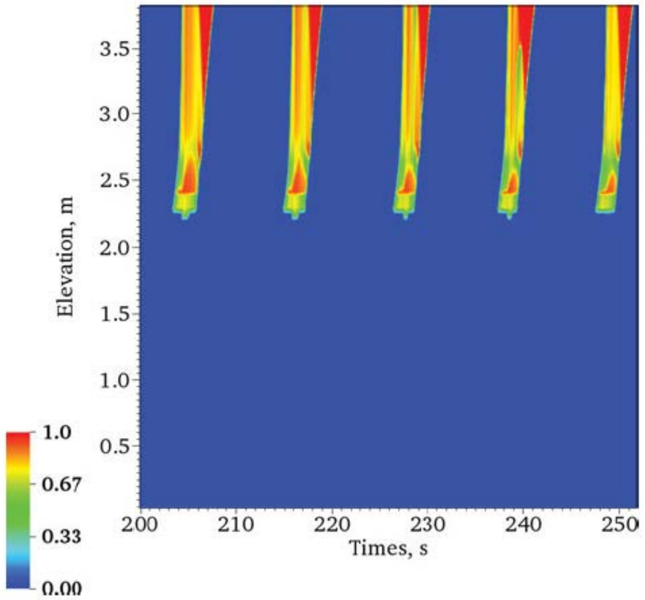


Figure 2 : Void fraction 1D axial profile along the hottest core subassembly

The profile of the void fraction evolution with time also leads us to consider that a chugging phenomenon is happening. Chugging is schematically represented below on Figure 3, and corresponds to cyclic flow rate oscillations.

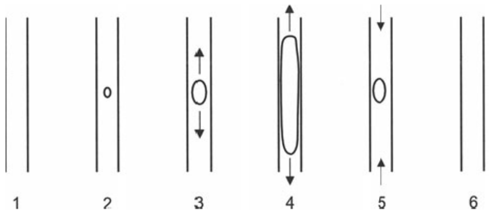


Figure 3: chugging phenomenon as in [13]

These computations therefore already show the possbility of reaching a stabilized boiling case in specific conditions. We report below on Figure 4 an alternative scenario that is obtained by increasing the considered power [14]. One can clearly see a chugging behaviour developing at first, which is then replaced by a clearly positive growing rate of subassembly voiding (the boiling front enters progressively deeper within the fissile length, z<2.4). These recent studies show the importance of a rigorous and complete stability analysis of the system, as we can witness a drift from a stabilized (bounded periodic situation with zero growing rate) to unstabilized (positive growing rate instability) situations.

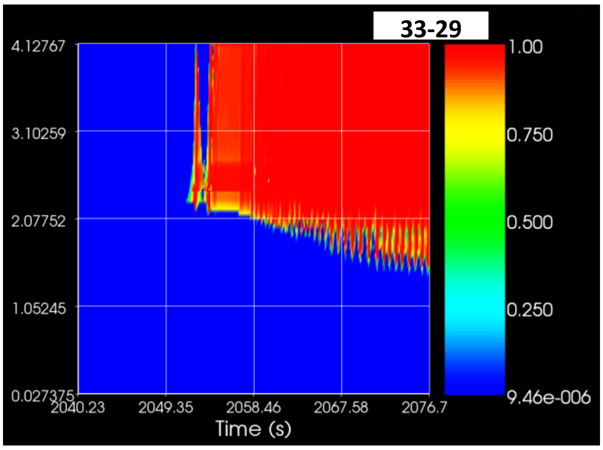


Figure 4: void fraction axial profile evolution for peak power subassembly

Goals

The main goal of our research project is to study the sodium boiling stability in a/several SFRs assembly(-ies). Considering the very dynamic context, developing then implementing a semi-analytical approach (in opposition to the numerical only-approach typically used by system codes) inspired by the methodology developed for BWRs (study of stability and bifurcations associated with fixed and singular points of the system) has many advantages. Furthermore, we would like to capitalize on the knowledge acquired during these analyses on BWRs while also taking advantage of implementing a complementary procedure, called Asymptotic Numerical Method (ANM), studied extensively at the Aix-Marseille University [15]. This would allow us to further develop the analytical side of the approach, hence giving our study a very general view of the stability map of sodium boiling in a SFR core. Our goals within this PhD thesis are therefore to show the usability of this ANM on a BWR case, to validate it. Then we are planning to adapt this method to the SFR case and analyze the stability and bifurcations of sodium boiling with this semi-analytical approach.

Moreover, this project has been thought around a longer-term vision as well, going further than this PhD thesis. Firstly, two-phase flows are difficult scenarios to study with CFD, for which it is still considered as a tool in R&D development state rather than a predictive tool as in single-phase cases. We would like therefore to use CFD as a complement to our semi-analytical approach. The first opportunity lies in a model developed at the Aix-Marseille University, whose main feature is an interface tracking aspect allowing it to study fast-dynamic phenomena, like chugging, which happens in SFR core in case of sodium boiling as shown in previous work.
Considering we would like to bring an innovative core design to the project, another aspect for CFD use is for us to capitalize on the solidity of single-phase CFD [16] to study the impact of our innovative design on the nominal single-phase situation of an SFR core.
Finally, we would like to run 3D CFD experiments on the basis of AR-1 geometry (7-pin) [14], to deepen the understanding of relative weight, with respect to the phenomenology, of geometrical effects and temperature gradients with relation to the uncertainties on the closure laws (thanks to sensibility studies), in order to further improve the characterization of the expectations of RANS CFD experiments and sub-channel codes experiments.
As a conclusion, from the results of this analysis, we would like to be able to deduce which closure laws and non-linearities have the most impact, hence on which the validation effort should pay special attention (e.g. wall and interfacial friction, neutronics coupling, multiple assemblies effects). Moreover, as this method is new to SFRs, we would like to reach results that can be used as a guide for an innovative assembly design helping to reach stabilized boiling, hence promoting safety.

Details of the Proposed Research

In this section, we will first focus on the methodology as developed for the BWRs. The dynamics of a BWR can be described by a set of non-linear partial differential equations coupling the thermal hydraulic and the neutron kinetic aspects. Such system of equations can show a very complex behavior under specific circumstances. Especially studying Operating Points (OP) where power oscillations are observed and their stability is crucial for safety. Reduced-order models (ROM) have therefore been developed to help study non-linear stability of such operating points [17][18][19]. These models consist in a minimum number of equations being able to describe the physics involved as accurately as possible. The global model can be divided into 3 separate sets coupled with each other: neutron kinetic, thermal-hydraulic and fuel rod heat conduction. The sketch below, Figure 5, schematically shows the inner workings of the model developed by Lange [18], which has the main advantage over the other BWR models of including a recirculation loop model while using the same equations.

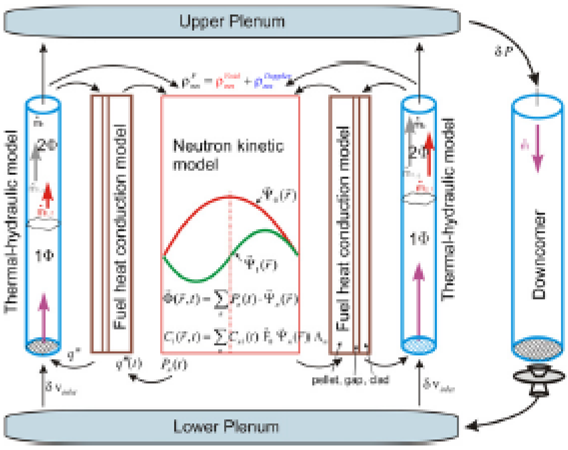


Figure 5: Schematics of ROM developed by Lange for BWRs [18]

As we can see on the schema, the model studies two channels in parallel in order to be able to consider multi-1D effects. The neutron kinetics equations are based on a one-energy group model with spatial mode expansion of neutrons considering the first 2 realistic lambda-modes only. The fuel rod heat conduction model considers a separation between three radial regions (fuel, gap and pellet) and two axial regions (single phase liquid and two-phase liquid-vapour). Finally, the thermal-hydraulic model considers two axial regions (single and two-phase flows) and uses a drift flux model to represent the dynamic behavior of the two-phase region under the assumption of thermal equilibrium. These models are coupled using the mode feedback reactivity calculation, assuming two main mechanisms: void and Doppler feedback reactivity. Finally the recirculation loop is modelled considering an incompressible fluid in the plenum and downcomer.

The ROM is used by Lange as a tool complementing a classical system code. The first step of the procedure is to choose the OP of interest, where the stability analysis will be run. A steady-state run of the system code is used to calibrate the ROM at that point. The values used to check this are for example the feedback reactivity coefficients or axial void profile. Once the reduced-order model is calibrated, the stability analysis can be run. Two approaches are then run in parallel: a semi-analytical one using a bifurcation analysis code, and a numerical integration of the ROM equations to show the advantage of the semi-analytical method when using exactly the same set of equations. When the stability map is drawn, the system code is used to analyze the transient in the neighborhood of the operating point of interest. The semi-analytical bifurcation analysis is here the feature of interest, and its typical results are shown in Figure 6 [19]. It shows the stability boundary in the basic case in comparison to the stability limits in case of a perturbation being introduced in the system. The amplitude of the perturbation is given as a percentage of the operating parameter (for example the inlet mass flow rate). The authors [17][19] typically find Hopf-bifurcations tend to appear at the onset of boiling in BWRs. Hopf bifurcations, as shown in [17] and Figure 7 are characteristic of the co-existence of a fixed point and limit cycle, hence further proving the possibility of a stabilized (bounded situation with zero growing rate) situation.

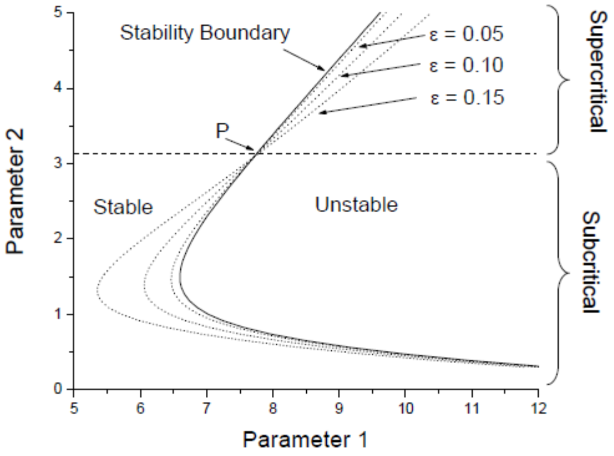
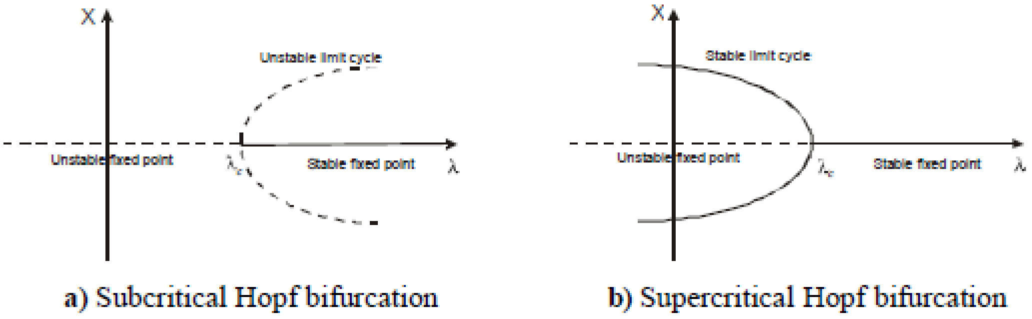


Figure 6: Example of stability boundary and impact of perturbations calculated by [19] around the operating point P and nature of related Hopf-bifurcations



a) Subcritical Hopf bifurcation

b) Supercritical Hopf bifurcation

Figure 7: Sub- and super-critical Hopf bifurcations and relationship between fixed point and limit cycle with analysis of their stability [17]

The second main topic in this section is the description of the semi-analytical method we will deploy in our project: the Asymptotic Numerical Method, or ANM. First-order predictor-corrector methods are the most commonly used in current software for bifurcation analysis of nonlinear equation solutions. The ANM proposes an alternative where solution branches are approximated by higher-order truncated Taylor expansions, which allows the range of validity to be computed *a posteriori* from the convergence properties of the series instead of being set as a calculation parameter *a priori* as required in all predictor-corrector methods. This provides adaptability to the non-linearities and singularities along the continuation, related to the bifurcation points, which can be automatically computed. This will hence give a very strong robustness to the method [20]. Our main task will be the adaptation of the simplified model developed for the BWRs to the ANM requirements, especially their implementation as developed at the Aix-Marseille University.

The ANM can be further improved by pushing the analytical, hence rigor and robustness, even further. It has been for example proved that the Taylor-expansion series always arise as geometric power series in the neighborhood of a simple bifurcation point [21]. Geometric power series can therefore be tracked and be used as tracer to find all the simple bifurcation points of a problem as reliably and automatically as possible.

Another improvement implemented previously to the ANM is the Automatic Differentiation (AD) [20]. It consists in interpreting a generic non-linear problem as a series of linear ones. Thanks to the generalization of the chain-rule derivation, the calculation of the derivative is automated and simplified, which then allows the application of the AD to compute the Taylor coefficients of the ANM series.

Considering the capabilities of the ANM, it is a very appropriate tool to help us finding all the bifurcation points in a very rigorous manner and creating a bifurcation map, which in turn helps the stability analysis. This analysis itself can be run considering different angles of attack. The most common, and widely used the previous studies focusing on BWRs, is the modal approach. It relies on assuming a shape for the perturbation introduced in the system, based on the space-time superposition (space and time dependent parts of the perturbation can be separated) and assuming infinitesimally small amplitude. Such an approach has its strength, but applying the ANM to resolve it would not add any more information compared to what has already been done before (using traditional bifurcation codes). Nevertheless, non-modal approaches exist too [22] [23], which don't rely on any assumption neither on the shape nor amplitude of the bifurcation, but rather find the optimal bifurcation, which is defined as the most destabilizing perturbation [15]. They can either be linear, for which the ANM is not beneficial either. However, non-modal non-linear stability method can also be considered thanks to the robustness of the ANM. As a conclusion, the ANM combined to a more general approach to the stability analysis will allow us to draw a more robust stability mapping of the reactor in case of boiling caused by an ULOF situation, which in turn will greatly help promoting safety.

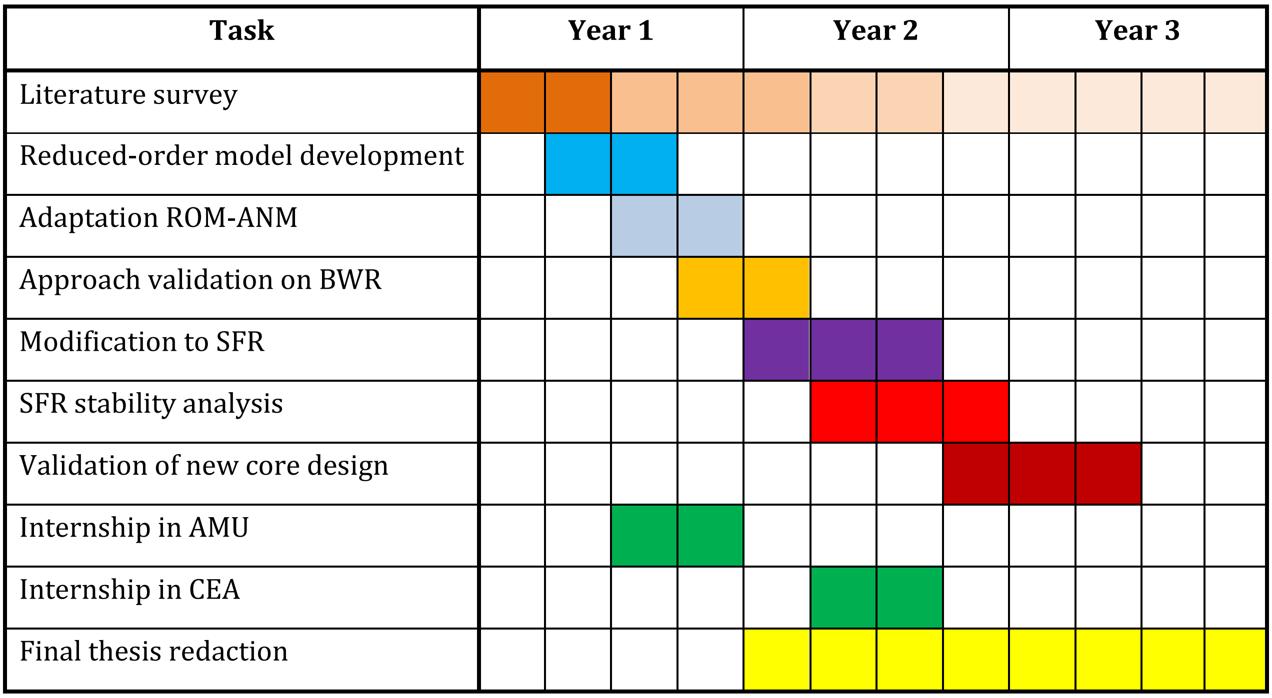
Research Plan

Regarding the timeframe of tasks for the three years of this thesis, which is summarized in the table hereunder, we have devised them into a logical series. We have defined two background tasks which will be kept in parallel to the main structure of this project during most of its duration: the literature survey, which should be allow us to stay on top of the state-of-the-art on the topic, and the final thesis redaction, which should be started early and will be the conclusion of this work.

Besides, our first important checkpoint is the development of our simplified model and its adaptation to the ANM semi-analytical approach. After having plugged these two tools together, we are planning to validate our approach on a BWR case so that we can compare our results to those in the literature and show the advantages of our method.

Having proved this, we will then attack the core of our project and modify our model as to fit it for studies on SFRs. To do this, we are planning to support an internship at the CEA which would work with system codes as to provide reference data for us to perfectly fit our ROM and semi-analytical approach, working on data set for existing experimental geometries such as GR19 or AR-1. Once we have a suitable tool, we will use it to analyze the stability of sodium boiling in an SFR core, which remains the heart of our whole project.

Finally, we want to keep some time as to be able to study the impact of the innovative core design we would like to deliver on the single-phase situation, using CFD single-phase tools. In parallel, an internship will be held at the AMU on fast-dynamic phenomenology which will give us some very interesting results from a different perspective and help us understanding the physical phenomena, hence promoting safety even further. Both these internships, at CEA and AMU, will allow us to support students into research and to gain a new perspective thanks to new people entering our research team.



Task	Year 1				Year 2				Year 3			
Literature survey	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Reduced-order model development		🟦	🟦									
Adaptation ROM-ANM			🟦	🟦								
Approach validation on BWR				🟨	🟨							
Modification to SFR					🟪	🟪	🟪					
SFR stability analysis						🟥	🟥	🟥				
Validation of new core design								🟥	🟥	🟥		
Internship in AMU			🟩	🟩								
Internship in CEA						🟩	🟩					
Final thesis redaction					🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

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