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EXECUTIVE SUMMARY OF THE THESIS

Transient Analysis on SUNRISE-LFR with an Updated Version of BELLA Plant Simulator

LAUREA MAGISTRALE IN NUCLEAR ENGINEERING - INGEGNERIA NUCLEARE

Author: ALESSANDRO PERSICO

Advisor: PROF. ANTONIO CAMMI

Co-advisor: PROF. JANNE WALLENIUS

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1. Introduction

As the world strives to achieve carbon neutrality, a new generation of nuclear power reactors promises to produce sustainable, reliable and safe energy at competitive costs. It is the Generation IV of nuclear power and this thesis is about one of the six families: lead-cooled fast reactors (LFRs). Thanks to lead excellent properties as coolant, they are claimed to enable small and compact designs that can rely on passive safety (e.g., natural circulation). Moreover, lead provides a strong *in situ* shielding against gamma radiation and retains a large fraction of volatile fission products, such as cesium and iodine, in case of an accident. Differently than sodium, it has a great compatibility with water and air avoiding the necessity of costly intermediate circuits.

Historically LFRs were associated to URSS nuclear-powered submarines. After the program ended, Russia declassified a lot of information and Western countries' interest in LFRs has increased. Nowadays, several prototypical units are being developed all around the World: BREST, ALFRED, CLFR, MYRRHA are only some of current projects.

In Sweden, a research center has formed with the aim of constructing the first demonstrator LFR by 2030 in Oskarshamn. The research reactor, whose design is described in a recently published paper [1], goes under the name of SUNRISE-LFR. It is taken as a reference in this thesis work.

In the development of advanced nuclear reactors, a special role is covered by general purpose plant simulators oriented to the study of their dynamics and control. To that end, this thesis proposes a new model for the steam generator adopting a well established method, the moving boundary approach. It is integrated within BELLA, a lumped-parameter code developed in the recent years by researchers at KTH, Stockholm, which is here improved and adapted to the most updated version of SUNRISE-LFR. The ultimate goal of BELLA is to show the interactions between primary and secondary circuits over short or long time scales and under accidental scenarios. In particular, four accidental transients have been simulated and commented with reference to the reactor's safety requirements.

All the work has been done in MATLAB/Simulink®.

This Executive Summary is divided into five sections. Section 1 introduces the topic and delineates the goals of the work. Section 2 describes the most updated version of BELLA. Section 3 is dedicated to the moving boundary model applied to the steam generator module. Section 4 goes through the simulations of four accidental scenarios, each described in a dedicated subsection. Lastly, Section 5 proposes conclusive remarks about the whole work.

2. Primary circuit modeling

BELLA (Bortot's Elegant Liquid Lead Analysis tool) [2] is a zero-dimensional code which provides a non-linear solution for the coupled neutron kinetics and thermal-hydraulics of the primary and secondary systems of a lead-cooled fast reactor. It is based on the use of point kinetics and balance equations for mass, momentum and energy, which are in general applied to all primary system components, namely core, steam generator and pool volumes, such as hot and cold legs.

This thesis takes the already existent mathematical version of BELLA, codes it in Simulink and improves the dynamical equations for the primary coolant mass flow rate and for the free surface level of the hot leg, according to the latest design changes of SUNRISE-LFR.

Neutronics

A point kinetics model with 8 groups of neutron precursors is adopted:

$$\frac{dn(t)}{dt} = \frac{\rho(t)-\beta_{\text{eff}}}{\Lambda_{\text{eff}}}n(t) + \sum_{i=1}^{8}\lambda_i C_i(t) \quad (1)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda_{\text{eff}}}n(t) - \lambda_i C_i(t) \quad (2)$$

Time-dependent reactivity is composed of five contributions: Doppler effect, fuel axial expansion, lead thermal expansion, fuel assembly diagrid radial expansion and external reactivity term.

Decay power is computed with 23 decay curves from ^{235}U fission products:

$$\frac{dh_j(t)}{dt} = \frac{\beta_j}{\varepsilon_{fiss}}n(t) - \lambda_j h_j(t) \quad (3)$$

Then, reactor thermal power:

$$\dot{Q}_{th}(t) = \frac{\dot{Q}_{th}(0)}{n(0)+\sum_{j=1}^{23} h_j(0)}\left[n(t)+\sum_{j=1}^{23} h_j(t)\right] \quad (4)$$

Thermal-hydraulics

It accounts for the exchange of energy, momentum and mass between core, hot leg (HL), steam generator (SG), cold leg (CL) and cold pool (CP).

Inside the core, fuel, cladding and gap temperatures are calculated. In particular, both fuel pellet and cladding are divided into three radial nodes, while a single node is conceived for the gap, filled with helium at 1 bar. Only one node is envisaged in axial direction. For each node, energy balance equation is implemented as follows:

$$\begin{aligned} m_i c_i \frac{dT_i}{dt} &= \dot{Q}_{in} + h_i(T_i - T_{i-1}) + \\ &- h_{i+1}(T_{i+1} - T_i) - \dot{Q}_{out} \end{aligned} \quad (5)$$

Energy balance in the primary circuit accounts for the heat propagation from reactor core to HL, SG, CL and CP adopting again Eq. (5). Thermal power is removed from the system by two sinks: the SG and thermal radiation from the reactor vessel (RVACS).

The conservation of momentum leads to the dynamical equation of lead mass flow rate:

$$\frac{d\dot{m}_{Pb}}{dt} = \frac{\Delta P_{buoyancy} - \Delta P_{friction} + \Delta P_{pump}}{\sum_k \frac{L_k}{A_k}} \quad (6)$$

where ΔP_{pump} is the primary pumps pressure head.

Mass balance equation allows to compute the time-dependent free surface level in the HL:

$$Z^{HL}(t) = \frac{M_{tot} - V^{core}\rho^{core} - V^{CL}\rho^{CL} - V^{CP}\rho^{CP}}{A^{HL}\rho^{HL}} \quad (7)$$

being M_{tot} the total lead inventory in the system.

3. Steam generator modeling

A new model for the SG is developed adopting the moving boundary approach. It is a zero-dimensional model compatible with the rest of BELLA and able to simulate the dynamics of the three SG regions (subcooled, saturated, superheated) by tracking their length. Since BELLA is a general purpose code interested in the interactions between primary and secondary circuits of an LFR, and therefore in the quantity of water/steam present in the SG rather than in single-phase regions temperatures distribution, the moving boundary method resulted more appropriate than distributed-parameter codes. Moreover, it is numerically faster compared to discretized models and very robust to sudden changes in the boundary conditions [3].
In order to adopt it, some assumptions need to be introduced, among which the change in geometry from the real component (spirally-coiled tubes and cross-flow between water and lead) to the modeled one (once-through SG in counter-current configuration) is likely to be the most important, albeit difficult to quantify.

Water side

Given the large superheating degree requested by the design of the SG, the superheated region has a very large extension. Thus, to improve accuracy, it is decided to split it into two equally spaced regions. Then, the total number of regions becomes four. They are numbered from 1 (subcooled) to 4 (second superheated region).
Dynamical equations for each region are derived starting from first principle mass and energy balances (no pressure losses are considered) applied to a 1-dimensional flow:

$$\frac{\partial A_s \rho_s}{\partial t} + \frac{\partial \dot{m}_s}{\partial z} = 0 \tag{8}$$

$$A_s \frac{\partial (\rho_s h_s - P)}{\partial t} + \frac{\partial \dot{m}_s h_s}{\partial z} = \pi D_{in} \alpha_s (T_w - T_s) \tag{9}$$

where subscript s stands for secondary fluid, water.

Lead side

Dynamical equations for each region are derived starting from first principle energy balance applied to a 1-dimensional flow:

$$A_p \frac{\partial (\rho_p c_p T_p)}{\partial t} + \Gamma \frac{\partial (c_p T_p)}{\partial z} = -\pi D_{out} \alpha_p (T_p - T_w) \tag{10}$$

where subscript p stands for primary fluid, lead, and $\Gamma = \dot{m}_{Pb}$.

Wall side

Dynamical equations for each region are derived starting from first principle energy balance applied to a 1-dimensional solid:

$$\begin{aligned} A_w \rho_w c_w \frac{\partial T_w}{\partial t} &= \pi D_{out} \alpha_p (T_p - T_w) \qquad (11) \\ &- \pi D_{in} \alpha_s (T_w - T_s) \end{aligned}$$

where subscript w stands for wall.

4. Codes coupling and simulations

BELLA and the newly developed SG model are written and integrated in Simulink. Due to Simulink causal approach in solving DAE systems, SG equations are rewritten in explicit form. Then, simulations of the reference accidental scenarios are performed.
SUNRISE-LFR requires to prevent fuel melting (at 2850 °C) and cladding tube creep rupture by all means. Thermal creep is assumed to become significant at 763 °C (red dashed line), so a first threshold is placed at 662 °C (green dashed line) where half of the margin is consumed (at nominal conditions cladding maximum temperature is at 550 °C).

UTOP

This is the unprotected transient overpower and it is triggered by a step-wise reactivity insertion of 0.2 $. It induces a surge in reactor core power (approximately +19%).

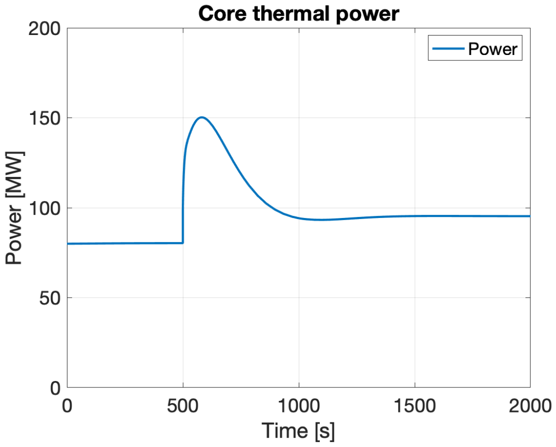

Figure 1: Core thermal power in UTOP.

As a consequence, system temperatures undergo a general increase. Fuel melting is still very far from occurring, while cladding temperature in the peak assembly (PA) consumes slightly more than half of the margin to cladding creep rupture.

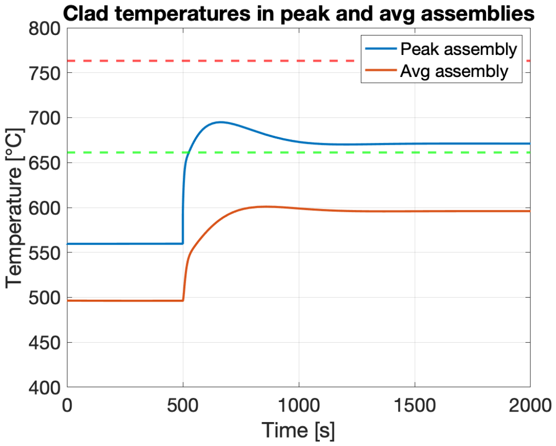

Figure 2: Average and PA cladding temperatures in UTOP.

ULOF

This is the unprotected loss of flow transient, which is provoked by a complete exponential failure of the pumps in the primary circuit. However, only partial failures of pumps have been considered because the current moving boundary SG model is not capable of simulating a complete loss of flow. A minimum of 3% of pump pressure head must be retained.

Considering the most severe ULOF that can be simulated, lead mass flow rate falls very shortly to approximately 35% of nominal value where then stabilizes thanks to buoyancy forces.

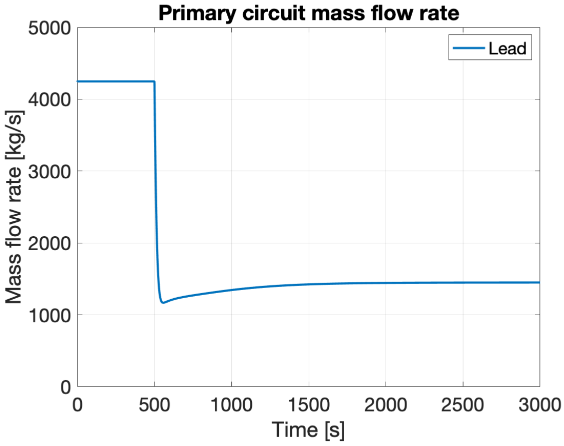

Figure 3: Lead mass flow rate in ULOF.

The system reacts by increasing the temperature difference across the core (and SG) which makes hot pools ever hotter and cold pools even colder. This is not beneficial for the reactor because consumes all the margin to cladding creep failure (Figure 4). Also, the risk of liquid metal embrittlement (LME) and of coolant solidification in cold pools is significantly enhanced. Nevertheless, fuel temperature still remains far from the melting point.

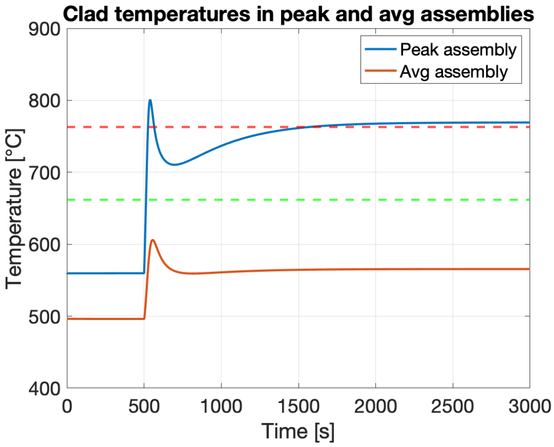

Figure 4: Average and PA cladding temperatures in ULOF.

This transient seems to be problematic because, even if the system reaches stable steady-state conditions, they are not optimal: fission continues to provide high thermal power with a very low coolant mass flow rate. This is why the system temperatures worsen. Figure 5 shows the core power level under different partial ULOF transients.

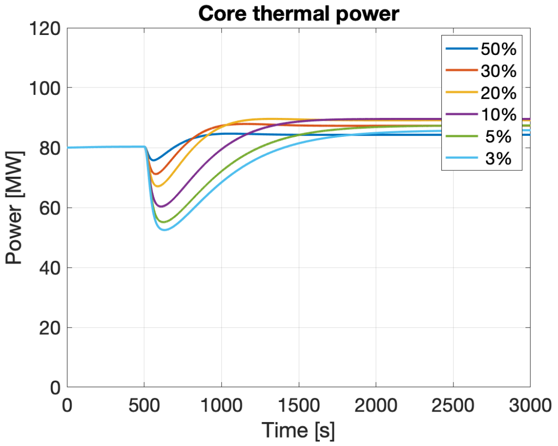

Figure 5: Different core power levels in partial ULOF. The percentage indicates the retained pump pressure head.

ULOHS

This is the unprotected loss of heat sink transient and is triggered by a step-wise failure of the SG module. Therefore, the moving boundary model does not play any role here because it is disconnected from the primary circuit.

Although core thermal power reduces very soon to the decay power (only a tiny fraction of reactor nominal power), in the first 1.5 hours the system temperatures increase a little due to the sudden loss of the main primary heat removal system, the SG. Subsequently, passive RVACS (reactor vessel auxiliary coolant system) removes efficiently the decay heat and the reactor temperatures decrease. SUNRISE-LFR proves to be able to withstand this accidental scenario without suffering at all from fuel melting or cladding tube thermal creep.

Station blackout

It is modeled by combining together ULOF and ULOHS, so it is triggered by contemporaneous exponential failure of the pump and step-wise failure of the SG. Because the moving boundary model does not play any role here, the code is capable of simulating a 100% failure of the pump module.

The behavior of the system is very similar to ULOHS alone, with the exception of the initial transient in which the system temperatures significantly increase, even consuming the whole margin to cladding tube creep rupture. However, this holds only for some minutes after which the system is cooled down effectively by the RVACS. Because thermal creep is a time-dependent phenomenon whose time scale is in the order of days at the reference temperatures, this transient does not result in any issue to the system. Fuel melting still remains far from occurring.

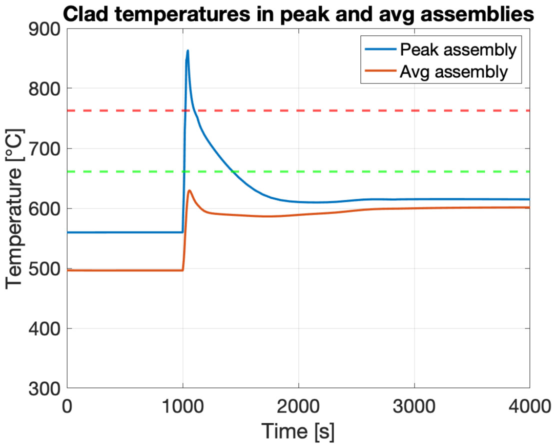

Figure 6: Average and PA cladding temperatures in ULOF-ULOHS (initial trend).

5. Conclusions

This thesis has succeeded in achieving its major goals.

First of all, a new model for the SG has been developed and coupled to the already existing BELLA. This extends the simulation capabilities of the code to the secondary side of the plant, in particular under accidental scenarios. The results of simulated transients are physically explainable in terms of the causal relations between input and output variables.

Secondly, it permits to investigate the safety requirements of SUNRISE-LFR by monitoring its safety margins to fuel melting and cladding tube rupture. It can be claimed that the system is capable of perfectly withstanding ULOHS and station blackout. Although half of the margin to creep failure is consumed, also in UTOP the general behavior of the system is safe and stable. On the contrary, further studies on ULOF transient must be pursued, in particular related to cladding creep rupture in the PA.

Anyway, it is worth to remember that such results are conditioned on the assumptions adopted in the modeling of the system and of the scenarios. The latter are extremely low probable events used to test passive safety systems while stressing the reactor conditions as much as possible.

In addition, the interpretation of the results is the consequence of the choices on safety margins. Speaking about cladding tube rupture, the safety thresholds are decided relying on an extremely conservative hypothesis on fission gas release, which seems to be unrealistic according to a recently published paper [4]. Nevertheless, from a regulatory point of view, it might potentially not be acceptable to assume anything other than the most conservative hypotheses. Moreover, SUNRISE-LFR is intended to be a research reactor for which safety margins larger than necessary are requested.

As a conclusive remark, this work provides an interesting general purpose tool to simulate the behavior of lead-cooled fast reactors. BELLA capabilities in simulating correct transients need to be verified by a benchmark against reference codes (e.g. SAS4A/SASSYS-1). Also the hypotheses on the SG, in particular on the geometry approximations, require to be checked. It can be foreseen in a future work. In general, the way the model is proposed and utilized allows for further improvements, both on primary circuit and on the SG, and sets the basis for control strategies on such innovative nuclear systems.

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