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Stress-testing the ALFRED design - Part III: Safety margins evaluation

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ABSTRACT

The advancement of the design of the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) beyond the conceptual phase, passes through the analysis of the impact of uncertainties, notably to what concerns safety-related conditions. Compliancy of plant safety to Design Extension Conditions is, according to IAEA and in line with the meaning itself of these beyond-design conditions, usually investigated by best estimates only. Due however to the demonstration nature of ALFRED, it was decided to assess the actual safety performances of this system even in ultimate conditions. To this regard, the emphasis was put on unprotected events like the UTOP (unprotected transient of over-power) and ULOOP (unprotected loss of offsite power, resulting from the combination of a loss of flow and loss of heat sink under unprotected conditions), pinpointed as the most challenging situations sought for the plant. The purpose of the present work, which has been divided in three parts, was then to assess the ultimate ALFRED safety margins against failure of the key core components and systems (Part III). To target this objective, the evaluation of uncertainties coming, on one hand, from nuclear data was performed at first, to retrieve their impact on the reactivity coefficients, thereby on the transient behavior driven by the latter (Part I); then, uncertainties from material properties, fabrication procedures, operation and measurement, and computational tools were propagated to assess their influence on the thermal-hydraulics of the system (Part II). In this work the efforts of Parts I and II are merged together and the effect of uncertainties on safety margins and salient parameters assessed. The retrieved uncertainties are propagated to the expected number of pins experiencing fuel melting during an UTOP and to the clad time-to-failure during an ULOOP. The former has been found to be quite affected by uncertainties, but still under limits not directly posing hazards to the people and the environment, even when extremely conservative assumptions are put forward; the latter shows a milder response to uncertainties, but always guaranteeing more than an order of magnitude of safety margin relative to WENRA recommendations.

1. Introduction

The fundamental leitmotiv behind the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) (Grasso et al., 2014) is proving the commercial viability of the general concept adopted in the design of all systems in the European Lead-cooled Fast Reactor (LFR) technology chain. In other words, the assumed safety margins – included to safely account for the uncertainties affecting the design – must be verified to cope with the abovementioned uncertainties, with the aimed confidence, practically substantiating that they are well suited or even reducible in future designs. This verification was the aim of the task “ALFRED core safety parameters and influence of model uncertainties on transients” in the collaborative project “Preparing ESNII for Horizon 2020” (ESNII Plus), co-funded by the European Commission within the 7th EURATOM Framework Programme. The task focused notably on the conservative assessment of system behavior even in Design Extension Conditions (DEC), so as to provide an extensively persuasive demonstration of the outstanding safety envisaged for LFRs.

By definition, DECs fall beyond the scope of design: for such low-probability events, the system is required to cope with management strategies so as to minimize the impact of the accident to the population and the environment. This notwithstanding, for ALFRED it is decided to target sufficiently long grace times even in DECs, so as to comply with the Generation-IV requirement of eliminating off-site emergency response. For this, it must be ensured that the main thermal limits associated with the integrity of the fuel and of all containment structures are respected. Since, therefore, temperatures (notably: those of the fuel and cladding) are to be checked, the related sources of uncertainties impacting on the evolution of the most challenging DECs are to be investigated:

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- uncertainties resulting in hot channels/hot spots;
- uncertainties affecting the thermal transient, hence the spontaneous equilibrium achieved by the system.

All these sources of uncertainties, along with their impact on the actual ALFRED response to unprotected accident conditions – particularly the Unprotected Transient of Over-Power (UTOP) and the Unprotected Loss Of Off-site Power (ULOOP), identified as the most challenging situations and enveloping all other DEC transients –, were investigated within the scope of the ALFRED task in ESNII Plus, and are presented in three companion papers, this being the third of the series. In particular, Part I (Grasso et al., 2018) focused on the effect of nuclear data uncertainties on reactivity coefficients, being the driving factors in establishing the dynamics of the transients; Part II (Lodi et al., 2018) concerned the translation of the various sources of uncertainties in hot channel/hot spot factors so to retrieve the uncertainties-perturbed temperature field in the core; Part III puts the previous results together so to estimate whether the safety margins are actually respected even under these extreme conditions, or to estimate the number and extent of failures the system should be expected to experience.

Focusing on Part III, specific object of this paper, it mainly concerns the estimation of the effect of uncertainties on the two DEC previously identified. More practically, the considered reference parameters are the expected number of pins experiencing fuel melting, for the UTOP, and the time-to-failure for the clad during the ULOOP.

The paper starts in Section 2 with a quick overview of ALFRED main core parameters followed by Section 3 with a summary of the uncertainty quantification work performed in Parts I and II; Section 4 follows, with the presentation of the methodology used in assessing the expected number of pins undergoing fuel melting, along with the obtained results, for the UTOP presented in Part I; in Section 5, the time-to-failure for the clad both in the nominal and uncertainties-perturbed ULOOP is calculated and discussed. Finally, the overall conclusions of the work are drawn in Section 6.

2. The ALFRED core

For better appreciating results of the present work and easing their discussion is it worth to quickly recall some of the main parameters of the ALFRED core in nominal conditions (Grasso et al., 2014), the layout of which is depicted in Fig. 1 together with that of the primary system:

- Core thermal power: 300 MW;
- Coolant temperature at core inlet/outlet: 400 °C/480 °C;
- Number of fuel sub-assemblies (FAs) in inner/outer zones: 57/114;
- Number of pins/FA: 127;
- Number of control/safety sub-assemblies: 12/4;
- Fuel composition: $(U\text{-}Pu)O_{1.97}$ at 21.8 at.% in the inner zone and 27.9 at.% in the outer zone;
- Clad material: AIM1 stainless steel coated by Al_2O_3 via pulsed laser deposition.

To target the aimed burnup a 5-years fuel in-pile residence time was selected envisaging a 5-batch reloading scheme, without reshuffling (cycle length of 1 year) so to reduce the initial enrichment, as well as the criticality swing during an irradiation cycle. The Beginning of Cycle (BoC) and End of Cycle (EoC) times correspond therefore to a 2 years and 3 years burned core, respectively.

3. Uncertainties summary

As explained in Section 1, two broad categories of uncertainties have been considered: the first made of those affecting the transient dynamics of the system, and the second comprising those resulting in hot channels/hot spots. The former, mainly stemming from uncertainties in nuclear data, have been evaluated in Part I (Grasso et al., 2018) for both the UTOP and ULOOP transients.

Results for the considered UTOP, which assumes a reactivity insertion of 250 pcm within 10 s, are summarized in Fig. 2. The selected amount of reactivity is chosen, coherently with the assumptions in (Bandini and Polidori, 2013), to conservatively envelop: the voiding of part of the active core region (whatever the cause, including possible void ingress among the fuel pins), core compaction following the most penalizing – yet credible – earthquake, spurious withdrawal of the most important control rod, etc. From Fig. 2 it can be seen that the effect of nuclear data uncertainties results in a ~6% increase of the maximum power reached in the transient according to both the system codes used, RELAP5 (Fletcher and Scuhltz, 1995) and SIM-LFR (Schikorr, 2001).

Concerning the ULOOP, the Loss Of Off-site Power (LOOP) is considered to result, at time t = 0 s, by the simultaneous failure of all primary pumps (Loss Of Flow, LOF) and the loss of the secondary circuit, hence of the primary means of heat removal (Loss Of Heat Sink, LOHS) by the Steam Generators (SGs). Additionally, despite the various signals for reactor shutdown, it was assumed the failure of the actuation signal for all reactor shut-down systems, so that the LOOP (LOF & LOHS) transient is simulated as unprotected. Finally, only one of the two Decay Heat Removal (DHR) systems foreseen in ALFRED is assumed to be available, which in turn is supposed to operate with only three loops out of the four the latter is made of (single failure assumption).

In Fig. 3, results for this transient are reported and the marginal effect of nuclear data uncertainties on the core power and mass flow (and thus temperatures) can be readily seen by the, *de facto*, overlapping of the reference and perturbed cases.

The second category of uncertainties, previously described, has been evaluated in Part II (Lodi et al., 2018) by means of a hot channels/hot spots analysis; the obtained results are summarized in Table 1 for the major temperature differences involved in the fuel pin thermal field, i.e., the coolant temperature rise (ΔT_{cool}), the coolant bulk-clad temperature difference (ΔT_{film}), the temperature rises through the clad (ΔT_{clad}), gap (ΔT_{gap}) and fuel pellet (ΔT_{fuel}), and assuming a 3σ confidence interval at both BoC and EoC. As can be seen, the total uncertainty is composed of two parts: the deterministic one collects the contributions by parameters that are not subject to random variation,

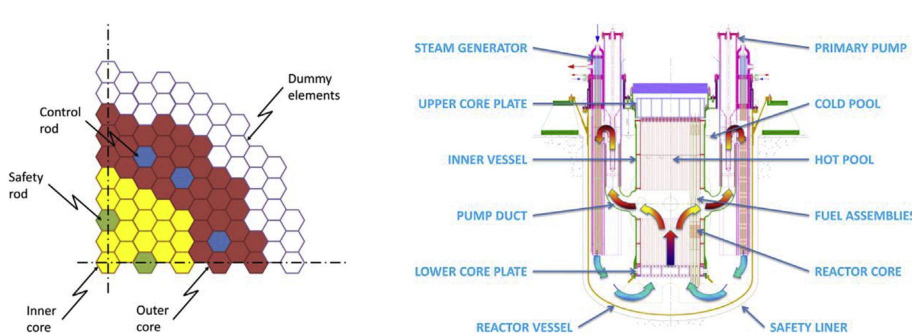

Fig. 1. ALFRED core (left) and primary system (right) layouts.