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Stress-testing the ALFRED design - Part II: Quantification of uncertainties on the fuel assembly temperature field

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A R T I C L E I N F O

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A B S T R A C T

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 computational tools were propagated to assess their influence on the thermal-hydraulics of the system (Part II). In this work the focus is on the latter uncertainties. The adopted methodology is presented at first, namely the semi-statistical vertical approach – characterized by an optimal degree of conservatism among the classical approaches – targeting a 3σ confidence interval. Then, the identification and propagation of each effect are shown, by means of the heat equations, so to retrieve the actual uncertainties on the parameters of interest (the temperatures themselves). Finally, a hot spot analysis to quantify the uncertainty-distorted temperature field is elaborated and presented. The performed analysis has revealed the great impact of fabrication tolerances for the coolant, film and clad temperature rises, particularly affecting safety margins during an ULOOP, while models and material properties uncertainties seem to dominate for the gap and fuel rises, which concur notably in challenging the respect of the fuel melting limit in an UTOP.

1. Introduction

A keystone objective for 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. Rephrasing, it must be verified that the assumed safety margins – included to safely account for the uncertainties affecting the design – 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 transient behavior of the system in 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, so as to provide an extensively persuasive demonstration of the outstanding safety envisaged for LFRs.

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Aiming at extremely long grace times, means ensuring 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, cladding and vessel) are to be checked, the related sources of uncertainties are to be investigated:

- 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 design extension conditions, were investigated within the scope of the ALFRED task in ESNII Plus, and are presented in three companion papers, the present being the second of the series. In particular, Part I focuses on the effect of nuclear data uncertainties on reactivity coefficients, being the driving factors in establishing the dynamics of the transients; Part II concerns the translation of the various sources of uncertainties in hot channels/hot spots 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 II, specific object of this paper, it mainly concerns the application of a semi-statistical vertical approach so to retrieve the final hot channel/hot spot factors, coming from all the identified sources of uncertainties so to propagate them to the temperature field of interest during the transient.

The paper starts with the presentation of the adopted semi-statistical vertical approach in Section 2; in Section 3, the deterministic and statistical components are assessed, estimating the uncertainties affecting each core parameter and propagating them into confidence intervals to the associated temperature rises (in the form of elementary hot factors). All the resulting elementary hot factors are then merged together in Section 4, establishing the values of the hot channel and hot spot factors. Finally, partial conclusions are drawn in Section 5.

2. Calculation methodology

The aim of the hot spot analysis is to calculate the so-called hot spot factors F_y (Todreas and Kazimi, 2001) for some temperature difference of interest y. In the present work, the focus is on the coolant temperature rise (ΔT_{cool}), the coolant bulk-clad difference (ΔT_{film}), and the temperature rises through the cladding (ΔT_{clad}), the gap (ΔT_{gap}) and the fuel pellet (ΔT_{fuel}). F_y is defined as

$$F_y = \frac{y'}{y}, \tag{1}$$

where y' is the off-nominal (i.e., uncertainty-perturbed) value of the reference temperature difference. The factor F_y can be decomposed in various ways, depending on the type of analysis performed; in the present work, the optimal trade-off between conservatism and accuracy has pinpointed the choice on the semi-statistical vertical approach (Todreas and Kazimi, 2001), in which F_y can be expressed as

$$F_y = F_y^D F_y^S, \tag{2}$$

where the superscripts D and S represent the deterministic and statistical parts of the hot spot factor. The deterministic part collects the contributions to y by parameters that are not subject to random variation, but for which the exact value cannot be predicted *a priori*; conversely, the statistical part sums up the contributions to y by parameters characterized by a frequency distribution of occurrence (Waltar et al., 2012). The two factors can be further decomposed coherently with their physical meaning. The deterministic part is expressed as

$$F_y^D = \prod_x^{N_D} f_{x,y}^D, \tag{3}$$

where N_D is the number of deterministic contributions to y and $f_{x,y}^D$ is the elementary hot factor describing the influence of the parameter x (e.g., the coolant velocity) on the target temperature difference y. The statistical part, based on the assumption of independent variables and with a logics identical to the one used for summing standard deviations (Todreas and Kazimi, 2001), can be expressed as

$$F_y^S = 1 + \sqrt{\sum_x^{N_S} \left(f_{x,y}^S - 1\right)^2}, \tag{4}$$

where N_S is the number of statistical contributions to y.

All factors $f_{x,y}$ can be in turn related to the elementary uncertainty factor $f_x = \frac{x'}{x}$ affecting the parameter x as

$$f_{x,y} = \frac{y(x')}{y(x)} = g(f_x), \tag{5}$$

where the functional form g stems, mainly, from the heat transfer equations.

It is usually convenient to express the intensity of the perturbation of the parameter x reported to its standard deviation (σ) so that we can talk about 1σ, 2σ, 3σ analysis and so on. Of course, the higher the perturbation considered, the more comprehensive the analysis becomes; for this reason a 3σ (99.87%) analysis has been chosen meaning that a residual probability of 0.13% exists for the hottest pin to exceed the calculated perturbed temperature state.

Summarizing, the analysis starts with the identification of the various x coming from data, model, fabrication and measurement errors along with the determination of their character – be it deterministic or statistic – and the quantification of f_x for a 3σ uncertainty; then, the factors $f_{x,y}$ are calculated by propagation of each f_x through the heat equations. Finally, all the factors are combined, as described in eqs. (3) and (4), into the corresponding hot spot factor.

3. Uncertainties identification

The first step is the identification and classification (i.e., deterministic or statistic) of all the uncertainties coming from elementary data (materials properties), system configuration (manufacturing tolerances), operative conditions (components characteristics, monitoring and control systems sensibilities) and computational tools (models' approximations and numerical errors) affecting the ALFRED plant layout, along with their translation in elementary hot factors. To this regard, it must be reminded that uncertainties due to computational tools are determined based on the validation results of the tools actually used in the whole work; for the temperature of the outer clad surface, for example, the Sub-Channel (SC) code ANTEO+ (Lodi et al., 2016) has been used. The code TEMIDE (Lodi, 2017) has been used for the temperature field inside the pin, but since its validation is not yet complete, experimentally retrieved uncertainties are preferred; this is justified since the dominant contribution to the overall uncertainties comes from material properties, as it will be shown.

3.1. Deterministic component

3.1.1. Power level measurement and dead band

As suggested in (Ku et al., 1994) the calibration error in power measurement instrumentation is around 2%, based mainly on measurement uncertainties in the steam cycle. An additional allowance of 1%, called a dead band, is added in the design of the control system to prevent excessive exercising of the control rod drives. The overall hot factor for power measurement and dead band is therefore 1.03.