Evaluation of data and model uncertainties and their effect on the fuel assembly temperature field of the ALFRED Lead-cooled Fast Reactor

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Abstract. One of the crucial objectives for the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) is proving the viability of the general concept adopted in the design. This proof passes through the successful operation of ALFRED, demonstrating that the design assumptions provide not only the foreseen performances, but also the aimed reliability. The demonstration of the reliability can be rephrased stating that the margins assumed for the design must be proven to be well suited, in the sense they accommodate the uncertainties on the main technological constraints. This, indeed, 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+), co-funded by the EU within the 7th EURATOM Framework Programme, where the first step, object of this work, was the evaluation of data, model, fabrication and measurement uncertainties and their effect on the fuel assembly temperature field. The paper presents first the identification of the various factors contributing to the overall uncertainty on the temperature field; then, the propagation of each effect, by means of the heat equations, so to retrieve the actual uncertainties on the parameters of interest (the temperatures themselves) and finally, a hot spot analysis to quantify the uncertainty-distorted temperature field. The hot spot analysis has been performed by means of a semi-statistical vertical approach – characterized by an optimal degree of conservatism among the classical approaches – targeting a 3σ (99.73%) confidence interval. The performed analysis has highlighted the importance of fabrication tolerances, especially on the assessment of the coolant bulk temperature, and of data/models especially on the clad outer, gap and fuel temperatures evaluation, pinpointing the research areas where more efforts are needed. The further step is the application of the present analysis to unprotected transients, combined with the uncertainties on the reactivity coefficients, so to gain a real insight on the safety performances and degree of forgiveness to be reckoned to ALFRED.

Key Words: Uncertainties, lead-cooled fast reactor, hot spot analysis.

1. Introduction

One of the most crucial objectives for the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) [1] is the demonstration of the viability of the general concept adopted in the design of all systems in the European Lead Fast Reactor (LFR) technology chain. This proof of concept passes through the successful operation of ALFRED, demonstrating that the design assumptions, harmonized all together, provide not only the foreseen performances, but also the aimed reliability. Concerning reliability, the design has to take into account several technological constraints that need to be respected despite the uncertainties affecting elementary data, design methodologies and fabrication procedures. Due to these unavoidable uncertainties, the robustness of the methodology used for the design of ALFRED stands on the systematic estimation, and the monitoring of the propagation, of all the uncertainties that are proper of every single evaluation or assumption. The propagation of these uncertainties on the parameters that are subject to technological constraints is finally translated into margins protecting the most crucial elements against the overcoming of their working limits. Accordingly, the demonstration of the reliability of the methodology adopted in designing all the systems of the European LFR technology chain can be rephrased stating that the margins assumed for the design of ALFRED have to prove to be well suited, or even reducible.

The quantification of these margins is 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+), co-funded by the European Union within the 7th EURATOM Framework Programme. The task is focused, in particular, on the assessment of the margins in some of the most challenging situations possible for a nuclear reactor: unprotected transients; in these scenarios, various sources of uncertainties are present including boundary conditions, reactivity coefficients [2] and the temperature field. Uncertainties affecting the latter are the object of this work and the very first step of the previously mentioned task.

The paper therefore presents at first the methodology used for the uncertainties propagation then, the identification of the various factors contributing to the overall uncertainty on the temperature field coming from data, model, fabrication and measurement and finally, the resulting hot spot factors.

2. Methodology

The aim of the hot spot analysis is to calculate the so-called hot spot factors F_y [3] 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 ($\Delta T_{cool-clad}$), the temperature rise 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 given temperature difference and y' is the same temperature difference but in the perturbed state. Depending on the type of analysis performed, the factor F_y can be decomposed and, in the present work, the optimal trade-off between conservatism and accuracy has pinpointed the choice on the semi-statistical vertical approach [3]. F_y can then be expressed as

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

where the superscripts D and S represent the deterministic and statistical part of the hot spot factor. The deterministic part collects the contributions to y by variables 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 variables characterized by a frequency distribution of occurrence [4]. The two factors can be further decomposed: 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 spot factor describing the influence of the variable x (e.g. the coolant velocity) on the target parameter y; the statistical part, based on the assumption of independent variables, can be expressed as

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

where N_S is the number of statistical contributions to y. The factors $f_{x,y}$ can be related to the elementary uncertainty factor f_x (defined similarly to F_y) as

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

where the functional form g stems, in the present case, from the heat transfer equations.

It is usually convenient to express the intensity of the perturbation of the variable 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 in the present work, a 3σ (99.87%) analysis has been chosen meaning that a residual probability of 0.07% 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 eq. (3) and (4), into the corresponding hot spot factor.

3. Identification of uncertainties

First of all, it must be reminded that the analysis presented hereafter is applied to the ALFRED core and plant layout, for which the reader can find more detailed information about the geometric arrangement and operative conditions in [1] and [5]. Secondly, that the perturbed state is analyzed relative to a reference one represented, in the following work, by the solution of the sub-channel code ANTEO+ [6]. Some of the sources of uncertainties are therefore due to the utilization of this specific tool and the approximations on which it is based. The quantification of some of these uncertainties therefore directly stems from the validation phase of the code.

The list of contributions is here presented separating the deterministic from the statistical component.

3.1.Deterministic component

3.1.1.Power level measurement and dead band

As suggested in [7] 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 channel factor for power measurement and dead band is therefore 1.03.

3.1.2.Inlet flow maldistribution

Due to turbulence and pressure non-uniformities within the inlet plenum, and due to the accumulation of fabrication tolerances in the orifice and the internals of the fuel assembly, the total flow around the fuel pins could be lower than nominal. Allowance for a 5% flow reduction yields the hot channel factor of 1.05 [7]. The flow reduction also affects the thermal exchange between the coolant and the cladding modifying both the Nusselt's number and the hydraulic diameter.

3.1.3.Assembly flow maldistribution

This factor takes into account the error done by ANTEO+ when redistributing the flow between the different sub-channels. Based on [6] the error on the flow split is taken as 1.031.

3.2.Statistical component

3.2.1.Inlet temperature variation

Borrowing results for a Sodium cooled reactor, where a statistical analysis on the combined reactor and plant systems indicated an uncertainty on the inlet temperature around 5°C [4] we assumed a hot channel factor of 1.05 based on a 80°C nominal temperature rise. Due to the lack of an intermediate loop in ALFRED this value is possibly conservative.

3.2.2.Reactor ΔT variation

Again, borrowing results from the same analysis in section 3.2.1 [4] a hot channel factor for the coolant flow rate uncertainty – and thus for the coolant enthalpy rise – of 1.04 was selected.

3.2.3.Power distribution

Due to uncertainties on the radial and axial peaking factors coming from design methods, control rod effects and nuclear data, a hot spot factor of 1.05 was selected, preliminarily based on the validation reported in [8].

3.2.4.Fuel density

A fabrication error on the fuel density of 2.1% was assumed [12]; this modifies the local linear heat rate but not the integrated rod power due to its statistical nature.

3.2.5.Fuel enrichment maldistribution

A fabrication error on the fuel enrichment of 1.2% was assumed [12]; similarly to Section 3.2.4 it does not affect the integrated rod power.

3.2.6.Coolant properties

3σ errors on the coolant density and specific heat are taken from [9] as, respectively, 2% and 6.4%.

3.2.7.Subchannel mixing

This factor takes into account the error done by ANTEO+ when calculating the energy exchange between sub-channels. Based on [6] the factor associated to this error is taken as 1.05.

3.2.8.Subchannel flow area

Due to uncertainties in the pins lattice pitch (0.7%) and clad outer diameter (0.3%), along with bowing [12], the sub-channel flow area could be lower than nominal, resulting in a hot channel factor of 1.052 for the coolant temperature raise. These uncertainties also affects the thermal exchange with the cladding but are compensated by the reduced hydraulic diameter resulting in a factor of 1.003.

3.2.9.Clad dimensions

Fabrication errors affect the cladding ovality, its thickness and its inner and outer diameters. The error on the clad inner diameter is taken equal to the outer one, which has already been discussed in Section 3.2.8. The uncertainty on the ovality is taken as twice the error on the outer diameter, while the thickness is subject to a 5% error [12]. All together, these uncertainties affect the coolant temperature rise, the thermal exchange between coolant and cladding and the cladding inner-outer surfaces temperature difference.

3.2.10.Clad conductivity

Uncertainty on the clad conductivity is assumed 8.7% based on [10].

3.2.11.Coolant-Clad heat transfer coefficient

This element takes into account the error on the correlation of the Nusselt's number. Based on [11] a factor of 1.265 was selected, reflecting the high uncertainty on the heat exchange of liquid metals flowing in bundle arrangements.

3.2.12.Pellet-cladding eccentricity

An erroneous eccentric positioning of the fuel pellet inside the cladding would result in an increased heat flux in the area of minimum fuel-cladding gap, causing an increase in temperature rise through the coolant-cladding interface and the cladding itself. Based on [3] a value of 1.15 was selected.

3.2.13.Gap conductance

Due to difficulties in exactly calculating and measuring the heat exchange through the fuel-clad gap a value of 1.47 for the hot spot factor is here used to account for uncertainties mainly coming from Beginning of Life (BoL) phenomena and fission gas release [4]. During irradiation this value will be lower but here it is conservatively taken equal to BoL conditions for all the pin life.

3.2.14.Pellet dimensions

Pellet dimensions affect the temperature rise through the pellet itself – due to the ratio between outer and inner radii – and due to the local alteration of the linear power. Uncertainties of 5% and 0.5% are taken for the inner and outer radii respectively [12].

3.2.15.Fuel conductivity

Uncertainties on the fuel conductivity directly affect the temperature rise inside the pellet; they stem from difficulties in high temperature measurements and in separating the effects of the multitude of parameters actually influencing the thermal conductivity. Irradiation effects are also another source of uncertainty. Based on [4] a factor of 1.11 is taken which is lower than the real error on the conductivity but gives an acceptable overall uncertainty when combined with the gap conductance error (Section 3.2.13).

3.2.16.Active height

The active height H_f is influenced by the convoluted error of the height of each pellet ($\sigma_{H_{pellet}}$) in the stack (taken from [12]) along with the possibility of an extra pellet inserted by mistake during assembling. The overall uncertainty can then be expressed as

$$3\sigma_{H_f} = \frac{3\sigma_{H_{pellet}}}{\sqrt{3N_{pellet}}} + \frac{1}{N_{pellet}} \ , \tag{6}$$

where N_{pellet} is the number of pellets in the stack.

3.2.17. Wrapper dimensions

Similarly to the sub-channel flow area discussed in Section 3.2.8, the wrapper fabrication tolerances can influence the coolant flow inside the fuel assembly. An uncertainty of 0.7% is here assumed for the wrapper inner flat-to-flat distance [12].

4. Results

Propagating the elementary uncertainties listed in Section 3 through the heat equations and the geometric relations among the different quantities, the results for the $f_{x,y}$ of each temperature difference reported in Table I were obtained.

TABLE I: Hot spot factors $f_{x,y}$ for the different sources of errors and the various temperature differences for the ALFRED case.

	$f_{x,y}$	ΔT_{cool}	$\Delta T_{cool-clad}$	ΔT_{clad}	ΔT_{gap}	ΔT_{fuel}
Deterministic	Power level measurement and deadband	1.030	1.030	1.030	1.030	1.030
	Inlet flow maldistribution	1.050	1.035			
	Assembly flow maldistribution	1.031				
Statistical	Inlet temperature variation	1.050				
	Reactor ΔT variation	1.040				
	Power distribution	1.050	1.050	1.050	1.050	1.050
	Fuel density		1.021	1.021	1.021	1.021
	Fuel enrichment maldistribution		1.012	1.012	1.012	1.012
	Coolant properties	1.085				
	Sub-channel mixing	1.050				
	Sub-channel flow area	1.052	1.003			
	Clad dimensions	1.028	1.000	1.053		
	Cladding conductivity			1.087		
	Coolant-Clad heat transfer coefficient		1.265			
	Pellet-cladding eccentricity		1.150	1.150		
	Gap conductance				1.470	
	Pellet dimensions		1.013	1.013	1.013	1.013
	Fuel conductivity					1.110
	Active height	1.022				
	Wrapper tolerance	1.044	1.000			

Combining the various $f_{x,y}$ for each column as reported in eq. (2), (3) and (4) the results depicted in Table II were obtained.

TABLE II: Hot spot factors F_y for the various temperature differences for the ALFRED case.

	ΔT_{cool}	$\Delta T_{cool-clad}$	ΔT_{clad}	ΔT_{gap}	ΔT_{fuel}
F_y^D	1.115	1.066	1.030	1.030	1.030
F_y^S	1.149	1.310	1.190	1.473	1.124
F_y	**1.281**	**1.396**	**1.226**	**1.518**	**1.158**

5. Discussion

Looking at results in Table I and II clearly emerge the high values of the uncertainties for the coolant and film temperature rises, which are directly linked to the clad outer temperature. Being corrosion, for a LFR, a substantial challenge, and being it strongly related to the clad outer temperature it is easily seen how the high uncertainty can affect the system design in nominal conditions at the possible expenses of performances; reducing their value is thus a mandatory task for LFRs, and also, one of the main objectives of ALFRED.

For what concerns the major contributors to the overall uncertainty, it can be seen that, for ΔT_{cool}, fabrication tolerances slightly dominate over the others. For $\Delta T_{cool-clad}$, the main contributors are the uncertainty on models (i.e. the heat transfer coefficient) followed by fabrication/assembling tolerances. ΔT_{clad} is also dominated by fabrication tolerances while ΔT_{gap} is mainly influenced by models uncertainties. For ΔT_{fuel}, the principal source of error comes from material property data.

Fabrication tolerances seem to play a major role for the ALFRED fuel assembly temperature field definition, also because the values assumed for each component were quite high if compared to nuclear standards for light water reactors. The motivation behind this choice descends from the will to test the effect of a cheap fabrication route on design conditions. One way to reduce the impact of the fabrication tolerances is thus to resort to more strict production processes at the expenses, however, of plant economic performances. The gain in design margins – corrosion for example – could however be sufficient to motivate such a choice. For the other sources of errors (data, models, measurement, etc.) there is no easy solution to their reduction other than further experimental activities in representative conditions, geometries and scales.

6. Conclusions

As the first step of the task “ALFRED core safety parameters and influence of model uncertainties on transients” in the collaborative project “Preparing ESNII for Horizon 2020” (ESNII+), co-funded by the European Union within the 7th EURATOM Framework Programme, a hot spot analysis has been performed. In the present paper, the methodology used for the overall uncertainty quantification has been described, followed by the identification of all the major sources of uncertainties coming from data, models, fabrication and measurements. Finally, the hot spot factors for each temperature difference of interest have been calculated; the analysis has revealed the great impact of fabrication tolerances for the coolant, film and clad temperature rises while models and material properties uncertainties seem to dominate for the gap and fuel ones. Due to the relation of clad corrosion to the component temperature, it is mandatory to reduce uncertainties in that area starting with more accurate (but more expensive) fabrication routes. Results of the present analysis – besides generating important feedbacks for the nominal design – when combined with the effect of nuclear data uncertainties on reactivity coefficients [2], will be used for evaluating the degree of forgiveness to be reckoned to the ALFRED concept in the extreme conditions of unprotected transients.

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