SENSITIVITY ANALYSIS OF ALFRED FUEL ELEMENT BEHAVIOUR

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Abstract

This paper deals with the fuel performance analysis of the ALFRED fuel element, employing the TRANSURANUS code. The paper contains a sensitivity study for ALFRED fuel element, using the same geometric characteristics and irradiation conditions, but different input models and parameters, to assess their impact on fuel performance behaviour. Many uncertainties exist, especially concerning fuel properties, like thermal conductivity and swelling. Whereas the former introduces an interval of plausible values, the last may change remarkably with the experimental setup, producing correlations with huge differences between each other. Hence, the sensitivity analysis was carried out, with two objectives: to identify the worst-case scenario; to assess the worst-case scenario results taking into consideration ALFRED indicative design limits. The main outcome of this analysis is that the ALFRED fuel element performs well below the design limits in normal operation conditions, corresponding to a channel characterized by average power levels.

Keywords: *Sensitivity analysis, ALFRED fuel element, MOX swelling, Fuel thermal conductivity*

Introduction

From a safety and performance perspective, whenever a new fuel is being developed, it is essential to predict the general behaviour of the fuel during its lifetime in the reactor core.

The modelling of the fuel behaviour is not an easy task as many of the phenomena occurring in the nuclear fuel during irradiation interact with each other in a complex manner. Today, by the means of dedicated computational tools, nuclear fuel behaviour can be predicted in an accurate mode. The simulation of a fuel element considers several phenomena occurring in the nuclear fuel (e.g. the fuel thermal conductivity, the mechanical interaction between the fuel element components, fission gas release, creep, cracking, and swelling) [1].

The present work is focused on predicting ALFRED fuel behaviour during normal operation, based on a sensitivity analysis performed using TRANSURANUS code, a fuel performance tool designed to analyze a whole fuel element in a 1.5D cylindrical geometry by adopting axis symmetry. It also contains most of the present day's physical models of the fuel in terms of densification, swelling, generation of fission gases, and several other models that allow dealing with a wide range of situations [2].

It is essential to understand that the various phenomena occurring in the fuel pellet are hypothesized by numerous existing models. Thus, a sensitivity study would show which parameter or property directly impacts the phenomena occurring in the fuel based on the models used.

Particularly, in the sensitivity analysis of ALFRED fuel element behaviour different models describing the fuel thermal conductivity and fuel swelling are considered.

The paper presents the main TRANSURANUS simulation results, focusing on the pellet central temperature, gap pressure, fission gas release, cladding stresses, and strains along with the gap dimension.

Based on the results obtained, a worst-case scenario is defined and the corresponding results regarding the fuel element performance are assessed in view of ALFRED design indicative limits.

Sensitivity Analysis

To conduct the sensitivity analysis, TRANSURANUS code was used to simulate the thermo-mechanical behaviour of ALFRED fuel element in normal operating conditions. To run a simulation, the code requires an input file with complete data, varying from control options (the user selects different models and materials properties), fuel composition parameters (geometrical and physical quantities), and macro time step inputs (e.g. linear element power, coolant temperature).

As a general setup for calculation purposes, the active fuel length (600 mm) is divided into 24 axial slices and the analysis is performed from slice 1 to slice 24. Regarding the boundary conditions, the linear power element is considered maximum at slices 13 and 14, while the maximum coolant temperature is reached at slice 24.

Therefore, in the macro time step inputs an axial variation of the linear power and coolant temperature is considered. TRANSURANUS provides results relevant to each slice of the fuel element. Other relevant input parameters are given in the table below.

Table 1. ALFRED fuel element parameters used in the analysis [3]

Fuel characteristics	
Fuel type	MOX
Fuel enrichment as Pu/(Pu+U) [wt.%]	21.7
O/M ratio	1.97
Fuel density [%] of theoretical density	95
Clad characteristics	
Clad type	15-15-Ti
Element Geometry	
Pellet inner diameter [mm]	2
Pellet outer diameter [mm]	9
Clad inner diameter [mm]	9.3
Clad outer diameter [mm]	10.5
Active length [mm]	600
Upper plenum length [mm]	120
Fill gas	He
Initial pressure [MPa]	0.1
Coolant	
Coolant inlet temperature [ºC]	400
Coolant outlet temperature [ºC]	480
Coolant pressure [MPa]	0.1
Coolant flow rate [kg/s]	25 700

Analyzing the ALFRED fuel element behaviour in the most accurate way requires a comprehensive selection of physical models and correlations. Since TRANSURANUS offers a wide range of options describing the same phenomenon or material property, the first task is to identify all the alternatives suitable for the simulation. A reference case was set up containing all the model options recommended by the code manual, the selected physical models addressing to FBR (Fast Breeder Reactors) conditions [2].

Many uncertainties exist, especially concerning fuel properties, like the thermal conductivity and swelling. Whereas the former introduces an interval of plausible values, the last may change remarkably with the experimental setup, producing correlations with some differences between each other. Accounting for such uncertainties can lead to very different scenarios in terms of fuel element performance. Hence, a sensitivity analysis on TRANSURANUS models is carried out, with two objectives: to identify the worst-case scenario, based on a set of input models; to assess the worst-case scenario results taking into account ALFRED fuel element design limits.

The sensitivity analysis is carried out based on the models available in TRANSURANUS and also on some correlations implemented in TRANSURANUS in a previous work [4].

Model Options

The considered input options (all addressed to fast reactors conditions) are summarized in Table 2. The blue frame is used to highlight the model options considered for the reference case (standard options recommended in TRANSURANUS).

Table 2. Model options selected for the sensitivity analysis

Model	Options	Input file
Fuel thermal conductivity	Model Best-estimate of ITU[a] [2]	ModFuel (6) = 31
	Model Conservative of ITU[a] [2]	ModFuel (6) = 32
	Model Lanning and Beyer[b] [4]	ModFuel (6) = 43
	Model Wiesenack[b] [4]	ModFuel (6) = 44
	Model Martin review 1982[b] [4]	ModFuel (6) = 45
	Model Carbajo[b] [5]	ModFuel (6) = 46
	Model Halden[b] [5]	ModFuel (6) = 47
	Model Baron Herve[b] [4]	ModFuel (6) = 48
Fuel swelling	Model TU 1.2% at open gap	ModFuel (4) = 3
	Model TU 2% at open gap	ModFuel (4) = 11
	Model TU 2% at startup, 1.2% open gap	ModFuel (4) = 13
	"Best estimate" swelling correlation, Austenitic steel materials	ModClad (4) = 2

[a] original code correlations
[b] Models implemented in TRANSURANUS code

Results and discussion

Thermal Conductivity Models

There are two conductivity models available in the TRANSURANUS code concerning MOX fuel and other six models have been implemented in previous work [4]. TRANSURANUS simulations are carried out for all these correlations. The assessment is performed to check the discrepancies in fuel temperature, gap pressure, gap size, fission gas release, and clad stresses and strains.

The assessment of fuel temperature is one of the primary goals of the performance modeling since the fuel temperature influences other phenomena such as gap pressure or fission gas release. On the other hand, in terms of cladding temperature, no variations are expected, since this parameter is mainly based on the coolant temperature and the heat transfer coefficient between cladding and coolant (HTC).

A clear difference can be observed between the model's predictions (see Fig.1). As far as the fuel temperature is concerned, the maximum obtained values are reported in Table 3, where it is also provided the ALFRED design indicative limit for the peak fuel temperature.

The fuel temperature is strongly influenced by the gap conductance. The conductance starts to increase due to gap closure and when the closure is complete, the central fuel temperatures settle to an almost constant level. In all cases, the peak temperature remains under the preliminary limit of 2000 ºC.

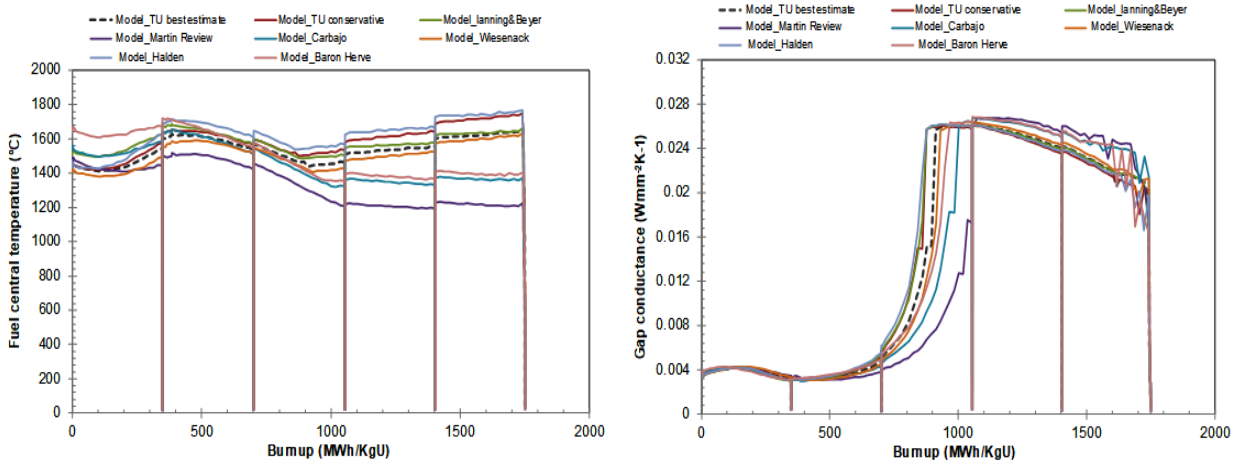


Fig. 1. Variation of fuel central temperature (left) and gap conductance (right) according to different conductivity models

Table 3. TRANSURANUS results for fuel central temperature, obtained with different conductivity models

Model	Maximum fuel temperature [°C]	Limit assumed [6]
Best-estimate of ITU	1654	2000 °C
Conservative of ITU	1749	
Lanning and Beyer	1688	
Wiesenack	1631	
Martin review 1982	1517	
Carbajo	1652	
Halden	1765	
Baron Herve	1720	

The fission gas release (FGR) along with the fuel element pressures are shown in Fig. 2. As it can be seen, for most of the models implied in the sensitivity analysis, the FGR reaches almost 50% at 600 MWh/kgU burn-up. In the last second part of the irradiation history (mainly in the case of Carbajo, Martin and Baron Herve models), when the temperature decreases the additional gas produced is retained in the fuel rather than being released in the free volume. In all cases, the maximum values of gap pressure are lower than the indicative design limit of 5MPa [6].

As expected, due to gap closure, the cladding stresses start to increase and higher values are reported for those models that predict anticipated gap closure (see Fig. 3).

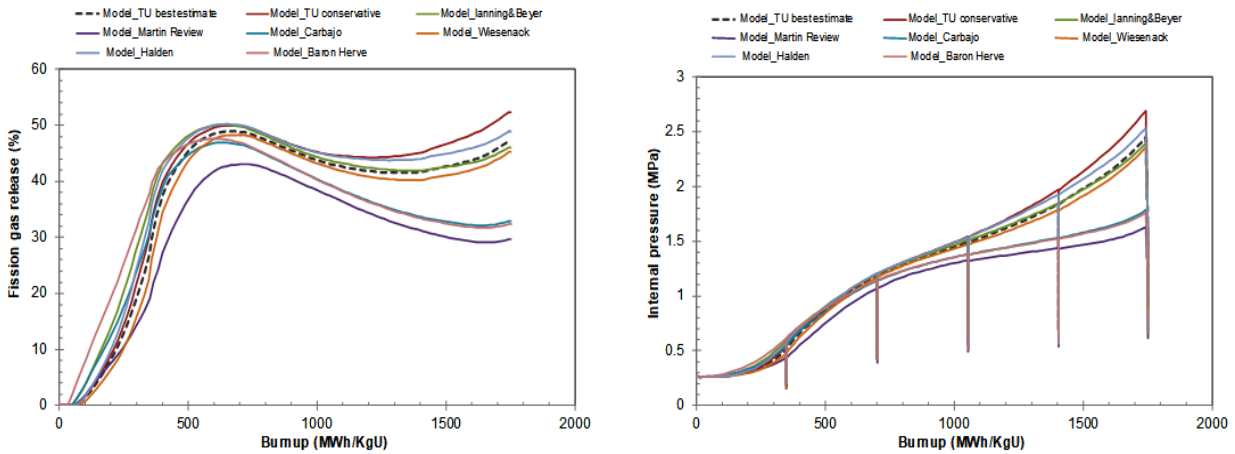


Fig. 2. Variation of FGR (left) and gap pressure (right) according to different conductivity models

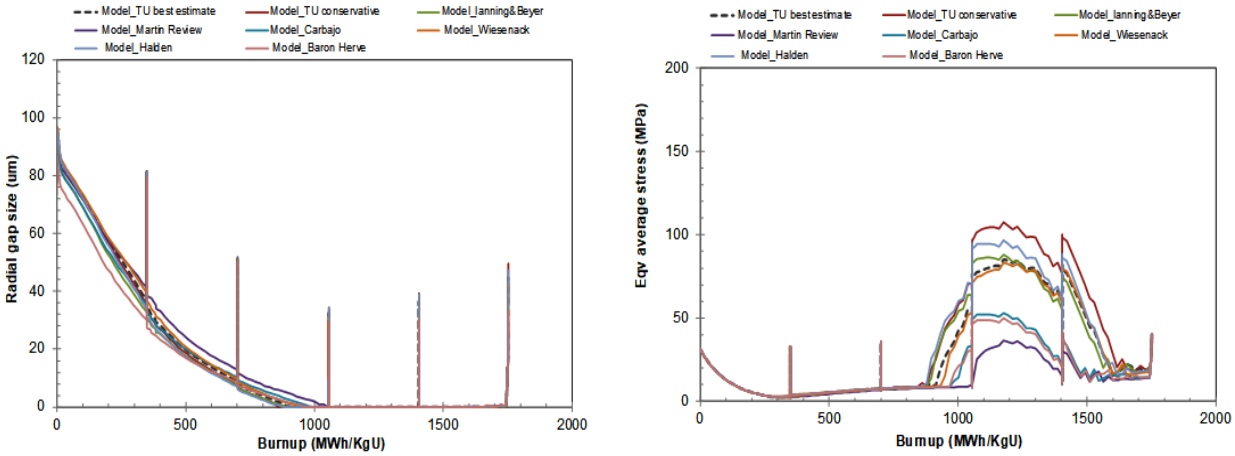


Fig. 3. Variation of gap size (left) and cladding equivalent average stresses (right) for different conductivity models

Additional indicative design limits for the ALFRED reactor refer to cladding instantaneous plastic strain (a value of 0.5% is assumed), as well as total creep strain (<3%) [7]. Therefore, Table 4 summarizes the values at the end of irradiation (~5 years) for cladding strain components (swelling, creep, plastic, and total).

Table 4. TRANSURANUS results for cladding strains, at the end of irradiation, obtained with different fuel conductivity models

Model	Strain due to swelling %	Creep strain %	Plastic strain %	Total strain %
Best-estimate of ITU	0.01034	0.00257	0	0.01282
Conservative of ITU	0.01034	0.00338	0	0.01363
Lanning and Beyer	0.01034	0.00266	0	0.01291
Wiesenack	0.01034	0.00247	0	0.01272
Martin review 1982	0.01034	0.00099	0	0.01123
Carbajo	0.01034	0.00143	0	0.01167
Halden	0.01034	0.00296	0	0.01321
Baron Herve	0.01034	0.00137	0	0.01161

Fuel Swelling Models

There are several swelling model options available in TRANSURANUS concerning (U, Pu)O_2 (see Table 2). The reason why fuel swelling has been included in the sensitivity study is that this property has an important influence on gap dynamics, leading to potential cladding plastic strains in case of gap closure with sufficient contact pressure. Therefore, the following sensitivity study is performed for all three models, in the same operating conditions of the ALFRED reactor to that of the previous subsection. This assessment is done to check the discrepancies in fuel temperature, gap size, and cladding stresses and strains.

The fuel swelling correlation given by Freund et al. predicts an anticipated gap closure (see Fig. 4). As expected, due to gap closure, the cladding stresses increase and lead to higher strains, compared to the other models. As far as the fuel temperature is concerned (see Fig. 5), the maximum value obtained with the Freund model is lower than for the other models, at least in the first three irradiation cycles. Similar values are reported for the last two irradiation cycles. The peak fuel temperature remains below the design limit, as well as cladding strains (values reported in Table 5 per component, at the end of the irradiation period).

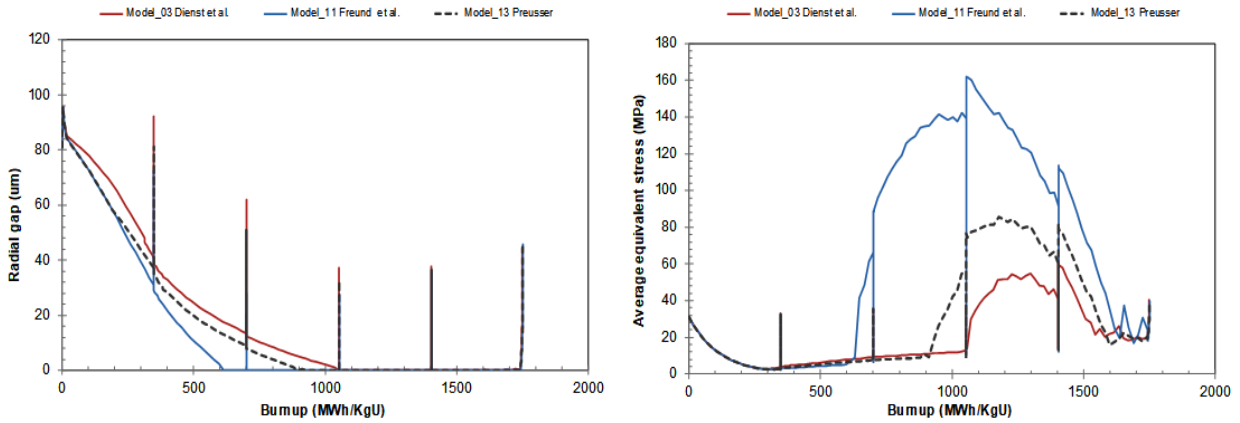


Fig. 4. Variation of gap size (left) and cladding average equivalent stresses (right) according to different swelling models

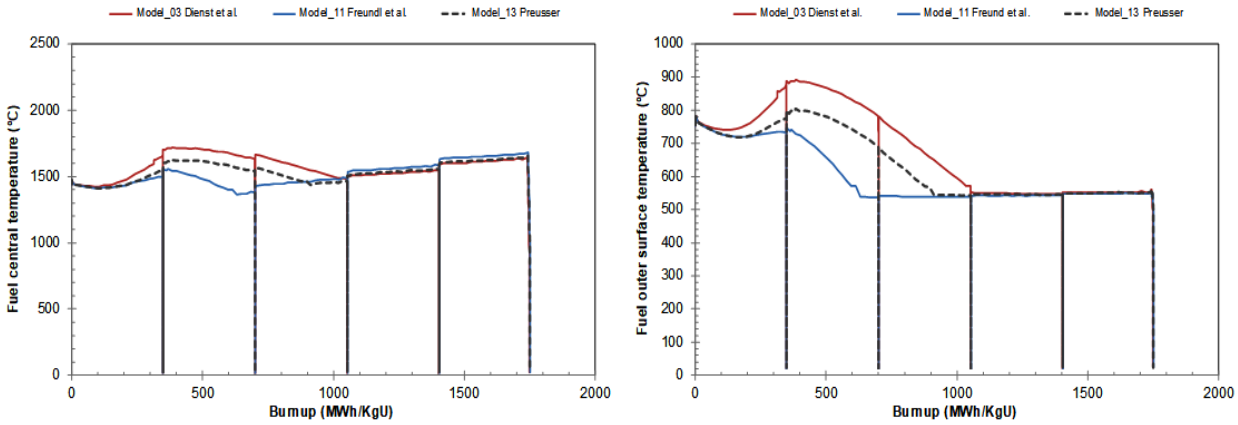


Fig. 5. Variation of fuel central temperature (left) and fuel outer surface (right) according to different swelling models

Table 5 summarizes the maximum values for different performance parameters obtained with different fuel swelling models.

Therefore, we considered all possible scenarios for the peak fuel temperature and the highest possible cladding strains. Furthermore, the correlation sets characterizing all the worst cases are reported in Table 6.

Table 5. TRANSURANUS results for ALFRED fuel element obtained with different swelling models

Phenomenon	Reference case (Preusser)	Freund Model	Dienst Model
Fuel peak temperature (ºC) [1]	1654	1681	1721
Contact Pressure (MPa) [1]	10.4	21.44	6.69
Fuel outer radius (mm) [2]	4.67	4.69	4.66
Clad inner radius (mm) [2]	4.71	4.71	4.74
Fission gas release (%) [1]	48.90	45.8	60.88
Swelling strain (%) [2]	0.0103	0.0103	0.0103
Creep strain (%) [2]	0.0026	0.0064	0.0017
Plastic strain (%) [2]	0	0	0
Total strain (%) [2]	0.0128	0.0166	0.0120
Gap closure	Occurs after the 2nd cycle ~ 895 MWh/kgU	Occurs after the 1st cycle ~ 610MWh/kgU	Occurs after the 3rd cycle ~ 1050MWh/kgU

[1] Maximum values obtained
[2] Values reported at the end of simulation

Table 6. Models leading to the worst-case in ALFRED irradiation conditions

Phenomenon	Fuel temperature	Cladding strains
Fuel thermal conductivity	Halden model	Conservative of ITU
Fuel swelling	Model_3 Dienst et al.	Model_11 Freund et al. model

The last step of this work implies additional simulations with the model combinations mentioned as the worst-case.

Worst case – Fuel temperature

The worst-case scenario in terms of peak fuel temperature has been obtained, as it is shown in Table 6.

The model combination supplies the widest possible gap, and, hence, the minimum conductance. Even in this scenario, the limit of 2000ºC for the peak fuel temperature is respected. At the same time, the gap pressure remains below 5MPa (see Fig. 6).

The results for worst case scenario in terms of peak fuel temperature are presented in Table 7.

Table 7. TRANSURANUS results for the worst-case in terms of peak temperature

Quantity	Maximum value
Peak fuel temperature [a]	1814 ºC
Peak cladding temperature	488 ºC
Inner gas pressure	2.62 MPa

[a] Maximum fuel temperature, which occurs at ~ 400MWh/kgU

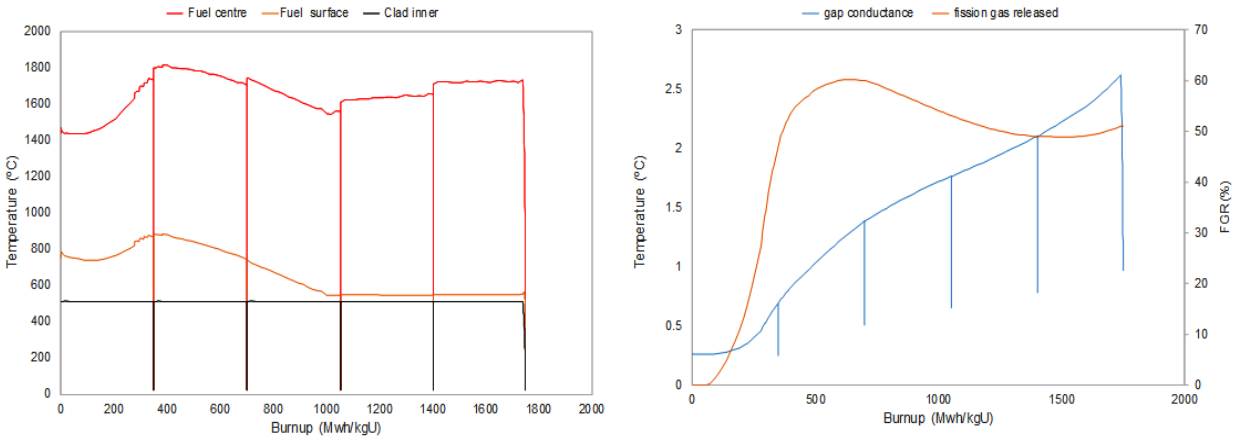


Fig. 6. Variation of fuel element temperature (left) and fission gas release with gap pressure (right) in worst-case

Worst case – Cladding strains

From the cladding strains perspective, the Freund et al. model for fuel swelling and the CONSERVATIVE-MOX model for the fuel thermal conductivity complete the worst scenarios. Therefore, the Freund et al. model predicts anticipated gap closure (see Fig. 7 on the left).

In accordance with gap closure, a contact pressure between fuel and cladding develops, although no plastic strain is obtained from the TRANSURANUS simulations (see Table 8.). The axial profile of the cladding outer radius is represented in Fig. 8 at two moments of irradiation period: at the end of the 5th cycle and at the end of the simulation (at shutdown).

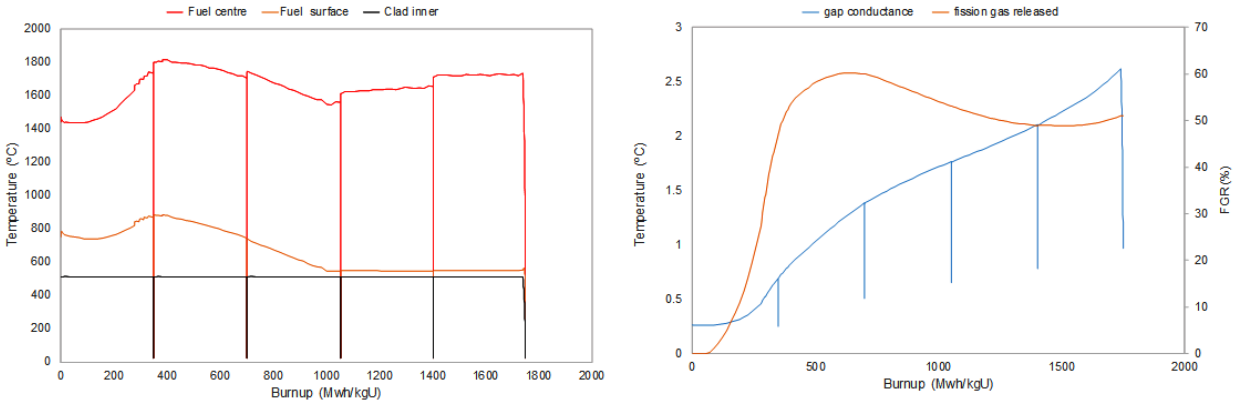


Fig. 7. Variation of gap size (left) and cladding average equivalent stress (right) in worst-case

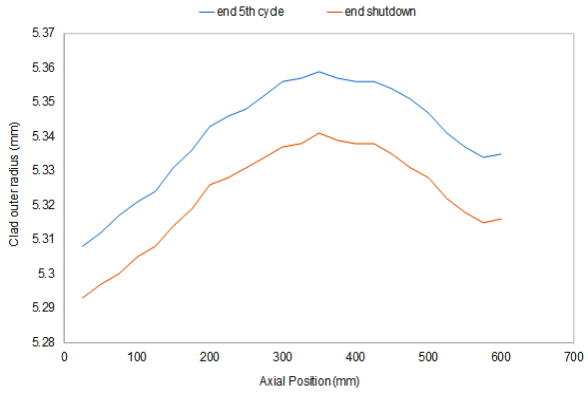


Fig. 8. Axial profiles of the cladding outer radius in worst-case

Table 8. TRANSURANUS results for the worst-case in terms of clad strains

Quantity	**Maximum value %**	**Design indications % [6-8]**
Total creep strain [1]	0.0067	< 3
Swelling strain [1]	0.0103	< 5
Plastic strain [1]	0	< 0.5
Cladding ΔD/D [2]	1.12	< 3

[1]Values reported at the end of simulation

[2] Maximum values obtained

Conclusions

This paper dealt with ALFRED fuel element sensitivity analysis performed with the TRANSURANUS code. The focus has been on the correlations addressing the fuel thermal conductivity and fuel swelling, to define the worst-case scenario in terms of peak fuel temperature and cladding strains.

Firstly, TRANSURANUS simulations were carried out for several fuel thermal conductivity models, in ALFRED normal operating conditions associated with a channel characterized by average power levels. The results were verified considering ALFRED design indicative limits, and based on this comparison no issues in terms of peak fuel temperature and gap pressure were observed.

Therefore, the next step implied TRANSURANUS simulations with different fuel swelling models to identify a set of correlations supplying the worst conditions in terms of fuel temperature and cladding strains.

The scenarios defined in the present analysis have proven a worst but anyway satisfactory response, leading to cladding strains far from their design limits. Summarizing, ALFRED fuel element showed a good behavior, even with the most severe set of input models used in this analysis.

Future work will be focused on the thermo-mechanical analysis for ALFRED fuel element irradiated in a channel characterized by the highest linear power, as well as a 3D structural analysis using finite element method.

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