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Original Article

Investigation on the effect of eccentricity for fuel disc irradiation tests

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ABSTRACT

A varying degree of eccentricity always exists in the initial configuration of a nuclear fuel rod. Its impact on traditional LWR fuel is limited as the radial gap closes relatively early during irradiation. However, the effect of misalignment is expected to be more relevant in rods with highly conductive fuels, large initial gaps and low conductivity filling gases. In this paper, we study similar characteristics in the experimental setup of two fuel disc irradiation campaigns carried out in the OECD Halden Boiling Water Reactor. Using the multi-dimensional fuel performance code OFFBEAT, we combine 2-D axisymmetric and 3-D simulations to investigate the effect of eccentricity on the fuel temperature distribution. At the same time, we illustrate how the advent of modern tools with multi-dimensional capabilities might further improve the design and interpretation of in-pile separate-effect tests and we outline the potential of such an analysis for upcoming experiments.

1. Introduction

Conventional fuel performance simulations assume the pellet stack to be concentric with the cladding, although a varying degree of eccentricity is inevitable in the initial rod configuration. The impact on typical Light Water Reactor (LWR) rods is small during most of the irradiation, as the gap closes at a relatively early stage due to thermal expansion, fuel fragment relocation and swelling, and cladding creep down. Additionally, the effect of eccentricity is generally embodied in the semi-empirical correlations and fitting parameters employed for the gap conductance modeling. However, under certain circumstances the uncertainties introduced by a misalignment of the fuel pellets may become much more important.

Already in 1974, it was pointed out that at the beginning of life, with the gap still open, the azimuthal asymmetry in gap conductance affects the heat transfer and can cause the heat flux to exceed its critical value, leading to film boiling and cladding failure [1]. In 1977, Williford and Hann [2] studied the impact of filling gasses and pellet eccentricity on the rods of the Instrumented Fuel Assembly IFA-431. They concluded that neglecting eccentricity leads to a significant underestimation of the average gap conductance, in particular for rods with high thermal gradient across the gap (due for example to large gap size or to filling gasses with low conductivity such as Xenon). In 1982, the importance of eccentricity was also analyzed experimentally during Reactivity Initiated Accident (RIA) condition tests [3], with temperature differences as high as 150° measured along the cladding circumference. In parallel, the findings of McNary et al. [4] confirmed the work of Williford and Ann, adding that eccentricity is expected to play a relevant role not only for rods with large gaps and low gap conductance (i.e. with large thermal gradients across the gap) but also for high conductivity fuels such as carbide. More recently the effect of eccentricity on the fuel temperature distribution for UO_2 rods was studied by Desampaio et al. [5] while BISON [6] (a multi-dimensional fuel performance code developed at the Idaho National Laboratory) was used to reproduce the temperature differences between concentric and eccentric rods in the IFA-431 [7,8].

In this paper, we study characteristics similar to those pointed out by Williford and Hann and by McNary, which are found in the experimental setup of the in-pile separate effect studies carried out in the OECD Halden Boiling Water Reactor (HBWR). Among the large database available at the Joint Research Center (JRC) in Karlsruhe, we have identified two fuel disc irradiation campaigns with on-line temperature measurements, where the combined presence of highly conductive materials, large gaps and low-

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conductivity filling gases hints at a significant impact of eccentricity. Using the multi-dimensional fuel performance code OFFBEAT, under collaborative development at the Ecole Polytechnique Fédérale de Lausanne (EPFL) and the Paul Scherrer Institute (PSI), we analyze the fuel temperature distribution and compare it to the thermocouple readings by means of 2-dimensional (2-D) axisymmetric and 3-dimensional (3-D) simulations.

While investigating the effect of eccentricity on fuel disc irradiation tests, we also aim to illustrate how modern multi-dimensional codes such as OFFBEAT can complement and extend the possibilities offered by fuel performance analysis. Indeed, separate-effect experiments like those analyzed in this work are becoming increasingly more relevant in nuclear fuel research to obtain a better understanding of specific properties and phenomena. However, they are often characterized by features that cannot be accurately reproduced with traditional tools such as the well-known TRANSURANUS code developed by the JRC [9]. The advent of advanced multi-dimensional fuel performance capabilities allows to improve further the interpretation and design of separate-effect tests which traditionally relied on a combination of conventional fuel performance codes and general-purpose finite element software. In conclusion to this paper, we outline the potential of such an analysis for upcoming experiments.

The paper is structured as follows. The OFFBEAT code is introduced in Section 2 and the two experimental campaigns are briefly described in Section 3. In Section 4, the attention is focused on a preliminary axisymmetric study, showing that the large differences between measured and predicted temperatures for some rods cannot be justified in the framework of a traditional fuel performance analysis, without considering 3-D effects. Section 5 presents a 3-D investigation on the effect that eccentricity might have on the temperature distribution in fuel disc irradiation tests. In the last section, we summarize the outcome and outline the further developments and applications.

2. The OFFBEAT code

The OpenFOAM® Fuel Behavior Analysis Tool or OFFBEAT is developed with the open-source C++ library OpenFOAM [10], in the frame of an international effort, initiated by the EPFL and the PSI and currently sponsored by the IAEA, towards an open-source platform for nuclear reactor analysis [11,12]. It solves the governing equations on unstructured meshes, employing modern finite volume techniques. OFFBEAT can thus be used to model fuel of arbitrary geometry by means of 1-D, 2-D and 3-D simulations. The code solves the coupled heat conduction and small-strain momentum balance equations, relying on a fixed-point segregated scheme, and is fully parallelized through geometrical domain decomposition.

The burnup and temperature dependence of the material properties is modeled through semi-empirical correlations, derived mostly from MATPRO [13] and other sources from the open literature. The code considers fuel densification, swelling and relocation and includes models for capturing the plastic behavior of Zircaloy, with both instantaneous plasticity and creep. Efforts are underway to introduce models for fuel isotropic cracking and time-dependent creep.

A gap-plenum model, derived from the FRAPCON code [14] and generalized for three-dimensional geometries, is used to track the volume available to the gas inside the pin and calculate its pressure. Custom boundary conditions have been developed to model the heat transfer between fuel and cladding, using the traditional thin gap assumption to calculate the gap conductance, and to treat the mechanical contact between the two facing surfaces.

More details about OFFBEAT's general structure, equations and models can be found in Ref. [15].

3. Description of the experimental campaigns

The experimental data used in this paper are obtained from two past fuel disc irradiation campaigns performed in the HBWR. Fuel samples with radially uniform temperature profiles are desirable to isolate the effect of temperature on fuel behavior. Due to the large temperature gradients found in commercial fuel, both campaigns adopted the irradiation of thin fuel discs sandwiched between molybdenum discs. With molybdenum having a thermal conductivity 40 times that of UO_2, most of the heat generated in the fuel flows vertically toward the molybdenum discs and then dissipates radially through the molybdenum-cladding gap. This unusual setup requires a full (at least) 2-D analysis.

3.1. Test 1: the High Burnup Rim Project

The High Burnup Rim Project (HBRP) was initiated in 1991 and was completed at the end of 2000 [16]. This international project responded to the industrial need to study the High Burnup Structure (HBS), typically found in the rim of LWR fuel pellets. Combining the use of molybdenum discs with a highly enriched fuel allowed fuel samples with relatively flat temperature and burnup profiles to be obtained.

The HBRP consisted of 4 rods loaded within an Instrumented Fuel Assembly (IFA) and irradiated in the mid 1990's. Each rod was made of 4 separate stacks consisting of 10 fuel discs sandwiched between molybdenum discs. The bottom and top stacks were the only ones equipped with a thermocouple (TC) measuring the (external) temperature of the molybdenum disc. The cladding tube enclosing the discs was made of Zircaloy.

As shown in Fig. 1, the experiment was designed to provide a burnup and temperature dependent matrix for the study of the HBS: the rods had different target temperatures, achieved by decreasing the radius of the molybdenum discs and switching the gas composition from pure helium to pure argon, while the stacks had different target burnups. In order to compensate for the axial power gradient and maintain the same rod temperature, different molybdenum disc thicknesses were used from the top to the bottom stack. More details about the geometrical configuration of each rod can be found in Table 1.

The top stack temperatures measured during operation were significantly lower than planned, due to an unexpected flux profile in the HBWR. In order to focus on the effect of the eccentricity in disc irradiations and for the sake of conciseness, the study performed in this paper is limited to the bottom stacks in each rod: S11, S21, S31 and S41 (see Fig. 1).

The main documents of the experimental campaign do not provide any estimate about the average eccentricity of the stacks, but pictures taken during the Post Irradiation Examination (PIE) do reveal the presence of eccentricity (both between molybdenum and cladding, and between molybdenum discs and UO_2 discs). However, these pictures provide a single 2D slice of the rod, so their analysis remains inconclusive. To our knowledge, there is no indication of the TC measurement uncertainty in the campaign documentation.

3.2. Test 2: the fuel creep test

This test [18] was originally designed to study the creep rate for different types of LWR fuel as a function of applied stress and at low temperature (below ~1000 °C). In this temperature range, the fuel creep behavior is dominated by an a-thermal fission-induced

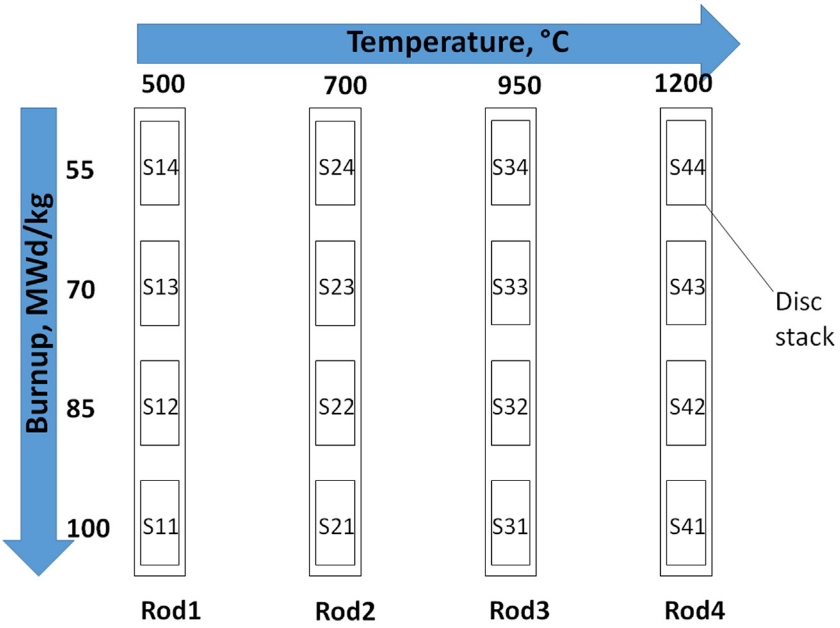

Fig. 1. General scheme of the HBRP experiment [17]. The Figure shows the target temperatures and burnups.

Table 1
Dimension and design parameters of the HBRP rods [17].

		Rod1	Rod2	Rod3	Rod4
Filling gas		~100% He	~75% He + Ar	~45% He + Ar	~100% Ar
Fuel disc diameter (mm)		5	5	5	5
Fuel disc thickness (mm)		1	1	1	1
Mo disc diameter (mm)		8.26	8.16	8.01	7.76
Mo-Clad radial gap (mm)		0.05	0.1	0.175	0.3
Mo disc thickness (mm)	4 (Top)	1.2	1.2	1.2	1.2
	3	1.8	1.8	1.8	1.8
	2	2.4	2.4	2.4	2.4
	1 (Bottom)	3.0	3.0	3.0	3.0
Clad thickness (mm)		0.57	0.57	0.57	0.57
Clad material		Zircaloy	Zircaloy	Zircaloy	Zircaloy

component, while fission-enhanced thermal creep is negligible.

The experiment consisted of 4 rods loaded in another IFA, between 2010 and 2012. Two types of fuel were used: standard UO_2 for the first pair of rods and Cr-doped UO_2 for the second. Most importantly, beside the fuel type and fuel disc diameter, the 4 rods had a similar geometrical configuration and were equipped with central thermocouples. More details can be found in Table 2.

Each rod was made of a single stack of 44 short fuel discs sandwiched between thicker molybdenum discs. The discs were enclosed in a cladding tube made of Inconel600. The rods were equipped with fuel stack elongation detectors and with centerline TCs inserted in a center tube passing through the disc central holes. It is assumed that the center tube (absent in Test 1) limits the eccentricity of the disc column. A bellows-based system was designed to apply an axial stress during the creep tests while measuring the change in stack length. Although the same irradiation history is shared between the two rods of a pair, only one of each pair was attached to the bellows-based system. Thus, the unstressed reference rod represented the behavior of the fuel in the absence of creep deformations.

Table 2
Dimension and design parameters of the fuel creep test rods [18].

	Rod1	Rod2	Rod3	Rod4
Fuel type	Cr-UO_2	Cr-UO_2	UO_2	UO_2
Filling gas	He-Ar	He-Ar	He-Ar	He-Ar
Fuel disc diameter (mm)	8.48	8.48	8.19	8.19
Fuel disc thickness (mm)	1.7	1.7	1.7	1.7
Mo disc diameter (mm)	11.7	11.7	11.7	11.7
Mo-Clad radial gap (mm)	0.2	0.2	0.2	0.2
Mo disc thickness (mm)	5	5	5	5
Clad thickness (mm)	0.57	0.57	0.57	0.57
Clad material	Inconel600	Inconel600	Inconel600	Inconel600

The second test was divided into 4 cycles: two irradiation periods at low applied stress, corresponding to cycles I and III; and two shorter creep testing periods at varying applied stress levels, corresponding to cycles II and IV. The analysis performed in this paper is limited to the first period up to ~110 days, when due to the low applied stress the change in fuel stack length was mostly due to thermal expansion and densification [18]. The rest of the irradiation requires the introduction of a model for UO_2 creep, which is beyond the scope of this work, and will be analyzed in the future to explore the modeling of fuel creep behavior within a multidimensional code, and its potential implications for conventional fuel performance codes.

We could not find any estimate about the average eccentricity of the rods and, differently from the HBRP campaign, no information nor pictures derived from PIE is included in the main documentation. Also, to our knowledge, there is no indication of measurement uncertainty.

4. 2-D axisymmetric analysis

The two experimental campaigns described above are analyzed by means of 2-D axisymmetric simulations. The main objective is to assess if the differences between predictions and measurements can be explained in the framework of traditional fuel performance analysis, without considering 3-D effects such as eccentricity. This would also pave the way for a reinterpretation of the disc irradiations, with a view to achieve more accurate boundaries for the HBS formation for instance.

4.1. Modeling approach and assumptions

In order to limit end-effects on the local temperature, while avoiding the full-length simulation of the entire stack, it is necessary to include at least a few fuel-molybdenum pairs surrounding the TC position. For this reason, the reduced stack shown in Fig. 2 is considered for each rod, including 5 fuel discs, 4 molybdenum full-discs and 2 molybdenum half-discs at the two ends. Nevertheless, making use of the geometrical symmetry, the actual numerical model is limited to half of the reduced stack. The computational grid, also shown in Fig. 2, was tested for convergence and a mesh refinement level of 20 × 5 divisions for the Mo discs, and 12 × 5 divisions for the UO_2 discs provided sufficiently accurate results (see also [15], Section 5.2).

The full irradiation history database acquired during the HBRP campaign was simplified to the ~30 data points per rod included in the final project report [16], including the experimental molybdenum temperature as well as the linear heat rate and burnup at the TC location. Likewise for the second test, the original irradiation history, containing more than 10000 data points recorded at 15 min intervals, was reduced to the more manageable size of ~400 using the FRA-TOOLBOX [19].

The numerical model in Fig. 2 requires a careful consideration of the displacement at the boundaries. A symmetry type boundary condition is applied to the bottom surfaces because of the model half-symmetry. This fixes the axial displacement of the mechanical system considered (the normal displacement is zero in the symmetry plane), but it does not anchor its tangential movement. Thus, the top surface is fixed in all degrees of freedom to make the mechanical problem mathematically well-posed. Since this constraint inevitably causes non-physical high stresses, the Young's modulus in the top molybdenum half-disc is decreased to 10% of its theoretical value. Acting as a cushion or as a spring, the top disc thus accommodates the axial expansion of the fuel stack and confines the high stresses to a region far from the location of the TC.

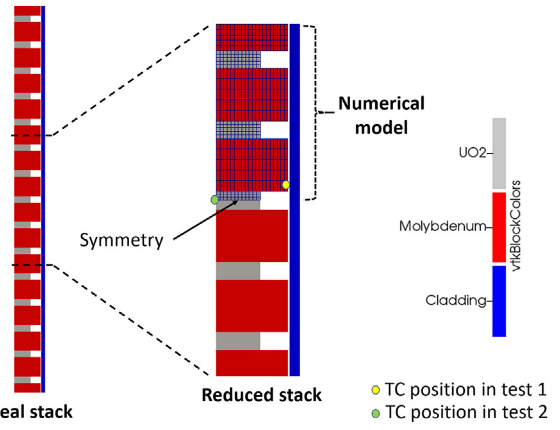

Fig. 2. Axisymmetric model for the separate-effect rods with discs. A reduced stack with 5 fuel discs is used to characterize the temperature distribution surrounding the TC position. Due to symmetry, the numerical model corresponds to the area overlaid with the mesh grid.

It must be underlined that decreasing the Young's modulus is not necessary for OFFBEAT to work and it is only a numerical trick useful for reproducing a computational model like the one described in this section. Alternatively, one could model the entire reduced stack, fix the bottom surfaces, and use a traction type boundary condition at the top surfaces. The mesh grid would be twice as large, and the computational cost would be higher. In preparation for this work, it was verified that the difference in temperatures obtained with the entire-stack model is smaller than the experimental uncertainties, or the effect of eccentricity, which is the actual objective of this study.

Another important issue derives from the presence of multiple free bodies (i.e. without fixed points) in contact with each other. Traditionally in FV solid mechanics codes [20], contact is modeled with the penalty method but its application to multiple free bodies problems would have terrible convergence properties. Experimental data are missing for the contact thermal resistance between fuel and molybdenum discs. However, the disc irradiation is setup to have a uniform temperature and burnup distribution in each disc. Based on this consideration, we have assumed a perfect contact between subsequent discs. The HBS formation is also relatively uniform, and no deformation is expected that would invalidate the assumption of perfect contact between UO_2 and Mo, which seems justified by analyzing the PIE pictures. Thus, the UO_2/molybdenum stack becomes effectively a single multi-material domain. When modeling such a domain in a FV framework numerical errors arise in the stress distribution close to the bi-material interface [21]. These numerical issues are solved using a newly developed boundary conditions that corrects for the stresses at the bi-material interface, following the implementation of Tuković [22] and Cardif [21]. A contact model based on the penalty-method and discussed in previous publications [15,23] is used instead for the surfaces facing the gap, although it reduces to applying the internal rod pressure in the absence of penetration.

Regarding the temperature field, symmetry boundary conditions can be used both at the top and bottom boundaries. This is equivalent to assuming that the reduced stack is part of an infinite rod made of fuel and molybdenum discs. Naturally, in this way we neglect full-length effects on the local temperature distribution but considering that the atmosphere of the rod is fixed and that there is no fission gas poisoning, this assumption will not affect the results. No additional thermal contact resistance is considered between fuel and molybdenum discs and the temperature field is assumed continuous between the two materials. Typical values of contact conductance are quite high and are not expected to have a significant impact on the disc temperature.

An important modeling choice concerns the gap heat transfer between molybdenum discs and Zircaloy cladding. In the absence of more appropriate alternatives, the classic gap conductance model implemented in OFFBEAT and derived from FRAPCON (see Section 2.3.4 in Ref. [14]) is chosen. This model has been compared with the results of the gap conductance model in TRANSURANUS for a set of simplified cases and has proven almost identical. The main issue is the presence of fitting parameters based on UO_2 rod data. The effect they have on the temperature jump across the gap cannot be known a priori. However, the main physical considerations on which the FRAPCON model is based are still valid, such as the decomposition of the heat conductance in the three components of conduction through the gas, radiative losses and contact heat exchange. Considering that the gap between the Mo discs and the cladding remains open and that the temperatures remain moderate the dominant contribution to heat transfer is due to gas conductance. Therefore, we assume that the FRAPCON model is considered as a good first approximation.

Regarding the molybdenum thermo-mechanical properties, correlations for conductivity, Young's modulus, Poisson's ratio and thermal expansion are derived from the BISON manual [6] and introduced in OFFBEAT. The correlations found in the BISON manual and other references do not provide any uncertainty estimation. No correlations were found in the public literature for the molybdenum emissivity. The few sources available agree in reporting values around 0.2 for the surface emissivity of molybdenum between 1500 °C and 2000 °C, hence a constant emissivity of 0.2 is adopted in this work. The same sources report a much higher emissivity (from 0.8 to 0.9) for oxidized molybdenum but no information is found in the test reports about the oxidation state of the molybdenum discs. Due to inert gas filling in the rods under consideration, it is reasonable to assume that little to no oxidation took place during irradiation.

4.2. Results and discussion

The results of the axisymmetric simulations are summarized in Fig. 3, where the temperatures calculated with OFFBEAT are plotted against the corresponding measurements. A temperature prediction matching the TC reading would lie on the diagonal "P = M" (full line "Predicted = Measured"), while the two dashed lines correspond to a temperature difference of ±100K, a range that is generally considered to embody a large fraction of the uncertainty on fuel temperature predictions under normal operation conditions (see Ref. [24]). Due to the different TC position, the outer molybdenum temperature is plotted for the HBRP, whereas the fuel centerline temperature is provided for creep test.

The temperatures calculated for the second series of rods lie very close to the "P = M" line in Fig. 3. The deviations are small and hint at a minor role, if any, of eccentricity. This is surprising if considering the characteristics of the rods, similar to those pointed out by McNary in his publication. We attribute the small deviations to the fact that the tube passing through the center holes limits the misalignment of the disc column. Eccentricity could only be relevant if the discs were broken, which has not been reported.

The deviations are considerably larger for the first series of test rods. While the predictions for the stacks S11 and S21 lie mostly within the band of ±100K, OFFBEAT overestimates the temperature for the stacks S31 and S41 by more than 300K and 700K, respectively. Also, a pattern can be identified in the first test series. Indeed, it appears that the deviations gradually increase from the low-temperature small-gap rods filled mostly with helium, to the high-temperature large-gap rods filled mostly with argon.

The deviations might be partially linked with neglected irradiation effects in the molybdenum discs, such as swelling. However, they are not mentioned in the campaign documents and no information can be found about similar phenomena in the relevant literature. Besides, the magnitude of the temperature deviations is too high to be justified with any reasonable expansion due to disc swelling. Additionally, the PIE pictures show that the molybdenum discs were intact at the end of irradiation, thus fragmentation can be excluded. Other relevant material properties have been taken into consideration in the sensitivity study in this paper.

The deviations might also be caused by poorly modeled mechanical effects in the fuel discs (such as relocation or densification), by the assumption of perfect contact (because it could limit the tangential movement of the UO_2 discs), or by a change in fuel microstructure due to the formation of the HBS (which is not considered in OFFBEAT). However, given that most of the heat flows vertically toward the highly conductive molybdenum, it is unlikely that the temperature distribution would be affected by small variations in the fuel microstructure or in the fuel-clad gap (which remains extremely large compared to the molybdenum-clad gap). This was verified in preparation for this work by running test simulations where the various nuclear models are sequentially shut down and where the top and bottom disc surfaces are left free to expand. The temperature results changed only slightly, in the order of few tens of degrees. Considering the rather uniform temperature and burnup profiles in the discs, the formation of the HBS is also not expected to change the assumptions in the calculation model (e.g. contact conditions).

In the HBRP rods, the TC is located near the edge of the molybdenum disc. Thus, in the framework of a 2-D fuel performance analysis neglecting 3-D effects (and based on the argumentations brought forth in the previous paragraphs), large deviations from the measurements can mostly be attributed to the errors and uncertainties embedded in the heat transfer model chosen for the molybdenum-cladding gap.

Naturally, the thin-gap approximation of the FRAPCON model is not accurate for the small fraction of heat transferred across the fuel-cladding gap. This region is quite large (more than 1.5 mm) if

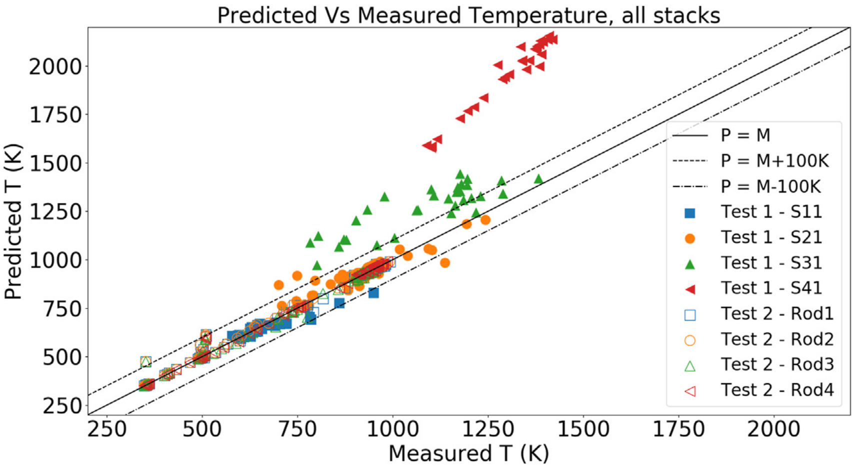

Fig. 3. Results of the axisymmetric simulations. Temperatures obtained with OFFBEAT are plotted against the corresponding TC measurements.

compared to commercial rods, and the radiative heat exchange involves also non-negligible portions of the top and bottom surfaces of the surrounding molybdenum discs. A proper assessment would require an explicit modeling of the gap heat transfer in the absence of contact. However, considering the low temperatures measured by the TCs (always lower than ~1400K), it is reasonable to assume that errors in the fuel-cladding heat exchange would have a negligible effect on the molybdenum temperature distribution.

4.3. Parametric study on the gap heat transfer model

In order to better understand the potential effect of various model parameters in the gap conductance on the observed discrepancies for test 1, a parametric study was carried out. The temperature jump across the molybdenum-cladding gap is directly proportional to the gap heat resistance and is affected mainly by:

- the filling gas conductivity k_{gas}, which contributes greatly to the conductive term of the heat resistance,
- the surface emissivity ε_{Mo} of the molybdenum discs, which limits the radiative heat exchange in the gap and
- the molybdenum thermal expansion α_{Mo} which changes the gap size.

Attention should be drawn to the effect that large uncertainties in these parameters would have on the temperature distribution. Focusing on the Ar-filled stack S41, the original axisymmetric simulation is repeated, each time increasing by 20% the value of one of the three parameters, k_{gas},ε_{Mo} and α_{Mo}, while the other two parameters keep the nominal value. A fourth simulation is performed with an emissivity of 0.8 in order to consider also the effect of possible molybdenum disc oxidation (see Section 4.1).

The results are summarized in Fig. 4 where the calculated temperatures are plotted against the corresponding measurements. Increasing α_{Mo} or ε_{Mo} by 20% has a negligible effect, while the change in k_{gas} causes the temperature to decrease by ~100K. Finally, with an emissivity of 0.8, realistic only if the molybdenum discs were oxidized, the deviations remain larger than ~300K. This first parametric study suggests that even (improbable) large errors on the main parameters affecting the gap heat exchange do not justify the large deviations seen for the stacks S31 and S41.

5. 3-D analysis of eccentricity

As shown in the previous section, it is impossible to explain the deviations seen for the HBRP stacks in the framework of a traditional axisymmetric analysis as applied in conventional fuel performance codes. Thus, a set of 3-D simulations is performed with OFFBEAT to evaluate the impact of eccentricity on the two experimental assemblies considered in this paper. This section refers only to the eccentricity between the inner stack (UO_2+Mo) and the cladding, although the PIE revealed also a considerable and variable amount of offset between consecutive discs. Due to the high conductivity of the molybdenum discs, it is reasonable to assume that their position relative to the fuel has a second order effect on the temperature distribution and for this reason it is not analyzed further in this paper.

5.1. Modeling approach and assumptions

For each stack, the irradiation history is combined with three different degrees of eccentricity, given as the amount of closed gap on the narrow side (in percent) and equal to 20%, 50% and 100%. Thus, an eccentricity of 100% is equivalent to the molybdenum disc touching the cladding at cold conditions. As shown on the left of Fig. 5 with a cross section view of the 100% eccentric model used for the stack S41 from the first campaign, only the bottom fuel-molybdenum pair where the TC is located is modeled as eccentric. The computational grid is similar to the one used for the 2-D axisymmetric simulations, with 40 total divisions in the azimuthal direction. The same boundary conditions and assumptions discussed in Section 4.1 are used.

5.2. Results

Fig. 6 shows the results of the 3-D analysis for Rod1 of the second test. The fuel centerline temperature calculated with the three different degrees of eccentricity is plotted against the irradiation time. The results of the axisymmetric simulation and the TC measurements are added for comparison, showing a very good agreement. Similar graphs (not shown) are obtained for the remaining rods. As expected for a rod with a relatively large gap and partly filled with argon, OFFBEAT predicts a significantly lower temperature with respect to the axisymmetric case once eccentricity is considered in the model. A difference of ~200K compared to the concentric simulation is obtained when the molybdenum disc is already in contact with the cladding at the start of irradiation.

Fig. 7 and Fig. 8 show the results of the 3-D simulations performed for the stacks S11 and S41 in the first test, which represent

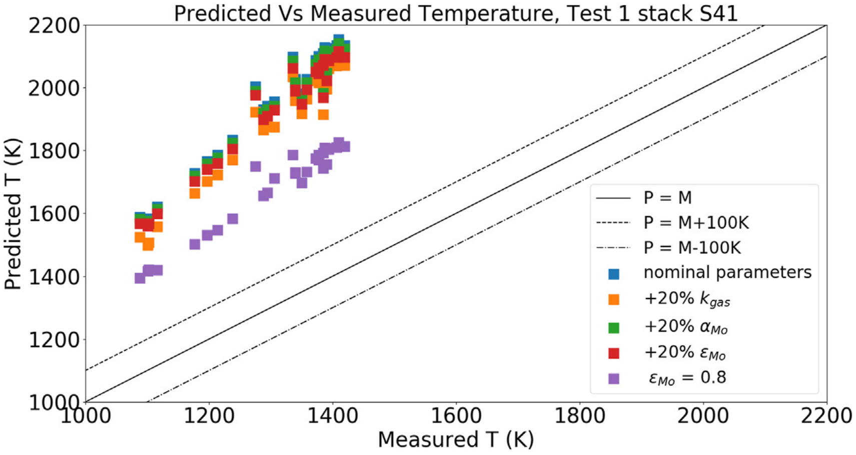

Fig. 4. Results of the parametric study on the gap heat transfer model. Temperatures obtained with OFFBEAT are plotted against the corresponding TC measurements.

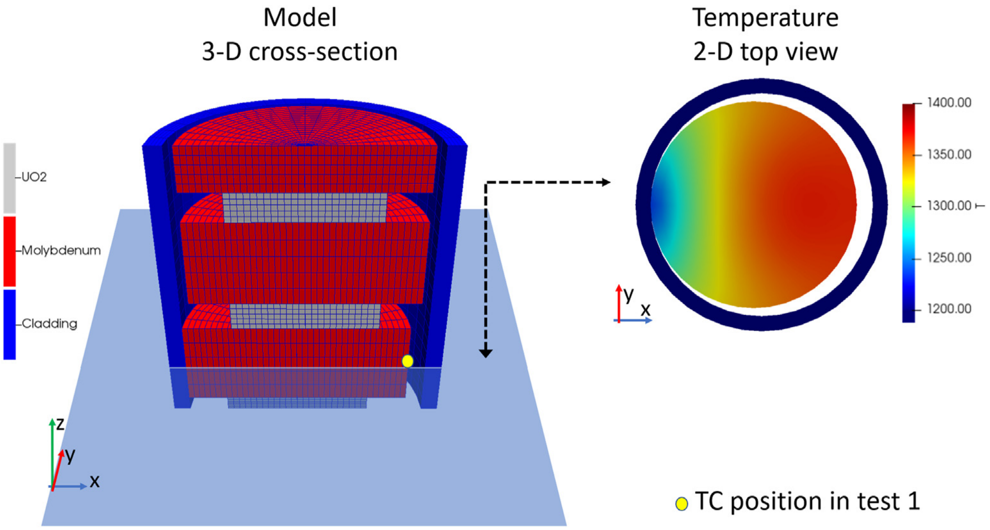

Fig. 5. Cross section of the 100% eccentricity model used for the stack S41 from the first campaign (left). Detail showing the 2-D temperature distribution on a horizontal slice at the center of the eccentric molybdenum disc (right).

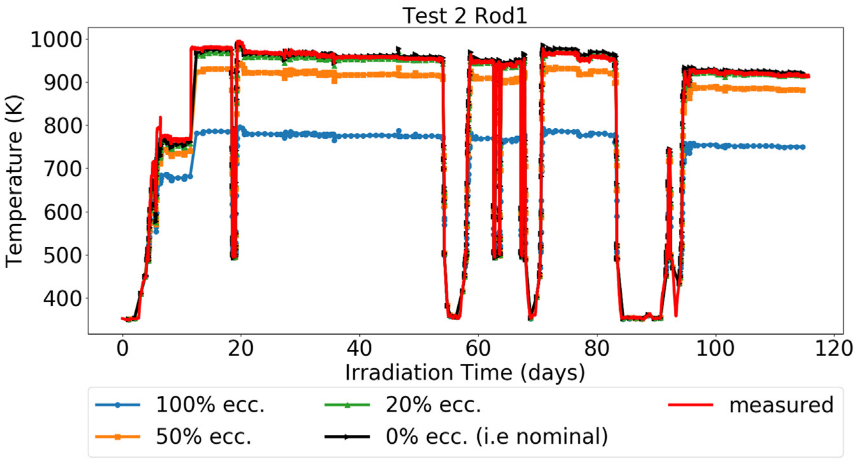

Fig. 6. Results of 3-D analysis for Rod1 of test 2 with varying degrees of eccentricity. Fuel centerline temperatures obtained with OFFBEAT are plotted against irradiation time. The measurements from centerline TC are included in the graph.

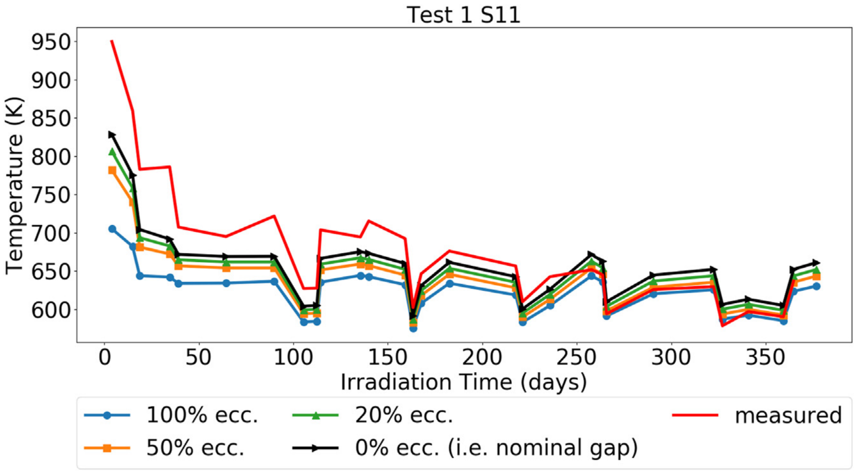

Fig. 7. Results of 3-D analysis for stack S11 from test 1 with varying degrees of eccentricity. Outer molybdenum temperatures obtained with OFFBEAT are plotted against irradiation time. The measurements from the TC are included in the graph.

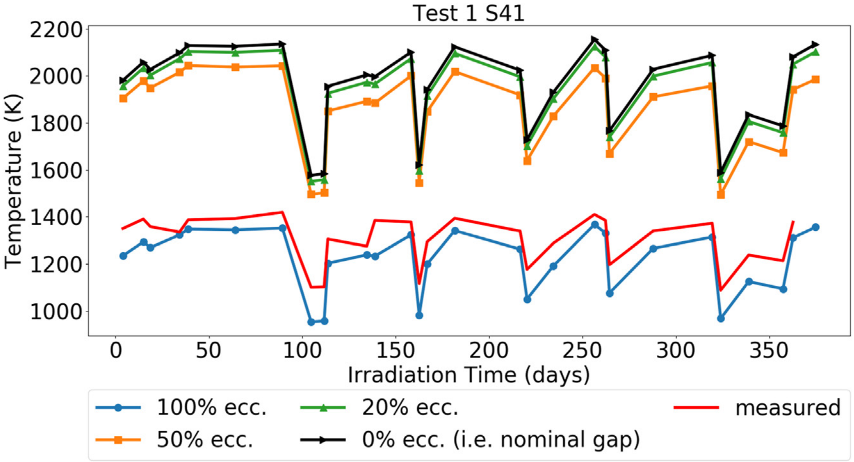

Fig. 8. Results of 3-D analysis for stack S41 from test 1 with varying degrees of eccentricity. Outer molybdenum temperatures obtained with OFFBEAT are plotted against irradiation time. The measurements from the TC are included in the graph.

the two opposite ends of the spectrum for this campaign in terms of temperature range. The distance between the calculation point and the TC location (which remains unknown) introduces a new degree of uncertainty in the results, given that, as shown in the top view on the right of Fig. 5, the eccentricity causes a temperature gradient across the molybdenum disc. However, although the temperature difference between the two sides of the disc can reach ~150K in the most extreme case, the presence of such gradient cannot explain the 300K and 700K deviations seen for S31 and S41, and does not change the nature of the conclusions drawn in this and in the following section. For the sake of conciseness and clarity of exposition, only the temperatures on the wide side gap (corresponding to the yellow dot in Fig. 5) are plotted in the following graphs.

Fig. 7 reveals an initial temperature decrease measured during irradiation, which is caused by a change of the gas composition, as reported in the campaign main document (the change in gas composition is explicitly modeled with OFFBEAT). The temperatures displayed in Figs. 7 and 8 are taken from the molybdenum outer surface on the wide gap side, close to the area of maximum temperature as it can be seen in Fig. 5. Because the results of the 3D simulations are always lower than those obtained with the nominal gap size, they suggest that any amount of eccentricity causes the temperature of the entire molybdenum disc to decrease. This is different from what is normally expected for traditional UO_2 pellets, where the wide gap side of the fuel surface becomes hotter than in the concentric case, and it is due to the much higher thermal conductivity of the molybdenum. The results also reveal that the effect of eccentricity is not linear: the reduction in temperature is more pronounced as the molybdenum surface approaches the cladding.

The large difference between the 50% and the 100% eccentricity curves in Figs. 6 and 8 (but partially also in Fig. 7) might seem excessive at a first glance. Because the conductance of the gap is dominated by its conductive component, one might expect that the temperature jump across the gap ΔT_{gap} would decrease in an approximately linear fashion with the gap size, and indeed this would be the case for two planar slabs approaching each other. However, when gradually increasing the eccentricity between two cylinders, the average gap conductance does not change linearly, as while the gap size decreases on one side, it increases on the other. This is evident from the curves for 50% eccentricity, which are far from showing a 50% decrease in ΔT_{gap} (the inner cladding temperature is always ~580K). It is only when a large part of the molybdenum outer surface is close to the cladding (i.e. at very high eccentricity) that the average conductance increases significantly. The effect of eccentricity, although always present, is relatively much more important for rods with large gradient across the gap (in our case, rods with large gaps and/or filled with Argon) as already noticed by Williford and Hann in their analysis of the IFA-431.

As a summary, Fig. 9 shows the results of the calculations obtained with the 100% eccentric assumption for all the stacks from the first test plotted against the corresponding TC measurements. The results obtained with the axisymmetric models are included for comparison. Once again, it is possible to notice that, although the qualitative behavior is the same in all the stacks, the relative importance of eccentricity increases from the small-gap He-filled S11 to the large-gap Ar-filled S41. When the gap is large, and the rod is filled with low-conductivity gas the axisymmetric gap conductance is very low. Thus, minor changes in eccentricity have a greater effect on the gap temperature jump, because the relative change in gap conductance is large. For helium-filled rods with smaller gaps, the axisymmetric conductance is very high, and the effect of eccentricity is less pronounced. This pattern is in line with the work of McNary et al. [4] who analyzed the effect of eccentricity on the fuel-clad gap conductance in two dimensions. According to their findings, the azimuthal asymmetry in heat transfer is more relevant for low values of the Biot number, defined as:

$$B = \frac{(h \cdot r)}{k} \qquad 1$$

where h represents the azimuthal average gap conductance, r corresponds to the disc radius and k is the disc thermal conductivity. The presence of the highly conductive molybdenum makes the Biot number small if compared to traditional LWR rods. Moreover, given the disc dimensions and gas compositions, the Biot number in the HBRP stacks is progressively decreasing, hence the effect of asymmetry is also expected to be gradually more pronounced from stack S11 to stack S41.

For commercial rods the Biot number is large, since the filling gas is pressurized helium (except when poisoned with fission gas, but then usually the gap is small if not closed), and the conductivity of the UO_2 is about 40 times smaller in comparison with Mo. Thus, the effect of eccentricity is expected to be less relevant for LWR fuel rods. This is in line with earlier findings obtained with OFFBEAT [25], confirming that pellet eccentricity might affect the heat flux distribution but the overall effect on maximum and average fuel

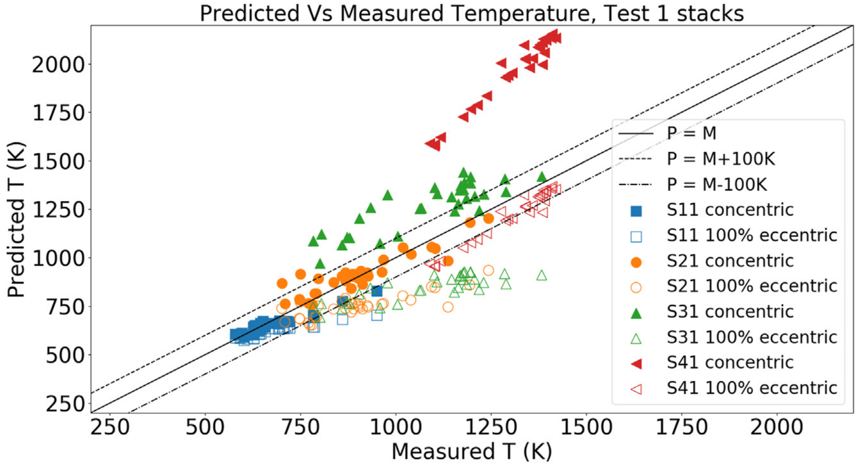

Fig. 9. Results of 3-D simulations with 0 and 100% eccentricity for the test 1 stacks. The calculated temperatures are plotted against the corresponding measurements.

temperatures is relatively small for BWR fuel at low burnup during base irradiation.

To better visualize the impact of eccentricity and the conclusions drawn in this section, we calculate for each of the Test 1 stacks the quantity $\Delta T_{100\%}$, defined as the time-average difference in molybdenum outer surface temperature between the 100% and 0% eccentricity curves. The metric $\Delta T_{100\%}$, shown in Table 3, is plotted against the respective Biot number in Fig. 10. The Biot number used in the Figure is calculated with the time-averaged quantities always shown in Table 3, obtained from the simulations with nominal gap size. For comparison, we include in Fig. 10 the Biot number range for typical LWR rods, which according to McNary et al. is between 8 and 20.

6. Conclusions

The works of Williford and Hann [2], and McNary et al. [4] pointed out that fuel eccentricity is expected to have a large impact on the temperature distribution of rods with high conductive fuel and large thermal gradients across the gap, due to the presence of large gaps or low conductive filling gases. In this paper, we have investigated similar characteristics in the experimental setup of two fuel disc irradiation campaigns carried out in the HBWR and we have compared the temperatures predicted by the multi-dimensional fuel performance code OFFBEAT against on-line measurements from thermocouples.

For the 4 rods of the first campaign, the results of 2-D axisymmetric simulations revealed a pattern, with the deviations gradually increasing from small-gap helium filled rods to large-gap argon filled rods. A sensitivity study on the main parameters affecting the gap heat transfer model confirmed that the large deviations seen for the two highest-temperature rods cannot be explained in the framework of a conventional fuel performance analysis without 3-D effects. For the 4 rods of the second experimental campaign, the temperature calculated with OFFBEAT were surprisingly close to the corresponding measurements, hinting at a minor role of eccentricity. We attributed this to the presence of a central tube passing through the disc holes (absent in the first test) which limits the stack misalignment.

A set of 3-D simulations with increasing degree of eccentricity was performed, suggesting that eccentricity can indeed cause a large range of uncertainties in fuel disc temperature. In line with the findings of previous theoretical studies, the results of the 3-D simulations showed that the rods with larger gaps and low-conductivity filling gasses are more sensitive to the relative position between fuel column and cladding. Supported by the almost perfect predictions for the rods of the second campaign, we identify eccentricity as the main factor contributing to the uncertainty in fuel disc temperature in the first test.

Nevertheless, no definitive conclusion can be drawn and a more quantitative estimation of the effects of eccentricity is premature at this stage. This would require knowledge about the exact positioning of all discs in each stack analyzed, as well as more temperature measurements. An extension of this work should also include assessing the effects of the fitting parameters of the FRAPCON gap conductance model. Being developed for conventional UO_2-filled Zircaloy rods, the fitting parameters should be re-evaluated to take into consideration the presence of molybdenum. Also, a small-scale analysis of the heat transfer in the large gap between fuel discs and cladding might reveal the impact of the thin-gap approximation on the measured molybdenum temperature. Such an analysis would benefit from a set of out-of-pile experiments with corresponding rod slices heated by means of laser beams, as already applied in the POLARIS facility of the JRC Karlsruhe.

Additionally, the analysis performed in this paper constitutes a first example of how the advent of modern fuel performance tools with multi-dimensional capabilities can help the design and interpretation of separate-effect experiments. For instance the design of a similar disc irradiation campaign in the High Flux Reactor in the Netherlands in the frame of the INSPYRE project for advanced fuel creep studies relied on the combined application of the TRANSURANUS code and a separate general-purpose tool for the 2D temperature calculations. A multi-dimensional fuel performance code is thus perfectly suited for the interpretation of such disc irradiations and for designing future experiments in new experimental reactors such as JHR. In view of the required computational costs, OFFBEAT can also be considered for coupling with a conventional fuel performance code like TRANSURANUS, in

Table 3
Time-averaged quantities for the calculation of the Biot number for Test 1.

Stack	Average h, W/(m^{2}K)	Average k, W/(mK)	r, m	B	$\Delta T_{100\%}$
S11	4.82E+03	123	0.00413	1.62E-02	~35
S21	1.65E+03	115	0.00408	5.87E-02	~140
S31	7.12E+02	103	0.00401	2.76E-02	~430
S41	3.33E+02	90	0.00388	1.44E-02	~750

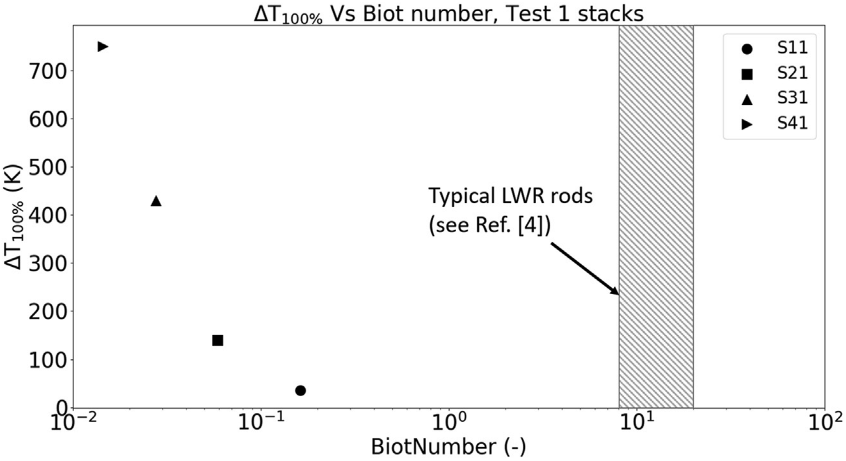

Fig. 10. Impact of eccentricity against Biot number for the stacks from Test 1. The impact of eccentricity is measured as $\Delta T_{100\%}$, i.e. the average temperature difference between the simulations with 100% and those with 0% eccentricity.

a similar way as the NUFORM3D module was coupled with the FRAPCON code [26]. The results of inexpensive 1.5D full-length simulations would help define more realistic initial and boundary conditions for computationally heavier multi-dimensional transients on a reduced geometry. This would allow the investigation of in-pile experiments with complicated irradiation histories addressing specific local phenomena such as PCMI, extending the analysis even for medium and high burnup.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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