MONK10: BURNUP CREDIT CAPABILITY

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ABSTRACT

MONK® is a Monte Carlo code for nuclear criticality and reactor physics analyses. It has a proven track record of application to the whole of the nuclear fuel cycle and is well established in the UK criticality community. Furthermore it is increasingly being used for reactor physics analysis (as described at ICNC 2011), which makes it an ideal tool for burn-up credit (BUC) calculations. Throughout the paper, example calculations based on a PWR are presented to illustrate the capabilities of the MONK10 code.

In order to account for the spatial dependence of material burn-up it has in the past been necessary to design models with multiple regions and materials specifically to allow material burn-up to vary spatially. This is very labour intensive and difficult to change at a later stage. A new code version, MONK10, was released last year which includes the facility to allow a burn-up (BU) mesh to be superimposed on an existing model in order to account for the spatial dependence of the burn-up. This facility is used to consider the effect of radial position of a fuel element in a PWR core on BUC.

Additionally, a thermal hydraulics (TH) mesh can be used to specify region dependent temperature. This, coupled with the fact that MONK10 also incorporates an on-the-fly Doppler broadening methodology facilitates the modelling of spatially dependent temperatures for the different components. A TH mesh is used to superimpose a temperature profile on a PWR based model and the effect of this on BUC is considered. The burn-up modelling in MONK has been benchmarked against the ANSWERS WIMS deterministic reactor physics code.

Once the burn-up calculation has been completed and the depleted fuel compositions determined the spent fuel compositions can be transferred into a model of a storage facility or transport flask in order to perform burn-up credit analysis. The initial model is usually described as the donor model and the latter model as the receiver model. This transfer is carried out using the COWL option which allows the specification of a material in the receiver model based on the material's composition in a given BU mesh cell from the donor model. This allows compositions and densities to be transferred and also allows user specified adjustments to be made. For example, this could include omitting the fission products in order to estimate their contribution to burn-up credit and provide an actinide-only analysis. The effect of excluding appropriate nuclides is presented.

An example of how the ANSWERS SPRUCE code can be used to quantify uncertainty in a BUC calculation is also presented.

KEYWORDS
Burn-up credit, reactor physics, criticality, MONK10

1. INTRODUCTION

MONK10A[1] was released in 2014 as a major update to the UK nuclear industry standard Monte Carlo nuclear criticality and reactor physics code. In a burn-up credit (BUC) calculation, the time dependent burn-up of a donor model is calculated. The material compositions are then transferred to a receiver model of a transport flask or storage facility and k-effective for this receiver model is calculated. This release introduced a large number of new features including mesh based burn-up and run-time Doppler broadening. These features, coupled with the COWL option for transferring material compositions from a donor model to a receiver model, make MONK10 an ideal tool for burn-up credit calculations.

In this paper, we present an overview of the techniques and analysis that it is possible to perform in MONK10 for burn-up credit. In particular, we look at:

- The inclusion and exclusion of nuclides during transfer to the receiver model.
- The effect of spatially-dependent burn-up on burn-up credit analysis.
- The effect of superimposing a temperature profile over the core using MONK's thermal hydraulics (TH) coupling.
- The effect of geometric tolerances on burn-up credit.

2. MODEL CONSTRUCTION

Two donor models were used for the work in this paper. The main donor model used was a model of a PWR core based on the Hoogenboom and Martin benchmark[2]. For the uncertainty analysis, an infinite array of fuel pins (with the same geometric and material properties as the pins in the Hoogenboom and Martin benchmark) was used. The initial fuel material in the benchmark model has a composition approximately equivalent to a burn up of 24,000 MWd/t. This was used as the initial starting composition for all calculations in this paper.

2.1. PWR Model

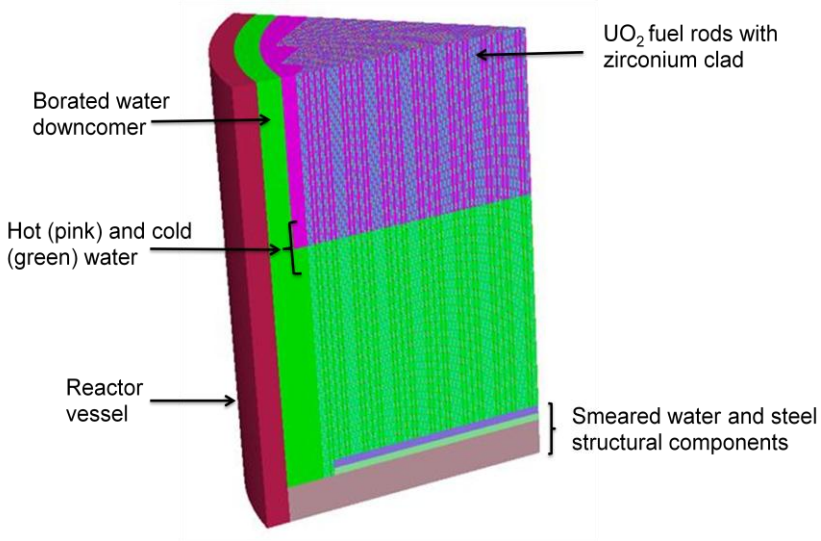

Figure 1 Visual Workshop image of 1/8th core PWR model based on the Hoogenboom and Martin benchmark.

The Hoogenboom and Martin benchmark consists of a homogenous PWR core with all fuel assemblies having the same construction. The original benchmark specifies not to take advantage of any symmetry of the model; however, for the purpose of this work, as the model has 8-fold rotational symmetry, a 1/8th core model was used. This model is shown in Figure 1.

The benchmark model is designed to be run at 293.6 K with the concentration of boron in the coolant modified to ensure that the model is close to critical. The water in the original model is further assumed to have different densities in the bottom and top parts of the model. For the purpose of looking at the effects of temperature on burn up credit analyses, the model was modified so that the fuel was at a constant temperature of 950K and the clad at a temperature of 655 K. These are average values for the fuel and clad temperature derived based on a standard heat transfer model as detailed in e.g. [3].The temperature of the water was taken to be 598.95K in the top half of the reactor and 565.05 K in the bottom half[4]. The concentration of boron in the coolant was then modified to keep the model close to critical.

2.2. Fuel pin model for uncertainty analysis

The fuel pin model for the uncertainty analysis was taken to be an infinite lattice of pins with the same composition, background coolant properties and active length as the unmodified benchmark model. The model was run at 293.6 K as the main purpose of this study is to show how changes in k-effective in the receiver model can be attributed to changes in the donor model. This model is described in more detail in Section 6.

2.3. Receiver model for BUC analysis

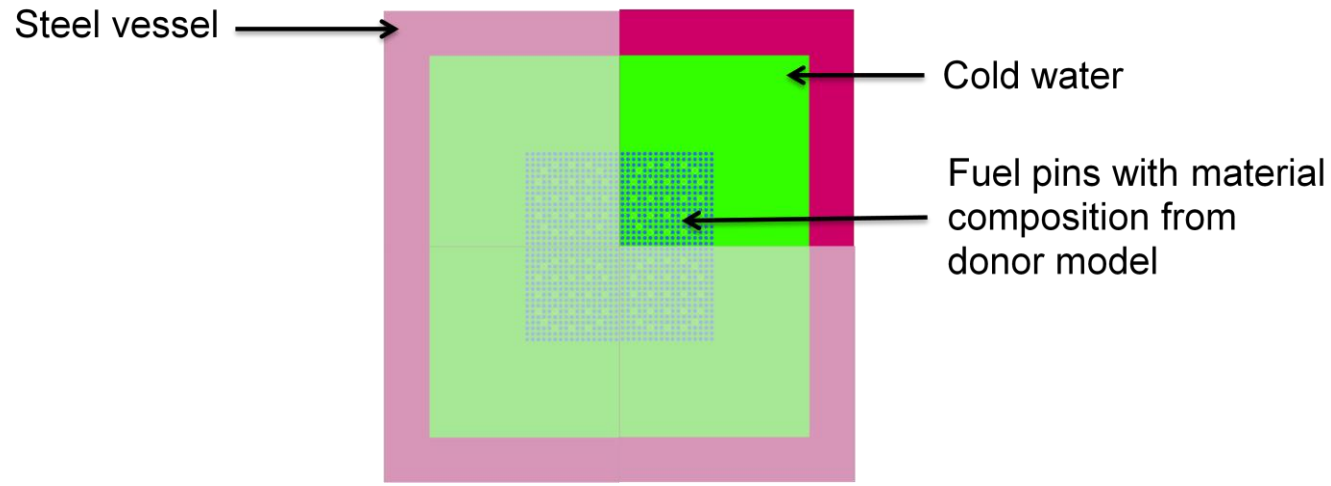

Figure 2 Receiver model for BUC analysis.

The receiver model used for the BUC analysis consisted of one fuel element inserted into a steel container and flooded with water. Reflected boundary conditions were then applied to two of the sides in the *x* and *y* directions to give a total of four fuel elements in the model. For the compositions of fuels transferred into this model from the donor model, the approximate value of k-effective is 0.65.

3. INCLUSION AND EXCLUSION OF NUCLIDES

MONK10 includes the ability automatically to include and exclude user-specified nuclides when transferred from the donor model to the receiver model. This facility may be used during burn up credit studies to exclude certain actinides or fission products. For example, excluding certain neutron absorbing fission products will yield conservative results..

The US NRC has issued ISG8[5] on Burn-up Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transportation and Storage Casks. They recommend inclusion of the following nuclides:

- For actinide only burn-up credit: ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am.
- For actinide and fission product burn-up credit, the addition of: ^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{147}Sm, ^{149}Sm, ^{150}Sm, ^{151}Sm, ^{152}Sm, ^{143}Nd, ^{145}Nd, ^{151}Eu, ^{153}Eu, ^{155}Gd, ^{236}U, ^{243}Am, ^{237}Np.

A fuel element from the radial mid-point between the center and edge of the core was transferred into the receiver model retaining only the nuclides from each of the two lists. The same element was also transferred into the receiver model without excluding any nuclides to provide a baseline for comparison. The effect of including the actinides only is clearly seen to be conservative and the effect of including some neutron absorbing fission products is also as expected.

Table 1 Including a subset of nuclides when transferring material composition to the receiver model

Nuclides included	k-effective	Standard deviation	Difference/ pcm
All	0.66125	0.00039	0
Specified actinides only	0.73237	0.00043	7112
Specified actinides and fission products only	0.69446	0.00041	3321

4. EFFECTS OF SPATIALLY-DEPENDENT BURNUP

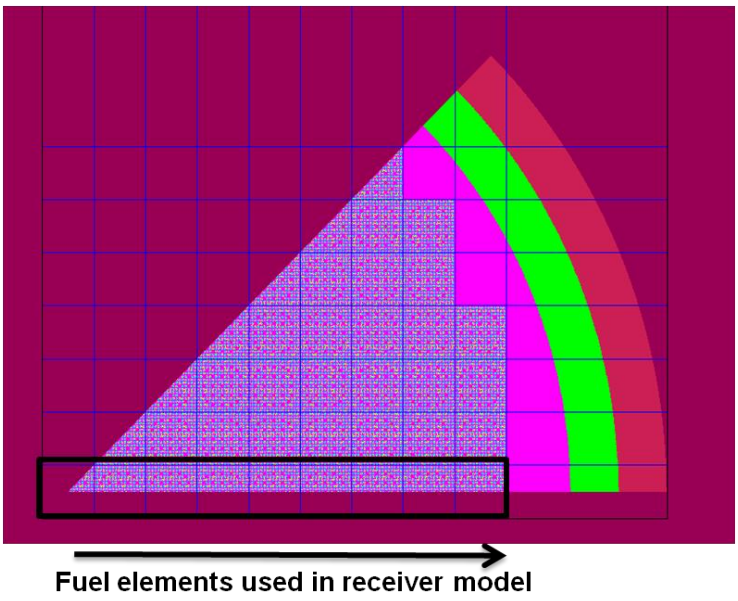

Figure 3 Burn-up mesh superimposed on PWR model showing the range of axial fuel elements that are considered as part of the spatially-dependent burn-up study

MONK allows the superposition of a BU (burn-up) mesh over the problem geometry to subdivide artificially the problem in to multiple regions. This allows the user to simply analyse the burn up in multiple regions and to use the materials from these regions in the receiver model as part of the burn up credit study. The BU mesh used for this model is shown in Figure 3; note that the mesh is also subdivided axially. The resulting number densities in the central axial slice of various important nuclides that are important for burn-up credit analysis (^{235}U, ^{238}U, ^{241}Am) are shown in Figure 4 below.

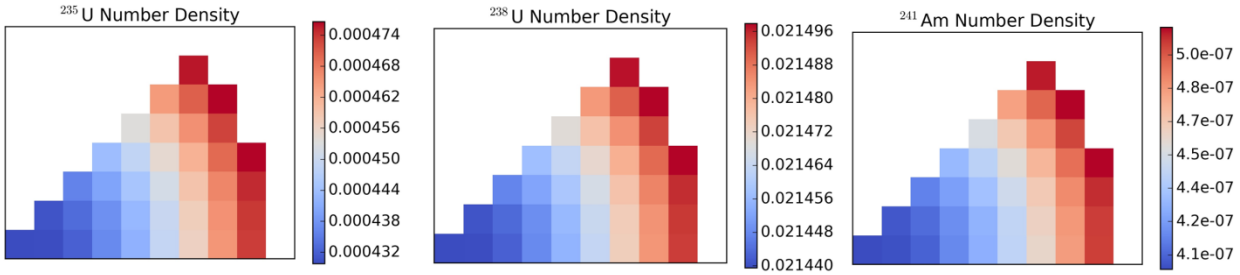

Figure 4 Post irradiation number densities of some important nuclides in each fuel element

The compositions from each of the nine fuel elements shown in Figure 3 were transferred into the receiver model detailed in section 2.3. The variation in receiver model k-effective is shown in Figure 5.

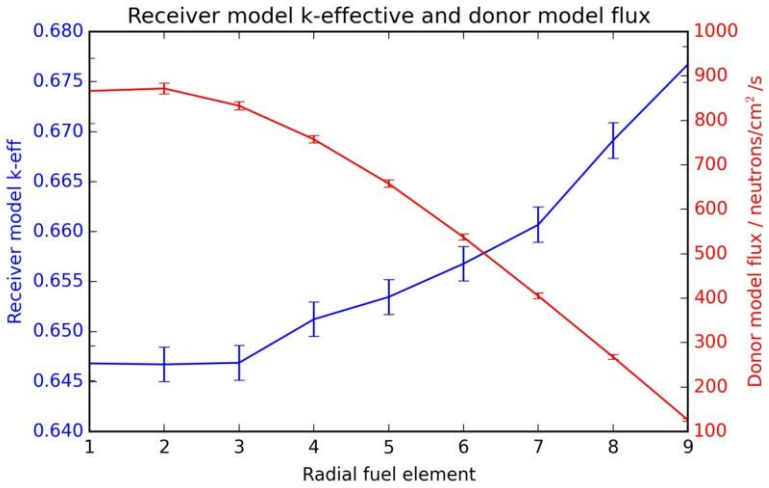

Figure 5 Variation in receiver model k-effective with changing radial fuel element, showing one group flux averaged axially over the fuel element. Errors are 3 standard deviations.

5. EFFECTS OF TEMPERATURE PROFILE

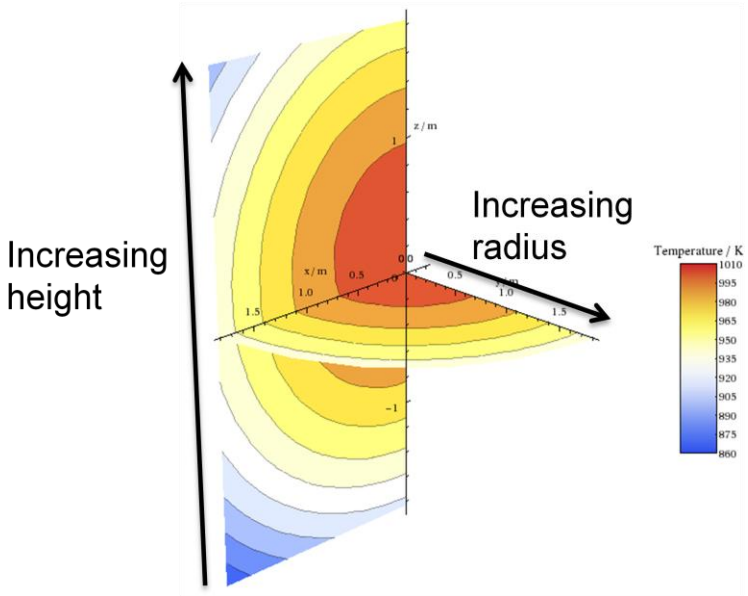

Figure 6 Fuel temperature profile showing axial and radial variation in temperature!

As described above, the original donor model has the fuel at a constant temperature of 950 K and the clad at a constant temperature of 655 K. A single group diffusion model, with cross-sections taken from [6], was used to derive an approximate flux profile for the reactor and a basic heat transfer problem was solved to generate an appropriate temperature profile for the fuel and the clad. This temperature profile is shown in Figure 6. It was applied to the MONK model using the thermal hydraulics coupling

methodology described in a previous ICNC paper[7]. The basic summary of the methodology is that it allows the superposition of a TH mesh onto the model. The output from a thermal hydraulics code can then be read in by MONK and artificial materials are then automatically created and used to apply appropriate temperatures to each of the materials in each of the mesh cells.

Table 2 Overall k-effective with and without superimposed temperature profile

Case	k-effective	Standard deviation / pcm
Constant temperature	1.013558	9
Temperature profile	1.034974	9.3
Difference / pcm	2141.6	12.9

The addition of the temperature profile was observed to make a difference of approximately 2,000 pcm to the calculated k-effective (see Table 2). Note that the increase in k-effective is due to the decrease in migration length and subsequent decrease in leakage. The number densities after burn up were also observed to differ, as shown in Figure 7. In particular, the calculated number density of ^{235}U for fuel elements near the center of the core post burn-up was observed to differ by 1.35% percent after the addition of the temperature profile.

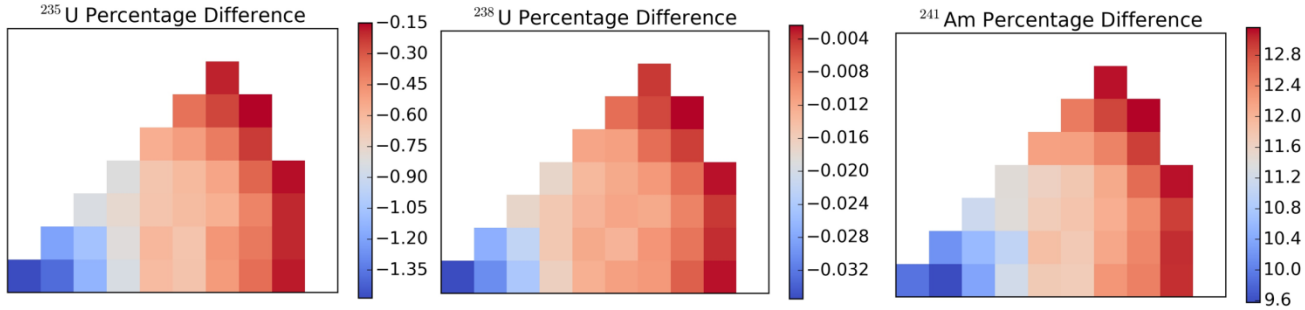

Figure 7 Percentage change in number density of a selection of nuclides due to the applied temperature profile.

Both burn-up calculations were carried out assuming the reactor power was 1100 MW. The effect on the receiver model k-effective of the addition of the temperature profile is shown in Figure 8. Note that the addition of a temperature profile can have an effect on the receiver model k-effective of the order of 1,000 pcm for fuel elements near the center, with the difference tailing off for elements at the edge of the core, as would be expected from the difference in normalized flux.

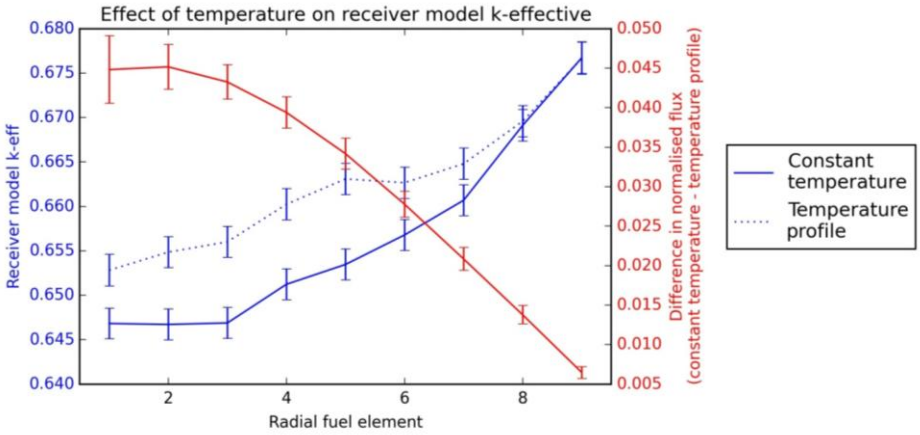

Figure 8 Effect of applying a realistic temperature profile on k-effective for the receiver model

6. UNCERTAINTY QUANTIFICATION

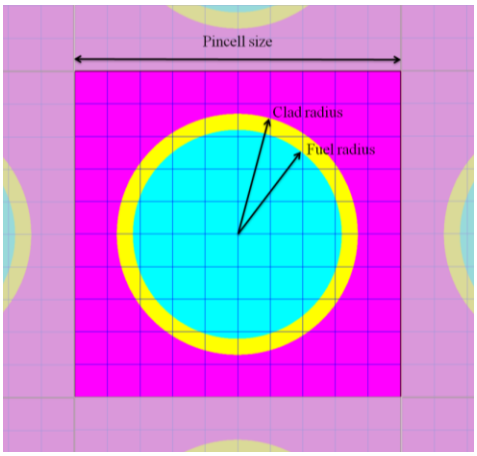

Figure 9 Infinite array of fuel pins showing geometric properties varied in uncertainty study

The model chosen for looking at uncertainty quantification is a single fuel pin infinitely tiled in the *x* and *y* directions with finite extent in the *z* direction. The model used, along with the superimposed BU mesh, is shown in Figure 9. The ANSWERS code SPRUCE was used to generate and run a family of 15 different burn-up calculations varying a variety of pin properties stochastically. SPRUCE can also be used for more general uncertainty quantification, including quantification of uncertainty due to nuclear data (for more details see [8]). The following properties were varied uniformly:

- the fuel radius;
- the clad radius;
- the pincell size;
- number density of ^{235}U.

Latin Hypercube sampling was used to ensure adequate coverage of the sample space. The fuel pins were then put into fuel elements in the same receiver model as used for the standard PWR model.

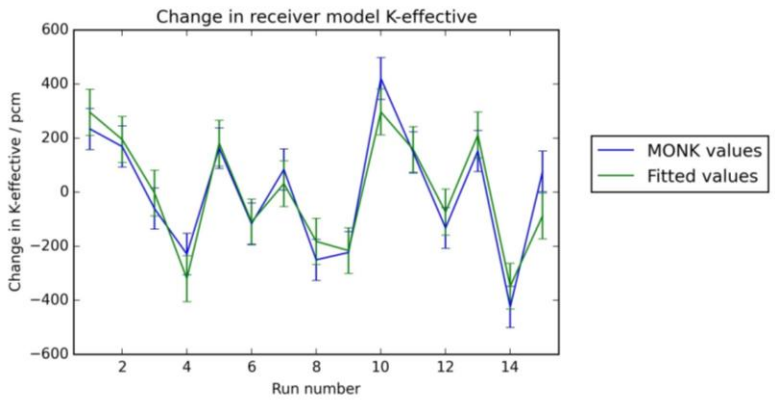

Figure 10 Change in k-effective of receiver model for each run showing validity of linear fit

k-effective was calculated and a linear fit to the perturbations used to generate sensitivity coefficients describing the sensitivity of the receiver model k-effective to the varied input parameters. The maximum percentage variation in any given parameter was 3% and Latin Hypercube sampling was used to ensure that the parameter space was adequately covered. The difference between the MONK calculated values and the linear fit is shown in Figure 10. This graph shows that, for the model and range of parameter values considered, the change in the receiver model k-effective is adequately represented by linear dependence on the change in geometric parameters, with the sensitivity coefficients given in Table 3. These coefficients show that, for example, a 1% increase in fuel radius would be expected to cause a 16.3 pcm increase in k-effective. Note that the change in 235U number density has a greater effect on k-effective than the fuel radius because varying the fuel radius also changes the fuel to moderator ratio.

Table 3 Calculated sensitivities of receiver model k-effective

Parameter	**Fuel radius**	**Clad radius**	**Pincell size**	**Number density ^{235}U**
Sensitivity / pcm/%	16.3	-0.0104	24.5	110

7. CONCLUSIONS

MONK10A was released in 2014 as a major update to the UK nuclear industry standard Monte Carlo nuclear criticality and reactor physics code. This release has a wide variety of features that make it an ideal tool for burn up credit analysis. In this paper, we have shown how some of these features can be used to carry out a detailed burn up credit analysis.

We have demonstrated:

- The use of the COWL option in MONK to transfer material compositions to a receiver model, including the transfer of a subset of the nuclides produced during burn up in order to carry out a conservative analysis. For the example calculation presented, we found the receiver model k-effective was approximately 7,000 pcm higher than transferring all materials when only actinides were transferred and approximately 3,000 pcm higher when only actinides and fission products were transferred. This development allows for more general BUC cases to be made, including demonstrating conservatism of some of the assumptions.

- The use of MONK's BU (burn-up) Mesh to look at burn-up on a fuel-element by fuel-element basis in a model of a PWR core, demonstrating the difference in receiver model k-effective as a function of radial position in the core. For the example case presented, the difference in receiver model k-effective was approximately 3,500 pcm over the radius of the core. This development considerably enhances the use of MONK as a tool for BUC analysis as it greatly facilitates the creation of burn-up credit cases involving materials from different parts of a core and taken from different times in the burn-up cycle.
- The use of MONK's TH (thermal hydraulic) mesh to superimpose a temperature profile on the reactor also demonstrating the use of Doppler broadening on-the-fly. Differences of up to 1,500 pcm in receiver model k-effective were observed for the case presented. The use of a TH mesh greatly facilitates looking at temperature effects and thermal hydraulics coupling, not just for BUC analyses but also for more general reactor physics analyses.
- The use of the SPRUCE code to carry out an uncertainty analysis on the sensitivity of the receiver model k-effective to variations in the geometric and material properties of the donor model. This development allows quantification of the effect of manufacturing tolerances on the receiver model k-effective and allows for far more accurate quantification of uncertainty on the results of BUC calculations and other criticality calculations. It is interesting to note that, over the range of parameter values considered, the behavior is accurately captured by a linear fit.

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