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Successful Application and Development of a Burn-Up Credit Methodology for Use in a UK Transport Criticality Assessment

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ABSTRACT

Rolls-Royce has obtained United Kingdom regulatory approval to transport fuel assemblies using a Burn-Up Credit (BUC) method. We believe this is the first time a transport criticality assessment using a BUC method has been obtained from a UK regulator. Extant transport criticality assessments for previous core designs have employed the Fresh Fuel Approximation (FFA), which involves taking credit for Start of Life (SoL) fissile loading and discounting the presence of burnable neutron absorbers. The FFA is straightforward, pessimistic and well known to the regulator. However, due to the relatively high SoL fuel loading of the latest assembly design the criticality criterion ($k_{eff} < 0.95$) could not be met using FFA. Therefore, a BUC method was developed to take credit for burn-up of fuel and neutron absorbers in order to use the extant transport flask (without the need for expensive re-design). The Regulator approved the transport licence application after the following steps were re completed:

- Reviewed applications of BUC in the IAEA SSR-6 regulations and associated guidance;
- Developed a method to exploit the operating profiles of the reactors where assemblies were installed;
- Evaluated candidate codes that can perform both depletion and criticality calculations;
- Perform robust validation using
    - Reactivity measurements and criticality control rod positions taken from through-life measurements;
    - In-Core Flux Measurements from the prototype core;
    - Isotopic composition measurements from Post Irradiated Examination measurements from irradiated assemblies of similar design;
    - Independent comparisons of bounding calculations were performed by the regulator using other well established criticality codes.

This paper describes how the above steps were carried out to reach this successful outcome.

INTRODUCTION

For many years, Rolls-Royce has applied for and obtained UK regulatory approval for transporting spent fuel assemblies in a package called the Used Fuel Flask (UFF). The spent assemblies were from a "one shot" core installed in an operational platform plant. In a "one-shot" core the newly manufactured fuel assemblies were brought together to form the core. During operational life of the core, the fuel assemblies remained in place, they were not moved to other locations in the core nor replaced.

The FFA assumes that each spent fuel assembly has the fuel loading at Start of Life (SoL), that is when newly manufactured and before it is irradiated, and no credit is taken for the presence of neutron absorber. The FFA is very pessimistic in terms of reactivity, widely used in the UK industry, well understood by the regulators and the SoL fissile loadings are easily verified.

The customer's requirements for a core with a longer operational life meant that the latest operational design of the assemblies has higher SoL fuel loading with more neutron absorbers to keep the initial reactivity down. With these fuel assemblies and extant flask design, it was not possible to use the FFA to keep the neutron multiplication constant, k_{eff}, below the UK regulator's requirement of $k_{eff}<0.95$ without expensive redesign of the UFF, more frequent transport of partially filled flasks or request for the criticality criterion to be relaxed. Implementation of one or more of these alternatives would also threaten the customer's programme requirements.

Rolls-Royce has developed a Burn-Up Credit (BUC) method where credit is claimed for the burn-up of the fuel and the presence of neutron absorber. With a BUC, the fall in the reactivity due to the reduction in the loading of fissile nuclides as the fuel is burned up is claimed to demonstrate that the maximum k_{eff} is below the criticality criterion. The licence application to transport spent assemblies with the latest operational design using the BUC methodology has been submitted and approved by a UK regulator.

There has been a licence application in the UK where a form of "inverse" BUC was used to transport spent MAGNOX assemblies (Reference 1). In this method, also known as "peak reactivity" BUC, burn-up calculations were performed to determine the build-up of actinides like plutonium during plant operation. The increase in reactivity due to the build-up of these nuclides was added to the reactivity for fresh fuel. However, we believe the approval of our transport licence application is the first time UK regulatory approval has been given where a 'true' BUC method has been employed.

BUC METHODOLOGY

Rolls-Royce has developed and applied the BUC method in the following stages:

1. Review of the transport regulatory requirements if BUC is to be employed for transport applications;

2. Develop a BUC methodology route that exploits the operational profile of one-shot cores with the hope of simplifying the criticality assessment;
3. Carry out the criticality assessment;
4. Validate the BUC method.

The literature review of regulatory requirements started with the International Atomic Energy Agency (IAEA) regulations (Reference 2) and the associated advisory guidance (Reference 3). The IAEA regulations state that the transport requirements are the same whether BUC is employed or not and that it is for the criticality assessor to decide how to represent the composition of the fissile material.

The literature review examined documents issued by the UK Working Party on Criticality (WPC) (Reference 4) and international standards (Reference 5, 6). These papers discussed which nuclides (actinides, neutron absorbers or fission products) should be included or excluded in the criticality assessment. In summary, all nuclides that have a positive contribution to the reactivity should be included. Another common theme was that credit should not be taken for the presence of selected nuclides if the validation of the depletion code did not include these nuclides. If the presence of any neutron absorber was claimed, the assessor should consider the possibility that the maximum reactivity could be well after SoL because the fall in reactivity due to the burn-up of fissile material may be less than the increase in reactivity due to the burn-up of the absorbers in the spent fuel assemblies.

An important issue is the treatment of the axial and radial profiles of the isotopic composition of spent fuel assemblies. This is of importance if two-dimensional (2D) depletion codes are employed and the necessity of creating very reactive but non-physical representations of assemblies where the composition of fuel is taken from different assemblies. There are a number of schemes in the literature to derive axial and radial profiles that are demonstrated to be bounding in terms of reactivity. Two schemes are described in References 7 and 8.

The BUC method developed by Rolls-Royce exploits how their assemblies are used in the core. This is because all the fuel assemblies in a core are installed before power operation and they are all removed at End of Life (EoL) of the core. Each assembly therefore shares the same operational power history and cooling times.

The basic method is to perform the burn-up calculations using a detailed representation of the core in a 3D depletion code. The isotopic compositions of the fuel and neutron absorber are then transferred to a 3D criticality code model of the same assembly in the UFF. The criticality code calculates the k_{eff} values that are used in the criticality assessment.

In order to calculate the local burn-up of fuel and neutron absorber, each assembly in the model of the core is divided into numerous small regions. The depletion code assigns a burnable material to each region to keep track of the local burn-up of fuel and neutron absorber.

In this methodology it is necessary that a mechanism is available to correctly map the location of each burnable material from an assembly in the depletion model to the same location in the assembly in the criticality model. This mapping avoids the requirement to create non-physical representations of a spent assembly with axial and radial profiles that are bounding in terms of reactivity. This is justified because of the way the core is operated and that whole, intact fuel assemblies are transported.

Rolls-Royce has used the same code for both the depletion and criticality calculations. The code uses the Monte Carlo method to simulate the transport of neutrons and photons in a system. A feature of the code is its scalability because it has been designed to represent the assemblies in a core in great detail. It has an efficient memory management system (necessary to keep track of the local burn-up in every region of the core), neutron tracking routines and optimised parallel processing, allowing the code to run numerous burn-up calculations and calculate quantities such as the local flux in reasonable timescales. The code has a 3D depletion solver with a predictor-corrector method to improve the accuracy of each burn-up calculation.

The code uses a library based primarily on ENDF/B-VII.1 nuclear data. The nuclear data has been tabulated for a number of material temperatures. The user can either request using nuclear data at the nearest tabulated temperature or use a scheme to interpolate the data between the nearest temperatures.

The BUC method consisted of the following steps:

1. Create a 3D model of the core for the code;
2. Run depletion calculations for the core using the standard operational power history for this core;
    a. The depletion is divided into a number of timesteps. Each timestep consists of a burn-up calculation for a period of time at power. After one or more timesteps (the frequency is decided by the user) the isotopic concentration of each burnable material is written in a file;
    b. Each timestep will include a specific core power, material temperatures, shutdown periods, the temperature and density of the coolant and the control of parameters needed to keep the reactor critical.
3. The files containing the isotopic compositions are retained for use in the criticality calculations;
4. Create a 3D model of the UFF transporting the spent assemblies from the core;
5. Select an assembly from the core and transfer the compositions of the burnable materials to each assembly in the UFF using the files retained in Step 3;
    a. It is assumed that the same assembly is placed in each assembly location in the UFF. In these calculations the UFF is fully laden.
    b. Rolls-Royce has taken credit for the presence of actinides and neutron absorbers but has excluded the presence of any fission products.
    c. Calculate the k_{eff} using a scenario which is bounding from previous criticality assessments using the FFA.

    d. This is repeated for every assembly in the core. The assembly that produces the largest value for the k_{eff} is taken as the most reactive assembly and is taken forward to the rest of criticality assessment.
    e. An infinite array of UFFs was modelled.
    f. In the criticality calculations water at 4 °C and at one bar was used because this is the maximum density of water at atmospheric pressure and will therefore maximise neutron moderation.
    g. The k_{eff} calculated by the code typically has a standard deviation of approximately 0.0002.
6. Sample calculations were performed with a mixture of fuel assemblies in the UFF to confirm that an UFF containing just the most reactive assembly found in the previous stage is still bounding.
7. Sensitivity calculations were performed where fission products were included to demonstrate that taking credit for the presence of just actinides and neutron absorbers is pessimistic and the degree of pessimism quantified.
8. Perform the rest of the criticality assessment assuming that the most reactive assembly found earlier is in each assembly location in the UFF.
    a. The calculations performed here are the same calculations expected in any criticality assessment required in Reference 2 where the FFA is employed.
    b. The calculations included the effect of flooding in the UFF, movement of any neutron absorbers, damage to the assemblies, orientation, assemblies clustering towards each other.
    c. The maximum value of the k_{eff} for each condition of transport was demonstrated to be well below the criticality criterion.
9. A calculation was run with the most reactive case found in the previous stage but using FFA. The results of the calculation using the code employed by Rolls-Royce were compared against the results of the same calculation using another independent code called MONK to demonstrate that the codes produces similar values for the k_{eff}.
10. Validation of the BUC method (discussed later in this paper).

CRITICALITY ASSESSMENT USING THE BUC METHODOLOGY

The k_{eff} was calculated for each assembly in the UFF to find the most reactive assembly. In the calculations, credit was only taken for the burn-up of nuclides in the fuel and nuclides in the neutron absorbers. A sensitivity study was performed on the most reactive assembly where the four fission products commonly used in BUC were also included. The four fission products were ^{103}Rh, ^{133}Cs, ^{143}Nd and ^{149}Sm. These four fission products are stable and their number densities will not be affected by the length of the cooling time. The variation of the k_{eff} as a function of lifetime (represented by the timestep number) is presented in Figure 1.

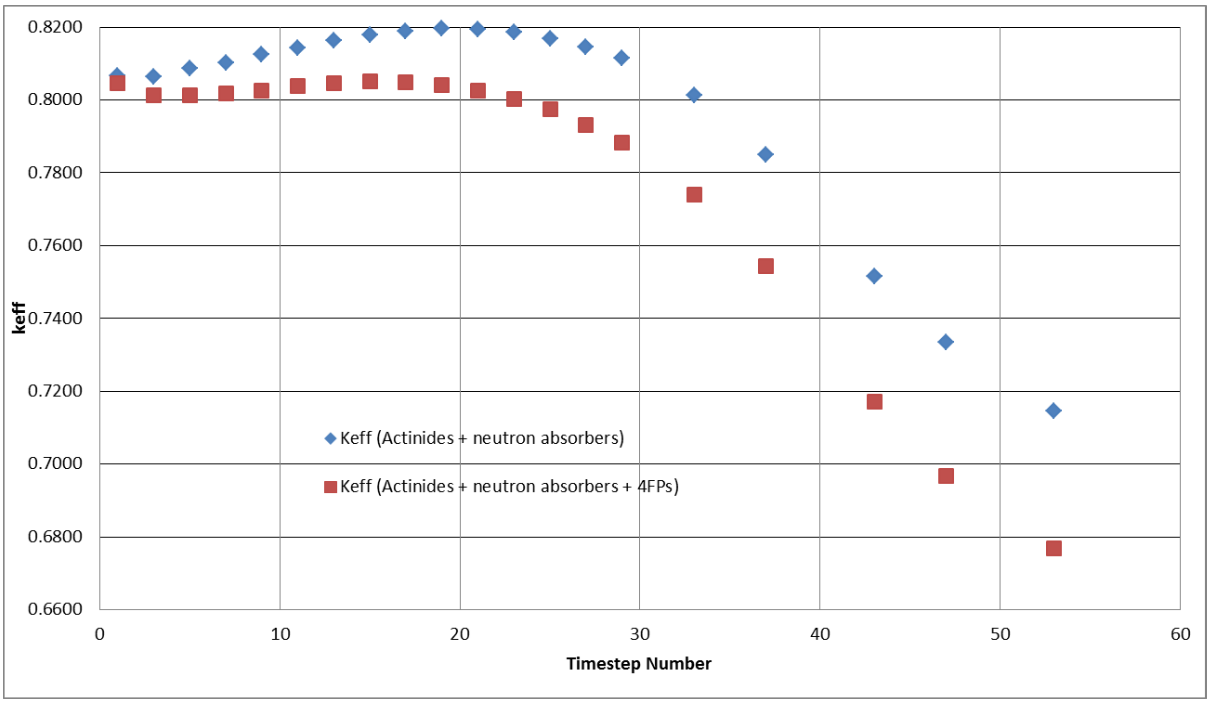

Figure 1 - Variation in the keff for the most reactive assembly as a function of lifetime

The results show that the maximum value of the k_{eff} is about 0.82 which is well below the criticality criterion. The EoL for the assembly is slightly beyond the lifetime where the k_{eff} is at its maximum. As expected, the addition of the four fission products decreases the reactivity. The fall in reactivity increases with lifetime as the fission products accumulate. The results show that taking credit for just the actinides and nuclides from the neutron absorbers is a pessimistic assumption.

The rest of the criticality assessment took credit for the presence of the actinides and nuclides from the neutron absorbers corresponding to core EoL. The calculations were the same as those required in Reference 2 where the FFA was employed. The worst case k_{eff} for all conditions of transport was 0.8397 after the addition of three standard deviations. This was still well below the criticality criterion.

The worst case was repeated using the FFA with the code and an independent Monte Carlo code, MONK Version 10A. MONK is a well-established code widely used in criticality assessments in the UK. The BINGO collision processor using the JEFF3.1.2 nuclear data library was used in the MONK calculation. The results are presented in Table 1. Note all results include the addition of three standard deviations.

Table 1 - Comparison of calculations performed by the code against MONK

Case	K_{eff}
Code used by RR - worst case – BUC employed	0.8397
Code used by RR - worst case – FFA employed	0.9785
MONK - worst case – FFA employed	0.9716

The results show that when the FFA is employed, the criticality criterion is exceeded but the system is still sub-critical. There is reasonable agreement between the code used by Rolls-

Royce and MONK. The difference is most likely due to the different nuclear data libraries employed.

Sensitivity calculations were performed where the loading of ^{235}U in the assembly was varied. The results show that just under twice the ^{235}U loading was required to exceed the criticality criterion. The results are presented in Figure 2.

A calculation was performed where nuclides from the neutron absorbers and fission products were excluded. The results showed that the k_{eff} (including the addition of three standard deviations) was 0.9193. This result showed that although a successful criticality assessment could be made with taking credit for just the actinides, it would be excessively pessimistic. This is because it can be demonstrated that the neutron absorbers are present when the assemblies are transported in the UFF.

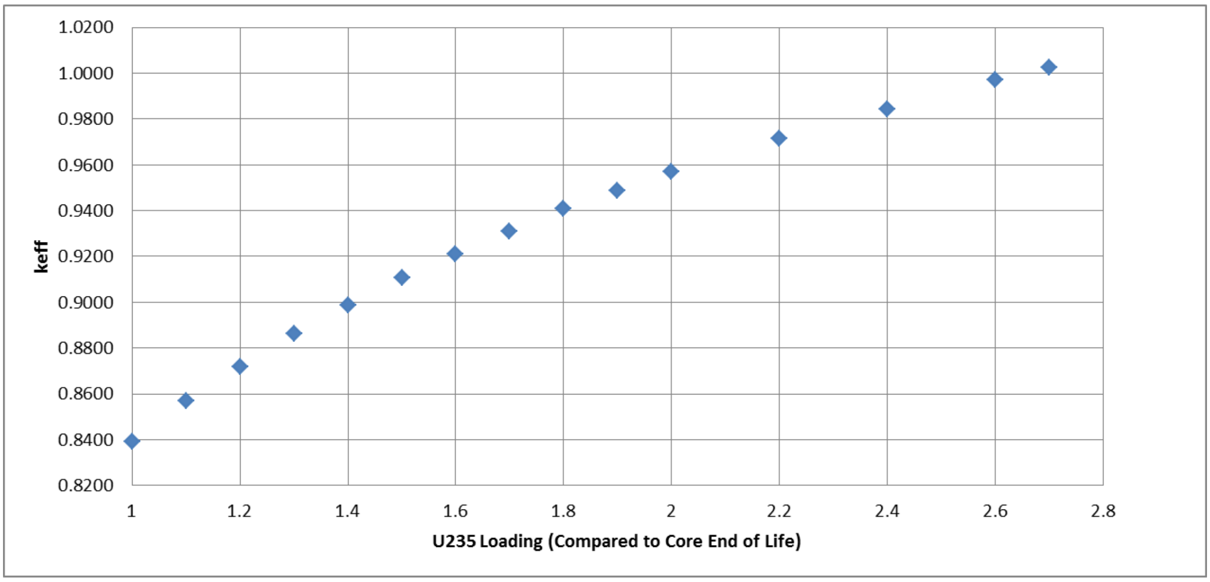

Figure 2 - Variation in U235 loading in the assembly

VALIDATION OF THE BURN-UP CREDIT METHODOLOGY

The validation of the BUC methodology consists of two stages. The first stage was to demonstrate that the code is performing the whole core burn-up calculations correctly. The validation for this stage was by calculation of the k_{eff} against through-life measurements of the critical core from physics trials. However, the UFF is not transporting fuel assemblies in a core configuration. In the second stage, validation was carried out to demonstrate that local burn-up of fuel and neutron absorbers in individual assemblies were correctly calculated by the code. The validation was against ICFM from a prototype core where the assemblies are of identical design to the assemblies transported in the UFF. The flux shape is a function of local fuel and poison burn-up so validation against these measurements provided evidence that the code is calculating local burn-up correctly. Isotopic measurements from PIE of a core of similar design to the assemblies transported in the UFF is included as part of this stage of the validation. The use of measurements of concentrations of uranium nuclides and neutron absorber nuclides can be used to determine the size for any allowance on the k_{eff} due to differences between calculation and measurement.

VALIDATION OF WHOLE CORE BURN-UP

Calculations were carried out using measurements of parameters needed to achieve criticality recorded from physics trials of a core. The assemblies transported in the UFF were removed from this core. The results are presented in Figure 3. The results show that the critical k_{eff} calculated by the code is close to unity for all the physics trials, providing evidence that the whole core burn-up is correctly calculated. These measurements were taken at the operational temperature and pressure for the plant which is above the temperature where the assemblies in the UFF will be transported. A number of measurements of the parameters needed to achieve criticality were performed where the temperature of the moderator in the plant was reduced. The results from these cooldown measurements during the physics trial for the plant closest to core EoL showed that the critical k_{eff} remained close to unity and there was no discernible trend for a large range in temperature.

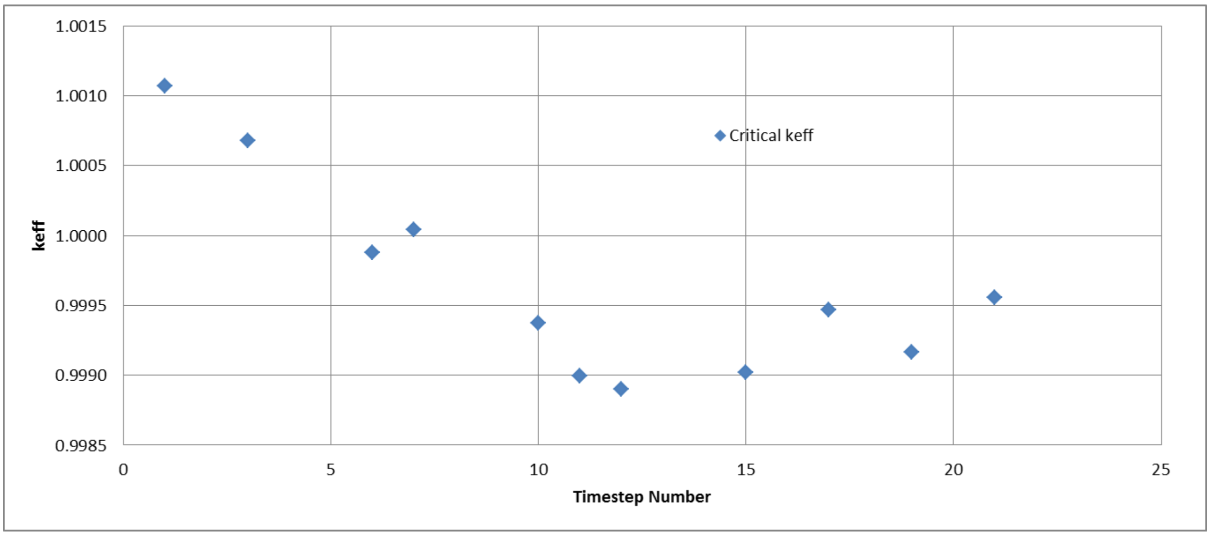

Figure 3 - Critical k_{eff} Taken from Physics Trials Measurements

VALIDATION OF INDIVIDUAL ASSEMBLY BURN-UP

The validation of whole core burn-up was based on measurements where the assemblies are put together to form the core. However, the arrangement of the assemblies in the UFF is different from the arrangement in the core. In addition there is no restriction on the placement of the assemblies in the UFF. Therefore, the validation of fuel and poison burn-up at the local assembly level was required.

One validation method was to compare the local neutron flux profile from ICFM against calculation of the local ^{235}U fission rate profile. ICFM consists of inserting metal wires containing fissile material into a number of assemblies in a prototype core. The prototype core uses assemblies of identical design to the assemblies being transported in the UFF. The wires were then irradiated for a period of time and the axial profile of the activation of each wire was measured using high resolution gamma detectors. ICFM trials were carried out throughout the life of the core and when the plant is operated under high and low power. The shape of the flux profile is dependent on the local compositions of fuel and neutron absorber. The measurements shown in Figure 4 were from the region where the most reactive assembly was located.

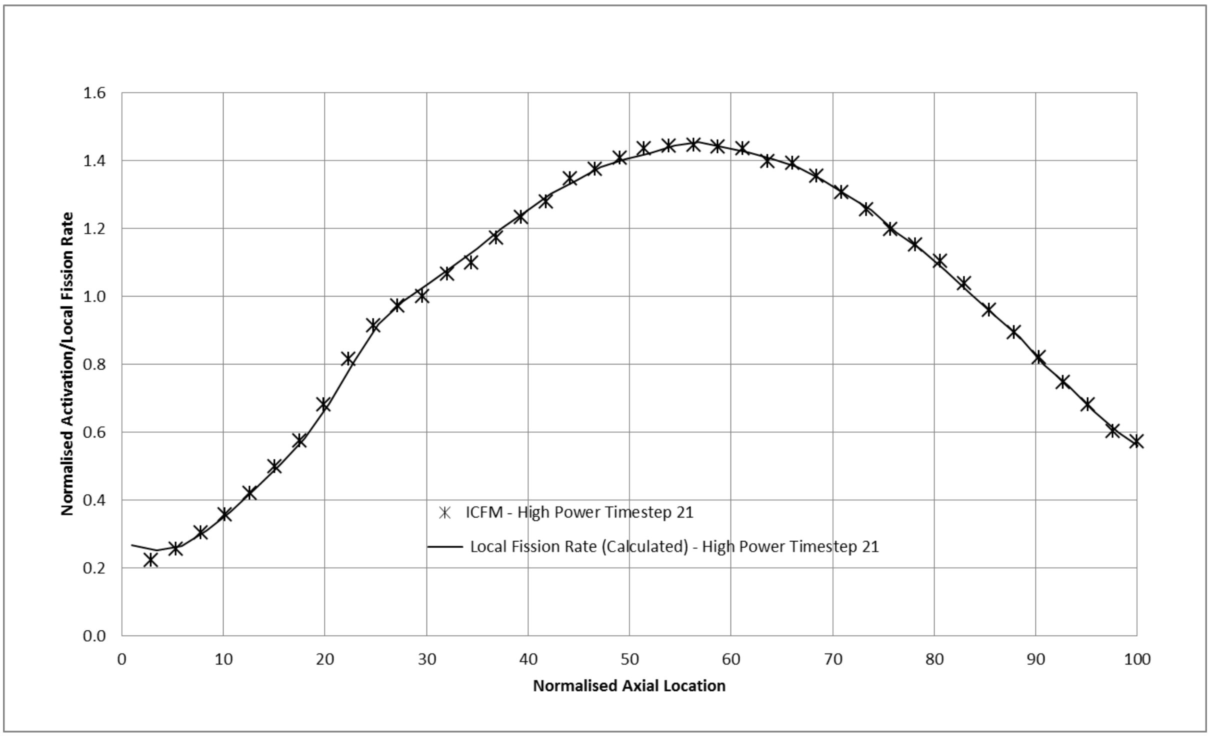

Figure 4 - ICFM Trial High Power Timestep 21

The results show that there is good agreement between the ICFM activation profile and calculation of the local fission rate.

The problem with using the shape of the flux profile is that it is difficult to convert differences between experiment and calculation into an allowance for reactivity.

The next validation method compared the isotopic composition from chemical measurements of PIE samples. The assemblies where the PIE measurements were taken share many of the design features with the assembly transported in the UFF. The following graphs present the experiment to theory ratios for the ^{235}U concentration and the atomic ratio of ^{236}U to ^{235}U.

The results show that there is a wide variation in the distribution of the E/T ratios for the mass of ^{235}U in the PIE samples. However, the E/T ratio for most samples lies in the range 0.9 to 1.3. It should be noted earlier in Figure 2 that the mass of ^{235}U in the assembly needs to be doubled to breach the k_{eff}<0.95 criterion. The outliers seen in Figure 5 are believed to be due to the friable nature of the irradiated samples leading to uncertainty regarding the actual mass of the sample. A more reliable measure of fuel burn-up is the atom ratio of ^{236}U to ^{235}U. Figure 6 shows there is better agreement between atomic the ratio of the uranium nuclides calculated by the code and measurement.

A similar set of PIE samples taken from the neutron absorbers was also used to validate the code. There is good agreement between experiment and calculation.

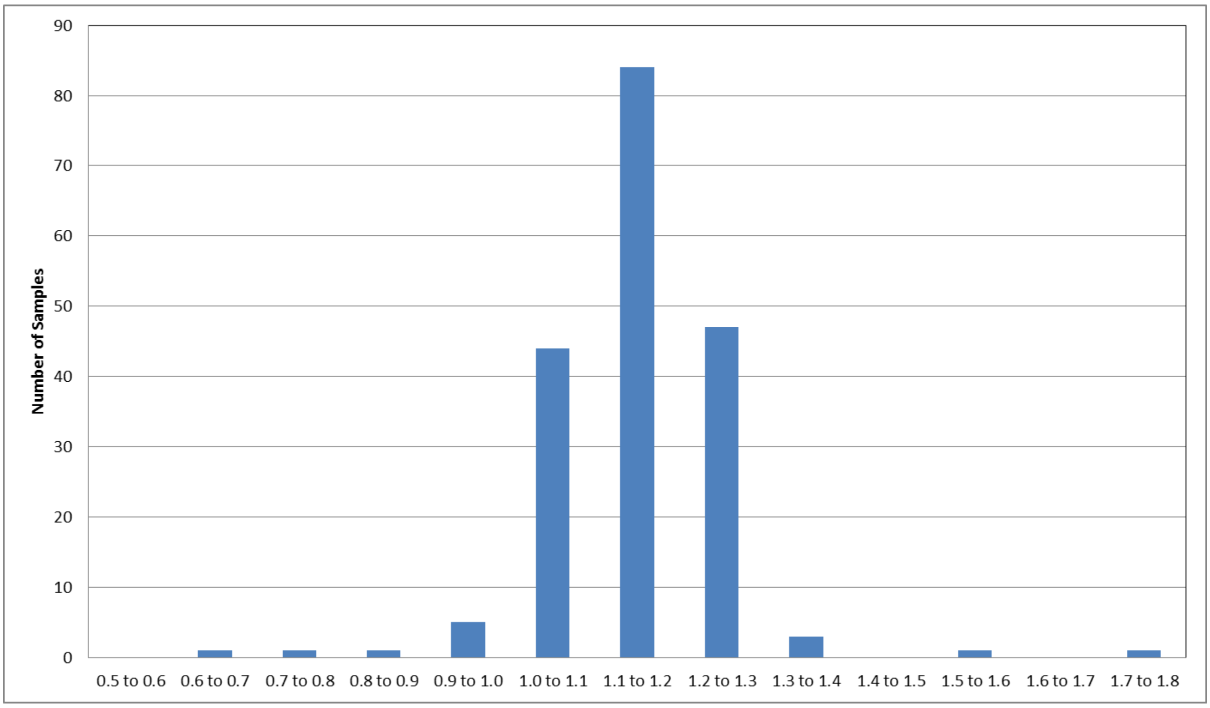

Figure 5 - Distribution of E/T for Mass of ^{235}U of PIE Samples

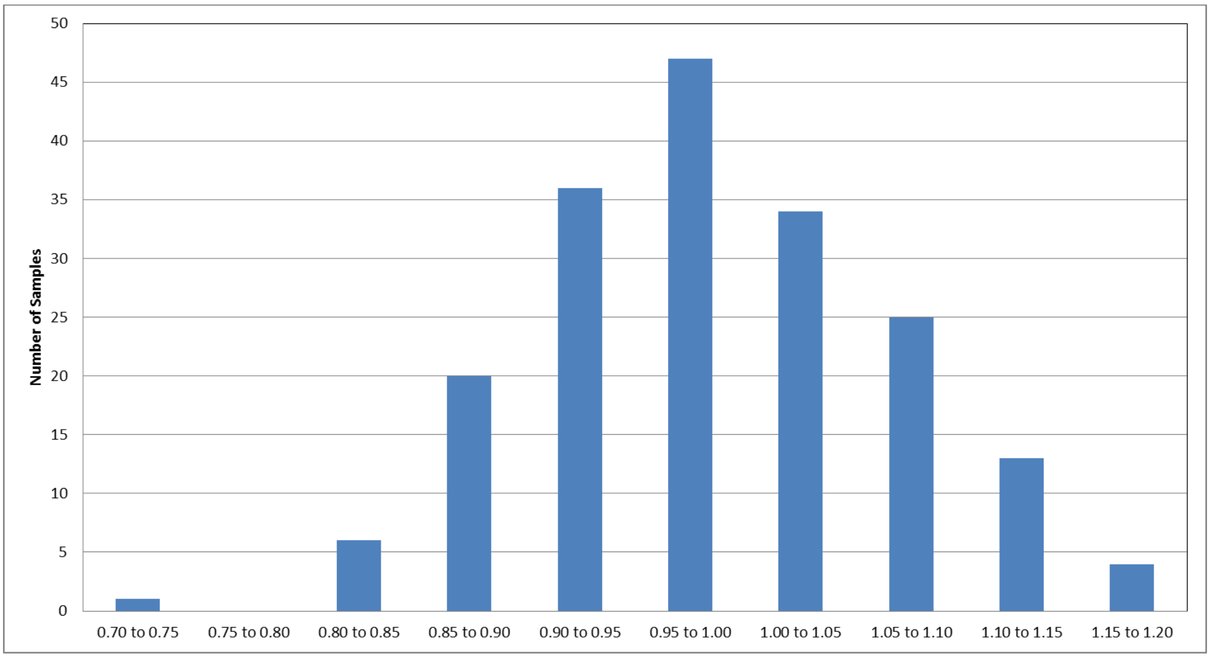

Figure 6 - Distribution of E/T Ratios for the Atomic Ratio of ^{236}U to ^{235}U for the PIE Samples

CONCLUSIONS

Rolls-Royce has developed and employed a method where credit is taken for the burn-up of fuel and neutron absorber. The methodology took advantage of how the spent assemblies were used in the core. By taking credit for actinides and neutron absorbers large margins to criticality (k_{eff}~0.82) were obtained. A robust validation programme was employed to demonstrate that whole core and local burn-up was correctly calculated by the code employed by Rolls-Royce.

The BUC methodology was used in the licence application to transport the latest operational design of spent fuel assemblies. This is the first time a UK regulator has approved a licence application where credit is taken for burn-up of fuel and neutron absorber.

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