Application of MCBEND to PBMR Shielding Analysis

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Shielding analysis of an early design of Pebble Bed Modular Reactor (PBMR) has been carried out using the Monte Carlo code MCBEND. The issues of concern were damage to the core barrel and RPV, activation of the core barrel, RPV, top plate and bottom plate and also burn-up of boron in the control layer underneath the core. The analysis below the core was complicated by the presence of the de-fuelling chute which meant that multiplication had to be taken into account. The analysis of boron burn-up was particularly challenging and was tackled using a combination of MCBEND and the criticality code MONK in depletion mode.

The application of MCBEND to the shielding analysis of the PBMR is described, with particular attention being paid to the regions below the core.

INTRODUCTION

The Pebble Bed Modular Reactor (PBMR) is an advanced reactor design that is intended to operate at high temperature and is helium cooled, with graphite moderator. Fuel consists of graphite spheres that contain thousands of coated particles of uranium dioxide. The fuel spheres are fed into the top of the reactor, travel down through it and are then returned to the top of the reactor to repeat the cycle. There is a central reflector of graphite spheres which undergo the same process. Control rods are present in the side reflector and a boron carbide control layer is placed underneath the core. In the analysis presented here the reactor is assumed to operate at full power for 35 years.

Shielding analysis of an early design of Pebble Bed Modular Reactor (PBMR) was performed using the Monte Carlo code MCBEND(1). The code utilises flexible geometry and source modelling packages and uses a very fine representation of nuclear data (for example 13,193 energy groups for neutron cross-sections). In this work ENDF/B-VI data were used. The standard variance reduction method utilised by MCBEND is splitting/Russian roulette in space and energy together with source weighting. The importances are calculated using adjoint diffusion theory in an orthogonal mesh that overlays the problem(2). MCBEND utilises track length or collision density scoring in regions. A response library, based largely on the IRDF90 dosimetry file, is included with the code.

Analysis of boron burn-up included use of the criticality Monte Carlo code MONK(3) in depletion mode. MONK uses the same geometry modelling package as MCBEND and in depletion mode utilises a 69 energy group WIMS library.

SIDE, TOP AND BOTTOM REFLECTORS

Issues of concern in the side, top and bottom reflectors were radiation damage to components such as the core barrel and RPV and dose-rates at reactor shutdown arising from activation of these components. An accurate model of the reactor was created and used for the analysis. Streaming paths to the top reflector were included. Figure 1 shows part of the top reflector model and Figure 2 shows part of the bottom reflector model.

The damage calculations for the side and top reflectors were straightforward, utilising the inbuilt importance generator, MAGIC, to drive the variance reduction using splitting and Russian roulette. Damage to the core barrel, RPV, top plate and other components was shown not to be a problem due to the large amount of graphite present.

Activation rates in the barrel, RPV and top plate were calculated in the same way as was used to calculate damage rates. The activationrates were then processed to give the activation sources at the end of the proposed reactor life, with an assumed shutdown time of 2 days. Further MCBEND calculations, using these activation sources, were then performed to calculate the resulting gamma-ray dose-rates in access locations.

These were found to be large (for example around 1 Sievert/hr from activation of the core barrel and RPV in the region between the RPV and the biological shield) if no boron shielding were present. The main contributor was cobalt activation. The effect of using layers of boron carbide in both the side and top reflectors was then calculated. Whilst the boron carbide effectively stopped thermal neutrons entering the core barrel, RPV and top plate, the activation rates were then dominated by fast neutrons that pass through the barrel and are moderated within either the RPV or the top plate. Thus the reduction in activation dose-rates, although large, was not sufficient to meet dose-rate criteria. For example, even filling the space between the side reflector and the barrel with boron carbide reduces the dose-rate between the RPV and the biological shield to 3 milliSievert/hr compared with a criterion of around 30 microSv/hr. Since there are structural and thermal problems associated with the use of boron carbide in these positions the use of boron carbide was abandoned at this stage. An alternative solution would be to use local gamma-ray shielding to reduce personnel access dose rates outside the RPV and top plate following shutdown.

The analysis of the bottom reflector is complicated by the presence of the de-fuelling chute, through which the fuel spheres pass before being returned to the top of the reactor. Since the k-effective value in the chute will be considerably lower than unity the source in the chute cannot be calculated easily using reactor physics methods. However, multiplication in the chute is significant and needs to be taken into account. MCBEND has a facility by which fission is treated explicitly (rather than as absorption, which is the default). This was used to calculate the fast flux in the de-fuelling chute, taking multiplication into account. A fixed source was then set up and adjusted until it produced the same fast flux. This fixed source was then used for the analysis. This technique was necessary to ensure accurate modelling of the fission source within the de-fuelling chute together with converged results for determining activation within the components in the lower parts of the reactor.

Following the additional step, calculations of damage and activation rates were carried out in the same way as for the side and top reflectors. These showed that damage would not cause problems but that dose-rates arising from cobalt activation would again be significant. The use of boron carbide shielding around the de-fuelling chute was observed to reduce activation rates and hence activation dose-rates considerably, although they would still be rather high. Consequently, it was proposed that an external shield be used to reduce the activation dose-rates.

BORON BURN-UP

The PBMR design studied in this work included various boron components to assist with reactor control or for shielding. These were layers of boron carbide in the side and top reflectors and a layer of boron carbide pins underneath the core. The boron will gradually burn-up during the life of the reactor and an important issue is whether or not sufficient boron will remain at the end of the reactor's life. The region of most concern was the layer of pins underneath the core.

The presence of boron massively perturbs the thermal neutron flux in its immediate vicinity. The burn-up of the boron itself is therefore much less than would be predicted using reaction rates from MCBEND together with the non-perturbed flux. Consequently, a combination of MCBEND and the criticality code MONK was used to investigate this issue. MCBEND was used to calculate the $^{10}B(n,\alpha)$ reaction-rate on the surface of the pin in full PBMR geometry. Thus this calculation includes transport from the core to the pin and takes account of multiplication in the de-fuelling chute. It also includes the effect of the boron pin size and pitch on the surface reaction-rate.

The burn-up in a single boron pin is then calculated using the burn-up option of MONK. This option applies methods developed in the lattice code WIMS to the general geometry of MONK. The MONK calculation includes transport near and inside the pin and takes account of the variation of the boron density with burn-up. In the MONK calculation the reactor lifetime (35 years) is divided into a number of time-steps. These were chosen to be sufficiently small (0.333 years) such that the results were not sensitive to the time-step length. The burn-up rating was normalised such that the surface reaction-rate in the first time-step matches the MCBEND surface $^{10}B(n,\alpha)$ reaction-rate. The source spectrum was taken from the MCBEND calculation. The model includes the pin, which is divided into 1mm thick annuli with a thin 0.001cm layer at the outer surface. The $^{10}B(n,\alpha)$ reaction-rate and hence burn-up was calculated in each annulus. The number densities were then altered to account for the burn-up and the calculation repeated for each time-step.

Since the burn-up option is designed for burn-up of fissile material this is a novel application and as such a number of devices (to make it work in this situation) and checks (to make sure it is working properly) were necessary. The calculation requires some fission material to be present. This was placed far from the pin so that the burn-up does not affect the fission-rate. The reaction-rate and hence burn-up was normalised to the rating using the number of fissions which have occurred in the time-step. Percentage variation of the number of fissions between time-steps must be small so the number of fissions in each time-step must be reasonably large. The number of fissions in any time-step must not be much larger than those in the first time-step, otherwise the rating will be effectively too low.

The calculations showed that burn-up would not be a problem. In a 10mm radius boron pin the outer 1mm layer will be 87% burned , the next 1mm layer will be 8% burned and the burn-up inside 8mm radius will be negligible. However, the size, arrangement and composition of the boron carbide pins has a large effect on the $^{10}B(n,\alpha)$ reaction-rate at the surface of the pin so any alterations in design would require the burn-up analysis to be repeated.

CONCLUSIONS

The Monte Carlo codes MCBEND and MONK have been used to analyse an early design of PBMR. The main issues of concern were radiation damage, activation dose-rates and boron burn-up. For the boron burn-up problem a combination of MCBEND and a novel application of the depletion option within MONK was used.

REFERENCES

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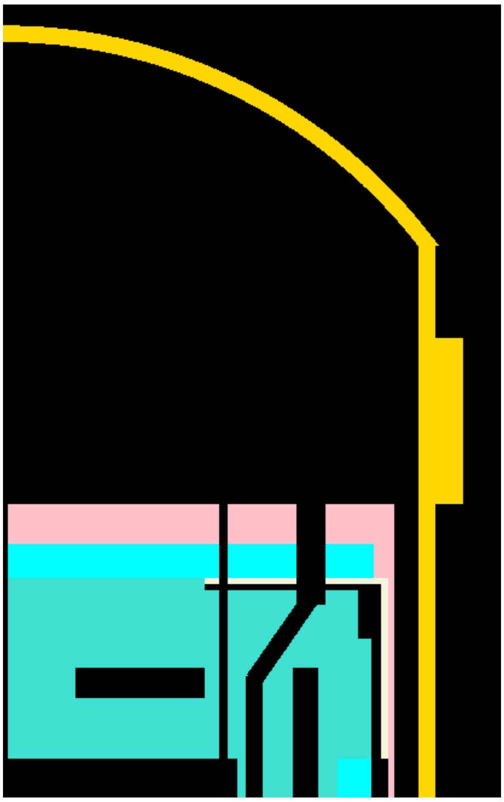

Figure 1 MCBEND Model of Top Reflector

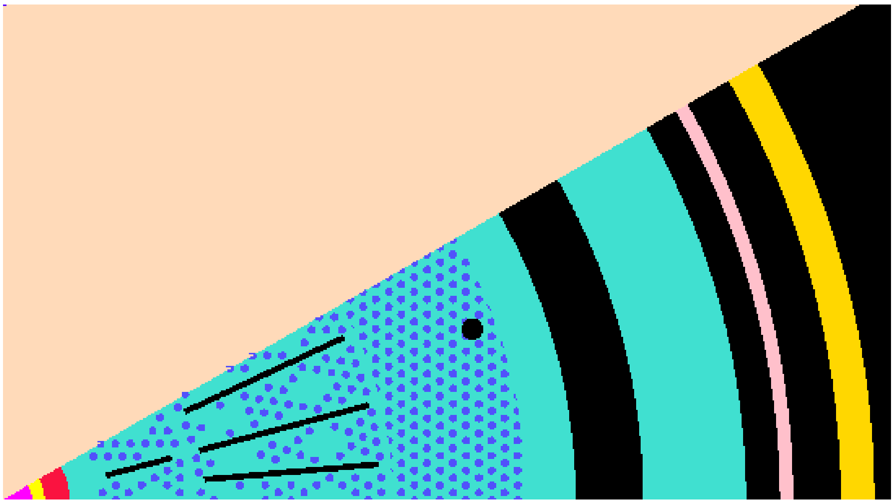

Figure 2 MCBEND Model of Bottom Reflector