Burnable Poison Calculations for Mk.III Gas-Cooled Reactor Systems

M. E. GUBBINS

1. Introduction

The use of burnable poison pins to prolong the life of the initial fuel charge is a possible feature in the design of a Mk.III Gas-Cooled Reactor for the British Nuclear Power Programme. The critical enrichment for unpoisoned fresh fuel is about 2.5%, whilst that for feed fuel to an equilibrium core is in the region of 5%. A low enrichment first charge would need rapid replacement with a consequent economic penalty. The extra control needed if a higher initial enrichment is used, is conveniently provided by using a poison which burns away so as to compensate for loss of reactivity with fuel burn-up. It can be shown that small cylindrical absorbing pins, which are virtually 'black' to thermal neutrons, have the desired burn-up characteristics. This is illustrated in Figure 1, which shows the variation of k_∞ with time for a typical Mk.III core, with and without poison pins.

The most likely poison to be used is gadolinium, since it presents the least problems under irradiation. The most important isotopes are Gd-155 and Gd-157 with 2200 m/sec cross-sections of 61,000 and 254,000 barns respectively. It is envisaged that small diameter poison pins made of gadolinium oxide diluted with aluminium oxide will be placed in vertical holes drilled in the graphite block. This paper describes a method of calculating the reactivity and burn-up history of the core which allows for a full interaction between fuel and poison, and caters for the special problems of poison burn-up.

2. Method of Calculation

The method of calculation chosen is the multi-cell option of the WIMSD code (1,2) combined with a modified burn-up routine designed to handle the burnable poison. The multi-cell model describes a core or reactor in terms of a number of different cell types, each being weighted in proportion to its frequency of occurrence in the system. The cells are effectively combined for a single collision probability transport solution by specifying the matrix of probabilities that a neutron leaving each cell type will enter a cell of the same or any other type. Two cell-types are used at present for the burnable poison calculations, these being a fuel element and a poison pin, each surrounded by a graphite annulus. This method has the advantage that it allows for interaction between fuel and poison, whilst avoiding a lengthy transport calculation in a complicated geometry.

To allow for differential burn up along the poison pin radius, the pin is divided into five annular regions. The special problems of poison burn-up are discussed in Section 3. Most calculations have been carried out with 10 energy groups, seven of which lie in the WIMS 'thermal' energy range, below 4 eV (97% of the gadolinium absorptions occur in this range). These numbers have been shown to be adequate by the comparative calculations described in Section 3. The number of groups could possibly be reduced. The WIMS cross-section library only contains data for the two high cross-section gadolinium isotopes. The other Gd isotopes, all of which absorb thermal neutrons, only become significant when Gd155 and 157 have burnt away. The reactivity worth of this residue has been estimated to be about 3% of the worth of the fresh pins.

It is necessary to justify the method described on two counts, first that the poison is burnt up correctly and secondly that the correct reactivity worth is predicted by the multi-cell model. This is done in the following two sections.

3. Poison Pin Burn Up

Owing to its very high thermal cross-section, the poison in a poison pin is heavily shielded and effectively burns up from the outside. Whilst the flux distribution within the pin changes with burn-up, the total absorption rate decreases slowly and approximately linearly with time. This is a very different state of affairs from a fuel region, where it can be assumed that the flux remains approximately constant and burn-up is exponential. The WIMS burn-up scheme had therefore to be modified to handle burnable poison regions. The main modification was to allow the flux distribution in the poison to be recalculated within the burn-up routine. A glance at Figure 2, which outlines the cycle of operations which make up a standard WIMS burn-up calculation, shows why this is necessary. In the standard calculation the spatial flux distribution can only be adjusted at the transport solution stage, so that each additional adjustment would demand an extra time-consuming and costly loop through the main cycle. In the modified routine an effective incident flux at the poison surface is calculated and this is assumed to remain constant between transport calculations, apart from spectrum modifications. The poison region fluxes are then recalculated from this incident flux at intervals during burn-up. A collision probability method is used with collision probabilities based on the current poison number densities.

The modified burn-up routine was tested by comparison with results from the code DECYGAD (3) in a version developed at Berkeley Nuclear Laboratories (4). This code can treat the simple problem of a rod burnt up under a constant incident flux. In the BNL calculations 99 thermal energy groups and 60 radial mesh points were used. In DECYGAD the flux at each radial mesh point is calculated from the mean optical path length to the pin surface. Results obtained for this simple problem with the modified WIMS burn-up routine, using equivalent data, showed good agreement with the results from the more detailed model. Assuming that the reactivity worth of a pin is proportional to the absorption rate in the pin, the WIMS-DECYGAD reactivity discrepancy was less than 5% of the initial worth of the pin (about 20 Niles) throughout the pin life. Variations in the number of groups and regions showed that five spatial regions in the pin and seven thermal energy groups were quite adequate.

4. The Multi-Cell Calculation

When using the multi-cell method, the user faces the problem of determining the cell-to-cell transfer probabilities. For a uniform flux distribution round the boundary of each cell these probabilities can be estimated simply in terms of the cell surface areas. The best approximation to this situation is obtained by associating with each cell an amount of graphite proportional to the absorptions in that cell. There is then on average zero net current at the cell surface. Thus for a design in which about 10% of all neutrons are absorbed in the poison during its lifetime, the poison cell incorporates 10% of the graphite. This somewhat crude recipe has been tested by comparing the results with those from a collision probability solution for a more exact geometry using the WIMSD 'PIJ' option. The results are shown in Table 1 and refer to a start of life situation.

6. Summary

A method of calculating the reactivity and burn-up history of a Mk.III GCR system containing burnable poisons has been described. The method allows for poison-fuel interaction. Using the method it has been shown that burn-up of the poison under a constant incident flux can give errors of the order of 1-2 niles. A calculation using the method described will take about 50% longer than a straightforward fuel burn-up calculation in the same number of groups. The multi-cell approach has a potential for handling greater geometrical complexity.

It is intended to compare the method against experiment as soon as suitable experimental results become available.

General Reactor Physics Division,
Room 133,
Building A.32.
A.E.E. Winfrith.

9th February, 1971

References

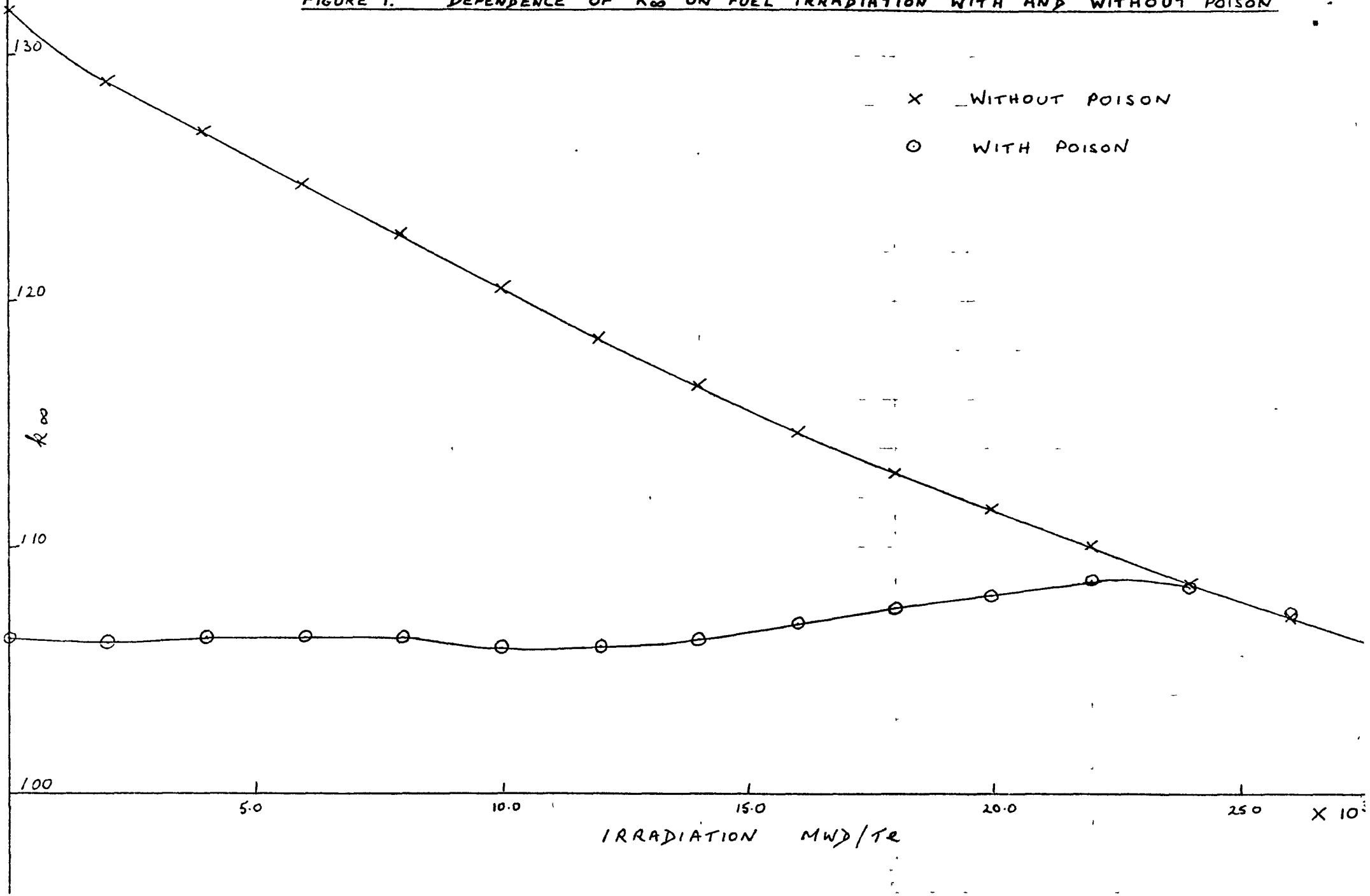
1. J. R. Askew et al. A General Description of the Lattice Code WIMS. JBNES October 1966, p.564.

2. M. J. Roth et al. The Preparation of Input Data for WIMS. AEEW - R 538.

3. P. Doscleve and P. Lacy. Shaped Burnable Poison Development Programme. ACNP - 64586, Allis Chalmers (1964).

4. R. M. Nunn. Private Communication.

FIGURE 1. DEPENDENCE OF K_∞ ON FUEL IRRADIATION WITH AND WITHOUT POISON



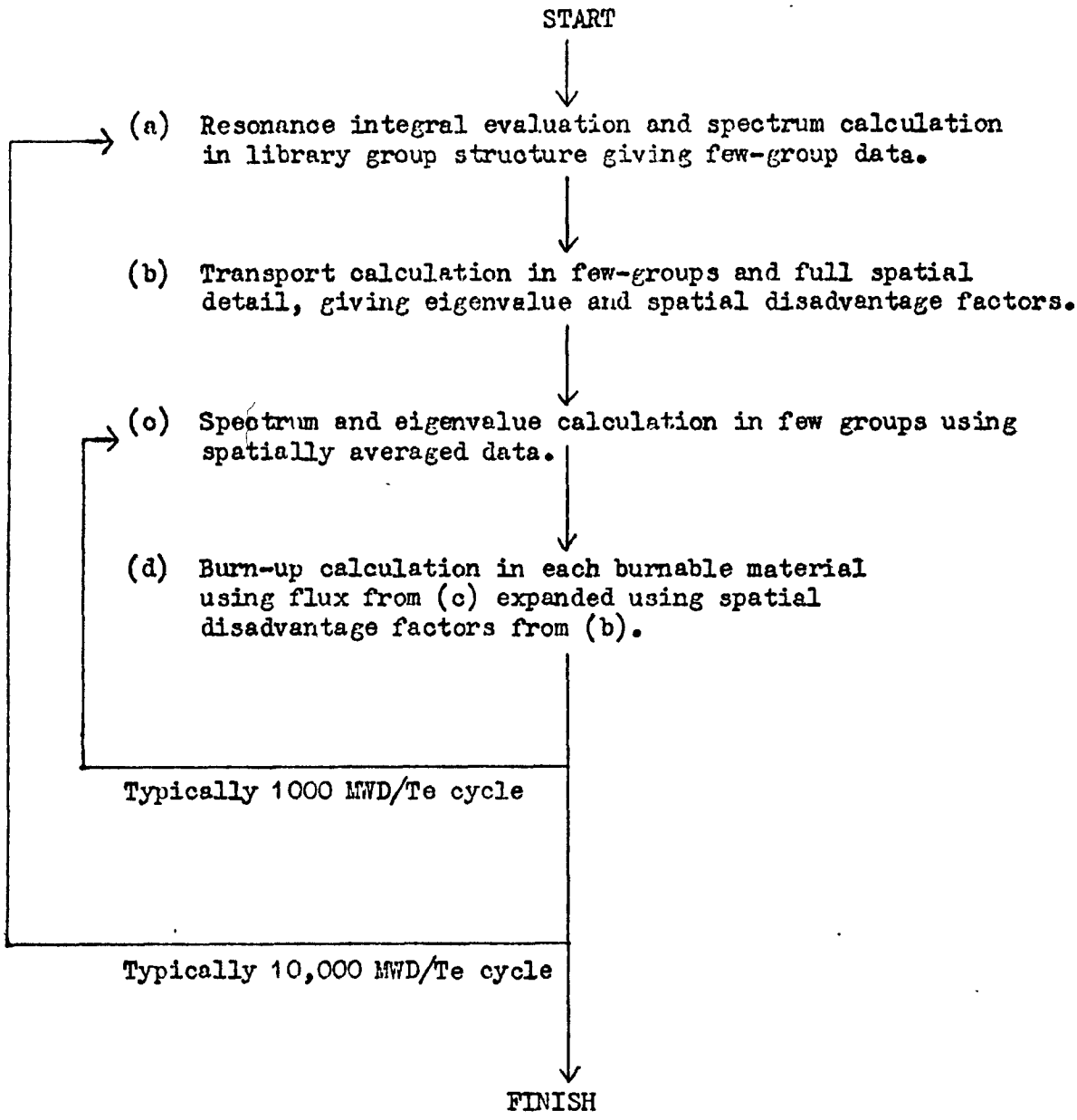


Figure 2. Cycle of Operations in a Standard WIMS Burn-Up Calculation

FIGURE 3 POISON BURN-UP FOR DIFFERENT INCIDENT FLUXES