# The Calculation of Resonance Capture in Granular Fuels

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## ABSTRACT

The methods used in the UK for the calculation of resonance capture in granular FTR fuels follow the long established path of determining a "geometric equivalence" which equates the resonance shielding to that in a homogeneous mixture of the resorance absorber in hydrogen.

Simple collision probability arguments, usually for the black limit, were used for AGR and SGHW systems. For granular fuel a 'grey' equivalence, convenient for numerical use, has been adopted, and the geometric solution performed in two ways: by a synthetic collision probability model which is rapid and appropriate for design work and by a Monte Carlo model which allows details of the grain lattice structure to be studied.

The results are in good agreement, and are shown to give good results compared with measured relative conversion ratios in the NESTOR stack experiments.

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## 1 Introduction

The basic model for equivalencing heterogeneous with hydrogenous resonance integrals is based upon the use of the rational approximation to approximate the fuel self collision probability

$$P(f\rightarrow f) \simeq \frac{\Sigma \bar{l}}{1+\Sigma \bar{l}} \qquad 1$$

This leads to a form for the absorptions in an asymptotic source which is identical in form to the hydrogenous equation.

$$\text{R.I.} = \text{Absorptions} = \int \Sigma_a \phi \, du \qquad 2$$

$$= \int \frac{\Sigma_a \Sigma_p}{\Sigma_p + \Sigma_t} \cdot du \qquad 3$$

where $\Sigma_p$ is the sum of the true potential scatter inside the fuel and a 'surface' term $\Sigma_x$. It will be seen from equation 1 that

$$\Sigma_x \simeq 1/\bar{l} \qquad 4$$

for a non-re-entrant body. A factor, a, is normally introduced to correct for the approximation inherent in equation 1 (the Bell factor), and a further term, $\gamma$, for interaction between adjacent rods in a lattice (the Dancoff factor). Thus

$$\Sigma_x = a\gamma/\bar{l} \qquad 5$$

Now equation 1 is exact at the black limit $\Sigma \rightarrow \infty$. As a first step to a numerical calculation for more complicated geometry, it was proposed in Reference 1 to replace this procedure by a direct calculation of the fuel self collision probability for a 'grey' fuel, whose cross-section was chosen to give a suitable approximation to the average resonance integral. Now

$$\overline{1 - P(f\rightarrow f)} = \int \Sigma_a (1 - P(f\rightarrow f))\, du \Big/ \int \Sigma_a \, du \qquad 6$$

$$= I(\Sigma_p)/I(\infty) \qquad 7$$

$$= \frac{\Sigma_p}{\Sigma_p + \Sigma} \qquad 8$$

hence we use $\bar{\Sigma} = \Sigma_p \left( \frac{I(\infty)}{I(\Sigma_p)} - 1 \right) \qquad 9$

In fact the proposals of Reference 1 are slightly more advanced than this, in that they propose to use a flux solution rather than the collision probabilities to determine the equivalence: this permits us to deal approximately with scattering materials of intermediate or large atomic weight outside the fuel. Although one of the codes described here uses this method, the differences are not important for typical HTR fuels.

## 2 Treatment of Energy

Before turning to the calculation of the collision probabilities for granular fuel, it is convenient, for completeness, to review briefly the energy treatment used in the WIMS [2, 3] code. This is basically a few group treatment in which partial resonance integrals for each group are converted into group constants in a manner consistent with the heterogeneity calculation to follow. For a simple two-region cell this results in a form

$$\Sigma_A(\text{fuel}) = \frac{I/\Delta U}{1 - I/\Sigma_p \Delta U} \qquad 10$$

Other corrections for the effect of absorption on the group removal cross-sections are also made for consistency. The resultant solution then allows for both spatial and energy depletion of the slowing down density, the former usually neglected in simple expositions.

Given these manipulations the quantity $I/\Delta U$ tabulated for each group is closely the classical resonance integral. It is deduced from exact solutions for homogeneous hydrogen/fuel mixtures by the inverse of the WIMS model.

Extensive comparisons between this model and detailed Monte Carlo studies have been published [4] for rod, plate and cluster geometries, where the Monte Carlo calculation has used identical cross-sections for the resonances.

In Reference 4 a slight adjustment to the calculated resonance integrals (a deduction of 0.9 barns) was recommended. We currently use 0.6 barns in place of this. The resultant resonance integral at 300°K is shown in Fig 2 plotted against $\sigma_p$. Note that for U metal the fuel contributes 2 b to $\sigma_p$, for $UO_2$ the corresponding figure is 9 b. These effects are typically negligible for HTR lattices where $\sigma_p \simeq 300$, $I \simeq 30$ barns.

## 3 The PPOCOL Collision Probability Method

Using an initial guess of the appropriate "effective scattering" cross-section of the fuel region, a value for the resonance integral of the fuel is calculated. From this an effective cross section for the grain is calculated and hence collision probabilities are synthesised for all regions of the cell, including the kernel and coating of the average grain. The neutron balance equation for the cell is then solved giving the flux in each region. From the flux distribution a new value of the effective cross section is computed. Iterations around this cycle continue until the difference between the last two consecutive values of the effective scattering cross section is less than a specified value. Finally the "Bell factor" is calculated.*

An accurate value of the fuel transport cross section is not required as this quantity is small in comparison to the effective absorption cross section; twenty per cent errors in magnitude of the scattering cross section resulting in errors of less than one per cent in the effective cross section of the fuel.

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*This relates to a feature of the WIMS code rather than to any physical effect. WIMS smears all "fuel" materials together into a rod of appropriate volume. This will include, in the present fuel design, an inner can, which thus contributes to the in fuel (volume) scattering rather than logically to the surface term in the resonance equivalence. The "Bell factor" modifies the outer surface contribution to give the required overall effective scatter within this peculiar model: it could be negative in extreme cases. This form is dictated by existing input facilities of WIMS: in principle $\Sigma_p$ would be input directly with a Dancoff factor of unity.

The iterative method used in PROCOL requires an initial guess at the effective cross section of the fuel ($\Sigma_p$), which is used in a modified form of the Gladstone resonance integral approximation.

$$I_p = 3.0\left(\frac{\Sigma_p}{N_8} + 9\right)^{0.415}$$

where $N_8$ is the number density of the fuel material

$\Sigma_p$ is the effective cross section of the fuel

$I_p$ is the resonance integral

This approximates to the one-group resonance integral for U-238 in WIMS to a sufficient accuracy for determining $\Sigma_p$ in the range $\Sigma_p \leq 500$. The method described here could be used in few-groups with the WIMS tabulation for each group being assessed directly.

The total cross section $\Sigma_T$ is then evaluated for the fuel from

$$\Sigma_T = \Sigma_a + \Sigma_p\left(\frac{I_\infty}{I_p} - 1.0\right)$$

where $\Sigma_a$ is the cross section of the fuel ignoring the absorption due to the resonant nuclide U-238.

$I_\infty$ is the resonance integral for an infinitely dilute mixture of U-238: approximately 280.0 barns

Because the grains are not isolated, but set in a matrix of material which has its own scattering properties, the matrix material is smeared into an additional spherical shell, around the fuel grain, whose volume is given by

$$V_{BM} = V_o\left(\frac{1 - f}{f}\right)$$

where $V_{BM}$ is the volume of the smeared matrix around the grain

$V_o$ is the volume of the grain

$f$ is the 'packing fraction' or volume fraction of fuel grains in the matrix

Having obtained the geometry of the fuel grain and associated matrix the spherical collision probabilities $P(i, j)$ for the various layers of the grain are calculated using the collision probability routine PROB[4]. The probability of a neutron born in layer i of the grain escaping from the grain is

$$P(i, s) = 1.0 - \sum_{i=1}^{J} P(i, j)$$

where J is the total number of layers comprising the grain. Hence the probability of a neutron born in any layer of the grain escaping to the surface is

$$P(o, s) = \sum_{i=1} P(i, s)$$

The probability of a neutron from outside the grain entering any layer i of the grain is given by $P(s, i)$ and values of $P(s, i)$ are obtained from values of $P(i, s)$ by reciprocity, thus assuming an isotropic inward flux distribution.

$$P(s, i) = \frac{4\Sigma_i V_i P(i, s)}{A_s}$$

where $A_s$ is the surface area of the grain

$V_i$ is the volume of the ith layer

Therefore the probability of a neutron from outside the grain suffering its next interaction in the grain is

$$\sum_{i=1}^{J} P(s,i) = \sum_{i=1}^{J} \left( \frac{4.0 \Sigma_i V_i P(i,s)}{A_s} \right)$$

$\sum_{i=1}^{J} P(s,i)$ is also assumed to equal the probability of that same neutron entering and interacting in an equivalent homogenised grain. Thus

$$\sum_{i=1}^{J} \left( \frac{4.0 \Sigma_i V_i P(i,s)}{A_s} \right) = 4.0 \left( \frac{V_o}{A_s} \right) \overset{o}{\Sigma}_t \; P(\overset{o}{\Sigma}_t, s)$$

where $\overset{o}{\Sigma}_t$ is the effective cross section of the homogenised grain.

$P(\overset{o}{\Sigma}_t, s)$ is the probability of a neutron born in the equivalent homogenised grain escaping to the surface.

An estimate of $\overset{o}{\Sigma}_t$ is made and $P(\overset{o}{\Sigma}_t, s)$ calculated using the PROB routine, the above identity then being calculated; if the balance is not within a set tolerance a new value of $\overset{o}{\Sigma}_t$ is calculated from

$$\overset{o}{\Sigma}_t = \sum_{i=1}^{J} \frac{\Sigma_i V_i P(i,s)}{P(\overset{o}{\Sigma}_t, s) V_o}$$

The new values of $\overset{o}{\Sigma}_t$ are used to repeat the iteration until the required accuracy is obtained.

As the effective cross section of the grain is identical to that of the layer, the annular collision probabilities, P(I,J) can be calculated using the routine THESEUS(5).

In order to obtain a one-dimensional flux solution, the spherical layers of the fuel grains must be represented by series of concentric annuli. By summing the volume of each type of material in a layer for all grains, the volume of the equivalent annular layers is obtained. The equivalent annular layers are ordered in an outward direction in the same order as in the fuel grain, Figure 1 refers. Collision probabilities for the equivalent annular regions of the cell are computed from the annular and spherical collision probabilities obtained for the cell and for the grains using the following equations, in which annular layers of the physical cell are represented by suffices I and J and the surface of the cell by S. Layers of individual grains are represented by m and n and the surface of the grain by s. Annular layers where the cell has been reduced to a set of equivalent annular rings are represented by suffixes K and L.

i Correction of Annular Cross Sections for Infinite Array

$$P^*(I,J) = P(I,J) + \frac{P(I,S)\,P(S,J)}{(1.0 - P(S,S))}$$

where P(I,J) is the probability of a neutron travelling from $I^{th}$ annular layer to $J^{th}$ annular layer of a cell before suffering interaction.

P*(I,J) is the probability of a neutron travelling from the Ith annular layer to the Jth annular layer of an infinite array of cells before suffering an interaction.

$P(I, S)$ is the probability of a neutron going from the $I^{th}$ annular layer of a cell to its surface

$P(S, J)$ is the probability of a neutron entering a cell suffering an interaction in the $J^{th}$ annular layer.

$P(S, S)$ is the probability of a neutron leaving the surface of one cell and entering the surface of another cell.

ii Correction for Both Annular Layers Unfuelled

$$P^*(K, L) = P(I, J)$$

$P^*(K, L)$ is the probability of a neutron going from the $K^{th}$ layer to the $L^{th}$ layer of an equivalent cell before suffering its next interaction.

iii Correction for Annular Layer I Unfuelled, Layer J Fuelled

$$P^*(K, L) = \frac{V_L (\Sigma_t)_L P(L, S) P(I, J)}{V_o \overset{o}{\Sigma}_t (1.0 - P(o, o))}$$

necessary otherwise the formula becomes wrong in the limit.

where

$V_L$ is the volume of the $L^{th}$ equivalent layer

$V_o$ is the volume of the grain

$(\Sigma_t)_L$ is the cross section of the $L^{th}$ equivalent layer

$\overset{o}{\Sigma}_t$ is the cross section of the smeared grain

$P(o, o)$ is the self collision probability of the homogenised grain

$P(L, S)$ is the probability of a neutron from region L of the grain in Layer J escaping from the grain

iv Correction for Layer I Fuelled, Layer J Unfuelled

$$P^*(K, L) = \frac{P(L, S) P(I, J)}{P(0, S)}$$

where $P(0, S)$ is the probability of a neutron leaving the smeared grain in Layer I suffering its next collision in another grain.

v Correction for Layers I and J Fuelled

$$P^*(K, L) = P(m, n) + \frac{(S_A)_I (\Sigma_{t_n})_J (V_n)_J P(K, S)_I P(L, S)_J P(I, J)}{(S_A)_J (\overset{o}{\Sigma}_t)_J (V_o)_J P(0, S)_I P(0, S)_J}$$

where

$P(m, n)$ is the probability of a neutron in spherical layer m sustaining its next interaction in spherical layer n of a fuel grain in annular region I.

$\Sigma_{t_n}$ is the macroscopic cross section of spherical layer n

$V_n$ is the volume of spherical layer n

$P(K, S)_I$ is the probability of a neutron born in spherical layer K of grain in region I escaping from the surface of the grain

$P(L, S)_J$ is the probability of a neutron born in spherical layer L of grain in region J escaping from the surface of the grain

Having obtained the complete set of probabilities, P*, the radial flux equations

$$\Sigma_{t_K} V_K \phi_K = \left[ \sum_{L=1}^{N} \left( \lambda_L \Sigma_{SL} \bar{\phi} + (1 - \lambda_L) \Sigma_{SL} \phi_L \right) V_L P^*(L,K) \right]_K$$

where $\bar{\phi}$ is the mean flux over the cell

$\phi_L$ is the flux in region L

N is the total number of regions

$\lambda$ is the hydrogeneous factor for nuclide in region L from Reference 7.

are solved, hence enabling a new value of $\Sigma_p$ to be evaluated for the fuel region using

$$\Sigma_p' = \Sigma_T \left( \frac{\phi}{1-\phi} \right)$$

where $\Sigma_p'$ is the new value of $\Sigma_p$

$\phi$ is the flux in the fuel region

If the value of $\Sigma_p'$ is now within pre-specified limits of $\Sigma_p$, it is taken as a new guess for $\Sigma_p$ and the cycle repeated. On final convergence all annular layers with fuel type spectrum are smeared on a volumetric basis and the Bell factor calculated from:-

$$\text{BELL} = 4.0 \left( \frac{\text{Volume}}{\text{Surface area}} \right)_{\substack{\text{smeared} \\ \text{region}}} \cdot \left( \begin{matrix} \text{Volume of fuel} \\ \text{in cluster} \end{matrix} \right) - (\lambda \Sigma_S)_{\text{smear}}$$

where $\lambda \Sigma_S$ is the volume weighted, mean hydrogen equivalent scattering cross section for non resonance materials in the smear.

## 4 The ANJMOC Monte Carlo Approach

### 4.1 Geometrical model for spherical grains in an annulus

In order to adequately simulate the passage of neutrons through a HTR fuel element which contains fuel grains an accurate geometrical model describing grains packed into an annular container is required. Such a model will have to satisfy the following conditions.

1 The packing density must agree with measured values.

2 The observed fuel elements have a high degree of ordering, hence we require a model that includes this feature.

3 In order that the method has validity over a wide range of experimental and design conditions the packing fraction and, to some extent, the structure of the grains must be adjustable.

The packing fraction for experimental fuel elements used in NESTOR was of the order of 0.66. For an amorphous structure the packing fraction is less than 0.63 whereas for regular lattice structures it can vary from 0.5 to 0.75. Hence conditions 1 and 2 are complimentary in that the large packing fractions observed in experimental fuel elements entail some regularity in the grain structure.

In the light of these considerations the geometrical model used to describe the grains in a container was what might be described as a distorted lattice model. A lattice structure with approximately the correct packing fraction is chosen and then the vectors joining the centres of grains

distorted so that the structure conforms to the contours of the container. As an illustration we consider a cubic lattice in the form of a slab. The distorted lattice structure would then be formed by rolling this slab up, in a similar fashion to rolling up a carpet, and hence form an annulus.

In general a regular lattice is uniquely described by three basic vectors. These vectors in cartesian geometry are given by the equation

$$\begin{aligned} \underset{\sim}{i} &= [a_1 \hat{\underset{\sim}{x}} + b_1 \hat{\underset{\sim}{y}} + c_1 \hat{\underset{\sim}{z}}]\, d. \\ \underset{\sim}{j} &= [a_2 \hat{\underset{\sim}{x}} + b_2 \hat{\underset{\sim}{y}} + c_2 \hat{\underset{\sim}{z}}]\, d. \\ \underset{\sim}{k} &= [a_3 \hat{\underset{\sim}{x}} + b_3 \hat{\underset{\sim}{y}} + c_3 \hat{\underset{\sim}{z}}]\, d. \end{aligned} \qquad 1$$

where d is the diameter of a grain, $a_i$, $b_i$ and $c_i$ are constants such that

$$a_i^2 + b_i^2 + c_i^2 = 1 \qquad 2$$

and $\hat{\underset{\sim}{x}}$, $\hat{\underset{\sim}{y}}$, $\hat{\underset{\sim}{z}}$ are unit vectors in the respective directions.

For example, in a cubic lattice all the values of $a_i$, $b_i$ $c_i$, are zero except $a_1$, $b_2$ and $c_3$. Any vector joining equivalent points in the lattice will then have the form

$$l\underset{\sim}{i} + m\underset{\sim}{j} + n\underset{\sim}{k} \qquad l, m, n \text{ integers} \qquad 3$$

On distorting the lattice the constants $a_i$, $b_i$, $c_i$ will become functions of (x, y, z) in cartesian geometry, the form of these functions depending on the distortion. The usefulness of this technique comes when these functions are very simple, or only a few of the constants become functions of a variable.

To facilitate the use of this method when treating annular fuel elements we return to our illustration of rolling a slab into an annulus. This operation can be performed by the transformation

$$\begin{aligned} x &\longrightarrow r w \\ y &\longrightarrow R_{out} - r \qquad \text{where } R_{out} \text{ is the outer radius of the annulus} \\ z &\longrightarrow z \end{aligned} \qquad 4$$

where r, w, z are cylindrical co-ordinates.

The lattice vectors then transform as

$$\begin{aligned} \hat{\underset{\sim}{x}} &\longrightarrow \hat{\underset{\sim}{w}}/r \\ \hat{\underset{\sim}{y}} &\longrightarrow -\hat{\underset{\sim}{r}} \\ \hat{\underset{\sim}{z}} &\longrightarrow z \end{aligned} \qquad 5$$

Under this transformation the layers in the x, z plane and hence at constant radius will retain their regularity but they will tend to slide one over the other.

If we choose our lattice so that $b_1 = b_3 = 0$ then in the distorted lattice

$$\begin{aligned} \underset{\sim}{i} &= [a_1 \hat{\underset{\sim}{w}}/r + c_1 \hat{\underset{\sim}{z}}]\, d. \\ \underset{\sim}{k} &= [a_3 \hat{\underset{\sim}{w}}/r + c_3 \hat{\underset{\sim}{z}}]\, d. \end{aligned} \qquad 6$$

In the case of an annular fuel the layers are taken to be concentric and hence r is the mean radius of a given layer. Hence we can rewrite eq 6 as

$$\underset{\sim}{i}^n = [a_1^n \, \underset{\sim}{\hat{w}} + c_1 \, \underset{\sim}{\hat{z}}] \, d.$$

$$\underset{\sim}{k}^n = [a_3^n \, \underset{\sim}{\hat{w}} + c_3 \, \underset{\sim}{\hat{z}}] \, d. \qquad 7$$

where $\underset{\sim}{i}^n$ refers to the $n^{th}$ layer counting from the outside and

$$a_i^n = a_i/\bar{r}_n \qquad \bar{r}_n = \text{mean radius of } n^{th} \text{ layer}$$

The distortion of one layer with respect to another will be described by vector $\underset{\sim}{j}$. Putting

$$\underset{\sim}{j} = [(a_2^n + \alpha^n) \, \underset{\sim}{\hat{w}} - (b_2 + \beta^n) \, \underset{\sim}{\bar{r}} + (c_2 + \delta^n) \, \underset{\sim}{\hat{z}}] \, d. \qquad 8$$

then $\alpha^n, \beta^n, \delta^n$ are functions of r, w, z which describe how one layer moves over the other. All these functions will be periodic.

We choose a simple value for $\alpha^n$, where

$$\alpha^n = \text{Modular}(\Delta_n \, (w - w_n)/a_2), \Delta_n = \frac{\bar{r}_{n-1} - \bar{r}_n}{\bar{r}_{n-1}} \qquad 9$$

and $w_n$ is some constant.

The values of $\beta^n$ and $\delta^n$ are dependent on $\alpha^n$ and now the layers are constrained to move one over the other. Hence in the computer programme there are facilities for feeding in various functions for these quantities.

However there is one constraint. If the outer layer conforms to the shape of the wall of the container then in order that the inner layer conforms to the other wall of the container we require

$$\Sigma_n \beta^n = \text{constant independent of w.}$$

The model thus satisfies two of our conditions. First there will be a high degree of ordering as the structure of the layers is similar to a pure lattice. Secondly, the model is general. Different lattices can be chosen and distorted in many ways.

The vectors in eq 1 all have length d so that every grain is touching. However the model can be easily adapted so that grain to grain distances in any direction can be adjusted. This is accomplished by altering the values of the constants $a_i$, $b_i$, $c_i$ so that equation 2 is no longer obeyed. In this way the packing density can be adjusted or the structure expanded or contracted in any direction.

Using the geometrical model presented here we can satisfy all the conditions stipulated in this section. The generality of the model lends it to studying details of the grain lattice structure.

## 4.2 Monte Carlo Calculation

The geometrical model defines the positions of the grains in the fuel region for a given lattice structure by means of the functions $\alpha^n$, $\beta^n$ and $\delta^n$. This model was incorporated in a simple one group Monte Carlo calculation of the fuel to fuel probability $P_{ff}$ using as the fuel cross section the average cross section given by eq. 9 section 1.

A conventional Monte Carlo calculation will be lengthy for these complex geometries as the path length will be re-evaluated at every boundary. Hence we adopted a technique called Woodcock tracking (5). In this case the path length of a neutron is determined by a cross section $\Sigma_{tot}$ which is constant for all materials. $\Sigma_{tot}$ is defined by the equation

$$\Sigma_{tot} = \Sigma_{true} + \Sigma_{dummy}$$

where $\Sigma_{true}$ is the physical cross section for a given material. At every collision there will be $\Sigma_{true}/\Sigma_{tot}$ physical event and $\Sigma_{dummy}/\Sigma_{tot}$ dummy events. If an event is a dummy event the neutron continues unchanged. The effect of using $\Sigma_{dummy}$ in this way is to remove the need to calculate the positions of grain and kernel boundaries, although more collisions (real plus dummy) are recorded. This greatly reduced the complexity of the code and saved time.

In the calculations reported here $\Sigma_{tot}$ was taken to equal the fuel cross section so that $\Sigma_{dummy}$ in the fuel was zero.

## 4.3 Effects of Different Grain Structure

In addition to the results reported in sections 5 and 6 calculations have been carried out for NESTOR fuel element 9/B-B using a variety of packing structures.

### 1 Results of changing the lattice structure

Due to the geometry of the experimental fuel elements the desired packing fraction can only be achieved if interlocking hexagonal layers of particles are used in the model. Hence only small changes in the lattice structure are possible. The orientation of the basic lattice structure can be rotated through angles from 0 - 30° with respect to a horizontal plane perpendicular to the axis of the annulus. Results of calculations with varying rotations are shown in Table 1 and indicate that $P_{ff}$ is not sensitive to this parameter.

TABLE 1

| Angle of rotation | 0° | 20.7° | 30° |
|---|---|---|---|
| $P_{ff}$ | 0.836 ± .0045 | 0.833 ± .0045 | 0.833 ± .0045 |

### 2 Results of varying the density of packing with radius

It is possible that in realistic compacts used in Mk III reactors the density of the layers of grains adjacent to the walls of the can will be less than elsewhere in the compact. To estimate the effect of such density variations we also carried out a calculation of $P_{ff}$ with the layers adjacent to the walls of the can reduced by 9% with respect to the other layers but keeping the total fuel content constant. The results are shown in Table 2. Again $P_{ff}$ was not sensitive to this variation in packing.

TABLE 2

| Reduction in density of outer layers | 0 | 9% |
|---|---|---|
| $P_{ff}$ | 0.836 ± .0045 | 0.834 ± .0045 |

## 5 Comparisons between Theories

Table 3 below shows the comparison between the two approaches.

TABLE 3

| Core Number | $\Sigma_p$ | | | $\gamma$ | PROCOL - Monte |
|---|---|---|---|---|---|
| | PROCOL | Monte ± 1% | Corrected Monte | | |
| AGN 3/C - 1 | 6.573 | 6.709 ± 0.067 | 6.441 ± 0.064 | 0.959 | 0.132 ± 0.067 |
| AGN 4/C - 1/√2 | 6.742 | 6.709 ± 0.067 | 6.679 ± 0.066 | 0.9954 | 0.063 ± 0.067 |
| AGN 6/B - B/√2 | 4.059 | 4.089 ± 0.041 | 4.070 ± 0.047 | 0.9951 | -0.011 ± 0.047 |
| AGN 7/P - B/√2 | 4.765 | 4.772 ± 0.048 | 4.750 ± 0.048 | 0.9953 | 0.015 ± 0.048 |
| AGN 8/P - B | 4.635 | 4.772 ± 0.048 | 4.575 ± 0.046 | 0.9571 | 0.060 ± 0.046 |
| AGN 9/B - B | 3.949 | 4.089 ± 0.041 | 3.912 ± 0.039 | 0.9549 | 0.037 ± 0.039 |
| AGN 10/B - B/Cu | 3.793 | 4.089 ± 0.041 | 3.912 ± 0.039 | 0.9549 | -0.119 ± 0.039 |
| AGN 11/B - B/C | 4.269 | 4.500 ± 0.045 | 4.345 ± 0.043 | 0.9643 | -0.076 ± 0.043 |
| AGN 12/G - 1 | 7.230 | 7.690 ± 0.077 | 7.390 ± 0.074 | 0.9691 | -0.160 ± 0.074 |
| AGN 13/A - 3 | 2.969 | 3.013 ± 0.03 | 2.881 ± 0.029 | 0.9530 | 0.088 ± 0.029 |

It will be noted that Dancoff factor has to be allowed for explicitly in ANJMOC which considers an isolated fuel element: the correction is of modest size. We conclude that, within the statistics of the Monte Carlo method, the two approaches agree.

## 6 Comparisons with Experiment

Table 4 shows relative conversion ratios calculated using ANJMOC equivalences for the NESTOR experiments as presented to the 9th DCPM in May 1970. The experimental data have been corrected for the small environmental mismatch where appropriate.

TABLE 4

| Core identification | Lattice pitch (mm) | Fuel | | | |
|---|---|---|---|---|---|
| | | Central 5 x 5 array | Outer zone | Measured R.C.R. | Discrepancy (%) |
| AGN 2/C-2 | 83.8 | C | 2 pin $UO_2$ | 4.59 | - 1.3 |
| AGN 3/C-1 | " | C | 1 pin $UO_2$ | 3.97 | + 1.2 |
| AGN 4/C-1/$\sqrt{2}$ | 118.4 | C | 1 pin $UO_2$ | 2.49 | + 0.3 |
| AGN 6/B-B/$\sqrt{2}$ | " | B | B | 2.90 | + 0.5 |
| AGN 9/B-B | 83.8 | B | " | 4.88 | + 1.4 |
| AGN 10/B-B/Cu* | " | B | " | 5.24 | + 1.0 |
| AGN 11/B-B/C+ | " | B | " | 4.86 | + 1.4 |
| AGN 12/G-1 | " | G | 1 pin $UO_2$ | 3.85 | + 0.1 |
| AGN 13/A-3 | " | A | 3 pin $UO_2$ | 6.12 | - 0.4 |
| AGN 14/G-1(S) | " | G | 1 pin $UO_2$ + graphite sleeve | 3.68 | + 1.8 |

*Copper poison tubes in central voids of each fuel pin.

+Graphite dowels " " " " " " " .

Agreement is seen to be good.

## 7 Conclusions

Methods of geometric equivalence which have been used for AGR and SGHW systems have been extended to deal with granular HTR fuels. Two approaches to the calculation of the equivalence have been tried, and shown to give similar results. The Monte Carlo studies show that these are insensitive to modest changes in the grain packing assumed, which is a necessary condition for the simple theory.

No full space/energy Monte Carlo has been carried out on this problem, and the efficacy of this model is thus not fully demonstrated. On the other hand, comparisons with experiment for a range of grain sizes show good agreement. Together with the experience previously gained in simpler geometries, this permits a modest confidence that the model is, in fact, of adequate accuracy.

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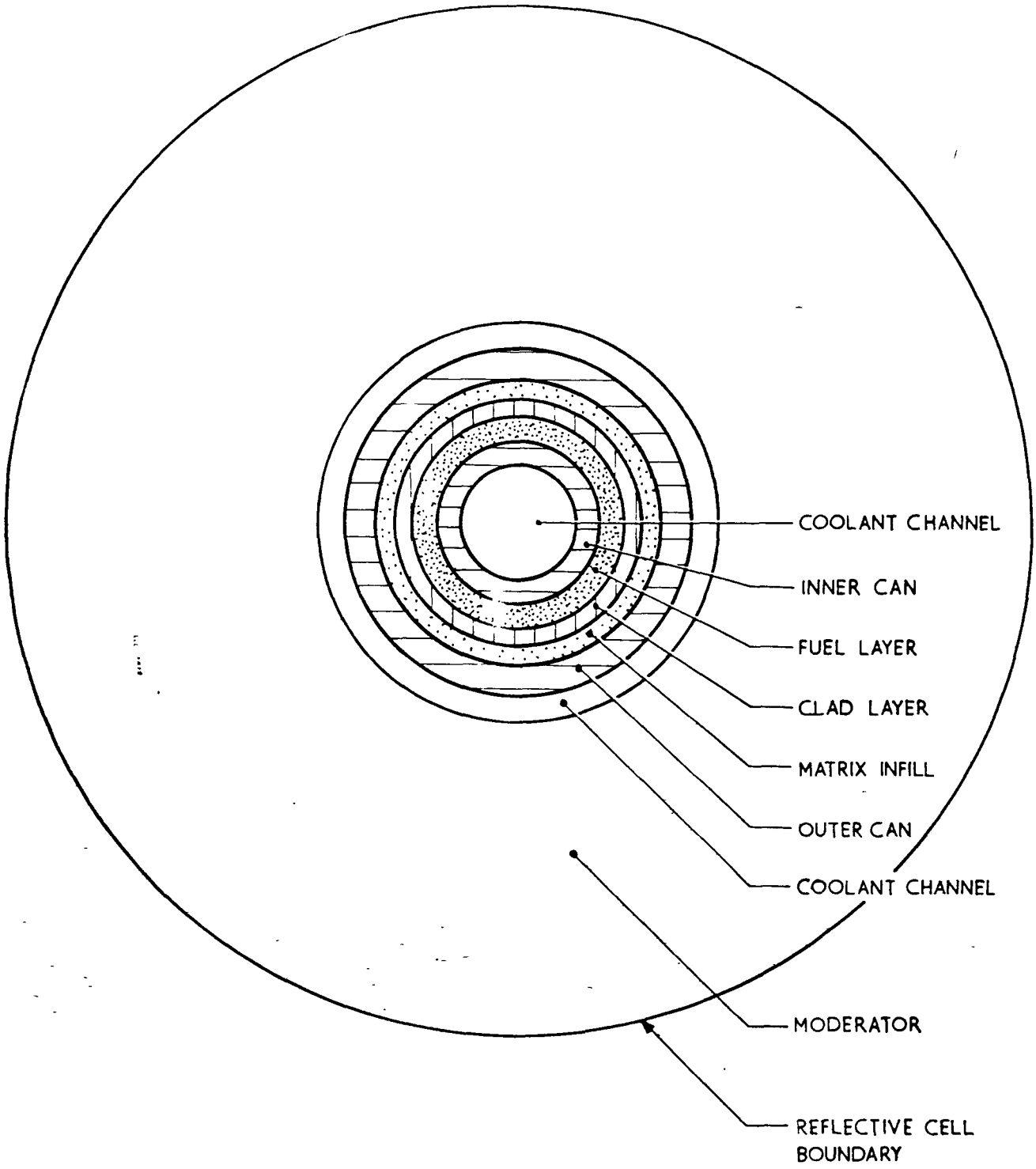


FIG. 1 PROCOL CELL REPRESENTATION FOR FLUX SOLUTION

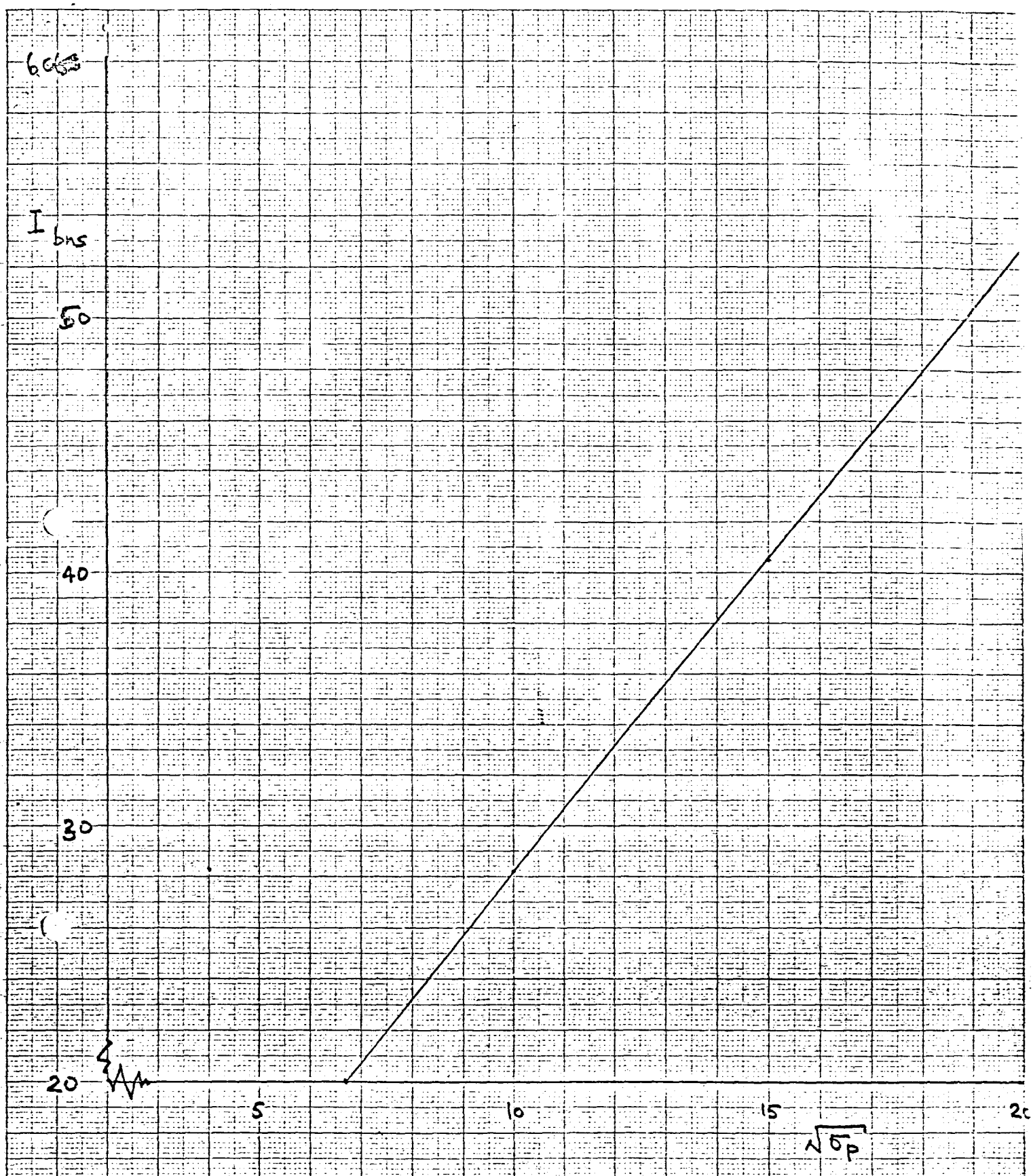


Fig. 2. WIMS Resonance Integral 0.5 eV – 111 KeV (300°K) including 1/v component. [Note that $\sigma_p$ includes 2.0 b for U and 3.5 b for O : 9.0 b for $UO_2$]