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HETERO: A SUBROUTINE FOR CALCULATION OF RESONANCE HETEROGENEITY IN FAST REACTOR LATTICE CELL

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This report begins with a brief description of the general property of the collision probability in plane geometry. A discussion is made on the asymptotic behavior of the resonance flux at the black limit as the resonance cross section tends to infinite. From the asymptotic behavior, a multiregion equivalence relation is derived on the analogy with the Wigner rational approximation for the collision probability. It is shown that the present formulation tends to the two-sided E_3 formulation of Meneghetti, for the special case where all the fuel plate sizes and the compositions of fuel regions are same. The derivation of Meneghetti's formula however seems to be based on intuition.

Following the method derived, a subroutine HETERO was developed for calculating the resonance heterogeneity effects in fast reactor lattice cells. A brief description is also made for the usage of the subroutine developed.

高速炉系格子内の共鳴非均質性計算サブ・ルーチン：HETERO

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まず，平板系における衝突確率の一般的性質を簡単に述べ，次に共鳴断面積が無限大になった時の共鳴中性子束の漸近的振舞を議論した。この漸近的振舞と衝突確率の有理近似の類推から，共鳴断面積に対する多領域等価関係を導いた。組成と平板の厚さが等しい燃料系では，導入された式はMeneghettiの two-sided E_3 公式と等価なことを示した。導入された式に従って，高速炉系格子内の共鳴非均質性を計算するために1つのサブ・ルーチンを開発した。このサブ・ルーチンの使用法についても簡単に述べた。

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I. INTRODUCTION

In the resonance energy region the plate absorption cross sections in a fast reactor cell have been calculated adequately by equivalence relations. Usually a two-region equivalence relation is used for this purpose, and the formulation of Meneghetti is occasionally applied to multiregion cases [1]. However in the complex situations encountered in fast reactor assemblies, it is generally difficult to see how one can construct a unit cell to which the equivalence formulae can be applied. There may be two approaches to generate the effective multigroup resonance cross sections of heavy elements in a heterogeneous system: The first approach calculates the cell-averaged effective cross sections on the basis of the usual two-region rational approximation with Dancoff correction factor. This approach has been used in the many computer codes, such as the MC^2 [2], which calculate the multigroup cross sections in a homonized system. The approach has been used also to estimate the background cross section used for the interpolation of a Bondarenko type cross-section set. In the second approach, the multigroup cross sections of "each plate" in the cell under study are calculated. The resulting heterogeneous cell is homonized to obtain representative cross sections in the cell, using integral transport theory fluxes. Which is adopted the first approach or the second depends on the code system used for the generation of the multigroup cross sections.

For the first approach, a generalized equivalence relation was derived [3]. The method used is essentially based on a natural extension of the well-known rational approximation of the collision probability to a more general situation where plates of different sizes and the interaction between plates consisting of two different compositions are allowed. Another equivalence relation for heterogeneity effects will be necessary also for the second approach. The primary object of this report is to provide a convenient and reliable method and a computer code for calculating the heterogeneity effect of each region in a complex multi-region problem.

II. THEORY

II. -1 Basic Formulation

Let us consider the neutron slowing-down problem in an infinite slab geometry extending from $x = -\infty$ to $x = \infty$. We assume that the geometry under consideration has a periodicity of thickness a, i.e., the system is built up of an infinite number of lattice cells. We introduce a space mesh, i.e., a set of discrete values of x, say x_i, where

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II. THEORY

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i = 0, 1, $\cdots$, I, such that the left boundary of the lattice is at x_0 ($\equiv 0$) and the right boundary at x_I ($\equiv a$). It is also assumed that the boundaries of each plate in the lattice always correspond to any of these mesh points.

Assuming the isotropic elastic neutron scattering in both the center-of-mass and laboratory systems, the neutron balance in a cell may be written by the neutron slowing down equation

$$V_i \Sigma_i(E) \phi_i(E) = \sum_j P_{ji}(E) [V_j S(E)] \qquad (1)$$

where

E = neutron energy
V_i = volume in region i ($\equiv d_i$ = width of region i)
$\Sigma_i(E)$ = macroscopic total cross section in region i
$\phi_i(E)$ = neutron flux in region i
$S_i(E)$ = neutron slowing down source in region i
$P_{ji}(E)$ = effective probability in the unit cell that a neutron scattered isotropically in region j , into energy E , will have its first collision in region i .

The effective collision probability, P_{ji} , can be given by [3)]

$$P_{ji} = \frac{1}{2 d_j \Sigma_j} \int_1^\infty \frac{dt\,[1 - \exp(-d_j \Sigma_j t)]}{t^3\,[1 - \exp(-h t)]}$$
$$\times \Big\{ \exp(h_j t) [\exp(-h_{i-1} t) - \exp(-h_i t)]$$
$$+ \exp[-(h + h_{j-1}) t] [\exp(h_i t) - \exp(h_{i-1} t)] \Big\}$$
$$\text{for} \quad j < i, \qquad (2)$$

$$P_{ii} = P_0(d_i \Sigma_i) + \frac{1}{d_i \Sigma_i} \int_1^\infty \frac{dt\,[1 - \exp(-d_i \Sigma_i t)]^2}{t^3\,[1 - \exp(-h t)]}$$
$$\times \exp[-(h - d_i \Sigma_i) t] \quad \text{for } j = i, \qquad (3)$$

$$P_{ji} = \frac{1}{2d_j\Sigma_j}\int_1^\infty \frac{dt\,[1-\exp(-d_j\Sigma_j t)]}{t^3[1-\exp(-ht)]}$$
$$\times\Big\{\exp(-h_{j-1}t)[\exp(h_i t)-\exp(h_{i-1}t)]$$
$$+\exp[-(h-h_j)t][\exp(-h_{i-1}t)-\exp(-h_i t)]\Big\}$$

$$=\frac{1}{2d_j\Sigma_j}\int_1^\infty \frac{dt\,[1-\exp(-d_i\Sigma_i t)]}{t^3[1-\exp(-ht)]}$$
$$\times\Big\{\exp(h_i t)[\exp(-h_{j-1}t)-\exp(-h_j t)]$$
$$+\exp[-(h+h_{i-1})t][\exp(h_j t)-\exp(h_{j-1}t)]\Big\}$$

$$\text{for } j>i, \tag{4}$$

with

$$P_0(x) = 1-\frac{1}{x}\Big[\frac{1}{2}-E_3(x)\Big], \tag{5}$$

being the first-flight collision probability in an isoloted plane [4]. Here, h_i and h are defined, respectively, by

$$h_i = \sum_{j=1}^{i} d_j\Sigma_j \quad \text{and} \quad h \equiv h_I. \tag{6}$$

Here, it should be noted that the above expressions for the collision probabilities is not always suitable for the numerical computation but they were derived to see the analytical behaviors. Several computer codes are available for the direct computation of to collision probability in plane geometry [5)-7)].

It is quite easy from Eqs. (2)-(4) to show that the conservation of the collision probabilities

$$\sum_{j=1}^{I} P_{ij} \equiv 1 \qquad \text{for all } i \tag{7}$$

and the reciprocity relation between the probabilities

$$V_i\Sigma_i P_{ij} = V_j\Sigma_j P_{ji} \tag{8}$$

are satisifed.

By using the above reciprocity relation, Eq. (1) can be written as

$$\phi_i = \sum_j P_{ij} \overline{W}_j \frac{\Sigma_{0j}}{\Sigma_j} = \sum_j P_{ij} \overline{W}_j \frac{X_{0j}}{X_j} \tag{9}$$

with

$$\overline{W}_j(E) = \frac{\Sigma_{0j}}{\Sigma_j}, \tag{10}$$

$$X_{0j} = 2d_j \Sigma_{0j} \quad \text{and} \quad X_j = 2d_j \Sigma_j \tag{11}$$

where Σ_{0j} is the nonresonant part of Σ_j.

Now, let us consider the limit on which the resonance cross section of one resonance isotope, say σ_f, tends to infinite. This black limit corresponds to a physical situation encountered near resonance energy. Then, all the macroscopic cross sections of the regions with the resonant isotope under consideration will also tend to infinite. We denote these regions by the symbol f and the collision probability, P_{ij}, is considered to be a function of σ_f. Equations (2) through (5) show that

$$P_{ij}(\sigma_f) \cong \delta_{ij} + \frac{\gamma_{ij}}{X_i}, \quad \text{for } i \in f \text{ and } \sigma_f \Rightarrow \infty \tag{12}$$

with

$$\gamma_{ij} \equiv \left[P_{ij}(\sigma_f) - \delta_{ij} \right] X_i \Big|_{\sigma_f \Rightarrow \infty}. \tag{13}$$

Using the conservation rule of Eq. (7), we can obtain the following important identity:

$$\sum_{j=1}^{I} \gamma_{ij} \equiv 0 \qquad \text{if } i \in f. \tag{14}$$

In particular, from the asymptotic expression of $P_0(x)$ (Ref. 4), we have

$$\gamma_{ii} = -(1 - C_i) \quad \text{if } i \in f, \tag{15}$$

where C_i is a generalized Dancoff factor defined by

$$C_i = \begin{cases} 2E_3(h_0) & \text{for the case where only one plate with } \sigma_f \text{ exists in the cell,} \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

with $h_0 \equiv \sum_{j \neq f} d_j \Sigma_j$.

A better way to obtain the geometrical quantity, γ_{ij} , is to use a computer code calculating the collision probability, following the difinition of Eq. (13). For example, we could use the code PATH developed by Tsuchihashi [7], which uses a somewhat different method to calculate P_{ij} .

By the use of the asymptotic behavior of Eq. (12), the flux ϕ_i ($i \in f$) can be written as

$$\phi_i \cong \left\{ \overline{W}_i^\infty X_{0i} + \sum_{j \notin f} \overline{W}_j^\infty \gamma_{ij} \frac{X_{0j}}{X_j} \right\} \frac{1}{X_i} \qquad for\ \sigma_f \Rightarrow \infty \tag{17}$$

where $\overline{W}_j^\infty$ is the value of $\overline{W}_j$ in the limit $\sigma_f \Rightarrow \infty$. It was shown that $\overline{W}_j$ ($j \notin f$) varies very little as a function of energy and position [3]. Hence, we can assume

$$\overline{W}_j^\infty \cong \overline{W}_m^\infty \qquad if\ j \notin f \tag{18}$$

where $\overline{W}_m^\infty$ is the averaged value of $\overline{W}_j^\infty$ ($j \notin f$).

We furthermore assume

$$X_{0j}/X_j \cong 1 \qquad \text{for if } j \notin f. \tag{19}$$

This assumption is reasonable when the accidental overlap of the different resonance sequences is not very important between different regions. Particularly for the diluent regions, Eq. (19) is completely valid. Then using Eq. (14), Eq. (17) can be written as

$$\begin{aligned} \phi_i &\cong \left\{ \overline{W}_i^\infty X_{0i} - \overline{W}_m^\infty \gamma_{ii} - \overline{W}_m^\infty \sum_{j'} \gamma_{ij'} \right\} \frac{1}{X_i} \\ &= \overline{W}_m^\infty X_{ti} \left\{ 1 + f_i^\infty - \sum_{j'} \frac{\gamma_{ij'}}{X_{ti}} \right\} \frac{1}{X_i} \ , \end{aligned} \tag{20}$$

$$X_{ti} \equiv X_{0i} - \gamma_{ii} = X_{0i} + 1 - C_i \ , \tag{21}$$

$$f_i^\infty \equiv \frac{X_{0i}}{X_{ti}} \left[\frac{\overline{W}_i^\infty}{\overline{W}_m^\infty} - 1 \right] \ , \tag{22}$$

where the summation on j' is extended over f excepting i .

II. -2 Derivation of Generalized Dancoff Factor

On the analogy of the two-fuel composition problem, we may postulate the following expression for ϕ_i $(i \in f)$:

$$\phi_i \cong \frac{\overline{W}_m \overline{X}_{ti}}{X_{ri} + \overline{X}_{ti}} \left\{ 1 + f_i - \sum_{j'} A_{ij'} \left[1 - \frac{\overline{X}_{tj'}(1+f_{j'})}{X_{rj'} + \overline{X}_{tj'}} \right] \right\} \tag{23}$$

$$X_{ri} = X_i - X_{oi} \qquad \text{and} \qquad \overline{X}_{ti} = X_{oi} + G_i \;, \tag{24}$$

where G_i and A_{ij} are assumed to be purely geometric quantities which do not depend on the resonance cross section σ_f and f_i is the effective fluctuation of the slowing down source in the fuel region i defined by

$$f_i(E) = \frac{X_{oi}}{\overline{X}_{ti}} \left[\frac{\overline{W}_i(E)}{\overline{W}_m(E)} - 1 \right] . \tag{25}$$

The assumption of Eq. (23) was shown to be adequate by using an extended rational approximation for the averaged collision probability in Ref. (3). The second term in Eq. (23) can be considered to express the interference between the regions with the resonance isotope, and the coefficient A_{ij} is the coupling constant denoting the strength of the interference. Considering the limit of Eq. (23) when $\sigma_f \Rightarrow \infty$ and comparing the resulting equation with Eq. (20), a consistent and convenient choice of G_i and A_{ij} is

$$G_i = 1 - C_i \qquad \text{and} \qquad A_{ij} = \frac{\gamma_{ij}}{X_{ti}} \quad . \tag{26}$$

Assuming weaker interference between the regions with the resonance isotope of interest, we have

$$\begin{aligned} \phi_i(E) &\cong \frac{\overline{W}_m X_{ti}(1+f_i)}{X_{ri} + X_{ti}} \Big/ \left\{ 1 + \sum_{j'} \frac{A_{ij} X_{rj'}}{X_{rj'} + X_{tj'}} \right\} \\ &\cong \frac{\overline{W}_m \overline{\sigma}_{ti}(1+f_i)}{\sigma_f(E) + \overline{\sigma}_{ti}} \;, \end{aligned} \tag{27}$$

where

$$\begin{aligned} \overline{\sigma}_{ti} &\equiv \sigma_{ti} \Big/ \left[1 + \sum_{j'} \frac{A_{ij'}}{\sigma_f(E) + \sigma_{tj'}} (\sigma_f(E) + \sigma_{ti}) \right] \\ &\cong \sigma_{ti} \Big/ \left[1 + \sigma_{ti} \sum_{j'} A_{ij'}/\sigma_{tj'} \right] = \frac{\sigma_{ti}}{1 + \dfrac{1}{N_i \ell_i} \sum_{j'} \dfrac{\gamma_{ij'}}{\sigma_{tj'}}} \end{aligned} \tag{28}$$

with

$$\sigma_{ti} \equiv \sigma_{oi} + \frac{1 - C_i}{N_i \ell_i} \qquad \text{and} \qquad \ell_i \equiv 2 d_i \;. \tag{29}$$

Here, the notation has standard meanings and the NR approximation was used when the second expression of Eq. (28) was obtained. It should be noted that the flux under study is an integrand used in the cross section averaging, hence the use of the NR approximation will be valid for the second order term in Eq. (28). Especially, to the extent that variations in σ_{t_j}'s are small, this approximation is quite reasonable.

Since we consider in general multiregion problems with several fuel regions, we have $C_i = 0$ from Eq. (16). Then we can write Eq. (28) as

$$\overline{\sigma}_{ti} \cong \left(\sigma_{0i} + \frac{1}{N_i \ell_i}\right)\left(1 - \frac{1}{N_i \ell_i}\sum_{j'} \frac{\gamma_{ij'}}{\sigma_{tj'}}\right)$$

$$= \sigma_{0i} + \frac{1-\overline{C}_i}{N_i \ell_i} \tag{30}$$

with

$$\boxed{\overline{C}_i \equiv \sum_{j'}\left(\frac{\sigma_{0i} + \frac{1}{N_i \ell_i}}{\sigma_{0j'} + \frac{1}{N_{j'} \ell_{j'}}}\right)\gamma_{ij'} \ .} \tag{31}$$

In particular, when all the plate sizes and the compositions of the fuel regions are same, using Eqs. (14) and (15) we have

$$\boxed{1 - \overline{C}_i = \sum_{j \notin f} \gamma_{ij} \ .} \tag{32}$$

III. DISCUSSIONS

Equation (30) was derived under the fairly rough approximation of "weak interference between plates". Hence, its accuracy and limitations should be assessed for the practical application, especially when the interaction effect become important. For the purpose of the assessment, let us consider a symmetric cell with two fuel plates, shown in Fig. 1. In this geometry, the interaction effect is significant when $x \to a$. The interaction effect in a complex geometry is supposed to be a combination of such fundamental interactions.

From Eqs. (2), (13) and (31), it is quite easy to show

$$\overline{C}_2 \equiv \gamma_{24} = E_3\left[2\Sigma_1(a+x)\right] + E_3\left[2\Sigma_2(a-x)\right] \tag{33}$$

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$$= \sigma_{0i} + \frac{1 - \overline{C}_i}{N_i l_i} \tag{30}$$

with

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$$\Rightarrow \begin{cases} E_3(2\Sigma_1 a) + E_3(2\Sigma_2 a) & \text{for} \quad x = 0 \\ \frac{1}{2} + E_3(4\Sigma_1 a) & \text{for} \quad x = a\ . \end{cases} \tag{34}$$

This expression is equivalent to the two-side E_3 formulation of Meneghetti[1]. Consequently, the heterogeneity effects for $x=0$ and $x=\infty$ can be written, respectively, as

$$\frac{1-\bar{C}_2}{N_2 l_2} = \begin{cases} \dfrac{1-2E_3(2\Sigma_m a)}{N_2 l_2} & \text{for} \quad x=0 \\ \dfrac{1-2E_3(4\Sigma_m a)}{2N_2 l_2} & \text{for} \quad x=a\ , \end{cases} \tag{35}$$

when $\Sigma_1 = \Sigma_2 \equiv \Sigma_m$. That is, Eq. (17) gives evidently the proper expression for the special cases, which is obtained from the well-known Wigner's rational approximation with Dancoff correction.

Generally, when the quantity $(\sigma_{0j} + 1/N_j l_j)$ is equal for all the fuel plates, it can readily be shown from Eqs. (2), (4), (13) and (32) that the Dancoff factor can be given by a generalized Meneghetti's formulation

$$1 - C = 1 - E_3(X_L) - E_3(X_R) \tag{36}$$

with

$$X \equiv \sum_j \Sigma_j d_j \ . \tag{37}$$

Here, the subscripts L and R stand for the left and right sides of the resonance plate, respectively, and the summation in Eq. (37) is extended over all the diluent regions which exist between the resonance plate under consideration and the left (or right) neighbor.

We shall prove the above relations. First, let us consider the fuel plate i of the case - I in Fig. 2. From Eqs. (2), (4) and (13), γ_{ij} $(j \notin f)$ for this plate can be given by

$$\gamma_{ij} = \begin{cases} E_3(h_{j-1} - h_i) - E_3(h_j - h_i) & \text{for } i < j < i_R \quad (38) \\ E_3(h_{i-1} - h_j) - E_3(h_{i-1} - h_{j-1}) & \text{for } i_L < j < i \quad (39) \\ 0 \quad \text{otherwise.} & \end{cases}$$

Hence, we obtain

$$1 - \bar{C}_i = \sum_{j \notin f} \gamma_{ij} = \sum_{j=i-1}^{i_L+1} \gamma_{ij} + \sum_{j=i+1}^{i_R-1} \gamma_{ij}$$

$$= \left[E_3(0) - E_3(h_{i-1} - h_{i_L})\right] + \left[E_3(0) - E_3(h_{i_R-1} - h_i)\right]$$

$$\equiv 1 - E_3(X_L) - E_3(X_R).$$

For the case - II , on the other hand γ_{ij} can be given by

$$\gamma_{ij} = \begin{cases} E_3(h+h_{i-1}-h_j) - E_3(h+h_{i-1}-h_{j-1}) & \text{for } i_L < j \leqq I \quad (40) \\ E_3(h_{i-1}-h_j) - E_3(h_{i-1}-h_{j-1}) & \text{for } 1 \leqq j < i \quad (41) \\ E_3(h_{j-1}-h_i) - E_3(h_j - h_i) & \text{for } i < j < i_R \quad (42) \\ 0 & \text{otherwise.} \end{cases}$$

We can obtain Eq. (26) also for this case, i.e.,

$$1 - \bar{C}_i = \sum_{j=i_L+1}^{I} \gamma_{ij} + \sum_{j=1}^{i-1} \gamma_{ij} + \sum_{j=i+1}^{i_R-1} \gamma_{ij}$$

$$= 1 - E_3(h - h_{i_L} + h_{i-1}) - E_3(h_{i_R-1} - h_i)$$

Similarly we can prove Eq. (26) for the fuel plate nearest to the righthand boundary of the cell. Consequently, from the discussions made, Eq. (30) and (31) can be considered to be an extension of the previous works. In Eq. (31), we had a weight

$$\omega_{ij} \equiv \frac{\sigma_{0i} + \frac{1}{N_i \ell_i}}{\sigma_{0j} + \frac{1}{N_j \ell_j}} = \frac{\sigma_{ti}}{\sigma_{tj}} \tag{43}$$

for the region j ($j \in f$). This factor is smaller where σ_{tj} is larger, compared with σ_{ti} , and conversely. We can think of the factor as representing a correction factor which takes account of the difference in the compositions or the widths of the interfering plates. The Meneghetti's formulation however gives the same value for the heterogeneity effect, regardless of whether the righthand (or left) plate is very strong absorbing plate or very weak.

The simple results of Eqs. (27) and (30) reveal an extended equivalence relation in a multiregion problem; that is, a plate with $\bar{\sigma}_{ti}$ has the same effective cross section as a homogeneous system with the same $\bar{\sigma}_{ti}$. Consequently, the effective cross sections of "each plate" in the cell can be estimated by a cross section set of the Bondarenko type [8].

Here, note that all the above discussions are not changed by the replacement

$$\sigma_f(E) \Rightarrow \sigma_f(E) + \sum_k a_k \sigma_k(E) \tag{44}$$

where the subscript k corresponds to other resonant isotopes.

We had an extended equivalence relation, mainly from $\sigma_f \Rightarrow \infty$. Hence, there might be some minor problems concerned with the choice of the so-called Bell and Levine factor [9)-12)]. Since most of resonance absorption occurs at finite values of $N_i\sigma_f$, especially in the higher energy range, we need some corrections for the value of $1-\bar{C}$ [9)-12)].

It can be shown that the rational approximation suggested by Levine [9)]

$$P_0(X) \cong \frac{X}{X+a} , \tag{45}$$

with $a = 1.2$, gives quite accurate values for the collision probability in an isolated plate and, in fact, that the accuracy of this modified rational approximation is much better for isolated plates than for isolated rods. On the other hand, the Wigner approximation which is obtained only from the behavior of $P_0(X)$ at $X \Rightarrow \infty$ gives $a = 1$.
The corresponding resonance flux to Eq. (45) can be written, in contrast with Eq. (27), as

$$\phi(E) = \frac{\overline{W}_m \sigma_b (1 + f(E))}{\sigma_f(E) + \sigma_b} \tag{46}$$

with

$$\sigma_b = \sigma_0 + \frac{a}{N\ell} . \tag{47}$$

Meanwhile, if we assume the usual relation between collision probabilities for an isolated lump and a lattice with the Dancoff factor $1-C$ [4), 10), 11)], we are led to the expression

$$\sigma_b = \sigma_0 + \frac{1}{N\ell} \frac{a(1-C)}{1+(a-1)C} , \tag{48}$$

where the lattice was assumed to include only one fuel plate.

The above discussions made suggest that the generalized Dancoff factor used in Eq. (30) should be replaced by

$$1 - \bar{C}_i \Rightarrow \frac{a(1-\bar{C}_i)}{1+(a-1)\bar{C}_i} . \tag{49}$$

Though we assumed $a = 1.2$, the exact choice of the value is not believed to be important for fast reactor lattice. The value of a is considered to depend on the neutron widths which follow the Porter-Thomas distribution [11), 13)].

A summarized paper of this report will be published in the near future[14].

IV. DESCRIPTION ON SUBROUTINE 'HETERO'

Following the method derived in the above sections, a subroutine HETERO was developed. The generalized Dancoff factor ($1-\overline{C}_i$) of 'each fuel plate' is calculated by Eqs. (31) and (49). In this case, the geometrical quantity, γ_{ij}, is computed by

$$\gamma_{ij}=\left[P_{ij}(\sigma_f)-\delta_{ij}\right]\times 2\sigma_f N_i d_i \Big|_{\sigma_f=20/N_{min}} \tag{50}$$

where N_{min} is the minimum density of the resonance isotope under consideration in the cell. Meanwhile the collision probability, P_{ij}, is computed by the code PATH developed by Tsuchihashi[7].

At this point, let us define the symbols involved in the subroutine HETERO:

NR	=	number of regions,
KRES	=	number of resonance isotopes,
KCOMP	=	number of compositions,
NOPT	=	option concerning with the output from the HETERO routine; for NOPT<0, $\overline{C}_i$ of Eq. (31) is computed, NOPT=0 corresponds to Eq. (49), while for NOPT>0 the background cross section is added to the heterogeneity,
IPRINT	=	option for intermediate results; they are printed for IPRINT$\neq 0$,
LSRG(I)	=	composition number to which the I'th region corresponds,
V(I)	=	volume of region I,
SIGM(M)	=	background cross section of composition M,
DEN(M, K)	=	density of the K'th resonance in composition M,
DANC(K, I)	=	output of the 'HETERO' routine specified by 'NOPT' of the K'th resonance isotope,
SIGR	=	$20/N_{min}$ (b.),
SIG(M)	=	total cross section of composition M,
KSUM	=	number of the regions in which the resonance isotope under consideration exists.
INDEX(I)	=	0 for the region where the resonance isotope does not exist,
	=	1 for the region where the isotope exists,

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IV. DESCRIPTION ON SUBROUTINE 'HETERO'

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DEN(M, K)= density of the K'th resonance in composition M,

DANC(K, I)= output of the 'HETERO' routine specified by 'NOPT' of the K'th resonance isotope,

SIGR = $20/N_{min}$ (b.),

SIG(M) = total cross section of composition M,

KSUM = number of the regions in which the resonance isotope under consideration exists.

INDEX(I) = 0 for the region where the resonance isotope does not exist,

= 1 for the region where the isotope exists, The listing of HETERO is given in the appendix A. A sample problem for ZPR-6 Assembly 7 unit cell in Fig. 3 is shown in the appendix B.

References

1. D. MENEGHETTI, " Calculational Studies of Sodium-Void Reactivity Variations Due to Thin Slab Heterogeneities in Fast Critical Assemblies ", Proc. Int. Conf. on Fast Critical Assemblies and Their Analysis, ANL-7320, p. 377 (1966).

2. B.J. TOPPEL, A.L. RAGO, and D.M. O'SHEA, " A Code to Calculate Multigroup Cross Sections ", ANL-7318 (1967).

3. Y. ISHIGURO, Nucl. Sci. Eng., 51, 441 (1973).

4. For example, see G.I. BELL and S. GLASSTONE, " Nuclear Reactor Theory ", Van Nostrand-Reinhold Company, New York (1970).

5. H.C. HONECK, BNL-5826 (1961).

6. A.P. OLSON, " RABID: Integral Transport-Theory Code for Neutron Slowing Down in Slab Cells, " ANL-7645 (1970).

7. K. TSUCHIHASHI, private communication (1970).

8. I.I. BONDARENKO, Ed., Group Constants for Nuclear Reactor Calculations, Consultants Bureau, New York (1964).

9. M.M. LEVINE, Nucl. Sci. Eng., 16, 271 (1963).

10. D.C. LESLIE, J.G. HILL, and A. JONSSON, Nucl. Sci. Eng., 22, 78 (1965).

11. H.H. HUMMEL, R.N. HWANG, and K. PHILLIPS, " Recent Investigation of Fast Reactor Coefficients ", Proc. Conf. Safety, Fuels, and Design in Large Fast Power Reactors, ANL-7120, p. 413 (1965).

12. H.H. HUMMEL and D. OKRENT, " Reactivity Coefficients in Large Fast Power Reactors ", American Nuclear Society, Hinsdale, Illinois (1970).

13. C.E. PORTER, " Statistical Theories of Spectra : Fluctuations ", Academic Press, New York (1965).

14. Y. ISHIGURO, to be published in Nucl. Sci. Eng.

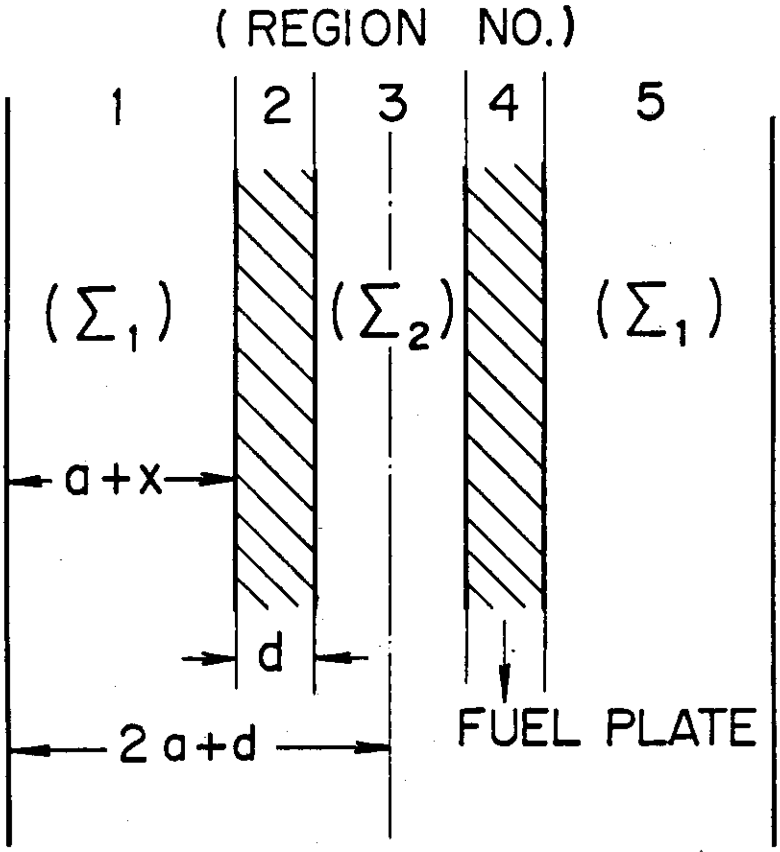

Fig. 1. Representative example of heterogeneous cell -1

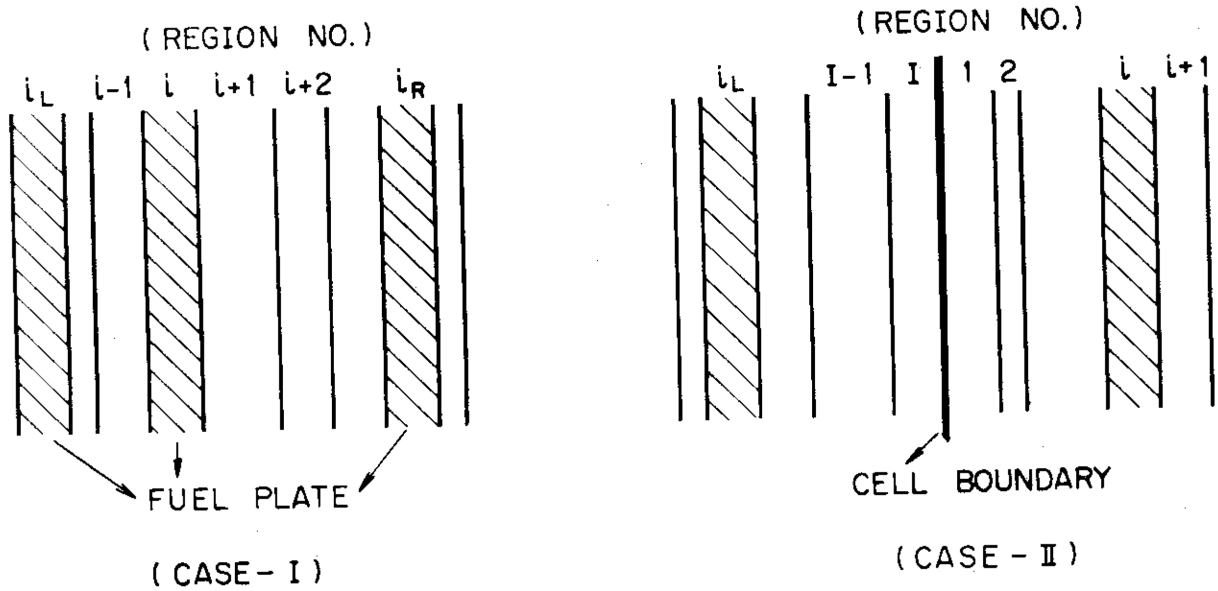

Fig. 2. Representative example of heterogeneous cell -2

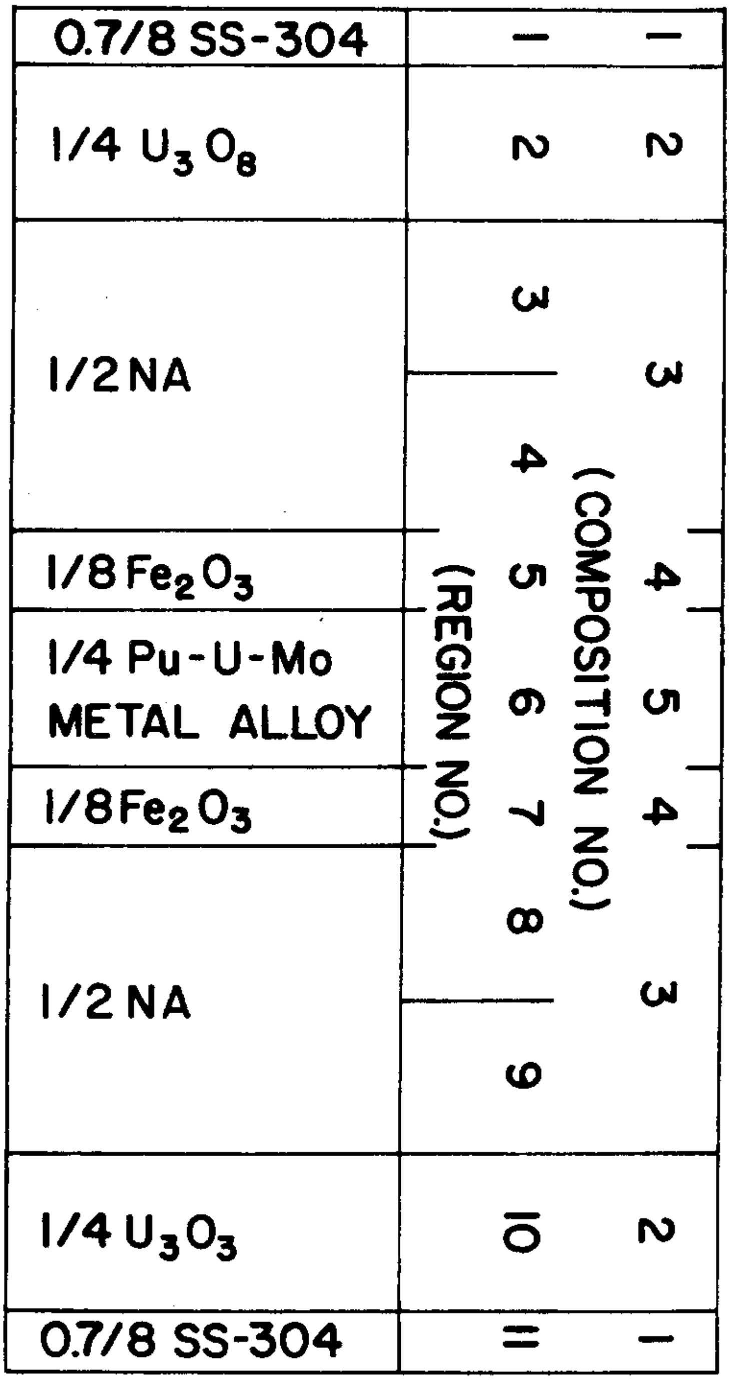

Fig. 3. ZPR-6 Assembly 7 unit cell

APPENDIX A LISTING OF 'HETERO'

```
FACOM 230-60     FORTRAN D  -730801-   (V-05,L-01)            COMPILATION      74.07.03    PAGE  1

      C  **** MAIN PROGRAM ****
            DIMENSION TITLE(18),NCOMP(30),NSUBR(30),RMAX(30),LSRG(30),V(30),
           1DEN(10,5),SIGM(10),DANC(5,30)
        100 FORMAT(18A4)
        101 FORMAT(12I6)
        102 FORMAT(2I6,E12.5)
        103 FORMAT(6E12.6)
       1000 FORMAT(1H0,//,20X,67H** INPUT DATA LIST **(THE LIST IS DONE IN THE
           1 SAME FORMAT AS INPUT)  ///20X,18A4)
       1001 FORMAT(1H0,20X,12I6)
       1002 FORMAT(1H0,20X,2I6,E12.5)
       1003 FORMAT(1H0,20X,6E12.5)
         99 READ(5,100) (TITLE(I),I=1,18)
            WRITE(6,1000) (TITLE(I),I=1,18)
            READ(5,101) KREG,KRES,KCOMP,NSYM,NOPT,NPRINT,MORE
            WRITE(6,1001) KREG,KRES,KCOMP,NSYM,NOPT,NPRINT,MORE
            READ(5,102) (NCOMP(I),NSUBR(I),RMAX(I),I=1,KREG)
            WRITE(6,1002) (NCOMP(I),NSUBR(I),RMAX(I),I=1,KREG)
            DO 10 I=1,KCOMP
            READ(5,103) SIGM(I),(DEN(I,J),J=1,KRES)
         10 WRITE(6,1003) SIGM(I),(DEN(I,J),J=1,KRES)
            RF=0.
            IF=1
            DO 12 J=1,KREG
            IL=NSUBR(J)
            NTMP=IL-IF+1
            TMP=NTMP
            RL=RMAX(J)
            DR=RL-RF
            DR=DR/TMP
            NA=NCOMP(J)
            DO 13 I=IF,IL
            LSRG(I)=NA
         13 V(I)=DR
            RF=RL
         12 IF=IL+1
            KSREG=NSUBR(KREG)
            NR=KSREG
            IF(NSYM.EQ.0) GO TO 14
            NR=2.*NR
            DO 15 I=KSREG+1,NR
            IN=2*KSREG-I+1
            LSRG(I)=LSRG(IN)
            V(I)=V(IN)
         15 CONTINUE
         14 CALL HETERO(NR,KRES,KCOMP,NOPT,NPRINT,LSRG,V,SIGM,DEN,DANC)
            IF(MORE) 1,1,99
          1 STOP
            END

            SUBROUTINE HETERO(NR,KRES,KCOMP,NOPT,IPRINT,LSRG,V,SIGM,DEN,DANC)
      C
      C     NR         ....TOTAL NO. OF REGIONS (LE.30).
      C     KRES       ....NO. OF RESONANCE ISOTOPES(NUMBER DENSITY.GT.0.00001)(LE.5)
      C     KCOMP      ....NO. OF COMPOSITIONS(LE.10)
      C
      C                ....(LT.0)**DANCOFF FACTOR (C) IS CALCULATED.
      C     NOPT       ....(EQ.0)**BELL FACTOR (A=1.2) IS TAKEN INTO ACCOUNT FOR (1-C).
      C                ....(GT.0)**BACKGROUND SCATTERING X-SECTION IS ADDED.
      C
```

```
FACOM 230-60     FORTRAN D  -730801-   (V-05,L-01)          COMPILATION     74,07,03     PAGE   2
C      IPRINT   ....(NE.0)**INTERMEDIADE RESULTS ARE PRINTED.
C      LSRG(I)  ....THE I'TH REGION CORRESPONDS TO THE LSRG'TH COMPOSITION.
C      V(I)     ....VOLUME OF REGION I.
C      SIGM(M)  ....BACKGROUND X-SECTION OF THE M'TH COMPOSITION.
C      DEN(M,K) ....DENSITY OF THE K'TH RESONANCE ISOTOPE IN THE M'TH COMPOSITION
C      DANC(K,I)....HETEROGENEITY SPECIFIED BY 'NOPT' OF THE K'TH RESONANCE.
C      THIS QUANTITY IS OUTPUT OF 'HETERO'.
C
       DIMENSION SIGM(10),SIG(10),DEN(10,5),INDEX(30),LSRG(30),V(30),
      1GAM(30,30),DANC(5,30),U(30)
       DO 20 K=1,KRES
       DO 21 I=1,NR
    21 DANC(K,I)=0.
       DO 10 I=1,KCOMP
       TMPI=DEN(I,K)
       IF(TMPI.LT.0.00001) GO TO 10
       DO 11 J=1,KCOMP
       TMPJ=DEN(J,K)
       IF(TMPI.GT.TMPJ.AND.TMPJ.GT.0.00001) GO TO 10
    11 CONTINUE
       MC=I
       GO TO 13
    10 CONTINUE
       MC=0
    13 IF(MC.EQ.0) GO TO 23
       SIGR=20./DEN(MC,K)
       USUM=0.
       KSUM=0
       DO 30 I=1,NR
       M=LSRG(I)
       TMP=DEN(M,K)
       IF(TMP.GT.0.00001) GO TO 31
       INDEX(I)=0
       SIG(M)=SIGM(M)
       GO TO 32
    31 INDEX(I)=1
       KSUM=KSUM+1
       SIG(M)=SIGR*TMP
    32 U(I)=SIG(M)*V(I)
       USUM=USUM+U(I)
    30 CONTINUE
       NPR=-1
       CALL COLLIS(NR,USUM,U,GAM)
       IF(IPRINT.NE.0) CALL PRINT(NPR,NR,SIG,V,GAM,LSRG)
       DO 50 I=1,NR
       IND=INDEX(I)
       M=LSRG(I)
       DO 51 J=1,NR
       IF(IND.EQ.1) GO TO 52
       GAM(I,J)=0.
       GO TO 51
    52 IF(I.EQ.J) GO TO 53
       GAM(I,J)=2.*U(I)*GAM(I,J)
       GO TO 51
    53 GAM(I,J)=2.*U(I)*(GAM(I,J)-1.)
    51 CONTINUE
       IF(IND.EQ.0) GO TO 50
       TMP=(SIGM(M)+0.5/V(I))/DEN(M,K)
       IF(KSUM.GT.1) GO TO 54
       DANC(K,I)=1.+GAM(I,I)
       GO TO 57
    54 DO 55 J=1,NR
```

Decision of the Composition with Minimum 'Fuel Density'

Setting $(N\sigma_F)_{min.} \Rightarrow 20$

Calculation of P_{ij}

Calculation of γ_{ij} (Eq.(13))

Eq.(31)

```
FACOM 230-60      FORTRAN D  -730801-   (V-05,L-01)               COMPILATION      74.07.03     PAGE    3

 55             INDJ=INDEX(J)
 56             IF(I.EQ.J.OR.INDJ.EQ.0) GO TO 55
 57             MJ=LSRG(J)                                                      --> Eq.(31)
 58             TMPJ=(SIGM(MJ)+0.5/V(J))/DEN(MJ,K)
 59             TMPJ=TMP/TMPJ
 60             DANC(K,I)=DANC(K,I)+TMPJ*GAM(I,J)
 61          55 CONTINUE
 62          57 IF(NOPT) 50,56,56
 63          56 DANC(K,I)=1.2*(1.-DANC(K,I))/((1.+0.2*DANC(K,I))*2.*V(I)*DEN(M,K))  --> Eq.(49)
 64             IF(NOPT.EQ.0) GO TO 50
 65             DANC(K,I)=DANC(K,I)+SIGM(M)/DEN(M,K)
 66          50 U(I)=DANC(K,I)
 67             NPR=0
 68             IF(IPRINT.NE.0) CALL PRINT(NPR,NR,SIG,V,GAM,LSRG)
 69          23 CONTINUE
 70             NPR=K
 71             IF(IPRINT.NE.0) CALL PRINT(NPR,NR,SIG,U,GAM,LSRG)
 72          20 CONTINUE
 73             RETURN
 74             END


  1             SUBROUTINE PRINT(NP,JMAX,SIG,V,P,LSRG)
  2             DIMENSION SIG(10),X(30),V(30),LSRG(30),P(30,30)
  3        1000 FORMAT(1H1,//,25X,48H=== COLLISION PROBABILITY IN PLANE GEOMETRY =
               1==  //,10X,83H(THIS PART COMES FROM COLLSION PROBABILITY ROUTINE M
               2ADE BY T.TSUCHIHASHI IN JAERI) )
  4        1001 FORMAT(1H0,6X,6HVOLUME ,3X,15F8.4)
  5        1002 FORMAT(1H ,4X,8HMATERIAL ,15I8)
  6        1003 FORMAT(1H ,3X,9HX-SECTION ,3X,15F8.4)
  7        1004 FORMAT(1H0,//,20X,54H=== CALCULATED RESULTS(GENERALIZED DANCOFF FA
               1CTOR)===  )
  8        1005 FORMAT(1H0,//,20X,55H=== FINAL RESULTS FOR DANCOFF FACTOR OF EACH
               1REGION ===  )
  9        1006 FORMAT(1H0,2X,10HREGION NO. ,15I8)
 10        1007 FORMAT(1H ,13X,I2,15F8.5)
 11             NHK=JMAX
 12             IF(JMAX.GT.15) NHK=15
 13             IF(NP) 10,20,30
 14          10 WRITE(6,1000)
 15             WRITE(6,1001) (V(I),I=1,NHK)
 16             WRITE(6,1002) (LSRG(I),I=1,NHK)
 17             DO 5 I=1,NHK
 18             M=LSRG(I)
 19           5 X(I)=SIG(M)
 20             WRITE(6,1003) (X(I),I=1,NHK)
 21             GO TO 40
 22          20 WRITE(6,1004)
 23             GO TO 40
 24          30 WRITE(6,1005)
 25          40 WRITE(6,1006) (I,I=1,NHK)
 26             IF(NP.GT.0) GO TO 7
 27             DO 6 I=1,JMAX
 28           6 WRITE(6,1007) (I,(P(I,J),J=1,NHK))
 29             GO TO 8
 30           7 WRITE(6,1007) NP,(V(J),J=1,NHK)
 31           8 RETURN
 32             END
```

```
FACOM 230-60      FORTRAN ( -730601-    (V-05,L-01)                    COMPILATION      74.07.03    PAGE   4

    1          SUBROUTINE COLLIS( ,USUM,U,EE)
    2          DIMENSION UU(4,3), (30),EE(30,30)
    3          PATH=20.
    4          ERROR=0.00001
         C
         C     .............
         C     THIS ROUTINE IS MADE BY K. TSUCHIHASHI,
         C     .............
         C
    5          RETURN
    6          END


    1          SUBROUTINE EISUM(U ,UI,UJ,ANS,ERROR)
    2          DIMENSION UU(4)
         C
         C     .............
         C     THIS ROUTINE IS CALLED BY SUBROUTINE COLLIS.
         C     .............
         C
    3          RETURN
    4          END


    1          FUNCTION  E(N,XX)
         C EN        *** SUBROUTINE EN(X) , N=1,2,3 ***
         C
         C     .............
         C     THIS ROUTINE IS CALLED BY SUBROUTINE 'COLLIS'.
         C     .............
    2          RETURN
    3          END
```

APPENDIX B OUTPUT FROM SAMPLE PROBLEM

```
                    FACOM 230-60 LIED  (V-02.L-16)   -730704-        74.07.03.          PAGE 00001
        NAME       NONAME.ENTRY=ELM(FTMAIN)
        DOMAIN     HCM,RWX,NOOVLY
        *    PGSLIB
        CALL       PRVLIB
        SGMT       SEG1
        SELECT     RELBIN
        FIN
******* LIED-60 FINIS ******

        ** INPUT DATA LIST **(THE LIST IS DONE IN THE SAME FORMAT AS INPUT)

         *** TEST CASE 2 (ZPR-6 ASSEMBLY 7 UNIT CELL ) ***
             9      2      5      0     -1      1      0
             1      1 0.22230E 00
             2      2 0.85730E 00
             3      4 0.21273E 01
             4      5 0.24448E 01
             5      6 0.30798E 01
             4      7 0.33973E 01
             3      9 0.46673E 01
             2     10 0.53023E 01
             1     11 0.55246E 01
         0.82400E 00 0.0          0.0
         0.32630E 00 0.15600E-01 0.0
         0.12150E 00 0.0          0.0
         0.57850E 00 0.0          0.0
         0.51960E 00 0.23300E-01 0.97000E-02
```

*** COLLISION PROBABILITY IN PLANE GEOMETRY ***

(THIS PART COMES FROM COLLSION PROBABILITY ROUTINE MADE BY T.TSUCHIHASHI IN JAERI)

VOLUME	0.2223	0.6350	0.6350	0.6350	0.3175	0.6350	0.3175	0.6350	0.6350	0.6350	0.2223
MATERIAL	1	2	3	3	4	5	4	3	3	2	1
X-SECTION	0.8240	20.0000	0.1215	0.1215	0.5785	29.8718	0.5785	0.1215	0.1215	20.0000	0.8240

REGION NO.	1	2	3	4	5	6	7	8	9	10	11
1	0.24544	0.37728	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.24836	0.12893
2	0.00544	0.96063	0.00263	0.00212	0.00381	0.01114	0.00000	0.00000	0.00000	0.01066	0.00358
3	0.00000	0.43229	0.13541	0.08386	0.11330	0.23514	0.00000	0.00000	0.00000	0.00000	0.00000
4	0.00000	0.34843	0.08386	0.13541	0.15786	0.27443	0.00000	0.00000	0.00000	0.00000	0.00000
5	0.00000	0.26316	0.04759	0.06631	0.24587	0.37707	0.00000	0.00000	0.00000	0.00000	0.00000
6	0.00000	0.00746	0.00096	0.00112	0.00365	0.97364	0.00365	0.00112	0.00096	0.00746	0.00000
7	0.00000	0.00000	0.00000	0.00000	0.00000	0.37707	0.24587	0.06631	0.04759	0.26316	0.00000
8	0.00000	0.00000	0.00000	0.00000	0.00000	0.27443	0.15786	0.13541	0.08386	0.34843	0.00000
9	0.00000	0.00000	0.00000	0.00000	0.00000	0.23514	0.11330	0.08386	0.13541	0.43229	0.00000
10	0.00358	0.01066	0.00000	0.00000	0.00000	0.01114	0.00381	0.00212	0.00263	0.96063	0.00544
11	0.12893	0.24836	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.37728	0.24544

*** CALCULATED RESULTS(GENERALIZED DANCOFF FACTOR)***

REGION NO.	1	2	3	4	5	6	7	8	9	10	11
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.13822	-1.00000	0.06671	0.05376	0.09667	0.28286	0.00000	0.00000	0.00000	0.27080	0.09099
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.00000	0.28286	0.03628	0.04235	0.13851	-1.00000	0.13851	0.04235	0.03628	0.28286	0.00000
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.09099	0.27080	0.00000	0.00000	0.00000	0.28286	0.09667	0.05376	0.06671	-1.00000	0.13822
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*** FINAL RESULTS FOR DANCOFF FACTOR OF EACH REGION ***

REGION NO.	1	2	3	4	5	6	7	8	9	10	11
1	0.0	0.63079	0.0	0.0	0.0	0.44450	0.0	0.0	0.0	0.63079	0.0

=== COLLISION PROBABILITY IN PLANE GEOMETRY ===

(THIS PART COMES FROM COLLSION PROBABILITY ROUTINE MADE BY T.TSUCHIHASHI IN JAERI)

VOLUME	0.2223	0.6350	0.6350	0.6350	0.3175	0.6350	0.3175	0.6350	0.6350	0.6350	0.2223
MATERIAL	1	2	3	3	4	5	4	3	3	2	1
X-SECTION	0.8240	0.3263	0.1215	0.1215	0.5785	20.0000	0.5785	0.1215	0.1215	0.3263	0.8240

REGION NO.	1	2	3	4	5	6	7	8	9	10	11
1	0.24544	0.14042	0.03219	0.02653	0.04752	0.22838	0.03297	0.01777	0.02088	0.07898	0.12893
2	0.12414	0.26565	0.06360	0.04605	0.07544	0.25502	0.02322	0.01224	0.01413	0.05070	0.06983
3	0.07644	0.17081	0.13541	0.08386	0.11330	0.29422	0.01817	0.00946	0.01082	0.03794	0.04956
4	0.06300	0.12367	0.08386	0.13541	0.15786	0.32736	0.01602	0.00831	0.00946	0.03287	0.04218
5	0.04739	0.08510	0.04759	0.06631	0.24587	0.42124	0.01307	0.00673	0.00763	0.02619	0.03288
6	0.00329	0.00416	0.00179	0.00199	0.00609	0.96535	0.00609	0.00199	0.00179	0.00416	0.00329
7	0.03288	0.02619	0.00763	0.00673	0.01307	0.42124	0.24587	0.06631	0.04759	0.08510	0.04739
8	0.04218	0.03287	0.00946	0.00831	0.01602	0.32736	0.15786	0.13541	0.08386	0.12367	0.06300
9	0.04956	0.03794	0.01082	0.00946	0.01817	0.29422	0.11330	0.08386	0.13541	0.17081	0.07644
10	0.06983	0.05070	0.01413	0.01224	0.02322	0.25502	0.07544	0.04605	0.06360	0.26565	0.12414
11	0.12893	0.07898	0.02088	0.01777	0.03297	0.22838	0.04752	0.02653	0.03219	0.14042	0.24544

=== CALCULATED RESULTS(GENERALIZED DANCOFF FACTOR)===

REGION NO.	1	2	3	4	5	6	7	8	9	10	11
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.08367	0.10568	0.04540	0.05051	0.15474	-0.86000	0.15474	0.05051	0.04540	0.10568	0.08367
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

=== FINAL RESULTS FOR DANCOFF FACTOR OF EACH REGION ===

REGION NO.	1	2	3	4	5	6	7	8	9	10	11
2	0.0	0.0	0.0	0.0	0.0	0.12000	0.0	0.0	0.0	0.0	0.0

* END OF FORTRAN *