PLUTHARCO,

A PLutonium, Uranium, THorium Assembly Reactivity COde
Physical Concepts, Comparisons with Experiments and Code Description

by

W. DE HAAN and R. MEELHUYSSEN

1966

Joint Nuclear Research Center
Ispra Establishment - Italy
Reactor Physics Department
Reactor Theory and Analysis
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In the framework of the ORGEL reactor physics development program, a new method for heavy water lattice calculations has been established.

This method is intended for design survey type calculations and for preliminary fuel cycle analysis.
Lattices fueled with uranium, thorium and plutonium can be investigated. The method is based on the four factor formula, the two group theory and the Westcott cross-section formalism.

The method has been written in Fortran II for the IBM-7090 computer, with the name PLUTHARCO (PLutonium, Uranium, THorium Assembly Reactivity COde). The code gives directly with the results the input data for RLT-4 burn-up calculations.
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SUMMARY

In the framework of the ORGEL reactor physics development program, a new method for heavy water lattice calculations has been established.

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Lattices fueled with uranium, thorium and plutonium can be investigated. The method is based on the four factor formula, the two group theory and the Westcott cross-section formalism.

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Introduction (*)

Since 1961 at Euratom a method is in use to calculate the physical constants of an ORGEL reactor lattice cell.

This method has been programmed under the name of CAROLINE I for the IBM 7090 and it has been found to be well adapted especially for survey and optimization calculations. However with the use a great number of shortcomings have been found giving rise to the necessity of an improvement and a greater serviceableness. A modification of the program has been done, called CAROLINE 1 M.

At first the program has been recoded such, that only the differences with respect to the former calculation have to be introduced, decreasing significantly the number of input cards.

Secondly new geometries have been added together with an increased choice of coolants. Furthermore an entry has been left open to introduce special materials in any of the compounds, like fuel, canning, filler, pressure tube, calandria tube. Only the moderator has to be a mixture of heavy water.

The physical scheme however was not changed. The recent interest in Thorium fuelled reactors showed the necessity to have again an easy to use method to study the possibilities of this fertile material together with U233, U235 or eventually Plutonium.

For this reason the existing code CAROLINE 1 M was modified again.

The geometrical part has remained as formerly but adaption to any general fuel composed of any U, Pu, or Th isotope made it necessary to change completely the physical base, from the correlational type to the straight-on physical type. For this reason it was decided not longer to speak about a member of the CAROLINE family, but give to the code a new name, PLUTHARCO.

It is realised, that this description, though fairly acceptable, is only a raw scheme. It should however be remembered, that the purpose of such a scheme is to allow the fast execution of reasonably reliable survey calculations often involving the variation

 (*) Manuscript received on August 25, 1966
of an appreciable number of parameters. For this reason the recipe must be fairly simply. In later stages where more accuracy is needed, these calculations should be compared with more refined schemes present at Euratom (Ref. 25).

Results of this scheme have been compared with measurements and are shown in another section of the paper. The agreement in general is quite reasonable.

The report is divided into sections being
I. The general description of the theory with the references
II. Comparison with experiments
III. A compilation of the formulae used in the program
IV. Tables of basic quantities and cross sections
V. Directions for use of the PLOTHARCO program.
Section I

1.1. The thermal multiplication factor

The thermal multiplication factor $\eta$ is defined as the number of fast neutrons produced per neutron absorbed in the fuel.

As this may be diluted with oxygen, carbon and other materials, their cross sections have to be taken into account in $\eta$.

It may thus be written as

$$\eta = \frac{\left(\nu ZF\right)^i}{\Sigma^i_a} = \frac{\sum \nu(i) \Sigma_f(i)}{\sum \Sigma_a(i) + N_d \Sigma_{a,d}}$$

where $i$ is one of the 8 isotopes being present in the fuel mixture

$\nu(i)$ is the mean number of fast neutrons born per absorption of a neutron in a fissionable nucleus

$\Sigma_f(i)$ is the fission cross section of each of the isotopes being present in the fuel mixture

$\Sigma_a(i)$ the absorption cross section of each of the isotopes being present in the fuel mixture

$\Sigma_{a,d}$ the absorption cross section of the $N_d$ diluent atoms per atom of fuel mixture.

The cross sections are the mean over the fuel spectrum. These spectrum effects are calculated assuming the Westcott conventions (Ref.1), i.e. the spectrum may be supposed to be built up of a Maxwellian and a $1/E$ tail characterised by the parameters $T$ and $r$.

The method to calculate $r$ is outlined in Ref.2 and 3.

The spectrum mean cross sections are then found from the formula

$$\langle \sigma \rangle = \frac{\Gamma}{4} \frac{\Gamma}{Y} \sigma = \frac{\Gamma}{4} \frac{\Gamma}{Y} (g + r s) \sigma_0$$
in which \( \sigma_0 \) is the 2200 m/sec cross section
\( g, s \) Westcott's constants
\( \hat{\sigma} \) the equivalent 2200 m/sec cross section averaged over the above defined spectrum
\( \sigma \) the mean cross section of neutrons with spectral constant \( T \) over the above defined spectrum
\( T_0 = 293,6^\circ \text{K} \)

For elements having resonances at low energies (Pu239, Pu240) \( s \) is replaced by \( s' \) (Ref.2) where

\[
\frac{s'}{s} = \frac{S_{p+4} V}{S_{\text{eff}}} N_i I
\]

with \( V/S_{\text{eff}} \) being the mean chord length in the fuel element
\( I \) the resonance integral
\( N_i \) the number density of atoms of species \( i \) in the fuel element.

In fact the former formula represents the assumptions of the N.R.I.M.1 approximation. For isotopes being present in large concentrations U238, Th232 the Westcott scheme is not usable any more, and the three values have been set zero. The resonance absorption due to these materials is calculated taking into account the self shielding of the resonances and not by taking the infinite dilution as is assumed in Westcott's treatment. Also for the structural materials \( s \) is set to zero, i.e. supposing them to be pure 1/\( V \) absorbers.

Having once the mean spectrum microscopic cross sections; the mean fuel cross section for fission, \( \sigma_{f(\text{fuel})} \) and absorption \( \sigma_{a(\text{fuel})} \) may be written as:

\[
\sigma_{f(\text{fuel})} = \sum_i \sigma_t(i) f(i) + N_d \cdot \sigma_d
\]

\[
\sigma_{a(\text{fuel})} = \sum_i \sigma_t(i) f(i)
\]

where \( \sum_i \) is the summation over \( i \) terms \( i = 1,8 \)
\( \sigma_t(i) \) the cross section of the \( i \)th isotope
\( f(i) \) the density fractions of the \( i \)th fuel or fertile isotope
\( N_d \) the number of diluent atoms per atom of fuel and fertile material (i.e. for UO2 is 2)
\( \sigma_d \) the spectrum mean cross section of the diluent atoms.
The macroscopic fuel cross section is now simply found from

$$\Sigma_{\text{fuel}} = \frac{\rho_{\text{fuel}} \cdot A}{M_{\text{fuel}}} \sigma_{\text{fuel}}$$

where $\Sigma_{\text{fuel}}$ is the mean fuel cross section over the Maxwellian $+ 1/E$ spectrum for the fuel composition as defined in input.

$\rho_{\text{fuel}}$ is the density of the fuel compound in g/cm$^3$.

$M_{\text{fuel}}$ is the molecular weight of the fuel mixture.

$A$ is Avogadro's constant.

To calculate the microscopic cross sections the spectral constants have to be known.

Very often however, i.e. in the case of Plutonium isotopes they cannot be defined properly.

For this reason a switch has been built into the program giving a choice of 3 different methods as given in the next table.

<table>
<thead>
<tr>
<th>Choice</th>
<th>input 20</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>Candu correlated spectral constants</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>Spectral constants to be provided by the user</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Input of TERMDOR parameters</td>
</tr>
</tbody>
</table>

Choice 1

Canadians have (Ref.5) measured the relative reaction rates Pu$^{239}$/U$^{235}$ and Lu/Mn in the fuel and moderator of a Candu lattice cell and analysed them to obtain the spectral constants of the Westcott formalism. Coolant channels containing different mixtures of light and heavy water at various temperatures were successively used in the experiments.

As result an empirical formula has been derived to calculate the spectral constants in fuel and moderator for lattices with similar geometry.

These formulae can be written as:
\[ T'_f = T_m + 300 \cdot r + b_1(V\Sigma_a) + b_2(V\Sigma_b) + b_k(V\Sigma_k)(T_k - T_m) + b_c(V\Sigma_c)(T_c - T_m) \]

\[ T'_m = T_m + 300 \cdot r \]

with \( r \) is the relative epithermal weight of the neutron spectrum
\( T \) physical temperature
\( T' \) spectral constant
\( m,f,t,c \) moderator, fuel, tubes and coolant respectively
\( b \) variables obtained from fit with experiments
\( a,s \) absorption, resp. scattering labels to macroscopic cross sections.

When no region subscripts are attached to the parameters \( V\Sigma \), the mean over the fuel bundle is meant.

Apart from these two most important spectral constants one needs the same for the tubes and outer coolant region. These were calculated supposing that in these regions the spectral constants were the mean of the former two.

Choice 2
Spectral constants are provided by the user.

Choice 3
TERMIDOR parameters input (Ref.6)

Giving the characteristics of a simplified lattice, the TERMIDOR code calculates the macroscopic cross sections of some important not 1/\( v \) (U235, Pu239) absorbers together with the 1/\( v \) cross sections (per unit cross section at 2200 m/sec) averaged over a neutron spectrum calculated by the code (f 1/\( v \)).

The not 1/\( v \) microscopic cross sections can directly be entered in PLUTHARCO, whether the \( f_1 \) parameter serves in calculating the spectral constants of every 1/\( v \) isotope.
The calculation of this spectral constant is done by the formula

\[ f = \frac{\pi}{4} \frac{\Gamma_0}{\pi} \frac{\Gamma_0}{\pi} \]

a formula on its turn derived from

\[ f = \sqrt{\frac{\pi}{4} \frac{\Gamma_0}{\pi}} \]

Although the not \(1/v\) cross sections (as said before) are entered directly, the code writes the spectral constants in the output for every isotope (thus included the not \(1/v\) ones).

Two iterations are made in every calculation. At the first iteration the value of \(r\) is taken to be zero. With this assumption a complete calculation is made until the lattice buckling. From these data another value of \(r\) is calculated. After entering this value in the Westcott formalism the microscopic cross sections are corrected and another buckling calculation performed.

The cross section values are given in tables\(^x\). Except the first method of calculations the fuel microscopic and macroscopic cross sections the program accepts directly the numerical values of the macroscopic cross sections by the so called "7 choice" (see: Directions for use).

\(^x\) see table 1 a and 1 b
1.2. The fast fission factor

The calculation of the fast fission factor $\varepsilon$ is based on the method of Fleishman and Soodak (Ref.7); however the scheme was simplified to a two group structure instead of a 3 group one. The main reason of this simplification is the uncertainty of the inelastically slowed down spectrum. This is supposed to be described by the function

$$n(E) = E e^{-E}$$

The form of this spectrum however is very similar to the fission spectrum of the region below 1 MeV, so that the division into 3 groups of different spectra was felt to be a little bit to luxurious. Although the scheme remained unchanged, the cross sections of the two groups until 1 MeV were taken equal.

The groups are separated by the fission threshold. The region in which fast fission appears is defined as the region surrounded by a rubberband strung around the fuel element. The fission source is supposed to be flat as well as the sources of the neutrons of the next generations. In the first group neutrons are able to give fission, capture and scatter elastically and inelastically.

In the second group fission is not permitted as well as inelastic scattering.

Atoms with fissioning capacity beneath the U238 fission threshold are corrected for the fact that sub-threshold fissioning is not permitted, i.e. the fast fission in the second group is normalized and added to the first.

The microscopic group cross sections are calculated from data of Ref.8 by contraction of 3 groups to the epifission threshold group and 6 groups to the subfission threshold group. They were calculated with the aid of the following relations:
\[
\sigma_{t,I} = S f_{I,k} \sigma_{t,}\kern1pt
\]

\[
\sigma_{I \rightarrow \Pi} = S f_{I,k} \sigma_{t,}\kern1pt + S f_{I,k} \sigma_{t,}\kern1pt \cdot \kern1pt W_{k}
\]

\[
\sigma_{c,1} = S f_{I,k} \sigma_{c,}\kern1pt
\]

\[
\tau_{t,1} = S f_{I,k} \sigma_{t,}\kern1pt + S f_{I,k} \sigma_{t,}\kern1pt \cdot \kern1pt W_{k}
\]

\[
\tau_{c,1} = S f_{I,k} \sigma_{c,}\kern1pt
\]

\[
\tau_{c,\Pi} = S f_{I,k} \sigma_{c,}\kern1pt
\]

with the notations: \( k \) is the group index for the calculation of cross sections of broad (epithres-hold) group \( I \) of the two group scheme.

\( j \) is the group index for the calculation of the cross sections for the subthreshold broad group \( \Pi \) of the two group scheme.
\( f_{I,k}, f_{I,j} \) are the fractions of fast neutrons born in fine group \( k \) resp. \( j \) per neutron born in any of the two bread groups \( I \) and \( II \).

\( W_2 \) is the number of neutrons born in group two per neutron born in group one after a fission of a fuel nucleus. It is thus the ratio of the fission spectrum integrals above and beneath the fission threshold of \( U_{238} \).

\( (\nu \sigma_f)_j \) the number of fast neutrons generated per neutron absorbed in fast group \( j \).

The subscripts:
- \( t = \text{total} \)
- \( I \rightarrow II = (\text{inelastic}) \text{scattering from group} \ I \text{to} II \)
- \( I \leftarrow I = (\text{elastic}) \text{scattering from group} \ I \text{to} I \)
- \( c = \text{capture} \)
- \( f = \text{fission} \)
- \( s = \text{scattering} \)
- \( n, n', k = \text{inelastic scattering out of fine group} \ k \)
- \( k, k' = \text{scattering from group} \ k \text{into group} \ k' \).

The calculation of the mean macroscopic cross sections is done in two steps:
1. The calculation of the macroscopic cross sections of the different materials by

\[
\Sigma = \frac{\rho A}{M} \left( N_1 \sigma_1 + N_2 \sigma_2 + \ldots \right)
\]

where again
- \( \rho = \text{density of the compound material} \)
- \( A = \text{Avogadro's number} \)
- \( M = \text{molecular weight of the compound} \)
- \( N_1, N_2 = \text{the number of atoms} \ 1, 2 \ldots \text{per molecule of the compound} \).

The calculation of the homogenized macroscopic cross sections by weighing the material cross sections with their respective volume fractions.

The volume fractions are calculated from the different volumes occupied within a rubber band stretched around the bare fuel pins.
The mean cross sections are calculated for all of the following interactions:

- $\Sigma_{t, I} = $ the total mean macroscopic cross sections in group I
- $\Sigma_{s, I} = $ scattering mean macroscopic cross section in group I
- $\Sigma_{t-x, I} = $ the mean macroscopic transfer cross section out of group I
- $\Sigma_{f, I} = $ the mean macroscopic fission cross section of group I
- $\nu \Sigma_{f, I} = $ the mean fission source density per unit of flux . second in group I
- $\Sigma_{c, I} = $ is the mean macroscopic capture cross section in group I
- $\Sigma_{t, II} = $ the mean macroscopic total cross section in group II
- $\Sigma_{c, II} = $ the mean macroscopic capture cross section in group II
- $\Sigma_{s, II} = $ the mean macroscopic scattering cross section in group II

The number of collisions in group $I$, $C_I$, per original fast neutron can now be written:

$$C_I = \frac{0.561 \cdot P(\alpha_b \Sigma_{t, I}) \cdot (0.561 \cdot \nu \Sigma_{f, I} + \Sigma_{t-x, I})}{(1 - P(\alpha_b \Sigma_{t, I}) \cdot \frac{\nu \Sigma_{f, I} \cdot C_I + \Sigma_{t-x, I}}{\Sigma_{t, I}})}$$

$$C_I = \frac{0.439 \cdot P(\alpha_b \Sigma_{t, II}) \cdot \left( \frac{\nu \Sigma_{f, II} \cdot C_I + \Sigma_{t-x, II}}{\Sigma_{t, II}} \right) + P(\alpha_b \Sigma_{t, II}) \cdot C_I \cdot \frac{\Sigma_{t-x, II}}{\Sigma_{c, II}}}{1 - P(\alpha_b \Sigma_{t, II}) \cdot \frac{\Sigma_{t-x, II}}{\Sigma_{t, II}}}$$

The extra number of fast neutrons generated per original fast neutron ($\varepsilon - 1$) is then the product of the collision probabilities and neutron gain per collision summed over the two groups or:

$$\varepsilon - 1 = C_I \frac{G_I}{\Sigma_{t, I}} + C_I \frac{G_{II}}{\Sigma_{t, II}}$$

where:

$$G_I = \frac{\nu \Sigma_{f, I} - \Sigma_{t, I} - \Sigma_{c, I}}{\Sigma_{t, I}}$$

$$G_{II} = \frac{- \Sigma_{c, II}}{\Sigma_{t, II}}$$
1.3. The resonance escape probability

The calculation of the resonance escape probability may be devided into the following parts.

1. The effective surface per gram of fuel

For the fuel element the effective surface per gram is calculated by the method of Hellstrand (Ref.9). This means, that the fuel element is replaced by a rod with external surface equal to the rubber band surface (strung around the bare rods). The inside moderator holes are supposed to be a number of circular cylinders whose radii \( r \) are those of the inscribed circles of the holes.

The surface generated by this cylinders however has an efficiency given by the formula

\[
\Sigma = 2 \Sigma' r \left( 1 - \rho_b (\Sigma') \right)
\]

where \( \Sigma' \) being the mean volume weighed scattering cross section of the canning, organic and filler present in the holes of the cluster, which on its turn derived from

\[
\frac{5}{4} - \Sigma' V (1 - \rho_b)
\]

This relation is derived in Ref.10 for cylindrised as well as cluster cases.

This recipe is easily usable in all regular lattices because in all these cases the holes are of cylindrical square or triangular shape.

For the 22 rod cluster, where the holes are irregular, the effective radius of the inscribed circle was calculated as follows.

The volume of the moderator inside the rubber band strung around the cluster was divided by the number of holes, to obtain the mean volume per hole.

If this hole was circular it would have an internal radius

\[
r_c = \sqrt{\frac{4 V_{ci}}{21 \pi}}
\]
For an hexagonal arrangement one can show that the effective radius of the circular hole would be

$$r'_e = \sqrt{\frac{1}{4} \frac{\pi d^3/\sqrt{3}}{\pi} - \frac{1}{2} \pi s^2}$$

with $d =$ cluster pitch  
$s =$ rod radius

In this case the inscribed circle would be

$$r'_i = \frac{d}{\sqrt{3}} - s$$

If it is supposed that the holes are hexagonal the inscribed radius might be written

$$r'_i = \frac{r'_e}{\frac{r'_e}{d}}$$

$$r'_i = \sqrt{\frac{V_0}{2\pi}} \cdot \frac{4}{\sqrt{3}} - \infty \cdot \sqrt{\frac{\frac{4}{\sqrt{3}}}{\frac{1}{2} \pi k^2}}$$

($k = \frac{s}{d}$)

The effective rod radius is found by the relation

$$2\pi s^2 = V_{fuel}$$

when $V_{fuel}$ is fuel volume.

2. Calculation of the resonance integral

The cluster is now identified with an effective rod with the same surface per gram. For this rod the resonance integral can be looked-up in a table.

These tables were prepared formerly by calculating for uranium and thorium compound (metal, dioxide, mono and dicarbide) the resonance integrals as a function of the surface per gram and temperature (Ref.11) by the method of Nordheim with the aid of the programs ZUT and TUZ.
The results were fitted for temperatures between 20° and 1600° C as

\[ I = A + \frac{B}{\sqrt{I}} \]

For any temperature the values of A and B can now be interpolated giving rise to its proper resonance integral (see table 1).

For fuels composed of more than one fertile material, the resonance integral of each material is obtained first and the density weighed mean value calculated afterwards, i.e. with the assumption that the resonances of the different materials do not interfere with each other.

3. Calculation of resonance escape probability

Being known now the slowing down cross section \( \xi \Sigma_s \) of the lattice, the resonance escape probability can be calculated by

\[ p' = e^{-\frac{NIV_f}{\xi \Sigma_s V_m}} \]

where

- \( N \) = number of atoms of the absorber per unit volume
- \( V \) = volume
- \( \rho \) = the flux ratio at the resonance energy between fuel and moderator
- \( f \) = fuel
- \( m \) = moderator

The factor \( \rho \) is the product of two terms:

- the first one (\( \omega \)) is due to the non uniformity of the fast sources.
- As a consequence of this fact, at large pitches, the slowing down distribution of the neutrons in the cell is not flat. \( \omega \) is calculated as in CAROLINE (Ref. 26), simply by assuming age theory to be valid and by calculating the energy-space distribution in a bath of heavy water for a linear source (neglecting the presence of the fuel rod);

- the second one (\( \gamma \)) due to the depression in one resonance occurred from the neutron absorption at higher resonances and, for the lowest resonances, to the fact that the NR-approximation in the moderator is not anymore valid.

The \( \gamma \) term is quite difficult to evaluate in a simplified manner. By assuming that the resonance absorption is spread out in a lethargy interval \( \Delta u \), and by using the diffusion theory, it can be written:
\[ \gamma = \frac{K_r I_0(K_r)}{2 \cdot I_1(K_r)} \approx \left(1 + \frac{1}{6} K_r^2 r^2\right)^{-1} \]

where \( K \) is the reciprocal slowing down length at resonance energies and \( r \) the effective fuel rod radius. \( K \) is calculated from

\[ K^2 = \frac{3 \xi s \Sigma_v}{\Delta \omega} \cdot \Sigma_{tr} \left(1 - 0.8 \frac{\xi s^2/\Delta \omega}{\Sigma_{tr}}\right) \]

\( \xi, \Sigma_s \) being the mean volume weighed slowing down cross section of the fuel, canning, organic and filler present in the homogenized cluster. \( \Sigma_{tr} \) the volume weighed mean transport cross section of the former four materials.

The choice of \( \Delta \omega \) is somewhat arbitrary. Different authors propose values between 3 and 7 lethargy units. Therefore a mean value of 5 lethargy units has been chosen and it was found that with this figure good results were obtained by comparison with different experiments.

1.4. The thermal utilisation factor

For the calculation of the thermal utilisation factor, defined as the number of neutrons absorbed in the fuel per neutron absorber in the total lattice cell, the lattice cell is approximated by a cylindrical homogeneous fuel assembly at the center being surrounded by five cylindrical regions, i.e.

1. the outer coolant region
2. the pressure tube region
3. the insulation region
4. the calandria tube region
5. the moderator region.

Having once decided this, the calculation of \( f \) can be divided into two parts
1. the calculation of the fuel to cluster utilisation factor \( f_{fc} \)
2. the calculation of the cluster to cell utilisation factor \( f_{cc} \)
with \( f \) equal to

\[
f = f_{fc} \cdot f_{cc}
\]

Because the cluster is composed of four materials being fuel \( (f) \), canning \( (g) \), filler \( (r) \) and coolant \( (θ) \) the factor \( f_{fc} \) can be written as the ratio of the reaction rates in fuel and cluster or

\[
f_{fc} = \frac{\mathcal{Q}_f \cdot V_f \cdot Z_f}{\mathcal{S} \cdot \mathcal{A}_f \cdot V_f \cdot Z_f}
\]

\( \mathcal{S} \) being the sum of the former four components of the fuel rod. Once the volumes and cross sections are known the only factors to be found are the relative fluxes.

These now are calculated from an expression suggested by Amouyal and Benoist (Ref. 12), giving the ratio of the flux at the fuel rod periphery to the mean flux in the rod.

In the program is supposed that canning, filler and coolant are exposed to the same flux being the one at the periphery.

The expression then writes

\[
\mathcal{Q}_g = \frac{\mathcal{Q}(\alpha)}{\mathcal{Q}} = 1 + \frac{Z_s}{Z_t} A \left[ 1 + \alpha \frac{Z_s}{Z_t} + \beta \left( \frac{Z_s}{Z_t} \right)^2 \right]
\]

where the subscripts \( c, s \) and \( t \) mean capture scattering and total respectively and \( A, \alpha \) and \( \beta \) are functions of \( z_t \), the pin radius in units of total mean free paths (Table 2).

The cluster to cell utilisation factor is calculated by the method of Amouyal, Benoist and Quionnet (Ref. 13). In this method the lattice cell has to be divided into a number of cylindrical regions (see description before) making the following hypotheses

1. the angular neutron density at the different surfaces is isotropic
2. the collision densities for the second order and multiple collisions are supposed to be independent of the place in the region.

From these two assumptions the collision probabilities for the inner, the proper and the outer region can be calculated for any of the regions.
Once these are known, the currents in out and inward directions can be found for every boundary. This gives rise to a set of two current equations for every region which may be solved by matrix calculus.

The currents on their turn give the absorption fraction in every region from the consideration that:

\[
\text{absorption fraction in region } i = \frac{\text{source in region } i - \text{net outscattering from region } i}{\text{total source in cell lattice}}
\]

For the homogenized fuel region this absorption fraction is equal to the former defined factor \( f_{cc} \).

The flux in every region can now easily be found from the equivalence relation between sinks and sources in a region

\[
\Sigma_{ai} V_i q_i = f_i \sum_{j=1}^{N} q_j V_j
\]

Furthermore the cell homogenized absorption cross section becomes

\[
\Sigma_a = \frac{\sum_{j=1}^{N} \Sigma_{aj} V_j q_j}{\sum_{j=1}^{N} V_j q_j}
\]

In these formulae \( j \) is the region index, \( \Sigma_a, V, \varphi \) the macroscopic absorption cross section, volume and flux respectively and \( f_i \) the absorption fraction in region \( i \).

I.5. Average to uranium thermal flux ratio

Once defined the cluster to uranium flux ratio and known the flux in the six regions the fuel to mean lattice flux ratio can be easily found to be the product of
\[
\frac{\Phi_{\text{cell}}}{\Phi_u} = \phi_{\text{fc}} \cdot \phi_{\text{cc}} = \frac{V_f + \phi_g(V_f + V_r + V_o)}{V_f + V_g + V_r + V_o}
\]

The following symbols have been used:

\begin{align*}
V &= \text{volume} \\
g &= \text{canning} \\
f &= \text{fuel} \\
o &= \text{coolant} \\
r &= \text{filler}
\end{align*}

In the thermal energy group the cluster is supposed to be formed by a rubber band strung around the canned cluster. The volumes have to be calculated in agreement with this assumption.

1.6. The diffusion area

For the calculation of the diffusion area, \( l^2 \), the lattice cell is supposed to be divided into two different regions, the central non-moderator region and the peripheral moderator region. It is furthermore supposed, that the absorption of the neutrons in the central region is totally due to the fuel so that

\[
f_c = f
\]

and

\[
f_m = 1 - f
\]

where \( f_c \) is the capture fraction of the central region, \( f \) the thermal utilisation factor for the lattice cell, \( f_m \) the capture fraction of the moderator.

Furthermore if the regions are thick one may write the diffusion area of the lattice (Ref.14) as:

\[
L^2 = \frac{f_c}{f_c} L_c^2 + \frac{f_m}{f_m} L_m^2
\]

The diffusion area of both the central and the moderator region are found with

\[
L^2 = \frac{1}{3 \Sigma_t \Sigma_a}
\]

For the moderator region these quantities can be directly calculated from microscopic cross sections.
For the central region however these data are derived with the formula
\[ \Sigma_{tr} = \frac{\sum_i \Sigma_{v_i} \nu_i \sigma_i}{\sum_i \nu_i \sigma_i} \quad \text{and} \quad \Sigma_{ai} = \frac{\nu_f \Sigma_{af}}{\sum_i \nu_i \sigma_i} \]
i.e. for the absorption cross section the absorption of all the other materials in the central region is neglected with respect to the fuel absorption.

1.7. The thermal diffusion coefficient

Once known the cell absorption cross section and the diffusion area the lattice diffusion coefficient is given by
\[ D = 1^2 \frac{\Sigma_{a}}{\nu} \]

1.8. The slowing down area

The insertion of a fuel element in a bath of heavy water influences on two different ways the Fermi-age:
1. by a change of the fast neutron spectrum
2. by a change of slowing down and transport properties.

1. The neutrons born in the fuel element have a definite probability to collide with the fuel to have an inelastic collision and the moderator atoms (especially H) to collide elastically.

Both collisions decrease the neutron energy giving rise to a perturbed fission spectrum.

Defining the Fermi-age of heavy water for a fission spectrum, inelastic scattered spectrum and elastic scattering (by H atoms) \( \tau_i \), \( \tau_e \) and \( \tau_m \) respectively, one may write the corrected value in the moderator by

\[ \tau_m = \tau_i (1 - P_a - P_f) + \tau_e P_a + \tau_i P_f \]
with

\[ p_{\mu} \] being the probability of a fission neutron to collide with an H atom in the fuel rod

\[ p_{i} \] the probability of a fission neutron to collide inelastically with an uranium atom in the fuel rod.

Assuming that inelastic scattering is only possible in group I of the fast spectrum (see calculation of \( \varepsilon \)) and knowing the total collision probability \( C_{i} \), the value is easily calculated from

\[ p_{i} = C_{i} \frac{V_{f} Z_{i \rightarrow x, f}}{V_{f} Z_{t, I}} \]

where

- \( f \) resp. \( b \) fuel and bundle respectively
- \( Z_{i \rightarrow x} \) the inelastic fuel scattering cross section
- \( Z_{t, I} \) the total fast cross section of the bundle

As elastic scattering to H atoms is possible in both fast groups I and II the formula \( p_{\mu} \) can be written

\[ p_{\mu} = C_{i} \frac{V_{f} Z_{i \rightarrow x, o}}{V_{f} Z_{t, I}} + C_{i} \frac{Z_{o, x, H} V_{o}}{V_{f} Z_{t, I}} \]

In the Fleischmann-Soodak scheme neutrons of group I only can scatter out of the group or scatter with conservation of energy in the group. For this reason the inelastic organic scattering cross section has been used in group I, thus supposing that inelastic scattering is only due to hydrogen.

In group II where all scattering is supposed to be with conservation of energy only the hydrogen part has been taken, i.e. multiplying the organic cross section with the fraction of the hydrogen scattering.

The Fermi-ages for the different fast spectra can be written as follows, supposing that the cross sections of the moderator are not energy dependent over the whole energy range from fast to 0.025 ev and the values of \( T_{i} \) and \( T_{i} \) are 120 and 72 cm\(^2\) respectively.
\[ \tau_i = 120 \left( \frac{\rho_0}{\rho} \right)^2 - Q \Delta u_i \]

\[ \tau_e = 120 \left( \frac{\rho_0}{\rho} \right)^2 - Q \left( 1 - \Delta u_i \right) \]

\[ \Delta \tau_{\text{res}} = Q \Delta u_{\text{res}} \]

with \[ Q^{-1} = 3 \left( \pi Z_b \right)_m \left( \xi_{\text{tr}} \right)_m \]

and \[ \Delta u = \ln \frac{T}{T_0} - \ln \frac{E}{E_0} \]

is the lethargy difference between neutrons of energy \( E \) and \( E_0 \). For \( \tau_i \) and \( \tau_e \), the last term on the right side corrects the age values to spectral constants \( T \).

In \( \tau_e \) another unit of lethargy is subtracted to take into account the elastic scattering due to the H atoms.

For \( \tau_{\text{res}} \) the same relation is used calculating the lethargy range between neutron temperature and mean resonance energy which is supposed to be 30 eV.

The Fermi-age to resonance energy in the moderator thus is the difference between the one over the total range and the range from thermal to resonance energy

\[ \tau_{\text{res},m} = \frac{T_m}{\Delta \tau_{\text{res}}} \]

2. Supposing that after one collision in the moderator the neutrons have been diffused out perfectly, i.e. the fluxes in the lattice cell are space independent, one may use the theory of homogeneous mixtures (Ref.15) to obtain

\[ \tau = \tau_m \left( \frac{\nu_i}{\nu_m} \right)^2 \frac{1}{ \left( \frac{1}{\left( \nu \xi_{\text{tr}} \right)_m} \right) \left( \frac{1}{\left( \nu \xi\right)_m} \right) } \]
Assuming further that also in the cluster the slowing down and transport cross sections are energy independent one may correlate the lattice cell ages to the moderator ones by

\[ \frac{\tau_{\text{res}}}{\tau} = \frac{\tau_{\text{res,m}}}{\tau_{m}} \]

The mean lattice cell slowing down cross section parameter i.e. \( \xi_{5} \) is obtained by taking the mean over the different materials present in the lattice cell weighing every cross section with the respective material volume of the cell i.e. again assuming that the flux is spatially constant.

1.9. Fast diffusion coefficient

The lattice cell fast diffusion coefficient is then calculated by

\[ D_f = \left( \xi_{5} \right) \cdot \frac{T}{\Delta u} \]

a formula obtained by assumptions already described in the former parts.

1.10. Lethargy range

The mean lethargy range travelled by the neutrons can easily be obtained from the fundamental formula

\[ \Delta u = \tau_{m} \left( \xi_{5} \right)_{m} \left( Z_{t'} \right)_{m} \]

1.11. The initial conversion ratio

The initial conversion ratio is defined as the number of fissile atoms produced per fissile atom burned.

The production of fissile atoms however takes place after absorption of neutrons of every energy, so that the production is divided into the thermal, fast and epithermal part.
For the thermal region the contribution is simply
\[ \Sigma_{\alpha}^{fe,t} \]
with \( \Sigma_{\alpha}^{fe,t} \) the fertile resp. fissile isotopes
\( t, f, e \) resp. the thermal, fast or epithermal energy group.

The fast and epithermal contribution to the fissionable isotope production can be found as follows, knowing that the number of fission neutrons per burned fissile nucleus is
\[ \frac{\gamma Z_{fi,t}^{fe,t}}{Z_{fi,t}} \]
one only needs to know what is the production of fissionable isotopes per fast neutron born in these two regions.

In the framework of the two group theory this may be written for the fast (fission region) as
\[ C_x \frac{Z_{c}^{fe(1)}}{Z_{t}^{(1)}} + C_x \frac{Z_{c}^{fe(2)}}{Z_{t}^{(2)}} \]

For the epithermal region this is easily found from the fact that \((1-p)\)

is the absorption per neutron entering the epithermal region. As
furthermore the number of these neutrons per fast neutron is:
\[ \varepsilon \frac{1}{1 + \beta^2 T} \]
the total production can then be written in the form:

\[ \chi_0 = \left[ C_x \frac{Z_{c}^{fe(1)}}{Z_{t}^{(1)}} + C_x \frac{Z_{c}^{fe(2)}}{Z_{t}^{(2)}} + \frac{\varepsilon (1-p)}{1 + \beta^2 T} \right] \frac{\gamma Z_{fi,t}^{fe,t}}{Z_{fi,t}} + \frac{\Sigma_{\alpha}^{fe,t}}{Z_{fi,t}} \]

Connected with these parameters are the parameters \( \chi_t \), being the number of fast fissions of the fertile material per fast born neutron, and:
\( \chi_f \) being the fast and epithermal capture in the fertile material per fast neutron born which are to be used in the long term reactivity program RLT 4.
This first formula can be derived easily from the former theory to be

\[ X_t - C_t \frac{\Sigma_t^{fe(1)}}{\Sigma_t(1)} \]

The second is already explained and is the form in square brackets in the formula of \( \gamma_o \).

The totals of \( X_t, X_0 \) and \( \gamma_o \) for a lattice are simply the sum of the respective terms for the different isotopes.

I.12. The infinite multiplication factor and buckling

From the detailed nuclear parameters described formerly the infinite multiplication factor is obtained as

\[ k_{\infty} = \eta e^p \]

and the buckling as defined in conventional theories is then calculated by

\[ B^2 = -\frac{1}{2} \left( \frac{4}{T^2} + \frac{4}{\tau} \right) + \frac{1}{2} \sqrt{\left( \frac{4}{T^2} + \frac{4}{\tau} \right)^2 + \frac{4(k_{\infty} - 1)}{L^2 T^2}} \]

as well as the negative root of the criticality equation being used in diffusion theory programs. This negative root is found with a minus sign before the square root.

I.13. Two group diffusion constants

For the study of spatial effects in reactors with the aid of diffusion theory a set of group constant is required.

The scheme used in the calculation method gives us the possibility to obtain a set of two group constants. Except of the thermal constants already mentioned before, the fast constants are calculated as follows:
II. Comparison with experimental results

To check the calculation scheme a number of comparisons has been made with experiments performed by different laboratories.

1. EXPO experiments (Euratom)
2. CISE experiments
3. Savannah River experiments
4. Chalk River experiments

A description of the lattice types will follow together with the method of interpretation and other details.

The comparison of the calculated and measured values is given in a series of plots at the end of this chapter.

II.1. EXPO experiments

A number of exponential measurements have been made at Euratom to find the buckling of a lattice composed of "7-rod cluster" elements fuelled with uranium carbide and cooled with diphyl.

The measurements were made for ten different pitches ranging from 22-30 cm. More details are given in ref.16. The inaccuracies are mainly originated by the limited number of test elements contained in the experimental facility giving rise to large inhomogeneity effects etc.

The error however is supposed not to exceed \( 0.2 \text{m}^{-2} \). A plot of the calculated curve, together with some measured data is given in fig.1. The agreement is very satisfactory for lattices with a pitch \( \alpha 22 \text{ cm} \). The differences are notably smaller than the inaccuracies remained at the interpretation of experimental results.

Table 1 gives the calculated detailed parameters, together with the measured values of the buckling.

\[
\nu Z_f = \frac{k_c e Z_a}{p}
\]

\[
Z_1 = \frac{D_1}{T}
\]

\[
Z_{\tau_1} = \frac{\rho}{Z_1}
\]

\[
Z_{\alpha_1} = Z_1 Z_{\tau_1}
\]
II.2. CISE Experiments

A set of buckling measurements in Aquilon II has been performed by CISE in contract with Euratom (ref.17). In this experiment the successive replacement method has been used. The tested configurations were made-up of concentric annuli elements, fuelled by natural uranium and having polystyrene to simulate the hydrogenous coolant.

Two concentric tubes have been used in the measurements; AC$_1$, a composition of two concentric tubes filled with "coolant" and AC$_2$, a tube with a bar of the same outer most size as the internal tube of AC$_1$. Two densities of polystyrene have been used with respective densities of .307 and .578 gram/cm$^2$ indicated by resp. $T_1$ and $T_3$ in the fuel element index.

One sees in fig.2 that the best agreement is found for the tube-and-bar element AC$_2$ at high pitches, where the difference is within the accuracy of the measurements. For the AC$_1$ cluster the disagreement between experiment and theory is the greatest of all the comparisons made and is of the order of .5 m$^{-2}$.

The only encouragement is here, that the Euratom scheme gives even better results than those obtained with the fundamental scheme used at CISE. In both cases the calculations give to low results (Ref.18).

Besides the fundamental scheme a correlated one has been constructed by CISE with adjustment parameters, in the resonance integral and $k_\infty$. In table 6 and 7 these results are compared with ours.

The factor $p$ in the CISE results given in the tables is corrected such, to give the correlated $k_\infty$ with the normal four factor formula. Although differences in the partial parameters occur, one sees that their total effect on the infinite multiplication factor is very small.

The main differences arise in the values of the migration areas $L^2$ and $\tau$, which on their turn lead to those large differences in the buckling.
II.3. Savannah River experiments

A generalised study of the reactor physics of natural uranium, heavy water systems has been made at Savannah River Laboratories (Ref.19). Detailed nuclear parameters \( \eta, \epsilon, p, f \) etc. were measured in the PDP for D\(_2\)O moderated lattices of natural uranium rod clusters of 1, 3, 7 and 19 rods. These rods were 1 inch in diameter and cladded with .032 inch of aluminium.

Apart from this way of obtaining the buckling this parameter was obtained by flux mapping analysis.

The first method however, can only be performed with the aid of a theoretical scheme, which is only a raw picture of reality. However it helps us to estimate the accuracy of every parameter.

It seems therefore, that the most confidence could be given to the flux mapping experiments. The figures of all the experiments are given in Fig.3-5.

For any of the 4 cluster types, measurements have been made for a wide range of pitches.

Tables 8-10 give the comparisons of the detailed nuclear parameters obtained from the experiments with the calculated ones.

One sees, that the Savannah River \( \eta \) and \( \epsilon \) are always greater than the ones calculated by us.

Their \( p \) values are mostly greater for small pitches and may sometimes obtain smaller values at large pitches especially in the small clusters.

Their \( f \) values are always a little smaller than the ones calculated by us.

Nevertheless the Savannah River k-inf values are always greater by some percents, the difference increasing at larger pitches.

This difference however is compensated by the fact that their values of the migration parameters are greater.

All these differences result in PLUTHARCO calculated bucklings, which are too large for the single rod compared with both types of experiments.

For the 3 rod clusters our calculated results are intermediate with respect to both experimental results, whereas for the 7-rod cluster both techniques give values which are larger the ones calculated by us.

In the 1 and 7 rod clusters the difference may amount to \( .5 \ m^{-2} \).
For the lowest pitches calculations of the spatial constants were made by using the CANDU-scheme as well as the TERMIDOR scheme.

The plots show, that for large clusters the TERMIDOR results are in favour to the CANDU ones.

Differences in the 7-rod cluster case amount to about $0.4 \, \text{m}^{-2}$ at under-moderated lattices. For single rod lattices the difference is of the same order of magnitude but of opposite sign.

II.4. Chalk River experiments

In the ZED-II reactor at Chalk River, a zero energy critical facility, a series of experiments has been made of the spectral constants, Westcott values in the fuel and moderator regions, thermal neutron spectrum spatial distributions relative conversion ratio's and fast fission ratio's. With the aid of these figures the detailed nuclear parameters could be calculated.

To obtain a broad experimental background for recipes to be checked measurements were made for various lattice arrangements, i.e. with as variables the lattice pitch, coolant (organic - $\text{HB}_{40}$, heavy water and air); fuel compounds (uranium metal and oxide) and cluster type (7 and 19 rod hexagonal with about the same fuel volume per cm).

From above mentioned parameters the critical buckling was calculated. Apart from this results direct buckling measurements were made (Ref.20-23).

Comparisons with PLUTHARCO calculations have been performed for oxide fuel only.

The clusters are identified by a symbol which is divided into three parts (eq.7 $D_0 18$) the number of fuel pins per cluster, the coolant type and lattice pitch respectively.

For the 7 rod clusters the comparisons with detailed data are given in Table 11-13, the bucklings in fig.6-8; for the 19 rod clusters resp. Table 14-16 and fig.9-11.

A very good agreement is found for $\eta$, $\varepsilon$ and $f$, with differences in the order of 1 permille, the only appreciable difference found is in $p$, being of the order of 15 permille for small pitches and decreasing for larger ones.
The migration areas $L^2$ and $\tau$ show relatively the greatest differences with the CANDU results $L^2$ being too great and $\tau$ too small by about 6%. For the 7 rod clusters the differences of $L^2$ and $\tau$ are of different sign, in the 19 rod case both are appreciably smaller than the ones obtained from the measurements. As a result of this, one sees (Fig. 6-8) that the calculated bucklings are better in agreement with the experiments (differences about $0.1 \text{m}^{-2}$) for the 7 rod cluster than for the 19 rod cluster, which are all too high by at most $0.5 \text{m}^{-2}$. The measured Westcott $r$ factor for the Chalk River cluster has been compared with PLUTHARCO. The measured values turned out to be $3^\circ/\circ$ smaller independent of the pitch.

The measured moderator spectral constants correspond very well with the calculated ones too, the last ones being smaller by about $3-5^\circ/\circ$. The calculated fuel spectral constants however, are too low by $30^\circ/\circ$ for small pitches decreasing to $15^\circ/\circ$ for large pitches. The resulting buckling difference on the other hand never exceed $0.2\text{m}^{-2}$.

II.5. Conclusions

As conclusion may be said that in general the detailed nuclear parameters $\eta, \epsilon, p$ and $f$ were good compared with the measurements.

The migration area $L^2$ and $\tau$ show relatively much greater differences than the former four. Whether $L^2$ shows differences in both directions little can be said from the comparisons. However the Fermi-age calculated in PLUTHARCO is without exception smaller than the values quoted from experiments.

The buckling values are generally sufficiently near to the values given by the experiments. Differences are mostly within $0.3 \text{m}^{-1}$.

Furthermore the results show that for small pitches systematically too low values of the buckling are obtained with PLUTHARCO. This may be caused by two effects:

1. Inaccuracy in the scheme describing the flux disadvantage factors in the epithermal range,
2. Approximation in the assumption of the Westcott scheme, due to spectrum hardening.
Indeed is found from the Savannah River comparisons that a more rigorous method to calculate the spectral constants improves the general agreement with the experimental results at low pitches (see Fig. 4).
Fig. 1 Comparison between EXPO experiments and PLUTHARCO calculations.

- ○ experiments
- → calculations
Fig. 2 Comparison between CISE experiments and PLUTHARC calculations.

- Experiments
- Calculations

Fig. 3 Comparison between Savannah River experiments and PLUTHARC calculations (Single rod).

- PLUTHARC
- foil experiments
- Flux mapping
- TERMIDOR
Fig. 4: Comparison between Savannah River experiments and PLUTHARCO calculations (3 rod cluster).

- PLUTHARCO
- foil experiments
- flux mapping
- TERMIDOR

Fig. 5: Comparison between Savannah River experiments and PLUTHARCO calculations (7 rod cluster).

- PLUTHARCO
- foil experiments
- flux mapping
- TERMIDOR
Fig. 6 Comparison between Chalk River experiments and PLUTHARCO calculations (7 rod cluster, D_0 cooled).

Fig. 7 Comparison between Chalk River experiments and PLUTHARCO calculations (7 rod cluster, air cooled).
Fig. 8 Comparison between Chalk River experiments and PLUTHARCO calculations (3 rod cluster, organic cooled).

- experiments
- calculations

Fig. 9 Comparison between Chalk River experiments and PLUTHARCO calculations (19 rod cluster, D/O cooled).

- experiments
- calculations
Fig. 10 Comparison between Chalk River experiments and PLUTHARCO calculations (19 rod cluster, air cooled)

Fig. 11 Comparison between Chalk River experiments and PLUTHARCO calculations (19 rod cluster, organic cooled)
III. Compilation of formulae

A complete set of formulae is given in the next part of the report together with a list of symbols.

List of symbols

III.1. Cross sections

a. Subscripts

The first index refers to the type of reaction, the second to the type of material.

Type of reaction
a = absorption = capture + fission
c = capture
e = fast elastic scattering
f = fission
i = fast inelastic scattering
s = elastic scattering
t = total = absorption + scattering
tr = transport

Type of material
c = fuel
g = canning
m = moderator
o = coolant (organic or heavy water)
r = filler
t = assembly of pressure tube (1) and calandria tube (3)
u = uranium

b. Superscripts

e = epithermal
FE = fertile isotope (Th-232, U-238, Pu-240)
FI = fissile isotope (U-233, U-235, Pu-239, Pu-241)
t = thermal
(1) = fast above fission threshold
(2) = fast beneath " "
1 = fast group in 2 group scheme
III. 2. Physical parameters

a.  

EXSAP = extra absorption in SAP due to impurities (value at 2200/sec x 10^5) 
F(i) = atomic fraction of isotope i 
f(1/v) = spectrum mean microscopic 1/v absorbing cross section/barn (2200m/sec) 
g = Westcott averaging factor 
HBR = percentage of high boiling residues in santowax 
M = molecular number 
N = number of nuclei/cm^3 
N_h = number of H-atoms/organic molecule 
N_c = number of C-atoms/organic molecule 
Pu = purity of heavy water 
r = epithermal flux fraction 
s = Westcott factor 
S = reference density 
T = temperature (°C) 
T_n = spectral constant (°K) 
T_o = room temperature (293°K)

b. Subscripts

c = fuel 
d = diphenyl 
g = canning 
gr = graphite 
m = moderator 
O = coolant (organic or heavy water) 
Oi = inner coolant 
OO = outer coolant 
r = filler 

ALFA = weight percentage of Al_2O_3 in SAP 
RHO = density (g/cm^3) 
RLTFÎ = inverse reference transport cross section 
B}H = averaged scattering cross section/H-atom 
SAL = effective absorption section (averaged over a Maxwellian flux at fuel temperature T_n) due to alloys contained in the fuel 
CHW = additional heavy water absorption section due to impurities other than light water (value at 2200m/sec)
III.3. Geometrical parameters

a.

\( V \) = volume
\( Z \) = square pitch
\( b \) = lattice cell radius
\( a \) = bundle radius
\( S \) = bundle effective fuel surface / cm
\( R_c \) = inscribed circle between fuel rods in cluster
\( \gamma \) = escape probability

b. subscripts

For region identification see 2. (physical parameters)

\( u \) = total (in connection with \( S \))
\( f \) = outer (in connection with \( S \))
\( t_1 \) = first tube (pressure tube)
\( t_2 \) = second tube (isolation tube)
\( t_3 \) = third tube (calandria tube)
\( t \) = three former tubes
\( B \) = bundle

c. superscripts

\( t \) = thermal
\( f \) = fast
\( e \) = epithermal
1. Calculation of spectral constants

a. Correlated spectral constants

\[ (T'_n)_f = 6.8 \cdot (V_c \cdot Z_{ae}^t + V_q \cdot Z_{ae}^t + V_b \cdot Z_{so}^t + V_r \cdot Z_{ae}^t) - 0.11 \cdot V_b \cdot Z_{so}^t \]
\[ + 0.0044 \cdot V_c \cdot Z_{ae}^t \cdot (T_c - T_m) + 0.00168 \cdot (V_q + V_b) \cdot Z_{ae}^t \cdot (T_b - T_m) \]
\[ + (T_b - T_m) \cdot (1 - 0.3 \cdot 0.1 \cdot V_b \cdot Z_{so}^t - 0.2 \cdot 0.7 \cdot V_b \cdot Z_{so}^t) + T_m + 800\gamma \]

\[ (T'_n)_q = (T'_n)_f \]
\[ (T'_n)_o = (T'_n)_f \]
\[ (T'_n)_r = \frac{(T'_n)_0 + (T'_n)_m}{2} \]
\[ (T'_n)_l_2 = (T_n)_r \]
\[ (T'_n)_l_0 = (T_n)_r \]
\[ (T'_n)_m = T_m + 800\gamma \]

b. Spectral constants directly entered

c. TERMIDOR spectral constants for calculating \( \frac{1}{V} \)-cross sections

\[ (T_n)_f = \frac{\pi}{4} \cdot \frac{a_{99.6}}{r^2(\frac{1}{4})_c} \]
\[ (T_n)_q = (T_n)_f \]
\[ (T_n)_o = (T_n)_f \]
\[ (T_n)_r = \frac{(T_n)_0 + (T_n)_m}{2} \]
\[ (T_n)_l_2 = (T_n)_r \]
\[ (T_n)_l_0 = (T_n)_r \]
\[ (T_n)_m = \frac{\pi}{4} \cdot \frac{a_{99.6}}{r^2(\frac{1}{4})_m} \]

For non-\( \frac{1}{V} \)-cross sections: data are entered directly

\[ \varphi_0 (238) \]
\[ \varphi_0 (239) \]
\[ \varphi_7 (238) \]
\[ \varphi_7 (239) \]
2. Calculation Westcott constants

\[ q_a(252) = 4. \]
\[ q_a(258) = 4. \]
\[ s_a(246) = 50 \cdot \frac{T_m}{295} \cdot \frac{T}{4} \]

\[ s_a(240) = \frac{s_a(240)}{\sqrt{1 + 4 \cdot V_c \cdot N \cdot 415000 \cdot F(240) \cdot 8000}} \]

\[ s_a(239) = \frac{s_a(239)}{\sqrt{1 + 4 \cdot V_c \cdot N \cdot F(239) \cdot 3400}} \]

3. Calculation Westcott cross sections

\[ \hat{d}_a(i) = q_a^+(i) \cdot \left[ q(i) + r \cdot s(i) \right] \]

\[ \hat{d}_f(i) = q_f^+(i) \cdot \left[ q(i) + r \cdot s(i) \right] \]

<table>
<thead>
<tr>
<th>i</th>
<th>Material</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
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<td>7</td>
<td>Pu 240</td>
</tr>
<tr>
<td>8</td>
<td>Pu 241</td>
</tr>
</tbody>
</table>
4. Mixed fuel microscopic cross sections

\[ \sigma_{\alpha}^t = \sum \frac{F(i) \cdot \phi_{\alpha}^t(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \sigma_{\beta}^t = \sum \frac{F(i) \cdot \sigma_{\beta}^t(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \sigma_{\gamma}^t = \sum \frac{F(i) \cdot \phi_{\gamma}^t(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ (\nu \sigma_{\gamma})^t = \sum \frac{F(i) \cdot \nu(i) \cdot \phi_{\gamma}^t(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \sigma_{\xi}^{(t)} = \sum \frac{F(i) \cdot \sigma_{\xi}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \phi_{\xi}^{(t)} = \sum \frac{F(i) \cdot \phi_{\xi}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \sigma_{\phi}^{(t)} = \sum \frac{F(i) \cdot \sigma_{\phi}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ (\nu \phi_{\phi})^{(t)} = \sum \frac{F(i) \cdot (\nu \phi_{\phi})^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \sigma_{\psi}^{(t)} = \sum \frac{F(i) \cdot \sigma_{\psi}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \phi_{\psi}^{(t)} = \sum \frac{F(i) \cdot \phi_{\psi}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \sigma_{\chi}^{(t)} = \sum \frac{F(i) \cdot \sigma_{\chi}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \phi_{\chi}^{(t)} = \sum \frac{F(i) \cdot \phi_{\chi}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \sigma_{\delta}^{(t)} = \sum \frac{F(i) \cdot \sigma_{\delta}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]

\[ \phi_{\delta}^{(t)} = \sum \frac{F(i) \cdot \phi_{\delta}^{(t)}(i)}{\sqrt{\frac{T}{4}} \cdot \frac{295.6}{T_n}} \]
5. Fertile isotope macroscopic cross sections

\[ \Sigma_{\text{Fert}}^F = \sum_{k=1}^{\infty} F(k) \cdot N \cdot \hat{\sigma}_k(k) \cdot \sqrt{\frac{\pi \cdot 295.6}{T_{20}}} = \sum_{k=1}^{\infty} \Sigma_{\text{Fert}}(k) \]

\[ \Sigma_{\text{Fert}}^{(1)} = \sum_{k=1}^{\infty} F(k) \cdot N \cdot \sigma_F^{(1)}(k) = \sum_{k=1}^{\infty} \Sigma_{\text{Fert}}^{(1)}(k) \]

\[ \Sigma_{\text{Fert}}^{(2)} = \sum_{k=1}^{\infty} F(k) \cdot N \cdot \left[ \psi_t^{(1)}(k) - \psi_e^{(1)}(k) - \psi_t^{(2)}(k) - \psi_e^{(2)}(k) \right] = \sum_{k=1}^{\infty} \Sigma_{\text{Fert}}^{(2)}(k) \]

\[ \Sigma_{\text{c}}^{(1)} = \sum_{k=1}^{\infty} F(k) \cdot N \cdot \left[ \psi_t^{(1)}(k) - \psi_e^{(1)}(k) \right] = \sum_{k=1}^{\infty} \Sigma_{\text{c}}^{(1)}(k) \]

6. Resonance integrals

\[ A(k,j) \quad \text{function of} \quad [T] \]

\[ B(k,j) \quad \text{function of} \quad [T] \]

\[ U_1(k) = F(k) \cdot N \cdot A(k,j) \]

\[ U_2(k) = \frac{F(k) \cdot N \cdot B(k,j)}{\sqrt{\rho \cdot F(k)}} \]

7. Fissile isotope macroscopic cross sections

\[ \Sigma_{\text{Fiss}}^P = \sum_{l=1}^{\infty} F(l) \cdot N \cdot \hat{\sigma}_k(l) \cdot \sqrt{\frac{\pi \cdot 295.6}{T}} = \sum_{l=1}^{\infty} \Sigma_{\text{Fiss}}(l) \]

\[ \Sigma_{\text{Fiss}}^{(1)} = \sum_{l=1}^{\infty} F(l) \cdot N \cdot \sigma_F^{(1)}(k) = \sum_{l=1}^{\infty} \Sigma_{\text{Fiss}}^{(1)}(k) \]

\[ \Sigma_{\text{Fiss}}^{(2)} = \sum_{l=1}^{\infty} F(l) \cdot N \cdot \left[ \psi_t^{(1)}(k) - \psi_e^{(1)}(k) - \psi_t^{(2)}(k) - \psi_e^{(2)}(k) \right] = \sum_{l=1}^{\infty} \Sigma_{\text{Fiss}}^{(2)}(k) \]

\[ \Sigma_{\text{c}}^{(1)} = \sum_{l=1}^{\infty} F(l) \cdot N \cdot \left[ \psi_t^{(1)}(k) - \psi_e^{(1)}(k) \right] = \sum_{l=1}^{\infty} \Sigma_{\text{c}}^{(1)}(k) \]
8. Fuel compound macroscopic cross sections

\[ \Sigma_h^f = N \cdot \left[ \sigma_h^f + \Sigma_{sd}^f (i) \right] \Sigma_{sd}^h \]

\[ \Sigma_f^f = N \cdot \left[ \sigma_f^f + \Sigma_{fd}^f (i) \right] \]

\[ (\odot \Sigma_{f})^f = N \cdot (\odot \sigma_f) \]

\[ \Sigma_{tr}^f = N \cdot \left[ \sigma_{tr}^f + \Sigma_{trd}^f (i) \right] \]

\[ \Sigma_{e}^f = N \cdot \left[ \sigma_{e}^f + \Sigma_{etd}^f (i) \right] \]

\[ \Sigma_{tr}^e = N \cdot \left[ \sigma_{tr}^e + \Sigma_{trd}^e (i) \right] \]

\[ (\odot \Sigma_{e})^e = N \cdot \left[ (\odot \sigma_{e})^e + (\odot \sigma_f)^e (i) \right] \]

\[ (\odot \Sigma_{f})^e = N \cdot (\odot \sigma_f) \]

\[ \Sigma_{i}^{(i)} = N \cdot \left[ \sigma_{i}^{(i)} + \Sigma_{i^d}^{(i)} (i) \right] \]

\[ \Sigma_{e}^{(i)} = N \cdot \left[ \sigma_{e}^{(i)} + \Sigma_{etd}^{(i)} (i) \right] \]

\[ \Sigma_{i}^{(i)} = N \cdot \left[ \sigma_{i}^{(i)} + \Sigma_{id}^{(i)} (i) \right] \]

\[ \Sigma_{f}^{(i)} = N \cdot \sigma_{f}^{(i)} \]

\[ \Sigma_{c}^{(i)} = N \cdot \left[ \sigma_{c}^{(i)} + \Sigma_{id}^{(i)} (i) - \Sigma_{etd}^{(i)} - \Sigma_{id}^{(i)} \right] \]

\[ \Sigma_{l}^{(s)} = N \cdot \left[ \sigma_{l}^{(s)} + \Sigma_{id}^{(s)} (i) \right] \]

\[ \Sigma_{e}^{(s)} = N \cdot \left[ \sigma_{e}^{(s)} + \Sigma_{etd}^{(s)} (i) \right] \]

\[ \Sigma_{c}^{(s)} = \Sigma_{i}^{(s)} - \Sigma_{e}^{(s)} \]
ORGANIC COOLANT (\(C_{N_c}H_{N_h}\))

\(\alpha\). Thermal cross sections

\[\Sigma^t_a = \frac{0.6024}{M} \left[ N_h \cdot 0.532 + N_c \cdot 0.00485 \right] \cdot \sqrt{\frac{T_0}{4T_{th}}} \cdot p_0\]

\[\Sigma^t_b = \frac{0.6024}{M} \left[ N_h \cdot \bar{v}_{bn}(T) + N_c \cdot 4.1 \right] \cdot p_0\]

\[\Sigma^t_{tr} = \frac{0.6024}{M} \left[ N_h \cdot [\lambda_{bn}]_d + N_c \cdot 4.5 \right] \cdot p_0\]

\(\beta\). Resonance and epithermal cross sections

\[\Sigma^r_e = \frac{0.6024}{M} \left[ N_h \cdot 20.4 + N_c \cdot 4.66 \right] \cdot p_0\]

\[\Sigma^r_{tr} = \frac{0.6024}{M} \left[ N_h \cdot 20.4 \cdot (1-0.667) + N_c \cdot 4.66 \cdot (1-0.056) \right] \cdot p_0\]

\[(\xi_2)^e = \frac{0.6024}{M} \left[ N_h \cdot 20.4 + N_c \cdot 0.1589 \cdot 4.66 \right] \cdot p_0\]

\(\gamma\). Fast cross sections

\[\Sigma^{(1)}_e = \frac{0.6024}{M} \left[ N_h \cdot 1.91 + N_c \cdot 1.69 \right] \cdot p_0\]

\[\Sigma^{(1)}_b = \frac{0.6024}{M} \left[ N_h \cdot 0.45 + N_c \cdot 1.27 \right] \cdot p_0\]

\[\Sigma^{(1)}_{tr} = \frac{0.6024}{M} \left[ N_h \cdot 1.46 + N_c \cdot 0.22 \right] \cdot p_0\]

\[\Sigma^{(2)}_e = \frac{0.6024}{M} \left[ N_h \cdot 4.56 + N_c \cdot 2.78 \right] \cdot p_0\]

\[\Sigma^{(2)}_{tr} = \frac{0.6024}{M} \left[ N_h \cdot 4.56 + N_c \cdot 2.78 \right] \cdot p_0\]
SANTOWAX (C$_{18}$H$_{14}$)

### a. Thermal cross sections

\[
\Sigma_\text{th} = 1.099 - 0.00072 T + 0.0009 \times x \quad (x = \% \text{ UBR} ; \ T \text{ in } ^\circ \text{C})
\]

\[
\begin{align*}
\Sigma_{\text{th}}^t &= \frac{0.6024}{280} \left[ 14.0 - 0.002 + 18.0 \cdot 0.0048 \right] \sqrt{\frac{T_L}{T_H}} \cdot \rho_s \\
\Sigma_{\text{th}}^f &= \frac{0.6024}{280} \left[ 14.0 \cdot 0.667 + 18.0 \cdot 4.56 \right] \cdot \rho_s \\
\Sigma_{\text{th}}^r &= \frac{0.6024}{280} \left[ 14.0 \cdot 0.048 \cdot 0.667 + 18.0 \cdot 4.66 \right] \cdot \rho_s
\end{align*}
\]

### b. Resonance and epithermal cross sections

\[
\begin{align*}
\Sigma_{\text{r}}^t &= \frac{0.6024}{280} \left[ 14.0 \cdot 0.45 + 18.0 \cdot 4.66 \right] \cdot \rho_s \\
\Sigma_{\text{r}}^f &= \frac{0.6024}{280} \left[ 14.0 \cdot 0.45 \cdot 0.667 + 18.0 \cdot 4.66 \cdot 0.0002 \right] \cdot \rho_s \\
\Sigma_{\text{r}}^r &= \frac{0.6024}{280} \left[ 14.0 \cdot 0.048 \cdot 0.667 \cdot 0.0002 + 18.0 \cdot 4.66 \cdot 0.0002 \right] \cdot \rho_s
\end{align*}
\]

### c. Fast cross sections

\[
\begin{align*}
\Sigma_{\text{f}}^{(1)} &= \frac{0.6024}{280} \left[ 14.0 \cdot 0.45 + 18.0 \cdot 1.49 \right] \cdot \rho_s \\
\Sigma_{\text{f}}^{(2)} &= \frac{0.6024}{280} \left[ 14.0 \cdot 4.56 + 18.0 \cdot 1.27 \right] \cdot \rho_s \\
\Sigma_{\text{f}}^{(3)} &= \frac{0.6024}{280} \left[ 14.0 \cdot 4.56 + 18.0 \cdot 2.78 \right] \cdot \rho_s \\
\Sigma_{\text{f}}^{(4)} &= \frac{0.6024}{280} \left[ 14.0 \cdot 4.56 + 18.0 \cdot 2.78 \right] \cdot \rho_s
\end{align*}
\]
DIPHENYL (C_{12} H_{10})

α. **Thermal cross sections**

\[
\begin{align*}
\Sigma^t_a &= \frac{0.6024}{154} \left[ 40 \cdot 0.392 + 42 \cdot 0.00453 \right] \sqrt{\frac{T_0}{4 \cdot T_m}} \cdot \rho_d \\
\Sigma^t_b &= \frac{0.6024}{154} \left[ 40 \cdot \frac{\bar{v}(\gamma)}{\bar{v}_n} + 42 \cdot 4.8 \right] \cdot \rho_d \\
\Sigma^t_{br} &= \frac{0.6024}{154} \left[ 40 \cdot \left[ \rho \lambda_{br} \right] + 42 \cdot 4.55 \right] \cdot \rho_d \\
\end{align*}
\]

β. **Resonance and epithermal cross sections**

\[
\begin{align*}
\Sigma^e_a &= \frac{0.6024}{154} \left[ 40 \cdot 80.4 + 42 \cdot 4.66 \right] \cdot \rho_d \\
\Sigma^e_{br} &= \frac{0.6024}{154} \left[ 40 \cdot 20.4 \left( 1 - 0.667 \right) + 42 \cdot 4.66 \left( 1 - 0.086 \right) \right] \cdot \rho_d \\
(2 \Sigma^e_{a'} &= \frac{0.6024}{154} \left[ 40 \cdot 80.4 + 42 \cdot 0.1839 \cdot 4.66 \right] \cdot \rho_d \\
\end{align*}
\]

γ. **Fast cross sections**

\[
\begin{align*}
\Sigma^{(1)}_t &= \frac{0.6024}{154} \left[ 40 \cdot 4.91 + 42 \cdot 4.49 \right] \cdot \rho_d \\
\Sigma^{(1)}_e &= \frac{0.6024}{154} \left[ 40 \cdot 0.45 + 42 \cdot 4.27 \right] \cdot \rho_d \\
\Sigma^{(1)}_i &= \frac{0.6024}{154} \left[ 40 \cdot 4.16 + 42 \cdot 0.21 \right] \cdot \rho_d \\
\Sigma^{(0)}_t &= \frac{0.6024}{154} \left[ 40 \cdot 4.56 + 42 \cdot 2.78 \right] \cdot \rho_d \\
\Sigma^{(0)}_e &= \frac{0.6024}{154} \left[ 40 \cdot 4.56 + 42 \cdot 2.78 \right] \cdot \rho_d \\
\end{align*}
\]
HEAVY WATER (coolant)

α. Thermal cross sections

\[ \Sigma_\text{th} = \left[ 0.6425 \times 10^{-4} - 0.0181 \left( \text{PU} - 0.998 \right) + \Sigma_\text{inj} \sqrt{\frac{E}{b}} \right] \sqrt{\frac{E}{b}} \cdot \rho_m \]

\[ \Sigma_\text{th} = \left[ 0.4216 \times \text{PU} + 2.68 \times (1 - \text{PU}) \right] \cdot \rho_m \]

\[ \Sigma_\text{th} = \left[ 0.3628 \times \text{PU} + 0.995 \times (1 - \text{PU}) \right] \cdot \rho_m \]

β. Resonance and epithermal cross sections

\[ \Sigma_{\text{res}} = 0.437 \times \text{PU} + 0.995 \times (1 - \text{PU}) \cdot \rho_m \]

\[ (\Sigma_{2\text{s}})_{\text{res}} = 0.4604 \times \text{PU} + 2.66 \times (1 - \text{PU}) \cdot \rho_m \]

γ. Fast cross sections

\[ \Sigma_{\text{f(1)}} = 0.1542 \cdot \rho_m \]

\[ \Sigma_{\text{f(2)}} = 0.0705 \cdot \rho_m \]

\[ \Sigma_{\text{f(3)}} = 0.0358 \cdot \rho_m \]

\[ \Sigma_{\text{c(1)}} = 0 \]

\[ \Sigma_{\text{i(1)}} = 0.2800 \cdot \rho_m \]

\[ \Sigma_{\text{i(2)}} = 0.2800 \cdot \rho_m \]

\[ \Sigma_{\text{i(3)}} = 0 \]
a. Thermal cross sections

\[ \Sigma_a^t = \left[ 0.004547 - 0.002163 a + \text{ExSAP} \right] \rho_{\text{SAP}} \sqrt{\frac{T}{T_o}} \]

\[ \Sigma_e^t = \left[ 0.0303 + 0.0618 a \right] \rho_{\text{SAP}} \]

\[ \Sigma_{1n}^t = \left[ 0.0000 + 0.0576 a \right] \rho_{\text{SAP}} + \Sigma_a^t \]

b. Epithermal cross sections

\[ (\Sigma_p^t) = \left[ 0.00222 + 0.00795 a \right] \rho_{\text{SAP}} \]

\[ \Sigma_{1n}^t = \left[ 0.0300 + 0.0576 a \right] \rho_{\text{SAP}} \]

c. Fast cross sections

\[ \Sigma_{11}^{(1)} = 0.60248 \left[ \frac{1-a}{27} \cdot 1.7 + \frac{2a}{402} \cdot 1.7 + \frac{3a}{402} \cdot 1.92 \right] \rho_{\text{SAP}} \]

\[ \Sigma_{11}^{(2)} = 0.60248 \left[ \frac{1-a}{27} \cdot 1.5 + \frac{2a}{402} \cdot 1.5 + \frac{3a}{402} \cdot 1.7 \right] \rho_{\text{SAP}} \]

\[ \Sigma_{11}^{(3)} = 0.60248 \left[ \frac{1-a}{27} \cdot 0.2 + \frac{2a}{402} \cdot 0.2 + \frac{3a}{402} \cdot 0.22 \right] \rho_{\text{SAP}} \]

\[ \Sigma_{11}^{(4)} = 0.60248 \left[ \frac{1-a}{27} \cdot 0.025 + \frac{2a}{402} \cdot 0.025 + \frac{3a}{402} \cdot 0.07 \right] \rho_{\text{SAP}} \]

\[ \Sigma_{11}^{(5)} = 0.60248 \left[ \frac{1-a}{27} \cdot 0.025 + \frac{2a}{402} \cdot 0.025 + \frac{3a}{402} \cdot 0.07 \right] \rho_{\text{SAP}} \]

\[ \Sigma_{11}^{(6)} = 0.60248 \left[ \frac{1-a}{27} \cdot 1.7 + \frac{2a}{402} \cdot 1.7 + \frac{3a}{402} \cdot 1.92 \right] \rho_{\text{SAP}} \]
STEEL

\section{Thermal cross sections}

\begin{align*}
Z_a^t & = 0.215 \frac{Z_a}{Z_m} \\
Z_n^t & = 0.843 \\
Z_{tr}^t & = 0.242 + Z_a^t
\end{align*}

\section{Epithermal cross sections}

\begin{align*}
(e,\gamma)^e & = 0.02472 \\
Z_{e}^{e} & = 0.832
\end{align*}

\section{Fast cross sections}

\begin{align*}
\Sigma_i^{(0)} & = 0.1766 \\
\Sigma_a^{(0)} & = 0.1534 \\
\Sigma_i^{(0)} & = 0.0424 \\
\Sigma_c^{(0)} & = 0.2058 \\
\Sigma_e^{(0)} & = 0.2058 \\
\Sigma_c^{(0)} & = 0.
\end{align*}
ALUMINUM OXIDE

a. Thermal cross sections

\[ \Sigma_a^t = 0.00934 \cdot \sqrt{\frac{\Sigma_t}{\Sigma_a}} \]

\[ \Sigma_e^t = 0.5548 \]

\[ \Sigma_{ew}^t = 0.3440 + \Sigma_a^t \]

b. Epithermal cross sections

\[ \Sigma_s^e = 0.5648 \]

\[ \Sigma_{te}^e = 0.3440 \]

\[ (q \Sigma_s^e) = 0.05949 \]

c. Fast cross sections

\[ \Sigma_t^{(0)} = 0. \]

\[ \Sigma_e^{(0)} = 0. \]

\[ \Sigma_i^{(0)} = 0. \]
SILICIUM OXIDE

\[ \alpha. \ \text{Thermal cross sections} \]

\[ \Sigma_a^t = 0.00 \times 10^2 g \cdot \frac{1}{T_a^t} \]
\[ \Sigma_s^t = 0.222 g \]
\[ \Sigma_{tr}^t = 0.2145 + \Sigma_a^t \]

\[ \beta. \ \text{Epithermal cross sections} \]

\[ \Sigma_s^e = 0.222 g \]
\[ \Sigma_{tr}^e = 0.2143 \]
\[ (\Sigma_s^e)^e = 0.02486 \]

\[ \gamma. \ \text{Fast cross sections} \]

\[ \Sigma_t^{(1)} = 0 \]
\[ \Sigma_a^{(2)} = 0 \]
\[ \Sigma_s^{(3)} = 0 \]
\[ \Sigma_{tr}^{(4)} = 0 \]
GRAPHITE

\textbf{Thermal cross sections}

\begin{align*}
\Sigma_{\text{a}}^t &= 0.0004 \cdot S_{\text{gr}} \cdot \sqrt{\frac{T_{\text{a}}}{T_{\text{n}}}} \\
\Sigma_{\text{b}}^t &= 0.3972 \cdot S_{\text{gr}} \\
\Sigma_{\text{fr}}^t &= 0.5372 (1 - 0.056) \cdot S_{\text{gr}}
\end{align*}

\textbf{Epithermal cross sections}

\begin{align*}
\Sigma_{\text{a}}^e &= 0.386 \cdot S_{\text{gr}} \\
\Sigma_{\text{fr}}^e &= 0.386 (1 - 0.056) \cdot S_{\text{gr}} \\
(\Sigma_2^e) &= 0.06127 \cdot S_{\text{gr}}
\end{align*}

\textbf{Fast cross sections}

\begin{align*}
\Sigma_{\text{t}}^{(1)} &= 0.1284 \cdot S_{\text{gr}} \\
\Sigma_{\text{t}}^{(2)} &= 0.4052 \cdot S_{\text{gr}} \\
\Sigma_{\text{t}}^{(3)} &= 0.0182 \cdot S_{\text{gr}} \\
\Sigma_{\text{c}}^{(1)} &= 0. \\
\Sigma_{\text{t}}^{(2)} &= 0.2303 \cdot S_{\text{gr}} \\
\Sigma_{\text{t}}^{(3)} &= 0.2303 \cdot S_{\text{gr}} \\
\Sigma_{\text{c}}^{(2)} &= 0.
\end{align*}
HEAVY WATER (moderator)

\( \alpha. \) Thermal cross sections

\[ \begin{align*}
\Sigma_t^t &= \left[ 0.6423 \cdot 10^{-4} - 0.0181 (1 - \text{Pu}) - 0.998 \right] \left( \frac{T_0}{T_m} \right) \cdot \Sigma_m^r \\
\Sigma_t^s &= \left[ 0.4216 \cdot \text{Pu} + (1 - \text{Pu}) \times 2.68 \right] \cdot \Sigma_m^r \\
\Sigma_t^{tr} &= \left[ 0.4216 \cdot (1 - 0.195) \cdot \text{Pu} + 0.998 (1 - \text{Pu}) \right] \cdot \Sigma_m^r \\
&= \left[ 0.3623 \cdot \text{Pu} + 0.998 (1 - \text{Pu}) \right] \cdot \Sigma_m^r
\end{align*} \]

\( \beta. \) Epithermal cross sections

\[ \begin{align*}
\Sigma_t^{tr} &= \left[ 0.257 \cdot \text{Pu} + 0.998 (1 - \text{Pu}) \right] \cdot \Sigma_m^r \\
(\Sigma T_0)^e &= \left[ 0.1604 \cdot \text{Pu} + 2.56 (1 - \text{Pu}) \right] \cdot \Sigma_m^r
\end{align*} \]

\( \gamma. \) Ages

\[ \begin{align*}
S_m^e &= \left[ \frac{\Sigma_m^r}{1.1054} \right]^2 \\
\tau^0 &= \text{function of} \left[ \ln (1 - \text{Pu}) \right] \\
\tau_e^0 &= \frac{\ln \frac{T_0}{T_m}}{S_m^e} - \frac{\ln \frac{T_0}{T_m}}{3 (\Sigma T_0)^e \cdot \Sigma_t^{trm}} \\
\tau_i^0 &= \frac{0.6 \tau^0}{S_m^e} - \frac{\ln \frac{T_0}{T_m}}{3 (\Sigma T_0)^e \cdot \Sigma_t^{trm}} \\
\tau_s^0 &= \frac{\tau^0}{S_m^e} - \frac{\ln \frac{T_0}{T_m} + 1}{3 (\Sigma T_0)^e \cdot \Sigma_t^{trm}} \\
\Delta \tau_m &= \frac{\ln \frac{T_0}{T_m}}{3 (\Sigma T_0)^e \cdot \Sigma_t^{trm}} \quad E_m = 50 \text{ ev}
\end{align*} \]
THERMAL UTILISATION

\[ R_f = \frac{Z_{\text{alloy}}}{Z_{\text{ac}}} \quad \text{[} Z_{\text{alloy}}, Z_{\text{ac}} \text{due to alloys]} \]

\[ Z_{\text{au}} = Z_{\text{ac}} + Z_{\text{alloy}} \]

For all cases: \( A ; \mu ; \rho \) function of \( \left[ (Z_{\text{uc}} + Z_{\text{au}}) \cdot s \right] \)

For circular tubes: \( A ; \mu ; \rho \) function of \( \left[ \frac{(Z_{\text{uc}} + Z_{\text{au}}) \cdot s}{\pi (2e_a + 2e_b + 2e_c + 2e_d + d_4)} \right] \)

\[ q_{\text{uc}} = 1 + A \cdot \frac{Z_{\text{au}}}{Z_{\text{uc}} + Z_{\text{au}}} \cdot \left[ 1 + \alpha \cdot \frac{Z_{\text{uc}}}{Z_{\text{uc}} + Z_{\text{au}}} \cdot \rho \cdot \left( \frac{Z_{\text{uc}}}{Z_{\text{uc}} + Z_{\text{au}}} \right)^2 \right] \]

\[ R_f = \frac{v_\text{C} \cdot Z_{\text{au}}}{v_\text{C} \cdot Z_{\text{ac}}} \cdot q_{\text{uc}} \]

For the calculation of the thermal utilisation factor \( f \) the cell is divided into 6 regions:

1. Homogenised Fuel region

\[ \bar{Z}_{\text{uc}} = \frac{V_\text{C} \cdot Z_{\text{uc}}}{V_\text{b}} \]

\[ \bar{Z}_{\text{at}} = \frac{V_\text{C} \cdot Z_{\text{at}} + q_{\text{uc}} \left[ V_\text{C} \cdot Z_{\text{at}} + V_\text{F} \cdot Z_{\text{at}} + V_\text{O} \cdot Z_{\text{at}} \right]}{V_\text{b}} \]

\[ \bar{Z}_{\text{et}} = \frac{V_\text{C} \cdot Z_{\text{et}} + q_{\text{uc}} \left[ V_\text{C} \cdot Z_{\text{et}} + V_\text{F} \cdot Z_{\text{et}} + V_\text{O} \cdot Z_{\text{et}} \right]}{V_\text{b}} \]

\[ \bar{Z}_{\text{ct}} = \frac{V_\text{C} \cdot \left( (E_2)_{\text{C}} \right) + V_\text{C} \cdot \left( (E_2)_{\text{C}} \right) + V_\text{O} \cdot \left( (E_2)_{\text{C}} \right) + V_\text{F} \cdot \left( (E_2)_{\text{C}} \right)}{V_\text{b}} \]

2. Homogenised outer coolant region

\[ \bar{Z}_{\text{at}} = \frac{(V_\text{C} - V_\text{O}) \cdot Z_{\text{at}} + (\pi a^2 - V_\text{b}) \cdot Z_{\text{at}}}{\pi a^2 - V_\text{b}} \]

\[ \bar{Z}_{\text{et}} = \frac{(V_\text{C} - V_\text{O}) \cdot Z_{\text{et}} + (\pi a^2 - V_\text{b}) \cdot Z_{\text{et}}}{\pi a^2 - V_\text{b}} \]

\[ \bar{Z}_{\text{ct}} = \frac{(V_\text{C} - V_\text{O}) \cdot \left( (E_2)_{\text{C}} \right) + (\pi a^2 - V_\text{b}) \cdot \left( (E_2)_{\text{C}} \right)}{\pi a^2 - V_\text{b}} \]

For pressure tube region

4. Insulation region

5. Calandria region

6. Moderator region
DIFFUSION AREA

\[ q_e = \frac{V_c + V_q \cdot q_e \cdot (V_{r0}^t \cdot V_{r1}^t) \cdot q_e}{V_{r0}^t} \]

\[ V_{r0} \cdot q_e = V_{r0}^t \cdot q_e \cdot [ (V_{r0}^t + V_{r1}^t) \cdot p(\pi) + V_{r1} \cdot p(\pi) + V_{r3} \cdot p(\pi) ] \]

\[ Z_{t1}, V_{r1} \cdot q_e = Z_{t1}^t \cdot V_{r1} \cdot q_e \cdot [ (Z_{t1}^t + Z_{t1}^t \cdot V_{r1}^t \cdot V_{r1}^t) \cdot q_e + q_e \cdot [ p(\pi) \cdot (V_{r0}^t \cdot Z_{t1}^t + V_{r3}^t \cdot Z_{t1}^t) \cdot q_e + q_e \cdot [ p(\pi) \cdot (V_{r3} \cdot Z_{t1}^t + p(\pi) \cdot V_{r3} \cdot Z_{t1}^t + p(\pi) \cdot V_{r3} \cdot Z_{t1}^t ] } \]

\[ R_m = \frac{L_m}{f} \]

\[ L^2 = \left[ \frac{(V_{r0} \cdot q_e)^2}{Z_{t1}^t \cdot V_{r0} \cdot q_e \cdot Z_{r0}^t} + \frac{R_m}{Z_{r1}^t \cdot Z_{r1}^t \cdot Z_{r1}^t} \right] \cdot f \]

AVERAGE THERMAL FLUX

\[ \frac{q_e}{q_0} = \frac{V_{r0} \cdot q_{0} + V_{r1} \cdot q_{0} \cdot p(\pi)}{Z^t} \]

AVERAGE THERMAL ABSORPTION CROSS SECTION

\( Z_{am} \) is calculated by method of Amouyal - Benoist

THERMAL DIFFUSION COEFFICIENT

\[ D_m = L^2 \cdot Z_{am} \]
FAST FISSION FACTOR

\[ \tilde{Z}_t^{(1)} = \frac{V_c \cdot Z_c^{(1)} + V_{q_1} \cdot Z_{q_1}^{(1)} + V_{q_2} \cdot Z_{q_2}^{(2)} + V_{q_3} \cdot Z_{q_3}^{(3)} + V_{n_1} \cdot Z_{n_1}^{(1)} + V_{n_2} \cdot Z_{n_2}^{(2)} + V_{n_3} \cdot Z_{n_3}^{(3)}}{V_b} \]

\[ P_f \text{ function of } \left[ \frac{\tilde{Z}_t^{(1)} \cdot p_f}{\tilde{Z}_e^{(1)}} \right] \]

\[ \tilde{Z}_e^{(1)} = \frac{V_c \cdot Z_c^{(1)} + V_{q_1} \cdot Z_{q_1}^{(1)} + V_{q_2} \cdot Z_{q_2}^{(2)} + V_{q_3} \cdot Z_{q_3}^{(3)} + V_{n_1} \cdot Z_{n_1}^{(1)} + V_{n_2} \cdot Z_{n_2}^{(2)} + V_{n_3} \cdot Z_{n_3}^{(3)}}{V_b} \]

\[ \tilde{Z}_c^{(1)} = \frac{V_c \cdot Z_c^{(1)} + V_{q_1} \cdot Z_{q_1}^{(1)} + V_{q_2} \cdot Z_{q_2}^{(2)} + V_{q_3} \cdot Z_{q_3}^{(3)} + V_{n_1} \cdot Z_{n_1}^{(1)} + V_{n_2} \cdot Z_{n_2}^{(2)} + V_{n_3} \cdot Z_{n_3}^{(3)}}{V_b} \]

\[ \tilde{Z}_e^{(2)} = \frac{V_c \cdot Z_c^{(2)} + V_{q_1} \cdot Z_{q_1}^{(2)} + V_{q_2} \cdot Z_{q_2}^{(3)} + V_{q_3} \cdot Z_{q_3}^{(3)} + V_{n_1} \cdot Z_{n_1}^{(2)} + V_{n_2} \cdot Z_{n_2}^{(2)} + V_{n_3} \cdot Z_{n_3}^{(3)}}{V_b} \]

\[ \tilde{Z}_c^{(2)} = \frac{V_c \cdot Z_c^{(2)} + V_{q_1} \cdot Z_{q_1}^{(2)} + V_{q_2} \cdot Z_{q_2}^{(3)} + V_{q_3} \cdot Z_{q_3}^{(3)} + V_{n_1} \cdot Z_{n_1}^{(2)} + V_{n_2} \cdot Z_{n_2}^{(2)} + V_{n_3} \cdot Z_{n_3}^{(3)}}{V_b} \]

\[ \tilde{Z}_e^{(3)} = \frac{V_c \cdot Z_c^{(3)} + V_{q_1} \cdot Z_{q_1}^{(3)} + V_{q_2} \cdot Z_{q_2}^{(3)} + V_{q_3} \cdot Z_{q_3}^{(3)} + V_{n_1} \cdot Z_{n_1}^{(3)} + V_{n_2} \cdot Z_{n_2}^{(3)} + V_{n_3} \cdot Z_{n_3}^{(3)}}{V_b} \]

\[ \tilde{Z}_c^{(3)} = \frac{V_c \cdot Z_c^{(3)} + V_{q_1} \cdot Z_{q_1}^{(3)} + V_{q_2} \cdot Z_{q_2}^{(3)} + V_{q_3} \cdot Z_{q_3}^{(3)} + V_{n_1} \cdot Z_{n_1}^{(3)} + V_{n_2} \cdot Z_{n_2}^{(3)} + V_{n_3} \cdot Z_{n_3}^{(3)}}{V_b} \]

\[ \tilde{Z}_t^{(3)} = \tilde{Z}_e^{(3)} + \tilde{Z}_c^{(3)} \]

\[ P_t \text{ function of } \left[ \left( \tilde{Z}_e^{(2)} + \tilde{Z}_c^{(2)} \right) \cdot q_a^{\beta} \right] \]

\[ C_1 = \frac{0.561 \cdot P}{1 - \left[ 0.561 \cdot (\tilde{Z}_e^{(1)}) \cdot \tilde{Z}_e^{(1)} \right] \cdot P} \]

\[ C_2 = \frac{(\tilde{Z}_e^{(1)}) \cdot C_1 + 1}{\tilde{Z}_e^{(1)} \cdot C_1 + 1} \]

\[ C_3 = \frac{0.455 \cdot P_t \cdot C_2 \cdot \tilde{Z}_e^{(1)}}{\tilde{Z}_e^{(1)} \cdot C_1 \cdot (1 - \frac{P_t \cdot \tilde{Z}_e^{(1)}}{\tilde{Z}_e^{(1)} \cdot \tilde{Z}_c^{(1)}})} \]

\[ C_4 = \frac{(\tilde{Z}_e^{(1)} - \tilde{Z}_c^{(1)}) \cdot \tilde{Z}_e^{(1)}}{\tilde{Z}_e^{(1)} \cdot (1 - \frac{P_t \cdot \tilde{Z}_e^{(1)}}{\tilde{Z}_e^{(1)} \cdot \tilde{Z}_c^{(1)}})} \]

\[ \phi = \frac{\tilde{Z}_e^{(1)} \cdot \tilde{Z}_c^{(1)} \cdot \tilde{Z}_e^{(1)} \cdot \tilde{Z}_c^{(1)}}{\tilde{Z}_e^{(1)} \cdot \tilde{Z}_c^{(1)}} \]

\[ \epsilon = 1 + C_1 + G_1 + (C_2 + C_3) \cdot G_2 \]
SLOWING DOWN AREA

\[ V_{\text{b}} Z_{\text{trb}} = V_{c} Z_{\text{ic}} + V_{q} Z_{\text{trq}} + V_{v} Z_{\text{tv}} + V_{t} Z_{\text{trt}} + V_{\text{t}1} \cdot Z_{\text{trt}1} + V_{\text{t}2} \cdot Z_{\text{trt}2} + V_{\text{t}3} \cdot Z_{\text{trt}3} \]

\[ V_{\text{b}} (\xi Z_{\text{b}})^{\circ} = V_{c} (\xi Z_{\text{c}})^{\circ} + V_{q} (\xi Z_{\text{q}})^{\circ} + V_{v} (\xi Z_{\text{v}})^{\circ} + V_{t} (\xi Z_{\text{t}})^{\circ} + V_{\text{t}1} (\xi Z_{\text{t}1})^{\circ} + V_{\text{t}2} (\xi Z_{\text{t}2})^{\circ} + V_{\text{t}3} (\xi Z_{\text{t}3})^{\circ} \]

\[ P_{\text{f}} = C_{1} \cdot \frac{V_{\text{b}} Z_{\text{ic}}^{(1)}}{V_{\text{b}} Z_{t}^{(1)}} \]

\[ P_{0} = C_{1} \cdot \frac{V_{01} \cdot Z_{\text{ic}}^{(1)}}{V_{\text{b}} Z_{t}^{(1)}} + 0.87 \cdot (C_{2} + C_{3}) \cdot \frac{V_{01} \cdot Z_{\text{ie0}}^{(2)}}{V_{\text{b}} Z_{t}^{(1)}} \]

\[ \tau_{m} = \tau_{1} \cdot (1 - P_{\text{f}} - P_{0}) + \tau_{1} \cdot P_{\text{f}} + \tau_{0} \cdot P_{0} \]

\[ \tau = \tau_{m} \left( \frac{Z_{\text{a}}^{2}}{V_{\text{m}}} \right)^{3} \cdot \frac{1}{\left(1 + \frac{V_{\text{b}} \cdot Z_{\text{trb}}}{V_{\text{m}} \cdot Z_{\text{trm}}} \right) \cdot \left(1 + \frac{V_{\text{b}} (\xi Z_{\text{b}})^{\circ}}{V_{\text{m}} (\xi Z_{\text{b}})^{\circ}} \right)} \]

\[ \tau_{\text{a}} = \frac{\tau \cdot \tau_{\text{m}}}{\tau_{m}} \]
SLOWING DOWN CROSS SECTION

\[(\xi z_b)_m = \frac{V_b \cdot (\xi z_b)_b + V_m \cdot (\xi z_b)_m}{z^4}\]

FAST DIFFUSION COEFFICIENT

\[\Delta u = \mu \cdot \tau_m \cdot (\xi z_b)_{eq} \cdot \Sigma_{trm}\]

\[D_{tr} = \frac{(\xi z_b)_{eq} \cdot \tau}{\Delta u}\]
### Resonance Escape Probability

\[ \Sigma_R = \frac{V_0^f \cdot \Sigma_{ev} + V_n^f \cdot \Sigma_{st} + \left[ V_{qj}^f + \tau (r^2 - (r - dr)^2) \right] \Sigma_{st}^f}{V_{bi}^f + V_{ni}^f + V_{ij}^f + \tau (r^2 - (r - dr)^2)} \]

\[ R_i = \frac{d}{V_b} \]

\[ P_c \text{ function of } [\Sigma_R, R_i] \]

\[ \psi' = 2 \cdot \Sigma_R \cdot R_i \cdot (1 - P_c) \]

\[ S_u = 14. T. S \]

\[ S_f = 6. d + 2. T. S \]

\[ R_{i1} = \frac{d}{V_b} \]

\[ R_{i2} = \frac{d}{V_b} \]

\[ P_{c1} \text{ function of } [\Sigma_R, R_{i1}] \]

\[ P_{c2} \text{ function of } [\Sigma_R, R_{i2}] \]

\[ \psi' = \frac{4 \cdot \Sigma_R \cdot R_{i1} \cdot (1 - P_{c1}) + 2 \cdot \Sigma_R \cdot R_{i2} \cdot (1 - P_{c2})}{2 \cdot R_{i1} + R_{i2}} \]

\[ S_u = 33. T. S \]

\[ S_f = 12. d + 2. T. S \]

\[ R_i = d - \delta - \tau \]

\[ P_c \text{ function of } [\Sigma_R, R_i] \]

\[ \psi' = 2 \cdot \Sigma_R \cdot R_i \cdot (1 - P_c) \]

\[ S_u = 3. T. S \]

\[ S_f = 4. V_b \cdot d + 2. T. S \]

\[ \text{7-Rod Hexagonal} \]

\[ \text{19-Rod Hexagonal} \]

\[ \text{19-Rod Circular} \]

\[ \text{4-Rod} \]
\[ R_i = \sqrt[ \frac{V_e}{22. \pi} ]{ \frac{1}{d} \sqrt{ \frac{1}{4} \cdot \sqrt{3} - \frac{1}{2} \cdot \pi \cdot \frac{V_e}{22. \pi \cdot d^2} } } \]

\[ P_c \text{ function of } Z_a, R_i \]

\[ y' = 2 \cdot Z_R \cdot R_i \cdot (1 - P_c) \]

\[ S_U = 44 \cdot T \cdot S \]

\[ S_Y = 6.2842 \cdot d + 2 \cdot T \cdot S_b \]

\[ y' = 1 \]

\[ S_U = 2 \cdot T \cdot S \]

\[ S_F = 2 \cdot T \cdot S \]

\[ S_{off} = S_F + y'(S_U - S_Y) \]

\[ \begin{align*}
    P_{1w} & & & \text{function of } \left[ \frac{S_Y}{S_1}, S_1, Z_{so} \right] \\
    P_{2w} & & & \text{function of } \left[ \frac{r}{S_3}, S_3, Z_{so} \right] \\
    P_3 & & & \text{function of } \left[ \frac{dr}{dr}, dr, Z_{so} \right] \\
    P_{4w} & & & \text{function of } \left[ 0, S_{so} (1 - \frac{V_f}{r \cdot dr}) + \frac{V_f}{r \cdot dr} \right] \\
\end{align*} \]

\[ P_w = \pi \cdot\left[ \left( P_{1w} + P_{2w} \right) \cdot \left( r^2 - s^2 \right) + \left( P_{3w} + P_{4w} \right) \cdot \left( r^2 - s^2 \right) + \left( P_{3w} + P_{4w} \right) \cdot \left( s^2 \cdot dr^2 \right) + \left( P_{3w} + P_{4w} \right) \cdot \left( s^2 \cdot d \cdot d \right) \right] \]

\[ S_0 = 2 \cdot T \cdot S \]

\[ S_i = 4 \cdot P_w \cdot S_{so} \]

\[ S_{off} = S_0 + S_i \]
\[ Z'_a = \frac{V_c \cdot (qZ_1)^2 \cdot V_{q_1} \cdot (qZ_2)^2 \cdot V_{q_2} \cdot (qZ_3)^2 \cdot V_{q_3} \cdot (qZ_4)^2}{5 \cdot V_b} \]

\[ Z'_a = \frac{V_c \cdot Z^a_c \cdot V_{q_1} \cdot Z^a_c \cdot V_{q_2} \cdot Z^a_c \cdot V_{q_3} \cdot Z^a_c \cdot V_{q_4} \cdot Z^a_c}{V_b} \]

\[ \kappa' = b \cdot Z^a_c \cdot Z^a_a \cdot (1 - 0.8 \cdot \frac{Z^a_e}{Z^a_a}) \]

\[ p_0' \text{ function of } \left[ \frac{Z^a}{4 \cdot V_b \cdot Z^a_a} \right] \]

\[ p_0 = \frac{p_0'}{1 + 0.425 \cdot \kappa^2 \cdot a^2} \]

\[ I_{res}(i) = u_1(i) + u_2(i) \cdot \sqrt{\frac{5q^2}{V_c}} \]

\[ p_0(i) = \exp - \frac{V_c \cdot I_{res}(i)}{V_c \cdot (qZ_1)^2 \cdot V_{q_1} \cdot (qZ_2)^2 \cdot V_{q_2} \cdot (qZ_3)^2 \cdot V_{q_3} \cdot (qZ_4)^2} \]

\[ p(i) = 1 - (1 - p_0(i)) \cdot p_0 \]

\[ p = \prod_{i=1}^{n} b(i) \]
THERMAL FISSION FACTOR

\[ \eta = \frac{(y z_r)^f}{z_{ac}^i} \]

MULTIPLICATION FACTOR

\[ k_{ac} = \eta \cdot b \cdot f \cdot \eta \]

MATERIAL BUCKLING

\[ b^2 \cdot \mu^4 = \frac{- \left( \frac{\eta}{\mu^4} \right) \cdot \sqrt{\left( \frac{b}{b} \right)} \cdot \left( \frac{\eta}{\mu^4} \right)}{2} + 4 \cdot \frac{k_{ac} - 1}{\eta \cdot b \cdot f} \]

RATIO OF EPITHERMAL TO THERMAL FLUX

\[ b' = 1.004 \cdot \frac{\eta \cdot p \cdot e}{1 + b^2 \cdot f} \cdot \frac{v_c \cdot z_{ac}^i}{z^i \cdot (\eta z_{ac})_e} \]

\[ b = \frac{4}{\sqrt{6 \pi}} \]

\[ r' = \frac{p_e'}{b \cdot (1 + p_e)} \]
Calculation of input data for RLT 4

\[
\begin{align*}
\overline{v}_z^t &= (v_z^t)_y \\
\overline{\Sigma}_{\alpha}^t &= \overline{\Sigma}_{\alpha}^t \\
\overline{\Sigma}_{\beta}^t &= \overline{\Sigma}_{\beta}^t \\
\overline{\Sigma}_{c}^t &= \overline{\Sigma}_{c}^t \\
\overline{\Sigma}_{f}^t &= \overline{\Sigma}_{f}^t \\
\overline{\Sigma}_{\alpha}^{\text{ref}}(i) &= \overline{\Sigma}_{\alpha}^{\text{ref}}(i) \\
\overline{\Sigma}_{f}^{\text{ref}}(i) &= \overline{\Sigma}_{f}^{\text{ref}}(i) \\
\overline{\Sigma}_{c}^{\text{ref}}(i) &= \overline{\Sigma}_{c}^{\text{ref}}(i) \\
\overline{\Sigma}_{c}^{\text{ref}}(i) &= \overline{\Sigma}_{c}^{\text{ref}}(i) \\
X_i(i) &= \frac{C_i \cdot \overline{\Sigma}_{f}^{\text{ref}}(i)}{\overline{\Sigma}_{f}^{\text{ref}}(i)} \\
X_o(i) &= \frac{C_i \cdot \overline{\Sigma}_{f}^{\text{ref}}(i)}{\overline{\Sigma}_{f}^{\text{ref}}(i)} + \frac{(C_a + C_b) \overline{\Sigma}_{a}^{\text{ref}}(i)}{\overline{\Sigma}_{a}^{\text{ref}}(i)} + \frac{6 \cdot (1 - \beta(i))}{4 + \beta^2 T} \\
Y(i) &= \frac{\overline{\Sigma}_{\alpha}^{\text{ref}}(i)}{\overline{\Sigma}_{\alpha}^{\text{ref}}(i)} + \frac{(\overline{v}_z^t)_y \cdot X_o(i)}{\overline{\Sigma}_{\alpha}^{\text{ref}}(i)} \\
x_1 &= \frac{p}{2} X_1(i) \\
x_0 &= \frac{p}{2} X_0(i) \\
y &= \frac{p}{2} Y(i) \\
w &= \frac{4 \overline{V}_c}{\overline{V}_b} \\
v &= \frac{\overline{V}_c}{\overline{V}_b} \\
\kappa &= \frac{\left[ v_b + \overline{v} \left( r^2 - (r - \Delta r)^2 \right) \right] \overline{v}_z^t + V_{bi}^{+} \cdot Z_{ao}^{+} + V_{ri}^{+} \cdot Z_{cr}}{\overline{V}_b^t} \\
Z &= \frac{\phi_b}{\overline{V}_b^t} \\
f_{b0} &= f_1
\end{align*}
\]
INITIAL CONVERSION FACTOR

\[ \gamma = \frac{\frac{\Sigma_{\text{eff}}}{\Sigma_{\text{eff}}}} {\Sigma_{\text{eff}}} + \frac{(\nu Z_f)^+ X_0}{\Sigma_{\text{eff}}} \]

TWO GROUP CONSTANTS FOR FLUX DISTRIBUTION CALCULATIONS

\[ \nu Z_f = \frac{L_{\text{eff}} \Sigma_{\text{eff}}}{p} \]

\[ \Sigma_1 = \frac{D_{\text{eff}}}{T} \]

\[ \Sigma_{r1} = \rho \cdot \Sigma_1 \]

\[ \Sigma_{a1} = \Sigma_1 - \Sigma_{r1} \]
SINGLE ROD

\[ V_c = \tau \cdot e^a \]
\[ V_g = \tau \cdot (e^a - e^b) \]
\[ V_o = \tau \cdot a^e - V_c - V_g \]
\[ V_v = \tau \cdot (e^a - e^b) \]
\[ V_{11} = \tau \cdot (a^a - a^c) \]
\[ V_{22} = \tau \cdot (a^a - a^b) \]
\[ V_{33} = \tau \cdot (a^b - a^c) \]
\[ V_1 = V_{11} + V_{22} + V_{33} \]
\[ V_m = \frac{V_m}{V_c} \]
\[ Z = \sqrt{V_m + V_c + V_g + V_o + V_v + V_1 + V_r} \]
\[ b = \frac{Z}{V^a} \]

For \( f \) calculation only

\[ V_b = \tau \cdot s^a \]
\[ a^b = s \]
\[ V_{ai} = 0 \]
\[ V_{0a} = V_0 \]

For \( \epsilon \) calculation only

\[ V_b = \tau \cdot s^a \]
\[ a^b = 0 \]
\[ V_{ai} = 0 \]
\[ V_{0a} = 0 \]
4 ROD ASSEMBLY
4 ROD ASSEMBLY

\[ V_c = 4 \pi r_s^2 \]
\[ V_q = 4 \pi \left( \varepsilon_{q}^2 - s^2 \right) + \pi \left[ r_s^2 - (r - dr)^2 \right] \]
\[ V_v = \pi (a_v^2 - r_s^2) - V_c - V_q - V_r \]
\[ V_r = \pi (a_r^2 - a_v^2) \]
\[ V_{l1} = \pi (a_v^2 - a_1^2) \]
\[ V_{l2} = \pi (a_2^2 - a_v^2) \]
\[ V_i = V_{l1} + V_{l2} + V_{l2} \]
\[ V_m = \frac{V_m}{V_c} \cdot V_c \]
\[ I = \sqrt{V_m + V_c + V_q + V_t + V_v + V_r} \]
\[ Z = \sqrt{V_m + \pi \cdot a_s^2} \]
\[ b = \frac{Z}{\sqrt{V_s}} \]

**For \( f \) calculation only**

\[ V_{b1} = V_{l1} - 2d_s^2 + \pi \cdot s_1^2 + 4 \cdot s_1 \cdot d \cdot \sqrt{s} \]
\[ a_{b1} = \sqrt{\frac{V_{b1}}{\pi}} \]
\[ V_{a1} = V_{b1} - V_c - V_q - V_{l1} - \pi \cdot r^2 \]
\[ V_{a2} = V_0 - V_{a1} \]

**For \( \varepsilon \) calculation only**

\[ V_{b1} = 2d_s^2 + \pi \cdot s_1^2 + 4 \cdot s_1 \cdot d \cdot \sqrt{s} \]
\[ a_{b1} = \sqrt{\frac{V_{b1}}{\pi}} \]
\[ V_{a1} = V_{b1} - V_c - V_q - V_{l1} - \pi \cdot r^2 \]
\[ V_{a2} = V_0 - V_{a1} \]

\[ V_{b1} = 4 \cdot \left( \varepsilon_{q1} \arccos \frac{c}{\epsilon_{r1}} - s \sqrt{\varepsilon_{q1}^2 - s^2} \right) - \pi \cdot (\varepsilon_{q1}^2 - s^2) \]
\[ V_{a1} = V_0 - V_c - V_{b1} - V_{l1} - \pi r^2 \]
7 ROD ASSEMBLY
7 ROD ASSEMBLY (7e)

\[
\begin{align*}
V_c & = 7 \pi \cdot s^2 \\
V_q & = 7 \pi \cdot (s_1^2 - s_2^2) \\
V_o & = \pi \cdot a^2 - (V_c + V_q + V_r) \\
V_a & = \pi \cdot (a_4^2 - a_1^2) \\
V_{a_2} & = \pi \cdot (a_4^2 - a_2^2) \\
V_{a_3} & = \pi \cdot (a_4^2 - a_3^2) \\
V_b & = V_{q1} \cdot V_{r2} + V_{q3} \\
V_m & = \left( \frac{V_m}{V_c} \right) \cdot V_c \\
Z & = \sqrt{V_m + V_c + V_q + V_o + V_r + V_v + V_t} \\
b & = \frac{Z}{\sqrt{r}}
\end{align*}
\]

For \( f \) calculation only

\[
\begin{align*}
V_{b1} & = V_{b3} \cdot 7 \cdot \frac{1}{2} \cdot V_6 \cdot d^2 \\
a_{b1} & = \frac{\sqrt{V_4}}{a} \\
V_6 & = V_6 - V_2 - V_q - V_{r1} \\
V_6 & = V_0 - V_{q1}
\end{align*}
\]

For \( \varepsilon \) calculation only

\[
\begin{align*}
V_{b5} & = \frac{1}{2} \cdot V_6 \cdot d^2 + \pi d^2 + \varepsilon \cdot d \cdot d \\
a_{b5} & = \frac{\sqrt{V_4}}{a} \\
V_{b5} & = V_6 - \left[ a \cdot (s_4^2 \cdot \arccos \frac{s_4}{s_6} - s \cdot \sqrt{s_6^2 - s_4^2}) + \pi (s_4^2 - s_6^2) \right] \\
V_{a5} & = V_6 - V_2 - V_{q1} - V_{r1}
\end{align*}
\]
19 ROD ASSEMBLY (19e)

\[ V_c = 19 \cdot \pi \cdot a^2 \]
\[ V_q = 19 \cdot \pi \cdot (s_t^2 - s^2) \]
\[ V_b = \pi \cdot a^2 \cdot V_c - V_q - V_r \]
\[ V_s = \pi \cdot (a_t^2 - a^2) \]
\[ V_{st} = \pi \cdot (a_t^2 - a^2) \]
\[ V_{st} = \pi \cdot (a_t^2 - a^2) \]
\[ V_t = V_{ts} + V_{tz} + V_{ts} \]
\[ V_m = \left( \frac{V_m}{V_c} \right) \cdot V_c \]
\[ Z = \sqrt{V_m + V_c + V_q + V_0 + V_t + V_r + V_b} \]
\[ = \sqrt{V_m + 2 \cdot a^2} \]
\[ b = \frac{Z}{V_c} \]

For \( f \) calculation only

\[ V_b^f = V_{rb} \cdot 19 \cdot \frac{1}{2} \cdot V_b \cdot d^2 \]
\[ a_b^f = \frac{V_d^f}{n} \]
\[ V_b^c = V_b^f - V_c - V_q - V_{rt} \]
\[ V_c^f = V_0 - V_{ca} \]

For \( \varepsilon \) calculation only

\[ V_b^f = 6 \cdot V_b \cdot d^2 + \pi \cdot s^3 + \pi d \cdot n \]
\[ a_b^f = \frac{V_d^f}{n} \]
\[ V_{st} = V_3 \cdot \frac{n}{6} \cdot (s_t^2 \cdot \arccos \frac{s}{s_t} - s \cdot s_t \cdot s^2 - \pi (s_t^2 - s^2)) \]
\[ V_{st} = V_3^f - V_c - V_{rt} \]
19 ROD ASSEMBLY (19c)
19 ROD ASSEMBLY (19c)

\[ V_c = 19 \cdot \pi \cdot s^2 \]
\[ V_q = 19 \cdot \pi \cdot (s^2 - 5^2) \]
\[ V_b = \pi \cdot s^2 - V_c - V_q - V_r \]
\[ V_s = \pi \cdot (a_s^2 - a_i^2) \]
\[ V_{ts} = \pi \cdot (a_s^2 - a_i^2) \]
\[ V_{tb} = \pi \cdot (a_s^2 - a_i^2) \]
\[ V_f = V_{11} + V_{12} + V_{13} \]
\[ V_m = \left( \frac{V_m}{V_c} \right) \cdot V_c \]
\[ I = \sqrt{V_m + V_c + V_q + V_b + V_r + V_s + V_f} \]
\[ b = \frac{I}{\sqrt{V_c}} \]

For \( f \) calculation only

\[ V_{f1} = V_{5b} = (\sqrt{6} \cdot s) \cdot s^2 + 12 \cdot d \cdot s + \pi \cdot s^2 \]
\[ a_{f1} = \sqrt{\frac{V_f}{s}} \]
\[ V_{f1}' = V_{f1} - V_c - V_q - V_{r1} \]
\[ V_{f1}'' = V_{b} - V_{f1}' \]

For \( \epsilon \) calculation only

\[ V_{\epsilon} = (\sqrt{5} \cdot s) \cdot s^2 + 12 \cdot d \cdot s + \pi \cdot s^2 \]
\[ a_{\epsilon} = \sqrt{\frac{V_{\epsilon}}{s}} \]
\[ V_{\epsilon1} = V_q - \left[ 12 \cdot (s^2 \cos \phi \sin \phi \cdot \frac{s}{2} - s \sqrt{s^2 - 5^2}) + \pi \cdot (a_s^2 - s^2) \right] \]
\[ V_{\epsilon1}' = V_b - V_{\epsilon1} - V_{r1} \]
22 ROD ASSEMBLY
22 ROD ASSEMBLY

\[ V_{c} = \pi \cdot a_1^4 + 7 \cdot \pi \cdot a_3^4 + 14 \cdot \pi \cdot a_5^2 \]
\[ V_{q} = \left[ \pi \cdot (s_2 + d_1)^2 \cdot \pi \cdot s_3^2 \right] + 7 \left[ \pi \cdot (s_2 + d_2 - s_3 + d_3)^2 \cdot \pi \cdot s_5^2 \right] \]
\[ V_{b} = \pi \cdot a^2 \cdot V_{q} - V_{c} - V_{r} \]
\[ V_{k} = \pi \cdot \left( a_1^4 - a_3^4 \right) \]
\[ V_{t} = \pi \cdot \left( a_1^4 - a_5^4 \right) \]
\[ V_{b} = \pi \cdot \left( a_1^4 - a_3^4 \right) \]
\[ V_{t} = V_{t1} + V_{t2} + V_{t3} \]
\[ V_{m} = \left( V_{m} \over V_{c} \right) \cdot V_{c} \]
\[ I = \sqrt{V_{m} \cdot V_{c} + V_{q} + V_{b} + V_{t} + V_{r}} \]
\[ b = \frac{I}{\sqrt{r}} \]

For \( f \) calculation only

\[ V_{b}^{t} = V_{b} \cdot \left( 3.0588 \cdot d_1^2 + \pi \cdot (s_2 + d_1)^2 + 6.2542 \cdot d \cdot (s_2 + d_1) \right) \]
\[ a_{b}^{t} = \sqrt{V_{b}^{t} \over \pi} \]
\[ V_{m}^{t} = V_{m} - V_{c} - V_{q} - V_{t1} \]
\[ V_{a}^{t} = V_{b} - V_{a1} \]

For \( e \) calculation only

\[ V_{b}^{f} = 3.0588 \cdot d_1^2 + \pi \cdot s_2^2 + 6.2542 \cdot d \cdot s_2 \]
\[ a_{b}^{f} = \sqrt{V_{b}^{f} \over \pi} \]
\[ V_{m}^{f} = V_{f} - 14 \left[ \left( s_2 \cdot d_2 \right)^2 \text{arccos} \left( \frac{s_2}{s_2 \cdot d_2} \right) - s_5 \left( s_2 \cdot d_2 \right)^2 \right] - \pi \left[ \left( s_2 \cdot d_2 \right)^2 \cdot s_5^2 \right] \]
\[ V_{a}^{f} = V_{c} - V_{a1} - V_{a1} \]
CIRCULAR TUBES

\[ V_c = \tau \left( s^3 - 3s^2 + 3s + r^2 - dr^3 + d^2 - d^4 \right) \]

\[ V_q = 2\tau \left( s + s_1 + s_2 + s_3 + r - dr - d^2 \right) \cdot d_b \]

\[ V_0 = V_{oi} + V_{0e} \]

\[ V_{31} = \tau (a_s^1 - a_s^2) \]

\[ V_{12} = \tau (a_s^1 - a_s^2) \]

\[ V_{1b} = \tau (a_s^1 - a_s^2) \]

\[ V_t = V_{31} + V_{12} + V_{1b} \]

\[ V_m = \left( \frac{V_m}{V_c} \right) \cdot V_c \]

\[ z = \sqrt{\tau \cdot a_s^1 + V_m} \]

\[ b = \frac{z}{V_r} \]

For calculation only

\[ V_{b^t} = \tau \cdot (s + d_b)^2 \]

\[ a_b^t = s + d_b \]

\[ V_{oi} = V_{b^t} - (V_c + V_0 + V_{n^t}) \]

\[ V_{0e} = \tau \cdot (a_s^1 - (s + d_b)^2) \cdot (V_r - V_{n^t}) \]

For calculation only

\[ V_{s^f} = \tau \cdot s^2 \]

\[ a_{s^f} = s \]

\[ V_{qi} = V_q - \tau \cdot d_s \cdot (d_b + 2s) \]

\[ V_{oi} = V_{oi} \]
### Table 1A  Thermal and epithermal cross sections

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 Comparison between PLUTHARCO and EXPO experiments

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Table 6

Comparison between PLUTHARCO and CISE results

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\(^x\) corrected to four factor scheme

+ experimental results in brackets
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\(^x\) corrected to four factor scheme

+ experimental results in

Table 7

Comparison between PLUTHARCO and CISE
Table 8

Comparison between PLUTHERCO and Savannah River

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*Values in parantheses are from flux mapping experiments*
Table 9

Comparison between PLUTHARCO and Savannah River experiments

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<td>181.</td>
<td>169.142</td>
<td>331.</td>
<td>313.126</td>
<td>459.</td>
<td>435.817</td>
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<tr>
<td><strong>τ [cm^2]</strong></td>
<td>128.</td>
<td>114.638</td>
<td>114.344</td>
<td>122.</td>
<td>112.957</td>
<td>120.</td>
<td>112.607</td>
<td>120.</td>
<td>112.542</td>
</tr>
<tr>
<td><strong>B^2 [m^-2]</strong></td>
<td>7.58</td>
<td>7.420</td>
<td>7.562</td>
<td>7.56</td>
<td>7.603</td>
<td>5.24</td>
<td>5.420</td>
<td>3.93</td>
<td>4.081</td>
</tr>
<tr>
<td><strong>(7.59)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>k_{co}</strong></td>
<td>1.173</td>
<td>1.153</td>
<td>1.159</td>
<td>1.238</td>
<td>1.226</td>
<td>1.244</td>
<td>1.241</td>
<td>1.231</td>
<td>1.232</td>
</tr>
</tbody>
</table>

* See note table 8
<table>
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<tr>
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<th>PLUTH + TERM</th>
<th>SRE</th>
<th>PLUTH</th>
<th>SRE</th>
<th>PLUTH</th>
<th>SRE</th>
<th>PLUTH</th>
<th>SRE</th>
<th>PLUTH</th>
<th>SRE</th>
<th>PLUTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>1.310</td>
<td>1.292</td>
<td>1.306</td>
<td>1.310</td>
<td>1.301</td>
<td>1.310</td>
<td>1.303</td>
<td>1.310</td>
<td>1.306</td>
<td>1.310</td>
<td>1.307</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>1.053</td>
<td>1.041</td>
<td>1.041</td>
<td>1.053</td>
<td>1.041</td>
<td>1.053</td>
<td>1.041</td>
<td>1.053</td>
<td>1.041</td>
<td>1.053</td>
<td>1.041</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.843</td>
<td>0.837</td>
<td>0.837</td>
<td>0.889</td>
<td>0.895</td>
<td>0.902</td>
<td>0.894</td>
<td>0.917</td>
<td>0.901</td>
<td>0.916</td>
<td>0.903</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f$</td>
<td>0.985</td>
<td>0.986</td>
<td>0.984</td>
<td>0.978</td>
<td>0.970</td>
<td>0.970</td>
<td>0.945</td>
<td>0.945</td>
<td>0.931</td>
<td>0.927</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L^2[\text{cm}^2]$</td>
<td>85.</td>
<td>83.356</td>
<td>84.038</td>
<td>164.</td>
<td>167.433</td>
<td>242.</td>
<td>244.113</td>
<td>496.</td>
<td>491.521</td>
<td>648.</td>
<td>663.890</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau[\text{cm}^2]$</td>
<td>129.</td>
<td>113.911</td>
<td>113.911</td>
<td>124.</td>
<td>111.265</td>
<td>123.</td>
<td>110.851</td>
<td>121.</td>
<td>110.159</td>
<td>120.</td>
<td>110.076</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_\infty$</td>
<td>1.145</td>
<td>1.111</td>
<td>1.119</td>
<td>1.199</td>
<td>1.172</td>
<td>1.207</td>
<td>1.176</td>
<td>1.195</td>
<td>1.158</td>
<td>1.176</td>
<td>1.139</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^x$ see note table 8
Table 11

Comparison between PLUTHARCO and Chalk River values

<table>
<thead>
<tr>
<th></th>
<th>$7 \text{D}_2\text{O} \ 18$</th>
<th>$7 \text{D}_2\text{O} \ 22$</th>
<th>$7 \text{D}_2\text{O} \ 28$</th>
<th>$7 \text{D}_2\text{O} \ 36$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>1.304</td>
<td>1.304</td>
<td>1.308</td>
<td>1.308</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>1.030</td>
<td>1.030</td>
<td>1.029</td>
<td>1.029</td>
</tr>
<tr>
<td>$p$</td>
<td>0.845</td>
<td>0.834</td>
<td>0.895</td>
<td>0.890</td>
</tr>
<tr>
<td>$f^2$</td>
<td>0.971</td>
<td>0.971</td>
<td>0.966</td>
<td>0.966</td>
</tr>
<tr>
<td>$L^2 [\text{cm}^2]$</td>
<td>83.810</td>
<td>86.406</td>
<td>139.518</td>
<td>241.801</td>
</tr>
<tr>
<td>$r [\text{cm}^2]$</td>
<td>134.012</td>
<td>124.855</td>
<td>128.602</td>
<td>120.089</td>
</tr>
<tr>
<td>$B^2 [\text{m}^{-2}]$</td>
<td>(4.585, 0.025)</td>
<td>(3.999, 0.029)</td>
<td>(5.926, 0.026)</td>
<td>(5.256, 0.011)</td>
</tr>
<tr>
<td>$k_{\infty}$</td>
<td>1.102</td>
<td>1.086</td>
<td>1.164</td>
<td>1.157</td>
</tr>
</tbody>
</table>

*Values in brackets from flux mapping experiments*
<table>
<thead>
<tr>
<th></th>
<th>CAN.</th>
<th>PLUTH.</th>
<th>CAN.</th>
<th>PLUTH.</th>
<th>CAN.</th>
<th>PLUTH.</th>
<th>CAN.</th>
<th>PLUTH.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>η</strong></td>
<td>1.304</td>
<td>1.305</td>
<td>1.307</td>
<td>1.308</td>
<td>1.312</td>
<td>1.311</td>
<td>1.314</td>
<td>1.313</td>
</tr>
<tr>
<td><strong>ε</strong></td>
<td>1.032</td>
<td>1.031</td>
<td>1.032</td>
<td>1.031</td>
<td>-</td>
<td>1.031</td>
<td>-</td>
<td>1.031</td>
</tr>
<tr>
<td><strong>ρ</strong></td>
<td>0.865</td>
<td>0.848</td>
<td>0.902</td>
<td>0.890</td>
<td>-</td>
<td>0.930</td>
<td>-</td>
<td>0.945</td>
</tr>
<tr>
<td><strong>f</strong></td>
<td>0.971</td>
<td>0.971</td>
<td>0.967</td>
<td>0.967</td>
<td>0.956</td>
<td>0.957</td>
<td>0.938</td>
<td>0.939</td>
</tr>
<tr>
<td><strong>L² [cm²]</strong></td>
<td>95.705</td>
<td>93.540</td>
<td>135.346</td>
<td>132.711</td>
<td>236.804</td>
<td>234.509</td>
<td>416.917</td>
<td>416.418</td>
</tr>
<tr>
<td><strong>τ [m⁻²]</strong></td>
<td>148.930</td>
<td>139.968</td>
<td>140.096</td>
<td>131.813</td>
<td>131.187</td>
<td>124.181</td>
<td>126.004</td>
<td>119.791</td>
</tr>
<tr>
<td><strong>B² [m⁻²]</strong></td>
<td>5.176</td>
<td>4.488</td>
<td>6.157</td>
<td>5.831</td>
<td>-</td>
<td>5.407</td>
<td>-</td>
<td>3.604</td>
</tr>
<tr>
<td><strong>κ∞</strong></td>
<td>1.130</td>
<td>1.107</td>
<td>1.177</td>
<td>1.160</td>
<td>-</td>
<td>1.202</td>
<td>-</td>
<td>1.200</td>
</tr>
</tbody>
</table>

*see note table 11*
Table 13

Comparison between PLUTHARCO and Chalk River values

<table>
<thead>
<tr>
<th></th>
<th>7 ORG 18</th>
<th>7 ORG 19</th>
<th>7 ORG 22</th>
<th>7 ORG 28</th>
<th>7 ORG 36</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>η</strong></td>
<td>1.306</td>
<td>1.305</td>
<td>1.308</td>
<td>1.309</td>
<td>1.311</td>
</tr>
<tr>
<td><strong>ε</strong></td>
<td>1.029</td>
<td>1.031</td>
<td>1.029</td>
<td>1.031</td>
<td>1.029</td>
</tr>
<tr>
<td><strong>ρ</strong></td>
<td>0.874</td>
<td>0.893</td>
<td>0.864</td>
<td>0.916</td>
<td>0.907</td>
</tr>
<tr>
<td><strong>f</strong></td>
<td>0.895</td>
<td>0.889</td>
<td>0.893</td>
<td>0.884</td>
<td>0.888</td>
</tr>
<tr>
<td><strong>L² [cm²]</strong></td>
<td>81.607</td>
<td>92.48</td>
<td>94.310</td>
<td>134.71</td>
<td>138.874</td>
</tr>
<tr>
<td><strong>τ [cm²]</strong></td>
<td>84.228</td>
<td>113.13</td>
<td>86.249</td>
<td>114.59</td>
<td>91.940</td>
</tr>
<tr>
<td><strong>β² [m⁻²]</strong></td>
<td>3.031</td>
<td>3.24</td>
<td>3.387</td>
<td>3.34</td>
<td>3.598</td>
</tr>
<tr>
<td><strong>kₐ</strong></td>
<td>1.051</td>
<td>1.068</td>
<td>1.062</td>
<td>1.085</td>
<td>1.085</td>
</tr>
</tbody>
</table>

*see note table 11*
### Table 14

Comparison between PLUTHARCO and Chalk River values (Ref. 23)

<table>
<thead>
<tr>
<th></th>
<th>ox-19-D$_2$O-18</th>
<th>ox-19-D$_2$O-21</th>
<th>ox-19-D$_2$O-24</th>
<th>ox-19-D$_2$O-26</th>
<th>ox-19-D$_2$O-36</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CAN.</td>
<td>PLUTH.</td>
<td>CAN.</td>
<td>PLUTH.</td>
<td>CAN.</td>
</tr>
<tr>
<td>$\eta$</td>
<td>1.302</td>
<td>1.301</td>
<td>1.305</td>
<td>1.305</td>
<td>1.309</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>1.028</td>
<td>1.027</td>
<td>1.027</td>
<td>1.027</td>
<td>1.026</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.830</td>
<td>0.805</td>
<td>0.873</td>
<td>0.863</td>
<td>0.902</td>
</tr>
<tr>
<td>$f$</td>
<td>0.940</td>
<td>0.942</td>
<td>0.936</td>
<td>0.937</td>
<td>0.931</td>
</tr>
<tr>
<td>$L^2 [cm^2]$</td>
<td>87.2</td>
<td>74.733</td>
<td>120.2</td>
<td>109.403</td>
<td>161.8</td>
</tr>
<tr>
<td>$\tau [cm^2]$</td>
<td>167.8</td>
<td>149.962</td>
<td>152.2</td>
<td>138.136</td>
<td>143.3</td>
</tr>
<tr>
<td>$B^2 [m^{-2}]$</td>
<td>1.73</td>
<td>0.640</td>
<td>3.42</td>
<td>3.374</td>
<td>4.07</td>
</tr>
<tr>
<td>$k_{\text{ex}}$</td>
<td>(1.407±0.05)</td>
<td>(3.48±0.03)</td>
<td>(4.05±0.02)</td>
<td>(3.95±0.013)</td>
<td>(2.75±0.012)</td>
</tr>
</tbody>
</table>

$\times$ see note table 11
Table 15

Comparison between PLUTHARCO and Chalk River values (ref. 24)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta )</td>
<td>1.301</td>
<td>1.306</td>
<td>1.308</td>
<td>1.310</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>1.031</td>
<td>1.031</td>
<td>1.031</td>
<td>1.031</td>
</tr>
<tr>
<td>( \rho )</td>
<td>0.798</td>
<td>0.862</td>
<td>0.898</td>
<td>0.925</td>
</tr>
<tr>
<td>( f )</td>
<td>0.945</td>
<td>0.941</td>
<td>0.936</td>
<td>0.928</td>
</tr>
<tr>
<td>( L^2 \ [cm^2] )</td>
<td>71.842</td>
<td>105.155</td>
<td>145.646</td>
<td>210.677</td>
</tr>
<tr>
<td>( \tau \ [cm^2] )</td>
<td>178.668</td>
<td>155.505</td>
<td>143.566</td>
<td>134.339</td>
</tr>
<tr>
<td>( b^2 \ [m^{-2}] )</td>
<td>0.444</td>
<td>3.35±0.055</td>
<td>3.429</td>
<td>4.115±0.036</td>
</tr>
<tr>
<td>( k_{\infty} )</td>
<td>1.011</td>
<td>1.091</td>
<td>1.134</td>
<td>1.159</td>
</tr>
</tbody>
</table>
### Table 16

Comparison between PLUTHARCO and Chalk River values

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta )</td>
<td>1.306</td>
<td>1.306</td>
<td>1.310</td>
<td>1.311</td>
<td>1.313</td>
</tr>
<tr>
<td>( \xi )</td>
<td>1.027</td>
<td>1.027</td>
<td>1.027</td>
<td>1.027</td>
<td>1.027</td>
</tr>
<tr>
<td>( p )</td>
<td>0.861</td>
<td>0.892</td>
<td>0.912</td>
<td>0.927</td>
<td>0.938</td>
</tr>
<tr>
<td>( f )</td>
<td>0.867</td>
<td>0.860</td>
<td>0.853</td>
<td>0.844</td>
<td>0.820</td>
</tr>
<tr>
<td>( L^2 \ [\text{cm}^2] )</td>
<td>65.104</td>
<td>102.150</td>
<td>147.519</td>
<td>220.719</td>
<td>409.131</td>
</tr>
<tr>
<td>( \tau \ [\text{cm}^2] )</td>
<td>93.958</td>
<td>97.904</td>
<td>101.027</td>
<td>103.778</td>
<td>106.920</td>
</tr>
<tr>
<td>( B^2 \ [\text{n}^2] )</td>
<td>0.109</td>
<td>1.214±0.035</td>
<td>1.544</td>
<td>1.568±0.019</td>
<td>1.865</td>
</tr>
<tr>
<td>( k_\infty )</td>
<td>1.002</td>
<td>1.031</td>
<td>1.047</td>
<td>1.054</td>
<td>1.039</td>
</tr>
</tbody>
</table>
V. PLUTHARCO, Directions for use

The code PLUTHARCO written in Fortran II, version 2, can be run on a normal IBM 7090 with a 32,000 words memory. The time of execution is about 20 seconds per case. The number of output lines is of the order of 250 per case. For the execution a tape is needed on channel B5, entering a table of Amouyal-Benoist escape probabilities (Tape no. 806).

For the perforation of the data for RLT4 input a tape shall be mounted on A6 (11).

V.1. Input

Much effort has been done to make the program as elastic as possible i.e. that heavy water moderated reactors of the most different types can be calculated.

This elasticity has been achieved by introducing an option for every structural part of the reactor e.g. fuel, canning, coolant, filler, tubes and geometry.

Apart from these choices, which are all possibilities foreseen in the program, a so-called "7 choice" exists, making it possible to enter the macroscopic cross sections and geometry directly.

In this case detailed constants for the calculation of these data need not to be entered (f.i. in the case of direct macroscopic coolant input the coolant spectral constant and physical temperature may be omitted).

By using the "7 choice" for the geometry the user should provide a Fortran subroutine, called DUMMY, which calculates the geometrical constants from detailed parameters or gives them directly.

Before beginning a calculation a vector of input data shall be provided to the program. This vector is not altered during the course of the calculation and will remain in the computer as long as no changements are made. Using this principle calculations belonging to one "family" can be made by simply altering the figures to be varied. Hereafter one has to give the order to start the cal-
culation again. This order is given by entering an asterisk (*
) in column 1 of the last input card of the calculation.

The advantage of this system is the very limited number of input
cards, because only changes have to be made with respect to
the former calculation, which very often are few. However one
has to be very careful to remove all old unnecessary data of the
former calculations from the vector before beginning a calculation
of another "family".

It is therefore very advantageous to provide a dummy input set,
which clears the whole vector between two series of calculations.
V.2. Card formats

Every calculation uses two sets of cards.

1. A set of two identity cards, in which any message may be punched in col. 1-72. This will be printed out on listing before starting the calculation.

2. Data cards

The data cards enter the desired input for the calculations into a storage block.

The data will remain, during the execution as long as they are not overwritten by other ones.

We thus need only to replace the entries which have to be changed after a calculation, instead of giving all the data again.

The set-up is as follows:

col. 1 Any figure (numeric or alphabetical card count f.i.) may be entered here. An asterisk (*) however must be used only in the last card of the set, which form part of one calculation.

col. 2-4 The inputlist location which will be modified by the first of the six data fields on the card.

col. 5-7 The inputlist location which will be modified by the last (between 1 and 6) data field of the card.

col. 8-17 Data fields The decimal point

18-27 may be placed on the places
28-37 \(0.10n + 12\ (n = 0,5)\)
38-47 If no decimal points are entered, the point is supposed to be between col. 10n + 12 and 10 n + 13 (n=0,5).
48-57
58-67
To obtain the complete RLT4 output (for description of this program see ref.27 ) punched automatically, attention should be payed to the following:

The two identity cards read in at the start of every calculation are written out in the testing but also punched out forming the first cards of the RLT4 input.

The total RLT4 input consists of a set of 6 cards, divided in one identity card, 1 option card and four physical data cards. The last four cards are output data of PLUTHARCO.

From this is clear that this second (option) card for RLT4 should already be entered in PLUTHARCO.

The following test describes the format of this card.

<table>
<thead>
<tr>
<th>Column</th>
<th>Format</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-6</td>
<td>E6.2</td>
<td>TEND2</td>
<td>End of life (n/kb)</td>
</tr>
<tr>
<td>7-18</td>
<td>E-12.8</td>
<td>FIE</td>
<td>Constant flux in units of $10^{13}$ neutrons/cm$^2$sec or constant power in MWD/T (see i2)</td>
</tr>
<tr>
<td>19-20</td>
<td>$I_2$</td>
<td>$K_1$</td>
<td>00 (obligatory)</td>
</tr>
<tr>
<td>27-28</td>
<td>$I_2$</td>
<td>$I_1$</td>
<td>Multiplication factor to be applied to the basic time step (the last being equal to 0.01n/kb)</td>
</tr>
<tr>
<td>29-30</td>
<td>$I_2$</td>
<td>$I_2$</td>
<td>if $i_2 = 00$ the flux is assumed to be constant during burn-up, if $i_2 = 01$, the power is assumed to be constant during burn-up</td>
</tr>
<tr>
<td>31-32</td>
<td>$I_2$</td>
<td>$I_3$</td>
<td>obligatory 01</td>
</tr>
<tr>
<td>35-36</td>
<td>$I_2$</td>
<td>$I_5$</td>
<td>if $i_5 = 00$ The principal data (buckling fuel atomic density etc) are printed out $I_5 = 01$ Print-out as option 00 together with fission product densities $I_5 = 03$ Printout as option 01 together with lattice parameters $I_5 = 04$ Print-out as option 03 but with burn-up integrals</td>
</tr>
<tr>
<td>Column</td>
<td>Format</td>
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<tr>
<td>37-38</td>
<td>I₂</td>
<td>L₁</td>
<td>Ideal circulation calculation performed if $L₁ \neq 0$</td>
</tr>
<tr>
<td>39-40</td>
<td>I₂</td>
<td>L₂</td>
<td>Two element circulation calculation performed if $L₂ \neq 0$</td>
</tr>
<tr>
<td>41-42</td>
<td>I₂</td>
<td>L₃</td>
<td>Single element circulation calculation performed if $L₃ \neq 0$</td>
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<tr>
<td>43-44</td>
<td>I₂</td>
<td>L₄</td>
<td>Crossed circulation calculation performed if $L₄ \neq 0$</td>
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</tbody>
</table>
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   1. METAL
   2. OXIDE
   3. MONOCARBIDE
   4. DICARBIDE
   7. OTHER FUEL (CROSS-SECTIONS TO BE ENTERED IN WRS 72-89)

2. DILUENT SPECTR. CONST. (K)

3. CANVING SPECTR. CONST. (K)

5. COOLANT INDEX
   0. VOID
   1. GILOTHERM (SANTOWAX)
   2. DIPHENYL
   3. HEAVY WATER
   6. OTHER ORGANIC COOLANT (DATA TO BE ENTERED IN NRS 90,91,104 AND 105)
   7. OTHER COOLANT (CROSS-SECTIONS TO BE ENTERED IN NRS 137-149 AND 167-179)

6. COOLANT AND INNER FILLER SPECTR. CONST. (K)

7. OUTER COOLANT AND OUTER FILLER SPECTR. CONST. (K)
10. PRESSURE TUBE SPECTR. CONST (K)

11. INSULATION INDEX
   0. VOID
   1. GILOTHERM (SANTOWAX)
   2. DIPHENYL
   3. HEAVY WATER
   4. AL2 O3
   5. SI O2
   7. OTHER MATERIAL (CROSS-SECTIONS TO BE ENTERED IN NRS.152-164)

12. INSULATION SPECTR. CONST. (K)

13. 

14. CALANDRIA SPECTR. CONST (K)

15. MODERATOR SPECTR. CONST (K)

16. PHYSICAL TEMPERATURE FUEL

17. PHYSICAL TEMPERATURE COOLANT

18. PHYSICAL TEMPERATURE INSULATION

19. PHYSICAL TEMPERATURE MODERATOR
20. SPECTRAL CONSTANT INDEX
   -1. CORRELATED SPECTR. CONST.
   0. OTHER SPECTR. CONST.
   1. TERMIDOR SPECTR. CONST. (ENTER DATA IN NRS. 195-200)

21.

22. SGR FILLER DENSITY (GRAPHITE) RELATIVE TO REFERENCE DENSITY
    (1.65 GR/CM³)

23. ALFA WEIGHT PERCENTAGE OF AL₂O₃ IN SAP (VALUE BETWEEN 0 AND 1)

24. RHO-SAP SAP DENSITY (IN GR/CM³)

25. HBR PERCENTAGE OF HIGH BOILING RESIDUES IN SANTOWAX
    (IN PERCENTS)

26. SAL EFFECTIVE ABSORPTION SECTION (AVERAGED OVER A MAXWELLIAN
    FLUX AT FUEL TEMPERATURE T(N)) DUE TO ALLOYS CONTAINED IN THE
    FUEL

27. PU PURITY OF HEAVY WATER (VALUE BETWEEN 0 AND 1)

28. CHW ADDITIONAL HEAVY WATER ABSORPTION SECTION DUE TO IMPURITIES
    OTHER THAN LIGHT WATER (VALUE AT 2200 M/SEC)

29. EXSAP EXTRA ABSORPTION IN SAP DUE TO IMPURITIES
    (VALUE AT 2200 M/SEC TIMES 1.0E-5)

30. S CYLINDRICAL GEOMETRY OUTER RADIUS OF FIRST (OUTER) TUBE
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<td>S1</td>
<td>7-rod Hexagonal</td>
<td>Clad Rod Radius</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19-rod Hexagonal</td>
<td>Clad Rod Radius</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19-rod Circular</td>
<td>Clad Rod Radius</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22-rod</td>
<td>Radius of Central Rod</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4-rod</td>
<td>Clad Rod Radius</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single Rod</td>
<td>Cladding Inner Radius</td>
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<tr>
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<td>Cylindrical</td>
<td>Inner Radius of First (Outer) Tube</td>
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<td>32.</td>
<td>S2</td>
<td>22-rod</td>
<td>Radius of Second-Ring Rods</td>
</tr>
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<td>Single Rod</td>
<td>Cladding Outer Radius</td>
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<td></td>
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<td>Cylindrical</td>
<td>Outer Radius of Second Tube</td>
</tr>
<tr>
<td>33.</td>
<td>S3</td>
<td>22-rod</td>
<td>Radius of Third-Ring Rods</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cylindrical</td>
<td>Inner Radius of Second Tube</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>All Geometries</td>
<td>Internal Radius of Pressure Tube</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>All Geometries</td>
<td>External Radius of Pressure Tube</td>
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<td>A2</td>
<td>All Geometries</td>
<td>Internal Radius of Calandria Tube</td>
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<tr>
<td></td>
<td>A3</td>
<td>All Geometries</td>
<td>External Radius of Calandria Tube</td>
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<td>38.</td>
<td>R</td>
<td>4-rod</td>
<td>External Radius of Central Filling Tube</td>
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<tr>
<td></td>
<td></td>
<td>Cylindrical</td>
<td>Outer Radius of Third Tube</td>
</tr>
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<td>39.</td>
<td>DR</td>
<td>4-rod</td>
<td>Thickness of Central Filling Tube</td>
</tr>
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2. 19-ROD HEXAGONAL
3. 19-ROD CIRCULAR
4. 22-ROD
5. 4-ROD
6. SINGLE ROD
7. OTHER GEOMETRY (TO BE SPECIFIED IN SUBROUTINE)
8. CYLINDRICAL
9. SPECIAL GEOMETRY (DATA TO BE ENTERED IN NRS. 107-126)

41. D  

7-ROD HEXAGONAL  AXIAL DISTANCE FROM RODS IN HEXAGONAL GEOMETRY
19-ROD HEXAGONAL  AXIAL DISTANCE FROM RODS IN HEXAGONAL GEOMETRY
19-ROD CIRCULAR  AXIAL DISTANCE FROM RODS IN HEXAGONAL GEOMETRY
22-ROD  DISTANCE FROM CENTRE OF EXTERNAL RING OF RODS TO CENTRE OF ELEMENT
4-ROD  DISTANCE FROM CENTRE OF ELEMENT TO OTHER RODS
CYLINDRICAL  OUTER RADIUS OF FOURTH (INNER) TUBE

42. D1  

22-ROD  CLADDING THICKNESS OF CENTRAL RODS
CYLINDRICAL  INNER RADIUS OF FOURTH (INNER) TUBE

43. D2  

22-ROD  CLADDING THICKNESS OF RODS IN FIRST RING
44. D3  22-ROD  CYLINDRICAL  CLADDING THICKNESS OF RODS IN SECOND RING
       CYLINDRICAL  CLADDING THICKNESS OF CYLINDRICAL TUBES

45. VR  CYLINDRICAL  TOTAL VOLUME OF FILLING AT CENTRE OF FUEL ELEMENT
       ALL OTHER GEOMETRIES  TOTAL VOLUME OF FILLING

46. VRIT CYLINDRICAL  VOLUME OF FILLING AT CENTRE OF FUEL ELEMENT FOR CALCULATION OF THERMAL UTILISATION FACTOR
       ALL OTHER GEOMETRIES  VOLUME OF FILLING INSIDE HOMOGENIZED CENTRAL ROD FOR CALCULATION OF THERMAL UTILISATION FACTOR

47. VRIF CYLINDRICAL  VOLUME OF FILLING AT CENTRE OF FUEL ELEMENT FOR CALCULATION OF FAST FISSION FACTOR
       ALL OTHER GEOMETRIES  VOLUME OF FILLING INSIDE HOMOGENIZED CENTRAL ROD FOR CALCULATION OF THERMAL UTILISATION FACTOR

48.

49. PUNCHING INDEX
    -1. PUNCH CARDS FOR RLT-2
    0. NO CARD-PUNCH
    1. PUNCH CARDS FOR RLT-4
50. PRINTING INDEX
   0. OUTPUT WITH INTERMEDIATE RESULTS
   1. OUTPUT WITHOUT INTERMEDIATE RESULTS

51. SECOND FLIGHT CORRECTION CORRECTION FACTOR TO MAKE ALLOWANCE
   FOR NON-UNIFORMITY OF NEUTRON DENSITY
   AFTER FIRST COLLISION

52. ATOMIC FRACTION TH-232

53. ATOMIC FRACTION U-233

54. ATOMIC FRACTION U-235

55. ATOMIC FRACTION U-236

56. ATOMIC FRACTION U-238

57. ATOMIC FRACTION PU-239

58. ATOMIC FRACTION PU-240

59. ATOMIC FRACTION PU-241

60. MIXED FUEL DENSITY

61. MIXED FUEL MOLECULAR NUMBER

62. SPECTR. CONST. (K) TH-232
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<td>2. Square Pitch</td>
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<td>3. Hexagonal Pitch</td>
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<td>Scattering (Thermal)</td>
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<td>Scattering (Epithermal)</td>
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<td>77</td>
<td>Transport (Epithermal)</td>
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<td>Slowing Down (Epithermal)</td>
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90. ORGANIC DENSITY AT 0 CENTIGRADE (SEE 5. COOLANT INDEX)

91. - (DENSITY TEMP. COEFF.) TIMES 1. E4 (SEE 5. COOLANT INDEX)

92. NU TIMES FISSION (THERMAL) (SNUFCT)

93-103

104. NUMBER OF C-ATOMS/ORGANIC MOLECULE (SEE 5. COOLANT INDEX)

105. NUMBER OF H-ATOMS/ORGANIC MOLECULE (SEE 5. COOLANT INDEX)

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GEOMETRICAL DATA FOR SPECIAL GEOMETRY (SEE 40. GEOMETRY INDEX)

107. VC

108. VG

109. VO

110. VT1
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137 ABSORPTION (AT 2200 M/SEC) (SANT)
138 SCATTERING (THERMAL) (SSNT)
139 TRANSPORT (THERMAL) (STRNT)
140 SCATTERING (EPITHERMAL) (SSNE)
141 TRANSPORT (EPITHERMAL) (STRNE)
142 SLOWING DOWN (EPITHERMAL) (SXSNE)
143 TOTAL (FAST) (STN)
144 ELASTIC (FAST) (SEN)
145 INELASTIC (FAST) (SJN)
146 CAPTURE (FAST) (SCN)
147 TOTAL 2 (FAST) (STN2)
### CROSS-SECTIONS FOR SPECIAL INSULATION (SEE 11. INSULATION INDEX)

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<td>AT 2200 M/SEC (SANT)</td>
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<td>Scattering</td>
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<td>Transport</td>
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<td>Scattering</td>
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<td>154</td>
<td>Transport</td>
<td>EPITHERMAL (STRNE)</td>
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<td>155</td>
<td>Slowing Down</td>
<td>EPITHERMAL (SXSN)</td>
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<td>156</td>
<td>Total</td>
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<td>157</td>
<td>Elastic</td>
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<td>160</td>
<td>Total 2</td>
<td>FAST (STN2)</td>
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<tr>
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<td>Scattering 2</td>
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<td>162</td>
<td>Capture 2</td>
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### CROSS-SECTIONS FOR SPECIAL OUTER COOLANT (SEE 5. COOLANT INDEX)

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<td>Absorption</td>
<td>AT 2200 M/SEC (SANT)</td>
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<td>Scattering</td>
<td>THERMAL (SSNT)</td>
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<td>Transport</td>
<td>THERMAL (STRNT)</td>
</tr>
<tr>
<td>168</td>
<td>Scattering</td>
<td>THERMAL (SSNE)</td>
</tr>
<tr>
<td>169</td>
<td>Transport</td>
<td>THERMAL (STRNE)</td>
</tr>
<tr>
<td>170</td>
<td>Slowing Down</td>
<td>EPITHERMAL (SXSN)</td>
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<td>171</td>
<td>Total</td>
<td>FAST (STN)</td>
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TERMIDOR CROSS-SECTIONS (SEE 20: SPECTRAL CONSTANT INDEX)

195 SPECTRUM MEAN MICROSCOPIC U-235 ABSORPTION CROSS-SECTION
196 SPECTRUM MEAN MICROSCOPIC U-235 FISSION CROSS-SECTION
197 SPECTRUM MEAN MICROSCOPIC Pu-239 ABSORPTION CROSS-SECTION
198 SPECTRUM MEAN MICROSCOPIC Pu-239 FISSION CROSS-SECTION
199 SPECTRUM MEAN MICROSCOPIC 1/V ABSORPTION CROSS-SECTION /BARN
   (2000 M/SEC) IN FUEL
200 SPECTRUM MEAN MICROSCOPIC 1/V ABSORPTION CROSS-SECTION /BARN
   (2200 M/SEC) IN MODERATOR

VOLUME FRACTIONS OF STRUCTURAL MATERIAL FOR CANNING

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202 BERYLIUM
203 GRAPHITE
204 MAGNESIUM
205 LEAD
206 SAP
207 STAINLESS STEEL
208 ZIRCALOY-
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<th>Volume Fractions of Structural Material for Pressure Tube</th>
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<td>219-220</td>
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<th>Volume Fractions of Structural Material for Calandria</th>
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<tr>
<th>Volume Fractions of Structural Material for Inner Filler</th>
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### Volume Fractions of Structural Material for Outer Filler

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<td>Graphite</td>
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<td>244</td>
<td>Magnesium</td>
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<td>Lead</td>
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<td>Stainless Steel</td>
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<td>Zircaloy-2</td>
</tr>
<tr>
<td>249-250</td>
<td>Zircaloy-2</td>
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</tbody>
</table>
V.4. Output

This part describes the output page by page.

Page 1: List of input to detect errors in punching or order

Page 2: Lay-out of the input vector; for abbreviations see V.3

Page 3: Properties of the 6 regions with their macroscopic cross sections, fluxes and capture fractions. The region division is described in I.4.

Page 4: Printing of the most important lattice characteristics and RLT 4 input data. On the bottom of this page a warning may be printed that some input lists have been extrapolated. These lists are found in part IV.

Page 5: Gives the properties of the different materials of the lattice cell. The abbreviations are to be divided into three parts.
Part 1, the symbols S resp. XS having the meaning of "sigma" and "Xsi-sigma"
Part 2, A, E, S, TR, T, E, I, F, C, T2, S2, C2 symbols corresponding with III.1 a
Part 3, T, E, F symbols with the meaning Thermal, epithermal and fast respectively
For the symbols TAU see I.8.

Page 6: Gives the volumes of the different components of the reactor lattice
The symbols are again divided into three groups
Group 1, V, Z, B, A, S, RC symbols corresponding with III. 3a
Group 2, C, G, O, M, T, T2, T3 symbols corresponding with III.2b
Group 3, T, E, F again meaning thermal, epithermal and fast respectively, see part III.4.
The next part of this page gives for atomic density calculations the volume fractions of the different components in the first two regions together with the total volume.

In the last version heterogeneous constants were also calculated and printed.
V.5. Example of output

PLUTHARCO
A PLUTONIUM-URANIUM-THORIUM ASSEMBLY REACTIVITY CODE

YOUR INPUT CARD ARRANGEMENT WAS AS FOLLOWS

<table>
<thead>
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<th>ORGEL-19-TH/235/2.0/10</th>
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<tr>
<td>1  6  0.25000E 01    0.80000E 01  0.35000E 03  0.35000E 01  0.15000E 01  0.35000E 03</td>
</tr>
<tr>
<td>7 12  0.               0.80000E 01  0.35000E 03  0.35000E 03  0.11000E 04  0.60000E 03  0.70000E 01</td>
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<tr>
<td>13 18  0.80000E 01    0.35000E 03  0.35000E 03  0.11000E 04  0.60000E 03  0.70000E 01  0.27300E 01</td>
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<tr>
<td>19 24  0.36300E 03    0.19000E 01  0.99800E 00  0.99800E 00  0.41300E 01  0.43300E 01  0.70900E 00</td>
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<tr>
<td>25 30  0.36300E 03    0.99800E 00  0.41300E 01  0.43300E 01  0.46300E 01  0.46300E 01  0.46300E 01</td>
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<tr>
<td>31 36  0.78900E 00    0.47800E 01  0.36000E 01  0.36000E 01  0.16700E 01  0.16700E 01  0.16700E 01</td>
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<tr>
<td>37 42  0.78900E 00    0.47800E 01  0.36000E 01  0.16700E 01  0.16700E 01  0.16700E 01  0.16700E 01</td>
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<td>52 57  0.98000E 00    0.26400E 03  0.26400E 03  0.26400E 03  0.26400E 03  0.26400E 03  0.26400E 03</td>
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## FUEL

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**Extrapolation in Calculation of...**

- RSH/Organic
- RLT7/Organic
### INTERMEDIATE RESULTS

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**Note:** The values are in [units] and represent the cross-sectional areas of various materials in the reactor.
### PLUTHARCO - JOB ORGEL-19-TH/235/2.0/10

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1431 LINES OUTPUT THIS JOB.

JOB START AT 21.30
COMPL./LOAD TIME 00.050
EXECUTION TIME 00.011
TOTAL JOB TIME 00.061
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References


2. Syret, Campbell, Gen-Paper 10, 1958, Book 16, pag.233


4. Spinrad, Gen. Conf. 16, 1958 pag.194


6. TERMIDOR, An IBM 7090 FORTRAN code to evaluate the thermal neutron spectrum in an ORGEL type fuel element, Internal Report (not available)


8. ANL 5800, Reactor physics constants, Section 7.1.2. Multigroup Constants


11. W. De Haan: Correlation of the analytical theory to the results of Nordheim's numerical resonance integral calculation method, Internal Report (not available)


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