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PLUTHARCO,

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

by

W. DE HAAN and R. MEELHUYSEN

1966

Joint Nuclear Research Center
Ispra Establishment - Italy

Reactor Physics Department
Reactor Theory and Analysis

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C O N T E N T S

SUMMARY

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.

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 optimation 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 choise 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 invólving 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 PLUTHARCO program.

Section I

I.1. The thermal multiplication factor

The thermal multiplication factor η 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 η .

It may thus be written as

$$\eta = \frac{(\nu \Sigma_f)^t}{\Sigma_a^t} = \frac{\sum_i \nu(i)\, \Sigma_f(i)}{\sum_i \Sigma_a(i) + N_d \Sigma_{a,d}}$$

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 sectionsare 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

$$\sigma = \sqrt{\frac{\pi}{4} \cdot \frac{T_0}{T}} \quad \hat{\sigma} = \sqrt{\frac{\pi}{4} \cdot \frac{T_0}{T}} \; (g + rs)\, \sigma_0$$

in which σ_o 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

σ the mean cross section of neutrons with spectral constant T over the above defined spectrum

T_o = 293,6° K

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

$$s_i' = s_i \Big/ \sqrt{1 + 4 \cdot \frac{V}{S_{eff}} \cdot N_i \cdot I}$$

with V/Seff 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. 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 Westcotts 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, $\sigma_{f(fuel)}$ and absorption $\sigma_{a(fuel)}$ may be written as:

$$\sigma_{a(fuel)} = \sum_i \sigma_a(i)\, f(i) + N_d \cdot \sigma_d$$

$$\sigma_{f(fuel)} = \sum_i \sigma_f(i)\, f(i)$$

where $\sum_i$ is the summation over i terms (i = 1,8)

$\sigma(i)$ the cross section of the ith isotope

$f(i)$ the density fractions of the ith fuel or fertile isotope

N_d the number of diluent atoms per atom of fuel and fertile material (i.e. for UO_2 is 2)

σ_d the spectrum mean cross section of the diluent atoms.

The macroscopic fuel cross section is now simply found from

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

where Σ fuel is the mean fuel cross section over the Maxwellian + 1/E spectrum for the fuel composition as defined in input

ρ fuel is the density of the fuel compound in gr/cm^3

M 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 f.i. 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.

Choice	input 20	Description
1	- 1	Candu correlated spectral constants
2	0	Spectral constants to be provided by the user
3	1	Input of TERMIDOR parameters

Choice 1
Canadians have (Ref.5) measured the relative reactionrates Pu239/U235 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:

$$T_f' = T_m + 300.r + b_1(V\Sigma_a) + b_2(V\Sigma_s)$$
$$+ b_f(V\Sigma_s)_f(T_f - T_m) + b_t(V\Sigma_s)_t(T_t - T_m) + b_c(V\Sigma_s)_c(T_c - T_m)$$
$$T_m' = T_m + 300\,r$$

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 $V\Sigma_s$, 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 $f_{\frac{1}{v}}$ parameter serves in calculating the spectral constants of every 1/v isotope.

The calculation of this spectral constant is done by the formula

$$T = \frac{\pi}{4} \cdot \frac{T_0}{f_{\frac{1}{v}}^2}$$

a formula on its turn derived from

$$f_{\frac{1}{v}} = \sqrt{\frac{\pi}{4} \cdot \frac{T_0}{T}}$$

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 num-erical values of the macroscopic cross sections by the so called "7 choice" (see: Directions for use).

[x] see table 1 a and 1 b

I.2. The fast fission factor

The calculation of the fast fission factor ϵ 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

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

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 luxuous. 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 thres-hold. 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 fissionning capacity beneath the U238 fission thres-hold are corrected for the fact that sub-thres-hold fissionning 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 thres-hold group and 6 groups to the subfission thres hold group.
They were calculated with the aid of the following relations:

$$\sigma_{t,I} = \sum_k f_{I,k}\, \sigma_{t,k}$$

$$\sigma_{I\to II} = \sum_k f_{I,k}\, \sigma_{k,I\to II} = \sum_k f_{I,k} \left(\sigma_{n,n',k} - \sum_{k'\neq k} \sigma_{k\to k'} \right)$$

$$\sigma_{I\to I} = \sigma_{t,I} - \sigma_{I\to II}$$

$$\sigma_{c,I} = \sum_k f_{I,k}\, \sigma_{c,k}$$

$$\sigma_{f,I} = \sum_k f_{I,k}\, \sigma_{f,k} + \sum_j f_{II,j}\, \sigma_{f,j}\, W_2$$

$$\nu\sigma_{f,I} = \sum_k f_{I,k} (\nu\sigma_f)_k + \sum_j f_{II,j} (\nu\sigma_f)_j \cdot W_2 \,.$$

$$\sigma_{t,II} = \sum_j f_{II,j}\, \sigma_{t,j}$$

$$\sigma_{c,II} = \sum_j f_{II,j}\, \sigma_{c,j}$$

$$\sigma_{s,II} = \sum_j f_{II,j}\, \sigma_{s,j} = \sigma_{t,II} - \sigma_{c,II}$$

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 subthres-hold broad group II 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 broad 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 thres-hold of U238.

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

The subscripts:

t = total

I→II = (inelastic) scattering from group I to II

I → I = (elastic) scattering from group I to I

c= capture

f = fission

s = scattering

n,n',k= inelastic scattering out of fine group k

k,k'= scattering from group k 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

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

where again

ρ = density of the compound material

A = Avogadro's number

M = molecular weight of the compound

N_1, N_2 = the number of atoms 1, 2 ... per molecule of the compound.

The calculation of the homogenized macroscopic cross sections by weigh ing 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

$\Sigma_{I\to I}$ = scattering mean macroscopic cross section in group I

$\Sigma_{I\to II}$ = 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:

$$C_I = \frac{0.561 \cdot P(a_B \Sigma_{t,I})}{\left(1 - P(a_B \Sigma'_{t,I}) \frac{(0.561 \cdot \nu\Sigma_{f,I} + \Sigma_{I\to I})}{\Sigma_{t,I}}\right)}$$

$$C_{II} = \frac{0.439\, P(a_B \Sigma_{t,II}) \cdot \left(\frac{\nu\Sigma_{F,I} \cdot C_1 + 1}{\Sigma_{t,I}}\right) + P(a_B \Sigma_{t,II}) \cdot C_I \cdot \frac{\Sigma_{I\to II}}{\Sigma_{c,I}}}{1 - P(a_B \Sigma_{t,II}) \cdot \frac{\Sigma_{s,II}}{\Sigma_{t,II}}}$$

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:

$$\varepsilon - 1 = C_I G_I + C_{II} G_{II}$$

where:

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

$$G_{II} = - \frac{\Sigma_{c,II}}{\Sigma_{t,II}}$$

I.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

$$\gamma = 2\,\Sigma' r\,(1 - P_0(\Sigma' r))$$

where

Σ' 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

$$\frac{S}{4} = \Sigma' V\,(1 - P_0)$$

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

$$r_e = \sqrt{\frac{4\,V_{oi}}{2\pi}}$$

For an hexagonal arrangement one can show that the effective radius of the circular hole would be

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

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

$$r_i = r_e \cdot \frac{r_i'/d}{r_e'/d}$$

$$r_i = \sqrt{\frac{V_0}{21\pi}} \cdot \frac{\frac{1}{\sqrt{3}} - \alpha}{\sqrt{\frac{1}{4}\sqrt{3} - \frac{1}{2}\pi\alpha^2}}$$

$$\left(\alpha = \frac{s}{d}\right)$$

The effective rod radius is found by the relation

$$22\,\pi s^2 = V_{fuel}$$

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

$$I = A + B\sqrt{\frac{S}{M}}$$

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 interfer 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

$$p' = e^{-\frac{NIV_f}{\xi\Sigma_s V_m}\beta}$$

where N = number of atoms of the absorber per unit volume
V = volume
β = the flux ratio at the resonance energy between fuel and moderator
f = fuel
m = moderator

The factor β is the product of two terms:
-the first one (ω) 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. ω 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 (γ) 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 γ term is quite difficult to evaluate in a simplified manner. By assuming that the resonance absorption is spread out in a lethargy interval Δu , and by using the diffusion theory, it can be written:

$$\gamma = \frac{\kappa r}{2} \frac{I_0(\kappa r)}{I_1(\kappa r)} \approx \left(1 + \frac{1}{8} \kappa^2 r^2\right)^{-1}$$

where κ is the reciprocal slowing down length at resonance energies and r the effective fuel rod radius.

κ is calculated from

$$\kappa^2 = \frac{3 \xi \Sigma_s}{\Delta u} \cdot \Sigma_{tr} \left(1 - 0.8 \frac{\xi \Sigma_s / \Delta u}{\Sigma_{tr}}\right)$$

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

The choice of Δu 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.

I.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 (0) the factor f_{fc} can be written as the ratio of the reaction rates in fuel and cluster or

$$f_{fc} = \frac{\varphi_f V_f \Sigma_f}{\sum_i \phi_i V_i \Sigma_i}$$

$\sum_i$ 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

$$\varphi_g = \frac{\phi(a)}{\bar{\phi}} = 1 + \frac{\Sigma_c}{\Sigma_t} A \left[1 + \alpha \frac{\Sigma_s}{\Sigma_t} + \beta \left(\frac{\Sigma_s}{\Sigma_t} \right)^2 \right]$$

where the subscripts c, s and t mean capture scattering and total respectively and A, α and ß are functions of a . Σ_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 Guionnet (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:

absorption fraction in region i =

$$\frac{\text{source in region i - net outscattering from region i}}{\text{total source in cell lattice}}$$

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

$$\Sigma_{ai} V_i \varphi_i = f_i \sum_{j=1}^{N} Q_j V_j$$

or

$$\bar{\varphi}_i = \frac{f_i}{\Sigma_{ai} V_i} \sum_{j=1}^{N} Q_j V_j$$

Furthermore the cell homogenized absorption cross section becomes

$$\bar{\Sigma}_a = \frac{\sum_{j=1}^{N} \Sigma_{aj} V_j \varphi_j}{\sum_{j=1}^{N} V_j \varphi_j}$$

In these formulae j is the region index, Σ_a, V, φ 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

$$\frac{\varphi_{cell}}{\bar{\varphi}_u} = \varphi_{fc} \cdot \varphi_{cc} = \frac{V_f + \varphi_g (V_g + V_r + V_o)}{V_f + V_g + V_r + V_o}$$

The following symbols have been used:

V = volume	g = canning
f = fuel	o = coolant
r = filler	

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.

I.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:

$$L^2 = f_c L_c^2 + f_m L_m^2$$

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

$$L^2 = \frac{1}{3 \Sigma_{tr} \Sigma_a}$$

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

$$\Sigma_{tr} = \frac{\sum_i \Sigma_{tri} V_i \varphi_i}{\sum_i V_i \varphi_i} \qquad \text{and} \qquad \Sigma_{ai} = \frac{V_f \Sigma_{af}}{\sum_i V_i \varphi_i}$$

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.

I.7. The thermal diffusion coefficient

Once known the cell absorption cross section and the diffusion area the lattice diffusion coefficient is given by

$$D = L^2 . \bar{\Sigma}_a$$

I.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) τ_1 , τ_i and τ_e respectively, one may write the corrected value in the moderator by

$$\tau_m = \tau_1 (1 - P_H - P_i) + \tau_e P_H + \tau_i P_i$$

with

P_H 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 ε) and knowing the total collision probability C_I , the value is easily calculated from

$$P_i = C_I \frac{V_f \Sigma_{I \to II, f}}{V_B \Sigma_{t,I}}$$

with

f resp. B fuel and bundle respectively

$\Sigma_{I \to II}$ the inelastic fuel scattering cross section

$\Sigma_{t,I}$ 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_H can be written

$$P_H = C_I \frac{V_o \Sigma_{I \to II, o}}{V_B \Sigma_{t,I}} + C_{II} \frac{\Sigma_{s,II,H} V_o}{V_B \Sigma_{t,II}}$$

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 .025 ev and the values of τ_1 and τ_i are 120 and 72 cm^2 respectively.

$$\tau_1 = 120 \left(\frac{\rho_0}{\rho}\right)^2 - Q\,\Delta u_1$$

$$\tau_i = 72 \left(\frac{\rho_0}{\rho}\right)^2 - Q\,\Delta u_1$$

$$\tau_e = 120 \left(\frac{\rho_0}{\rho}\right)^2 - Q\,(1 - \Delta u_1)$$

$$\Delta\tau_{res} = Q\,\Delta u_{res}$$

with $$Q^{-1} = 3\,(\xi z_s)_m \cdot (\Sigma_{tr})_m$$

and $$\Delta u = \ln\frac{\tau}{\tau_0} = \ln\frac{E}{E_0}$$

is the lethargy difference between neutrons of energy E and E_0. For τ_1 and τ_i the last term on the right side corrects the age values to spectral constants T.
In τ_e another unit of lethargy is subtracted to take into account the elastic scattering due to the H atoms.
For τ_{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

$$\tau_{res,m} = \tau_m - \Delta\tau_{res}$$

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

$$\tau = \tau_m \cdot \left(\frac{V_f}{V_m}\right)^2 \frac{1}{\left(1 + \frac{(V\Sigma_{tr})_B}{(V\Sigma_{tr})_m}\right)\left(1 + \frac{(V\Sigma_s\xi)_B}{(V\xi\Sigma_s)_m}\right)}$$

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

$$\frac{\tau_{res}}{\tau} = \frac{\tau_{res,m}}{\tau_m}$$

The mean lattice cell slowing down cross section parameter i.e. $\overline{\xi\Sigma_s}$ 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.

I.9. Fast diffusion coefficient

The lattice cell fast diffusion coefficient is then calculated by

$$D_f = \frac{(\xi\Sigma_s) \cdot \tau}{\Delta u}$$

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

I.10. Lethargy range

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

$$\Delta u = \tau_m (\xi\Sigma_s)_m (\Sigma_{tr})_m$$

I.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

$$\frac{\Sigma_a^{fe,t}}{\Sigma_a^{fi,t}}$$

with fe resp. fi 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

$$\frac{\nu\ \Sigma_f^{fi,t}}{\Sigma_a^{fi,t}}$$

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

$$C_I\ \frac{\Sigma_c^{fe(1)}}{\Sigma_t^{(1)}} + C_{II}\ \frac{\Sigma_c^{fe(2)}}{\Sigma_t^{(2)}}$$

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:

$$\epsilon\ .\ \frac{1}{1+B^2\tau}$$

the total production can then be written in the form:

$$\gamma_o = \left[C_I\ \frac{\Sigma_c^{fe(1)}}{\Sigma_t^{(1)}} + C_{II}\ \frac{\Sigma_c^{fe(2)}}{\Sigma_t^{(2)}} + \frac{\epsilon\,(1-p)}{1+B^2\tau} \right] \frac{\nu\ \Sigma_f^{fi,t}}{\Sigma_a^{fi,t}} + \frac{\Sigma_a^{fe,t}}{\Sigma_a^{fi,t}}$$

Connected with these parameters are the parameters X_1, being the number of fast fissions of the fertile material per fast born neutron, and:

X_o 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

$$X_1 = C_I \frac{\Sigma_f^{fe(1)}}{\Sigma_t^{(1)}}$$

The second is already explained and is the form in square brackets in the formula of γ_0 .
The totals of X_1, X_0 and γ_0 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

$$k_\infty = \eta \varepsilon p f$$

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

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

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:

$$\nu\Sigma_f = \frac{k_\infty \Sigma_a}{p}$$

$$\Sigma_1 = \frac{D_1}{\tau}$$

$$\Sigma_{r1} = p.\Sigma_1$$

$$\Sigma_{a1} = \Sigma_1 - \Sigma_{r1}$$

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 $.2m^{-2}$. 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 $\geq$ 22 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.

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 hydrogeneous coolant.

Two concentrical tubes have been used in the measurements; AC_1 a composition of two concentrical 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 prameters, in the resonance integral and k_∞ . 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_∞ 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 τ, 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 η, ε, p, f etc. were measured in the PDP for D_2O 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 η and ε 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 who 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 .4 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 - 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 devided into three parts (eq.7 D_2O 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 η, ϵ 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 τ show relatively the greatest differences with the CANDU results L^2 being too great and τ too small by about 8 %. For the 7 rod clusters the differences of L^2 and τ 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 .1 m^{-2}) for the 7 rod cluster than for the 19 rod cluster, which are all too high by at most .5 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 °/oo 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°K.

The calculated fuel spectral constants however, are too low by 30°K for small pitches decreasing to 15°K for large pitches. The resulting buckling difference on the other hand never exceed .2m^{-2}.

II.5. Conclusions

As conclusion may be said that in general the detailed nuclear parameters η, ϵ, p and f were good compared with the measurements. The migration area L^2 and τ 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 .3 m^{-1}.

Furthermore the results show that for small pitches systematicly 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. Appoximation 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).

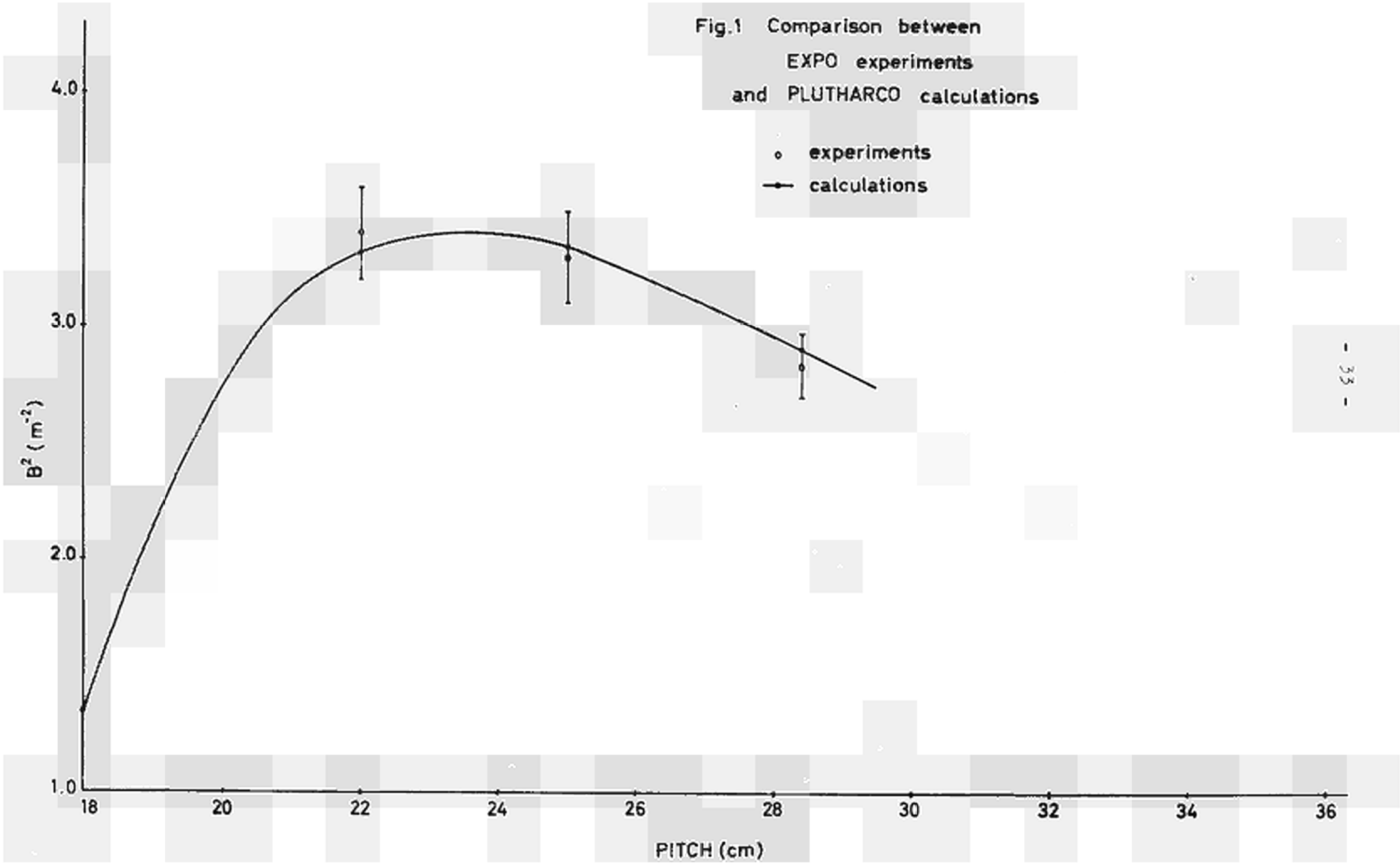


Fig.1 Comparison between EXPO experiments and PLUTHARCO calculations

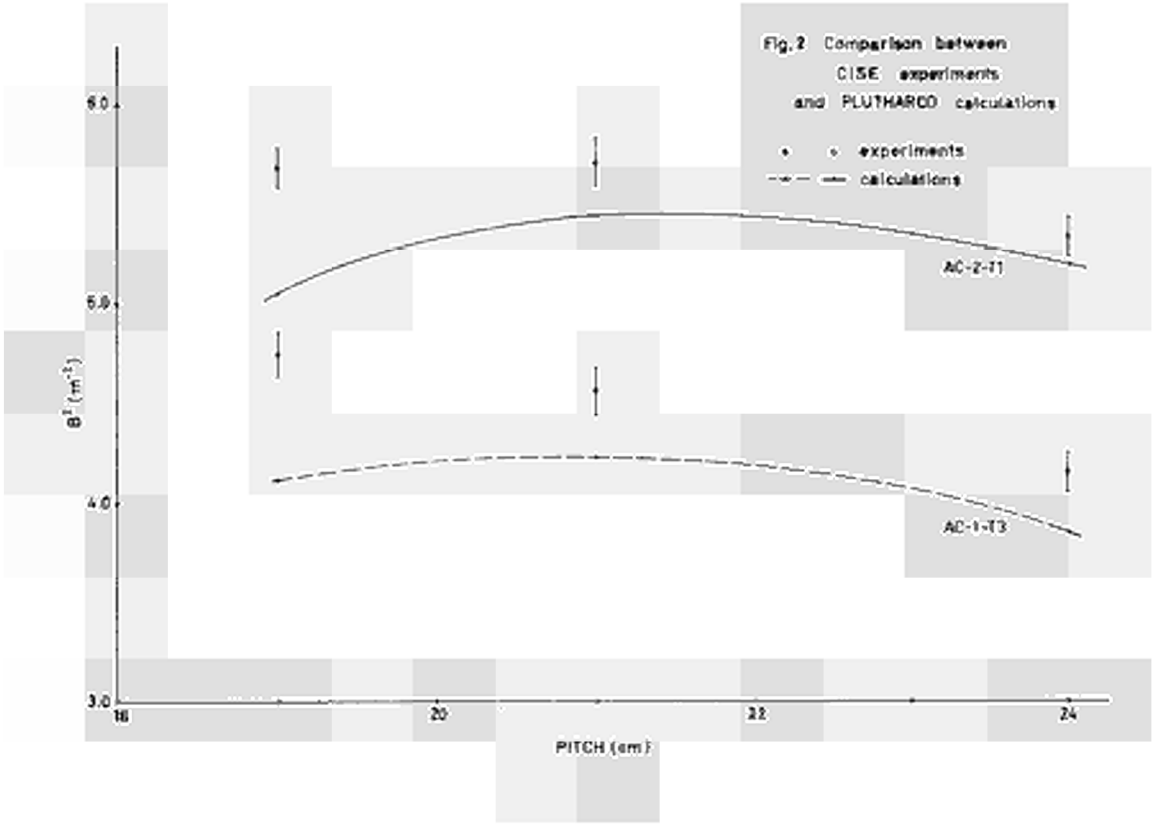


Fig. 2 Comparison between CISE experiments and PLUTHARCO calculations

• ◦ experiments

— — — — calculations

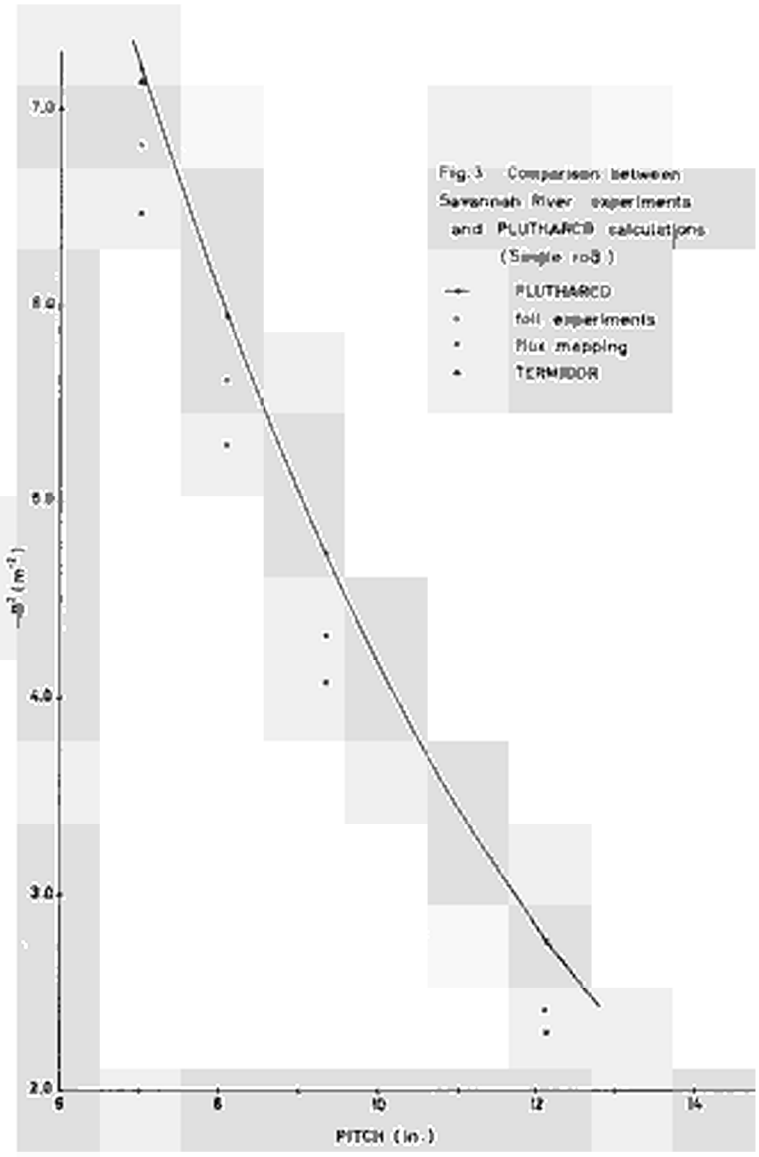


Fig. 3 Comparison between Savannah River experiments and PLUTHARCO calculations (Single rod)

PLUTHARCO

◦ foil experiments

▪ flux mapping

▲ TERMIDOR

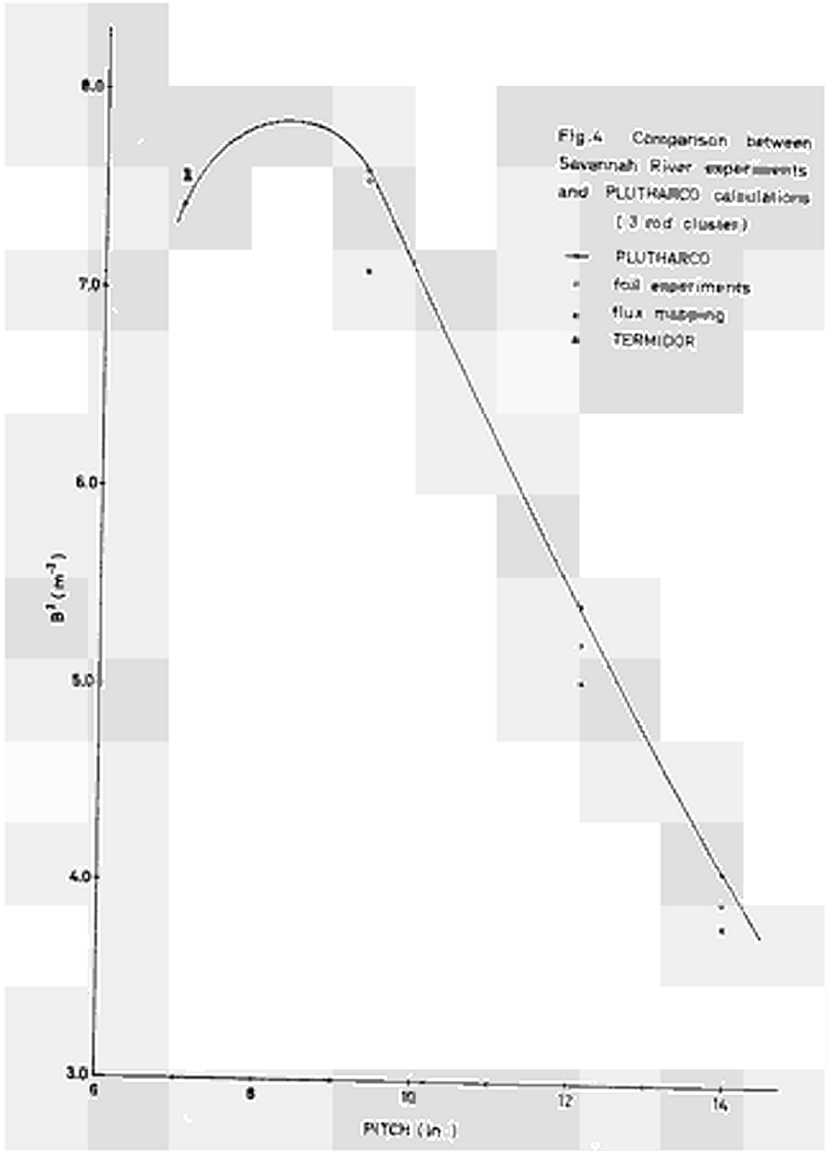


Fig. 4 Comparison between Savannah River experiments and PLUTHARCO calculations (3 rod cluster)

— PLUTHARCO
◦ foil experiments
• flux mapping
▲ TERMIDOR

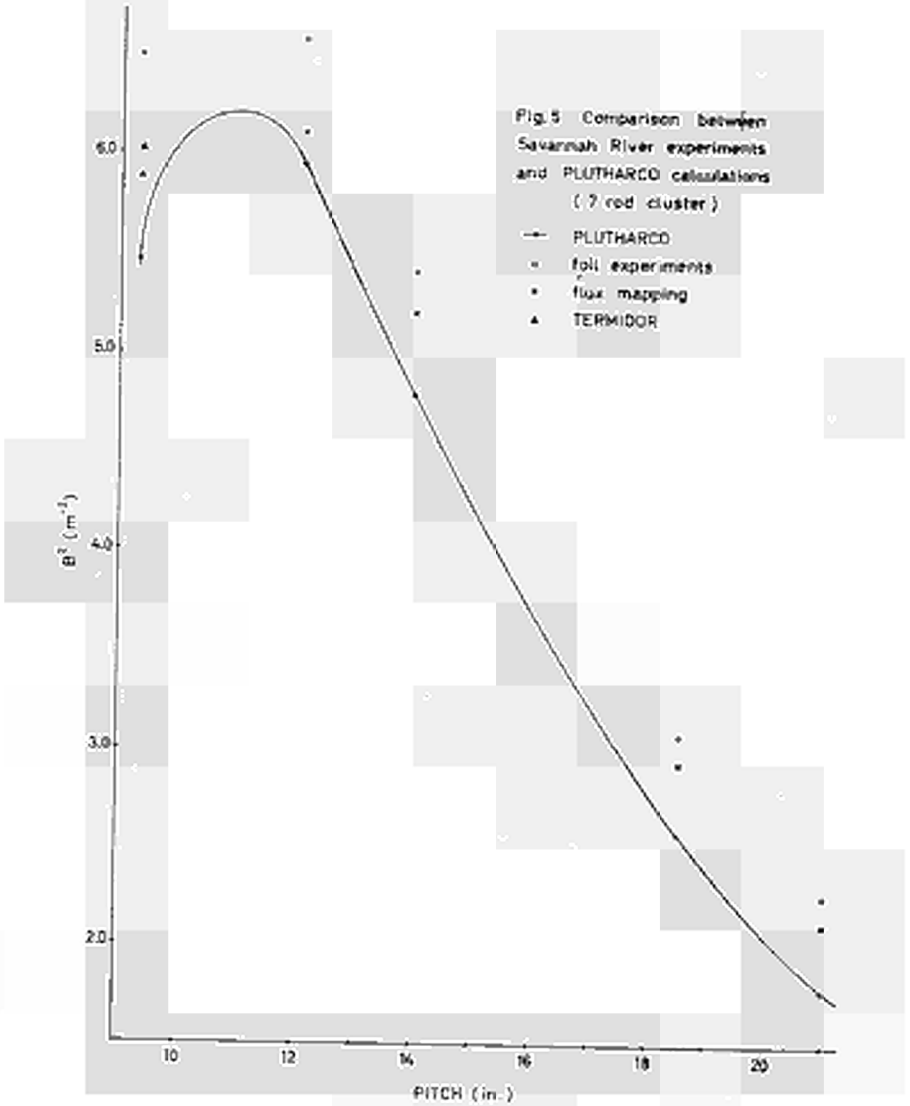


Fig. 5 Comparison between Savannah River experiments and PLUTHARCO calculations (7 rod cluster)

— PLUTHARCO
◦ foil experiments
• flux mapping
▲ TERMIDOR

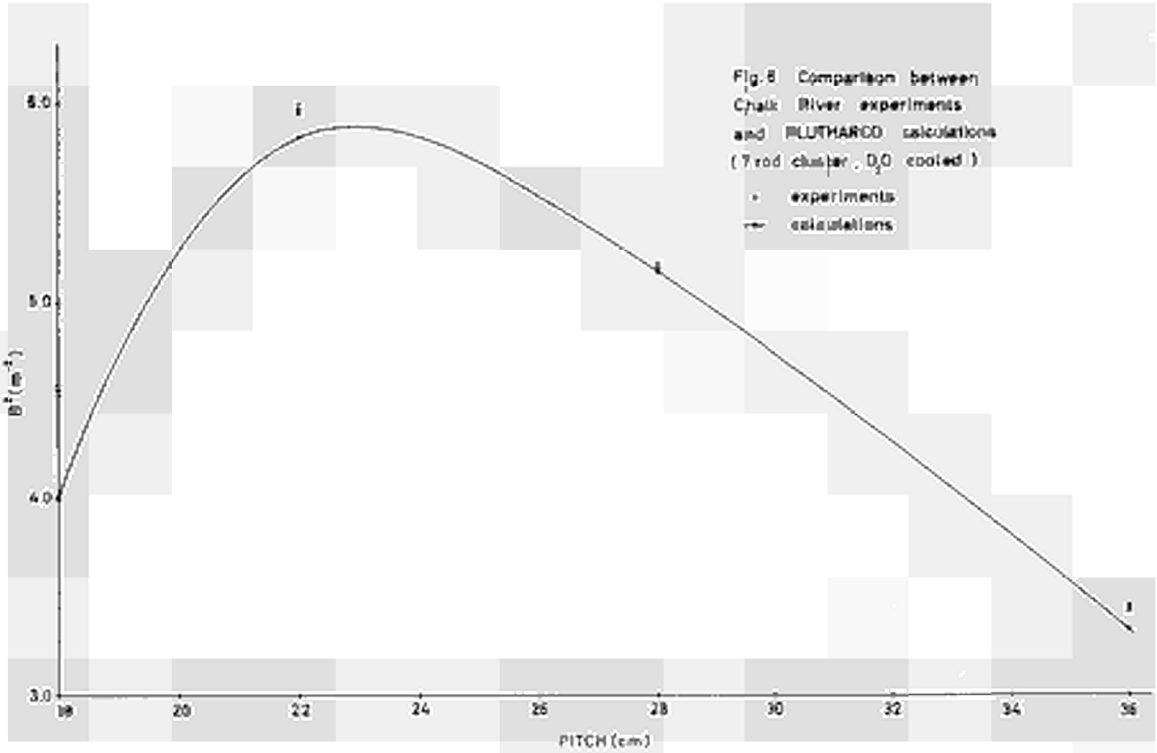


Fig. 6 Comparison between Chalk River experiments and PLUTHARCO calculations (7 rod cluster, D_2O cooled)

• experiments
— calculations

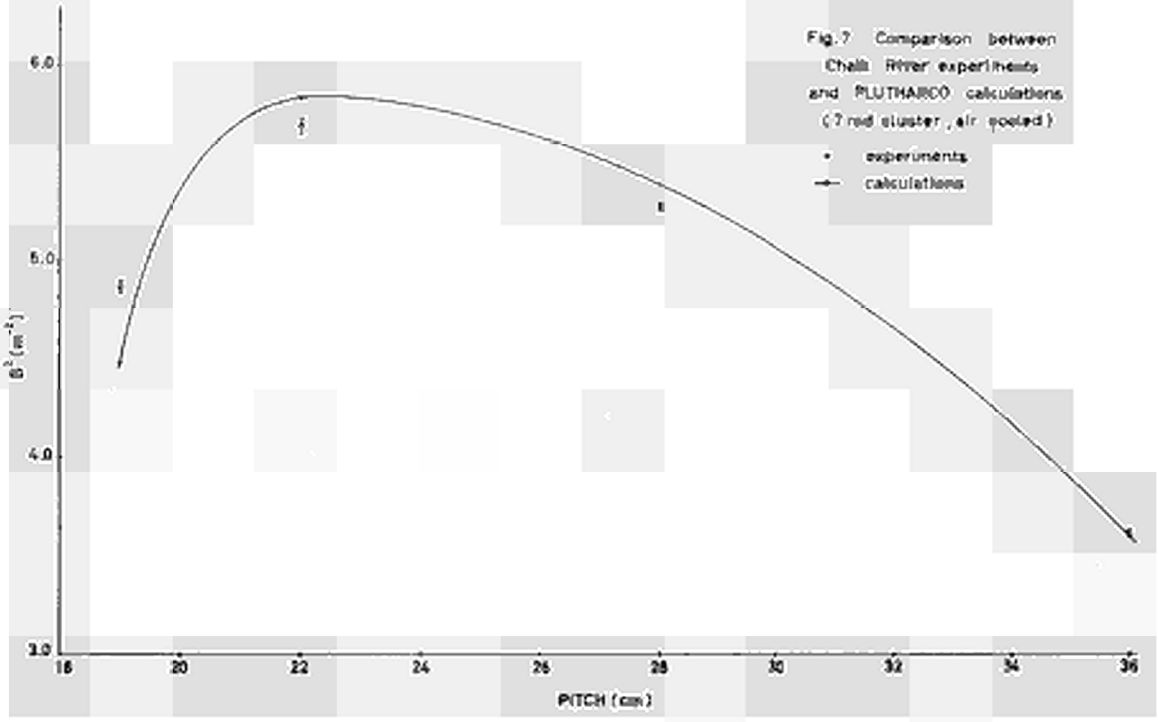


Fig. 7 Comparison between Chalk River experiments and PLUTHARCO calculations (7 rod cluster, air cooled)

• experiments
— calculations

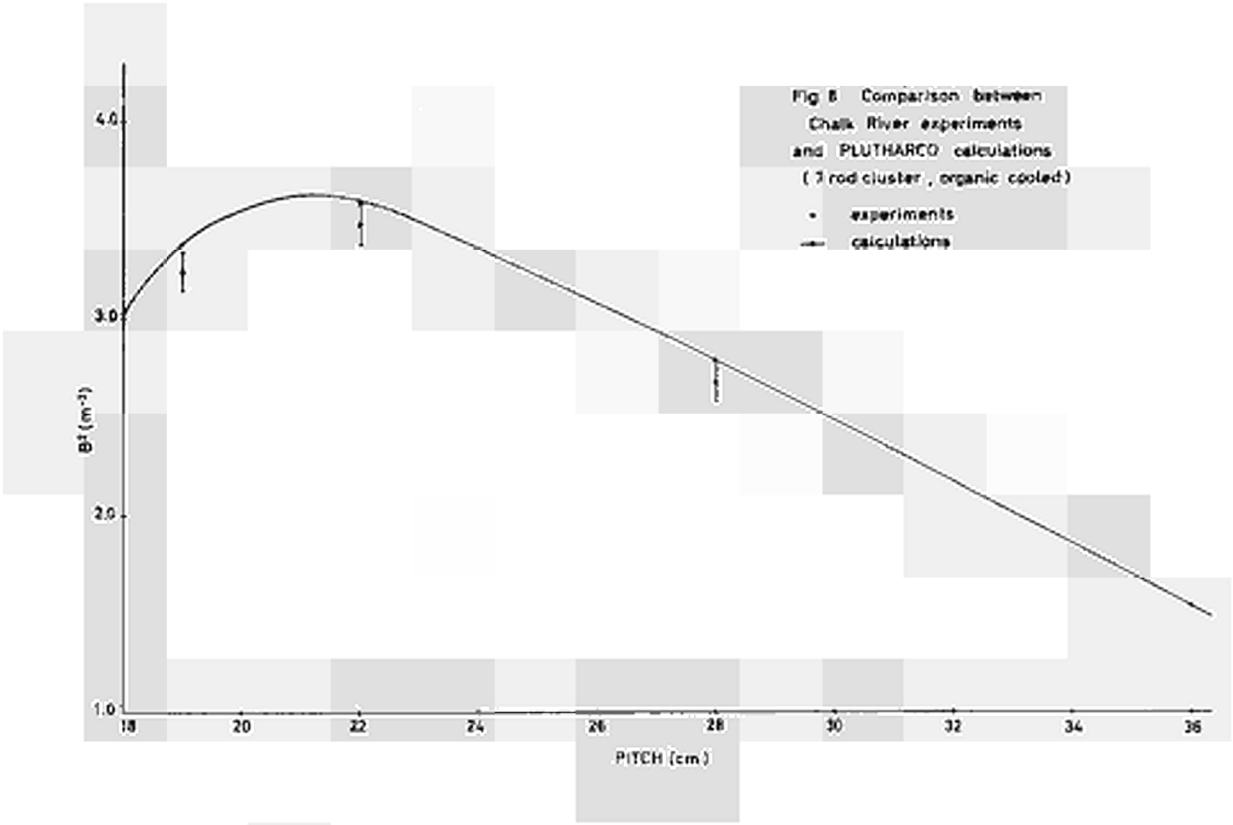


Fig 8 Comparison between Chalk River experiments and PLUTHARCO calculations (7 rod cluster, organic cooled)

- experiments
- calculations

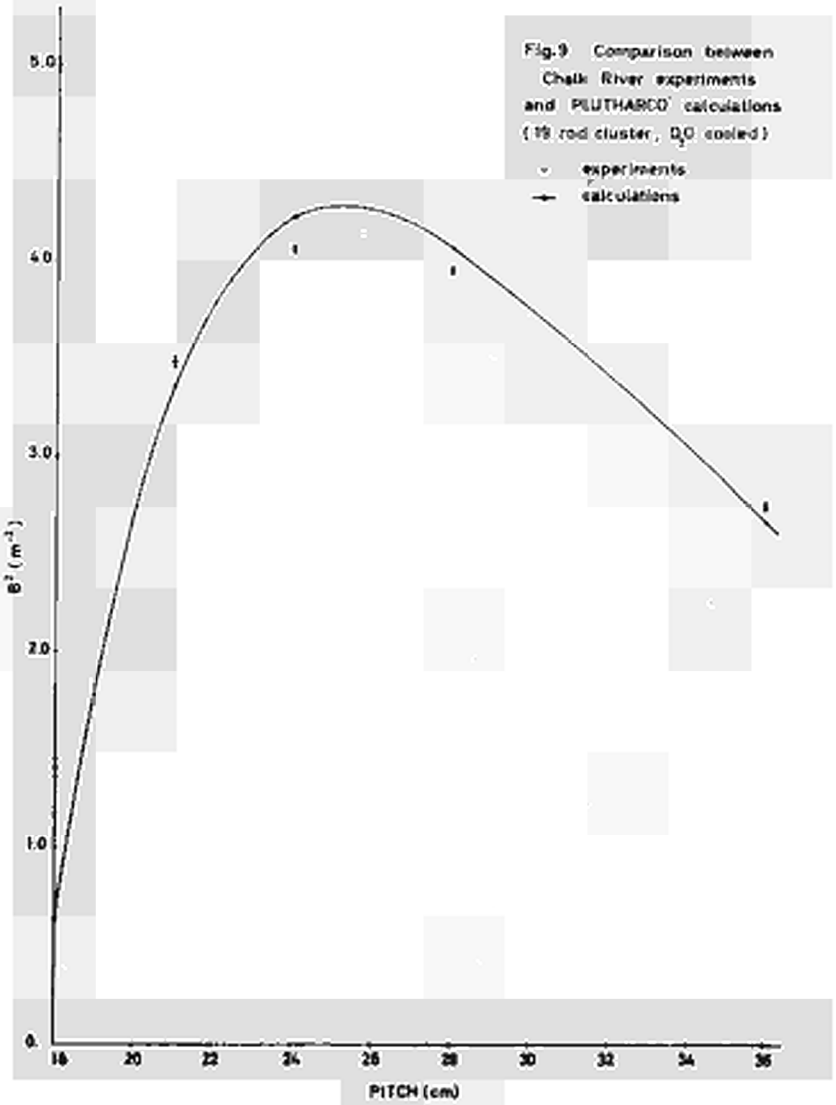


Fig.9 Comparison between Chalk River experiments and PLUTHARCO calculations (19 rod cluster, D_2O cooled)

- experiments
- calculations

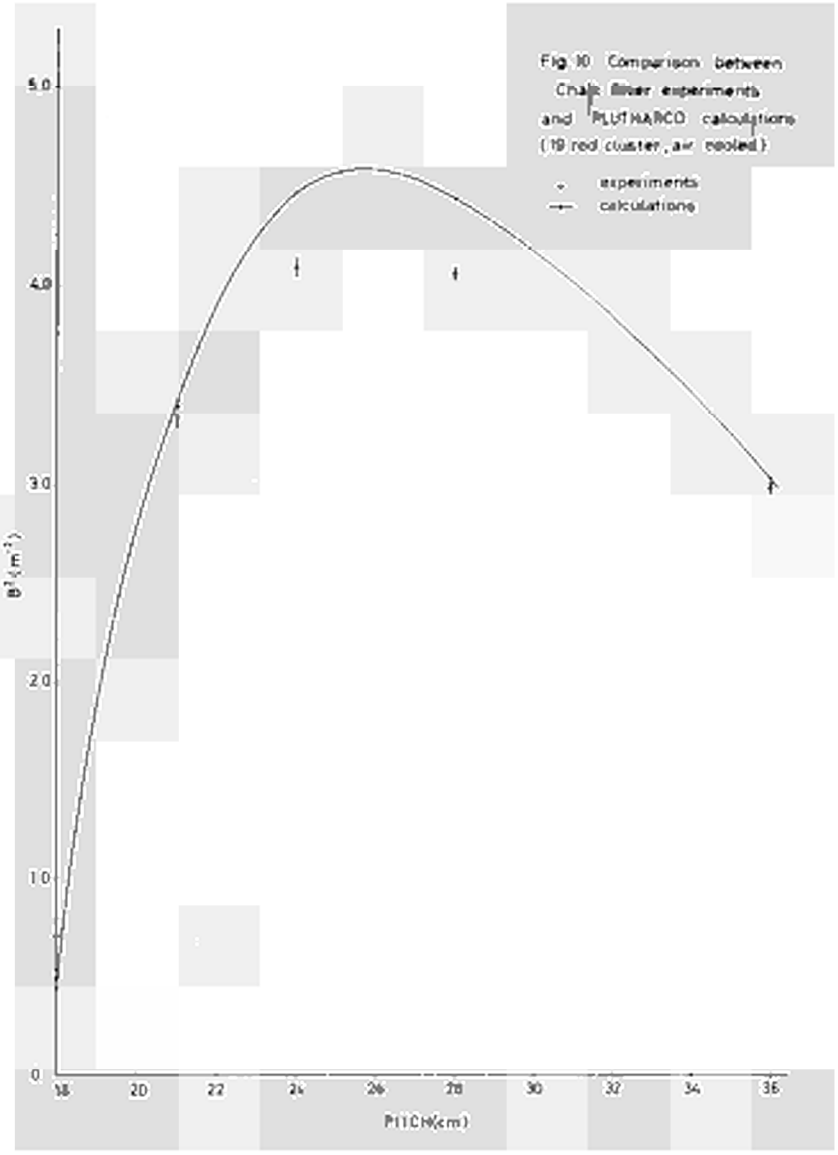


Fig. 10 Comparison between Chalk River experiments and PLUTHARCO calculations (19 rod cluster, air cooled)

- experiments
- calculations

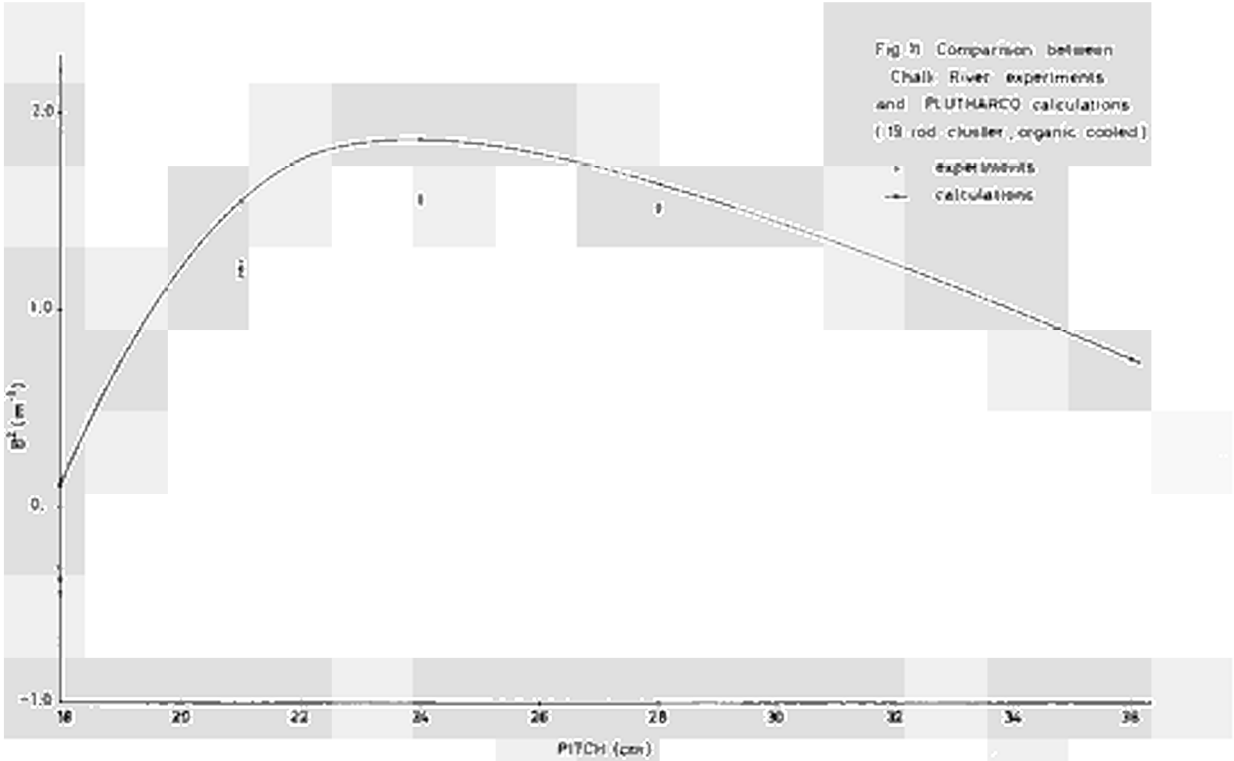


Fig. 11 Comparison between Chalk River experiments and PLUTHARCO calculations (19 rod cluster, organic cooled)

- experiments
- calculations

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 thresshold
(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/secx10^5)

F (i) = atomic fraction of isotope i

f(1/v)= spectrum mean microscopic 1/v abs.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 (^oC)

T_n = spectral constant (^oK)

T_o = room temperature (293^oK)

ALFA = weight percentage of Al_2O_3 in SAP

RHO = density (gr/cm^3)

RLTR = inverse reference transport cross section

BSH = 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)

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

s = Santowax

SAP = Sintered Aluminium Power

t = assembly of pressure tube (1) and calandria tube (3)

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

γ = 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

FUEL

1. Calculation of spectral constants

a. Correlated spectral constants

$$(T_n')_f = 6.8 \cdot (V_c \cdot \Sigma_{ac}^t + V_q \cdot \Sigma_{aq}^t + V_o \cdot \Sigma_{ao}^t + V_r \cdot \Sigma_{ar}^t) - 0.11 \cdot V_o \cdot \Sigma_{so}^t$$
$$+ 0.0044 \cdot V_c \cdot \Sigma_{sc}^t \cdot (T_c - T_m) + 0.00163 \cdot (V_q + V_{t1}) \cdot \Sigma_{sq}^t \cdot (T_o - T_m)$$
$$+ (T_o - T_m) \cdot \left(1 - 0.8\, e^{-0.1\, V_o \Sigma_{so}^t} - 0.2\, e^{-0.7\, V_o \Sigma_{so}^t}\right) + T_m + 300°$$

$$(T_n')_q = (T_n')_f$$

$$(T_n')_{oi} = (T_n')_f$$

$$(T_n')_r = (T_n')_{oo} = \frac{(T_n')_f + (T_n')_m}{2}$$

$$(T_n')_{t2} = (T_n)_r$$

$$(T_n')_{t3} = (T_n)_r$$

$$(T_n')_m = T_m + 300°$$

b. Spectral constants directly entered

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

$$(T_n)_f = \frac{\pi}{4} \cdot \frac{293.6}{F^2 (\frac{1}{v})_c}$$

$$(T_n)_q = (T_n)_f$$

$$(T_n)_o = (T_n)_f$$

$$(T_n)_r = (T_n)_{oo} = \frac{(T_n)_f + (T_n)_m}{2}$$

$$(T_n)_{t2} = (T_n)_r$$

$$(T_n)_{t3} = (T_n)_r$$

$$(T_n)_m = \frac{\pi}{4} \cdot \frac{293.6}{F^2 (\frac{1}{v})_m}$$

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

$\sigma_a(235)$ $\sigma_a(239)$

$\sigma_f(235)$ $\sigma_f(239)$

2. Calculation Westcott constants

$$g_a(232) = 1.$$

$$g_a(238) = 1.$$

$$s_a(236) = 50 \cdot \sqrt{\frac{T_n}{293.6} \cdot \frac{T}{4}}$$

$$s_a(240) = \frac{s_a(240)}{\sqrt{\frac{1 + 4 \cdot V_c \cdot N \cdot 115000 \cdot F(240)}{s_{eff}}}}$$

$$s_a(239) = \frac{s_a(239)}{\sqrt{\frac{1 + 4 \cdot V_c \cdot N \cdot F(239) \cdot 3400}{s_{eff}}}}$$

$$s_f(239) = \frac{s_f(239)}{\sqrt{\frac{1 + 4 \cdot V_c \cdot N \cdot F(239) \cdot 3400}{s_{eff}}}}$$

3. Calculation Westcott cross sections

$$\hat{\sigma}_a(i) = \sigma_a^t(i) \cdot \left[g(i) + r \cdot s(i) \right]$$

$$\hat{\sigma}_f(i) = \sigma_f^t(i) \cdot \left[g(i) + r \cdot s(i) \right]$$

i =	1	Th 232
	2	U 238
	3	U 235
	4	U 236
	5	U 238
	6	Pu 239
	7	Pu 240
	8	Pu 241

4. Mixed fuel microscopic cross sections

$$\sigma_a^t = \sum_{i=1}^{8} F(i) \cdot \hat{\sigma}_a(i) \cdot \sqrt{\frac{\pi}{4} \cdot \frac{293.6}{T_n}}$$

$$\sigma_s^t = \sum_{i=1}^{8} F(i) \cdot \sigma_s^t(i)$$

$$\sigma_f^t = \sum_{i=1}^{8} F(i) \cdot \hat{\sigma}_f(i) \cdot \sqrt{\frac{\pi}{4} \cdot \frac{293.6}{T_n}}$$

$$(\nu\sigma_f)^t = \sum_{i=1}^{8} F(i) \cdot \nu(i) \cdot \hat{\sigma}_f(i) \cdot \sqrt{\frac{\pi}{4} \cdot \frac{293.6}{T_n}}$$

$$\sigma_{tr}^t = \sum_{i=1}^{8} F(i) \cdot \left[\sigma_{tr}^t(i) + \hat{\sigma}_a(i)\right]$$

$$\sigma_s^e = \sum_{i=1}^{8} F(i) \cdot \sigma_s^e(i)$$

$$\sigma_{tr}^e = \sum_{i=1}^{8} F(i) \cdot \sigma_{tr}^e(i)$$

$$(\xi\sigma_s)^e = \sum_{i=1}^{8} F(i) \cdot (\xi\sigma_s)^e(i)$$

$$\sigma_t^{(1)} = \sum_{i=1}^{8} F(i) \cdot \sigma_t^{(1)}(i)$$

$$\sigma_e^{(1)} = \sum_{i=1}^{8} F(i) \cdot \sigma_e^{(1)}(i)$$

$$(\nu\sigma_f)^{(1)} = \sum_{i=1}^{8} F(i) \cdot (\nu\sigma_f)^{(1)}(i)$$

$$\sigma_i^{(1)} = \sum_{i=1}^{8} F(i) \cdot \sigma_i^{(1)}(i)$$

$$\sigma_f^{(1)} = \sum_{i=1}^{8} F(i) \cdot \sigma_f^{(1)}(i)$$

$$\sigma_c^{(1)} = \sum_{i=1}^{8} F(i) \cdot \sigma_c^{(1)}(i)$$

$$\sigma_t^{(2)} = \sum_{i=1}^{8} F(i) \cdot \sigma_t^{(2)}(i)$$

$$\sigma_s^{(2)} = \sum_{i=1}^{8} F(i) \cdot \sigma_s^{(2)}(i)$$

i =	1	Th 232
	2	U 238
	3	U 235
	4	U 236
	5	U 233
	6	Pu 239
	7	Pu 240
	8	Pu 241

5. Fertile isotope macroscopic cross sections

$$\Sigma_a^{Fet} = \sum_{k=1}^{3} F(k) \cdot N \cdot \hat{\sigma}_a(k) \cdot \sqrt{\frac{\pi}{4} \cdot \frac{293.6}{T_n}} = \sum_{k=1}^{3} \Sigma_a^{Fet}(k)$$

$$\Sigma_f^{Fs(1)} = \sum_{k=1}^{3} F(k) \cdot N \cdot \sigma_f^{(1)}(k) = \sum_{k=1}^{3} \Sigma_f^{Fs(1)}(k)$$

$$\Sigma_c^{Fs(1)} = \sum_{k=1}^{3} F(k) \cdot N \cdot \left[\sigma_t^{(1)}(k) - \sigma_e^{(1)}(k) - \sigma_i^{(1)}(k) - \sigma_f^{(1)}(k)\right] = \sum_{k=1}^{3} \Sigma_c^{Fs(1)}(k)$$

$$\Sigma_c^{Fs(2)} = \sum_{k=1}^{3} F(k) \cdot N \cdot \left[\sigma_t^{(2)}(k) - \sigma_s^{(2)}(k)\right] = \sum_{k=1}^{3} \Sigma_c^{Fs(2)}(k)$$

k = 1	Th 232
2	U 238
3	Pu 240

6. Resonance integrals

$A(k,j)$ function of $[T]$

$B(k,j)$ function of $[T]$

$$U1(k) = F(k) \cdot N \cdot A(k,j)$$

$$U2(k) = \frac{F(k) \cdot N \cdot B(k,j)}{\sqrt{\rho \cdot F(k)}}$$

k = 1	Th 232	j = 1	Metal
2	U 238	2	Oxide
3	Pu 240	3	Monocarb.
		4	Dicarbide

7. Fissile isotope macroscopic cross sections

$$\Sigma_a^{Fit} = \sum_{l=1}^{4} F(l) \cdot N \cdot \hat{\sigma}_a(l) \cdot \sqrt{\frac{\pi}{4} \cdot \frac{293.6}{T}}$$

l = 1	U 233
2	U 235
3	Pu 239
4	Pu 241

8. Fuel compound macroscopic cross sections

$$\Sigma_a^t = N \cdot \left[\sigma_a^t + \sigma_{ad}^t(i) \right] + \Sigma_{absorv}$$

$$\Sigma_f^t = N \cdot \left[\sigma_f^t + \sigma_{fd}^t(i) \right]$$

$$(\nu\Sigma_f)^t = N \cdot (\nu\sigma_f)^t$$

$$\Sigma_s^t = N \cdot \left[\sigma_s^t + \sigma_{sd}^t(i) \right]$$

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

$$\Sigma_s^e = N \cdot \left[\sigma_s^e + \sigma_{sd}^e(i) \right]$$

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

$$(\xi\Sigma_s)^e = N \cdot \left[(\xi\sigma_s)^e + (\xi\sigma_s)^e(i) \right]$$

$$(\nu\Sigma_f)^{(1)} = N \cdot (\nu\sigma_f)^{(1)}$$

$$\Sigma_t^{(1)} = N \cdot \left[\sigma_t^{(1)} + \sigma_{td}^{(1)}(i) \right]$$

$$\Sigma_e^{(1)} = N \cdot \left[\sigma_e^{(1)} + \sigma_{ed}^{(1)}(i) \right]$$

$$\Sigma_i^{(1)} = N \cdot \left[\sigma_i^{(1)} + \sigma_{id}^{(1)}(i) \right]$$

$$\Sigma_f^{(1)} = N \cdot \sigma_f^{(1)}$$

$$\Sigma_c^{(1)} = N \cdot \left[\sigma_c^{(1)} + \sigma_{td}^{(1)}(i) - \sigma_{ed}^{(1)} - \sigma_{id}^{(1)} \right]$$

$$\Sigma_t^{(2)} = N \cdot \left[\sigma_t^{(2)} + \sigma_{td}^{(2)}(i) \right]$$

$$\Sigma_s^{(2)} = N \cdot \left[\sigma_s^{(2)} + \sigma_{sd}^{(2)}(i) \right]$$

$$\Sigma_c^{(2)} = \Sigma_t^{(2)} - \Sigma_s^{(2)}$$

ORGANIC COOLANT ($C_{N_C} H_{N_H}$)

α. Thermal cross sections

$$\Sigma_a^t = \frac{0.6024}{M} \left[N_H \cdot 0.332 + N_C \cdot 0.00483 \right] \cdot \sqrt{\frac{\pi T_0}{4 T_n}} \cdot \rho_0$$

$$\Sigma_s^t = \frac{0.6024}{M} \left[N_H \cdot \bar{\sigma}_{sH}(T) + N_C \cdot 4.8 \right] \cdot \rho_0$$

$$\Sigma_{tr}^t = \frac{0.6024}{M} \left[N_H \cdot \left[\rho \lambda_{tr} \right]_H + N_C \cdot 4.53 \right] \cdot \rho_0$$

β. Resonance and epithermal cross sections

$$\Sigma_s^e = \frac{0.6024}{M} \left[N_H \cdot 20.4 + N_C \cdot 4.66 \right] \cdot \rho_0$$

$$\Sigma_{tr}^e = \frac{0.6024}{M} \left[N_H \cdot 20.4 \cdot (1-0.667) + N_C \cdot 4.66 \cdot (1-0.056) \right] \cdot \rho_0$$

$$(\xi \Sigma_s)^e = \frac{0.6024}{M} \left[N_H \cdot 20.4 + N_C \cdot 0.1589 \cdot 4.66 \right] \cdot \rho_0$$

γ. Fast cross sections

$$\Sigma_t^{(1)} = \frac{0.6024}{M} \left[N_H \cdot 1.91 + N_C \cdot 1.49 \right] \cdot \rho_0$$

$$\Sigma_e^{(1)} = \frac{0.6024}{M} \left[N_H \cdot 0.45 + N_C \cdot 1.27 \right] \cdot \rho_0$$

$$\Sigma_i^{(1)} = \frac{0.6024}{M} \left[N_H \cdot 1.46 + N_C \cdot 0.22 \right] \cdot \rho_0$$

$$\Sigma_t^{(2)} = \frac{0.6024}{M} \left[N_H \cdot 4.56 + N_C \cdot 2.78 \right] \cdot \rho_0$$

$$\Sigma_e^{(2)} = \frac{0.6024}{M} \left[N_H \cdot 4.56 + N_C \cdot 2.78 \right] \cdot \rho_0$$

SANTOWAX ($C_{18} H_{14}$)

α. Thermal cross sections

$\rho_s = 1.099 - 0.00072\ T + 0.0009\ .\ x$ (x = % HBR ; T in °C)

$\Sigma_a^t = \frac{0.6024}{230} \left[14.\ 0.332 + 18.\ 0.00488 \right] \sqrt{\frac{\pi T_o}{4 T_n}} \cdot \rho_s$

$\Sigma_s^t = \frac{0.6024}{230} \left[14.\ \bar{\sigma}_{SH}(T) + 18.\ 4.8 \right] \cdot \rho_s$

$\Sigma_{tr}^t = \frac{0.6024}{230} \left[14.\ \left[\rho \lambda_{tr} \right]_{cl} + 18.\ 4.55 \right] \cdot \rho_s$

β. Resonance and epithermal cross sections

$\Sigma_s^e = \frac{0.6024}{230} \left[14.\ 20.4 + 18.\ 4.66 \right] \cdot \rho_s$

$\Sigma_{tr}^e = \frac{0.6024}{230} \left[14.\ 20.4\ (1-0.667) + 18.\ 4.66\ (1-0.056) \right] \cdot \rho_s$

$(\xi \Sigma_s)^e = \frac{0.6024}{230} \left[14.\ 20.4 + 18.\ 0.1589.\ 4.66 \right] \cdot \rho_s$

γ. Fast cross sections

$\Sigma_t^{(1)} = \frac{0.6024}{230} \left[14.\ 1.91 + 18.\ 1.49 \right] \cdot \rho_s$

$\Sigma_e^{(1)} = \frac{0.6024}{230} \left[14.\ 0.45 + 18.\ 1.27 \right] \cdot \rho_s$

$\Sigma_i^{(1)} = \frac{0.6024}{230} \left[14.\ 1.46 + 18.\ 0.22 \right] \cdot \rho_s$

$\Sigma_t^{(2)} = \frac{0.6024}{230} \left[14.\ 4.66 + 18.\ 2.78 \right] \cdot \rho_s$

$\Sigma_e^{(2)} = \frac{0.6024}{230} \left[14.\ 4.56 + 18.\ 2.78 \right] \cdot \rho_s$

DIPHENYL ($C_{12}H_{10}$)

α. Thermal cross sections

$$\Sigma_a^t = \frac{0.6024}{154}\left[\,10 \cdot 0.332 + 12 \cdot 0.00483\,\right]\sqrt{\frac{T\,T_0}{4\,T_n}}\cdot \rho_{cl}$$

$$\Sigma_s^t = \frac{0.6024}{154}\left[\,10 \cdot \bar{\sigma}_{SH}(T) + 12 \cdot 4.8\,\right]\cdot \rho_{cl}$$

$$\Sigma_{tr}^t = \frac{0.6024}{154}\left[\,10 \cdot \left[\rho\,\lambda_{tr}\right]_{cl} + 12 \cdot 4.53\,\right]\cdot \rho_{cl}$$

β. Resonance and epithermal cross sections

$$\Sigma_s^e = \frac{0.6024}{154}\left[\,10 \cdot 20.4 + 12 \cdot 4.66\,\right]\cdot \rho_{cl}$$

$$\Sigma_{tr}^e = \frac{0.6024}{154}\left[\,10 \cdot 20.4\,(1-0.667) + 12 \cdot 4.66\,(1-0.056)\,\right]\cdot \rho_{cl}$$

$$(\xi\,\Sigma_s)^e = \frac{0.6024}{154}\left[\,10 \cdot 20.4 + 12 \cdot 0.1589 \cdot 4.66\,\right]\cdot \rho_{cl}$$

γ. Fast cross sections

$$\Sigma_t^{(1)} = \frac{0.6024}{154}\left[\,10 \cdot 1.91 + 12 \cdot 1.49\,\right]\cdot \rho_{cl}$$

$$\Sigma_e^{(1)} = \frac{0.6024}{154}\left[\,10 \cdot 0.45 + 12 \cdot 1.27\,\right]\cdot \rho_{cl}$$

$$\Sigma_i^{(1)} = \frac{0.6024}{154}\left[\,10 \cdot 1.46 + 12 \cdot 0.22\,\right]\cdot \rho_{cl}$$

$$\Sigma_t^{(2)} = \frac{0.6024}{154}\left[\,10 \cdot 4.56 + 12 \cdot 2.78\,\right]\cdot \rho_{cl}$$

$$\Sigma_e^{(2)} = \frac{0.6024}{154}\left[\,10 \cdot 4.56 + 12 \cdot 2.78\,\right]\cdot \rho_{cl}$$

HEAVY WATER (coolant)

α. Thermal cross sections

$$\Sigma_a^t = \left[0.6428 \cdot 10^{-4} - 0.0181 \, (PU - 0.998) + \Sigma_{am} \sqrt{\frac{\pi}{4}} \right] \cdot \sqrt{\frac{T_0}{T_m}} \cdot \rho_m$$

$$\Sigma_s^t = \left[0.4216 \cdot PU + 2.68 \, (1 - PU) \right] \cdot \rho_m$$

$$\Sigma_{tr}^t = \left[0.3628 \cdot PU + 0.995 (1 - PU) \right] \cdot \rho_m$$

β. Resonance and epithermal cross sections

$$\Sigma_{tr}^e = 0.297 \cdot PU + 0.995 \, (1 - PU) \cdot \rho_m$$

$$(\xi \Sigma_s)^e = 0.1601 \cdot PU + 2.56 \, (1 - PU) \cdot \rho_m$$

γ. Fast cross sections

$$\Sigma_t^{(1)} = 0.1542 \cdot \rho_m$$

$$\Sigma_e^{(1)} = 0.0705 \cdot \rho_m$$

$$\Sigma_i^{(1)} = 0.0838 \cdot \rho_m$$

$$\Sigma_c^{(1)} = 0.$$

$$\Sigma_t^{(2)} = 0.2300 \cdot \rho_m$$

$$\Sigma_e^{(2)} = 0.2300 \cdot \rho_m$$

$$\Sigma_c^{(2)} = 0.$$

SAP

α. Thermal cross sections

$$\Sigma_a^t = \left[0.004547 - 0.002139\,\alpha + \text{EXSAP} \right] \rho_{SAP} \sqrt{\frac{T_0}{T_n}}$$

$$\Sigma_s^t = \left[0.0308 + 0.0608\,\alpha \right] \cdot \rho_{SAP}$$

$$\Sigma_{tr}^t = \left[0.0300 + 0.0576\,\alpha \right] \cdot \rho_{SAP} + \Sigma_a^t$$

β. Epithermal cross sections

$$(\xi \Sigma_s)^e = \left[0.00222 + 0.00793\,\alpha \right] \cdot \rho_{SAP}$$

$$\Sigma_{tr}^e = \left[0.0300 + 0.0576\,\alpha \right] \cdot \rho_{SAP}$$

γ. Fast cross sections

$$\Sigma_t^{(1)} = 0.60248 \left[\frac{1-\alpha}{27} \cdot 1.7 + \frac{2\alpha}{102} \cdot 1.7 + \frac{3\alpha}{102} \cdot 1.92 \right] \cdot \rho_{SAP}$$

$$\Sigma_e^{(1)} = 0.60248 \left[\frac{1-\alpha}{27} \cdot 1.5 + \frac{2\alpha}{102} \cdot 1.5 + \frac{3\alpha}{102} \cdot 1.7 \right] \cdot \rho_{SAP}$$

$$\Sigma_i^{(1)} = 0.60248 \left[\frac{1-\alpha}{27} \cdot 0.2 + \frac{2\alpha}{102} \cdot 0.2 + \frac{3\alpha}{102} \cdot 0.22 \right] \cdot \rho_{SAP}$$

$$\Sigma_c^{(1)} = 0.$$

$$\Sigma_t^{(2)} = 0.60248 \left[\frac{1-\alpha}{27} \cdot 3.025 + \frac{2\alpha}{102} \cdot 3.025 + \frac{3\alpha}{102} \cdot 3.57 \right] \cdot \rho_{SAP}$$

$$\Sigma_e^{(2)} = 0.60248 \left[\frac{1-\alpha}{27} \cdot 3.025 + \frac{2\alpha}{102} \cdot 3.025 + \frac{3\alpha}{102} \cdot 3.57 \right] \cdot \rho_{SAP}$$

$$\Sigma_c^{(2)} = 0$$

STEEL

α. Thermal cross sections

$\Sigma_a^t = 0.2152 \cdot \sqrt{\frac{T_0}{T_n}}$

$\Sigma_s^t = 0.843$

$\Sigma_{tr}^t = 0.852 + \Sigma_a^t$

β. Epithermal cross sections

$(\xi \Sigma_s)^e = 0.02972$

$\Sigma_{tr}^e = 0.852$

γ. Fast cross sections

$\Sigma_t^{(1)} = 0.1755$

$\Sigma_a^{(1)} = 0.1331$

$\Sigma_i^{(1)} = 0.0424$

$\Sigma_c^{(1)} = 0.$

$\Sigma_t^{(2)} = 0.2055$

$\Sigma_a^{(2)} = 0.2055$

$\Sigma_c^{(2)} = 0.$

ALUMINUM OXIDE

α. Thermal cross sections

$\Sigma_a^t = 0.00938 \cdot \sqrt{\frac{T_0}{T_n}}$

$\Sigma_s^t = 0.3548$

$\Sigma_{tr}^t = 0.3410 + \Sigma_a^t$

β. Epithermal cross sections

$\Sigma_s^e = 0.3548$

$\Sigma_{tr}^e = 0.3410$

$(\xi \Sigma_s)^e = 0.03949$

γ. Fast cross sections

$\Sigma_t^{(1)} = 0.$

$\Sigma_e^{(1)} = 0.$

$\Sigma_i^{(1)} = 0.$

SILICIUM OXIDE

α. Thermal cross sections

$\Sigma_a^t = 0.003429 \cdot \sqrt{\frac{T_0}{T_n}}$

$\Sigma_s^t = 0.2229$

$\Sigma_{tr}^t = 0.2143 + \Sigma_a^t$

β. Epithermal cross sections

$\Sigma_s^e = 0.2229$

$\Sigma_{tr}^e = 0.2143$

$(\xi \Sigma_s)^e = 0.02486$

γ. Fast cross sections

$\Sigma_t^{(1)} = 0.$

$\Sigma_e^{(1)} = 0.$

$\Sigma_i^{(1)} = 0.$

GRAPHITE

α. Thermal cross sections

$$\Sigma_a^t = 0.0004 \cdot S_{gr} \cdot \sqrt{\frac{\pi}{4}\frac{T_0}{T_n}}$$

$$\Sigma_s^t = 0.3972 \cdot S_{gr}$$

$$\Sigma_{tr}^t = 0.3972\,(1-0.056) \cdot S_{gr}$$

β. Epithermal cross sections

$$\Sigma_s^e = 0.386 \cdot S_{gr}$$

$$\Sigma_{tr}^e = 0.386\,(1-0.056) \cdot S_{gr}$$

$$(\xi\Sigma_s)^e = 0.06127 \cdot S_{gr}$$

γ. Fast cross sections

$$\Sigma_t^{(1)} = 0.1234 \cdot S_{gr}$$

$$\Sigma_e^{(1)} = 0.1052 \cdot S_{gr}$$

$$\Sigma_i^{(1)} = 0.0182 \cdot S_{gr}$$

$$\Sigma_c^{(1)} = 0.$$

$$\Sigma_t^{(2)} = 0.2303 \cdot S_{gr}$$

$$\Sigma_e^{(2)} = 0.2303 \cdot S_{gr}$$

$$\Sigma_c^{(2)} = 0.$$

HEAVY WATER (moderator)

α. Thermal cross sections

$$\Sigma_a^t = \left[0.6423 \cdot 10^{-4} - 0.0181 \, (PU - 0.998) + \Sigma_{MW} \sqrt{\frac{\pi}{4}} \right] \sqrt{\frac{T_0}{T_n}} \cdot \rho_m$$

$$\Sigma_s^t = \left[0.4216 \cdot PU + (1. - PU) \times 2.68 \right] \cdot \rho_m$$

$$\Sigma_{tr}^t = \left[0.4216 \cdot (1 - 0.1395) \cdot PU + 0.995 \, (1 - PU) \right] \cdot \rho_m$$

$$= \left[0.3628 \cdot PU + 0.995 \, (1 - PU) \right] \cdot \rho_m$$

β. Epithermal cross sections

$$\Sigma_{tr}^e = \left[0.297 \cdot PU + 0.995 \, (1 - PU) \right] \cdot \rho_m$$

$$(\xi \Sigma_s)^e = \left[0.1601 \cdot PU + 2.56 \, (1 - PU) \right] \cdot \rho_m$$

γ. Ages

$$S_m^2 = \left[\frac{\rho_m}{1.1054} \right]^2$$

τ^* function of $\left[\ln (1 - PU) \right]$

$$\tau_1 = \frac{\tau^*}{S_m^2} - \frac{\ln \frac{T_n}{T_0}}{3 (\xi \Sigma_s)_m^e \cdot \Sigma_{trm}^e}$$

$$\tau_i = \frac{0.6 \, \tau^*}{S_m^2} - \frac{\ln \frac{T_n}{T_0}}{3 (\xi \Sigma_s)_m^e \cdot \Sigma_{trm}^e}$$

$$\tau_\infty = \frac{\tau^*}{S_m^2} - \frac{\ln \frac{T_n}{T_0} + 1.}{3 (\xi \Sigma_s)_m^e \cdot \Sigma_{trm}^e}$$

$$\Delta \tau_R = \frac{\ln \frac{E_R}{kT}}{3 (\xi \Sigma_s)_m^e \cdot \Sigma_{trm}^e} \qquad E_R = 50 \text{ eV}$$

THERMAL UTILISATION

$$R_l = \frac{\Sigma_{alloy}}{\Sigma^t_{ac}} \qquad \left[\Sigma_{alloy}, \Sigma_{abs} \text{ due to alloys}\right]$$

$$\Sigma^t_{au} = \Sigma^t_{ac} + \Sigma_{alloy}$$

For all cases : $A ; \alpha ; \beta$ function of $\left[(\Sigma^t_{sc} + \Sigma^t_{au}) . s\right]$

For circular tubes : $A ; \alpha ; \beta$ function of $\left[\frac{(\Sigma^t_{sc} + \Sigma^t_{au}) . s}{\pi(s+s_1+s_2+s_3+r+dr+d+d_1)}\right]$

$$\varphi_{fc} = 1 + A . \frac{\Sigma^t_{au}}{\Sigma^t_{sc} + \Sigma^t_{au}} . \left[1 + \alpha \frac{\Sigma^t_{sc}}{\Sigma^t_{sc} + \Sigma^t_{au}} + \beta . \left(\frac{\Sigma^t_{sc}}{\Sigma^t_{sc} + \Sigma^t_{au}}\right)^2\right]$$

$$R_g = \frac{V_g . \Sigma^t_{ag}}{V_c . \Sigma^t_{ac}} . \varphi_{fc}$$

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

1. Homogenised fuel region

$$\bar{\Sigma}_{ac} = \frac{V_c . \Sigma^t_{ac}}{V^t_B}$$

$$\bar{\Sigma}_{at} = \frac{V_c . \Sigma^t_{au} + \varphi_{fc}\left[V_g . \Sigma^t_{ag} + V^t_{ri} . \Sigma^t_{ar} + V^t_{oi} . \Sigma^t_{ao}\right]}{V^t_B}$$

$$\bar{\Sigma}_{st} = \frac{V_c . \Sigma_{st} + \varphi_{fc}\left[V_g . \Sigma^t_{sg} + V^t_{ri} . \Sigma^t_{sr} + V^t_{oi} . \Sigma^t_{so}\right]}{V^t_B}$$

$$\overline{\xi\Sigma_s} = \frac{V_c . (\xi\Sigma_s)^e_c + V_g . (\xi\Sigma_s)^e_g + V^t_{ri} . (\xi\Sigma_s)^e_r + V^t_{oi} . (\xi\Sigma_s)^e_o}{V^t_B}$$

2. Homogenised outer coolant region

$$\bar{\Sigma}_{at} = \frac{(V_r - V^t_{ri}) . \Sigma^t_{ar} + (\pi.a^2 - V^t_B) . \Sigma^t_{ao}}{\pi.a^2 - V^t_B}$$

$$\bar{\Sigma}_{st} = \frac{(V_r - V^t_{ri}) . \Sigma^t_{sr} + (\pi.a^2 - V^t_B) . \Sigma^t_{so}}{\pi.a^2 - V^t_B}$$

$$\overline{\xi\Sigma_s} = \frac{(V_r - V^t_{ri}) . (\xi\Sigma_s)^e_r + (\pi.a^2 - V^t_B) . (\xi\Sigma_s)^e_o}{\pi.a^2 - V^t_B}$$

3. Pressure tube region
4. Insulation region
5. Calandria region
6. Moderator region

DIFFUSION AREA

$$\varphi_B = \frac{V_c + V_q \cdot \varphi_q + (V_{oi}^t + V_{ri}^t)\,\varphi_q}{V_B^t}$$

$$V_D \cdot \varphi_D = V_B^t \cdot \varphi_B + \varphi_B \left[(V_{oB}^t + V_{rB}^t) \cdot \beta(I) + V_{t1} \cdot \beta(II) + V_{t2} \cdot \beta(III) + V_{t3} \cdot \beta(IV) \right]$$

$$\Sigma_{trD} \cdot V_D \cdot \varphi_D = \Sigma_{trc}^t \cdot V_c + \Sigma_{trq}^t \cdot V_q \cdot \varphi_q + (\Sigma_{tro}^t \cdot V_{oi}^t + \Sigma_{trr}^t \cdot V_{ri}^t) \cdot \varphi_q + \varphi_B \left[\beta(I) \cdot (V_{oB}^t \cdot \Sigma_{tro}^t + V_{rB}^t \cdot \Sigma_{trr}^t) + \right.$$
$$\left. + \beta(II) \cdot V_{t1} \cdot \Sigma_{trt_1}^t + \beta(III) \cdot V_{t2} \cdot \Sigma_{trt_2}^t + \beta(IV) \cdot V_{t3} \cdot \Sigma_{trt_3}^t \right]$$

$$R_m = \frac{f_m}{f}$$

$$L^2 = \left[\frac{(V_D \cdot \varphi_D)^2}{3 \cdot (\Sigma_{trD} \cdot V_D \cdot \varphi_D) \cdot V_c \cdot \Sigma_{ac}^t} + \frac{R_m}{3 \cdot \Sigma_{trm}^t \cdot \Sigma_{am}^t} \right] \cdot F$$

AVERAGE THERMAL FLUX

$$\frac{\phi_R}{\phi_U} = \frac{V_D \cdot \varphi_D + V_m \cdot \varphi_B \cdot \beta(II)}{Z^2}$$

AVERAGE THERMAL ABSORPTION CROSS SECTION

Σ_{aR} is calculated by method of Amouyal - Benoist

THERMAL DIFFUSION COEFFICIENT

$$D_R = L^2 \cdot \Sigma_{aR}$$

FAST FISSION FACTOR

$$\bar{\Sigma}_t^{(1)} = \frac{V_c \cdot \Sigma_{tc}^{(1)} + V_{qi}^f \cdot \Sigma_{tq}^{(1)} + V_{0i}^f \cdot \Sigma_{t0}^{(1)} + V_{ri}^f \cdot \Sigma_{tr}^{(1)}}{V_B^f}$$

P function of $\left[\bar{\Sigma}_t^{(1)} \cdot a_B^f\right]$

$$\bar{\Sigma}_e^{(1)} = \frac{V_c \cdot \Sigma_{ec}^{(1)} + V_{qi}^f \cdot \Sigma_{eq}^{(1)} + V_{0i}^f \cdot \Sigma_{e0}^{(1)} + V_{ri}^f \cdot \Sigma_{er}^{(1)}}{V_B^f}$$

$$\bar{\Sigma}_i^{(1)} = \frac{V_c \cdot \Sigma_{ic}^{(1)} + V_{qi}^f \cdot \Sigma_{iq}^{(1)} + V_{0i}^f \cdot \Sigma_{i0}^{(1)} + V_{ri}^f \cdot \Sigma_{ir}^{(1)}}{V_B^f}$$

$$\bar{\Sigma}_f^{(1)} = \frac{V_c \cdot \Sigma_{fc}^{(1)}}{V_B^f}$$

$$(\bar{\nu\Sigma}_f)^{(1)} = \frac{V_c \cdot (\nu\Sigma_f)^{(1)}}{V_B^f}$$

$$\bar{\Sigma}_c^{(1)} = \frac{V_c \cdot \Sigma_{cc}^{(1)} + V_{qi}^f \cdot \Sigma_{cq}^{(1)} + V_{0i}^f \cdot \Sigma_{c0}^{(1)} + V_{ri}^f \cdot \Sigma_{cr}^{(1)}}{V_B^f}$$

$$\bar{\Sigma}_e^{(2)} = \frac{V_c \cdot \Sigma_{ec}^{(2)} + V_{qi}^f \Sigma_{eq}^{(2)} + V_{0i}^f \cdot \Sigma_{e0}^{(2)} + V_{ri}^f \cdot \Sigma_{er}^{(2)}}{V_B^f}$$

$$\bar{\Sigma}_c^{(2)} = \frac{V_c \cdot \Sigma_{cc}^{(2)} + V_{qi}^f \cdot \Sigma_{cq}^{(2)} + V_{0i}^f \cdot \Sigma_{c0}^{(2)} + V_{ri}^f \cdot \Sigma_{cr}^{(2)}}{V_B^f}$$

$$\bar{\Sigma}_t^{(2)} = \bar{\Sigma}_e^{(2)} + \bar{\Sigma}_c^{(2)}$$

P_1 function of $\left[(\bar{\Sigma}_e^{(2)} + \bar{\Sigma}_c^{(2)}) \cdot a_B^f\right]$

$$C_1 = \frac{0.561 \cdot P}{1 - \left[0.561\,(\bar{\nu\Sigma}_f)^{(1)} + \bar{\Sigma}_e^{(1)}\right] \cdot P}{\bar{\Sigma}_t^{(1)}}$$

$$\ell_2 = 0.489\, P_1 \cdot \frac{\frac{(\bar{\nu\Sigma}_f)^{(1)} \cdot C_1}{\bar{\Sigma}_t^{(1)}} + 1}{1 - \frac{\bar{\Sigma}_e^{(2)} \cdot P_1}{\bar{\Sigma}_e^{(2)} + \bar{\Sigma}_c^{(2)}}}$$

$$\ell_3 = \frac{P_1 \cdot C_1 \cdot \bar{\Sigma}_i^{(1)}}{\bar{\Sigma}_t^{(1)} \cdot \left(1 - \frac{P_1 \cdot \bar{\Sigma}_e^{(2)}}{\bar{\Sigma}_e^{(2)} + \bar{\Sigma}_c^{(2)}}\right)}$$

$$G_1 = \frac{(\bar{\nu\Sigma}_f)^{(1)} - \bar{\Sigma}_f^{(1)} - \bar{\Sigma}_c^{(1)}}{\bar{\Sigma}_t^{(1)}}$$

$$G_2 = -\frac{\bar{\Sigma}_c^{(2)}}{\bar{\Sigma}_e^{(2)} + \bar{\Sigma}_c^{(2)}}$$

$$\varepsilon = 1 + C_1 + G_1 + (C_2 + C_3) \cdot G_2$$

SLOWING DOWN AREA

$$V_B \Sigma_{trB} = V_c \cdot \Sigma^e_{trc} + V_q \cdot \Sigma^e_{trg} + V_o \cdot \Sigma^e_{tro} + V_r \cdot \Sigma^e_{trr} + V_{t1} \cdot \Sigma^e_{trt_1} + V_{t2} \cdot \Sigma^e_{trt_2} + V_{t3} \cdot \Sigma^e_{trt_3}$$

$$V_B (\xi \Sigma_s)_B = V_c \cdot (\xi \Sigma_s)^e_c + V_q \cdot (\xi \Sigma_s)^e_q + V_o \cdot (\xi \Sigma_s)^e_o + V_r \cdot (\xi \Sigma_s)^e_r + V_{t1} \cdot (\xi \Sigma_s)^e_{t1} + V_{t2} \cdot (\xi \Sigma_s)^e_{t2} + V_{t3} \cdot (\xi \Sigma_s)^e_{t3}$$

$$P_i = C_1 \cdot \frac{V_c \cdot \Sigma^{(1)}_{ic}}{V^f_B \cdot \bar{\Sigma}^{(1)}_t}$$

$$P_o = C_1 \cdot \frac{V^f_{oi} \cdot \Sigma^{(1)}_{io}}{V^f_B \cdot \bar{\Sigma}^{(1)}_t} + 0.678 \cdot (C_2 + C_3) \frac{V^f_{oi} \cdot \Sigma^{(2)}_{oo}}{V^f_B \cdot \bar{\Sigma}^{(1)}_t}$$

$$\tau_m = \tau_1 \cdot (1 - P_i - P_o) + \tau_i \cdot P_i + \tau_o \cdot P_o$$

$$\tau = \tau_m \cdot \left(\frac{Z^2}{V_m}\right)^2 \cdot \frac{1}{\left(1 + \frac{V_B \cdot \Sigma_{trB}}{V_m \cdot \Sigma^e_{trm}}\right) \cdot \left(1 + \frac{V_B (\xi \Sigma_s)_B}{V_m (\xi \Sigma_s)^e_m}\right)}$$

$$\tau_{mR} = \tau_m - \Delta \tau_R$$

$$\tau_R = \tau \cdot \frac{\tau_{mR}}{\tau_m}$$

SLOWING DOWN CROSS SECTION

$$(\xi\Sigma_s)_R = \frac{V_B \cdot (\xi\Sigma_s)_B + V_m \cdot (\xi\Sigma_s)^e_m}{\Sigma^2}$$

FAST DIFFUSION COEFFICIENT

$$\Delta U = 3 \cdot \tau_m \cdot (\xi\Sigma_s)^e_m \cdot \Sigma^e_{trm}$$

$$D_{rR} = \frac{(\xi\Sigma_s)_R \cdot \tau}{\Delta U}$$

RESONANCE ESCAPE PROBABILITY

$$\Sigma_R = \frac{V_{oi}^f \cdot \Sigma_{so}^e + V_{ri}^f \cdot \Sigma_{sr}^e + \left[V_{qi}^f + \pi\left(r^2-(r-dr)^2\right) \right] \cdot \Sigma_{eq}^t}{V_{oi}^f + V_{ri}^f + V_{qi}^f + \pi\left(r^2-(r-dr)^2\right)}$$

7 - ROD HEXAGONAL

$R_i = \frac{d}{\sqrt{3}} - s$

P_c function of $\left[\Sigma_R \cdot R_i \right]$

$\gamma' = 2 \cdot \Sigma_R \cdot R_i \cdot (1-P_c)$

$S_u = 14 \cdot \pi \cdot s$

$S_f = 6 \cdot d + 2 \cdot \pi \cdot s$

19 - ROD HEXAGONAL

$R_i = \frac{d}{\sqrt{3}} - s$

P_c function of $\left[\Sigma_R \cdot R_i \right]$

$\gamma' = 2 \cdot \Sigma_R \cdot R_i \cdot (1-P_c)$

$S_u = 38 \cdot \pi \cdot s$

$S_f = 12 \cdot d + 2 \cdot \pi \cdot s$

19 - ROD CIRCULAR

$R_{i1} = \frac{d}{\sqrt{3}} - s$

$R_{i2} = \frac{d}{\sqrt{2}} - s$

P_{c1} function of $\left[\Sigma_R \cdot R_{i1} \right]$

P_{c2} function of $\left[\Sigma_R \cdot R_{i2} \right]$

$\gamma' = \frac{4 \cdot \Sigma_R \cdot R_{i1}^2 \cdot (1-P_{c1}) + 2 \Sigma_R \cdot R_{i2}^2 \cdot (1-P_{c2})}{2 R_{i1} + R_{i2}}$

$S_u = 38 \cdot \pi \cdot s$

$S_f = 12 \cdot d + 2 \cdot \pi \cdot s$

4 - ROD

$R_i = d - s - r$

P_c function of $\left[\Sigma_R \cdot R_i \right]$

$\gamma' = 2 \cdot \Sigma_R \cdot R_i \cdot (1-P_c)$

$S_u = 8 \cdot \pi \cdot s$

$S_f = 4 \cdot \sqrt{2} \cdot d + 2 \cdot \pi \cdot s$

$$R_i = \frac{\frac{1}{\sqrt{3}} - \frac{\sqrt{\frac{V_c}{22.\pi}}}{d}}{\sqrt{\frac{\frac{1}{4}.\sqrt{3} - \frac{1}{2}.\pi.\frac{V_c}{22.\pi.d^2}}{\pi}}} \sqrt{\frac{V_{01,2}}{21.\pi}}$$

P_c function of $Z_R . R_i$

$\gamma' = 2 . \Sigma_R . R_i . (1 - P_c)$

$S_u = 44 . \pi . s$

$S_f = 6.2542 . d + 2 . \pi . S_3$

} 22 - ROD

$\gamma' = 1.$

$S_u = 2 . \pi . s$

$S_f = 2 . \pi . s$

} SINGLE ROD

$S_{eff} = S_f + \gamma' . (S_u - S_f)$

P_1^{vi} & P_1^{VE} function of $\left[\frac{S_3}{S_1} , S_1 . \Sigma_{so}^e \right]$

P_2^{vi} & P_2^{VE} function of $\left[\frac{r}{S_3} , S_3 . \Sigma_{so}^e \right]$

P_3^{vi} & P_3^{VE} function of $\left[\frac{d}{dr} , dr . \Sigma_{so}^e \right]$

P_4^{vi} & P_4^{VE} function of $\left[0. , \Sigma_{so}^e . \left(1 - \frac{V_{ri}^f}{\pi . d_1^2} \right) + \Sigma_{sr}^e . \frac{V_{ri}^f}{\pi d_1^2} \right]$

$P^{vv} = \pi . \left[(P_1^{vi} + P_1^{VE}) . (S_1^2 - S_3^2) + (P_2^{vi} + P_2^{VE}) . (S_3^2 - r^2) + (P_3^{vi} + P_3^{VE}) . (dr^2 - d^2) + (P_4^{vi} + P_4^{VE}) . d_1^2 \right]$

$S_e = 2 . \pi . s$

$S_i = 4 . P^{vv} . \Sigma_{so}^e$

$S_{eff} = S_e + S_i$

} CIRCULAR TUBES

$$\Sigma'_R = \frac{V_c \cdot (\xi Z_s)^e_c + V^f_{qi} \cdot (\xi Z_s)^e_q + V^f_{oi} \cdot (\xi Z_s)^e_o + V^f_{ri} \cdot (\xi Z_s)^e_r}{5 \cdot V^f_o}$$

$$\Sigma''_R = \frac{V_c \cdot Z^e_{sc} + V^f_{qi} \cdot Z^e_{trq} + V^f_{oi} \cdot Z^e_{tro} + V^f_{ri} \cdot Z^e_{trr}}{V^f_o}$$

$$K^2 = 5 \cdot \Sigma'_R \cdot \Sigma''_R \cdot \left(1 - 0.5 \frac{\Sigma'_R}{\Sigma''_R}\right)$$

P'_b function of $\left[\frac{I^2}{4 \cdot \pi \cdot \tau_m}\right]$

$$P_b = \frac{P'_b}{1 + 0.125 \cdot K^2 \cdot a^2_o}$$

$$I_{res}(i) = U1(i) + U2(i) \cdot \sqrt{\frac{S_{eff}}{V_c}}$$

$$P_o(i) = \exp - \frac{V_c \cdot I_{res}(i)}{V_D \cdot (\xi Z_s)^e_D + V_r \cdot (\xi Z_s)^e_r + V_m \cdot (\xi Z_s)^e_m}$$

$$P(i) = 1 - (1 - P_o(i)) \cdot P_B$$

$$P = \prod_{i=1}^{6} P(i)$$

THERMAL FISSION FACTOR

$$\eta = \frac{(\nu \Sigma_f)^t}{\Sigma_{ac}^t}$$

MULTIFLICATION FACTOR

$$k_\infty = \varepsilon . p . f . \eta$$

MATERIAL BUCKLING

$$B^2 = \mu^2 = \frac{-\left(\frac{1}{L^2} + \frac{1}{\tau}\right) + \sqrt{\left(\frac{1}{L^2} + \frac{1}{\tau}\right)^2 + 4\ \frac{k_\infty - 1}{\tau . L^2}}}{2}$$

$$-\nu^2 = \frac{-\left(\frac{1}{L^2} + \frac{1}{\tau}\right) - \sqrt{\left(\frac{1}{L^2} + \frac{1}{\tau}\right)^2 + 4 . \frac{k_\infty - 1}{\tau . L^2}}}{2}$$

RATIO OF EPITHERMAL TO THERMAL FLUX

$$\beta_v' = 1.0061\ \frac{\eta . p . \varepsilon}{1 + B^2 \tau}\ .\ \frac{V_c . \Sigma_{ac}^t}{I^2 . (\xi \Sigma_s)_g}$$

$$b = \frac{4}{\sqrt{\varepsilon . \pi}}$$

$$r = \frac{\beta_v'}{b . (1 + \beta_v')}$$

Calculation of input data for RLT 4

$$(\bar{\nu\Sigma}_f)^t = (\nu\Sigma_f)^t \cdot \frac{V_c}{V_B^f}$$

$$\bar{\Sigma}_a^{Pst} = \Sigma_a^{Pst} \cdot \frac{V_c}{V_B^f}$$

$$\bar{\Sigma}_a^{Pit} = \Sigma_a^{Pit} \cdot \frac{V_c}{V_B^f}$$

$$\bar{\Sigma}_e^{FE(1)} = \Sigma_e^{FE(1)} \cdot \frac{V_c}{V_B^f}$$

$$\bar{\Sigma}_f^{FE(1)} = \Sigma_f^{FE(1)} \cdot \frac{V_c}{V_B^f}$$

$$\bar{\Sigma}_a^{Pst}(i) = \Sigma_a^{Pst}(i) \cdot \frac{V_c}{V_B^f}$$

$$\bar{\Sigma}_f^{FE(1)}(i) = \Sigma_f^{FE(1)}(i) \cdot \frac{V_c}{V_B^f}$$

$$\bar{\Sigma}_e^{FE(1)}(i) = \Sigma_e^{FE(1)}(i) \cdot \frac{V_c}{V_B^f}$$

$$\bar{\Sigma}_e^{FE(2)}(i) = \Sigma_e^{FE(2)}(i) \cdot \frac{V_c}{V_B^f}$$

$$X_1(i) = \frac{C_1 \cdot \bar{\Sigma}_f^{FE(1)}(i)}{\bar{\Sigma}_{tc}^{(1)}}$$

$$X_0(i) = \frac{C_1 \cdot \bar{\Sigma}_e^{FE(1)}(i)}{\bar{\Sigma}_{tc}^{(1)}} + \frac{(C_2+C_3)\,\bar{\Sigma}_a^{FE(2)}(i)}{\bar{\Sigma}_{tc}^{(2)}} + \frac{\varepsilon \cdot (1-p(i))}{1+B^2\tau}$$

$$\gamma(i) = \frac{\bar{\Sigma}_a^{Pst}(i)}{\bar{\Sigma}_a^{Pit}} + \frac{(\bar{\nu\Sigma}_f)^t \cdot X_0(i)}{\Sigma_a^{Pit}}$$

$$X_1 = \sum_{i=1}^{3} X_1(i)$$

$$X_0 = \sum_{i=1}^{3} X_0(i)$$

$$\gamma = \sum_{i=1}^{3} \gamma(i)$$

$$W = \frac{4 \cdot V_c}{S_{eH}}$$

$$V = \frac{V_c}{V_B^t}$$

$$K = \frac{\left[V_q + \pi(r^2-(r-dr)^2)\right] \cdot \Sigma_{aq}^t + V_{oi}^t \cdot \Sigma_{ao}^t + V_{ri}^t \cdot \Sigma_{ar}^t}{V_B^t}$$

$$Z = \frac{\varphi_B}{a_B^t}$$

$$f_{Bo} = f_1$$

INITIAL CONVERSION FACTOR

$$\gamma = \frac{\bar{\Sigma}_a^{Fst}}{\bar{\Sigma}_a^{Fit}} + \frac{(\overline{\nu\Sigma_f})^t \cdot X_0}{\bar{\Sigma}_a^{Fit}}$$

TWO GROUP CONSTANTS FOR FLUX DISTRIBUTION CALCULATIONS

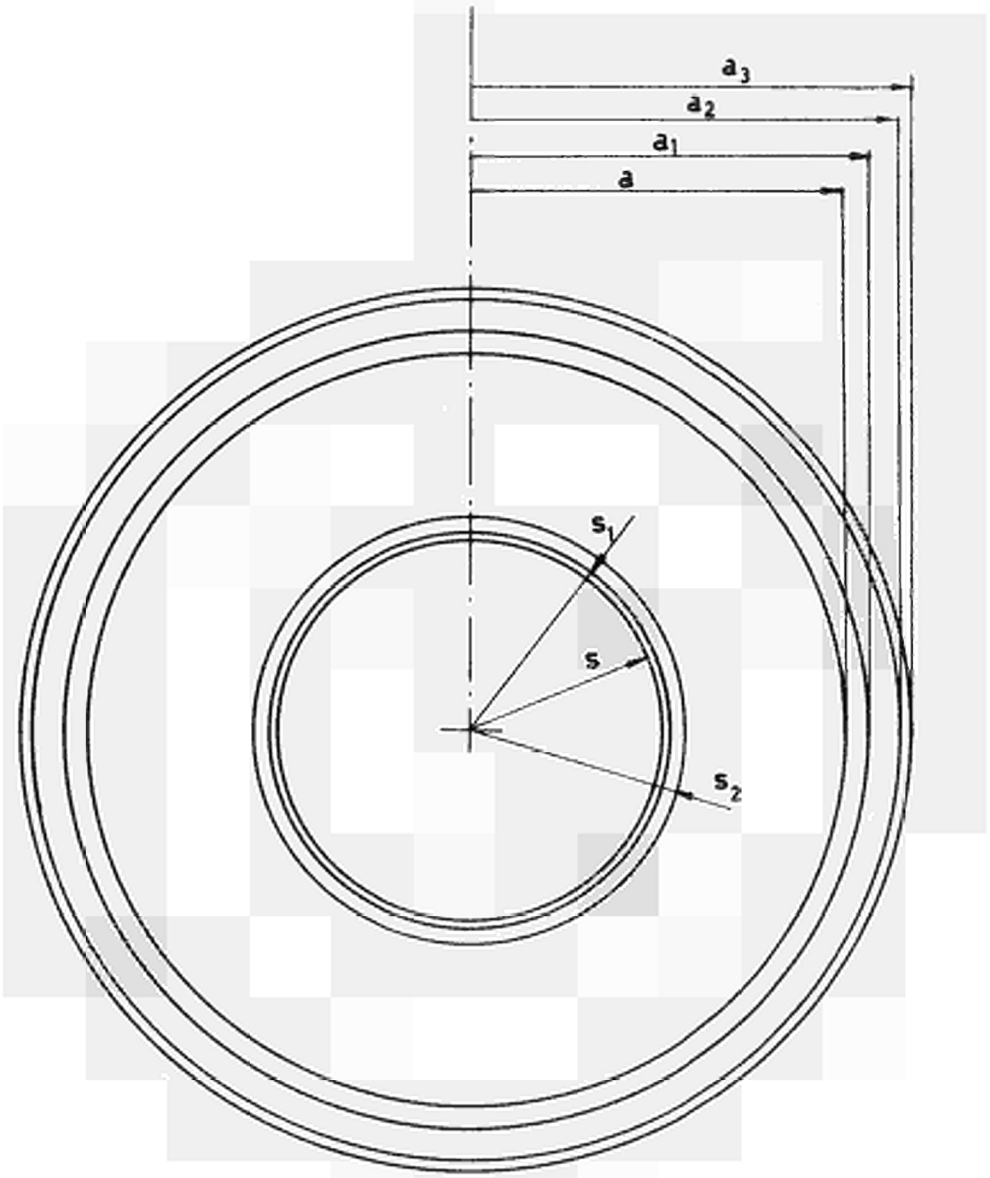
$$\nu\Sigma_f = \frac{k_\infty \cdot \Sigma_{aR}}{p}$$

$$\Sigma_1 = \frac{D_{VR}}{\tau}$$

$$\Sigma_{r1} = p \cdot \Sigma_1$$

$$\Sigma_{a1} = \Sigma_1 - \Sigma_{r1}$$

SINGLE ROD



SINGLE ROD

$$V_c = \pi \cdot c^2$$

$$V_g = \pi \cdot (c_2^2 - c_1^2)$$

$$V_0 = \pi \cdot a^2 - V_c - V_g$$

$$V_v = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t1} = \pi \cdot (a_1^2 - a^2)$$

$$V_{t2} = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t3} = \pi \cdot (a_3^2 - a_2^2)$$

$$V_t = V_{t1} + V_{t2} + V_{t3}$$

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

$$Z = \sqrt{V_m + V_c + V_g + V_0 + V_v + V_t + V_r}$$

$$= \sqrt{V_m + \pi \cdot a_3^2}$$

$$b = \frac{Z}{\sqrt{\pi}}$$

For f calculation only

$$V_B^t = \pi \cdot s_2^2$$

$$a_B^t = s_2$$

$$V_{01}^t = 0$$

$$V_{02}^t = V_0$$

For ε calculation only

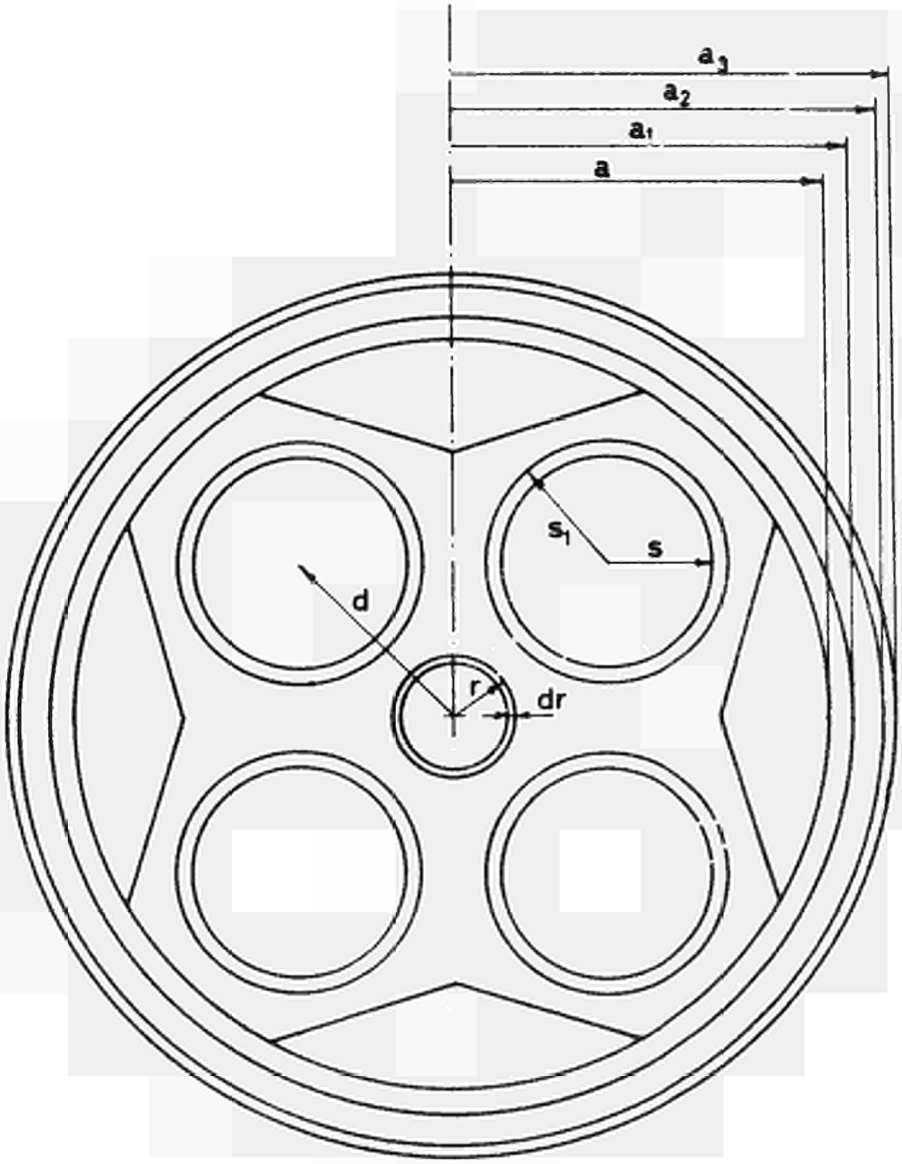
$$V_B^f = \pi \cdot s^2$$

$$a_B^f = s$$

$$V_{g1}^f = 0$$

$$V_{02}^f = 0$$

4 ROD ASSEMBLY



4 ROD ASSEMBLY

$$V_c = 4 \cdot \pi \cdot s^2$$

$$V_g = 4 \cdot \pi \cdot (s_1^2 - s^2) + \pi \cdot \left[r^2 - (r - dr)^2 \right]$$

$$V_o = \pi \cdot (a^2 - r^2) - V_c - V_g - V_r$$

$$V_v = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t1} = \pi \cdot (a_1^2 - a^2)$$

$$V_{t2} = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t3} = \pi \cdot (a_3^2 - a_2^2)$$

$$V_t = V_{t1} + V_{t2} + V_{t3}$$

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

$$I = \sqrt{V_m + V_c + V_g + V_o + V_t + V_v + V_r}$$

$$= \sqrt{V_m + \pi \cdot a_3^2}$$

$$b = \frac{I}{\sqrt{\pi}}$$

For f calculation only

$$V_B^t = V_{rb} = 2d^2 + \pi \cdot s_1^2 + 4 \cdot s_1 \cdot d \cdot \sqrt{2}$$

$$a_B^t = \sqrt{\frac{V_B^t}{\pi}}$$

$$V_{o1}^t = V_B^t - V_c - V_g - V_{ri}^t - \pi \cdot r^2$$

$$V_{o2}^t = V_o - V_{o1}^t$$

For ε calculation only

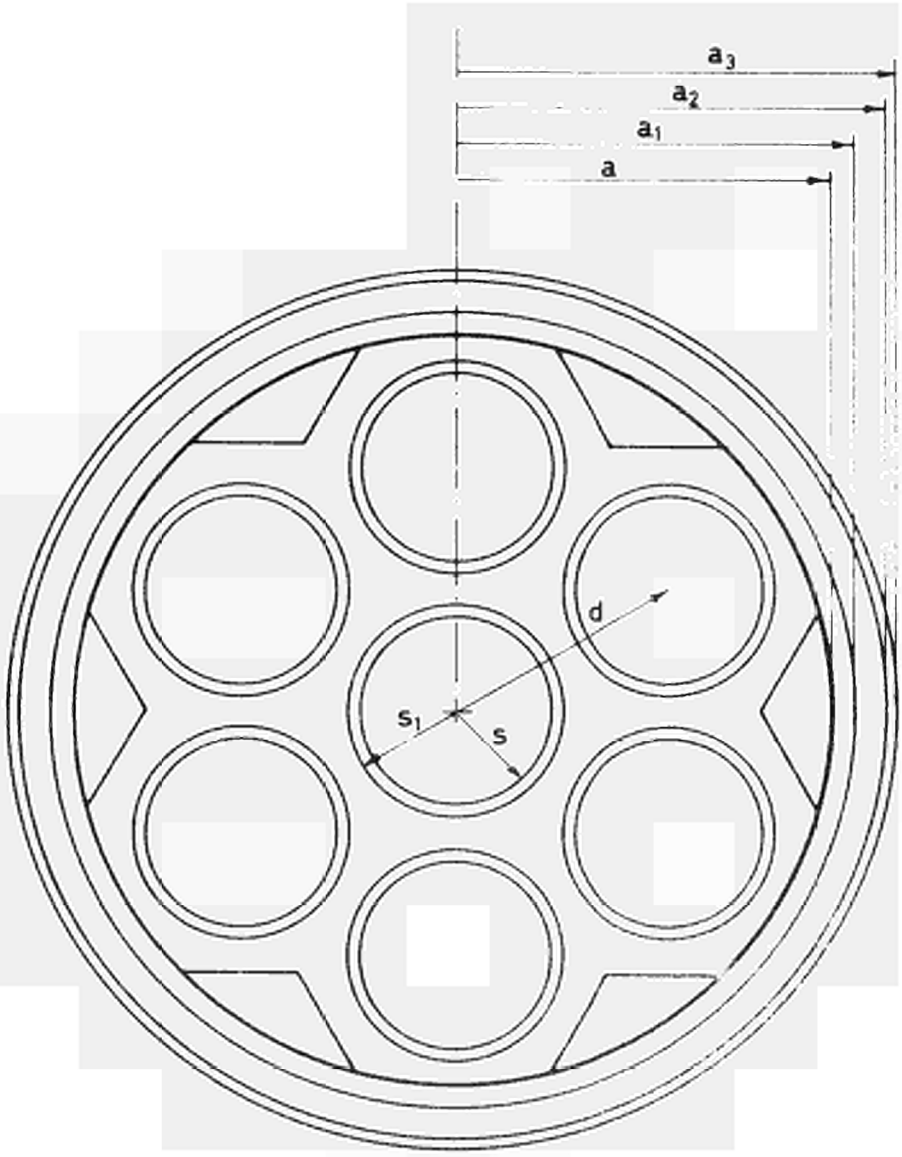
$$V_B^f = 2 \cdot d^2 + \pi \cdot s^2 + 4 \cdot s \cdot d \cdot \sqrt{2}$$

$$a_B^f = \sqrt{\frac{V_B^f}{\pi}}$$

$$V_{gI}^f = V_g - 4 \cdot \left(s_1^2 \arccos \frac{s}{s_1} - s \sqrt{s_1^2 - s^2} \right) - \pi \cdot (s_1^2 - s^2)$$

$$V_{o1}^f = V_B^f - V_c - V_{gI}^f - V_{ri}^f - \pi r^2$$

7 ROD ASSEMBLY



7 ROD ASSEMBLY (7e)

$$V_c = 7 \cdot \pi \cdot s^2$$

$$V_q = 7 \cdot \pi \cdot (s_1^2 - s^2)$$

$$V_o = \pi \cdot a^2 - (V_c + V_q + V_r)$$

$$V_v = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t1} = \pi \cdot (a_1^2 - a^2)$$

$$V_{t2} = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{tb} = \pi \cdot (a_b^2 - a_2^2)$$

$$V_t = V_{t1} + V_{t2} + V_{tb}$$

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

$$Z = \sqrt{V_m + V_c + V_q + V_o + V_r + V_v + V_t}$$

$$= \sqrt{\pi \cdot a_b^2 + V_m}$$

$$b = \frac{Z}{\sqrt{\pi}}$$

For f calculation only

$$V_B^t = V_{rb} = 7 \cdot \frac{1}{2} \cdot \sqrt{3} \cdot d^2$$

$$a_B^t = \sqrt{\frac{V_B^t}{\pi}}$$

$$V_{OI}^t = V_B^t - V_c - V_q - V_{rI}^t$$

$$V_{OE}^t = V_o - V_{OI}^t$$

For ε calculation only

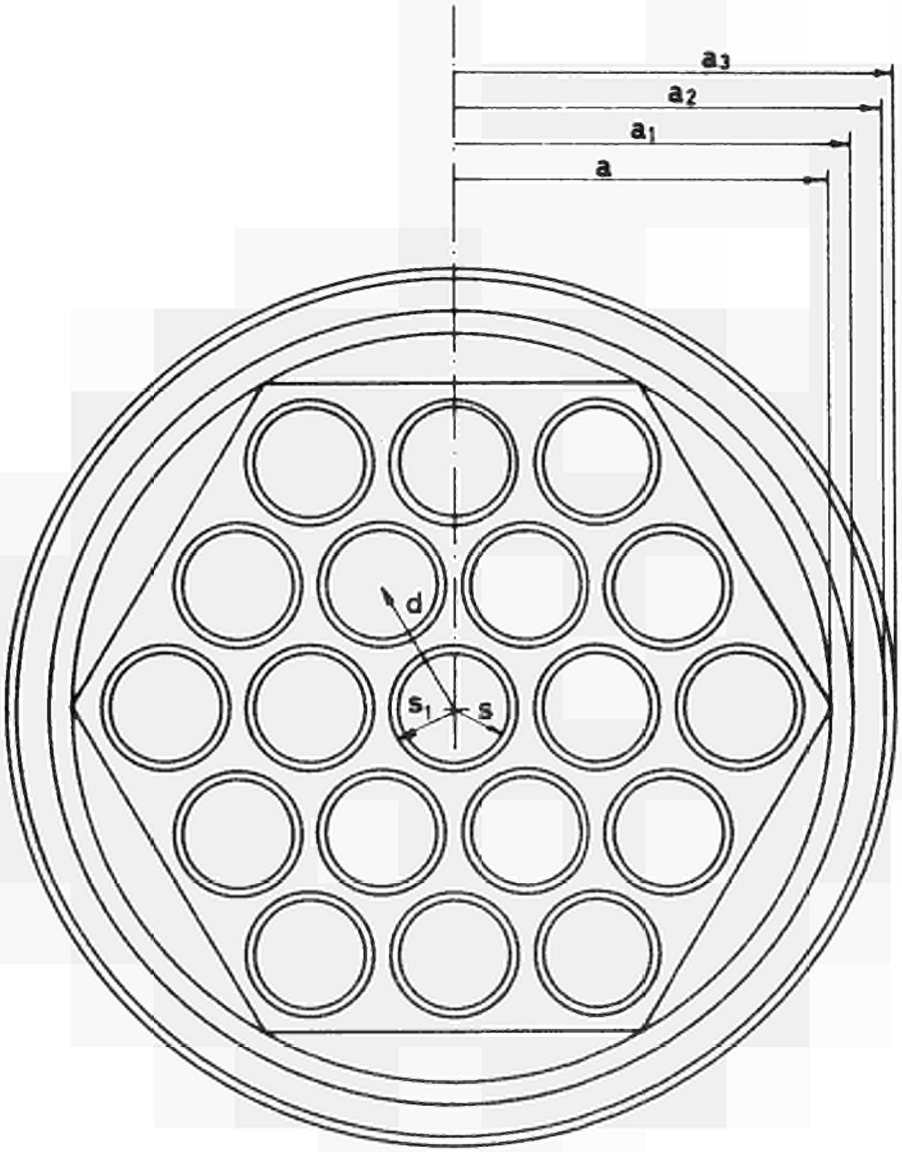
$$V_B^f = \frac{3}{2} \cdot \sqrt{3} \cdot d^2 + \pi s^2 + 6 \cdot d \cdot s$$

$$a_B^f = \sqrt{\frac{V_B^f}{\pi}}$$

$$V_{qI}^f = V_q - \left[6 \cdot \left(s_1^2 \cdot \arccos \frac{s}{s_1} - s \cdot \sqrt{s_1^2 - s^2}\right) + \pi (s_1^2 - s^2)\right]$$

$$V_{OE}^f = V_B^f - V_c - V_{qI}^f - V_{rI}^f$$

19 ROD ASSEMBLY (19e)



19 ROD ASSEMBLY (19e)

$$V_c = 19 \cdot \pi \cdot s^2$$

$$V_g = 19 \cdot \pi \cdot (s_1^2 - s^2)$$

$$V_o = \pi a^2 - V_c - V_g - V_r$$

$$V_v = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t1} = \pi \cdot (a_1^2 - a^2)$$

$$V_{t2} = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t3} = \pi \cdot (a_3^2 - a_2^2)$$

$$V_t = V_{t1} + V_{t2} + V_{t3}$$

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

$$Z = \sqrt{V_m + V_c + V_g + V_o + V_t + V_v + V_r}$$

$$= \sqrt{V_m + \pi a_3^2}$$

$$b = \frac{Z}{\sqrt{\pi}}$$

For f calculation only

$$V_B^t = V_{rb} = 19 \cdot \frac{1}{2} \cdot \sqrt{3} \cdot d^2$$

$$a_B^t = \sqrt{\frac{V_B^t}{\pi}}$$

$$V_{OI}^t = V_B^t - V_c - V_g - V_{rI}^t$$

$$V_{OE}^t = V_o - V_{OI}^t$$

For ε calculation only

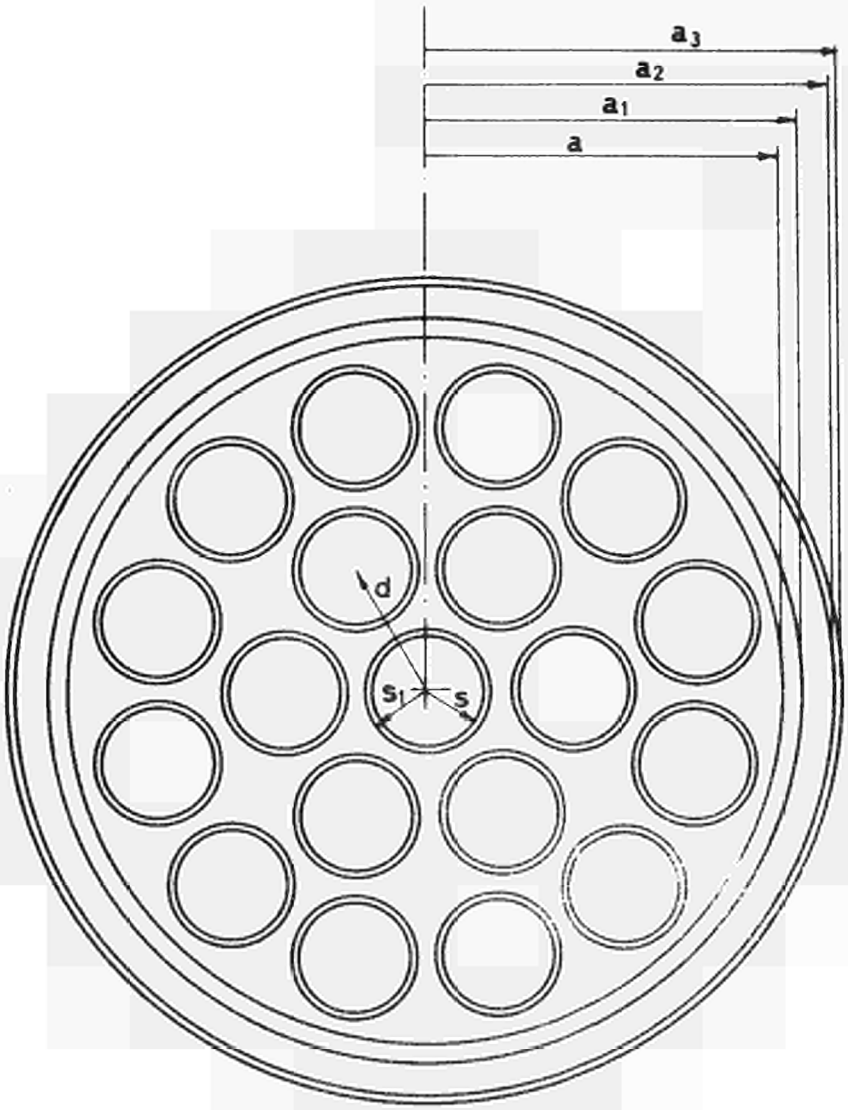
$$V_B^f = 6 \cdot \sqrt{3} \cdot d^2 + \pi \cdot s^2 + 12 d \cdot s$$

$$a_B^f = \sqrt{\frac{V_B^f}{\pi}}$$

$$V_{gI}^f = V_g - 12 \cdot \left(s_1^2 \cdot \arccos \frac{s}{s_1} - s\sqrt{s_1^2 - s^2}\right) - \pi (s_1^2 - s^2)$$

$$V_{OI}^f = V_B^f - V_{gI}^f - V_c - V_{rI}^f$$

19 ROD ASSEMBLY (19c)



19 ROD ASSEMBLY (19c)

$$V_c = 19 \cdot \pi \cdot s^2$$

$$V_q = 19 \cdot \pi \cdot (s_1^2 - s^2)$$

$$V_0 = \pi a^2 - V_c - V_q - V_r$$

$$V_v = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t1} = \pi \cdot (a_1^2 - a^2)$$

$$V_{t2} = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t3} = \pi \cdot (a_3^2 - a_2^2)$$

$$V_t = V_{t1} + V_{t2} + V_{t3}$$

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

$$Z = \sqrt{V_m + V_c + V_q + V_0 + V_r + V_v + V_t}$$

$$= \sqrt{V_m + \pi a_3^2}$$

$$b = \frac{Z}{\sqrt{\pi}}$$

For f calculation only

$$V_B^t = V_{rb} = (3\sqrt{3} + 6) \cdot a^2 + 12 \cdot d \cdot s_1 + \pi \cdot s_1^2$$

$$a_B^t = \sqrt{\frac{V_B^t}{\pi}}$$

$$V_{OI}^t = V_B^t - V_c - V_q - V_{rI}^t$$

$$V_{OE}^t = V_0 - V_{OI}^t$$

For ε calculation only

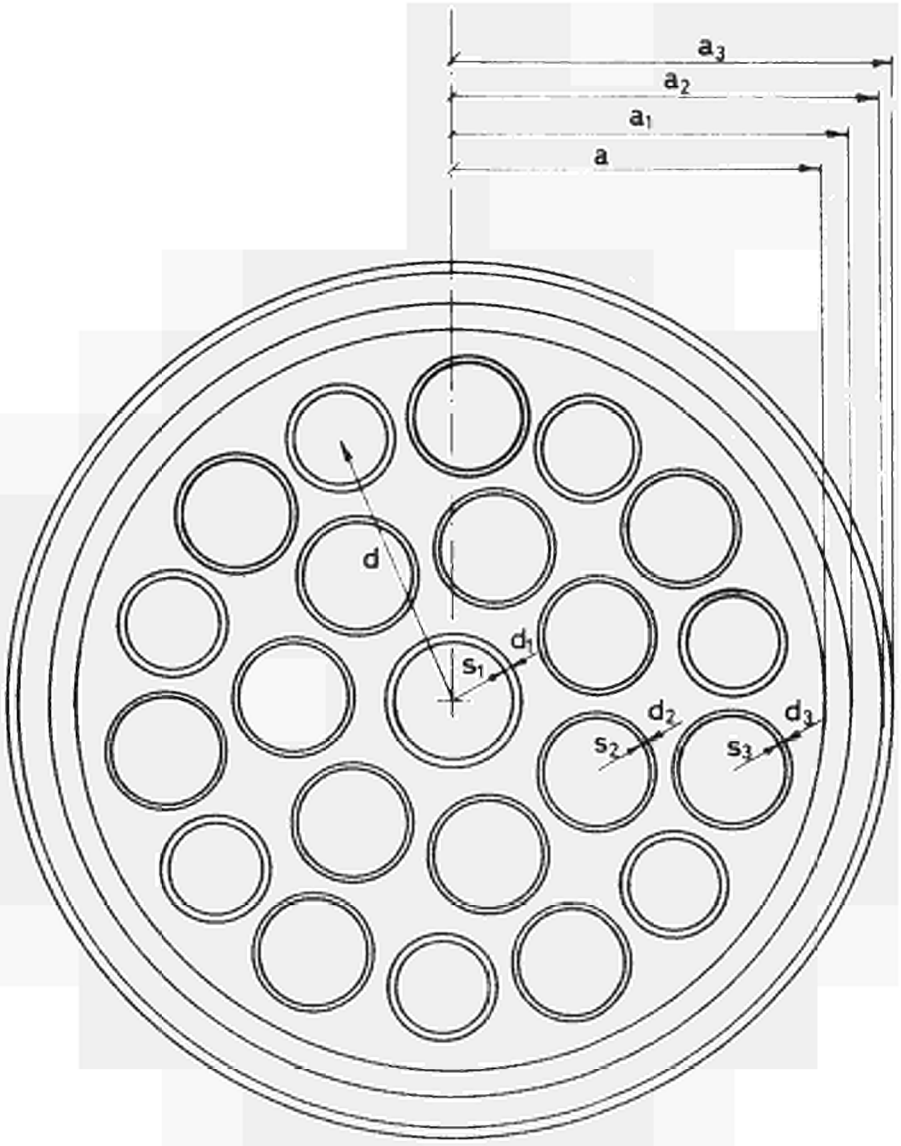
$$V_B^f = (3\sqrt{3} + 6) \cdot a^2 + 12d \cdot s + \pi s^2$$

$$a_B^f = \sqrt{\frac{V_B^f}{\pi}}$$

$$V_{qI}^f = V_q - \left[12 \cdot \left(s_1^2 \arccos \frac{s}{s_1} - s\sqrt{s_1^2 - s^2}\right) + \pi \cdot (s_1^2 - s^2)\right]$$

$$V_{OI}^f = V_B^f - V_c - V_{qI}^f - V_{rI}^f$$

22 ROD ASSEMBLY



22 ROD ASSEMBLY

$$V_c = \pi \cdot s_1^2 + 7 \cdot \pi \cdot s_2^2 + 14 \cdot \pi \cdot s_3^2$$

$$V_g = \left[\pi \cdot (s_1+d_1)^2 - \pi \cdot s_1^2\right] + 7 \cdot \left[\pi \cdot (s_2+d_2)^2 - \pi \cdot s_2^2\right] + 14 \cdot \left[\pi \cdot (s_3+d_3)^2 - \pi \cdot s_3^2\right]$$

$$V_o = \pi \cdot a^2 - V_g - V_c - V_r$$

$$V_v = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t1} = \pi \cdot (a_1^2 - a^2)$$

$$V_{t2} = \pi \cdot (a_2^2 - a_1^2)$$

$$V_{t3} = \pi \cdot (a_3^2 - a_2^2)$$

$$V_t = V_{t1} + V_{t2} + V_{t3}$$

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

$$I = \sqrt{V_m + V_c + V_g + V_o + V_t + V_v + V_r}$$

$$= \sqrt{V_m + \pi \cdot a_3^2}$$

$$b = \frac{I}{\sqrt{\pi}}$$

For f calculation only

$$V_B^t = V_{rb} = 3.0388\, d^2 + \pi \cdot (s_3+d_3)^2 + 6.2342 \cdot d \cdot (s_3+d_3)$$

$$a_B^t = \sqrt{\frac{V_B^t}{\pi}}$$

$$V_{OI}^t = V_B^t - V_c - V_g - V_{rI}^t$$

$$V_{OE}^t = V_o - V_{OI}^t$$

For ε calculation only

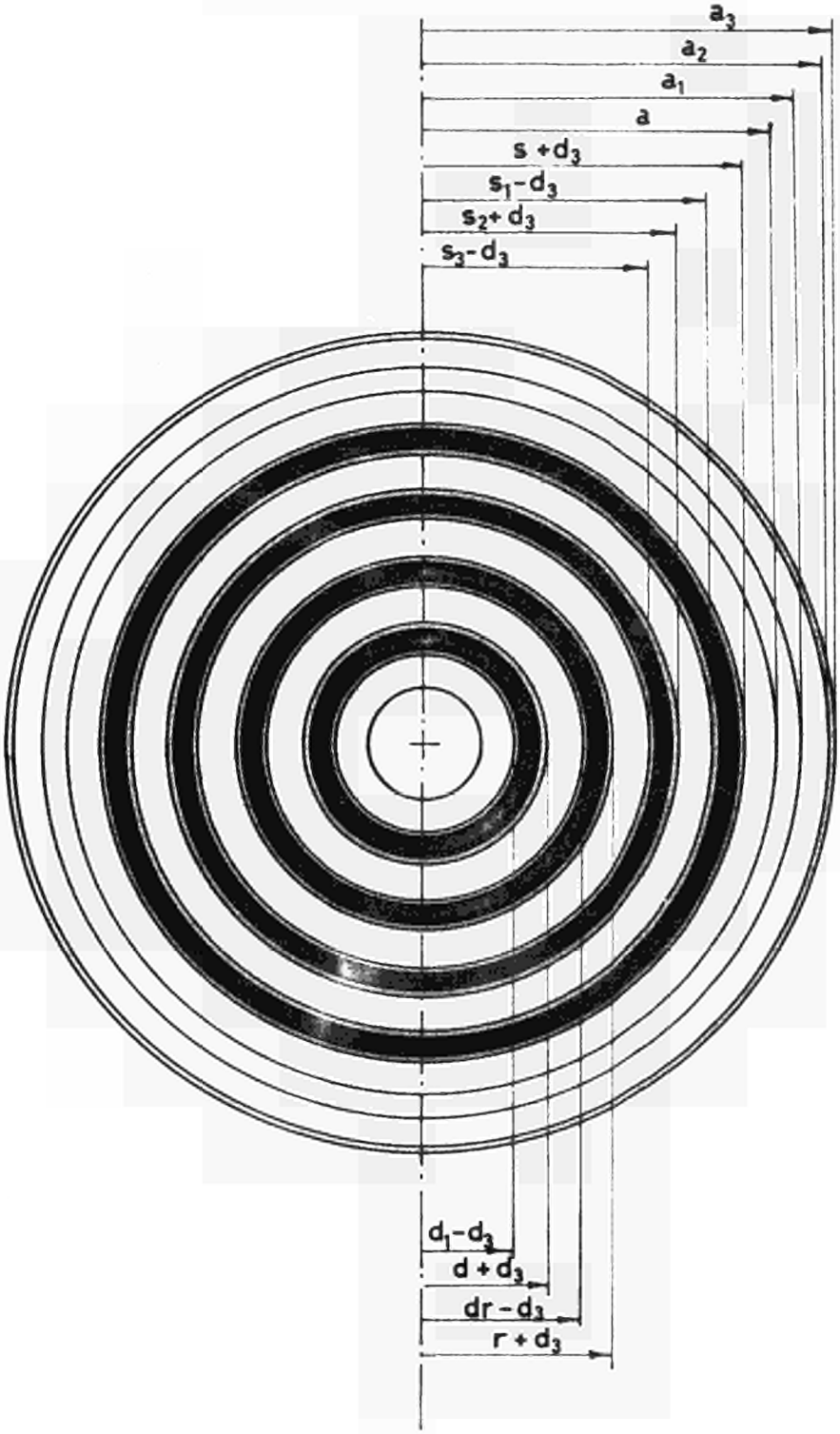
$$V_B^f = 3.0388 \cdot d^2 + \pi \cdot s_3^2 + 6.2342 \cdot d \cdot s_3$$

$$a_B^f = \sqrt{\frac{V_B^f}{\pi}}$$

$$V_{gI}^f = V_g - 14 \cdot \left[(s_3+d_3)^2 \arccos \frac{s_3}{s_3+d_3} - s_3 \sqrt{(s_3+d_3)^2 - s_3^2}\right] - \pi \cdot \left[(s_3+d_3)^2 - s_3^2\right]$$

$$V_{OI}^f = V_B^f - V_c - V_{gI}^f - V_{rI}^f$$

CIRCULAR TUBES



CIRCULAR TUBES

$$V_c = \pi \left(s^2 - s_1^2 + s_2^2 - s_3^2 + r^2 - dr^2 + d^2 - d_1^2 \right)$$

$$V_q = 2 \cdot \pi \cdot \left(s + s_1 + s_2 + s_3 + s + dr + d + d_1 \right) \cdot d_3$$

$$V_0 = V_{0i}^t + V_{0E}^t$$

$$V_{t1} = \pi \left(a_1^2 - a^2 \right)$$

$$V_{t2} = \pi \left(a_2^2 - a_1^2 \right)$$

$$V_{t3} = \pi \left(a_3^2 - a_2^2 \right)$$

$$V_t = V_{t1} + V_{t2} + V_{t3}$$

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

$$z = \sqrt{\pi \cdot a_3^2 + V_m}$$

$$b = \frac{z}{\sqrt{\pi}}$$

For f calculation only

$$V_B^t = \pi \cdot (s + d_b)^2$$

$$a_B^t = s + d_b$$

$$V_{0i}^t = V_B^t - \left(V_c + V_q + V_{ri}^t \right)$$

$$V_{0E}^t = \pi \cdot \left(a^2 - (s + d_b)^2 \right) - \left(V_r - V_{ri}^t \right)$$

For ε calculation only

$$V_B^f = \pi \cdot s^2$$

$$a_B^f = s$$

$$V_{qi}^f = V_q - \pi \cdot d_3 \cdot (d_b + 2s)$$

$$V_{0i}^f = V_{0i}^t$$

IV. List of Tables

Table 1 A Thermal and epithermal cross sections

	Thermal					Epithermal		
	σ_{a0}	σ_{f0}	σ_s	σ_{tr}	ν	σ_s	σ_{tr}	$\Sigma\sigma_s$
Th 232	7.56	-	12.5	12.46	-	11.	10.97	.0924
U 233	578.	525.	12.5	12.46	2.5091	12.5	12.46	.105
U 235	683.04	577.01	17.	16.95	2.4491	10.	9.97	.084
U 236	6.0	-	14.	13.96	-	10.	9.97	.084
U 238	2.71	-	10.5	10.47	-	9.5	9.47	.08
Pu 239	1029.1	742.2	20.	19.94	2.885	20.	19.94	.168
Pu 240	277.87	-	30.	29.91	-	30.	29.91	.252
Pu 241	1397.4	1015.2	60.	59.92	3.06	60.	59.82	.504
O	-	-	4.23	4.05	-	4.23	4.05	.507
C	.007	-	4.8	4.53	-	4.8	4.53	.76
H	.332	-	!	!	-	20.4	6.8	20.4
Al	.225	-	1.38	1.34	-	1.38	1.34	.1
Fe	.218E-4*	-	.843x	.832x	-	-	.832x	.0297x
D	.6423	-	.422x	.363x	-	-	.237x	.1601x
Zr	.18	-	8.	8.2	-	8.	8.	.17

! variable

* macroscopic

Table 1 B Fast microscopic cross sections

	Group 1						Group 2		
	σ_t	σ_e	σ_i	σ_f	$\nu\sigma_f$	σ_c	σ_t	σ_s	σ_c
Tn 232	4.51	2.23	2.28	.116	.302	.049	6.01	5.85	.16
U 233	4.69	1.48	1.27	3.35	9.15	.027	6.18	6.05	.13
U 235	4.59	2.01	1.26	2.23	6.04	.041	6.14	5.95	.19
U 236	-	-	-	-	-	.033	-	-	-
U 238	4.56	1.95	2.05	.527	1.53	.033	6.12	5.98	.14
Pu 239	4.82	1.72	1.08	3.22	10.05	.081	6.36	6.20	.16
Pu 240	4.56	1.79	1.12	2.20	7.52	.054	6.12	6.06	.06
Pu 241	4.64	1.53	1.27	3.17	10.01	.027	6.13	6.	.13
O	1.92	1.70	.22	-	-	-	3.57	3.57	-
C	1.49	1.27	.22	-	-	-	2.78	2.78	-
H	1.91	.45	1.46	-	-	-	4.56	4.56	-
Al	1.70	1.5	.20	-	-	-	3.03	3.03	-
Fe	2.07	1.57	.50	-	-	-	2.40	4.40	-
D	1.60	.32	1.28	-	-	-	2.03	2.03	-
Zr	3.13	2.36	.77	-	-	-	5.65	5.64	.01

Table 1 Effective Resonance integrals

Thorium

Temp. (°K)	Metal		Oxide		Monocarbide		Dicarbide	
	A	B	A	B	A	B	A	B
300	3.8053	16.0746	3.9734	17.2043	3.8506	16.5815	3.8958	17.0884
700	3.6863	19.1923	3.8124	20.5542	3.7846	19.5718	3.8830	19.9514
1100	3.6059	21.3037	3.7347	22.7674	3.6818	21.8064	3.7576	22.3092
1500	3.5350	22.9836	3.6467	24.6020	3.6426	23.4234	3.7502	23.8633
1900	3.5793	24.0501	3.5560	26.1745	3.6650	24.6586	3.7507	25.2671

Uranium

	Metal		Oxide		Monocarbide		Dicarbide	
	A	B	A	B	A	B	A	B
293	2.79	25.286	4.652	25.090	4.123	24.519	5.456	23.752
693	2.805	27.12	4.787	27.092	4.224	26.411	5.643	25.702
1093	2.706	28.695	4.784	28.781	4.199	28.005	5.692	27.315
1493	2.630	30.019	4.774	30.269	4.175	29.397	5.720	28.775
1893	2.515	31.273	4.730	31.619	4.116	30.671	5.717	30.069

Table 2 - Amouyal-Benoist Constants

$a\Sigma_t$	α
0.	0.
0.5	0.0325
1.	0.0628
1.5	0.0900
2.	0.1124
2.5	0.1315
3.	0.1468
3.5	0.1626
4.	0.1733
4.5	0.1828
5.	0.1868
5.5	0.1885
6.	0.1895

$a\Sigma_t$	β
0.	0.
0.5	0.0190
1.	0.0260
1.5	0.0280
2.	0.0270
2.5	0.0250
3.	0.0225
3.5	0.0215
4.	0.0208
4.5	0.0203
5.	0.0200
5.5	0.0199
6.	0.0198

$a\Sigma_t$	A
0.	0.
0.4	0.1346
0.8	0.3334
1.2	0.5920
1.6	0.8952
2.	1.2292
2.4	1.5841
2.8	1.9524
3.2	2.3295
3.6	2.7126
4.	3.0998
4.4	3.4897
4.8	3.8815
5.2	4.275
5.6	4.669
6.	5.064
6.4	5.458
6.8	5.853

Collision probability

Σ^t_{as}	p
0.0	0.
0.3	0.28351
0.6	0.45225
0.9	0.56389
1.2	0.64183
1.5	0.69843
1.8	0.74087
2.1	0.77357
2.4	0.79936
2.7	0.82012
3.0	0.83714
3.3	0.85130
3.6	0.86325
3.9	0.87346
4.2	0.88228
4.5	0.88996
4.8	0.89671
5.1	0.90268
5.4	0.90802
5.7	0.91280
6.0	0.91711
6.3	0.92102

Flux disadv. factor

$\frac{Z^2}{4\pi\tau}$	P_B
0.0	1.0
0.2	1.0
0.4	1.0
0.6	1.0212
0.8	1.0850
1.0	1.1875
1.2	1.3250
1.4	1.4950
1.6	1.6550
1.8	1.8300
2.0	2.0037
2.2	2.1820
2.4	2.3610
2.6	2.5400
2.8	2.7190
3.0	2.8980
3.2	3.0770
3.4	3.2560
3.6	3.4350
3.8	3.6140
4.0	3.7930
4.2	3.9720

Fermi-age $\ln(1-P_U)$	Heavy water τ^*
-9.	120.
-8.	120.
-7.	119.45
-6.	118.1
-5.	116.9
-4.	112.4
-3.	98.9
-2.	68.1
-1.	45.6
0.	36.75

Table 4

Density	Heavy water
T(°C)	ρ_w
10.	1.106
30.	1.103
50.	1.096
70.	1.085
90.	1.071
110.	1.055
130.	1.037
150.	1.017
170.	0.995
190.	0.970
210.	0.942
230.	0.913
250.	0.881
270.	0.849
290.	0.815
310.	0.781

Density	Diphenyl
T(°C)	ρ_d
140.	0.945
160.	0.928
180.	0.910
200.	0.891
220.	0.873
240.	0.855
260.	0.837
280.	0.818
300.	0.800
320.	0.780
340.	0.759
360.	0.738
380.	0.715
400.	0.690
420.	0.664
440.	0.636
460.	0.606
480.	0.574

Scattering cross section Hydrogen	
T(°K)	σ_{sH}
290.160	45.37
319.176	44.22
348.192	43.16
377.208	42.16
406.224	41.25
435.240	40.39
464.256	39.58
493.272	38.84
522.288	38.15
551.304	37.49
580.320	36.87
609.336	36.31
638.352	35.79
667.368	35.28

Transport cross section Hydrogen	
T(°K)	σ_{trH}
290.16	34.23
348.19	30.86
406.22	28.16
464.25	26.03
522.28	24.29
580.31	22.86

Table 5

Comparison between PLUTHARCO and EXPO experiments

	Pitch 18		Pitch 22		Pitch 25		Pitch 28.2	
	EXPO	PLUTH	EXPO	PLUTH	EXPO	PLUTH	EXPO	PLUTH
η		1.298		1.303		1.305		1.307
ϵ		1.041		1.041		1.041		1.041
p		0.833		0.878		0.897		0.909
f		0.908		0.901		0.896		0.890
L^2 $[cm^2]$		67.222		118.936		168.273		234.851
τ $[cm^2]$		96.363		100.391		102.760		104.614
B^2 $[m^{-2}]$		1.356	3.42	3.321	3.38	3.340	2.85	2.909
k_{∞}		1.022		1.074		1.092		1.101

Table 6

Comparison between PLUTHARCO and CISE results

	AC1-T3-19		AC1-T3-21		AC1-T3-24	
	CISE	PLUTH	CISE	PLUTH	CISE	PLUTH
η	1.3199	1.307	1.3201	1.309	1.3202	1.310
ϵ	1.0322	1.036	1.0322	1.036	1.0322	1.036
p	0.8819[x]	0.893	0.8961[x]	0.910	0.9119[x]	0.927
f	0.9191	0.911	0.9161	0.907	0.9110	0.902
L^2 [cm^2]	115.6	128.760	148.1	165.160	205.1	229.166
τ [cm^2]	112.5	110.434	112.7	110.425	112.9	110.949
B^2 [m^{-2}][x]	4.69	4.121	4.59	4.227	4.13	3.954
	(4.74±.10)		(4.56±.12)		(4.15±.07)	
k_∞	1.1044	1.101	1.1187	1.120	1.1321	1.135

[x] corrected to four factor scheme

+ experimental results in brackets

Table 7

Comparison between PLUTHARCO and CISE

	AC2-T1-19		AC2-T1-21		AC2-T1-24	
	CISE	PLUTH	CISE	PLUTH	CISE	PLUTH
η	1.319	1.303	1.319	1.306	1.3192	1.308
ϵ	1.0414	1.047	1.0414	1.047	1.0414	1.047
p	0.8675[x]	0.874	0.8852[x]	0.896	0.9042[x]	0.918
F	0.9443	0.944	0.9416	0.940	0.9369	0.936
L^2 [cm^2]	111.5	116.686	141.9	149.101	195.	205.974
τ [cm^2]	123.8	122.670	121.8	120.314	119.7	118.295
B^2 [m^{-2}] [x]	5.48 (5.67±.10)	5.067	5.55 (5.70±.12)	5.448	5.16 (5.33±.09)	5.206
k_∞	1.1252	1.125	1.1450	1.152	1.1639	1.175

[x] corrected to four factor scheme

+ experimental results in

Table 8

Comparison between PLUTHARCO and Savannah River

	1 Rod - 7.00			1 Rod - 8.08		1 Rod - 9.33		1 Rod - 12.2	
	SRE	PLUTH	PLUTH + TERM	SRE	PLUTH	SRE	PLUTH	SRE	PLUTH
η	1.316	1.315	1.314	1.316	1.315	1.316	1.316	1.316	1.317
ϵ	1.039	1.033	1.033	1.039	1.033	1.039	1.033	1.039	1.033
p	0.956	0.951	0.951	0.968	0.963	0.972	0.972	0.979	0.981
f	0.969	0.971	0.975	0.960	0.963	0.948	0.952	0.914	0.923
L^2 [cm^2]	247.	220.688	228.975	336.	301.379	456.	407.892	783.	698.838
τ [cm^2]	121.	115.009	113.411	120.	114.832	120.	114.687	119.	114.485
B^2 [m^{-2}]*	6.82	7.203	7.164	5.62	5.958	4.32	4.742	2.42	2.768
	(6.48)			(5.29)		(4.08)		(2.30)	
k_∞	1.266	1.255	1.259	1.270	1.260	1.260	1.258	1.223	1.231

*Values in parantheses are from flux mapping experiments

Table 9

Comparison between PLUTHARCO and Savannah River experiments

	3 Rod - 7.00			3 Rod - 9.33		3 Rod - 12.12		3 Rod - 14.00	
	SRE	PLUTH	PLUTH + TERM	SRE	PLUTH	SRE	PLUTH	SRE	PLUTH
η	1.314	1.302	1.309	1.314	1.308	1.314	1.311	1.314	1.312
ϵ	1.048	1.036	1.036	1.048	1.036	1.048	1.036	1.048	1.036
p	0.866	0.864	0.864	0.921	0.922	0.940	0.946	0.943	0.951
f	0.984	0.989	0.989	0.976	0.981	0.961	0.966	0.948	0.953
$L^2[cm^2]$	95.	84.713	87.789	181.	169.142	331.	313.126	459.	435.817
$\tau[cm^2]$	128.	114.638	114.344	122.	112.957	120.	112.607	120.	112.542
$B^2[m^{-2}]$ *	7.58 (7.59)	7.420	7.562	7.56 (7.11)	7.603	5.24 (5.05)	5.420	3.93 (3.81)	4.081
k_∞	1.173	1.153	1.159	1.238	1.226	1.244	1.241	1.231	1.232

* See note table 8

Table 10

Comparison between PLUTHARCO and Savannah River Exp.

	7 Rod - 9.33			7 Rod - 12.12		7 Rod - 14.00		7 Rod - 18.52		7 Rod - 21.00	
	SRE	PLUTH	PLUTH + TERM	SRE	PLUTH	SRE	PLUTH	SRE	PLUTH	SRE	PLUTH
η	1.310	1.292	1.306	1.310	1.301	1.310	1.303	1.310	1.306	1.310	1.307
ε	1.053	1.041	1.041	1.053	1.041	1.053	1.041	1.053	1.041	1.053	1.041
p	0.843	0.837	0.837	0.889	0.885	0.902	0.894	0.917	0.901	0.916	0.903
f	0.985	0.986	0.984	0.978	0.978	0.970	0.970	0.945	0.945	0.931	0.927
$L^2[cm^2]$	86.	83.356	84.038	164.	167.433	242.	244.113	496.	491.521	648.	663.890
τ $[cm^2]$	129.	113.911	113.911	124.	111.265	123.	110.851	121.	110.159	120.	110.076
$B^2[m^{-2}]$ [x]	6.49 (6.02)	5.465	5.886	6.57 (6.11)	5.943	5.41 (5.20)	4.781	3.07 (2.92)	2.563	2.24 (2.10)	1.768
k_∞	1.145	1.111	1.119	1.199	1.172	1.207	1.176	1.195	1.158	1.176	1.139

[x] see note table 8

Table 11

Comparison between PLUTHARCO and Chalk River values

	7 D_2O 18		7 D_2O 22		7 D_2O 28		7 D_2O 36	
	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.
η	1.304	1.304	1.308	1.308	1.312	1.311	1.314	1.313
ϵ	1.030	1.029	1.030	1.029	1.029	1.029	1.028	1.029
p	0.845	0.834	0.895	0.890	0.932	0.928	0.947	0.929
f	0.971	0.971	0.966	0.966	0.954	0.955	0.934	0.936
$L^2[cm^2]$	83.810	86.406	134.779	139.518	241.801	246.111	435.754	437.889
τ $[cm^2]$	134.012	124.855	128.602	120.089	124.747	117.199	122.430	115.498
$B^2[m^{-2}]$ x	4.585 (4.56±.025)	3.999	5.992 (5.969±.027)	5.826	5.256 (5.160±.011)	5.152	3.382 (3.448±.009)	3.342
k_∞	1.102	1.086	1.164	1.157	1.201	1.195	1.195	1.191

x values in brackets from flux mapping experiments

Table 12

Comparison between PLUTHARCO and Chalk River values

	7 Air 19		7 Air 22		7 Air 28		7 Air 36	
	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.
η	1.304	1.305	1.307	1.308	1.312	1.311	1.314	1.313
ε	1.032	1.031	1.032	1.031	-	1.031	-	1.031
p	0.865	0.848	0.902	0.890	-	0.930	-	0.945
f	0.971	0.971	0.967	0.967	0.956	0.957	0.938	0.939
L^2 [cm^2]	95.705	93.540	135.346	132.711	236.204	234.509	416.917	418.418
τ [cm^2]	148.930	139.968	140.090	131.813	131.187	124.181	126.004	119.791
B^2 [m^{-2}] [x]	5.176 (4.87±.03)	4.488	6.157 (5.69±.038)	5.831	- (5.28±.018)	5.407	- (3.617±.007)	3.604
k_∞	1.130	1.107	1.177	1.160	-	1.202	-	1.200

[x] see note table 11

Table 13

Comparison between PLUTHARCO and Chalk River values

	7 ORG 18		7 ORG 19		7 ORG 22		7 ORG 28		7 ORG 36	
	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.
η		1.306	1.305	1.308	1.308	1.309	1.311	1.312		1.314
ϵ		1.029	1.031	1.029	1.031	1.029	1.030	1.029		1.029
p		0.874	0.893	0.884	0.910	0.907	0.932	0.931		0.941
f		0.895	0.889	0.893	0.884	0.888	0.872	0.876		0.856
L^2 [cm^2]		81.607	92.48	94.310	134.71	138.874	254.84	255.039		464.287
τ [cm^2]		84.228	113.13	86.249	114.59	91.940	116.27	99.094		104.165
B^2 [m^{-2}] [x]		3.031	3.24 (3.24)	3.387	3.34 (3.48)	3.598	2.55 (2.68)	2.787		1.537
k_∞		1.051	1.068	1.062	1.085	1.085	1.097	1.101		1.088

[x] see note table 11

Table 14

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

	ox-19-D_2O-18		ox-19-D_2O-21		ox-19-D_2O-24		ox-19D_2O-28		ox-19-D_2O-36	
	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.
η	1.302	1.301	1.305	1.305	1.309	1.307	1.310	1.309	1.313	1.311
ε	1.028	1.027	1.027	1.027	1.026	1.027	1.025	1.027	1.025	1.027
p	0.830	0.805	0.873	0.863	0.902	0.897	0.927	0.922	0.954	0.940
f	0.940	0.942	0.936	0.937	0.931	0.932	0.922	0.923	0.901	0.901
L^2 [cm^2]	87.2	74.733	120.9	109.403	161.8	152.006	230.2	220.263	407.3	395.480
τ [cm^2]	167.8	149.962	152.2	138.136	143.3	131.269	136.3	125.795	129.2	120.259
B^2 [m^{-2}]	1.73 (1.407±.05)	0.640	3.42 (3.48±.03)	3.374	4.07 (4.05±.02)	4.229	3.91 (3.95±.013)	4.075	2.82 (2.75±.012)	2.675
k_∞	1.045	1.014	1.096	1.085	1.128	1.123	1.148	1.146	1.155	1.141

[x] see note table 11

Table 15

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

	ox-19-Air-18		ox-19-Air-21		ox-19-Air-24		ox-19-Air-28		ox-19-Air-36	
	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.
η		1.301		1.306		1.308		1.310		1.312
ϵ		1.031		1.031		1.031		1.031		1.031
p		0.798		0.862		0.898		0.925		0.944
f		0.945		0.941		0.936		0.928		0.907
L^2 [cm^2]		71.842		105.155		145.646		210.677		378.323
τ [cm^2]		178.668		155.505		143.566		134.339		125.278
B^2 [m^{-2}]		0.444	3.35±.055	3.429	4.115±.036	4.471	4.07±.018	4.439	2.97±.006	3.042
k_∞		1.011		1.091		1.134		1.159		1.158

Table 16

Comparison between PLUTHARCO and Chalk River values

	ox-19-ORG-18		ox-19-ORG-21		ox-19-ORG-24		ox-19-ORG-28		ox-19-ORG-36	
	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.	CAN.	PLUTH.
η		1.306		1.308		1.310		1.311		1.313
ε		1.027		1.027		1.027		1.027		1.027
p		0.861		0.892		0.912		0.927		0.938
f		0.867		0.860		0.853		0.844		0.820
L^2 [cm^2]		65.104		102.150		147.519		220.719		409.131
τ [cm^2]		93.958		97.984		101.027		103.778		106.920
B^2 [m^{-2}]		0.109	1.214±.035	1.544	1.568±.019	1.865	1.528±.012	1.640		0.750
k_∞		1.002		1.031		1.047		1.054		1.039

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 elastical as possible i.e. that heavy water moderated reactors of the most different types can be calculated.

This elasticallity has been achieved by introducing an option for every structural part of the reactor e.q. 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 changements 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 alfabetical 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 10 n + 12 (n = 0,5)
38-47 If no decimal points are entered, the point is supposed to
48-57 be between col. 10n + 12 and 10 n + 13 (n=0,5).
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.

Column	Format	Symbol	Description
1-6	E6.2	TEND2	End of life (n/kb)
7-18	E-12.8	FIE	Constant flux in units of 10^{13} neutrons/ cm^2sec or constant power in MWD/T (see i2)
19-20	I_2	K_1	00 (obligatory)
27-28	I_2	I_1	Multiplication factor to be applied to the basic time step (the last being equal to 0.01n/kb)
29-30	I_2	I_2	if i2 = 00 the flux is assumed to be constant during burn-up, if i2= 01, the power is assumed to be constant during burn-up
31-32	I_2	I_3	obligatory 01
35-36	I_2	I_5	if i5 = 00 The principal data (buckling fuel atomic density etc) are printed out I5 = 01 Print-out as option 00 together with fission product densities I 5 = 03 Printout as option 01 together with lattice parameters I5 = 04 Print-out as option 03 but with burn-up integrals

Column	Format	Symbol	Description
37-38	I_2	L_1	Ideal circulation calculation performed if $L_1 \neq 00$
39-40	I_2	L_2	two element circulation calculation performed if $L_2 \neq 00$
41-42	I_2	L_3	single element circulation calculation performed if $L_3 \neq 00$
43-44	I_2	L_4	crossed circulation calculation performed if $L_4 \neq 00$

V.3. LIST OF ENTRIES FOR PLUTHARCO
VERSION 26.04.66

LIST OF ENTRIES IN PLUTHARCO

1. COMPOUND INDEX
    1. METAL
    2. OXIDE
    3. MONOCARBIDE
    4. DICARBIDE
    7. OTHER FUEL (CROSS-SECTIONS TO BE ENTERED IN NRS 72-89)

2. DILUENT SPECTR. CONST. (K)

3.

4. CANNING 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.

8. OUTER COOLANT AND OUTER FILLER SPECTR. CONST. (K)

9.

10. PRESSURE TUBE SPECTR. CONST (K)

11. INSULATION INDEX
    0. VOID
    1. GILOTHERM (SANTOWAX)
    2. DIPHENYL
    3. HEAVY WATER
    4. AL2 03
    5. SI 02
    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 AL2 03 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 TH 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

		ALL OTHER GEOMETRIES	FUEL ROD RADIUS
31.	S1	7-ROD HEXAGONAL	CLAD ROD RADIUS
		19-ROD HEXAGONAL	CLAD ROD RADIUS
		19-ROD CIRCULAR	CLAD ROD RADIUS
		22-ROD	RADIUS OF CENTRAL ROD
		4-ROD	CLAD ROD RADIUS
		SINGLE ROD	CLADDING INNER RADIUS
		CYLINDRICAL	INNER RADIUS OF FIRST (OUTER) TUBE
32.	S2	22-ROD	RADIUS OF SECOND-RING RODS
		SINGLE ROD	CLADDING OUTER RADIUS
		CYLINDRICAL	OUTER RADIUS OF SECOND TUBE
33.	S3	22-ROD	RADIUS OF THIRD-RING RODS
		CYLINDRICAL	INNER RADIUS OF SECOND TUBE
34.	A	ALL GEOMETRIES	INTERNAL RADIUS OF PRESSURE TUBE
35.	A1	ALL GEOMETRIES	EXTERNAL RADIUS OF PRESSURE TUBE
36.	A2	ALL GEOMETRIES	INTERNAL RADIUS OF CALANDRIA TUBE
37.	A3	ALL GEOMETRIES	EXTERNAL RADIUS OF CALANDRIA TUBE
38.	R	4-ROD	EXTERNAL RADIUS OF CENTRAL FILLING TUBE
		CYLINDRICAL	OUTER RADIUS OF THIRD TUBE
39.	DR	4-ROD	THICKNESS OF CENTRAL FILLING TUBE

		CYLINDRICAL	INNER RADIUS OF THIRD TUBE

40. GEOMETRY INDEX

1. 7-ROD HEXAGONAL
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	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

63 SPECTR. CONST.(K) U-233

64 SPECTR. CONST.(K) U-235

65 SPECTR. CONST.(K) U-236

66 SPECTR. CONST.(K) U-238

67 SPECTR. CONST.(K) PU-239

68 SPECTR. CONST.(K) PU-240

69 SPECTR. CONST.(K) PU-241

70. LATTICE CELL INDEX
    1. VM/VF
    2. SQUARE PITCH
    3. HEXAGONAL PITCH

71. VALUE OF VM/VF (DIMENSIONLESS) OR PITCH (CM)

CROSS-SECTIONS FOR SPECIAL FUEL (SEE 1. COMPOUND INDEX)

72. ABSORPTION (THERMAL) (SACT)
73. FISSION (THERMAL) (SFCT)
74. SCATTERING (THERMAL) (SSCT)
75. TRANSPORT (THERMAL) (STRCT)
76. SCATTERING (EPITHERMAL) (SSCE)
77. TRANSPORT (EPITHERMAL) (STRCE)
78. SLOWING DOWN (EPITHERMAL) (SXSCE)

79. TOTAL (FAST) (STCF)
80. ELASTIC (FAST) (SECF)
81. INELASTIC (FAST) (SICF)
82. FISSION (FAST) (SFCF)
83. CAPTURE (FAST) (SCCF)
84. NU TIMES FISSION(FAST) (SNUCF)
85. TOTAL 2 (FAST) (STCF2)
86. SCATTERING 2 (FAST) (SSCF2)
87. CAPTURE 2 (FAST) (SCCF2)
88. A- RES. INT. (U1)
89. B- RES. INT. (U2)

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)

106

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

107. VC
108. VG
109. VO
110. VT1

111. VT2
112. VT3
113.
114.
115.
116. VBT
117. ABT
118. VOIT
119. VOET
120. VBF
121. ABF
122. VGIF
123. VOIF
124 SU
125 SF
126 DANCOFF CORRECTION FACTOR
127-136

CROSS-SECTIONS FOR SPECIAL COOLANT (SEE 5. COOLANT INDEX)

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)

148 SCATTERING 2 (FAST) (SEN2)
149 CAPTURE 2 (FAST) (SCN2)

150-151

CROSS-SECTIONS FOR SPECIAL INSULATION (SEE 11. INSULATION INDEX)

152 ABSORPTION (AT 2200 M/SEC) (SANT)
153 SCATTERING (THERMAL) (SSNT)
154 TRANSPORT (THERMAL) (STRNT)
155 SCATTERING (EPITHERMAL) (SSNE)
156 TRANSPORT (EPITHERMAL) (STRNE)
157 SLOWING DOWN (EPITHERMAL) (SXSNE)
158 TOTAL (FAST) (STN)
159 ELASTIC (FAST) (SEN)
160 INELASTIC (FAST) (SJN)
161 CAPTURE (FAST) (SCN)
162 TOTAL 2 (FAST) (STN2)
163 SCATTERING 2 (FAST) (SEN2)
164 CAPTURE 2 (FAST) (SCN2)

165-166

CROSS-SECTIONS FOR SPECIAL OUTER COOLANT (SEE 5. COOLANT INDEX)

167 ABSORPTION (AT 2200 M/SEC) (SANT)
168 SCATTERING (THERMAL) (SSNT)
169 TRANSPORT (THERMAL) (STRNT)
170 SCATTERING (THERMAL) (SSNE)
171 TRANSPORT (THERMAL) (STRNE)
172 SLOWING DOWN (EPITHERMAL) (SXSNE)
173 TOTAL (FAST) (STN)

174	ELASTIC	(FAST)	(SEN)
175	INELASTIC	(FAST)	(SJN)
176	CAPTURE	(FAST)	(SCN)
177	TOTAL 2	(FAST)	(STN2)
178	SCATTERING 2	(FAST)	(SEN2)
179	CAPTURE 2	(FAST)	(SCN2)

180-194

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 (2200 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

201 AIR

202 BERYLIUM

203 GRAPHITE

204 MAGNESIUM

205 LEAD

206 SAP

207 STAINLESS STEEL

208 ZIRCALOY-2

209-210

VOLUME FRACTIONS OF STRUCTURAL MATERIAL FOR PRESSURE TUBE

211 AIR
212 BERYLIUM
213 GRAPHITE
214 MAGNESIUM
215 LEAD
216 SAP
217 STAINLESS STEEL
218 ZIRCALOY-2
219-220

VOLUME FRACTIONS OF STRUCTURAL MATERIAL FOR CALANDRIA

221 AIR
222 BERYLIUM
223 GRAPHITE
224 MAGNESIUM
225 LEAD
226 SAP
227 STAINLESS STEEL
228 ZIRCALOY-2
229-230

VOLUME FRACTIONS OF STRUCTURAL MATERIAL FOR INNER FILLER

231 AIR
232 BERYLIUM
233 GRAPHITE
234 MAGNESIUM
235 LEAD
236 SAP
237 STAINLESS STEEL

238 ZIRCALOY-2

239-240

VOLUME FRACTIONS OF STRUCTURAL MATERIAL FOR OUTER FILLER

241 AIR

242 BERYLIUM

243 GRAPHITE

244 MAGNESIUM

245 LEAD

246 SAP

247 STAINLESS STEEL

248 ZIRCALOY-2

249-250

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"
Part2, 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_1, T_2, T_3 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

ORGEL-19-TH/235/2.0/10

1	6	0.20000E 01	0.	0.80000E 01	0.35000E 03	0.10000E 01	0.35000E 03
7	12	0.	0.35000E 03	0.80000E 01	0.35000E 03	0.	0.35000E 03
13	18	0.80000E 01	0.35000E 03	0.35000E 03	0.11000E 04	0.60000E 03	0.60000E 03
19	24	0.36360E 03	-0.10000E 01	-0.	0.	0.70000E-01	0.27300E 01
25	30	0.30000E 02	0.	0.99800E 00	-0.	-0.	0.70900E 00
31	36	0.78900E 00	-0.	-0.	0.41300E 01	0.43300E 01	0.46300E 01
37	42	0.47800E 01	-0.	-0.	0.30000E 01	0.16780E 01	-0.
49	49	0.10000E 01					
52	57	0.98000E 00	-0.	0.20000E-01	-0.	-0.	-0.
60	61	0.97000E 01	0.26400E 03				
62	67	0.35000E 03	-0.	0.35000E 03	-0.	-0.	-0.
* 70	71	0.10000E 01	0.10000E 02				

PLUTHARCO - A PLUTONIUM-URANIUM-THORIUM ASSEMBLY REACTIVITY CODE

JOB ORGEL-19-TH/235/2.0/10

FUEL		DENSITY	MOL.WEIGHT	PHYSICAL TEMP. (K)	DILUENT SPECTR.CONST. (K)
	OXIDE	9.70	264.00	1100.00	614.12
	COMPOSITION	ATOMIC FRACTION	SPECTRAL CONST. (K)	REAL TEMPERATURE (K)	
	THORIUM-232	0.98000	614.12		
	URANIUM-235	0.02000	614.12		
CANNING	SAP		614.12		
COOLANT	CILOTHERM		614.12	600.00	
OUTER COOLANT	CILOTHERM		512.29		
FILLER	VOID		512.29		
PRESSURE TUBE	SAP		512.29		
INSULATION	VOID				
CALANDRIA	SAP		512.29		
MODERATOR	HEAVY WATER		410.45	363.60	

OTHER PHYSICAL DATA

CANNING
PRESSURE TUBE
CALANDRIA RHO-SAP= 2.7300 ALFA= 0.0700 EXSAP= -0.

COOLANT HBR = 30.0000 N(CARBON)= 0. N(HYDROGEN)= 0. RHO = 0.
VOL.EXP.COEFF./DEGR.C = 0. E-4

FILLER SCR = 0.

MODERATOR SAL = 0. PU = 0.9980 CHW = -0. W/U RATIO= 10.00

GEOMETRY 19 RODS CIRCULAR

S = 0.7090 S1 = 0.7090 S2 = -0. S3 = -0.
A = 4.1300 A1 = 4.3300 A2 = 4.6300 A3 = 4.7800
D = 1.6760 D1 = -0. D2 = 0. D3 = 0.
R = -0. DR = -0.
VR = 0. VRIT= 0. VRIF= 0.

PLUTHARCO - JOB ORGEL-19-TH/235/2.0/10

THERMAL CHARACTERISTICS OF THE LATTICE CELL

REGION	FUEL ABSORBTION	TOTAL ABSORBTION	TOTAL SCATTER	SOURCE	VOLUME	EXT. RADIUS
1	0.168693E-00	0.171780E-00	0.665597E 00	0.188496E-00	0.493678E 02	0.396412E 01
2	0.	0.741331E-02	0.145569E 01	0.697567E 00	0.421800E 01	0.413000E 01
3	0.	0.908799E-02	0.956073E-01	0.757602E-02	0.531557E 01	0.433000E 01
4	0.	0.	0.	0.	0.844460E 01	0.463000E 01
5	0.	0.908799E-02	0.956073E-01	0.757602E-02	0.443436E 01	0.478000E 01
6	0.	0.581801E-04	0.389913E-00	0.176608E-00	0.300052E 03	0.108792E 02

REGION	RELATIVE FLUX	CAPTURE FRACTION
1	0.100000E 01	0.971654E 00
2	0.157931E 01	0.565822E-02
3	0.173367E 01	0.959571E-02
4	0.	0.
5	0.178960E 01	0.926320E-02
6	0.241412E 01	0.482863E-02

SECOND FLIGHT CORRECTION= 0. CANNING TO FUEL FLUX RATIO= 1.07314

PLUTHARCO - JOB ORGEL-19-T I/235/2.0/10

PRINCIPAL PHYSICAL RESULTS

FAST FISSION FACTOR	0.99976	THERMAL UTILISATION FACTOR	0.95419
SLOWING DOWN AREA	116.579	DIFFUSION AREA	77.942
SLOWING DOWN CROSS-SECTION	0.17565	THERMAL ABS. CROSS-SECTION	0.0109434
FAST DIFFUSION COEFFICIENT	1.27051	THERMAL DIFFUSION COEFFICIENT	0.85295
INFINITE MULT. FACTOR	1.08712	THERMAL FISSION FACTOR	1.09357
CRITICAL BUCKLING	4.389069	NEG. MATERIAL BUCKLING	-215.4755
TAU MODERATOR	119.076	MODERATOR S.D. AREA RES. EN.	63.076
EFFECTIVE SURFACE	44.26973	EPITH. FLUX FRACTION	0.12095
RESONANCE PROBABILITY	0.98783	CELL S.D. AREA RES.EN.	66.64612
LETHARGY RANGE	16.116	FAST SOURCE (NU S.F)	0.013400
FAST ABS. CROSS-SECTION	0.001223	FAST REMOVAL CROSS-SECTION	0.009677

INPUT DATA FOR PLT-4

XO(TH-232)	= 0.109948	X1(TH-232)	= 0.003780	GAMMA(TH-232)	= 0.788567
XO(U-238)	=-0.	X1(U-238)	=-0.	GAMMA(U-238)	=-0.
XO(PU-240)	=-0.	X1(PU-240)	= 0.	GAMMA(PU-240)	= 0.
XO(TOTAL)	= 0.109948	X1(TOTAL)	= 0.003780	GAMMA(TOTAL)	= 0.788567
W (4V/S)	= 2.711122	V	= 0.607786	K	= 0.009677
Z	= 0.380748	FBO	= 0.971654	CHORD LENGTH	= 2.711122
RES.INT.(TH-232)	= 0.275531	RES.INT.(U-238)	= 0.	RES.INT.(PU-240)	= 0.
RES.PROB.(TH-232)	= 0.897830	RES.PROB.(U-238)	= 1.000000	RES.PROB.(PU-240)	= 1.000000

...EXTRAPOLATION IN CALCULATION OF....

BSH/ORGANIC

RLTR/ORGANIC

INTERMEDIATE RESULTS

CROSS-SECTIONS

FUEL

S.AT = 0.27755E-00 S.FT = 0.14542E-00 S.ST = 0.46585E-00 S.TRT = 0.90934E 00 S.SE = 0.43022E-00
XS.SE = 0.24482E-01 S.TRE = 0.42159E-00 S.TF = 0.16483E-00 S.EF = 0.12450E-00 S.IF = 0.59744E-01
S.FF = 0.35028E-02 S.CF = 0.10809E-02 S.T2F = 0.22198E-00 S.S2F = 0.28752E-00 S.C2F = 0.35542E-02

CANNING

S.AT = 0.83004E-02 S.ST = 0.95607E-01 S.TRT = 0.10121E-00 XS.SE = 0.75760E-02 S.TRE = 0.92907E-01
S.TF = 0.10662E-00 S.IF = 0.12524E-01 S.EF = 0.94098E-01 S.CF = 0. S.T2F = 0.19024E-00
S.S2F = 0.19024E-00 S.C2F = 0.

COOLANT

S.AT = 0.67708E-02 S.ST = 0.13650E 01 S.TRT = 0.54204E-01 S.SE = 0.86223E 00 S.TRE = 0.40698E-00
XS.SE = 0.69757E 00 S.TF = 0.12499E-00 S.EF = 0.60048E-01 S.IF = 0.56940E-01 S.CF = 0.
S.T2F = 0.26575E-00 S.S2F = 0.26575E-00 S.C2F = 0.

OUTER-COOLANT

S.AT = 0.74133E-02 S.ST = 0.14557E 01 S.TRT = 0.99300E 00 S.SE = 0.86223E 00 S.TRE = 0.40698E-00
XS.SE = 0.69757E 00 S.TF = 0.12499E-00 S.EF = 0.60048E-01 S.IF = 0.56940E-01 S.CF = 0.
S.T2F = 0.26575E-00 S.S2F = 0.26575E-00 S.C2F = 0.

GRAPHITE

S.AT = 0. S.ST = 0. S.TRT = 0. S.SE = 0. S.TRE = 0.
XS.SE = 0. S.TF = 0. S.EF = 0. S.IF = 0. S.CF = 0.
S.T2F = 0. S.S2F = 0. S.C2F = 0.

PRESS.TUBE

S.AT = 0.90880E-02 S.ST = 0.95607E-01 S.TRT = 0.10200E-00 XS.SE = 0.75760E-02 S.TRE = 0.92907E-01
S.TF = 0.10662E-00 S.IF = 0.12524E-01 S.EF = 0.94098E-01 S.CF = 0. S.T2F = 0.19024E-00
S.S2F = 0.19024E-00 S.C2F = 0.

INS.TUBE

S.AT = 0. S.ST = 0. S.TRT = 0. S.SE = 0. S.TRE = 0.
XS.SE = 0. S.TF = 0. S.EF = 0. S.IF = 0. S.CF = 0.
S.T2F = 0. S.S2F = 0. S.C2F = 0.

CALANDRIA-TUBE

S.AT = 0.90880E-02 S.ST = 0.95607E-01 S.TRT = 0.10200E-00 XS.SE = 0.75760E-02 S.TRE = 0.92907E-01
S.TF = 0.10662E-00 S.IF = 0.12524E-01 S.EF = 0.94098E-01 S.CF = 0. S.T2F = 0.19024E-00
S.S2F = 0.19024E-00 S.C2F = 0.

HEAVY WATER

S.AT = 0.58180E-04 S.ST = 0.45637E-00 S.TRT = 0.38991E-00 S.TRE = 0.25545E-00 XS.SE = 0.17661E-00
TAU1 = 0.12350E 03 TAU1 = 0.73111E 02 TAUE = 0.11611E 03 DTR = 0.49823E 02

PLUTHARCO - JOB ORGEL-19-TH/235/2.0/19

GEOMETRIC DATA

VC	= 0.30005E 02	VG	= 0.71533E 01	VO	= 0.16427E 02	VM	= 0.30005E 03	VT1	= 0.53156E 01
VT2	= 0.84446E 01	VT3	= 0.44344E 01	VT	= 0.18195E 02	Z	= 0.19283E 02	B	= 0.10879E 02
VBT	= 0.49368E 02	ABT	= 0.39641E 01	VOIT	= 0.12209E 02	VOET	= 0.42180E 01	VBF	= 0.47380E 02
ABF	= 0.38835E 01	VGIF	= 0.63290E 01	VOIF	= 0.11046E 02	SU	= 0.84641E 02	SF	= 0.24591E 02
GAM	= 0.32771E-00	RC	= 0.						

VOLUME-RATIO

V1R	= 0.49368E 02	VC/V1R	= 0.60779E 00	VG/V1R	= 0.14490E-00
VRIT/V1R	= 0.	VOIT/V1R	= 0.24731E-00	VV/V1R	= 0.14901E-07
V2R	= 0.42180E 01	VR2/V2R	= 0.	VO2/V2R	= 0.10000E 01

LISTING OF PUNCHED INPUT FOR RLT-4

ORGEL-19-TH/235/2.0/10

. .00377966.10994832.12095214 2.7111222.60778762.00287723.38074770
.95418929.97165423116.57005 77.941671.0871228 577.0731 9.700000264.00000
0110.98000000. . . .02000000. .
. . .

1431 LINES OUTPUT THIS JOB.

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

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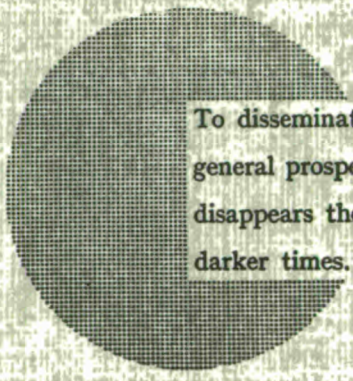

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Alfred Nobel

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