Control rod calculations for the steam cooled fast breeder reactor D-1

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Control Rod Calculations for the Steamed Cooled Fast Breeder Reactor D-1

by

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Netherlands
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Summary.

For the steam cooled fast breeder reactor D-1 the optimization of the location and management of the control elements is performed in a first step.

With one-dimensional diffusion code calculations those locations of one and two rings of control and safety elements are determined which will result in the maximum shutdown reactivity. Perturbation theory provides an expression to calculate the control rod worth of two rings of absorber elements using the results of the calculations for two single rings.

For the optimum ring radii of two rings of control elements that procedure of inserting some control rods a certain depth is determined which maintains the reactor critical with the most favourable power distribution. These calculations are done in two-dimensional (r-z) and (r-θ) geometries.

To show the effect of homogenization of the absorber material in a cylindrical ring, some (r-θ) calculations were performed indicating the influence of the absorber rod perimeter on the reactivity worth of the rods.

The main purpose of this work was not the determination of absolute values but to give a physical insight into the problems and to show possible simple procedures of solving them.

The calculations were performed with the Karlsruhe Nuclear Program System NUSYS.
List of Symbols Used.

α = volume fraction of coolant.
β = volume fraction of cladding and structural material.
ω = Volume fraction of fuel.
ω abs = Volume fraction of absorber material.
ρ = Density ( gr/cm³).
σ = Microscopic cross section ( cm²).
σ* = Integral microscopic capture rate = \( \int_{E} \sigma_{c}(E) \phi(E) dE \).
ν = Number of neutrons produced per fission.
Σ = Macroscopic cross section ( cm⁻¹).
\( \phi_{i} \) = Neutron flux in energy group i.
\( \phi \) = Neutron flux ( vector or variable ). ( n cm² sec⁻¹).
\( \phi_{i}^{+} \) = Adjoint flux in energy group i.
\( \phi^{+} \) = Adjoint flux ( vector or variable ).
\( \phi^{*} \) = Neutron fission weight = \( \int_{E} \phi(E) \chi(E) dE \).
\( \langle \phi, \phi^{+} \rangle \) = Product of flux \( \phi \) and adjoint flux \( \phi^{+} \) = \( \sum_{i=G}^{i=1} \phi_{i} \phi_{i}^{+} \).
θ = Azimuthal angle ( angular coordinate).
\( \chi \) = Fission source distribution.
i, j = Indices for energy groups. \( 1 \leq i, j \leq G \).
k eff = Effective multiplication constant.
Δk = Reactivity change or reactivity worth of control elements.
p = Fission density = \( \sum_{E} \phi(E) dE \) ( fissions/cm³ sec ).
\( \hat{p} \) = Maximum fission density ( fissions/cm³ sec ).
\( \bar{p} \) = Average fission density ( fissions/cm³ sec ).
r = Radial coordinate. ( cm ).
y = Ratio of volume fraction of fertile material to the volume fraction of fissile material = \( \frac{U_{3}+Pu_{0}+Pu_{2}}{U_{5}+Pu_{9}+Pu_{1}} \).
\[ B^2 \] = Buckling (cm\(^{-2}\)).

\[ D_i \] = Diffusion coefficient in energy group \( i \).

\[ D \] = Thickness of cylindrical ring (cm).

\[ E \] = Neutron energy (eV).

\[ G \] = Total number of energy groups.

\[ H \] = Active absorber length of a control rod (cm).

\[ N^+ \] = Transpose of matrix \( M \).

\[ N \] = Number of control elements in a ring of control elements.

\[ R \] = Radius of a ring of control elements (cm).

\[ V \] = Volume of a reactor zone (cm\(^3\)).
1. Introduction.

1.1 Purpose of the Study.

Within the framework of the Fast Breeder Project at the Karlsruhe Nuclear Research Center the first reference design of a steam cooled fast reactor D - 1 has been published [1]. Because there is no steam cooled reactor up to now the reference design D - 1 is established in such a way as to be suitable to systems analysis and to a more advanced design. The systems analysis includes dynamics, safety and cost optimization.

The study, which is described in this report, is based on the design criteria of the D - 1 and deals with the problem of control rod optimization in the steam cooled fast power reactor. The purpose of this study is twofold. Primarily, we will try to find that spatial distribution of the 13 control elements that provides the maximal shut-down reactivity. These calculations will be done in a one-dimensional geometry only, mainly for reasons of consumption of computing time. In this study we do not intend primarily to determine the absolute values of the shut-down reactivity of the control rods, but to show the relative tendencies and to give a physical insight into the problems and results.

In the second part of this study we will use two-dimensional calculations to find that management of partially inserted control rods which will bring an unperturbed reactor of given excess reactivity down to criticality and, in addition, will allow the maximum power output to be reached. In this way this study also contributes to the design and operating optimization.
1.2. Description of the Core Structure.

The cylindrical reactor with an equivalent diameter of 339 cm is loaded with 301 hexagonal elements. The core consists of two concentric fission regions surrounded by a radial blanket (zones I, II, and III).

Above and below the fission regions there are the upper and lower blankets. In the fission regions two concentric rings with 18 positions for control elements are proposed. Finally, a gas plenum at the top of the reactor will complete the structure.

Fig. 1.1. shows the dimensions of the core structure.

Each hexagonal element represents a reactor cell with a length of about 300 cm and a cross section of 300 cm$^2$ (opening across flats = 18.6 cm). Each fuel element consists of a number of fuel pins filled with Pu-U-dioxide.

Table 1.1. gives the volume fractions and some important data for the reactor cell in several reactor regions (zones).

![Diagram of the core structure](image)

- a. Inner fission region (Zone I).
- b. Outer fission region (Zone II).
- c. Radial blanket (Zone III).
- d. Lower axial blanket.
- e. Upper axial blanket.
- f. Gas plenum.
<table>
<thead>
<tr>
<th></th>
<th>Zone I</th>
<th>Zone II</th>
<th>Zone III</th>
<th>Upper blanket</th>
<th>Lower blanket</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>88</td>
<td>93</td>
<td>120</td>
<td>181</td>
<td>181</td>
</tr>
<tr>
<td>Equivalent outer</td>
<td>91.5</td>
<td>131.5</td>
<td>169.5</td>
<td>131.5</td>
<td>131.5</td>
</tr>
<tr>
<td>radius (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>150</td>
<td>150</td>
<td>220</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Number of fuel pins</td>
<td>469</td>
<td>469</td>
<td>169</td>
<td>469</td>
<td>133</td>
</tr>
<tr>
<td>per fuel element</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume fractions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>per fuel element</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \alpha ) =</td>
<td>0.322</td>
<td>0.322</td>
<td>0.241</td>
<td>0.322</td>
<td>0.389</td>
</tr>
<tr>
<td>fraction of coolant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta ) =</td>
<td>0.198</td>
<td>0.198</td>
<td>0.183</td>
<td>0.198</td>
<td>0.168</td>
</tr>
<tr>
<td>fraction of struct.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mat. and cladding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \omega ) =</td>
<td>0.480</td>
<td>0.480</td>
<td>0.576</td>
<td>0.480</td>
<td>0.443</td>
</tr>
<tr>
<td>fraction of fuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume fractions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>per control element</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \alpha ) =</td>
<td>0.310</td>
<td>0.310</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fraction of coolant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta ) =</td>
<td>0.220</td>
<td>0.220</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fraction of struct.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mat. and cladding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \omega ) =</td>
<td>0.308</td>
<td>0.308</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fraction of fuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \omega ) =</td>
<td>0.162</td>
<td>0.162</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fraction of absorber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mat.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of fuel pins</td>
<td>300</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>per control element</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of absorber</td>
<td>19</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pins per contr. el.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel enrichment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>((\text{Pu}^{239}+\text{Pu}^{241})/(\text{Pu}+\text{U}))\text{ tot}</td>
<td>10.03%</td>
<td>12.40%</td>
<td>1.85%</td>
<td>1.85%</td>
<td>1.85%</td>
</tr>
<tr>
<td>U-composition ( \frac{\text{U}^{235}}{\text{U}^{238}} )</td>
<td>0 %</td>
<td>0 %</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004%</td>
</tr>
<tr>
<td>( \gamma ) = \frac{\text{Pu}^{239}+\text{Pu}^{241}}{\text{U}^{235}+\text{Pu}^{239}+\text{Pu}^{241}} \text{ %}</td>
<td>9.32</td>
<td>7.34</td>
<td>43.7</td>
<td>43.7</td>
<td>43.7</td>
</tr>
<tr>
<td>Pu-composition ( \frac{\text{Pu}^{239}}{\text{Pu}^{239}+\text{Pu}^{241}} \text{ %}</td>
<td>74/22.7/2.3/1</td>
<td>100/0/0/0</td>
<td>100/0/0/0</td>
<td>100/0/0/0</td>
<td></td>
</tr>
<tr>
<td>Burn-up (MWD/tonne)</td>
<td>27,500</td>
<td>27,500</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Steam density (g/cm³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(average)</td>
<td>0.0706</td>
<td>0.0706</td>
<td>0.100</td>
<td>0.0994</td>
<td>0.0503</td>
</tr>
<tr>
<td>Struct. material</td>
<td>Incaloy 625</td>
<td>Incaloy 800</td>
<td>Inconel 625</td>
<td>Incaloy 625</td>
<td>Incaloy 800</td>
</tr>
<tr>
<td></td>
<td>8.44 g/cm³</td>
<td>8.01 g/cm³</td>
<td>8.44 g/cm³</td>
<td>8.01 g/cm³</td>
<td>8.44 g/cm³</td>
</tr>
</tbody>
</table>
1.3 Control Rod Elements of the Steam Cooled Fast Breeder D - 1.

The movable control rods are located within special control elements. (see Fig. 1.2). The control elements are of the same geometric shape as the normal fuel elements. Therefore, they may be placed in any position in the core instead of a fuel element. The reactor design provides for 18 control elements. This number of control elements allows their being distributed in such a way over the reactor that the neutron flux and power distributions can be kept small.

The center part of the control element consists of a cluster of 19 movable absorber pins. The absorber rods have a diameter of 20 mm and a length of 2000 mm. This cluster is surrounded by the same fuel pins as in the normal fuel elements. The lower part of the absorber rod is filled with $\text{Al}_2\text{O}_3$. The upper part is filled with $\text{B}_4\text{C}$.

The boron carbide may have a higher enrichment than normal in the strong neutron absorber $\text{B}^{10}$. The enrichment in $\text{B}^{10}$ depends on the function of the rod: safety, shim or regulating rod. The control rod drive system is at the top of the reactor. At the bottom of the cluster a shock absorber avoids damage of the control element.

The lower part of the absorber rods, which is filled with $\text{Al}_2\text{O}_3$, is the follower to retain the same coolant fraction if the control rods are withdrawn and to ensure proper action of the elements in case they are needed.

The design limits the effective control rod length to 102 cm. If the fuel pins in the control element have reached a certain burnup, the whole control element including the control rod cluster will be changed. Care must be taken also to avoid excessive burnup of the control rods to guarantee their effective worth. The helium gas released in the $\text{B}^{10} (n, \alpha) \text{Li}^7$ - process will be stored in the free volumes of the porous carbide.
The cross section of the control rod cluster is 95 cm$^2$ and the volume fractions for the cluster components are as follows:

\[
\begin{align*}
\alpha &= \text{fraction of coolant} = 0.27 \\
\beta &= \text{fraction of cladding and structural material} = 0.22 \\
\omega_{\text{abs}} &= \text{fraction of absorber material} = 0.51
\end{align*}
\]

In this study we take the following data for the absorber material:

- Absorber material: $B_{10}C$
- $B^{10}$ enrichment: 20% ($B^{10}/B^{11}=20/80$, natural boron)
- Absorber density: 2.50 gr/cm$^3$
- Follower material: $Al_2O_3$
- Cladding + structural material: Inconel 625
- Effective absorber length: 100 cm

Fig. 1.2 Control Element.
1.4. General Remarks on Reactor Control.

In reactor operation it is convenient to use three types of control element.
The shim rods provide adjustment for processes with a long time cycle, such as fuel consumption and fission product buildup. The regulating rods adjust the power level of the reactor and compensate for short-term changes in reactivity, for example from hot to cold conditions. Finally, the safety rods stand by for emergency shutdown.

In the engineering design of a reactor it is not possible to arrange the absorber elements arbitrarily close to each other, because the dimensions of the control rod drive systems will limit the minimum distance between two adjacent absorber elements. In general, however, the minimum distance of two adjacent absorber elements will be about 20-30 cm.

Because, in our case, there are no defined descriptions of how to manage the control rods, we only can give some remarks on control operation. Besides, there seem to be no published studies about this subject.

For the steam cooled fast reactor D-1 about half of the available 18 absorber elements will serve as safety rods and the intention is to have about 2 or 3 regulating rods. So, about 6 to 8 control elements will be used as shim rods.

A reactor which has a reactivity above the prompt critical level is very difficult to control. Therefore, it is desirable that the reactivity worth of one regulating rod be below 1 $\$, since it may happen that such an element moves out of the core under accident conditions.

For safety conditions it is desirable also to shut down the reactor even without the absorber element with maximum control rod worth because this element eventually will stick.
During reactor operation the active absorber material will be burned up if the absorber rod is inserted into the reactor core. So it seems desirable to avoid the insertion of all absorber rods, otherwise we have to change all absorber rods at the same time.

1.5. Methods of Calculation.

All reactor calculations are based on multi-group diffusion codes for homogeneous reactor regions. These computer codes are part of the "Karlsruher Nuklear Programm System NUSYS."

The diffusion code applied to the homogenized material distribution in the different zones is acceptable if the pitch of the fuel pins is small compared to the mean free path of the neutrons. In a fast reactor the validity of this assumption is pretty well fulfilled.

The multigroup diffusion equations have the form

\[-D_i(r)\nabla^2 \phi_i(r) + \sum_{\text{rem},i} <r> \phi_i(r) = \sum_{j \neq i} \sum_{\text{rem},j} <r> \phi_j(r) + \sum_{j \rightarrow i} \sum_{\text{rem},j} <r> \phi_j(r) \]

\[\chi_i = \text{fission source in group } i.\]

For the cross sections used in the NUSYS system, which are constants in each energy group, a slightly modified ABN-set is used. The energetic self-shielding of the resonances is taken into account.
by a subprogram of NUSYS (program 00446). The evaluation code of NUSYS (00447) enables us to calculate the integral fission and capture rates \( \int \Sigma_i \phi \, dE \) and \( \int \Sigma_c \phi \, dE \) for each desired isotope as function of the position in the reactor or integrated over the volume of each material zone.

For the two-dimensional calculations a condensation of the 26-group set into a 5-group set is convenient. For the two-dimensional calculations the DIXY program 00940 and the evaluation program 01029 are used.
2. One-Dimensional Calculations

2.1 Calculations for the Core Without Control Elements.

In the one-dimensional calculations for the cylindrical reactor we have eliminated the axial and angular coordinates.

In this one-dimensional $r$-geometry the control elements, which are parallel to the axial Z-axis and located on 1 or 2 rings with the radius $R$, are assumed to be smeared to cylindrical rings of equal radius and have the same mass of absorber material. Besides, it is possible only to study fully inserted and completely withdrawn control rings.

Partially inserted control rings can be studied only in the two-dimensional ($r$-$z$)-geometry.

Before the study of the inserted and withdrawn control rings it is of interest to know some characteristics of the unperturbed reactor. We will define here the unperturbed or base reactor as the reactor in which the control elements are replaced by normal fuel elements.

The overall geometry of this base reactor is unchanged. We will use the results of the unperturbed reactor as reference data.

Fig. 2.1 shows the fission and power distributions, respectively, as functions of the radius. The inner fission zone of the core has a flat fission distribution. Furthermore, it is seen that the point of maximum fission density is in the outer fission zone.

About 50% of the fissions occurs in the inner zone and about 45% in the outer zone. The blanket zone (zone 3) contributes roughly 5% to the total fissions.
Fig. 2.2 shows the neutron energy spectrum for the different zones. The graphs are volume-integrated.

As expected, the spectrum in the outer fission zone is not very different from the spectrum of the inner zone. The difference in these two zones is only in the fuel enrichment.

The increased coolant density, the higher $^2$$H$ concentration, and the reduction of the fission source in the blanket cause a spectrum softening in the blanket zone.

Fig. 2.3 shows the radial dependence of the microscopic capture rate of the strong neutron absorber $^{10}$B. Compared with the fission distribution it is seen that the capture rate for each zone is nearly proportional to the integral flux distribution.

The increase in the capture rate in the blanket zone at the core-blanket interface is due to the spectrum softening and the high absorption cross section of $^{10}$B in the low neutron energy range.

The volume-integrated capture rate of $^{10}$B as a function of the neutron energy is given in Fig. 2.4.

All graphs are normalized in such a way that the whole reactor over a height of 1 cm gives a total of 1 fission per sec, so

$$\int \Sigma_f \Phi \, dE = 1 \text{ (sec}^{-1}\text{).}$$

Finally, Fig. 2.5 indicates the neutron fission weight as a function of the radius.

For some numerical data of the base reactor see Table 2.1.
Table 2.1  Numerical Data of the Unperturbed Reactor.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Volume (cm$^3$) per cm core height</th>
<th>$\int \Sigma_f \phi dE dV$ (fissions per sec)</th>
<th>Maximum fission density $\rho$ (fiss/cm$^3$sec)</th>
<th>Average fission density $\bar{\rho}$ (fiss/cm$^3$sec)</th>
<th>Power factor $\Phi/\bar{\rho}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$2.6302 \times 10^4$</td>
<td>0.50353</td>
<td>$2.0092 \times 10^5$</td>
<td>$1.914 \times 10^{-5}$</td>
<td>1.045</td>
</tr>
<tr>
<td>II</td>
<td>$2.8023 \times 10^4$</td>
<td>0.44462</td>
<td>$2.1135 \times 10^5$</td>
<td>$1.587 \times 10^{-5}$</td>
<td>1.332</td>
</tr>
<tr>
<td>III</td>
<td>$3.5933 \times 10^4$</td>
<td>0.05185</td>
<td>$3.4070 \times 10^6$</td>
<td>$1.442 \times 10^{-6}$</td>
<td>2.360</td>
</tr>
<tr>
<td>I+II</td>
<td>$5.4325 \times 10^4$</td>
<td>0.94815</td>
<td>$2.1135 \times 10^5$</td>
<td>$1.747 \times 10^{-5}$</td>
<td>1.210</td>
</tr>
<tr>
<td>I+II+III</td>
<td>$9.0258 \times 10^4$</td>
<td>1.00000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2. One Ring of Control Elements.

2.2.1. Effectiveness of One Ring of Control Elements.

The determination of the shutdown reactivity worth of a ring of control rods is of interest, because the effectiveness of the rods is a function of the position in the reactor. If we know the reactivity worth of one control element in the center of the reactor ($\Delta k_0$), we can calculate the reactivity worth of the same rod at position $r$ as follows: $\Delta k(r) = \Delta k_0 \cdot W(r)$, in which $W(r)$ is a weighting factor. In first-order perturbation theory this weighting factor is $W(r) = \frac{\langle \phi(r), \phi^+(r) \rangle}{\langle \phi(0), \phi^+(0) \rangle}$.

In this expression $\phi$ is the neutron flux and $\phi^+$ the adjoint flux. $\langle \phi, \phi^+ \rangle$ is the scalar product, which is the same as $\int \phi(\epsilon) \phi^+(\epsilon) d\epsilon = \sum_{i=1}^{\infty} \phi_i \phi_i^+$. To determine the effectiveness of a ring of control elements it is not sufficient to multiply the $\Delta k(r)$ of a single rod with the number of elements. In the case of multiple control elements, however, the influence of one rod on the adjacent rods must be considered (mutual shielding or shadowing).

It is known that, with one rod inserted, the flux adjacent to the inserted rod is depressed and the flux elsewhere must be higher to maintain the same integral fission rate.

If more rods are close together, they will shadow each other, that is, each rod finds itself partially in the flux depression caused by the other rods, so it absorbs fewer neutrons than it would do in the absence of the other rods. If the rod separation increases, each rod finds itself in the flux peak which occurs beyond the depression and each rod therefore absorbs more neutrons than it would do in the absence of the other rods. However, if we insert the rod too far from the center axis of the core, the effectiveness decreases rapidly, since the flux decreases and disappears at the boundary of the reactor. So, there exists an optimum location of the control rod rings in the reactor.
For the smeared cylindrical absorber ring the same description as above is valid. Since the total mass of absorber material in the ring is a constant, the density of absorber material in a ring with a smaller radius will be higher. This higher density causes stronger self-shielding and has the same effect as the shadowing in a cluster of control elements.

Fig. 2.6. indicates the computed reactivity worth per control element as a function of the radius of the cylindrical absorber ring. It should be noted that the main purpose of this work is not to determine absolute values of the control rod worth but to show the tendencies and to give a physical insight into the problems and results.

The absolute value of the control rod worth can be changed easily by varying the $\text{B}^{10}$ enrichment.

The parameter N in Fig. 2.6. is the number of control elements in the ring. For higher numbers of N the optimum radius of the ring increases slightly and the reactivity worth per element decreases. This can be explained as follows:

If for a certain radius of the ring the number of elements in the ring increases, the absorber density increases. (In the actual setup the distance between two control elements will become smaller.). So, shadowing or self-shielding will be stronger for a larger number of control elements. Therefore, the effectiveness for each rod will decrease if the number of control elements in the ring is increased. It is evident that the density of the absorber material in the homogenized absorber ring decreases with increasing radius of the absorber ring, keeping the thickness of the ring constant. For this reason, the optimum radius will shift to higher values with increasing number of elements in the ring.

Fig. 2.6. shows that the optimum radius changed from $R = 75$ cm (3 control elements in the absorber ring) to $R = 80$ cm (12 control elements in the absorber ring). The calculations are done for a ring of N elements which are smeared in a homogeneous ring of a thickness of 11 cm. The ring thickness is about the same as the diameter of one absorber pin cluster. The homogeneous ring consists of fuel, coolant, cladding and structural material, and absorber
material with volume fractions which are modifications of those shown in Table 1.1., but in such a way that the total absorber material in a ring will be constant and independent of the absorber ring radius.

Table 2.2. contributes some numerical values of the one-dimensional one-ring problem.

2.2.2. Capture Rate of $^{10}$B

To study the effect of the neutron absorption in $^{10}$B we calculate the integral microscopic capture rate

$$\sigma^*(r) = \int E^0 \rho_{^{10}B}(E,r) \phi(E,r) \, dE$$

as a function of the position in the reactor. As we have seen in Chapter 2.2.1. we expect a depression of the capture rate near the absorber ring and elsewhere the capture rate can even be higher than in the unperturbed case because of the normalization which provides no change in the total power. As we will see in Chapter 2.3.1. the radial dependence of the capture rate of $^{10}$B is a quantity to determine approximately the effectiveness $\Delta k$ in the case of two rings of absorber elements. Fig. 2.7. up to Fig. 2.10. show this effect for several positions of the absorber ring. The parameter in these figures is the number of control elements ($N$) which are smeared out in one cylindrical absorber ring.

If we take the example of a ring radius $R = 43.0$ cm we see that the capture rate $\sigma^*$ near the boundary of zone I and zone II is higher than for the unperturbed reactor (with $N=0$).

The $^{10}$B concentration in the unperturbed case is practically infinitely small.

If we take higher values of the ring radius (for example $R = 86.0$ cm) we see that the capture rate $\sigma^*$ in zone II will be lower than for the base reactor. From this we expect that in the case of two absorber rings with the first ring located in zone I and the second ring in zone II the effectiveness of the second ring will be reduced if the radius of the inner ring increases (more shadowing).

On the other hand, we saw in Chapter 2.2.1 that the effectiveness of one absorber ring, up to a certain radius of the ring, will increase
with increased radius of the ring. So, we expect that for the two-ring problem with a fixed radius for the second ring there will be an optimum radius for the inner ring in zone I of about half the inner zone radius.

2.2.3. Power Distribution for One Absorber Ring.

The analogous arguments as for the flux depression and flux increase can be applied to the power distribution; See Fig. 2.11 to Fig. 2.14 which give the fission distribution \( p = \int \sum_f \phi \, dE \) as a function of the radius. \( p = \text{fissions/sec cm}^3 \). It will be noted that all distributions are normalized to one fission/sec over the complete reactor. An integral quantity which characterizes the radial power distribution is the radial power factor \( \frac{\phi}{\phi} \). It is defined as the ratio of radial peak to radial average fission density \( \int \sum_f \phi \, dE \) in the core. For the radial average fission density we take the average value of the density in zone I and zone II (we note that only about 5% of the fissions occurs in the blanket). Fig. 2.15 shows the radial power factor as a function of the absorber ring radius with the number of control elements as a parameter. It is seen that the optimum power factor (lowest peak-to-average ratio) appears for absorber rings with a radius of about 65 cm, which is not far from the ring radius with optimum absorber effectiveness. This can be explained as follows: For a constant number of control elements and for a ring radius near the radius of optimum effectiveness the flux distribution will be more favourable for the \( \text{B}_{10} \) absorption and the flux depression not so strong \( \int \sum_f \phi \, dE \) higher as in the case of an absorber ring with a radius far from the optimum radius. Compare also Fig. 2.7 and Fig. 2.9. This means that for a ring radius near the radius with optimum absorber effectiveness the power distribution will be fairly good and consequently the peak-to-average power ratio will be low.
**Table 2.2** Numerical data of the One-Dimensional One-Ring Problem.

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2.3. Two Rings of Control Elements.

2.3.1. Application of the Perturbation Theory.

For the following we start from the multigroup diffusion equation for a multiplying system.

\[- D_i \nabla^2 \phi_i + \sum_{\text{rem},i} \phi_i = \sum_{j \neq i} \chi_i \phi_j + \frac{\chi_i}{k_{\text{eff}}} \sum_{j} (\Sigma_f)_{ij} \phi_j \]  

(1)

\(i,j\) are indices of energy groups, see Chapter 1.5. As usual, we assume that the fission spectrum is independent of energy of the neutron which induces the fission. The normal boundary conditions will be fulfilled. In operator form we write (1) as follows:

\[ M \phi = \frac{1}{k_{\text{eff}}} \chi \langle \Sigma_f, \phi \rangle \]  

(2)

\(\phi, \chi, \Sigma_f\) are vectors, 
\(M\) is a matrix with the elements

\[ M_{ij} = - D_i \nabla^2 + \Sigma_{\text{rem},i} \]

\[ M_{ij} = - \Sigma_{j \rightarrow i} \quad (j < i) \]

\[ M_{ji} = 0 \quad (j < i) \]

\[ \langle \Sigma_f, \phi \rangle = \text{scalar product} = \sum_{j} (\Sigma_f)_{ij} \phi_j = \int \Sigma_f(E) \phi(E) dE . \]

In the perturbation theory formalism we have to take the adjoint flux \(\phi^+\) and the adjoint operator \(M^+\). \(M^+\) is defined by

\[ \int (\psi M \varphi - \varphi M^+ \psi) dV = 0 \]  

(3)

in which \(\psi\) and \(\varphi\) are functions with the boundary condition that \(\psi\) and \(\varphi\) vanish at the extrapolated surface of the reactor volume. \(\phi^+\) is the solution of the adjoint equation

\[- D_i \nabla^2 \psi_i + \sum_{\text{rem},i} \psi_i = \sum_{j \neq i} \psi_j + \frac{\Sigma_f}{k_{\text{eff}}} \sum_{j} \chi_j \psi_j \]  

(4)
In the matrix form we have from (4)

\[ M^+ \Phi = \frac{\Sigma p}{\kappa_{eff}} \langle X, \Phi \rangle \]

(5)

with \( M^+_{ij} = M_{ji} \);

\( M^+ \) is the transpose of the matrix \( M \).

Equation (3) is satisfied by the solutions of (2) and (5).

Equation (5) can be written also as

\[ \phi^+ M = \frac{\Sigma p}{\kappa_{eff}} \langle \phi^+, \chi \rangle \]

(6)

where \( \phi^+ = \Psi_i \).

Now we write (2) and (6), respectively, for two different conditions of the system.

\[ M_a \phi_a = \frac{1}{\kappa_{eff a}} \chi \langle \Sigma p_a \phi_a \rangle \]

(7)

\[ \phi^+ M_b = \frac{1}{\kappa_{eff b}} \Sigma p_b \langle \phi^+, \chi \rangle \]

(8)

(7) and (8) can be transformed into

\[ -\int \langle \phi^+ B, (M_b - M_a) \phi_a \rangle dV = \int \langle \phi^+, \chi \rangle \left[ \frac{\langle \Sigma p_a, \phi_a \rangle}{\kappa_{eff a}} - \frac{\langle \Sigma p_b, \phi_b \rangle}{\kappa_{eff b}} \right] dV \]

(9)

The integration is done over the total volume of the reactor.

With \( M_b = M_a + \delta M \)

and \( \Sigma p_b = \Sigma p_a + \delta \Sigma f \)

we obtain:

\[ -\int \langle \phi^+ B, M_a \phi_a \rangle dV + \int \langle \phi^+, \chi \rangle \frac{\langle \delta \Sigma f, \phi_a \rangle}{\kappa_{eff b}} dV = \]

\[ = \int \langle \phi^+, \chi \rangle \langle \Sigma p_a, \phi_a \rangle \left[ \frac{1}{\kappa_a} - \frac{1}{\kappa_b} \right] dV \]

(10)

Near criticality we can write

\[ \frac{1}{\kappa_a} - \frac{1}{\kappa_b} \approx \kappa_b - \kappa_a = \delta k \]

\[ \delta k = \frac{-\int \langle \phi^+ B, M_a \phi_a \rangle dV + \frac{1}{\kappa_b} \int \langle \phi^+, \chi \rangle \langle \delta \Sigma f, \phi_a \rangle dV}{\int \langle \phi^+, \chi \rangle \langle \Sigma p_a, \phi_a \rangle dV} \]

(11)
In this study we take condition a as the reactor with inserted $B_4C$ rods and condition b as the reactor in which the control rods are withdrawn and the $Al_2O_3$ followers are used instead of $B_4C$. This means that the fission cross sections are not changed, so (11) reduces to

$$\Delta k = -\frac{\int \langle \phi^+_{nl}, \delta M_{nl} \phi_{nl} \rangle dV}{\int \langle \phi^+_{nl}, \chi \rangle \langle \Sigma_f, \phi_{nl} \rangle dV}$$

(12)

The influence of the change in resonance self-shielding can be neglected. In the NUSYS program the flux is normalized to

$$\int dV \int \phi \phi dE = 1 \quad (\text{sec}^4)$$

(fission source).

The computer program normalizes the adjoint flux to

$$\int dV \int \phi^+ \chi dE = 1 \quad (\text{neutron fission weight}).$$

The volume integration is over the total reactor volume and the energy integration over the total neutron energy spectrum.

We now examine the reactor with three types of control rod configurations.

**Configuration 1:** Only one ring of $N_1$ control elements at radius $R_1$.

**Configuration 2:** Only one ring of $N_2$ control elements at radius $R_2$.

**Configuration 12:** One ring of $N_1$ control elements at radius $R_1$ and a second ring of $N_2$ control elements at radius $R_2$.

With the definition of control rod effectiveness $\Delta k = k_{eff} (B_4C) - k_{eff} (Al_2O_3)$, we obtain from (12)

$$\Delta k_{12} = \frac{\int \langle \phi^+_{12 nl}, \Delta M_{12} \phi_{12 nl} \rangle dV}{\int \langle \phi^+_{12 nl}, \chi \rangle \langle \Sigma_f, \phi_{12 nl} \rangle dV}$$

(13)

$$\Delta k_1 = \frac{\int \langle \phi^+_{1 nl}, \Delta M_1 \phi_{1 nl} \rangle dV}{\int \langle \phi^+_{1 nl}, \chi \rangle \langle \Sigma_f, \phi_{1 nl} \rangle dV}$$

(14)

$$\Delta k_2 = \frac{\int \langle \phi^+_{2 nl}, \Delta M_2 \phi_{2 nl} \rangle dV}{\int \langle \phi^+_{2 nl}, \chi \rangle \langle \Sigma_f, \phi_{2 nl} \rangle dV}$$

(15)

It is clear that the control rod regions are the only regions where the matrix elements will be perturbed.
With a rearrangement of (13) (14) (15) we obtain from one-group theory:

$$\Delta k_{12}^2 = \Delta k_1^2 \frac{\langle \phi_{12 A1}^+ \phi_{12 B} \rangle}{\phi_{1 A1}^+ \phi_{1 B}^+} + \Delta k_2^2 \frac{\langle \phi_{12 A2}^+ \phi_{12 B} \rangle}{\phi_{2 A2}^+ \phi_{2 B}^+}$$

(16)

In this expression we have the following notations:

$$F_{12} = \int \langle \phi_{12 A1}^+ \phi_{12 B} \rangle dV$$

$$F_1 = \int \langle \phi_{1 A1}^+ \phi_{1 B} \rangle dV$$

$$F_2 = \int \langle \phi_{12 A2}^+ \phi_{12 B} \rangle dV$$

$$\left( \frac{\phi_{12 A1}^+}{\phi_{1 A1}^+} \right)_{R_1} = \text{average value of } \phi_{12 A1}^+ \text{ over the control rods with radius } R_1.$$ 

With expression (16) we have a formalism to obtain the control rod effectiveness of two rings of control elements if we know the rod effectiveness of two systems with a single control ring. To obtain a manageable formalism (it is very lengthy to calculate the F factor), we use the following approximation:

$$F_{12} \approx F_1 \approx F_2.$$ 

If we proceed from the result of one-group theory (Eq. (16)) to multigroup theory, it is evident to assume the following equivalence:

$$\langle \phi_{12 A1}^+ \rangle \rightarrow \langle \phi_{12 A1}^+(R_i), \chi(R_i) \rangle$$

$$\langle \phi_{12 A2}^+ \rangle \rightarrow \langle \phi_{1 A1}^+(R_i), \chi(R_i) \rangle$$

With these assumptions we obtain from (16)

$$\Delta k_{12} = \Delta k_1 \frac{\phi_{12 A1}^*(R_i) \phi_{12 B}^*(R_i)}{\phi_{1 A1}^*(R_i) \phi_{1 B}^*(R_i)} + \Delta k_2 \frac{\phi_{12 A2}^*(R_i) \phi_{12 B}^*(R_i)}{\phi_{2 A2}^*(R_i) \phi_{2 B}^*(R_i)}$$

(17)

in which:

$$\phi_{12 A1}^*(R_i) = \int \chi dE$$

= neutron fission weight at position of the control rod with radius $R_1$ in the configuration of two rings with control rods withdrawn.

$$\phi_{1 A1}^*(R_i) = \int \chi dE$$

= neutron fission weight at position of the control rod with radius $R_1$ in the configuration of one ring with withdrawn rods.
\[ \sigma_{1,b}^*(R_1) = \int_{E}^{E_2} \sigma_{1,b}^* \phi \, dE \]

= capture rate of \( B^{10} \) at the position of the control rod with radius \( R_1 \) in the configuration of two rings with inserted rods.

\[ \sigma_{1,b}^*(R_1) = \int_{E}^{E_2} \sigma_{1,b}^* \phi \, dE \]

= capture rate of \( B^{10} \) at the position of the control rod with radius \( R_1 \) in the configuration of one ring with inserted rods.

If we change the conditions \( g \) and \( b \) in (11) so that condition \( b \) is the reactor with \( B_{12} \) rods inserted and condition \( g \) is the reactor with control rods withdrawn (\( Al_{2}O_{3} \) followers inserted), we obtain a similar equation

\[ \Delta k_{12} = \Delta k_1 \phi_{1,b}^*(R_1) \sigma_{1,b}^*(R_1) + \Delta k_2 \phi_{1,b}^*(R_2) \sigma_{1,b}^*(R_2) + \Delta k_{12} \phi_{1,b}^*(R_2) \sigma_{1,b}^*(R_2) \]

(18)

2.3.2. Effectiveness and Power Distribution for Two Rings.

In the core design of D-1 18 control elements will be used for reactor control. In this study we locate these 18 elements within two rings of control elements. For reasons of symmetry we examine only the following two possibilities:

a. Inner ring of 6 elements, outer ring of 12 elements.

b. Inner ring of 9 elements, outer ring of 9 elements.

The radius \( R_1 \) of the inner ring and the radius \( R_2 \) of the outer ring are variable parameters. Fig. 2.16 to Fig. 2.21 show the radial distribution of the \( B^{10} \) capture rate \( \int \sigma_c \phi \, dE \) and the fission density \( \int \phi \, dE \) for various positions of the two rings. If we compare the figures with those of the one-ring problem, we see the very important effect of the additional ring on the radial distributions. With a single ring in the outer fission zone we have a strong maximum for capture and fission in the center of the core. As it is seen, we obtain a much better capture and fission distribution by an additional absorber ring in the inner zone. In addition, we can see that the power distribution of Fig. 2.19 is much better than that of Fig. 2.21. In Chapter 2.3.1. we calculated the reactivity worth \( \Delta k_{12} \) of two rings of control elements by the perturbation theory (Equation(16)).
To show the validity of Eq. (16) in one case we calculated $\Delta k_{12}$ from Eq. (16) for various positions of the inner ring with a constant radius of the second ring ($R_2 = 97$ cm). In Fig. 2.22 this value $\Delta k_{12}$ is compared with the exact results of the computer calculations $\Delta k_{exact}^e$. It is seen that the perturbation formalism overestimates the reactivity worth by about 5%. Since we know that the total effectiveness of 18 rods is about $\Delta k \approx 0.075$, it is very probable that the difference between $\Delta k_{12}$ and $\Delta k_{exact}^e$ (which is about 0.004) will be small compared to the uncertainty which arises from the application of the homogeneous diffusion theory to the determination of the control rod worth. For the simpler equation (17) we obtain a difference from $-2\%$ to $10\%$. Fig. 2.23 gives the total reactivity worth $\Delta k_{exact}^e$ of two rings of control elements as a function of the radius of the inner absorber ring. The parameter is the thickness of the absorber ring. It is seen that the position of the inner ring for a maximum $\Delta k$ is independent of the ring thickness. Table 2.3 gives some numerical values of the exact two-ring problem.

2.3.3. Synthesis.

As we have seen in Fig. 2.22, the equations of Chapter 2.3.1. are applicable to an estimate of the effectiveness of a reactor with two rings of control elements. This will be especially important if one wishes to determine the ring radii for which the absorber rings have the maximum reactivity worth. To estimate the positions for maximum effectiveness we would have to make many computer calculations in which the ring radii have been varied. This will
take too much computing time. With the aid of the solutions of chapter 2.3.1, however, it is possible to calculate the optimum ring radii for the two-ring problem with the results of the one-ring problem, so we can reduce the expensive computer calculations. This can be made as follows:

With reference to the capture rate distribution \(\Sigma^{\infty}(r) = \int \phi(r) \phi(E) dE\) of the unperturbed reactor we approximate the capture rate distribution for the two-ring problem \(\Sigma_{12}^{\infty}(r)\) by:

\[
\frac{\sigma_{12}^{\infty}(r)}{\sigma_{\infty}^{\infty}(r)} = \frac{\sigma_{1}^{\infty}(r)}{\sigma_{\infty}^{\infty}(r)} \times \frac{\sigma_{2}^{\infty}(r)}{\sigma_{\infty}^{\infty}(r)} \tag{1}
\]

where

- \(\sigma_{\infty}^{\infty}(r)\) = capture rate \(\int \phi dE\) at position \(r\) in the unperturbed reactor.
- \(\sigma_{1}^{\infty}(r)\) = capture rate \(\int \phi dE\) at position \(r\) in the reactor with a single absorber ring at radius \(R_1\).
- \(\sigma_{2}^{\infty}(r)\) = capture rate \(\int \phi dE\) at position \(r\) in the reactor with a single absorber ring at radius \(R_2\).
- \(\sigma_{12}^{\infty}(r)\) = capture rate \(\int \phi dE\) at position \(r\) in the reactor with one ring at \(R_1\) and a second ring at \(R_2\).

To show the quality of this approximation we have plotted for one special case in Fig. 2.24 the direct result \(\frac{\sigma_{12}^{\infty}(r)}{\sigma_{\infty}^{\infty}(r)}\) from the exact two-ring problem \(R_1(N_1=6) = 43.0, R_2(N_2=12) = 97.0\) (see also Fig. 2.18), and the approximation \(\frac{\sigma_{12}^{\infty}(r)}{\sigma_{\infty}^{\infty}(r)} = \frac{\sigma_{1}^{\infty}(r)}{\sigma_{\infty}^{\infty}(r)} \times \frac{\sigma_{2}^{\infty}(r)}{\sigma_{\infty}^{\infty}(r)}\) from the two single ring problems \(R(N=6) = 43.0\) cm and \(R(N=12) = 97.0\) cm. (see also Fig. 2.7 and Fig. 2.10).

In the same way as for the capture rate distribution we approximate the fission neutron weight \(\phi^{\infty}(r) = \int \phi \chi dE\) by

\[
\frac{\phi_{12}^{\infty}(r)}{\phi_{\infty}^{\infty}(r)} = \frac{\phi_{1}^{\infty}(r)}{\phi_{\infty}^{\infty}(r)} \times \frac{\phi_{2}^{\infty}(r)}{\phi_{\infty}^{\infty}(r)} \tag{2}
\]

See also Fig. 2.25 in which we see that the approximation corresponds to the exact distribution within 2%.
With (1) and (2) we write Eq. (16) of Chapter 2.3.1.

\[
\Delta k_{12} = \Delta k_1 \frac{\phi_{2B}(R_1) \sigma_{2B}(R_1)}{\phi^*_0(R_1) \sigma^*_0(R_1)} + \Delta k_2 \frac{\phi_{1B}(R_2) \sigma_{1B}(R_2)}{\phi^*_c(R_2) \sigma^*_c(R_2)}
\]

With this equation we can estimate the absorber effectiveness of two rings of control rods using the results of the calculations for two single rings.

With Equation (3) we have calculated \(\Delta k_{12}\) as a function of the ring radius \(R_1\) for various positions of the outer absorber ring. Fig. 2.26 shows \(\Delta k_{12}(R_1)\) for the condition with 6 absorber elements in the inner ring (\(N_1=6\)) and 12 absorber elements in the outer ring (\(N_2=12\)). In Fig. 2.27 \(\Delta k_{12}(R_1)\) is given for \(N_1=9\) and \(N_2=9\). If we compare Fig. 2.26 with Fig. 2.23 we see that the solution of Eq. (3) agrees fairly well with the direct computer calculations.

To determine the optimum ring radii, for which \(\Delta k_{12}\) has a maximum, we plotted in Fig. 2.28 \(\Delta k_{12}\) max., the maximum value of \(\Delta k_{12}(R_1)\), (that means at the optimum value of \(R_1\)) as a function of the ring radius \(R_2\). The ring radius \(R_2\) for which \(\Delta k_{12}\) max. has an extremum gives us the optimum position of the outer absorber ring.

From Fig. 2.28 we can conclude that the optimum position of the outer absorber ring is close to the boundary of the first and second fission region. The optimum inner ring radius consequently will be about 57 cm. (\(\Delta k_{12}\)exact gives an optimum of \(R_1\) opt. \(\approx 50\) cm) See also Fig. 2.29 in which \(R_1\) max. is given as a function of \(R_2\). \(R_1\) max. is defined as the ring radius \(R_1\) for which \(\Delta k_{12}(R_1)\) has the maximum value \(\Delta k_{12}\) max.

It will be noted here that near the optimum inner ring radius the reactivity worth \(\Delta k\) varies slowly with \(R_1\). Therefore, a small deviation of the inner ring radius from the optimum radius is allowed.
As we saw in Chapter 1.4 the distance of two adjacent absorber elements should be larger than 30cm.

For a ring of absorber elements of radius 50cm the distance in the azimuthal direction between two adjacent absorber elements will be about 52cm for 6 absorber elements in the ring and about 35cm for 9 absorber elements in the ring. Therefore, the results of this chapter match the requirement of engineering design.

This is true also of the outer ring at a radius of about 95cm and for the radial distance between both rings.

2.3.4. Effect of Power Peak Factor Deviation.

For a reactor of a given geometric arrangement and maximum tolerable power density one should try to get the power peak factor $\delta/\bar{\delta}$ as low as possible, since the total power output will then be at its maximum value.

If, e.g., the power factor decreases by 1%, the real total power output increases by 1%, i.e. 10 MWe for a 1000 MWe steam cooled fast power reactor. Assuming a load factor of 0.80 and power generation costs of Dpf 1.85/kWh, this would amount to a cost saving of DM 1.6 $10^6$/year.

It is therefore evident that one tries to minimize the power factor.

In the two-ring problem, for example, we have from Table 2.3 a power factor of $\delta/\bar{\delta}$=1.287 and $\delta/\bar{\delta}$=1.380, respectively, for the configuration $R_1(N_1=6)=43.0$ and $R_1(N_1=6)=21.5$, respectively.

For a constant maximum tolerable power density the first configuration can go to an average power which is $1.380/1.287 = 1.072$ times higher as for the second configuration.

This will save about DM 11.5 $10^6$ a year.
Table 2.3. One-Dimensional Two-Ring Problem.

$R_1 (N_1=6) =$ variable, $R_2 (N_2=12) =$ interface zone I - zone II.

<table>
<thead>
<tr>
<th>$D$ (cm)</th>
<th>$R_1$ (cm)</th>
<th>$k(Al_2O_3)$</th>
<th>$k(B_4C)$</th>
<th>$\Delta k$</th>
<th>$\int \Sigma^0 \phi dV$</th>
<th>$\int \Sigma^0 \phi dV$</th>
<th>$\int dV/\Sigma_f \phi dE$</th>
<th>$\hat{P}_{I+II}$ (fissions/sec)</th>
<th>$\hat{P}_{I+II}$ (Fission/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>21.5</td>
<td>1.0164</td>
<td>0.9470</td>
<td>0.0694</td>
<td>6.107 x 10^{-2}</td>
<td>1.795 x 10^{-1}</td>
<td>6.316 x 10^{-2}</td>
<td>2.382 x 10^{-5}</td>
<td>1.380</td>
</tr>
<tr>
<td></td>
<td>43.0</td>
<td>1.0162</td>
<td>0.9327</td>
<td>0.0835</td>
<td>9.665 x 10^{-2}</td>
<td>1.843 x 10^{-1}</td>
<td>7.092 x 10^{-2}</td>
<td>2.202 x 10^{-5}</td>
<td>1.287</td>
</tr>
<tr>
<td></td>
<td>64.5</td>
<td>1.0166</td>
<td>0.9413</td>
<td>0.0753</td>
<td>1.226 x 10^{-1}</td>
<td>1.493 x 10^{-1}</td>
<td>5.572 x 10^{-2}</td>
<td>4.396 x 10^{-5}</td>
<td>2.527</td>
</tr>
<tr>
<td></td>
<td>75.25</td>
<td>1.0169</td>
<td>0.9539</td>
<td>0.0630</td>
<td>1.116 x 10^{-1}</td>
<td>1.291 x 10^{-1}</td>
<td>4.479 x 10^{-2}</td>
<td>4.923 x 10^{-5}</td>
<td>2.800</td>
</tr>
<tr>
<td>5</td>
<td>21.5</td>
<td>1.0162</td>
<td>0.9514</td>
<td>0.0648</td>
<td>5.332 x 10^{-2}</td>
<td>1.672 x 10^{-1}</td>
<td>6.644 x 10^{-2}</td>
<td>2.241 x 10^{-5}</td>
<td>1.302</td>
</tr>
<tr>
<td></td>
<td>43.0</td>
<td>1.0159</td>
<td>0.9594</td>
<td>0.0765</td>
<td>8.405 x 10^{-2}</td>
<td>1.695 x 10^{-1}</td>
<td>7.340 x 10^{-2}</td>
<td>2.096 x 10^{-5}</td>
<td>1.228</td>
</tr>
<tr>
<td></td>
<td>64.5</td>
<td>1.0162</td>
<td>0.9459</td>
<td>0.0703</td>
<td>1.067 x 10^{-1}</td>
<td>1.421 x 10^{-1}</td>
<td>5.982 x 10^{-2}</td>
<td>4.003 x 10^{-5}</td>
<td>2.310</td>
</tr>
<tr>
<td></td>
<td>75.25</td>
<td>1.0166</td>
<td>0.9563</td>
<td>0.0603</td>
<td>9.937 x 10^{-2}</td>
<td>1.261 x 10^{-1}</td>
<td>4.984 x 10^{-2}</td>
<td>4.519 x 10^{-5}</td>
<td>2.582</td>
</tr>
</tbody>
</table>

Normalization: $\int dV \int \Sigma_f \phi dE = 1$ (fissions/sec).
3. Two - Dimensional Calculations.


In the preceding chapter we studied the one - dimensional problem. Now we will show the effect of the homogeneous ring on the worth of the control rods as a function of ring thickness and compare this with the two - dimensional (r - θ) calculations.

In Fig. 2.23 the reactivity worth \( \Delta k \) was given for the ring thickness 5 and 11 cm, as a function of the inner ring radius. We concluded, that the ring thickness has no influence on the determination of the optimum ring radius. Only the absolute value of the reactivity worth will decrease for a smaller ring thickness, keeping the total amount of absorber material constant. Fig. 3.1 and also Table 3.1 show this effect in the one - dimensional geometry, (this is for fixed radii).

We see that \( \Delta k \) depends nearly linearly on the ring thickness in the range studied. In the same figure we plotted the integral absorption rate \( \int \Sigma_c \phi dE dV \) of \( B^{10} \) in the absorber rings, which gives also a linear dependence. We can explain this as follows:

The volume of an absorber ring depends nearly linearly on the ring thickness, i.e. the macroscopic cross section \( \Sigma_c \) of \( B^{10} \) in the ring will be inversely proportional to the ring thickness. The shadowing (or flux depression) in a ring of smaller ring thickness is stronger than for a larger ring thickness (roughly proportional to \( \Sigma_c \) of \( B^{10} \)).

The criticality change will be approximately inversely proportional to the flux depression, which explains the behaviour just mentioned. In the same way of arguing one may state that the integral \( B^{10} \) capture rate \( \int \Sigma_c \phi dE dV \) decreases and, consequently, the reactivity worth \( \Delta k \) will be lower for smaller ring thickness.

In some (r - θ) calculations (θ is the azimuthal angle with respect to the axis of the core) we studied the effect of the rod perimeter as a measure of the rod surface on the control rod worth.
For a constant distance of the rods from the center of the core and a constant cross section of the absorber rod of 95 cm\(^2\) per absorber element the rod perimeter is varied in the \((r - \theta)\) geometry as shown in the next picture:

1) perimeter 40 cm
2) perimeter 56 cm
3) perimeter 100 cm

The configuration is chosen in such a way that for the largest perimeter (100 cm) the control rods on one ring will be connected with each other and so a homogeneous ring of absorber material is formed with a ring thickness of 2 cm. Moreover, the results of the latter can be compared with the results of the one-dimensional calculations.

Fig. 3.2 shows the reactivity worth as a function of the control rod perimeter. We see that the effect of the rod perimeter is considerable, but not as pronounced as in thermal reactors.

It will be noticed here that the absorber perimeter of one absorber element in the D - 1 design is about 35 - 40 cm. Thus we conclude that for the determination of the absolute value of the reactivity worth \(\Delta k\) of control rods only proper 2 or 3-dimensional calculations for the real geometric configuration will give correct results.

In addition the validity of the application of diffusion theory must be proved for the exact determination of the control rod worth. To determine the optimum location of the rings the one-dimensional calculations are sufficient.

The next point to be considered is the problem of determining the most suitable ring thickness of a homogeneous ring for
which the radial fission distribution from a one-dimensional calculation shows the best agreement with the radial fission distribution \( p(r) \) of the \((r - \theta)\) calculations in which all control rods are separated.

To study this we plotted the one-dimensional radial fission distribution \( p = \int \Sigma \phi dE \) for three different ring thicknesses (see Fig. 3.3). The fission distribution for the two-dimensional \((r - \theta)\) geometry with inserted rods is given in Fig. 3.4.

Table 3.1 contains some numerical values of fission rate and power factors for one-dimensional and \((r - \theta)\) geometry.

It is seen that a homogeneous ring with a thickness of 11 cm gives the best agreement with \((r - \theta)\) calculations, a fact which ensures that the calculations of Chapter 2 are legitimate.

For this reason we decided to perform our two-dimensional \((r - z)\) calculations with rings of 11 cm thickness.
Table 3.1. One-Dimensional Problem $R_1(N_1=6)=43.0$ $R_2(N_2=12)$ at interface of zone I-zone II.

<table>
<thead>
<tr>
<th>D (cm)</th>
<th>$k(Al_2O_3)$</th>
<th>$k(B_4C)$</th>
<th>$\Delta k$</th>
<th>$\int \sum E \phi dE dV$ captures sec</th>
<th>$\int \sum f \phi dE dV$ fissions sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>abs 1</td>
<td>abs 2</td>
</tr>
<tr>
<td>11</td>
<td>1.0162</td>
<td>0.9327</td>
<td>0.0835</td>
<td>9.665 $10^{-2}$</td>
<td>1.843 $10^{-1}$</td>
</tr>
<tr>
<td>5</td>
<td>1.0159</td>
<td>0.9394</td>
<td>0.0765</td>
<td>8.405 $10^{-2}$</td>
<td>1.695 $10^{-1}$</td>
</tr>
<tr>
<td>2</td>
<td>1.0167</td>
<td>0.9437</td>
<td>0.0730</td>
<td>7.828 $10^{-2}$</td>
<td>1.613 $10^{-1}$</td>
</tr>
<tr>
<td>(r-θ)</td>
<td>1.0170</td>
<td>0.9548</td>
<td>0.0622</td>
<td>7.172 $10^{-2}$</td>
<td>1.353 $10^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D (cm)</th>
<th>$\hat{P}_I$ fissions/cm$^3$</th>
<th>$\hat{P}_{II}$ fissions/cm$^3$</th>
<th>$\frac{\hat{P}_I}{P}$</th>
<th>$\frac{\hat{P}_{II}}{P}$</th>
<th>$\frac{\hat{P}_{I+II}}{P}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>2.2020 $10^{-5}$</td>
<td>1.8571 $10^{-5}$</td>
<td>1.200</td>
<td>1.164</td>
<td>1.287</td>
</tr>
<tr>
<td>5</td>
<td>2.0964 $10^{-5}$</td>
<td>1.9800 $10^{-5}$</td>
<td>1.206</td>
<td>1.183</td>
<td>1.228</td>
</tr>
<tr>
<td>2</td>
<td>2.0396 $10^{-5}$</td>
<td>2.0304 $10^{-5}$</td>
<td>1.200</td>
<td>1.182</td>
<td>1.196</td>
</tr>
<tr>
<td>(r-θ)</td>
<td>2.2320 $10^{-5}$</td>
<td>2.1270 $10^{-5}$</td>
<td>1.225</td>
<td>1.312</td>
<td>1.297</td>
</tr>
</tbody>
</table>

Normalization:

$$\int dV \int \sum f \phi dE = 1 \left(\frac{\text{fissions}}{\text{sec}}\right)$$

$V(\text{zone I}) = 2.63022 \times 10^4 \text{ cm}^3$

$V(\text{zone II}) = 2.80230 \times 10^4 \text{ cm}^3$
3.2 Control Rod Worth for Partially Inserted Rods.

As we saw in Chapter 2 we can find the $\Delta k$ of a control rod at a certain radial position by the first-order perturbation theory.

For a partially inserted rod along the vertical $z$-axis we obtain in the same way the expression

$$\Delta k(z) = \Delta k(H) \frac{\int_0^z \langle \phi^+ \phi \rangle \, dz}{\int_0^H \langle \phi^+ \phi \rangle \, dz}$$

in which $\Delta k(z)$ is the reactivity worth of the partially inserted rod to a depth of $z$ cm and $\Delta k(H)$ is the reactivity worth of the fully inserted rod (to a depth of $H$ cm).

In some one-dimensional axial calculations we determined $\frac{\Delta k(z)}{\Delta k(H)}$ in two different ways.

In the axial direction the reactor is divided into an upper and a lower blanket and 5 core zones with different steam densities as given in the following sketch:

<table>
<thead>
<tr>
<th>upper blanket</th>
<th>0.0994</th>
<th>0.0921</th>
<th>0.0799</th>
<th>0.0681</th>
<th>0.0591</th>
<th>0.0534</th>
<th>0.0503</th>
<th>0.0503</th>
<th>steam (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>35</td>
<td>65</td>
<td>95</td>
<td>125</td>
<td>155</td>
<td>185</td>
<td>220</td>
<td>(cm from top of the reactor)</td>
</tr>
<tr>
<td>RODS fully withdrawn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RODS fully inserted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The sketch shows the geometry for the axial calculations. For the value of $y$ in the core we chose $y=8.72$ and for the radial buckling $B_{\text{rad}}^2 = 2.68 \times 10^{-4}$ cm$^{-2}$.

For the volume fraction of the absorber material we took 1.6%.

The maximum active absorber length $H$ is 100 cm for reasons of reactor construction. The rod will be inserted from the top of the reactor.

With the axial flux distribution of the configuration with fully withdrawn absorber material, we calculated

$$\frac{\int_0^z \langle \phi^+ \phi \rangle \, dz}{\int_0^H \langle \phi^+ \phi \rangle \, dz}$$
as a function of the inserted absorber depth $z$.

In these calculations we approximate $\langle \phi_f \psi \rangle$ by the product of the fission source $\int_{E}^{\infty} \phi_f \, dE$ and the neutron fission weight $\int_{E}^{\infty} \chi \, dE$. The results are shown in curve 1 of Fig. 3.5.

In the next step we calculated $\Delta k$ as a function of the inserted depth by a series of one-dimensional axial calculations for the radially homogenized core. The results of this calculation are given in Table 3.2, and in curve 2 of Fig. 3.5.

<table>
<thead>
<tr>
<th>Absorber depth $z$ (cm)</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{\text{eff}}$</td>
<td>1.01632</td>
<td>1.01272</td>
<td>1.00444</td>
<td>0.99929</td>
<td>0.97453</td>
<td>0.95047</td>
</tr>
<tr>
<td>$\Delta k$</td>
<td>0.00360</td>
<td>0.01183</td>
<td>0.02423</td>
<td>0.04179</td>
<td>0.06585</td>
<td></td>
</tr>
<tr>
<td>$\Delta k(z)/\Delta k_{\infty}$</td>
<td>0.00547</td>
<td>0.01183</td>
<td>0.02423</td>
<td>0.04179</td>
<td>0.06585</td>
<td></td>
</tr>
<tr>
<td>$\int_{p=0}^{p} dV$ upper blanket</td>
<td>0.01026</td>
<td>0.00790</td>
<td>0.00600</td>
<td>0.00607</td>
<td>0.00622</td>
<td>0.00756</td>
</tr>
<tr>
<td>$\int_{p=0}^{p} dV$ lower blanket</td>
<td>0.01516</td>
<td>0.01615</td>
<td>0.01858</td>
<td>0.02155</td>
<td>0.02508</td>
<td>0.02738</td>
</tr>
<tr>
<td>$\int_{p=0}^{p} dV$ core</td>
<td>9.74585</td>
<td>9.7595</td>
<td>9.77542</td>
<td>0.97233</td>
<td>0.96870</td>
<td>0.96506</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>8.732153</td>
<td>9.063153</td>
<td>9.593153</td>
<td>1.005153</td>
<td>1.041153</td>
<td>1.000152</td>
</tr>
<tr>
<td>$\bar{z} , (p)$</td>
<td>79</td>
<td>81</td>
<td>85</td>
<td>89</td>
<td>103</td>
<td>111</td>
</tr>
<tr>
<td>$\bar{z} , (p)$</td>
<td>6.5010-3</td>
<td>6.5110-3</td>
<td>6.5110-3</td>
<td>6.4810-3</td>
<td>6.4610-3</td>
<td>6.4410-3</td>
</tr>
<tr>
<td>$\bar{z} / \bar{p}$</td>
<td>1.344</td>
<td>1.393</td>
<td>1.473</td>
<td>1.551</td>
<td>1.612</td>
<td>1.553</td>
</tr>
</tbody>
</table>

**Table 3.2.** One-Dimensional Axial Calculations.

$P = \int_{p=0}^{p} dE = $ fission density (fissions/cm$^3$ sec).

$z = $ distance in cm from top of the core.
3.3. Optimum Control of the Critical Reactor.

3.3.1. Introduction to the Problem.

From the discussion above we already have the next results:

With the one-dimensional calculations of Chapter 2 we determined fairly well the optimum location of two rings of absorber rods. This optimum location gives a maximum shutdown reactivity worth of the absorber rods and a favourable radial power distribution, i.e. a low value of the power factor $\frac{\Delta \rho}{\rho}$.

The $(r-\theta)$ calculations showed that with homogeneous rings of 11 cm thickness we get the best agreement compared to the more realistic $(r-\theta)$ results.

In an operating power reactor we have to insert the absorber rods in such a way that the criticality of the reactor is maintained. Usually the reactor becomes critical with a few partially inserted absorber rods.

Because the flux distribution in the critical reactor differs greatly from those distributions of the one-dimensional systems with fully inserted control rings, it is evident that the one-dimensional calculations are not the right tool for determining the optimum control rod management.

As we saw in Chapter 2.3.4, a decrease of the power factor $\frac{\Delta \rho}{\rho}$ by 1% causes a positive gain of about $10^6$ a year.

The purpose of the calculations we are going to report on now is this:

For a reactor with a fresh fuel loading the excess reactivity must be controlled by inserting some absorber rods in such a way that the reactor becomes just critical and has the most favourable power distribution, i.e. the minimum power factor.
3.3.2. Quantities Kept Constant in the Calculations.

In our two-dimensional calculations we locate the 18 control elements on two rings. The inner ring, which is in the inner fission zone, contains 6 control elements. The radius of this ring is fixed at \( R_1 = 53.5 \) cm, which is between the optimum ring radii determined by the exact calculations and by the synthesis method. (See Chapter 2.3.3.). The outer ring contains 12 control elements and is located in the outer fission zone on the boundary of the two fission regions.

In (r-z) calculations the absorber material is smeared in homogenous rings of 11 cm thickness. Fig. 1.1. gives the dimensions of the cylindrical reactor.

In (r-\( e \)) calculations we chose the control rods with a cross section of 95 \( \text{cm}^2 \) and a perimeter of 40 cm.

The values of \( y_1 \) and \( y_{11} \) of the two fission zones are chosen in such a way that the reactor in (r-\( e \)) geometry, for a burn-up of 18,000 MWD/tonne (corresponding to the beginning of the reactor cycle) and for fully withdrawn absorber rods gives an excess reactivity of about 1.5 % and that the maximum fission (and power, respectively) density in the outer fission region (\( \hat{\rho}_{11} \)) is about 10 % above the maximum fission density of the inner fission region (\( \hat{\rho}_1 \)).

It was found \( \therefore \) that with increasing burn-up from 18,000 to 37,000 MWD/tonne, which corresponds to a reactor cycle of 175 days, the ratio \( \hat{\rho}_{11}/\hat{\rho}_1 \) will decrease by about 10 %. Also, if we start up the reactor with 10 % more maximum power density in the outer fission region, the maximum power density in fission zone I and II will be about the same at the end of the reactor cycle.

We calculated that for \( y_1 = 9.74 \) and \( y_{11} = 7.38 \) the above requirements are fulfilled.

For all two-dimensional calculations, we decided to condense the 26 energy groups into a 5-group set. For the condensation spectra we take for each new calculation the 26-group spectra of the corresponding zone obtained from the one-dimensional problem.
The condensation into the 5 groups for all two-dimensional calculations is as follows:

<table>
<thead>
<tr>
<th>5-group set</th>
<th>group nr.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>26-group set</td>
<td>group nr.</td>
<td>1-5</td>
<td>6-11</td>
<td>12-18</td>
<td>19-24</td>
<td>25-26</td>
</tr>
</tbody>
</table>

3.3.3. Results.

In Table 3.3, the numerical results of the two-dimensional (r-z) calculations are given. 

\( N_1 \) and \( N_2 \) are the numbers of \( B_4C \) rods which will be inserted in the inner ring and the outer ring. The quantities \( z_1 \) and \( z_2 \) are the inserted depths of the absorber rods in the core to obtain a critical reactor. The normalization of the values in Table 3.3, is such that \( \int dV \sum_{f} dE = 1 \) fissions/sec over the total volume of the reactor. 

The quantity \( \hat{P}_{\text{extr}} \) means the estimated maximum fission density at the interface of the first and the second fission zone which may be extrapolated from the fission distribution in the second fission zone. It also represents the maximum fission density between the control rods of the outer ring. (Analogous to the azimuthal fission distribution between the control rods in the (r-\( \theta \)) calculations.)

The results of the (r-\( \theta \)) calculations are given in Table 3.4. In the same way as in the one-dimensional calculations the volume integration of the fission density in the (r-\( \theta \)) geometry is over a core height of 1 cm.

With respect to the fission distribution we calculated for each fission zone and for the total core the maximum fission density, the average fission density and the power factor, which was defined as the ratio of maximum-to-average fission density.

To compare the results, Table 3.3 contains also some numerical values of the reactor with the absorber rods withdrawn. It can be seen that the reactor with the rods withdrawn gives an excess reactivity of about 1.4% in the (r-z) geometry and an excess reactivity of 1.6% in the (r-\( \theta \)) geometry.
The value $k_{\text{eff}}(z_1, z_2=100 \text{ cm})$ in Table 3.3. means the reactivity of the reactor if all rods of the corresponding configuration are fully inserted (i.e. 100 cm active absorber length in the core).

If we compare the configurations in which 6 control rods are inserted, we see that the configuration with the most favourable fission distribution (low value of the power factor of the total core $\frac{\hat{P}_{I+II}}{\tilde{P}_{I+II}}$) also has a high value of the control rod worth. It is seen that the configuration of 3 rods inserted in the inner ring and 3 rods inserted in the outer ring has the most favourable value of $\frac{\hat{P}_{I+II}}{\tilde{P}_{I+II}}$. Next will be the configuration with only 6 rods inserted in the outer ring.

To show the shifting of the spatial fission distributions arising from the insertion of absorber rods into the core we drew the two-dimensional fission distributions for the reactor with the control rods withdrawn and for those two possible control rod configurations which have the best fission distribution for the critical reactor; see Fig. 3.6. to Fig. 3.10. It is easy to see that the maximum fission density changes to the lower part of the core.

The azimuthal fission distribution between the control rods (especially in the second ring) is expressed in Fig. 3.11 to Fig. 3.13. It is seen that the fission density close to the $\text{Al}_2\text{O}_3$ follower rods increases, which is not the case with $\text{B}_4\text{C}$ absorber rods. This is due to the following effect: $\text{Al}_2\text{O}_3$ is a weak neutron absorber but a good scatterer, so it is expected and verified that around the $\text{Al}_2\text{O}_3$ rods the spectrum will be softer than elsewhere in the core. ($\text{Al}_2\text{O}_3$ acts as a moderator.). Because the fission rate increases for lower neutron energy, the fission density near the $\text{Al}_2\text{O}_3$ will be higher therefore.

In Fig. 3.5, finally, we plotted the results $\Delta k(z)/\Delta k(H)$ of the two-dimensional ($r$-$z$) calculations. The agreement with the curve from first-order perturbation theory is very good.
To underline once more the importance of the fission distribution we calculated, for example, the savings in power generation costs for the two most favourable control rod configurations with respect to the arbitrary configuration of 6 rods inserted in the inner ring to a depth of 78 cm.

The savings for the configuration of $N_1=3, N_2=3$ to a depth of 74 cm is about $DM\ 11.10^6$ a year.

For the configuration with only 6 rods inserted in the outer ring the savings will be about $DM\ 9.10^6$ a year.

Finally, it is seen from Table 3.3 that the breeding ratio B.R. varies not so strongly as a function of the method of reactor control. The B.R. is defined here as the ratio of the integral capture rate in the fertile material to the capture and fission rate in the fissile material. (The integration is over the total volume of the reactor).

We have to be careful to compare these results of the two-dimensional calculations for the critical reactor with the results of the one-dimensional calculations because the two-dimensional calculations have two different starting points compared to the one-dimensional calculations. These differences will be explained below:

To simulate the power distribution of the condition of lowest burn-up, which occurs after reloading of fuel elements, the fuel enrichments in the core were chosen in such a way for the two-dimensional calculations as to make the maximum power density in zone II 10% higher than the maximum power density in zone I. The result is that the ratio of the fuel enrichment in zone II to that in zone I is higher than the ratio used in the one-dimensional calculations. So, the power factor for the unperturbed reactor is higher for the two-dimensional geometry.

The next point is connected with the fact that in the two-dimensional calculations of this chapter we always used the configuration of 6 control elements on a inner ring and 12 control elements at the interface of zone I-zoneII. In the one-dimensional calculations, however, only for a few cases a ring of 12 control elements was present at the interface of zone I-zone II. Exchanging fuel rods by either control or follower...
rods at this position greatly influences the power distribution. Because the maximum power density occurs at the interface zone I-zone II in most cases the power factor is influenced also. So, care must be taken in the comparison of the two-dimensional results of this chapter with the one-dimensional results of the preceding chapter.

The (r-z) and (r-θ) calculations are very useful to show the tendencies of the reactivity worth and fission distribution. To determine more realistic absolute values of the shutdown reactivity and control rod worth, proper three-dimensional calculations will be preferable.
### Table 3.3 (r-z) Geometry. Critical reactor with partially inserted control rods.

<table>
<thead>
<tr>
<th>(N_1)</th>
<th>(N_2)</th>
<th>Zone 1 (\vec{P} = \int \Sigma_t \phi , dE) max</th>
<th>Zone I (\int dV \int \Sigma_t \phi , dE)</th>
<th>Zone II (\int dV \int \Sigma_t \phi , dE)</th>
<th>Zone III (\int dV \int \Sigma_t \phi , dE)</th>
<th>(\frac{\vec{P}_{1}}{P_I})</th>
<th>(\frac{\vec{P}<em>{II}}{P</em>{II}})</th>
<th>(\frac{\vec{P}<em>{I+II}}{P</em>{I+II}})</th>
<th>(B_nR_e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>74</td>
<td>1.857 \times 10^{-7}</td>
<td>1.842 \times 10^{-7}</td>
<td>2.025 \times 10^{-7}</td>
<td>0.4720</td>
<td>0.4404</td>
<td>0.0629</td>
<td>1.719</td>
<td>1.932</td>
</tr>
<tr>
<td>0</td>
<td>73</td>
<td>2.058 \times 10^{-7}</td>
<td>1.793 \times 10^{-7}</td>
<td>1.992 \times 10^{-7}</td>
<td>0.5030</td>
<td>0.4128</td>
<td>0.0591</td>
<td>1.612</td>
<td>2.030</td>
</tr>
<tr>
<td>6</td>
<td>51</td>
<td>1.856 \times 10^{-7}</td>
<td>1.952 \times 10^{-7}</td>
<td>2.404 \times 10^{-7}</td>
<td>0.4640</td>
<td>0.4488</td>
<td>0.0639</td>
<td>1.574</td>
<td>1.971</td>
</tr>
<tr>
<td>6</td>
<td>78</td>
<td>1.674 \times 10^{-7}</td>
<td>1.948 \times 10^{-7}</td>
<td>2.150 \times 10^{-7}</td>
<td>0.4217</td>
<td>0.4849</td>
<td>0.0687</td>
<td>1.569</td>
<td>1.823</td>
</tr>
<tr>
<td>0</td>
<td>9</td>
<td>2.078 \times 10^{-7}</td>
<td>1.849 \times 10^{-7}</td>
<td>2.038 \times 10^{-7}</td>
<td>0.5046</td>
<td>0.4118</td>
<td>0.0590</td>
<td>1.626</td>
<td>2.085</td>
</tr>
<tr>
<td>all rods out</td>
<td>k=1.0140</td>
<td>1.730 \times 10^{-7}</td>
<td>1.791 \times 10^{-7}</td>
<td>1.960 \times 10^{-7}</td>
<td>0.4742</td>
<td>0.4417</td>
<td>0.0604</td>
<td>1.435</td>
<td>1.868</td>
</tr>
</tbody>
</table>

Normalization: \(\int dV \int \Sigma_t \phi \, dE = 1 \) (fissions/sec).

### Table 3.4 (r-\(\theta\)) Geometry. With fully inserted control rods.

<table>
<thead>
<tr>
<th>(N_1)</th>
<th>(N_2)</th>
<th>(k_{\text{eff}})</th>
<th>(\vec{P} = \int \Sigma_t \phi , dE) max</th>
<th>Zone I (\int dV \int \Sigma_t \phi , dE)</th>
<th>Zone II (\int dV \int \Sigma_t \phi , dE)</th>
<th>Zone III (\int dV \int \Sigma_t \phi , dE)</th>
<th>(\frac{\vec{P}_{1}}{P_I})</th>
<th>(\frac{\vec{P}<em>{II}}{P</em>{II}})</th>
<th>(\frac{\vec{P}<em>{I+II}}{P</em>{I+II}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1.0159</td>
<td>1.959 \times 10^{-5}</td>
<td>2.270 \times 10^{-5}</td>
<td>0.4861</td>
<td>0.4580</td>
<td>0.0569</td>
<td>1.060</td>
<td>1.391</td>
</tr>
<tr>
<td>0</td>
<td>6</td>
<td>0.9969</td>
<td>2.324 \times 10^{-5}</td>
<td>2.320 \times 10^{-5}</td>
<td>0.5174</td>
<td>0.4268</td>
<td>0.0558</td>
<td>1.217</td>
<td>1.523</td>
</tr>
<tr>
<td>0</td>
<td>9</td>
<td>0.9888</td>
<td>2.662 \times 10^{-5}</td>
<td>2.558 \times 10^{-5}</td>
<td>0.5373</td>
<td>0.4082</td>
<td>0.0545</td>
<td>1.303</td>
<td>1.753</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.9972</td>
<td>2.035 \times 10^{-5}</td>
<td>2.430 \times 10^{-5}</td>
<td>0.4181</td>
<td>0.5149</td>
<td>0.0670</td>
<td>1.277</td>
<td>1.322</td>
</tr>
</tbody>
</table>

Normalization: \(\int 2\pi r \, dr \int \Sigma_t \phi \, dE = 1 \) (fissions/sec).
4. Conclusion.

As we have seen before, this investigation had two purposes. The conclusion of Chapter 2 is that the optimum location for maximum shutdown reactivity of a single or two rings of absorber elements can be determined very well by one-dimensional calculations. For the cases studied it was further seen that the configuration with maximum control rod worth for the absorber rings also has a favourable fission distribution. The two-dimensional (r-θ) calculations showed that we have to perform the calculations in a better geometric arrangement to determine more accurately the absolute values of the control rod worths.

The examples of Chapter 3 showed that it is desirable to determine that special location and insertion depth of the shim rods for which it is possible to maintain the reactor critical with the most favourable fission distribution. The (r-z) calculations show (Table 3.3) that the insertion of three rods in the inner ring and three rods in the outer ring results in the best fission distribution, but the difference to the case of six rods inserted in the outer ring is not so pronounced.
Acknowledgement.

The author would like to thank Prof. K. Wirtz for the opportunity to complete this study at the Institute of Neutron Physics and Reactor Engineering. In particular, I am grateful to Dr. E. Kiefhaber for the many valuable discussions and advice in all phases of the investigation. I would like to thank everybody at Karlsruhe who helped making my stay in Germany instructive and rewarding.

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Case: $R_1(N_1=6)=43.0$, $R_2(N_2=12)=86.0$ cm.

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Case: $R_1(N_1=6)=43.0$, $R_2(N_2=12)=97.0$ cm.

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Case: $R_1(N_1=6)=43.0$, $R_2(N_2=12)=97.0$ cm.

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Case: $R_1(N_1=6)=43.0$, $R_2(N_2=12)=97.0$ cm.

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Case: All absorber rods withdrawn.

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Neutron energy spectrum for the reactor without control elements.
Radial dependence of the microscopic capture rate of Bi.

Zone I

Zone II

Zone III

Blanket
Volume integrated capture rate of $D^{10}$ as function of the neutron energy for the unperturbed reactor.

$\int E_i dN$
Neutron fission weight as function of the radius for the unperturbed reactor.
Fig. 26

Reactivity worth per control element as function of the radius of one cylindrical absorber ring.
Radial dependence of the capture rate of $\beta^+$ for the reactor with one absorber ring of radius $R = 45.0$ cm.

$$\sigma^+ = \int \sigma^+ d\alpha$$
Radial dependence of the capture rate of $\beta$ for the reactor with one absorber: $8.45$ m.
Radial dependence of the capture rate of $6\%$ for the reactor with one absorber ring of radius $R = 86.0$ cm.
Radial dependence of the capture rate of $\beta^+$ for the reactor with one absorber ring of radius $R = 97.0$ cm.
Eine Achse logarithmisch geteilt von 1 bis 1000, Einheit 90 mm, die andere in mm
Radial dependence of the fission rate for the reactor with one absorber.

\[ \beta = \sum \rho \Delta \text{tube ring of radius } R = 64.5 \text{ cm.} \]
Radial dependence of the fission rate for the reactor with one absorber ring of radius $R = 270$ cm:

$$\beta = \int_{0}^{\infty} \varepsilon f(s) \phi(r) \, ds$$

$N = 12$
Radial power factor as function of the absorber ring radius.
Fig. 2.16

Radial distance of the reactor wall for the capture ratio of B to U.

Absorber rings:
- N (B) = 0.01 m
- N (U) = 0.01 m

Absorber rings: Case: B(U)0 = U0.

Eine Achse logar. geteilt von 1 bis 1000. Einheit 90 mm, die andere in mm.
Radial dependence of the fission rate for the reactor with two absorber rings.

\[ \rho = \int_{0}^{1} (1 - e^{\lambda r}) \, dr \]

Case: \( R_1 (N_1 = 6) = 430 \text{ cm} \)
\( R_2 (N_2 = 11) = 260 \text{ cm} \)
Radial dependence of the capture rate of $\beta_0$ for the reactor with two absorber rings: $R_2(\alpha=0) = 120$ cm.
Radial dependence of the capture rate of $\beta^{10}$ for the reactor with two absorber rings.

Case 1: $R_1 = 64.5$ cm, $R_2 = 970$ cm

$\sigma = \int \sigma^{e^{10}} \varphi(r) dr$

- $N_1 = 6, N_2 = 12$
- $N_1 = 9, N_2 = 9$
Ratio of the reactivity worths from direct calculations and perturbation theory as function of the radius of the inner absorber ring.

\( R_1(N_1=6) \) variable, \( R_2(N_2=12) = 970 \text{ cm} \)

\[
\frac{\Delta k_{12}}{\Delta k_{\text{exact}}} = \frac{\sigma_{\text{eff}}^*(2)}{\sigma_{\text{eff}}^*(2)} - 1
\]

\[
\Delta k_{12} = \frac{\phi_{\text{eff}}^*(2)}{\phi_{\text{eff}}^*(2)} - 1
\]

\[
\Delta l_{12} = \frac{F_1 \phi_{\text{eff}}^*(2)}{F_2 \phi_{\text{eff}}^*(2)} - 1
\]

Graph showing the relationship between the radius of the inner absorber ring and the ratio of reactivity worths.
Total reactivity worth for the reactor configuration of two cylindrical control rings as a function of the radius of the inner absorber ring.

1) Ring Thickness 11 cm
2) Ring Thickness 5 cm

$R_1(N=6)$ = variable
$R_2(N=12)$ = interface zone I-II
Comparison of the capture rate of $\theta^4$ from direct two-ring results and single ring calculations

Case: $R_1 (N_1 = 6) = 170 \text{ cm}$

$R_2 (N_2 = 12) = 970 \text{ cm}$
Comparison of the neutron fission weight from direct two-ring results and single ring calculations.

Case: $P_1$ ($N = 6$) = 450 cm
$P_2$ ($N = 12$) = 970 cm
Calculated reactivity worth as function of the radius of the inner absorber ring.

Case: \( N_1 = 6 \)
\( N_2 = 12 \)

\( \Delta k_{12} \)

- \( R_2 = 75.0 \text{ cm} \)
- \( R_2 = 85.0 \text{ cm} \)
- \( R_2 = 97.0 \text{ cm} \)
- \( R_2 = 110.0 \text{ cm} \)

\[ \Delta k_{12} = \frac{\phi_1^*(R_2) \phi_1^*(R_2) \Delta k_1 + \phi_2^*(R_2) \phi_2^*(R_2) \Delta k_2}{\phi_0^*(R_2) \phi_0^*(R_2) \phi_0^*(R_2) \phi_0^*(R_2)} \]

Radius of Inner Absorber Ring \( R_2 \) (cm)
Calculated reactivity
worth as function of
the radius of the
inner absorber ring.

Case 1: \( \frac{1}{\tau_2} = 9 \)
\( \frac{1}{\tau_1} = 9 \)

\[ \Delta k = \frac{d^3 \phi_1}{d^3 \phi_2} \phi_2 \Delta k_1 + \frac{d^3 \phi_2}{d^3 \phi_2} \phi_2 \Delta k_2 \]

Radius of Inner Absorber Ring: \( R_2 \text{ (cm)} \)
Reactivity worth as function of the outer absorber ring radius ($R_2$) for the optimum value of the inner absorber ring.
Optimum radius of the inner absorber ring as function of the location of the outer absorber ring.

Radius of Outer Absorber Ring \( R_2 \) (cm)

- \( N_1 = 6, N_2 = 12 \)
- \( N_1 = 9, N_2 = 9 \)
Total reactivity worth and integral capture rate of homogeneous absorber rings as function of the ring thickness.

(From one-dimensional calculations)
Reactivity worth of 18 control rods as function of the control rod perimeter. (From two-dimensional (r-z) calculation)
Radial fission distribution in two-dimensional (r-θ) geometry for the reactor with all control rods inserted.

\[ \rho = \frac{1}{\theta} \int \phi \, d\theta \]

\[ \theta = 0 \]
\[ \theta = \pi/12 \]
\[ \theta = \pi/6 \]

\[ \theta = \pi/12 \]
\[ \theta = \pi/6 \]

- Absorber Rod
Reactivity worth as function of the inserted absorber depth.

\[
\frac{\Delta k(z)}{\Delta k(H)}
\]

\(H = 100\,\text{cm}\)

1) From First Order Perturbation Theory

2) From One-Dimensional Axis Calculations

\((r=2)\) Calculations:

\(N_r(z_1)\), \(N_r(z_2)\)

- \(d(z_2)\)
- \(e(z_1)\), \(e(z_2)\)
- \(f(z_2)\)
- \(g(z_3)\)
- \(h(z_4)\)

\(z = \text{Inserted Depth of Absorber Rods}\) (cm from top of core)
Radial fission distribution in (r-z) geometry for the critical reactor with 6 control rods inserted in the outer ring to a depth of 73 cm.

\[ f = \int f(r,z) \, dr \]

\( r = 50 \text{ cm} \)
\( r = 85 \text{ cm} \)
\( r = 110 \text{ cm} \)

(\( z = \text{distance from top of the core} \))
Two-dimensional fission distribution for the reactor in (r-z) geometry with all absorber rods withdrawn.

\[ \rho = \frac{1}{2} (x_0)^2 10^{-6} \text{ fissions/cm}^2 \text{ sec} \]

Normalization \( \frac{dN}{d^2 r d \rho} = \frac{270}{2 \pi} \text{ fissions/sec} \)
Two-dimensional fission distribution

for the critical reactor in (r-z) geometry.

Case 1:

\[ N_1 (z=74) = 2, \quad N_2 (z=74) = 3 \]

\[ f = \left( \frac{a}{2} \right) \frac{d \alpha}{d \omega} \left( \text{fissions/sec} \right) \]

Normalization: \( \int_{\alpha} f d \alpha = 1 \)

\( \text{fissions/sec} \)
Mission distribution as function of the azimuthal angle, for different radii.

Case: \( N_1 = 0, N_2 = 6 \)
Two-dimensional fission distribution in (r-θ) geometry.

Case: \( N_1 = 6, N_2 = 0 \)

\[ p = \int \theta \cdot d(\theta) \cdot d\theta \]

\( (\text{ft}^2\text{fissions/sec}) \)

- \( \text{ByC Absorber Rod} \)
- \( \text{PuF}_3 \text{ Follower} \)

Diagram showing the distribution with zones and angles.