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# Design criteria and preliminary calculations of SEFOR second and third cores*

by

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with thirty figures in the text

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## Abstract

The design criteria for the SEFOR second and for a possible third cores have been analyzed.

Scope of the "SEFOR second core" is the measurement of the Doppler coefficient at high fuel temperatures with a Pu enrichment similar to that of a power reactor and with a neutron spectrum harder than that of the SEFOR first core. Scope of the possibly envisaged "SEFOR third core" is to test fuel elements and fuel assemblies at the same design conditions as those chosen for the 1000 MW Sodium cooled reference reactor. The SEFOR third core would consist of a "Test Zone" and a "Driver Zone". In the "Test Zone" fuel elements and the fuel assemblies would be tested. The functions of the "Driver Zone" are to make the whole reactor critical and the Doppler Coefficient negative and big.

Two different core design types for the SEFOR third core have been developed.

(a) First design type in which the fuel rods of the SEFOR second core have been used in the "Driver Zone".

(b) Second design type in which the fuel rods of the "Driver Zone" are different from those of the SEFOR second core and are designed and built only with the purpose to fill the "Driver Zone".

The designs of both SEFOR second and third cores described in this paper are only speculative and must not be intended as a final proposal.

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## 1. Introduction

Scope of the SEFOR second core is the measurement of the Doppler coefficient at high fuel temperatures with a Pu enrichment similar to that of a power reactor and with a neutron spectrum harder than that of the SEFOR first core.

Scope of the SEFOR third core is to test fuel elements and fuel assemblies at the same design conditions as those chosen for the 1000 MW Sodium cooled reference reactor.

The SEFOR third core will consist of a "Test Zone" and a "Driver Zone". In the "Test Zone" the fuel elements and fuel assemblies will be tested. The functions of the "Driver Zone" are to make the whole reactor critical and the Doppler coefficient negative and big.

The designs of both second and third cores described in this paper are only speculative and must not be intended as a final proposal.

## 2. SEFOR second core

### 2.1 Design Criteria

As mentioned in the introduction, the scope of the SEFOR second core is the measurement of the Doppler coefficient at high fuel temperatures and with a Pu enrichment similar to that of a power reactor and a neutron spectrum harder than that of the SEFOR first core. For this last reason the SEFOR second core will have no BeO.

The choice of the main core parameters depends upon geometric, nuclear and thermodynamic considerations.

The second core will be placed in the already designed SEFOR plant.

The fuel rods will fill the hexagonal cells shown in fig. 1. The parameters which must be determined are the following:

1 N = Number of fuel rods in an hexagonal cell

2 R = Radius of the fuel pellets

3 $\eta_f$ = Fuel volume fraction

4 $\eta_{st}$ = Steel volume fraction

5 $\eta_{Na}$ = Sodium volume fraction

6 e = Pu-239 enrichment

7 $\Delta p_a$ = Total pressure drop in the primary coolant circuit

8 $\Delta p_b$ = Pressure drop in the circuit external to the core

9 $\Delta p_c$ = Pressure drop in the core

10 v = Average sodium speed in core

11 g = Coolant volume flow

In fixing these parameters, we have to keep in mind the following relationships.

Geometric equations

$$\eta_f + \eta_{Na} + \eta_{st} = 1 \qquad (1)$$

$$\eta_{st} = \frac{6ls}{\frac{3\sqrt{3}}{2} l^2 + 6ls} + \eta_f \frac{2t}{R} = B + \frac{2t}{R} \eta_f \tag{2}$$

$$\eta_f = N \frac{\pi R^2}{A} \tag{3}$$

$$g = \eta_{Na} vS \tag{4}$$

where:

$l$ = side length of the hexagonal core cell = 4.52 cm

$s$ = wall thickness of the hexagonal cell = 0.15 cm

$t$ = cladding wall thickness = 0.13 cm

$A$ = area of the hexagonal cell cross section = 53.21 $cm^2$

$$B = \frac{6ls}{\frac{3\sqrt{3}}{2} l^2 + 6ls} = 0.078 \tag{3'}$$

$S$ = total core cross section = 5800 $cm^2$

<u>Power density in fuel rods</u>

$$p = 2 \frac{T - \bar{\Theta}}{\beta_{loc}\beta_{ax}\beta_{rad}} \frac{1}{\frac{R}{h} + R^2/2\lambda} \tag{5}$$

where

$p$ = fuel power density

$T$ = maximum fuel temperature

$\bar{\Theta}$ = average coolant temperature

$\beta_{ax}$ = axial hot spot factor

$\beta_{rad}$ = radial hot spot factor

$\beta_{loc}$ = local hot spot factor

$h$ = Fuel-Sodium heat transfer coefficient (including the cladding) = = 0.6 Watt/$cm^2$ $^oC$

$\lambda$ = Fuel thermal conductivity = 0.038 Watt/cm $^oC$

Coolant temperature rise in the core

$$\theta_o - \theta_i = \frac{H}{c\rho} \frac{\eta_f P}{\eta_{Na} v} \tag{6}$$

where

$\theta_o$ = average outlet coolant temperature

$\theta_i$ = inlet coolant temperature = 370°C

H = height of the active core = 85.85 cm

c = Sodium specific heat capacity = 1.277 $\frac{\text{Watt sec}}{\text{gr °C}}$

$\rho$ = Sodium density = 0.86 gr/cm$^3$

Pressure drop in an hexagonal cell (see Appendix 1)

$$\frac{\Delta p_c}{v_o^{1.8}} = F \left[ \frac{\frac{C(1-\eta_{Na})-D}{R} + E}{2\eta_{Na} C} \right]^{1.2} \tag{7}$$

where

$F = 2\ k\ \rho^{0.8} \mu^{0.2} L$ = const.

$\mu$ = Sodium viscosity = $2.895 \cdot 10^{-3}$ $\frac{\text{gr sec}}{\text{cm}^2}$ (7')

L = height of the hexagonal cell = 269 cm

R' = fuel rods radius = R + t (7'')

$C = 2\left(\frac{3\sqrt{3}}{2}\ l^2 + 61s\right)$ = const (7''')

D = 12 ls = const

E = 61 = const (7'''')

Fig. 3 gives $\frac{\Delta p_c}{v^{1.8}}$ as function of $\eta_{Na}$ for different values of R' (7''''')

Total pressure drop

$$\Delta p_a = \Delta p_b + \Delta p_c \tag{8}$$

Equation of the pump

$$\Delta p_a = f(g) \tag{9}$$

Fig. 4 gives the characteristic of the pump

Pressure drop in the circuit external to the core

$$\Delta p_b = Q\, g^{1.8} \tag{10}$$

where:

$Q$ = constant coefficient

Fig. 4 shows also "$\Delta p_b$" as function of "g"

Criticality condition

$$k_{eff} = 1 \tag{11}$$

Fig. 5 shows the Pu enrichment "e" as function of the fuel volume fraction "$\eta_f$" for which condition 11 is satisfied. Looking at fig. 5, condition 11 can also be written

$$e\eta_f = \alpha = \text{const} \tag{11'}$$

Doppler coefficient

$$T \frac{dk}{dT} \text{ negative and as big as possible.} \tag{12}$$

From eqs. 1 and 2 eliminating $\eta_{st}$, we get

$$\eta_f = \frac{1-B-\eta_{Na}}{1+\frac{2t}{R}} \tag{13}$$

From eqs. 6, 7, 8 and 9 eliminating $\Delta p_c$; $\Delta p_b$ and v, we get:

$$\frac{\Delta p_a - Qg^{1.8}}{(g/S)^{1.8}} = \frac{F}{\eta_{Na}^{3}} \left[\frac{C(1-\eta_{Na})-D}{2C(R+t)} + \frac{E}{2C}\right]^{1.2} \tag{14}$$

Fig. 4 shows the pump characteristic "$\Delta p_a$" (that is eq. 8) and the pressure drop in the circuit external to the core (that is eq. 9) as functions of "g". From this figure we can obtain the minimum value $g_o$ and the associated value of $\left[\Delta p_a - Qg^{1.8}\right]_o$ beyond which the pump is unstable. If we put these two values in the first part of eq. 14, we get the minimum value of Sodium volume fraction, $\eta_{Na}$, which must be present in the core in order to be sure that the pump functions in the stable region.

$$(\eta_{Na})_{1min} = \sqrt[3]{\frac{F}{K_o}} \left[\frac{C[1-(\eta_{Na})_{1min}-]-D}{2C(R+t)} + \frac{E}{2C}\right]^{0.4} \tag{15}$$

where:

$$K_o = \frac{(\Delta p_a - Qg^{1.8})_o}{g_o/S} \tag{16}$$

If in eq. 13 we use $(\eta_{Na})_{min}$, we get

$$\eta_{f\ 1max} = \frac{1-B-(\eta_{Na})_{1min}}{1+\frac{2t}{R}} \tag{17}$$

Eqs. 15 and 17 can be used to determine in the plane $\eta_f$; R the first limiting curve

$$(\eta_f)_{1max} = f(R) \tag{18}$$

This curve is shown in fig. 6 (curve SM). We can conclude that, due to the limitations of the pump stability, the design point of the SEFOR second core must lie under the curve SM in fig. 6.

Eliminating "p" and $\eta_{Na}v$ among eqs. 4, 5 and 6 we get:

$$\eta_f = \frac{c\rho}{H} \frac{\beta_{loc}\ \beta_{rad}\ \beta_{ax}}{2} \frac{\theta_o - \theta_i}{T-\bar{\theta}} \frac{g}{S} \left(\frac{R}{S} + \frac{R^2}{2\lambda}\right) \tag{19}$$

A maximum allowable value $(\theta_o - \theta_i)_{max}$ can be fixed on the basis of the limitations due to mechanical stresses in the core structures.
It must be:

$$(\theta_o - \theta_i) < (\theta_o - \theta_i)_{max} = 80^{\circ}C \tag{20}$$

On the other hand the value of $T-\bar{\theta}$ can be fixed keeping in mind that it must be the maximum possible compatibly with fuel melting because one of the scopes of the SEFOR second core is to measure the Doppler coefficient at high fuel temperatures.

We can therefore define a second limiting curve $(\eta_f)_{2max}$ so defined

$$(\eta_f)_{2max} = \gamma\ g \left(\frac{R}{h} + \frac{R^2}{2\lambda}\right) \tag{21}$$

where:

$$\gamma = \frac{\rho c}{HS} \frac{\beta_{loc}\ \beta_{ax}\ \beta_{rad}}{2} \frac{(\Theta_o - \Theta_i)_{max}}{T - \bar{\Theta}} = 9.24 \cdot 10^{-8} \frac{\text{Watt sec}}{cm^6\ {}^oC} \tag{22}$$

is a constant.

Eq. 21 associated to eqs. 9 (pump characteristic), 13 and 14 allows to calculate the second limiting curve OABM in fig. 6.

$$(\eta_f)_{2max} = f(R) \tag{23}$$

In other words, if we want that the coolant temperature rise in the core does not exceed the limit set by (20) and that the maximum fuel temperature is that specified by the scope of the SEFOR second core, the design point of the SEFOR second core must lie under the curve OABM in fig. 6.

Fig. 6 shows also the curves

$$\eta_f = N \frac{\pi R^2}{A} \tag{24}$$

with N = constant and entire.

The design point must lie on one of these curves.

Fig. 7 shows an hexagonal channel with seven fuel rods in it.

In fig. 6 the vertical line CB represents the fuel pellets radius at which the fuel rods would touch each other inside the hexagonal channel in the cases N=6 and 7.

From fig. 5, which shows the necessary Pu enrichment as function of $\eta_f$ to get the reactor critical, we can fix a minimum value of $\eta_f$. This minimum value is set on the basis that the Pu enrichment must not be much higher than the usual values of the power reactors and on the fact that high Pu enrichments makes the Doppler coefficient small.

In fig. 6 the horizontal line AC represents the minimum allowable value of $\eta_f$ due to the considerations on the maximum allowable Pu enrichment. The triangle ABC delimits the design locus. In other words, if we want to satisfy the experimental purposes of the SEFOR second core together with all the other restrictions which have been analysed, the design point must lie inside the triangle ABC of fig. 6.

On the other hand, since the number of fuel rods in an hexagonal channel must be entire, the design point must lie on one of the curves N = const shown in fig. 6.

Looking at fig. 6 we can conclude that the radius of the fuel pellets cannot be too different from that of the pellets of the first core (R = 1.13 cm).

## 2.2 Choice of the main parameters

In the preceding paragraph we have concluded that the design point of the SEFOR second core must lie inside the triangle ABC shown in fig. 6 and on one of the curves N=const. In para 4.1 we shall see that, for the later use of the fuel rods of the SEFOR second core in the "Driver Zone" of the SEFOR third core, it is advantageous to choose N as big as possible.

Looking at fig. 6, we choose therefore

$$N = 7 \tag{1}$$

In para 4.1 we shall see (for the same reasons as stated above) that it is convenient to choose the fuel pellets radius as small as possible. However, we shall also see that this last requirement gives practically a negligible advantage.

We choose

$$R = 1.13 \text{ cm} \tag{2}$$

Taking into account 1 and 2, from fig. 6, we get

$$\eta_f = 0.53 \tag{3}$$

From eq. 2 of para 2.1 we get

$$\eta_{st} = 0.20 \tag{4}$$

and from eq. 1 of para 2.1

$$\eta_{Na} = 0.27 \tag{5}$$

From fig. 5, taking into account 3, we get

$$e = 0.13 \tag{6}$$

The Doppler coefficient, $T \frac{dk}{dT}$, has been calculated

$$T \frac{dk}{dT} = - 0.00733 \tag{7}$$

The fuel rod radius, R', is given by

$$R' = R + t = 1.13 + 0.13 = 1.26 \text{ cm} \tag{8}$$

We take the value

$$\frac{\Delta p_c}{v^{1.8}} = 15 \frac{\text{dyne/cm}^2}{(\text{cm/sec})^{1.8}} \tag{9}$$

which is higher than that obtainable from fig. 3.

From fig. 4, taking into account (9), we have:

$$g \simeq 320 \cdot 10^3 \text{ cm}^3/\text{sec} \tag{10}$$

and

$$v = \frac{g}{\eta_{Na} S} = \frac{320 \cdot 10^3}{0.27 \cdot 5800} = \frac{320 \cdot 10^3}{1566} = 204 \text{ cm/sec} \tag{11}$$

From fig. 2, we get:

$$p\beta_{rad} \simeq 180 \text{ Watt/cm}^3 \tag{12}$$

Fig. 10 shows the power density distribution in the SEFOR second core.

From fig. 10 we get $\beta_{rad} = 1.8$ and therefore

$$p = \frac{180}{1.8} = 100 \text{ Watt/cm}^3 \tag{13}$$

From eq. 6 of para 2.1, we get

$$\Theta_o - \Theta_i = H \frac{\eta_f p}{\eta_{Na} v \cdot c\rho} = 85.85 \frac{0.53 \cdot 100}{0.27 \cdot 204 \cdot 1.277 \cdot 0.86} \simeq 75^\circ\text{C} \tag{14}$$

The total power, $P_r$, produced in the core will be:

$$P_t = HS\eta_f p = 85.85 \cdot 5800 \cdot 0.53 \cdot 100 \simeq 26 \text{ MW} \tag{15}$$

Fig. 11 shows the flux spectrum at an intermediate point.

## 2.3 Characteristics of the SEFOR second core

Here the main characteristics of the proposed SEFOR second core are given:

1. General Core Characteristics

| | |
|---|---|
| core type | 1 zone, fast neutron |
| fuel | mixed $PuO_2$-$UO_2$ |
| coolant | Sodium |
| Power output | 26 Mwatt |
| Purpose of the core | measurements of doppler coefficient at high fuel temperatures |

## 2. Core description

2.1 Geometry

| | | |
|---|---|---|
| height of the active core | 85.85 cm | |
| core diameter | 92.48 cm | |
| number of channels | 109 | |
| type of channels | hexagonal | |

2.2 Physics data

| | | |
|---|---|---|
| volume fraction of fuel | 0.53 | |
| volume fraction of Sodium | 0.27 | |
| volume fraction of steel | 0.20 | |
| nuclear composition of the fuel | Pu-239 | 0.13 |
| | Pu-240 | 0.012 |
| | U-238 | 0.858 |

## 3. Control

$K_{eff}$ of the clean reactor 1.014839

Doppler coefficient $T\,\frac{dk}{dT} = -\,0.00733$

## 4. Thermal hydraulic design

4.1 maximum fuel temperature 2696°C

4.2 fuel power density average 100 Watt/cm$^3$

4.3 power shape factors

| | |
|---|---|
| axial factor | 1.24 |
| radial factor | 1.8 |
| local factor | 1.10 |
| total factor | 2.45 |

4.4 Coolant

| | |
|---|---|
| Core pressure drop | 0.219 at. |
| inlet temperature | 371°C |
| outlet temperature | 446°C |
| velocity | 204 cm/sec |

4.5

| | |
|---|---|
| Radius of fuel pellets | 1.13 cm |
| Radius of fuel rods | 1.26 cm |

## 3. Generalities on the SEFOR third core

Scope of the SEFOR third core is to test fuel elements and fuel assemblies at the same design conditions as those chosen for the 1000 MWe Sodium cooled reference reactor (Bibl. 1)

The fuel conditions which must be simulated are the following:

1. High Burn-up ($\sim 10^5$ MWday/ton)
2. Same maximum fuel power density ($p_{1max}$ = 3000 Watt/cm$^3$)
3. Same fuel rod radius ($R_1'$ = 0.3175 cm)
4. Same radius of fuel pellets ($R_1$ = 0.2794 cm)
5. Same Plutonium 239 enrichment ($e_1$ = 0.1835)
6. Same core composition
7. Similar neutron spectrum

Due to the limited cooling capabilities in SEFOR only part of the core can be loaded with fuel working at high power density similar to that of the 1000 MWe reference reactor. This part of the core will be called "test zone" or "first zone".

In order to get the reactor critical the second part of the core will be loaded with fuel working at low fuel power density. This part will be called "driver zone".

Since the "test zone" will function at high power density while the "driver zone" will function at low power density, it is necessary that the enrichment of the fissile material in the "test zone" should be much higher than that in the "driver zone".

In order to preserve the same physical and chemical fuel properties of the 1000 MWe reference design, the extra fissile material required in the "test zone" will be U-235.

Due to the high enrichment of fissile material in the "test zone", the Doppler coefficient of the "test zone" is expected to be positive. Purpose of the "driver zone" is also to make the total Doppler coefficient negative.

The core composition of the "test zone" has been chosen as follows:

$$\text{Sodium volume fraction } \eta_{Na1} = 0.47 \tag{1}$$

$$\text{Fuel volume fraction } \eta_{f1} = 0.34 \tag{2}$$

$$\text{Steel volume fraction } \eta_{st1} = 0.18 \tag{3}$$

Fig. 1 shows the arrangement of the core hexagonal channels.

The "test zone" will be situated at the central part of the core. It must be large enough to test a sufficient number of fuel rods, but not too large otherwise there would be cooling and safety problems.

Due to these considerations the number of reactor hexagonal channels filled with fuel rods to be tested has been chosen equal to seven.

According to Bibl. 2, in order to decrease the heat produced in the reflector, part of the external channels will be filled with steel rods.

In order to increase the cooling capabilities of the SEFOR third core, two electromagnetic Sodium pumps (instead of one) in series will be provided.

It has been suggested to try to load the "driver zone" with the fuel rods of the SEFOR second core.

Two different core design types have been therefore developed:

(a) First design type in which the fuel rods of the SEFOR second core have been used in the "Driver Zone"

(b) Second design type in which the fuel rods of the "driver zone" are different from those of the SEFOR second core, and are designed and built only with the purpose to fill the "driver zone" of the third SEFOR core.

In the next paragraphs both the design types of the third core will be described.

It is important to remind the following:

(a) In the SEFOR second core all the hexagonal channels are filled with fuel rods and there is only one Sodium pump in the primary circuit to cool the reactor.

(b) In both the design types of the SEFOR third core part of the external hexagonal channels will be filled with steel rods and the primary circuit will have two Sodium pumps in series.

## 4. SEFOR third core - First design type

### 4.1 Design criteria

In this paragraph we intend to examin the general design criteria of the SEFOR third core in the case in which the fuel rods of the SEFOR second core will fill the "Driver Zone" of the third core.

In addition we want to analyze what are the requirements for the design of the SEFOR second core dictated by the fact that the fuel rods of the SEFOR second core are intended to be used later in the "Driver-Zone" of the SEFOR third core.

Some results of this analysis have already been anticipated in para. 2.1. In the following equations subscript "1" refers to the "Test Zone" and subscript "3" refers to the "Driver Zone".

Using eq. 5 of para 2.1 we can write

$$T_3 - \bar{\theta}_3 = \frac{\beta_3}{2}\, p_3 \left(\frac{R_3}{h} + \frac{R_3^{\,2}}{2\lambda}\right) \tag{1}$$

where $\beta_3$ is the total hot spot factor.

Applying the one group diffusion theory for the neutron flux, we can write the following equation which compares power densities and fluxes in both the zones

$$\frac{p_1}{p_3} = \frac{e_1' \,\phi_1}{e_3\, \phi_3} \tag{2}$$

where

$\phi_i$ = average flux in zone "i"

$e_3$ = Pu-239 enrichment in the "Driver Zone"

$e_1'$ = equivalent Pu-239 enrichment in the "Test Zone"

In eq. 2 "$e_1'$" must be intended as an effective enrichment, because in the fuel rods of the "Test Zone" (as said in para 3) there will be two fissile materials: Pu-239 und U-235

Since the fuel rods of the "Driver Zone" must make the SEFOR second core critical, the following equation of the criticality of the SEFOR second core is valid (see eq. 11' of para 2.1):

$$\eta_f\, e_3 = \alpha = \text{const} \tag{3}$$

The following geometric relationship also exists (see eq. 3 of para 2.1)

$$\eta_{f3} = \frac{N_3 \ \pi \ R_3^{\ 2}}{A} \tag{4}$$

From eqs. 1; 2; 3 and 4 we get:

$$T_3 - \bar{\theta}_3 = \frac{\alpha A \beta_3 p_1}{2\pi} \ \frac{1}{e_1' \ N_3} \ \frac{\frac{R_3}{h} + \frac{R_3^{\ 2}}{2\lambda}}{R_3^{\ 2}} \ \frac{\phi_3}{\phi_1} \tag{5}$$

In order to avoid fuel melting in the "Driver Zone" it must be $T_3 - \theta_3$ as small as possible. Looking at eq. 5, we conclude that in order to satisfy this requirement it is convenient to adopt the following criteria

(a) Fissile materials enrichment, $e_1'$, in the "Test Zone" as high as possible.

(b) Number of fuel rods, $N_3$, in each hexagonal cell of the "Driver Zone" as high as possible (compatibly with the requirments of the design of the SEFOR second core).

(c) Radius of the fuel pellets, $R_3$, of the "Driver Zone" as small as possible (compatibly with the requirements of the design of the SEFOR second core).

(d) Ratio between the average fluxes $\frac{\phi_3}{\phi_1}$ of the "Driver Zone" and of the "Test Zone" as small as possible.

Criteria "C" is not very helpful because it is

$$\frac{R_3}{h} \ll \frac{R_3^{\ 2}}{2\lambda} \tag{6}$$

So that $T_3 - \theta_3$ is practically indipendent from the fuel pellets radius in the "Driver Zone".

A core which has the seven channels of the "Test Zone" filled with high enriched fuel and the remaining fillid with fuel rods of the SEFOR second core will be certainly supercritical.

To make the reactor critical it will be necessary either to reduce the dimensions of the core or to create an intermediate zone (between "Test Zone" and "Driver Zone") filled with non fissile material or with low enriched fuel rods.

Criterion "d" suggests to follow the second alternative.

On the basis of these considerations, it was therefore decided to divide the core in the following three zones:

1. Test Zone or First Zone
2. Intermediate Zone or Second Zone
3. Driver Zone or Third Zone

The position of the various zones in the core are shown in fig. 12.

It is convenient to fill the "Intermediate Zone" with low enriched fuel rods because in this way this zone will give a negative contribution to the Doppler coefficient of the whole reactor.

We now proceed to an analysis of the various parameters and of the various equations between these parameters.

The following parameters are already known:

Test Zone (Zone 1)

$e_1$ Pu-239 enrichment

$\eta_{f1}$ fuel volume fraction

$\eta_{st1}$ steel volume fraction

$\eta_{Na1}$ Natrium volume fraction

$S_1$ Cross section of zone 1

Driver Zone (Zone 3)

$e_3$ Pu-239 enrichment

$\eta_{f3}$ fuel volume fraction

$\eta_{st3}$ steel volume fraction

$\eta_{Na3}$ Natrium volume fraction

$R_3$ fuel pellets radius

The following parameters must be determined:

Test Zone (Zone 1)

1. $e_1^{235}$ = U-235 enrichment

2. $\Delta p_{c1}$ = Core pressure drop in Zone 1

3. $v_1$ = average coolant speed

Intermediate Zone (Zone 2)

4. $e_2^{235}$ = U-235 enrichment

5. $\eta_{f2}$ = fuel volume fraction

6. $\eta_{st2}$ = steel volume fraction

7. $\eta_{Na2}$ = Natrium volume fraction

8. $\eta_{2BeO}$ = BeO volume fraction

9. $p_2$ = fuel power density

10. $R_2$ = fuel pellets radius

11. $S_2$ = Cross section of zone 2

12. $v_2$ = coolant average speed

Driver Zone (Zone 3)

13. $p_3$ = fuel power density

14. $S_3$ = cross section of zone 3

15. $v_3$ = average coolant speed

Primary loop

16. $\Delta p_a$ = Total pressure drop in the primary coolant circuit

17. $\Delta p_b$ = Pressure drop in the circuit external to the core

18. $g$ = Total coolant volume flow

In fixing these parameters we have to keep in mind the following relationships.

Test Zone (Zone 1)

Coolant temperature rise

$$\Theta_{o1} - \Theta_i = \frac{H}{c\rho} \frac{p_1 \eta_{f1}}{\eta_{Na1} v_1} \tag{7}$$

where:

$\Theta_{o1}$ = average outlet coolant temperature in Zone 1

$\Theta_i$ = inlet coolant temperature

H = height of the active core

c = Sodium specific heat capacity

$\rho$ = Sodium density

<u>Pressure drop in an hexagonal cell</u> (fig. 3)

$$\frac{\Delta p_{1c}}{v_1^{1.8}} = F\left[\frac{\frac{C(1-\eta_{Na1})-D}{R_1'} + E}{2\,\eta_{Na1}\,C}\right]^{1.2} \tag{8}$$

where

$$F = 2\,K^{0.8}\,\mu^{0.2}\,L = \text{const} \tag{8'}$$

$\mu$ = Sodium viscosity

L = height of the hexagonal cell

$R_1'$ = fuel rod radius

$$C = 2\left(\frac{3\sqrt{3}}{3}\,l^2 + 6ls\right) = \text{const} \tag{8''}$$

l = side length of the hexagonal cell

s = wall thickness of the hexagonal cell

$$D = 12\,ls = \text{const} \tag{8'''}$$

$$E = 6l = \text{const} \tag{8''''}$$

<u>Intermediate Zone</u> (Zone 2)

<u>Geometric equation</u>

$$\eta_{f2} + \eta_{Na2} + \eta_{st2} + \eta_{2BeO} = 1 \tag{9}$$

Power density in fuel rods

$$p_2 = 2\,\frac{T_2 - \bar{\Theta}_2}{\beta_{2loc}\,\beta_{2ax}\,\beta_{2rad}}\;\frac{1}{\frac{R_2}{h} + \frac{R_2^2}{2\lambda}} \tag{10}$$

where:

$p_2$ = fuel power density

$T_2$ = maximum fuel temperature

$\bar{\Theta}_2$ = average coolant temperature

$\beta_{2ax}$ = axial hot spot factor

$\beta_{2rad}$ = radial hot spot factor

$\beta_{2loc}$ = local hot spot factor

$h$ = fuel sodium heat transfer coefficient (including the cladding)

$\lambda$ = fuel thermal conductivity

Coolant temperature rise

$$(\Theta_o - \Theta_i)_2 = \frac{H}{c\rho} \frac{p_2 \, \eta_{f2}}{\eta_{Na2} v_2} \tag{11}$$

Driver Zone (Zone 3)

Fuel power density (fig. 2)

$$p_3 = 2 \frac{T_3 - \bar{\Theta}_3}{\beta_{3loc} \, \beta_{3ax} \, \beta_{3rad}} \frac{1}{\frac{R_3}{h} + \frac{R_3^2}{2\lambda}} \tag{12}$$

Coolant temperature rise

$$(\Theta_o - \Theta_i)_3 = \frac{H}{c\rho} \frac{\eta_{f3} \, p_3}{\eta_{Na3} \, v_3} \tag{13}$$

Primary loop

Geometric equations

$$g = \eta_{Na1} S_1 v_1 + \eta_{Na2} S_2 v_2 + \eta_{Na3} S_3 v_3 \tag{14}$$

where $g$ = Total coolant volume flow

$S_1$ = Test zone cross section

$S_2$ = Intermediate zone cross section

$S_3$ = Driver zone cross section

$$S_1 + S_2 + S_3 = S \tag{15}$$

where:

$S$ = total core cross section

Pumps characteristics (fig. 19)

$$\Delta p_a = f(g) \tag{16}$$

Pressure drop in the circuit external to the core (fig. 19)

$$\Delta p_b = Qg^m \tag{17}$$

Total pressure drop (fig. 19)

$$\Delta p_a = \Delta p_{c1} + \Delta p_b \tag{18}$$

Core Conditions

Criticality condition

$$K_{eff} = 1 \tag{19}$$

Doppler coefficient

$$T \frac{dk}{dT} \text{ negative and as big as possible} \tag{20}$$

In addition to the expressions (7) to (20), it must be remembered that the U-235 enrichment, $e_1^{235}$, in zone 1, as already seen, must be chosen as high as possible.

## 4.2 Nuclear Calculations

The various zones with their dimensions are shown in fig. 13

The nuclear calculations were carried out by using the MGP Karlsruhe program with the 26 groups ABN set. The axial bucklings used in the calculations are the same as those of the SEFOR first core. These bucklings are referred to the composition of the SEFOR first core and therefore, strictly speaking, new axial bucklings should be calculated for the SEFOR third core. However, it is expected that they should not be very different from those of the first core.

In any case it seemed sufficient for preliminary calculations to use the same axial bucklings of the SEFOR first core.

Fig. 14 shows the core composition and power distribution in case A.

The Doppler coefficient was calculated by using the following expression (see Appendix 2):

$$\bar{T}\frac{dk}{d\bar{T}} = \frac{\bar{T}}{\bar{T}_1}\ \frac{p_1}{p} A_1 + \frac{\bar{T}}{\bar{T}_2}\ \frac{p_2}{p} A_2 + \frac{\bar{T}}{\bar{T}_3}\ \frac{p_3}{p} A_3 \qquad (1)$$

where:

$\bar{T}_i$ = average fuel temperature in zone "i" $(i = 1;2;3)$

$p_i$ = average fuel power density in zone "i" $(i = 1;2;3)$

$p$ = average fuel power density in all the core

$A_i$ = Doppler coefficient in zone "i" with no temperature change in the other zones $(i = 1;2;3)$

$$\bar{T} = \frac{\bar{T}_1 V_1 \eta_{f1} + \bar{T}_2 V_2 \eta_{f2} + \bar{T}_3 V_3 \eta_{f3}}{V_1 \eta_{f1} + V_2 \eta_{f2} + V_3 \eta_{f3}} \qquad (2)$$

where:

$V_i$ = core volume in zone "i" $(i = 1;2;3)$

$\eta_{fi}$ = fuel volume fraction in zone "i" $(i = 1;2;3)$

The Doppler coefficient has been calculated for

$$\frac{\bar{T}}{\bar{T}_1} = \frac{\bar{T}}{\bar{T}_2} = \frac{\bar{T}}{\bar{T}_3} \quad \text{(isothermal):}$$

$$\left(\bar{T}\frac{dk}{d\bar{T}}\right)_{is.} = -\ 0.00218 \qquad (3)$$

In order to improve the Doppler coefficient, BeO have been incorporated in the second zone. This case, called "case B", is shown in fig. 15. As it can be seen from this figure, the power ratios between the various zones have remained practically unchanged, while the Doppler coefficient is improved.

$$\left(\bar{T}\frac{dk}{d\bar{T}}\right)_{is.} = -\ 0.003814 \qquad (4)$$

The Doppler coefficient was also calculated for the following conditions:

$$\frac{\bar{T}}{\bar{T}_1} = 0{,}75 \qquad \frac{\bar{T}}{\bar{T}_2} = 1{,}86 \qquad \frac{\bar{T}}{\bar{T}_3} = 0{,}82 \qquad (5)$$

With these conditions it was found

$$\bar{T}\frac{dk}{d\bar{T}} = -\ 0.0057 \qquad (6)$$

From this calculation we can reach the conclusions that for safety purposes it is convenient to have

$$\bar{T}_2 < \bar{T}_1 \tag{7}$$

which means fuel rods with small diameter in the "intermediate zone" (second zone).

The flux spectrum in cases A and B are compared at different core radius of the "test zone" in figs. 16; 17 and 18. The presence of BeO in the "Second Zone" makes the spectrum of the "First Zone" a little softer.

## 4.2 Thermodynamic Calculations

The thermodynamic calculations refer to the case B shown in fig. 15.
From this figure we get:

$$\beta_{3rad}\, p_3 = \frac{\beta_{1rad}\, p_1}{9.454} = \frac{1.025}{9.454}\, p_1 = 0.1085\, p_1 \tag{1}$$

It is:

$$p_1 = \frac{p_{1max}}{\beta_{1loc}\, \beta_{1ax}\, \beta_{1rad}} = \frac{3000}{1.54 \cdot 1.24 \cdot 1.027} = \frac{3000}{1.96} \simeq 1550\ \frac{\text{Watt}}{\text{cm}^3} \tag{2}$$

The values $\beta_{1loc} = 1.54$ and $\beta_{1ax} = 1.24$ have been assumed to be equal, the first to the corresponding coefficient in the 1000 MWe reference reactor, and the second to the corresponding coefficient in the SEFOR first core.

From eq. 1 we get:

$$\beta_{3rad}\, p_3 = 0.1085\, p_1 = 0.1085 \cdot 1550 = 168\ \text{Watt/cm}^3 \tag{3}$$

Since it is the fuel pellet radius $R_3 = 1.13$ cm, looking at fig. 2, we are sure that the maximum fuel temperature in zone 3 will not exceed 2700°C.

Fig. 19 shows the pumps characteristic and that of the primary circuit external to the core.

Fig. 3 shows the channel pressure drop characteristic $\frac{\Delta p_c}{v^{1.8}}$ as function of $\eta_{Na}$ and fuel rod radius R'.

For $\eta_{Na1} = 0.47$ and (4)

$R'_1 = 0.3175$ cm (5)

we choose the pessimistic value

$$\frac{\Delta p_{1c}}{v_1^{1.8}} \simeq 21 \frac{\text{dyne/cm}^2}{(\text{cm/sec})^{1.8}} \tag{6}$$

which is higher than that obtainable from fig. 3.

From eq. 6 we get fig. 20 which shows the pressure drop "$\Delta p_{1c}$" in the core "test zone" as function of the coolant speed "$v_1$" in the "test zone".

From figs. 19 and 20 we get fig. 21 which gives "$v_1$" as function of the total coolant volume flow "g".

It is

$$g = \eta_{Na1}\, v_1\, S_1 + \eta_{Na2}\, v_2\, S_2 + \eta_{Na3}\, v_3\, S_3 \tag{7}$$

where

$S_i$ = core cross section belonging to zone "i"

From (7) we get:

$$\eta_{Na2}\, v_2 \frac{S_2}{S_2+S_3} + \eta_{Na3}\, v_3 \frac{S_3}{S_2+S_3} = \frac{g-\eta_{Na1}\, v_1\, S_1}{S-S_1} \tag{8}$$

where: $S = S_1 + S_2 + S_3$ (9)

Since (fig. 21) "g" is a function of $v_1$, from (8) we get the function

$$\eta_{Na2}\, v_2 \frac{S_2}{S_2+S_3} + \eta_{Na3}\, v_3 \frac{S_3}{S_2+S_3} = f(v_1) = \frac{g-\eta_{Na1}\, v_1\, S_1}{S-S_1} \tag{10}$$

which is shown in fig. 22.

We call with $(\Theta_o-\Theta_i)_1$ the coolant temperature rise in the "test zone" and with $(\Theta_o-\Theta_i)_{av}$ the average coolant temperature rise in the other two zones.

It is:

$$(\Theta_o-\Theta_i)_1 = \frac{H}{c\rho} \frac{\eta_{f1}\, p_1}{\eta_{Na1} v_1} \tag{11}$$

and

$$(\Theta_o-\Theta_i)_{av} = \frac{H}{c\rho} \frac{\eta_{f2} p_2 \frac{S_2}{S_2+S_3} + \eta_{f3} p_3 \frac{S_3}{S_2+S_3}}{\eta_{Na2} v_2 \frac{S_2}{S_2+S_3} + \eta_{Na3} v_3 \frac{S_3}{S_2+S_3}} \tag{12}$$

Taking into account eq. 10, eq. 11 becomes:

$$(\Theta_o-\Theta_i)_{av} = \frac{H}{c\rho} \frac{\eta_{f2} p_2 \frac{S_2}{S_2+S_3} + \eta_{f3} p_3 \frac{S_3}{S_2+S_3}}{f(v_1)} \tag{13}$$

Fig. 23 shows $(\Theta_o - \Theta_i)_1$ and $(\Theta_o - \Theta_i)_{av}$ as function of "$v_1$". Looking at this figure, in order to have not too high coolant temperature rises in the different core zones, the coolant speed $v_1$ must be:

$$v_1 \simeq 715 \text{ cm/sec} \tag{14}$$

to which it corresponds:

$$(\Theta_o - \Theta_i)_1 = (\Theta_o - \Theta_i)_{av} \simeq 120^\circ\text{C} \tag{15}$$

From fig. 22, we get:

$$\eta_{Na2}\, v_2 \frac{S_2}{S_2+S_3} + \eta_{Na3}\, v_3 \frac{S_3}{S_2+S_3} = 38 \text{ cm/sec} \tag{16}$$

In order to have the same coolant temperature rise in both second and third zone, we must put:

$$\frac{\eta_{Na2}\, v_2}{\eta_{Na3}\, v_3} = \frac{\eta_{f2}\, P_2}{\eta_{f3}\, P_3} = 0.739 \tag{17}$$

From eqs. (16) and (17) we get:

$$\eta_{Na3}\, v_3 = 45.8 \text{ cm/sec} \tag{18}$$

and

$$\eta_{Na2}\, v_2 = 33.9 \text{ cm/sec} \tag{19}$$

From (18) and (19) we get

$$v_3 = \frac{45.8}{0.27} = 170 \text{ cm/sec} \tag{20}$$

and

$$v_2 = \frac{33.9}{0.27} = 126 \text{ cm/sec} \tag{21}$$

From eqs. (6) and (14), we can calculate the pressure drop, $\Delta p_{1c}$, in the "test zone"

$$\Delta p_{1c} = 2.85 \cdot 10^6 \frac{\text{dyne}}{\text{cm}^2} = 2.89 \text{ at.} \tag{22}$$

From fig. 3 we get

for $R_2' = 0.3175$ and $\eta_{Na2} = 0.27$ $\quad \dfrac{\Delta p_{2c}}{v_2^{1.8}} \simeq 60 \dfrac{\text{dyne/cm}^2}{(\text{cm/sec})^{1.8}}$ (23)

and

for $R_3' = 1.2$ and $\eta_{Na3} = 0.27$ $\quad \dfrac{\Delta p_3}{v_3^{1.8}} \simeq 15 \dfrac{\text{dyne/cm}^2}{(\text{cm/sec})^{1.8}}$ (24)

It follows

$$\Delta p_{2c} = 0.37 \cdot 10^6 \frac{\text{dyne}}{\text{cm}^2} = 0.374 \text{ at.} \tag{25}$$

and

$$\Delta p_{3c} = 0.18 \cdot 10^6 \frac{\text{dyne}}{\text{cm}^2} = 0.182 \text{ at.} \qquad (26)$$

Since $p_{2c}$ and $p_{3c}$ are much smaller than $p_{1c}$, some additional means to increase the resistance to the coolant motion must be incorporated in the second and third zones. This can be done by making smaller input orifices in the grid plate or by putting special obstacles to the coolant motion along the reactor channels.

If the coolant speed "$v_1$" is chosen smaller than 715 cm/sec than the difference between the pressure drops in the various core zones will be smaller but the coolant temperature rises will be not any more everywhere equal (fig. 23).

## 4.3 Characteristics of the proposed SEFOR third core - First design type

The so called case B seems more convenient because has an higher negative Doppler coefficient.

Its main characteristics are listed below:

1 General Core Characteristics

| | |
|---|---|
| core type | 3 zones, fast neutron |
| fuel | in Z2 and Z3 mixed $PuO_2$-$UO_2$; in Z2 $UO_2$ |
| spectrum softener | BeO in Z2 |
| coolant | Sodium |
| Power output | 40 MW |
| Purpose of the core | Testing fuel elements at the same power density, flux spectrum and burn up as in the 1000 MWe prototype reactor |

2 Core Description

2.1 Geometry

| | |
|---|---|
| height of the active core | 85.85 cm |
| core diameter | 79.44 cm |
| Number of channels | 109 |
| type of channels | hexagonal |
| **Zone 1 (Test Zone)** | |
| number of channels | 7 |
| equivalent radius | 10.89 cm |

Zone 2 (Intermediate Zone)

| | |
|---|---|
| number of channels | 30 |
| equivalent radius | 25.04 cm |

Zone 3 (Driver Zone)

| | |
|---|---|
| equivalent radius | 39.72 cm |

2.2 Physics data

| | | | |
|---|---|---|---|
| Zone 1 | volume fraction of fuel | 0.34 | |
| | volume fraction of Sodium | 0.47 | |
| | volume fraction of steel | 0.18 | |
| | volume fraction of void | 0.01 | |
| | nuclear composition of the fuel | U-235 | 0.72 |
| | | U-238 | 0.08 |
| | | Pu-239 | 0.1835 |
| | | Pu-240 | 0.0165 |
| Zone 2 | volume fraction of fuel | 0.43 | |
| | volume fraction of sodium | 0.27 | |
| | volume fraction of steel | 0.20 | |
| | volume fraction of BeO | 0.10 | |
| | nuclear composition of the fuel | U-235 | 0.05 |
| | | U-238 | 0.95 |
| Zone 3 | volume fraction of fuel | 0.53 | |
| | volume fraction of sodium | 0.27 | |
| | volume fraction of steel | 0.20 | |
| | nuclear composition of the fuel | U-238 | 0.8584 |
| | | Pu-239 | 0.13 |
| | | Pu-240 | 0.0116 |

3 Control

$k_{eff}$ of the clean core = 1.030536

Doppler coefficient = - 0.03814 (isothermal)

4 Thermal hydraulic design

| | | |
|---|---|---|
| 4.1 Maximum fuel temperature | Z.1 | 2670°C |
| | Z.3 | 2571°C |

4.2 Fuel Power density, average

| | | |
|---|---|---|
| Z.1 | 1550 Watt/$cm^3$ |
| Z.2 | 111 Watt/$cm^3$ |
| Z.3 | 122 Watt/$cm^3$ |

4.3 Power shape factors

| | | |
|---|---|---|
| Z.1 | axial factor | 1.24 |
| | radial factor | 1.027 |
| | local factor | 1.54 |
| | total factor | 1.96 |
| Z.2 | axial factor | 1.24 |
| | radial factor | 1.439 |
| | local factor | 1.1 |
| | total factor | 1.96 |
| Z.3 | axial factor | 1.24 |
| | radial factor | 1.375 |
| | local factor | 1.1 |
| | total factor | 1.87 |

4.4 Power

| | |
|---|---|
| total power production in the zone 1 | 16.8 MW |
| total power production in the zone 2 | 6.5 MW |
| total power production in ehe zone 3 | 16.6 MW |
| total power production in core | 39.9 MW |

4.5 Coolant

| | |
|---|---|
| Core pressure drop | = 2.9 at. |
| inlet temperature | = 370°C |
| outlet temperature | = 490°C |
| Velocity Z.1 | = 715 cm/sec |
| Z.2 | = 126 cm/sec |
| Z.3 | = 170 cm/sec |

4.6 Radius of fuel pellets:

Z.1 0.2794 cm

Z.2 as small as possible

Z.3 1.13 cm

## 5. SEFOR third core - Second design type

In this "Second design type" the core composition and the dimension of the "test zone" are equal to that of the first design type.

The only difference is that the design of the fuel rods in the "driver zone" is free so that no conditions are imposed by the requirements of the SEFOR second core.

The core is divided in two zones

(a) Test zone or First zone

(b) Driver zone or Second zone

The core arrangement is shown in fig. 24.

### 5.1 Nuclear calculations

Fig. 25 shows the various core zones and their dimensions
Fig. 26 shows the core composition and the core power distribution in case A.

The isothermal Doppler coefficient is:

$$\left(\bar{T}\frac{dk}{d\bar{T}}\right)_{is} = -\ 0.00256 \qquad (1)$$

In order to improve the Doppler coefficient some BeO was added in the driver zone (case B). Fig. 27 shows the core composition and the core power distribution in case B.

The isothermal Doppler coefficient in this case is:

$$\left(\bar{T}\frac{dk}{d\bar{T}}\right)_{is} = -\ 0.0041 \qquad (2)$$

The flux spectrums in both the cases at different radius of the "test zone" are compared in figs. 28, 29 and 30.

### 5.2 Thermodynamic calculations

Since we are free in the design of the fuel rods which will fill the "driver zone", we are not bound any more to build them with a big radius. The radius instead must be as small as possible so that the average fuel temperature in the "driver zone" is lower than in the "test zone". This improves the Doppler coefficient.

From fig. 23, choosing the coolant temperature rises

$$(\Theta_o-\Theta_i)_1 = (\Theta_o-\Theta_i)_2 = 120 \tag{1}$$

we have:

$$v_1 = 715 \text{ cm/sec} \tag{2}$$

From fig. 3 for

$$\eta_{Na1} = 0.47 \tag{3}$$

and

$$R_1' = 0.3175 \text{ cm} \tag{4}$$

we get

$$\frac{\Delta p_{1c}}{v_1^{1.8}} \simeq 21 \frac{\text{dyne/cm}^2}{(\text{cm/sec})^{1.8}} \tag{5}$$

and therefore

$$\Delta p_{1c} = 2.89 \text{ at.} \tag{6}$$

From fig. 22, we get

$$\eta_{Na2}\, v_2 = 38 \text{ cm/sec} \tag{7}$$

and therefore

$$v_2 = \frac{38}{0.27} = 140 \text{ cm/sec} \tag{8}$$

The total power produced $P_t$, will be

$$P_t = 40 \text{ MW} \tag{9}$$

## 5.3 Considerations on a possible proposal for a SEFOR third core second design type

The calculations carried out for the SEFOR third core second design type are very preliminary.

Here we put in evidence the direction which should be followed in order to improve the design.

1. Since the fuel rods of the "driver zone" will have a small diameter, it is not any more necessary to have a big ratio between the fuel power

densities of the "test and driver zones". It follows that the U-235 enrichment in the "test zone" can be decreased and this would surely improve the safety.

2. In both the cases A and B, Pu-239 was used as fissile material in the "driver zone". It could be more convenient to use U-235 (instead of Pu-239).

## 6. Conclusions

The design of both SEFOR second and third cores described in this paper must not be intended as a final proposal.

The first conclusion is that the fuel rods of the SEFOR second core cannot be too much different from those of the first core (see triangle ABC in fig. 6). From this it follows that the most reasonable thing to do would be to use in the SEFOR second core the same fuel rods of the first core and to replace the BeO rods of the first core with some other material which makes the neutron spectrum harder than in the first core. One solution could be to replace the BeO rods with Uranium rods enriched with enough Pu to obtain a multiplication factor sufficient for reactor operation.

The only incentive to choose the "first design type" of the "SEFOR third core" lies in the use of about half of the fuel rods of the SEFOR second core in the "Driver Zone" of the SEFOR third core. The "Intermediate Zone" would be filled with low enriched fuel rods which would have a relatively low cost.

Since we want to have the possibility to study the effects of the burn-up on the fuel rods as they develop with time, only some of the fuel rods in the "Test Zone" will reach $10^5$ MW day/ton, while the others will be taken away from the reactor before they reach this limit, and replaced by new fuel rods. We can suppose that the maximum average burn-up in the "Test Zone" will not exceed $0.5 \cdot 10^5$ MW day/ton.

It is expected that the maximum burn-up effect will take place in the "Test Zone" so that the power density ratios between this zone and the other two should decrease with time.

A decision should be taken whether or not it is convenient to use the fuel rods of the "SEFOR second core" in the "Driver Zone" of the SEFOR third core, which means a choice between First and Second design types of the SEFOR third core.

## 7. Appendix 1 Calculation of pressure drop characteristic of a reactor channel

We assume for the loss of pressure in a core channel the following law

$$\Delta p_c = 2\ f\ \frac{\rho L\ v^2}{D_e} \qquad (1)$$

where "f" is a factor given by:

$$f = K\ R_e^{-0.2} \qquad (2)$$

$\rho$ = coolant density

L = length of core channel

v = coolant velocity

$D_e$ = hydraulic diameter of core channel

K = constant

$$R_e = \text{Reynolds number} = \frac{\rho v D_e}{\mu} \qquad (3)$$

$\mu$ = coolant viscosity

Equation (1), with the subtitutions (2) and (3) becomes:

$$\Delta p_c = 2\ K\ \frac{\rho^{0.8}\ L\ \mu^{0.2}\ v^{1.8}}{D_e^{1.2}} \qquad (4)$$

The hydraulic diameter is so defined

$$D_e = \frac{4 \cdot \text{flow area}}{\text{bained perimeter}} = \frac{4\ A}{q} \qquad (5)$$

Looking at fig. 7, the flow area is given by $A = n_{Na}(\frac{3\sqrt{3}}{2}\ 1^2 + 61s)$ (6)

where:

$n_{Na}$ = Sodium volume fraction in the core

1 = side length of the hexagonal channel

s = wall thickness of the hexagonal channel

The bained perimeter is given by $q = N\ 2\pi R' + 6\ 1$ (7)

where:

N = number of rods in the channel =

$$= \frac{(\frac{3\sqrt{3}}{2}\ 1^2 + 6\ 1\ s)(1-n_{Na}) - 6\ 1\ s}{\pi(R')^2} \qquad (8)$$

R' = rod radius

Taking into account eq. 8, eq. 7 becomes:

$$q = 2\,\frac{\left(\frac{3\sqrt{3}}{2}\,l^2 + 6\,l\,s\right)(1-\eta_{Na}) - 6\,l\,s}{R'} + 6\,l \qquad (9)$$

Taking into account eqs. 6 and 9, eq. 5 becomes:

$$D_e = \frac{4\eta_{Na}\left(\frac{3\sqrt{3}}{2}\,l^2 + 6\,l\,s\right)}{2\,\frac{\left(\frac{3\sqrt{3}}{2}\,l^2 + 6\,l\,s\right)(1-\eta_{Na}) - 6\,l\,s}{R'} + 6\,l} \qquad (10)$$

Substituting eq. 10 in eq. 4, we obtain:

$$\Delta p_c = \frac{2\,K\,\rho^{0.8}\,\mu^{0.2}\,L\,v^{1.8}}{\left[\dfrac{4\eta_{Na}\left(\frac{3\sqrt{3}}{2}\,l^2 + 6\,l\,s\right)}{2\,\frac{\left(\frac{3\sqrt{3}}{2}\,l^2 + 6\,l\,s\right)(1-\eta_{Na}) - 6\,l\,s}{R'} + 6\,l}\right]^{1.2}} =$$

$$= 2\,K\,\rho^{0.8}\,\mu^{0.2}\,L\left[\frac{2\,\frac{\left(\frac{3\sqrt{3}}{2}\,l^2 + 6\,l\,s\right)(1-\eta_{Na}) - 6\,l\,s}{R'} + 6\,l}{4\,\eta_{Na}\left(\frac{3\sqrt{3}}{2}\,l^2 + 6\,l\,s\right)}\right]^{1.2} v^{1.8} \qquad (11)$$

Fig. 3 shows $\frac{\Delta p_c}{v^{1.8}}$ as function of $\eta_{Na}$ and R'.

Equation 11 can be written as follows

$$\frac{\Delta p_c}{v^{1.8}} = F\left[\frac{\frac{C(1-\eta_{Na})-D}{R'} + E}{2C\eta_{Na}}\right]^{1.2} \qquad (12)$$

where

$$F = 2\,K\,\rho^{0.8}\,\mu^{0.2}\,L \qquad (13)$$

$$C = 2\left(\frac{3\sqrt{3}}{2}\,l^2 + 6ls\right) \qquad (14)$$

$$D = 12\ ls \qquad (15)$$

$$E = 6\ l \qquad (16)$$

## 8. Appendix 2 Calculation of the Doppler coefficient

The variation of the reactivity dk, due to changes of the fuel temperatures in the three core zones, is given by the following expression:

$$dk = \frac{\partial k}{\partial \bar{T}_1} d\bar{T}_1 + \frac{\partial k}{\partial \bar{T}_2} d\bar{T}_2 + \frac{\partial k}{\partial \bar{T}_3} d\bar{T}_3 \tag{1}$$

where $\bar{T}_i$ = average fuel temperature in zone i

$\frac{\partial k}{\partial \bar{T}_i} d\bar{T}_i$ = change of reactivity due to the change of the average fuel temperature in zone "i" while in the other zones the fuel temperatures remain constant.

We assume for $\frac{\partial k}{\partial \bar{T}_i}$ the following expression

$$\frac{\partial k}{\partial \bar{T}_i} = \frac{A_i}{\bar{T}_i} \tag{2}$$

with $A_i$ = constant.

Equation 1 becomes:

$$dk = \frac{A_1}{\bar{T}_1} d\bar{T}_1 + \frac{A_2}{\bar{T}_2} d\bar{T}_2 + \frac{A_3}{\bar{T}_3} d\bar{T}_3 \tag{3}$$

Let us define the average fuel temperature in all the core as follows:

$$\bar{T} = \frac{\bar{T}_1 V_1 \eta_{f1} + \bar{T}_2 V_2 \eta_{f2} + \bar{T}_3 V_3 \eta_{f3}}{V_1 \eta_{f1} + V_2 \eta_{f2} + V_3 \eta_{f3}} \tag{4}$$

here:

$V_i$ = core volume of the zone i

$\eta_{fi}$ = fuel volume fraction in zone i

We can write equation 3 as follows

$$\bar{T} \frac{dk}{d\bar{T}} = A_1 \frac{\bar{T}}{\bar{T}_1} \frac{d\bar{T}_1}{d\bar{T}} + A_2 \frac{\bar{T}}{\bar{T}_2} \frac{d\bar{T}_2}{d\bar{T}} + A_3 \frac{\bar{T}}{\bar{T}_3} \frac{d\bar{T}_3}{d\bar{T}} \tag{5}$$

If we suppose that there is no heat loss from the fuel during a temperature change then:

$$\frac{d\bar{T}_i}{d\bar{T}} = \frac{p_i}{p} \tag{6}$$

where

$p_i$ = average fuel power density in zone i

$p$ = average fuel power density in the core, defined as follows:

$$p = \frac{p_1 V_1 n_{f1} + p_2 V_2 n_{f2} + p_3 V_3 n_{f3}}{V_1 n_{f1} + V_2 n_{f2} + V_3 n_{f3}} \qquad (7)$$

Expression (5) assumes the form:

$$\bar{T}\frac{dk}{d\bar{T}} = A_1 \frac{p_1}{p}\frac{\bar{T}}{\bar{T}_1} + A_2 \frac{p_2}{p}\frac{\bar{T}}{\bar{T}_2} + A_3 \frac{p_3}{p}\frac{\bar{T}}{\bar{T}_3} \qquad (8)$$

The coefficients $A_i$ can be easily calculated by using equation 2.

We calculate with the MG-program the reactivity change due to average fuel temperature change only in zone i.

From eq. 2 for a finite difference we get:

$$A_i = \frac{k_2 - k_1}{\lg \frac{\bar{T}_{i2}}{\bar{T}_{i1}}} \qquad (9)$$

where:

$k_1$ = multiplication factor at reactor condition 1

$k_2$ = multiplication factor at reactor condition 2

$\bar{T}_{i1}$ = average fuel temperature in zone "i" at reactor condition 1

$\bar{T}_{i2}$ = average fuel temperature in zone "i" at reactor condition 2

## 9. Bibliography

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2. E.E.Olich - SEFOR conversion to 50 MW fuel test facility - Oct. 13, 64

3. SEFOR Plant - First quarterly progress report - April/June 64 - July 64 GECR 4595

4. E.G.Schlechtendahl - 50 MW SEFOR reactor minutes of march, 8 1965 meeting of APED, March, 19 1965

5. SEFOR Plant - Fifth quarterly progress report - May/July 65 - Augs. 65 GEAP-4934

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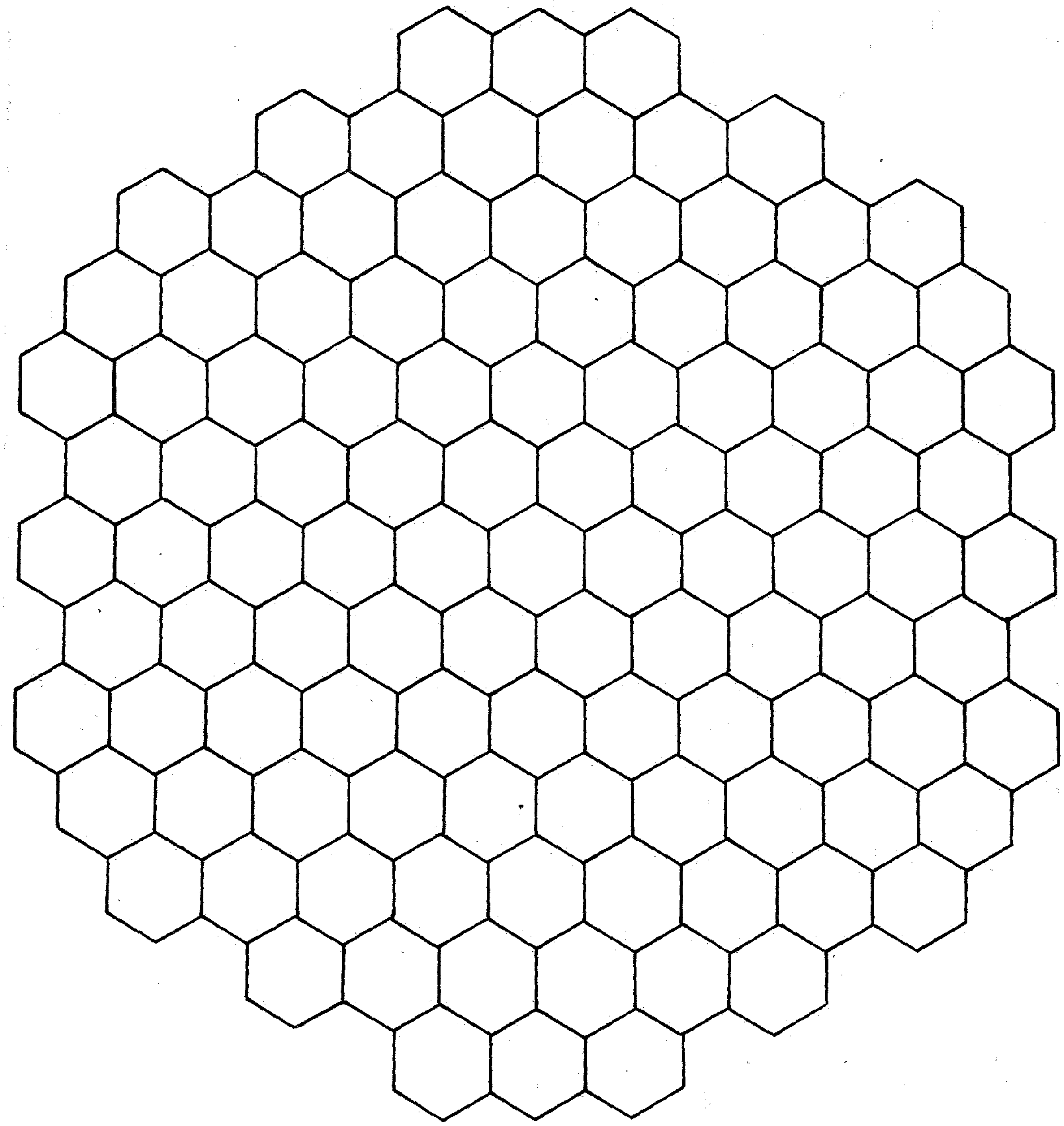
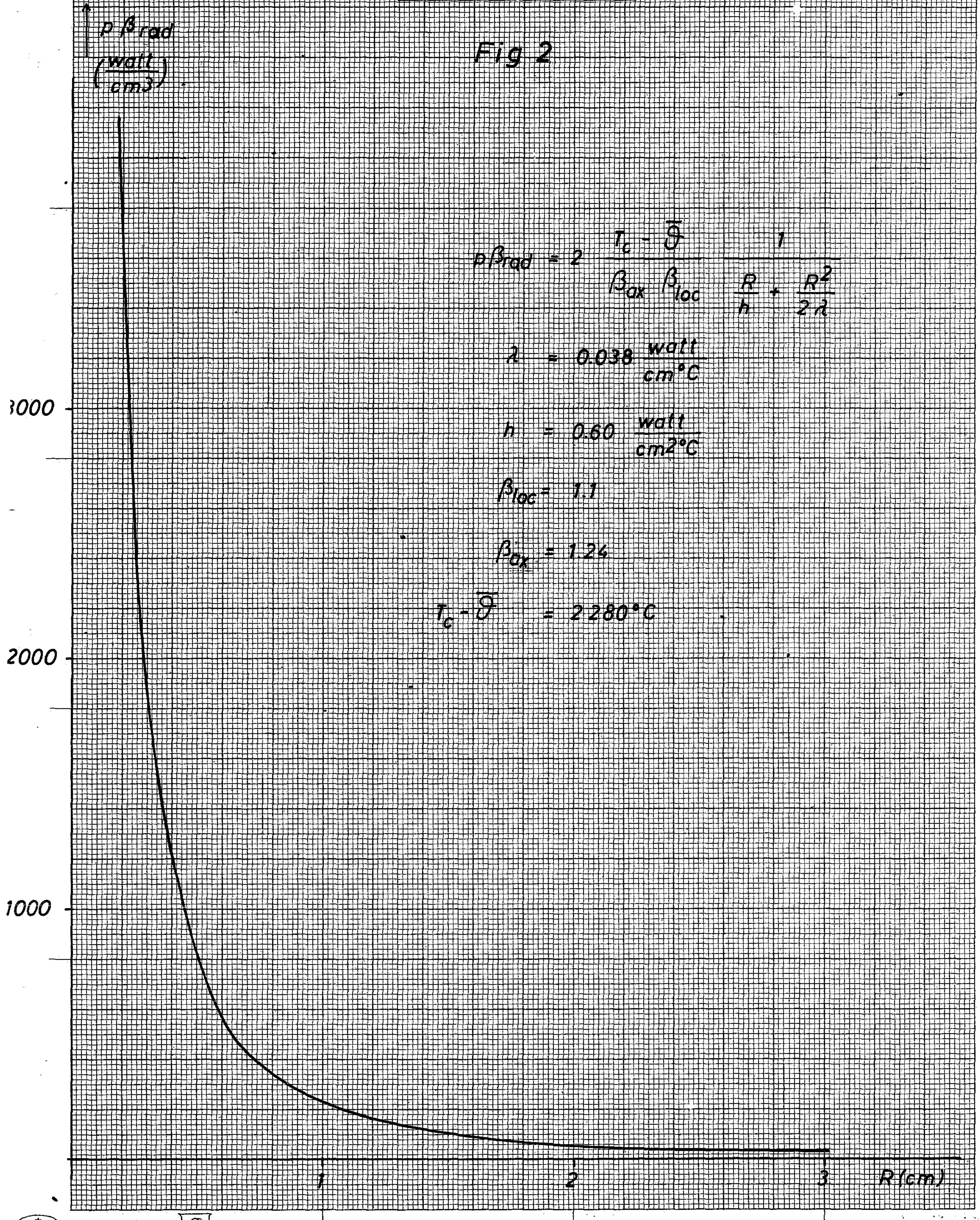


*Arrangement of core hexagonal channels*

*Fig 1*

# Fuel power density as function of fuel pellets radius

Fig 2




$$p\beta_{rad} = 2\,\frac{T_c - \overline{\vartheta}}{\beta_{ax}\;\beta_{loc}}\;\frac{1}{\frac{R}{h} + \frac{R^2}{2\lambda}}$$

$$\lambda = 0.038\ \frac{watt}{cm\,^\circ C}$$

$$h = 0.60\ \frac{watt}{cm^2\,^\circ C}$$

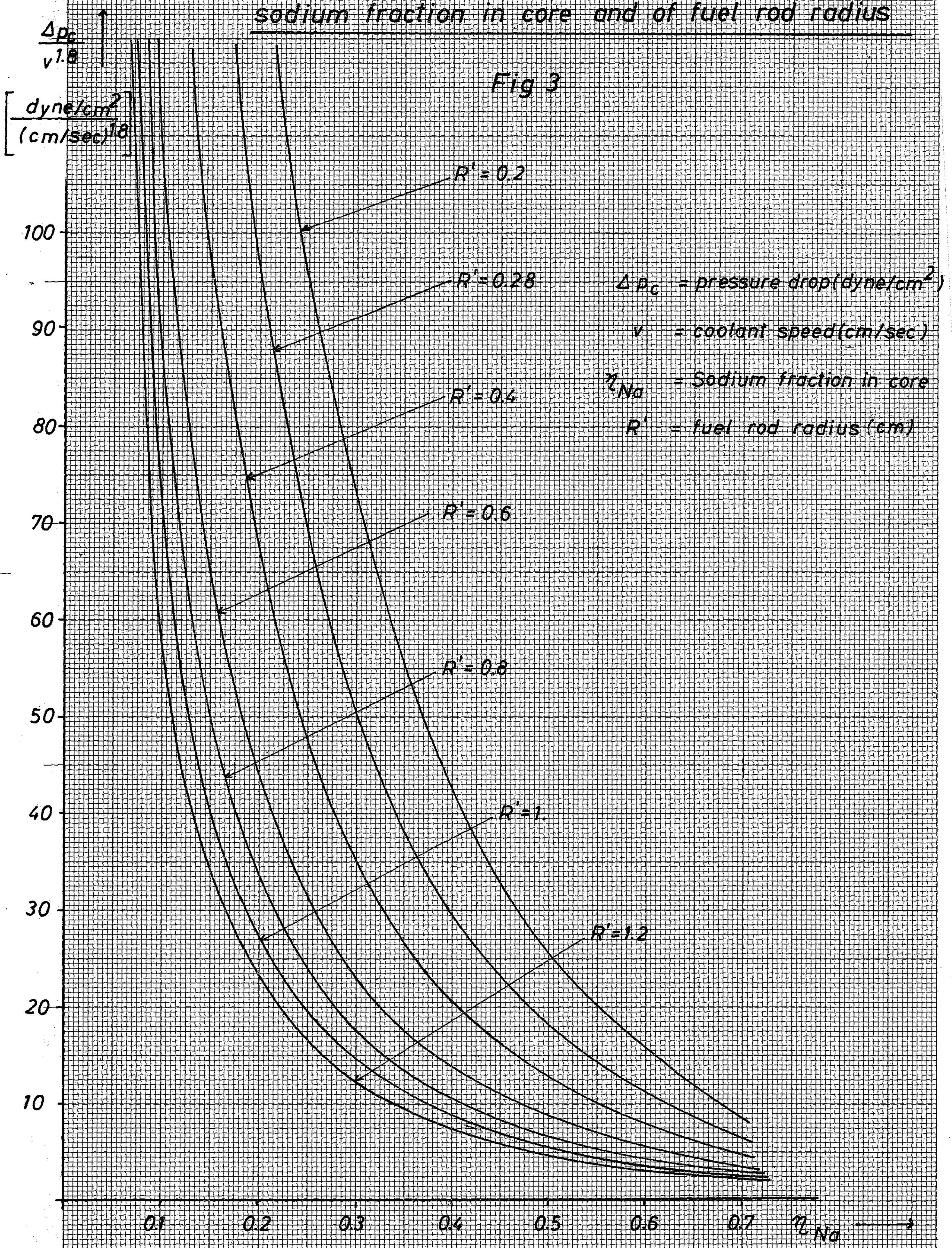
$$\beta_{loc} = 1.1$$

$$\beta_{ax} = 1.24$$

$$T_c - \overline{\vartheta} = 2\,280\,^\circ C$$

Channel pressure drop characteristic as function of sodium fraction in core and of fuel rod radius

Fig 3




SELECTA A4 210 x 297 mm

# Sefor Second Core

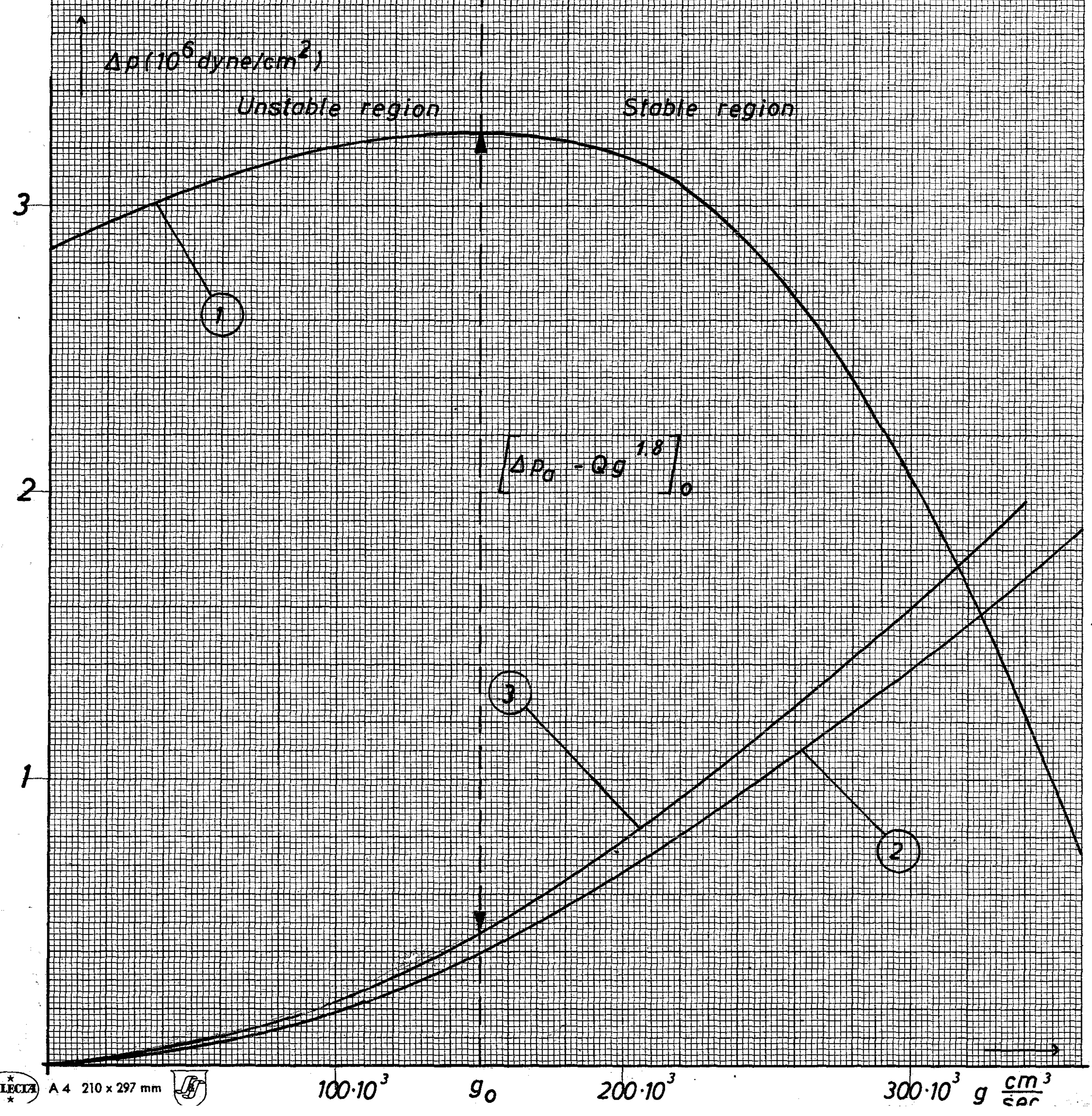
## Characteristics of the pump and of the primary circuit

### Fig 4

(1) Pump pressure rise ($\Delta p_a$) against coolant volume flow ($g$)

(2) Primary circuit (without core) pressure drop ($\Delta p_b$) against volume flow ($g$)

(3) Primary circuit (including core) pressure drop: $\Delta p_c = 3 \cdot 10^{-5} g^{1,8}$
($\Delta p_t$) against volume flow: $\Delta p_t = \Delta p_b + \Delta p_c$
$\Delta p_c$ = core pressure drop



## Sefor 2nd Core

Pu enrichment as function of fuel percentage in core

$e$ = Pu 239 enrichment (Pu 240 = 8.9 % of Pu 239)

$\eta_f$ = fuel volume fraction

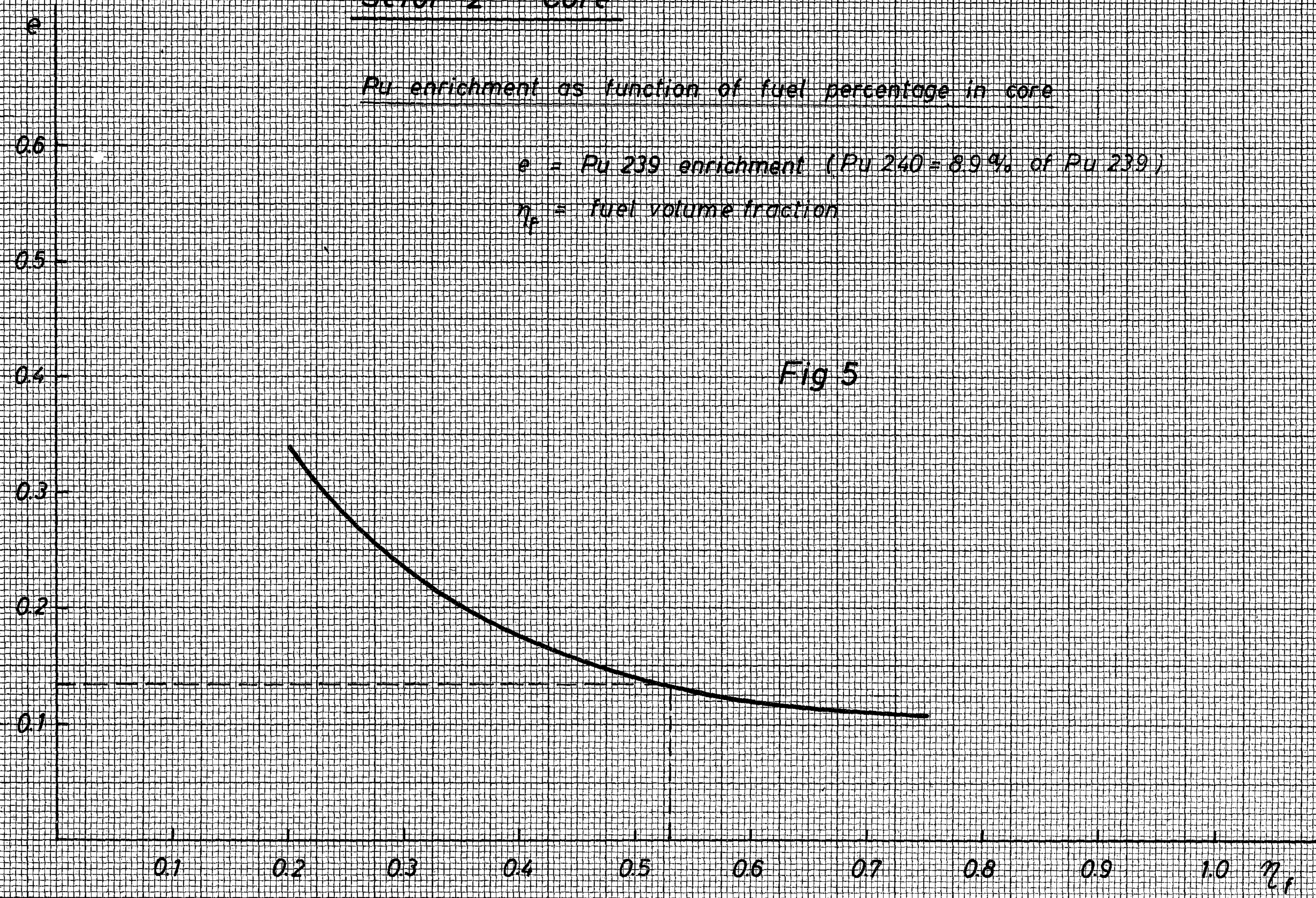



Fig 5

Fig. 6 SEFOR second core - Design Locus

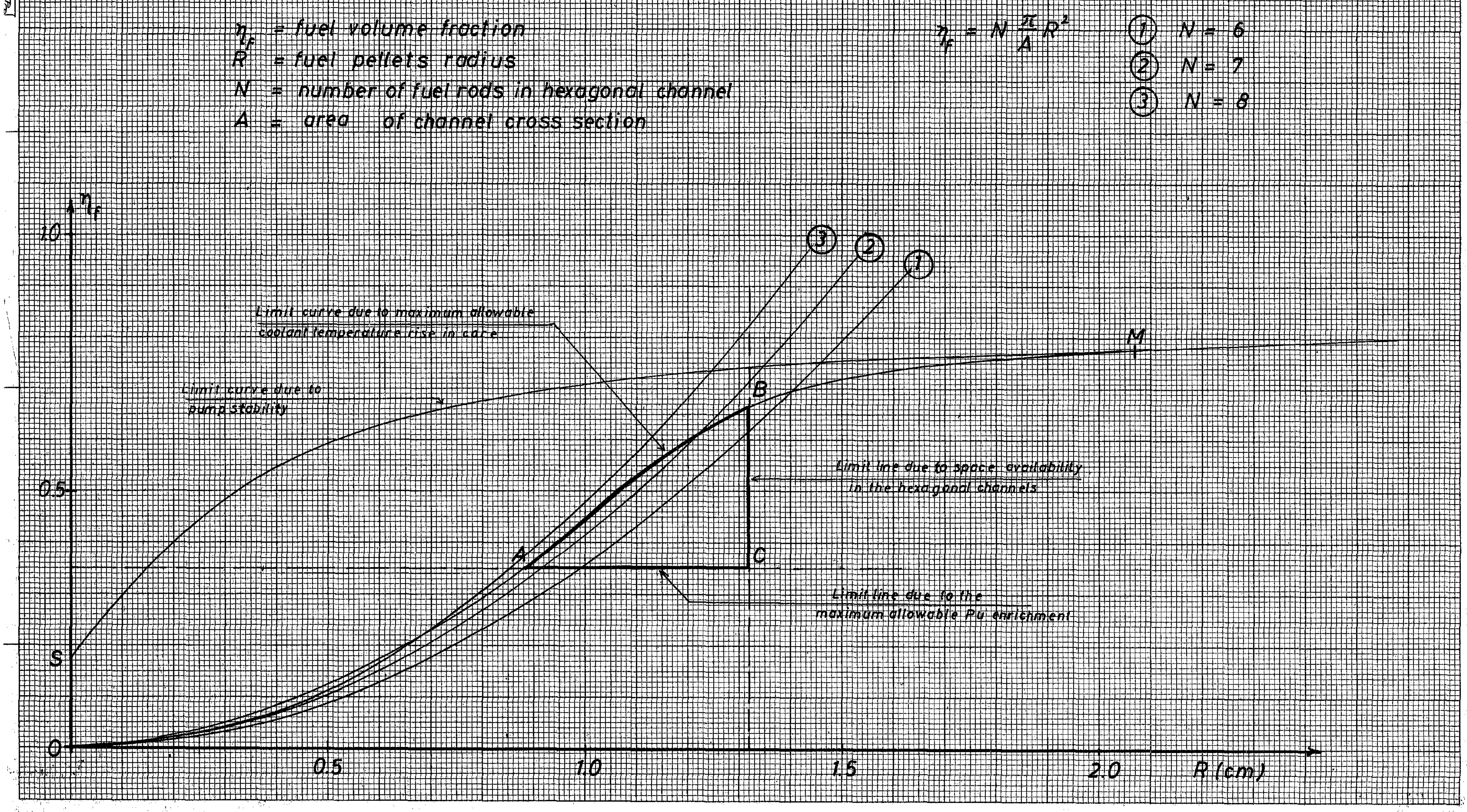
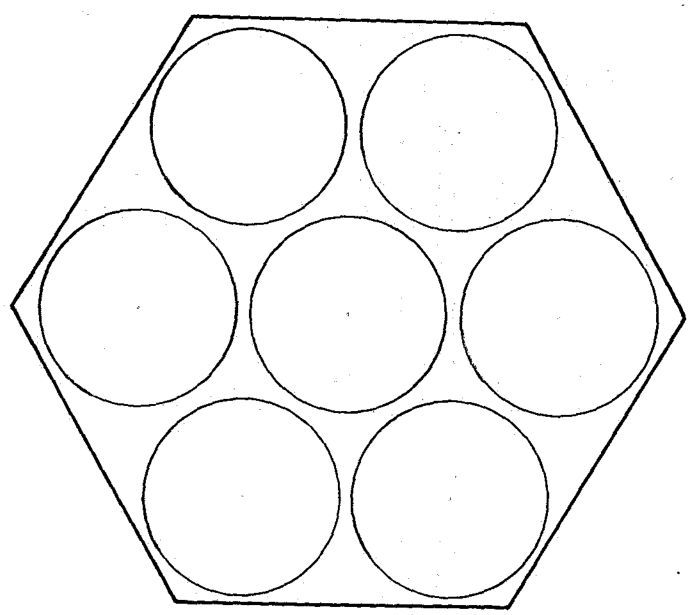
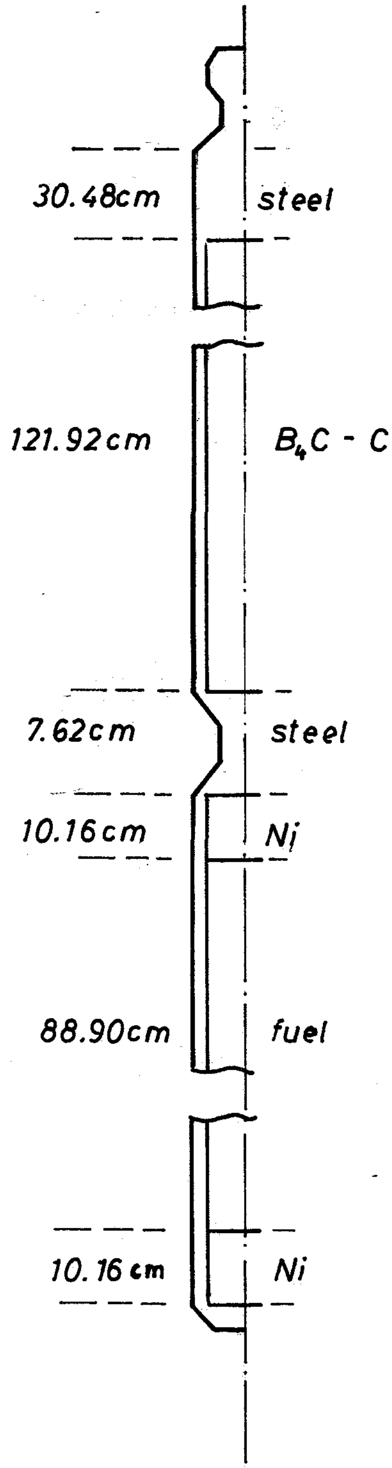


Fig 7

Sefor Second Core

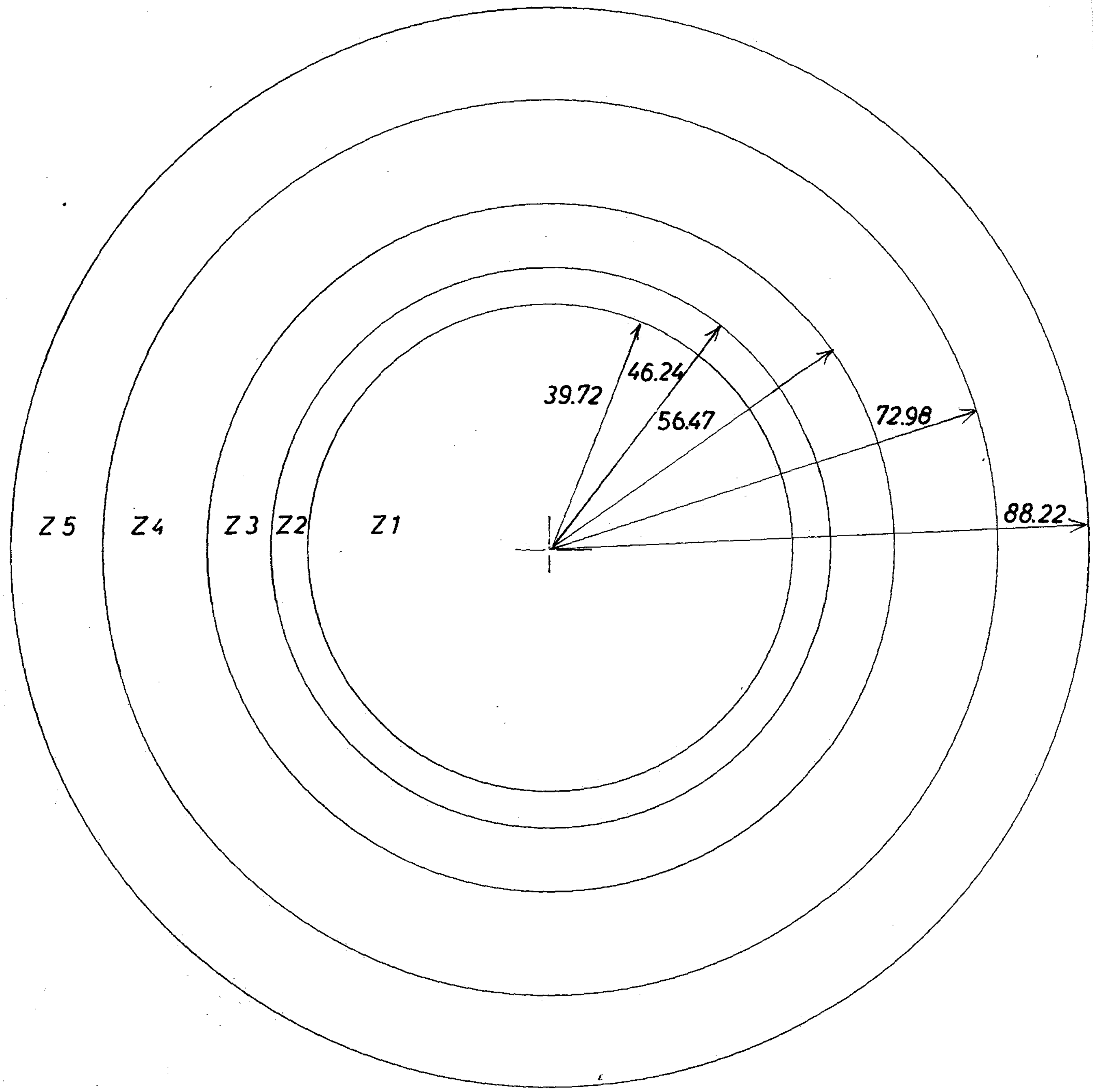
Fuel rods arrangement in hexagonal reactor channel






Fuel rod - Schematic diagram

Fig. 8




Z.1 = Core

Z.2 = Rand zone

Z.3 = Shroud zone

Z.4 = Reflector zone

Z.5 = Absorber zone

SEFOR 2nd Core

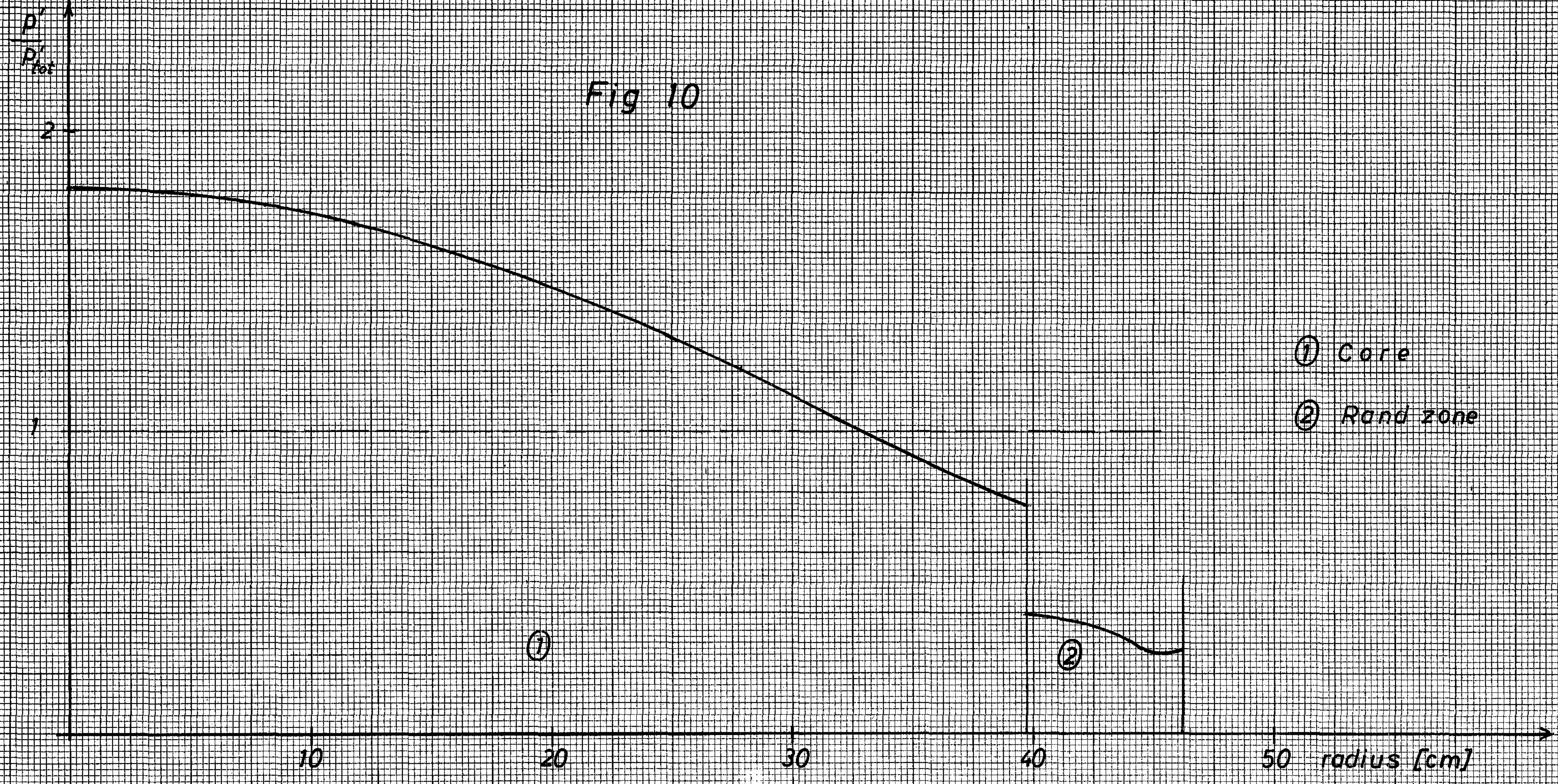
Schematic diagram showing the radial zones

Fig 9

## SE FOR second core

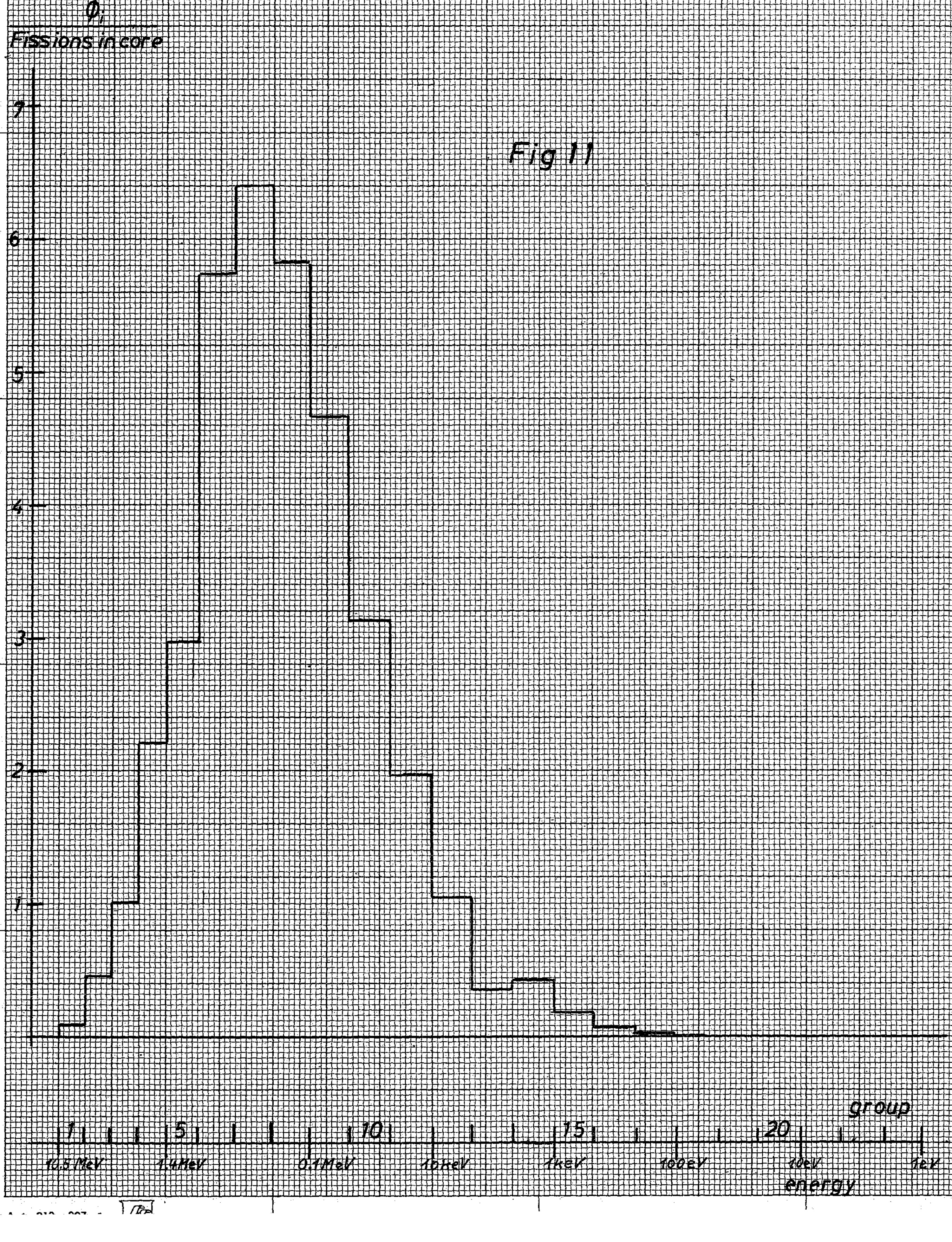
Core power density distribution referred to average power density taken as equal to 1

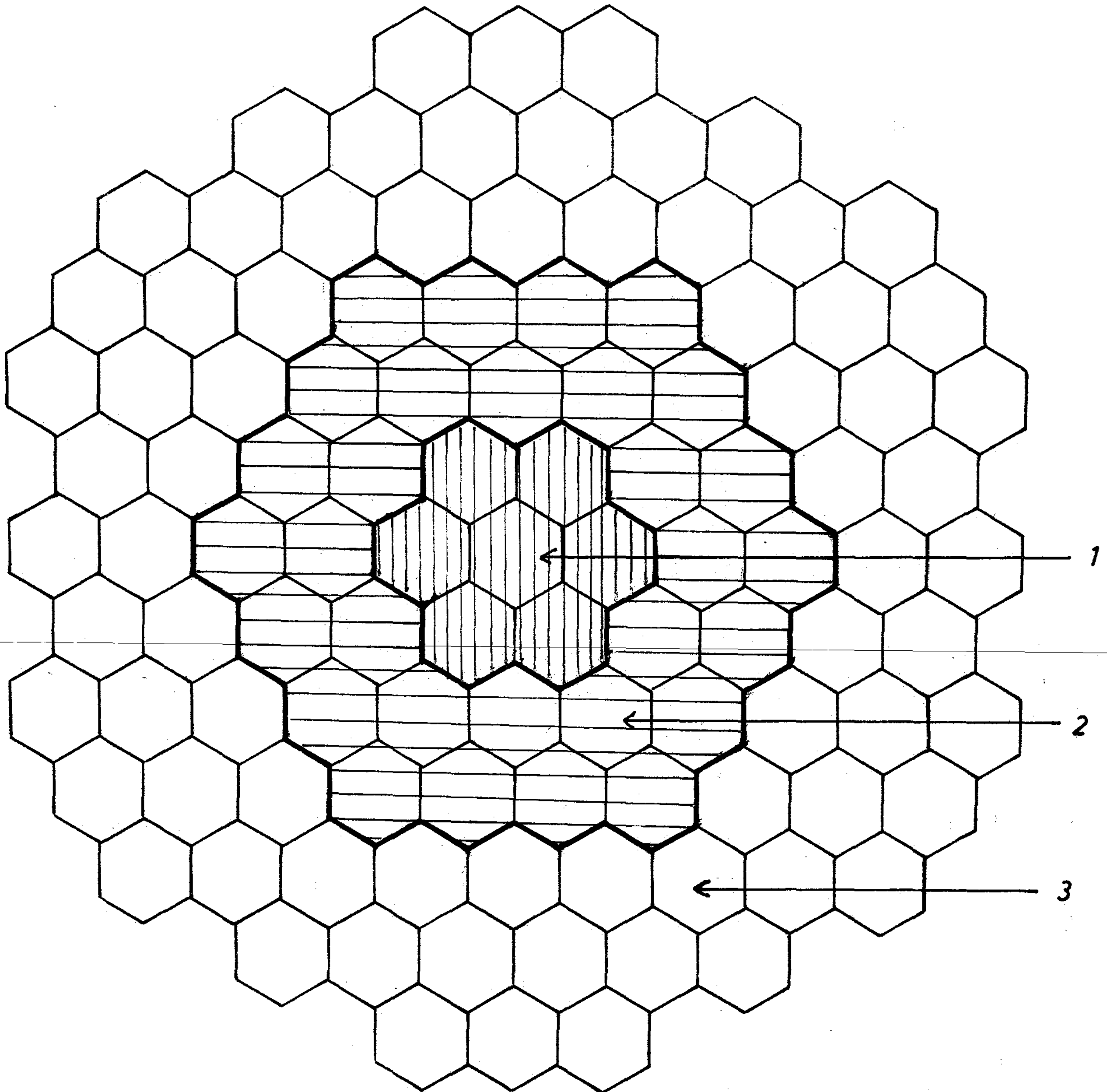
Fig 10



## SEFOR second core

*flux spectrum at an intermediate point (r = 11.916 cm)*





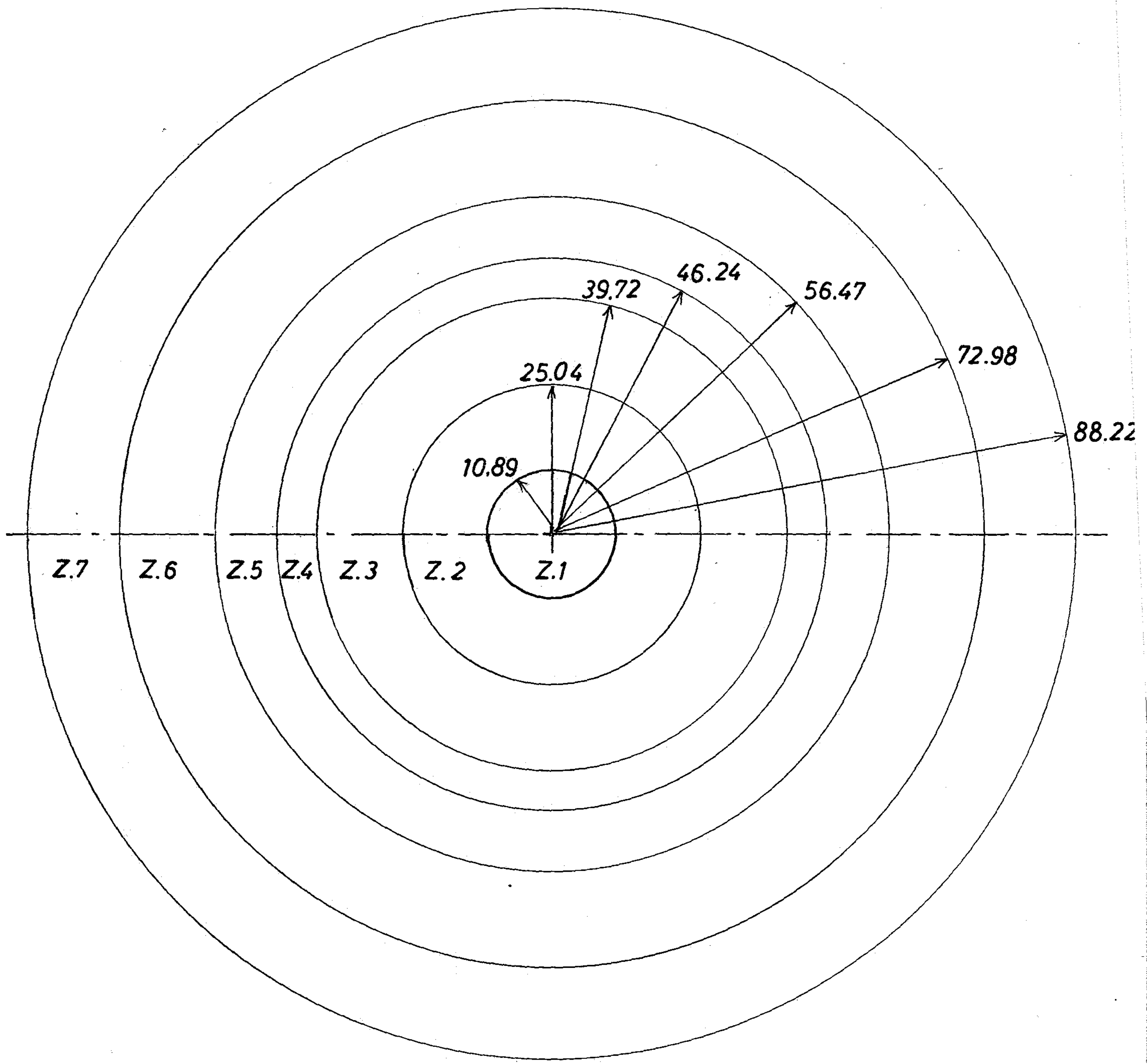

1 First zone (Test zone)

2 Second zone (Intermediate zone)

3 Third zone (Driver zone)

SEFOR third core - first design type - Core Arrangement

Fig. 12




Z.1 = Test zone
Z.2 = Intermediate zone
Z.3 = Driver zone
Z.4 = Rand zone
Z.5 = Shroud zone
Z.6 = Reflector zone
Z.7 = Absorber zone

SEFOR third core – first design type

Schematic diagram showing the radial zones

Fig. 13

# SEFOR third core – First design type – Case A (R601)

## Core power distribution (average core power density = 1)

### Fig. 14

**A. Composition**

1st zone 7 channels

$\eta_f = 0.34$ $\left\{ \begin{array}{l} Pu\ 239 = 0.1835 \\ Pu\ 240 = 0.0165 \\ U\ 235 = 0.72 \\ U\ 238 = 0.08 \end{array} \right.$

$\eta_{Na} = 0.47$

$\eta_{st} = 0.18$

2nd zone 30 channels

$\eta_f = 0.53$ $\left\{ \begin{array}{l} U\ 235 = 0.05 \\ U\ 238 = 0.95 \end{array} \right.$

$\eta_{Na} = 0.27$

$\eta_{st} = 0.20$

3rd zone 56 channels

$\eta_f = 0.53$ $\left\{ \begin{array}{l} Pu\ 239 = 0.13 \\ Pu\ 240 = 0.0116 \\ U\ 238 = 0.8584 \end{array} \right.$

$\eta_{Na} = 0.27$

$\eta_{st} = 0.20$

**B. Core power density ratios**

$\frac{P_1'}{P_2'} = 9.46$

$\frac{P_1'}{P_3'} = 7.62$

$\frac{\beta_{1rad} P_1'}{\beta_{2rad} P_2'} = 6.70$

$\frac{\beta_{1rad} P_1'}{\beta_{3rad} P_3'} = 6.16$

**C. Fuel power density ratios**

$\frac{P_1}{P_2} = 14.75$

$\frac{P_1}{P_3} = 11.88$

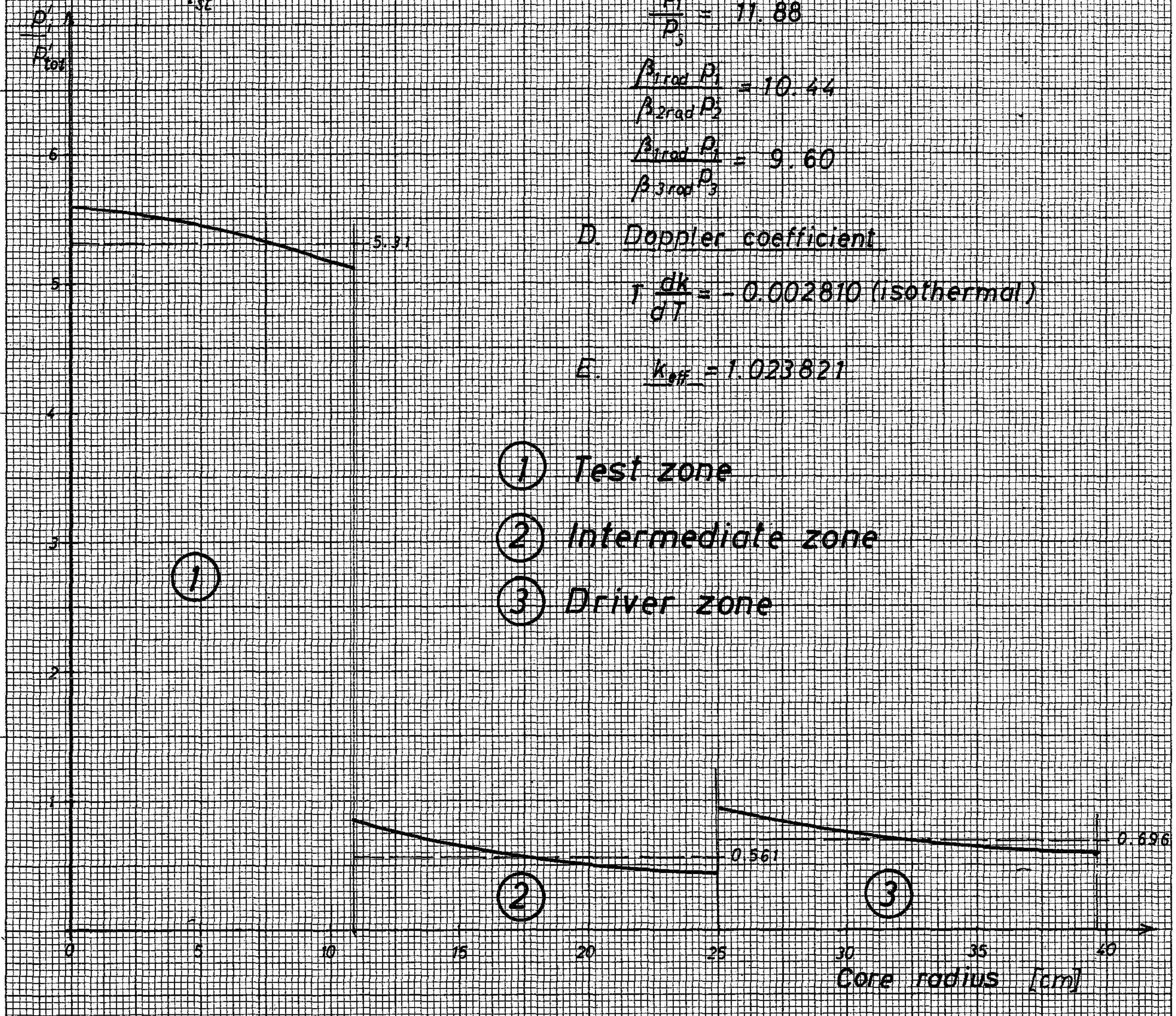
$\frac{\beta_{1rad} P_1}{\beta_{2rad} P_2} = 10.44$

$\frac{\beta_{1rad} P_1}{\beta_{3rad} P_3} = 9.60$

**D. Doppler coefficient**

$T \frac{dk}{dT} = -0.002810$ (isothermal)

**E.** $k_{eff} = 1.023821$



# SEFOR third core – First design type – Core B (R 601 D)

## Core power distribution (average core power density = 1)

### Fig. 15

**A. Composition**

1st zone 7 channels

$\eta_f = 0.34$ $\left\{\begin{array}{l} Pu\,239 = 0.1835 \\ Pu\,240 = 0.0165 \\ U\,235 = 0.72 \\ U\,238 = 0.08 \end{array}\right.$

$\eta_{Na} = 0.47$

$\eta_{st} = 0.18$

2nd zone 30 channels

$\eta_f = 0.43$ $\left\{\begin{array}{l} U\,235 = 0.05 \\ U\,238 = 0.95 \end{array}\right.$

$\eta_{Be} = 0.10$

$\eta_{Na} = 0.27$

$\eta_{st} = 0.20$

3rd zone 56 channels

$\eta_f = 0.53$ $\left\{\begin{array}{l} Pu\,239 = 0.13 \\ Pu\,240 = 0.0716 \\ U\,238 = 0.8584 \end{array}\right.$

$\eta_{Na} = 0.27$

$\eta_{st} = 0.20$

**B. Core power density ratios**

$\frac{p_1'}{p_2'} = 10.991$

$\frac{p_1'}{p_3'} = 8.122$

$\frac{\beta_{1rod}\, p_1'}{\beta_{2rod}\, p_2'} = 7.844$

$\frac{\beta_{1rod}\, p_1'}{\beta_{3rod}\, p_3'} = 6.065$

**C. Fuel power density ratios**

$\frac{p_1}{p_2} = 17.13$

$\frac{p_1}{p_3} = 12.66$

$\frac{\beta_{1rod}\, p_1}{\beta_{2rod}\, p_2} = 9.920$

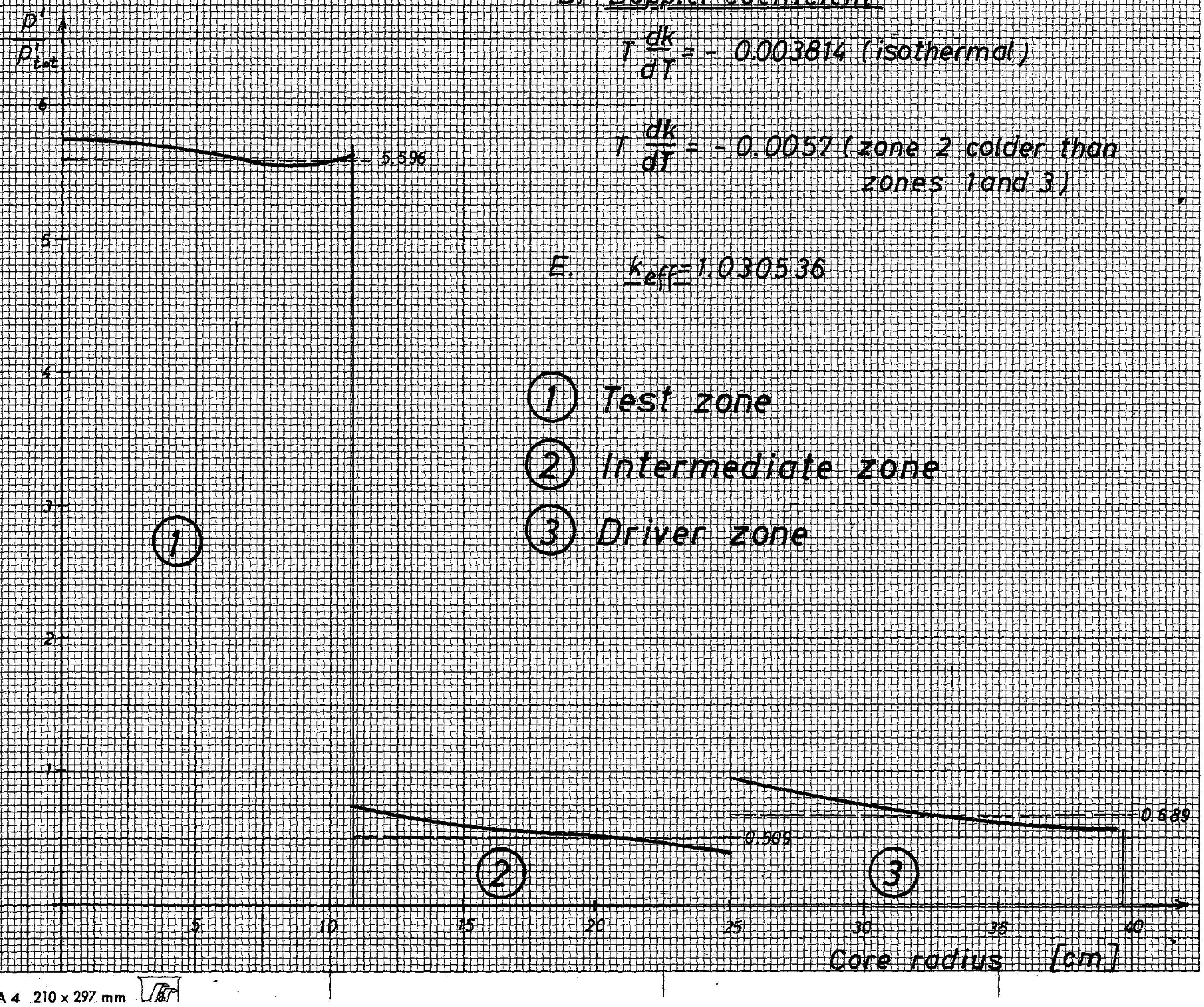
$\frac{\beta_{rod}\, p_1}{\beta_{3rod}\, p_3} = 9.454$

**D. Doppler coefficient**

$T\frac{dk}{dT} = -0.003814$ (isothermal)

$T\frac{dk}{dT} = -0.0057$ (zone 2 colder than zones 1 and 3)

E. $k_{eff} = 1.030536$



# Sefor third core First design type

flux spectrum at center of zone 1 (r = 0)

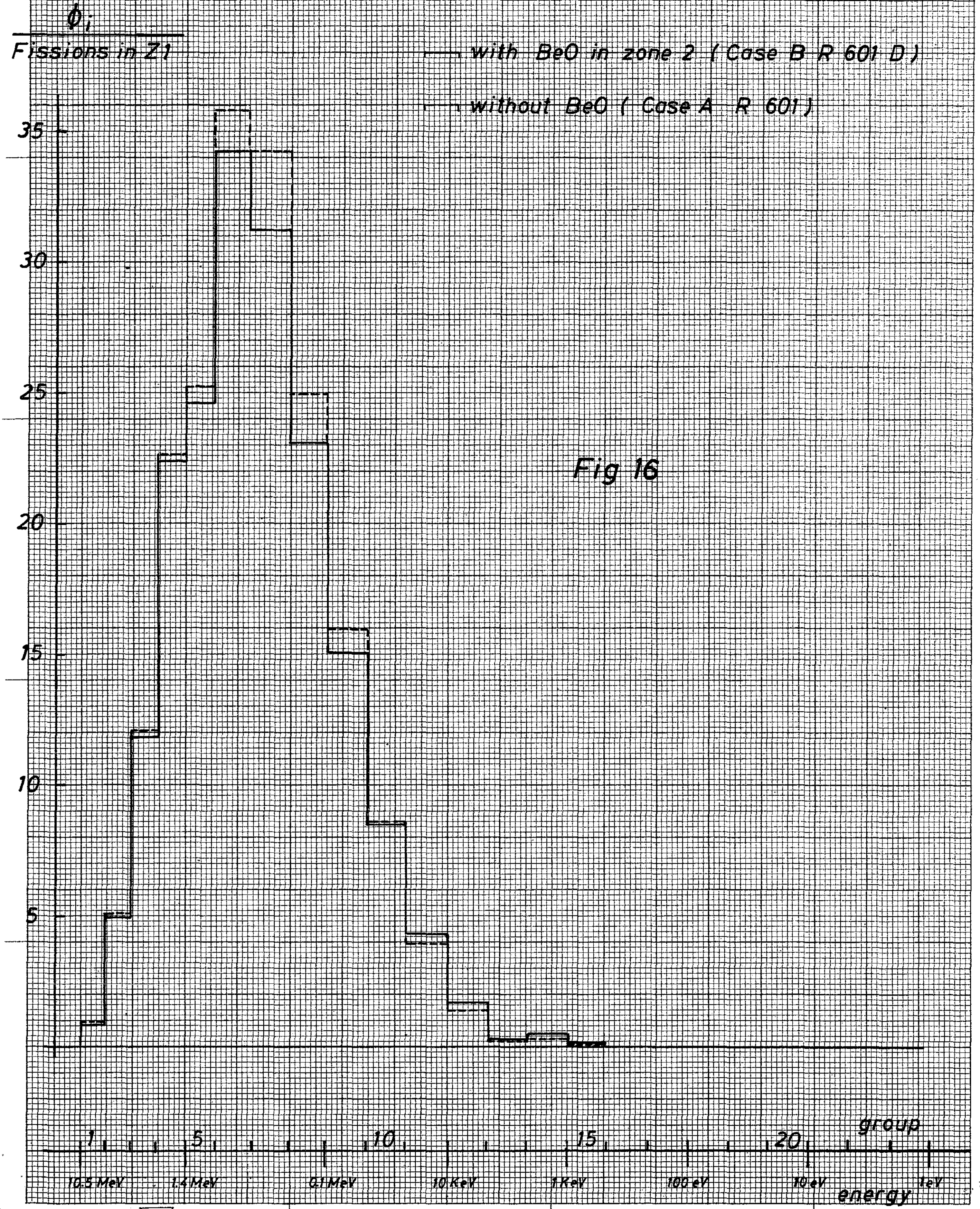
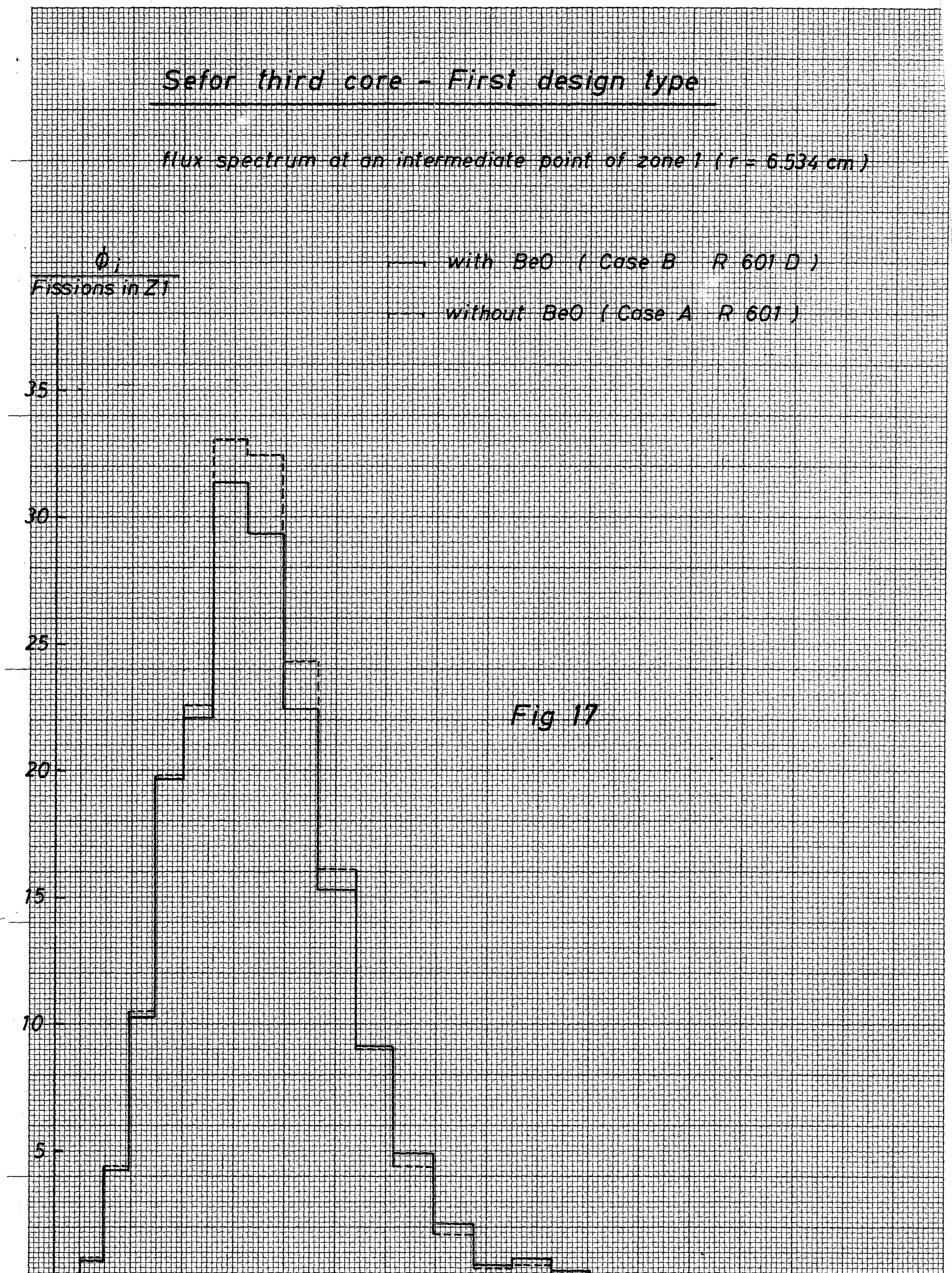



Fig 16

LECTA A 4 210 x 297 mm


Sefor third core - First design type
flux spectrum at an intermediate point of zone 1 ( r = 6.534 cm )
$\phi_i$ / Fissions in Z1
with BeO ( Case B R 601 D )
without BeO ( Case A R 601 )
35
30
25
20
15
10
5
Fig 17
group
1
5
10
15
20
10.5 MeV
1.4 MeV
0.1 MeV
10 KeV
1 KeV
100 eV
10 eV
1 eV
energy

# Sefor third core – First design type

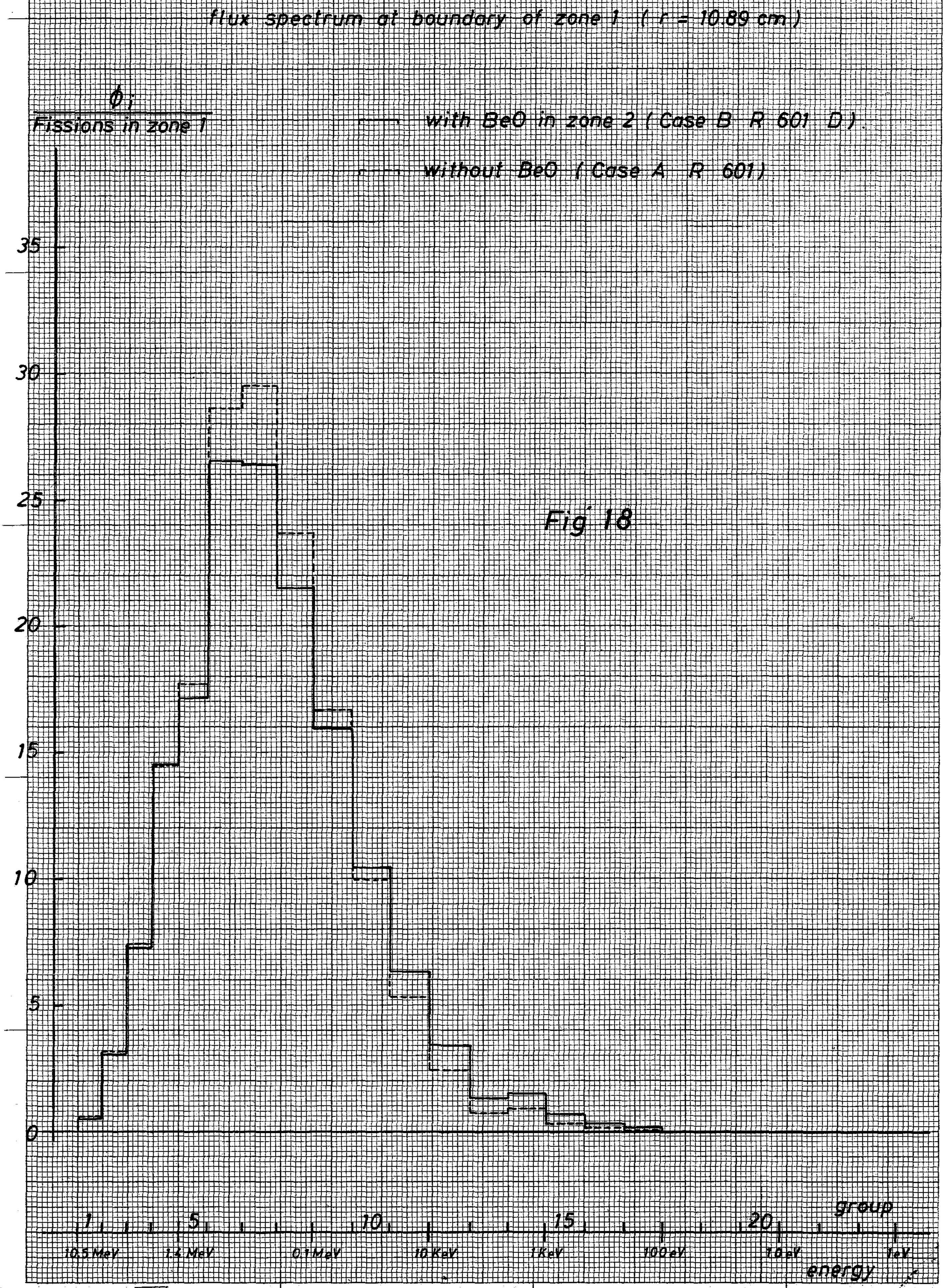
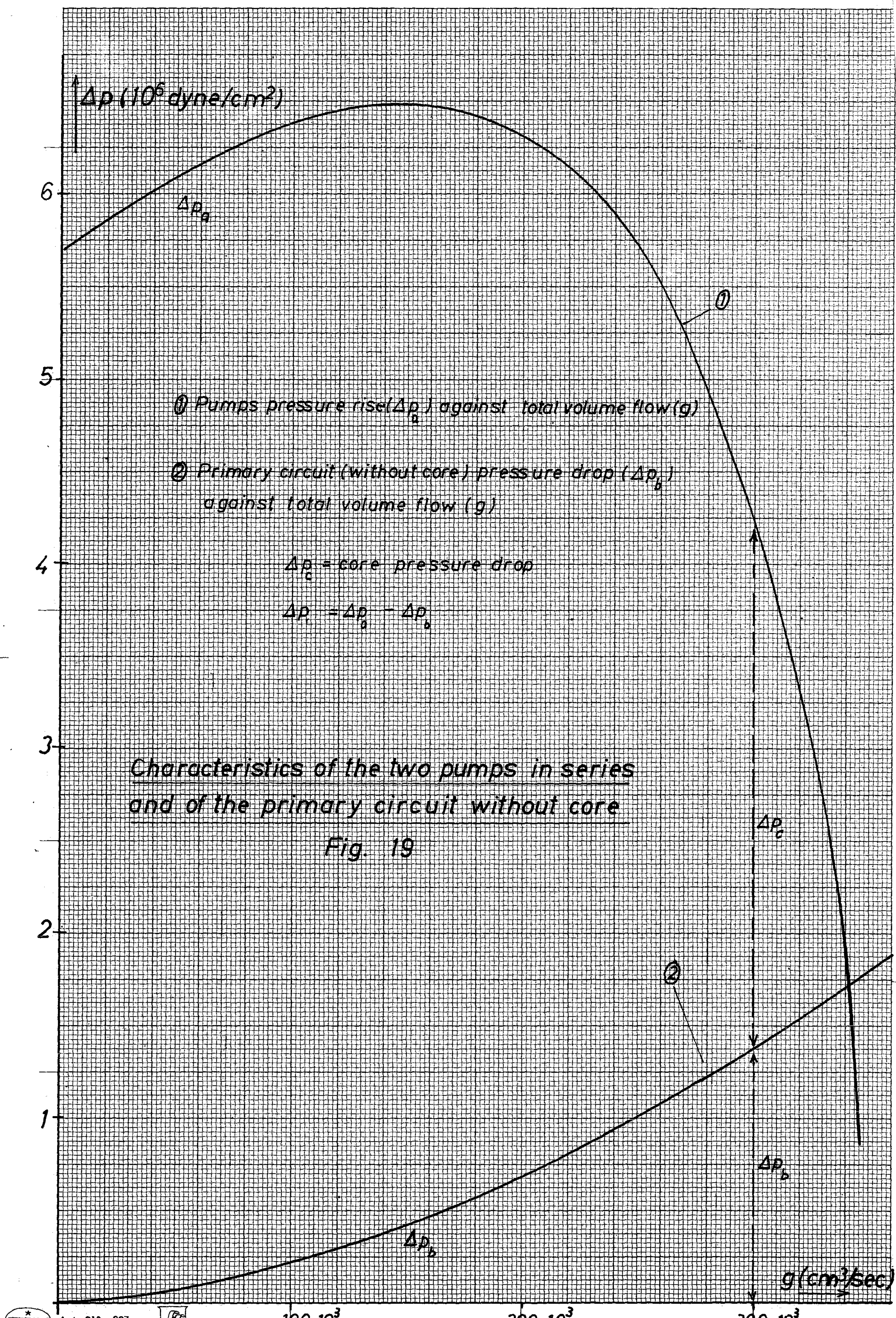
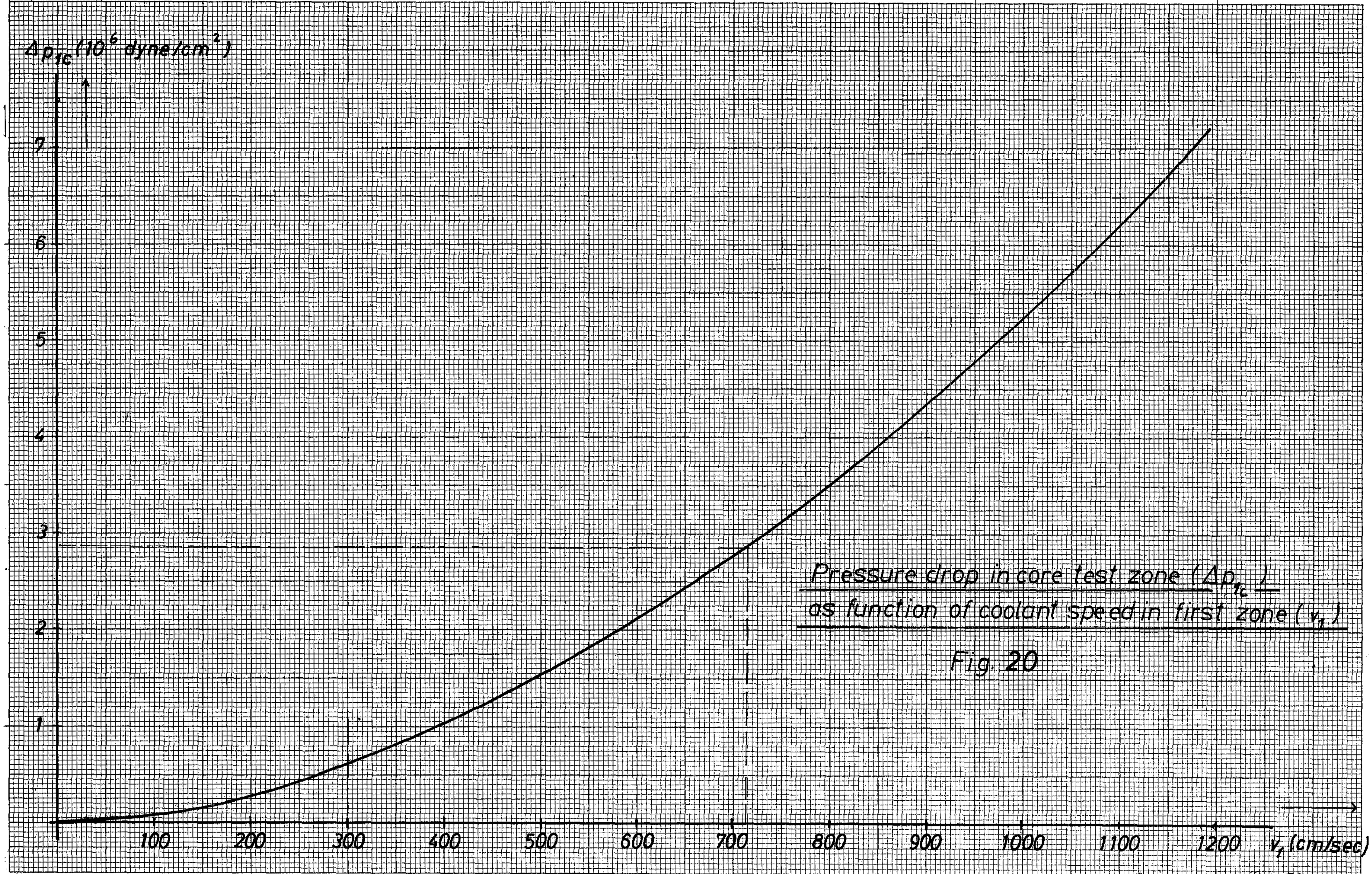



Fig 18




Characteristics of the two pumps in series and of the primary circuit without core

Fig. 19

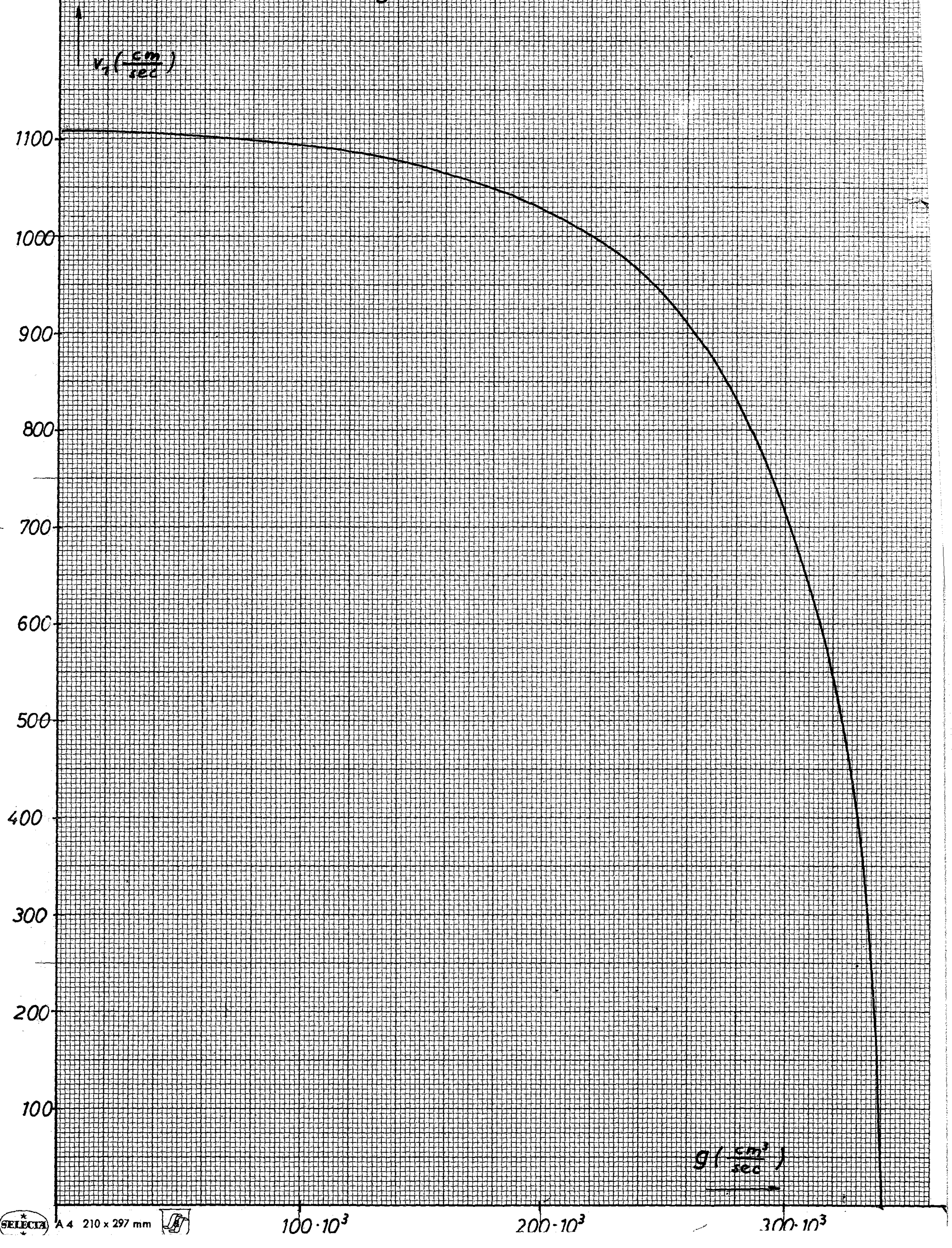


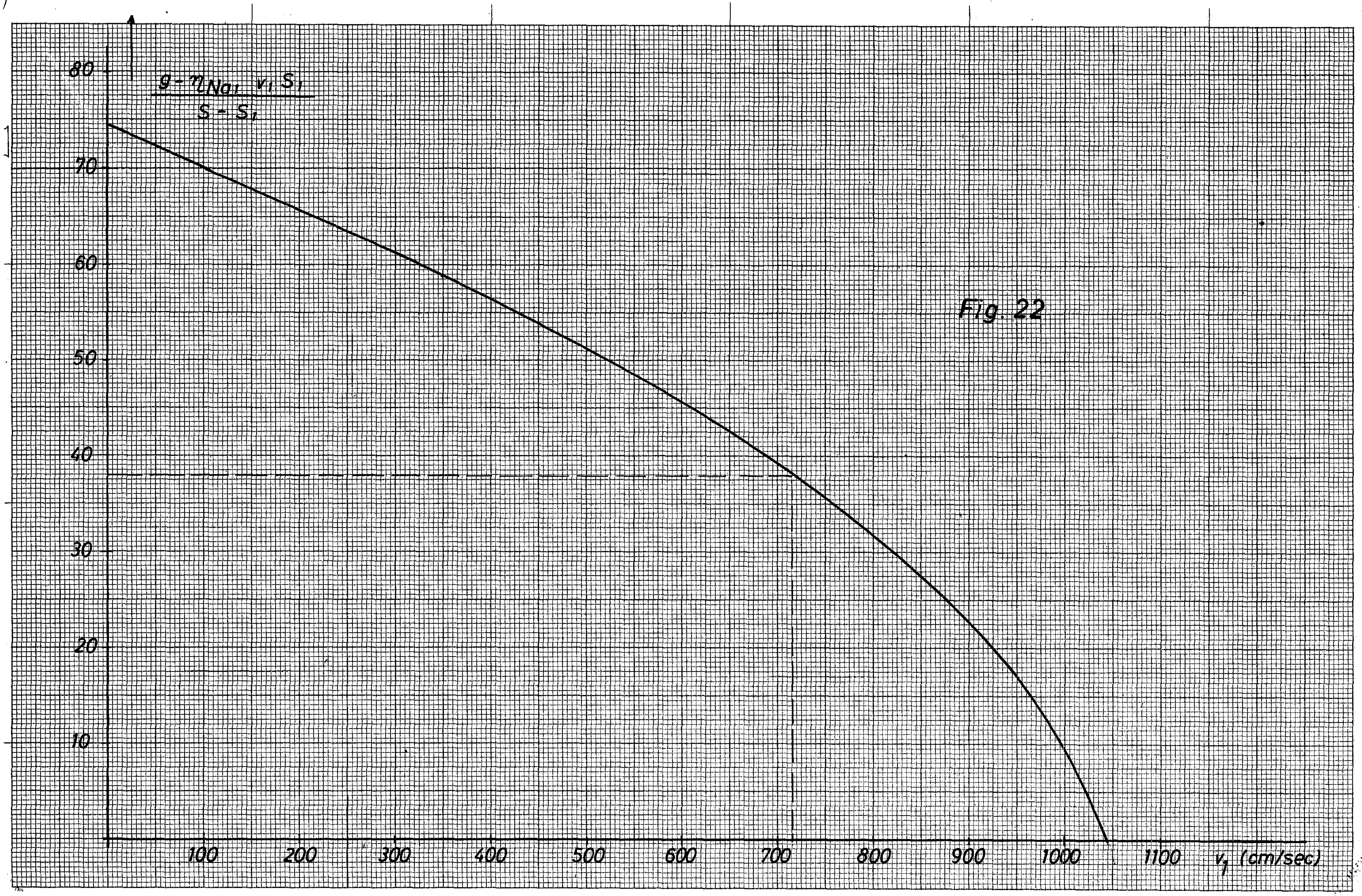

Pressure drop in core test zone ($\Delta p_{1c}$)
as function of coolant speed in first zone ($v_1$)

Fig. 20

Coolant speed in core test zone ($v_z$) as function of total volume flow ($g$)

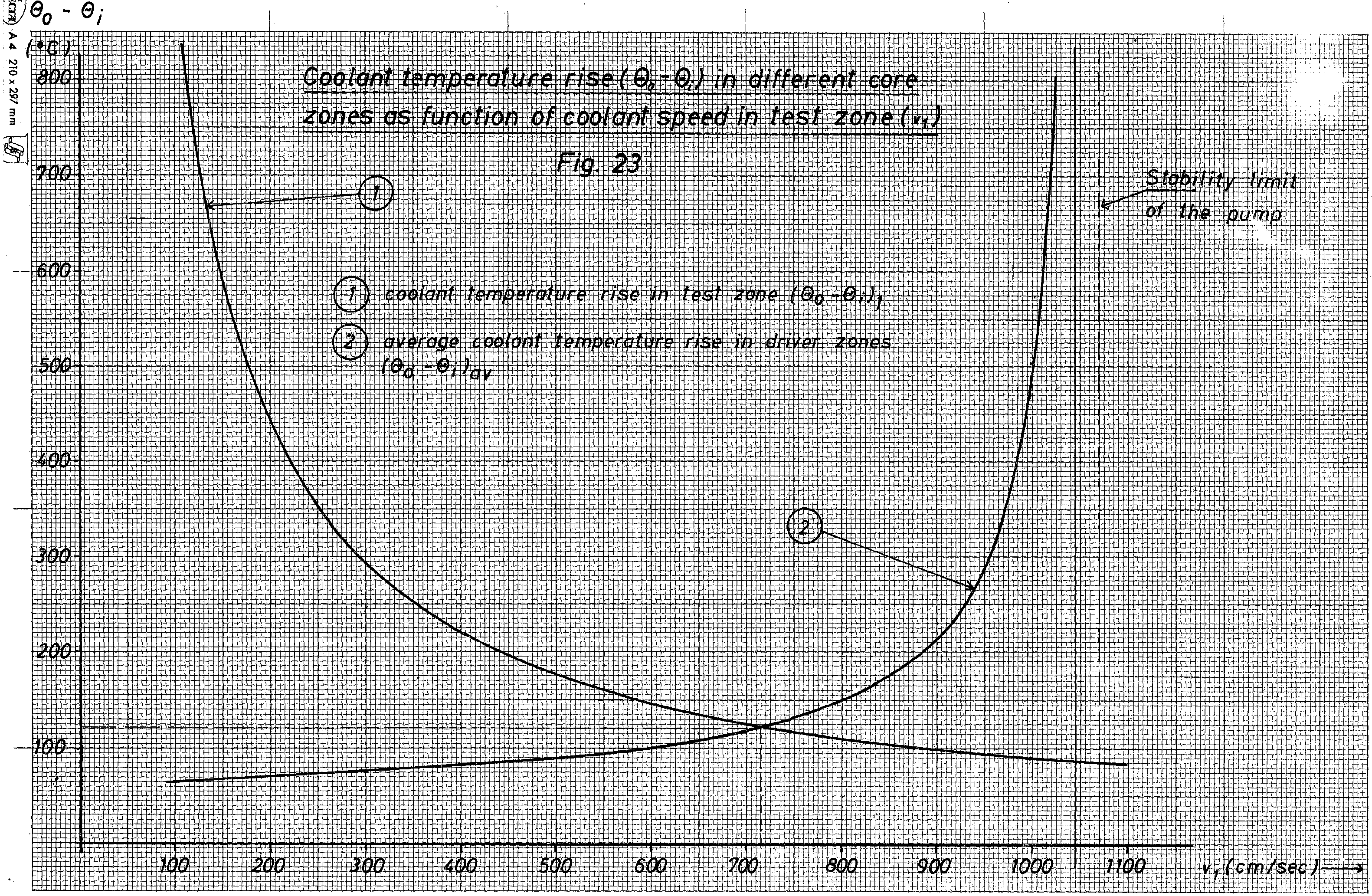
Fig. 21

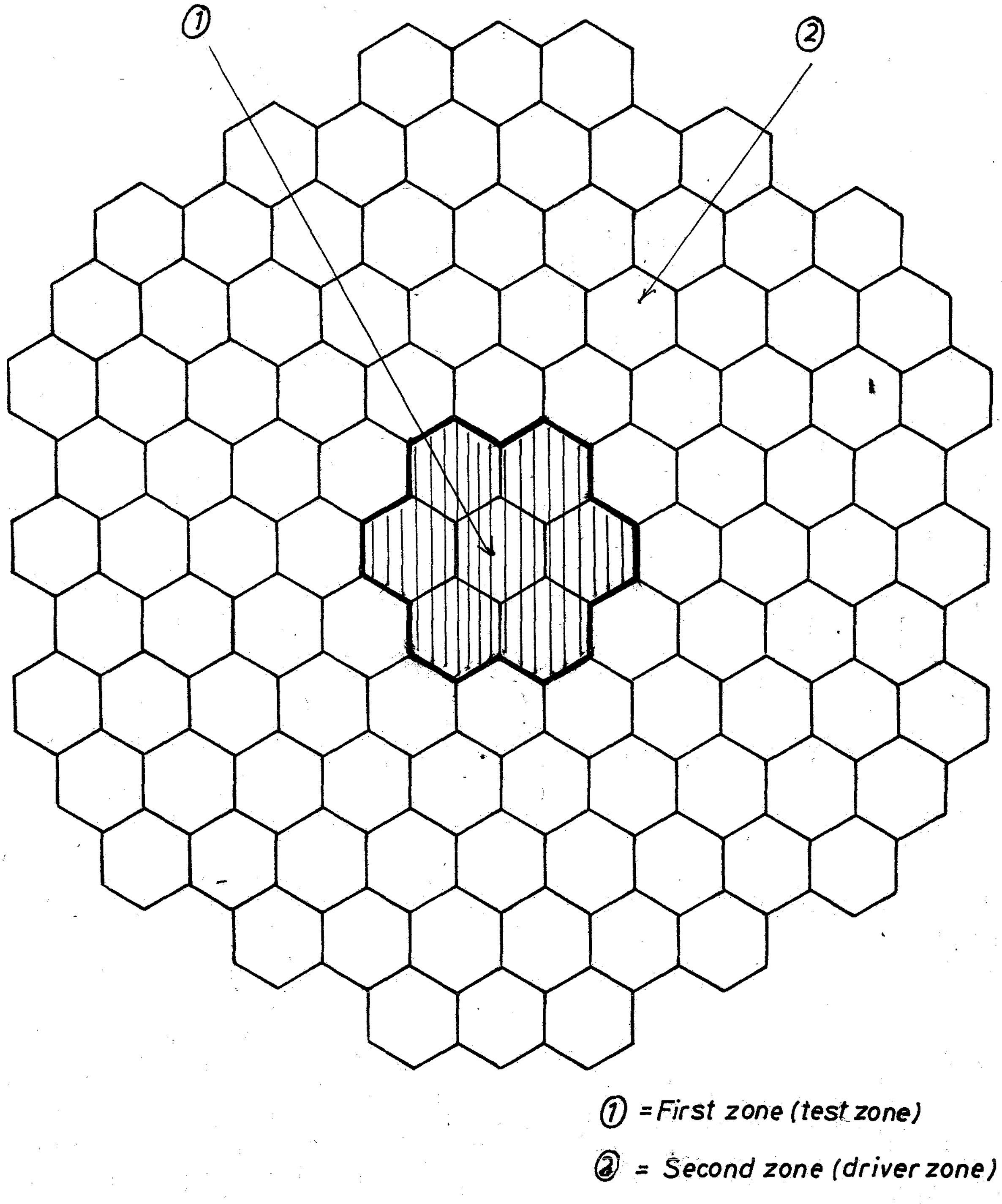




$\frac{g - \eta_{Na_1} \ v_1 \ S_1}{S - S_1}$
80
70
60
50
40
30
20
10
100
200
300
400
500
600
700
800
900
1000
1100
$v_1$ (cm/sec)

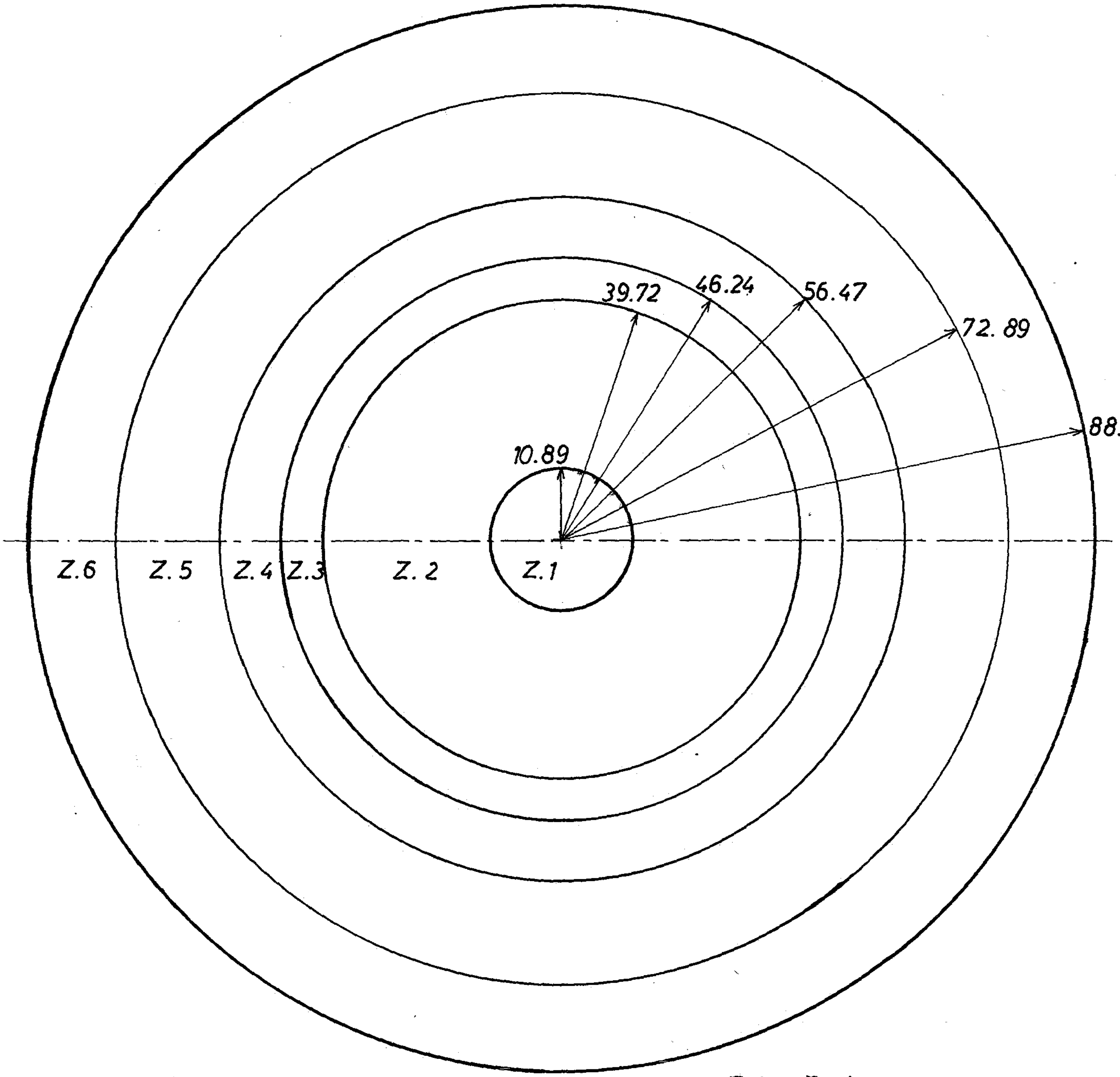

Fig. 22


Coolant temperature rise ($\Theta_o - \Theta_i$) in different core
zones as function of coolant speed in test zone ($v_1$)
Fig. 23
(1) coolant temperature rise in test zone $(\Theta_0 - \Theta_i)_1$
(2) average coolant temperature rise in driver zones $(\Theta_0 - \Theta_i)_{av}$
Stability limit of the pump
1
2
$\Theta_0 - \Theta_i$
(°C)
800
700
600
500
400
300
200
100
100
200
300
400
500
600
700
800
900
1000
1100
$v_1$ (cm/sec)




SEFOR third core - Second design type - Core arrangement

Fig. 24




Z.1 = Test zone
Z.2 = Driver zone
Z.3 = Rand zone
Z. 4 = Shroud zone
Z. 5 = Reflector zone
Z. 6 = Absorber zone

SEFOR third core – Second design type
Schematic diagram showing the radial zones

Fig. 25

## SEFOR third core – Second design type – Case A (R 504)

### Core power distribution (average core power density = 1)

### Fig. 26

A. Composition

1st zone 7 channels

$$\eta_f = 0.34 \quad \eta_{Na} = 0.47 \quad \eta_{st} = 0.18 \quad \begin{cases} Pu\ 239 = 0.1835 \\ Pu\ 240 = 0.0165 \\ U\ 235 = 0.72 \\ U\ 238 = 0.08 \end{cases}$$

2nd zone 86 channels

$$\eta_f = 0.53 \quad \eta_{Na} = 0.27 \quad \eta_{st} = 0.20 \quad \begin{cases} Pu\ 239 = 0.08 \\ Pu\ 240 = 0.007 \\ U\ 238 = 0.913 \end{cases}$$

B. Core power density ratios

$$\frac{P_1'}{P_2'} = 9.71$$

$$\frac{\beta_{1rad} P_1'}{\beta_{2rad} P_2'} = 4.66$$

C. Fuel power density ratios

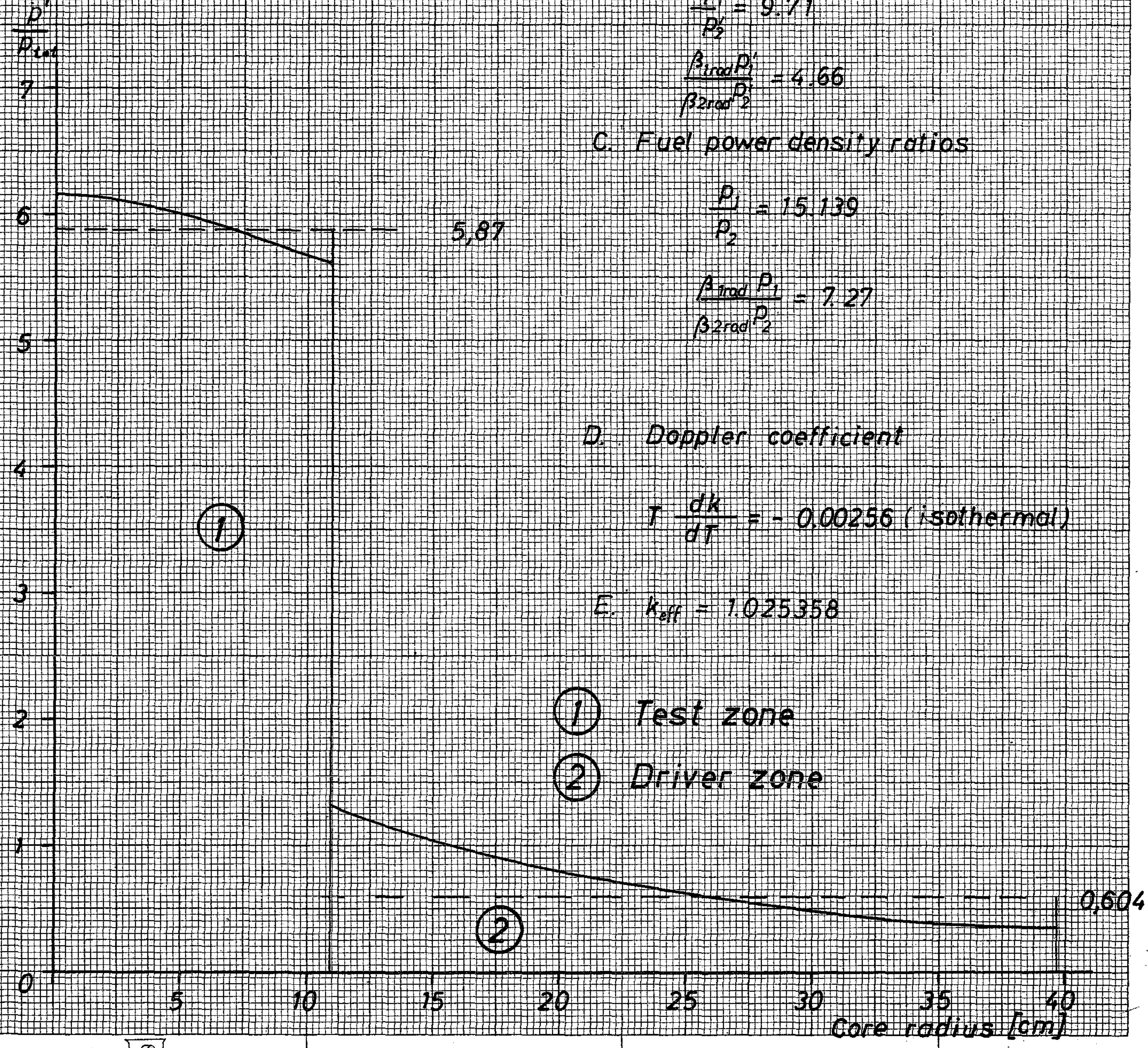
$$\frac{P_1}{P_2} = 15.139$$

$$\frac{\beta_{1rad} P_1}{\beta_{2rad} P_2} = 7.27$$

D. Doppler coefficient

$$T \frac{dk}{dT} = -0.00256 \text{ (isothermal)}$$

E. $k_{eff} = 1.025358$




ECMA A 4 210 x 297 mm

# SEFOR third core - Second design type - Case B (R 301)

## Core power distribution (average core power density=1)

Fig. 27

A. Composition

1st zone 7 channels

$$\eta_f = 0.34 \quad \begin{cases} Pu\,239 = 0.1835 \\ Pu\,240 = 0.0165 \\ U\;235 = 0.72 \\ U\;238 = 0.08 \end{cases}$$

$$\eta_{Na} = 0.47$$

$$\eta_{st} = 0.18$$

2nd zone 86 channels

$$\eta_f = 0.418 \quad \begin{cases} Pu\,239 = 0.087 \\ Pu\,240 = 0.0077 \\ U\,238 = 0.9053 \end{cases}$$

$$\eta_{Be} = 0.112$$

$$\eta_{Na} = 0.27$$

$$\eta_{st} = 0.20$$

B. core power density ratios

$$\frac{P_1'}{P_2'} = 11.72$$

$$\frac{\beta_{1rad} P_1'}{\beta_{2rad} P_2'} = 5.72$$

C. fuel power density ratios

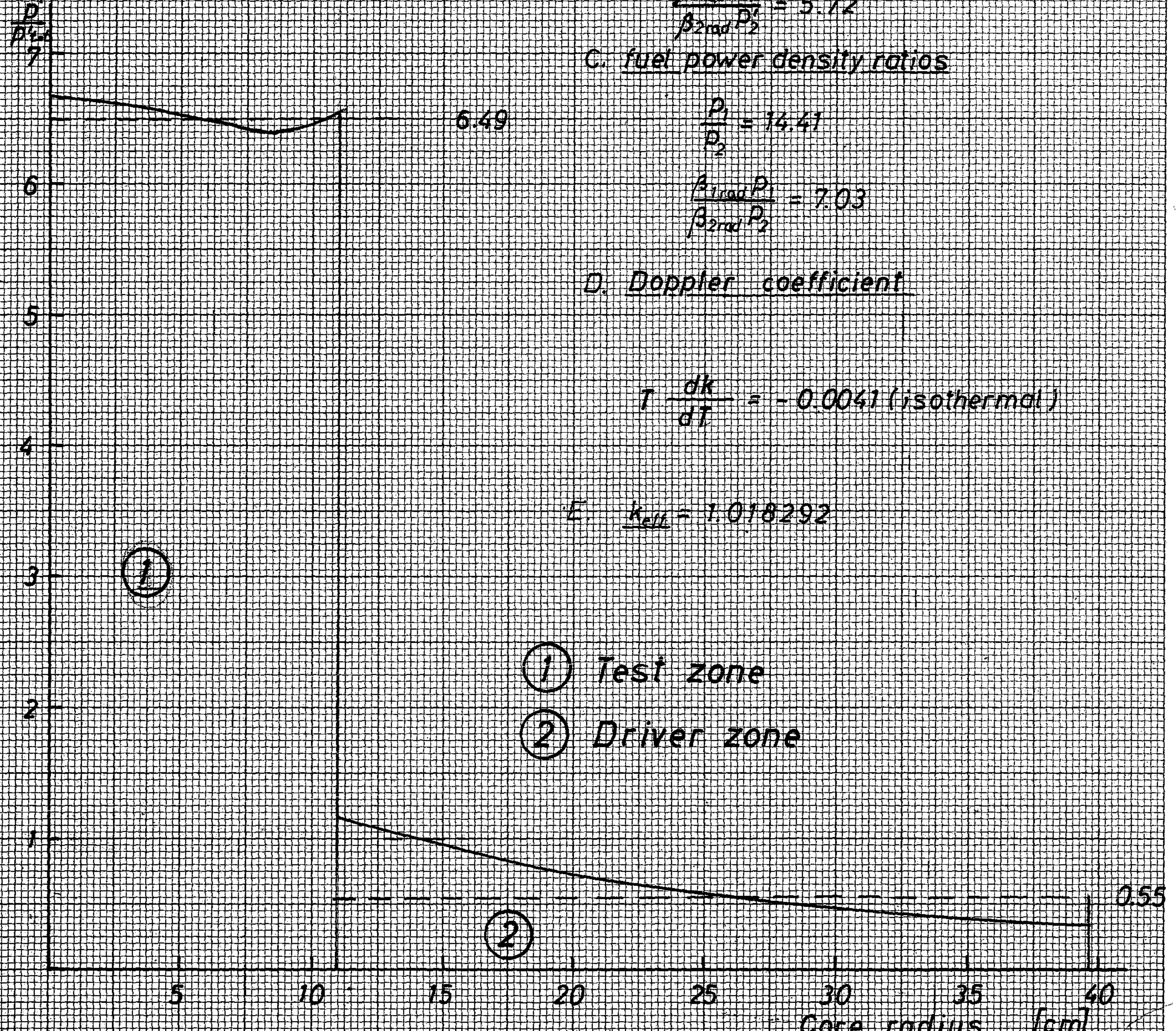
$$\frac{P_1}{P_2} = 14.41$$

$$\frac{\beta_{1rad} P_1}{\beta_{2rad} P_2} = 7.03$$

D. Doppler coefficient

$$T \frac{dk}{dT} = -0.0041 \text{ (isothermal)}$$

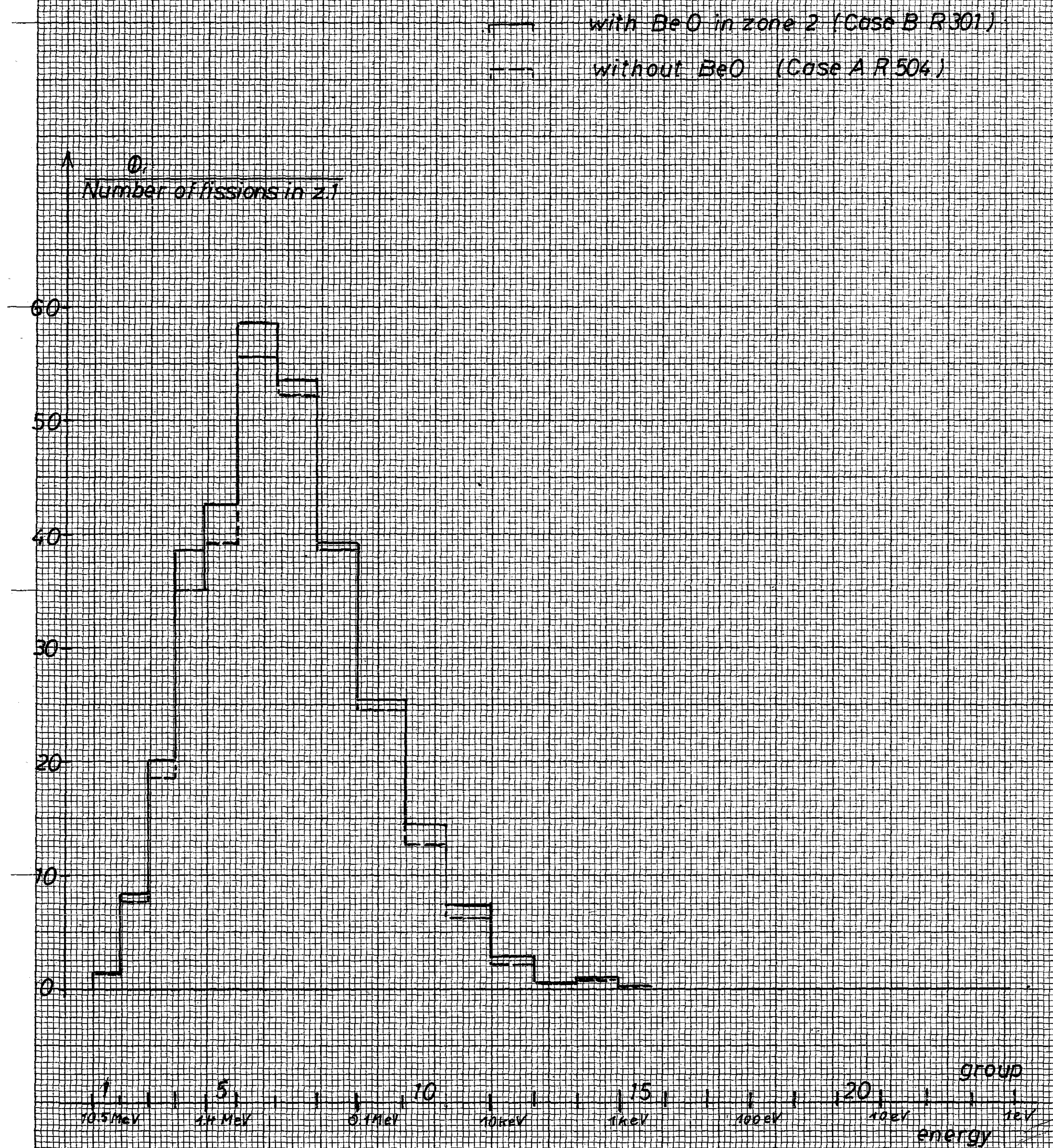
E. $k_{eff} = 1.018292$



SEFOR third core – Second design type

flux spectrum at center of zone 1 (r = 0)

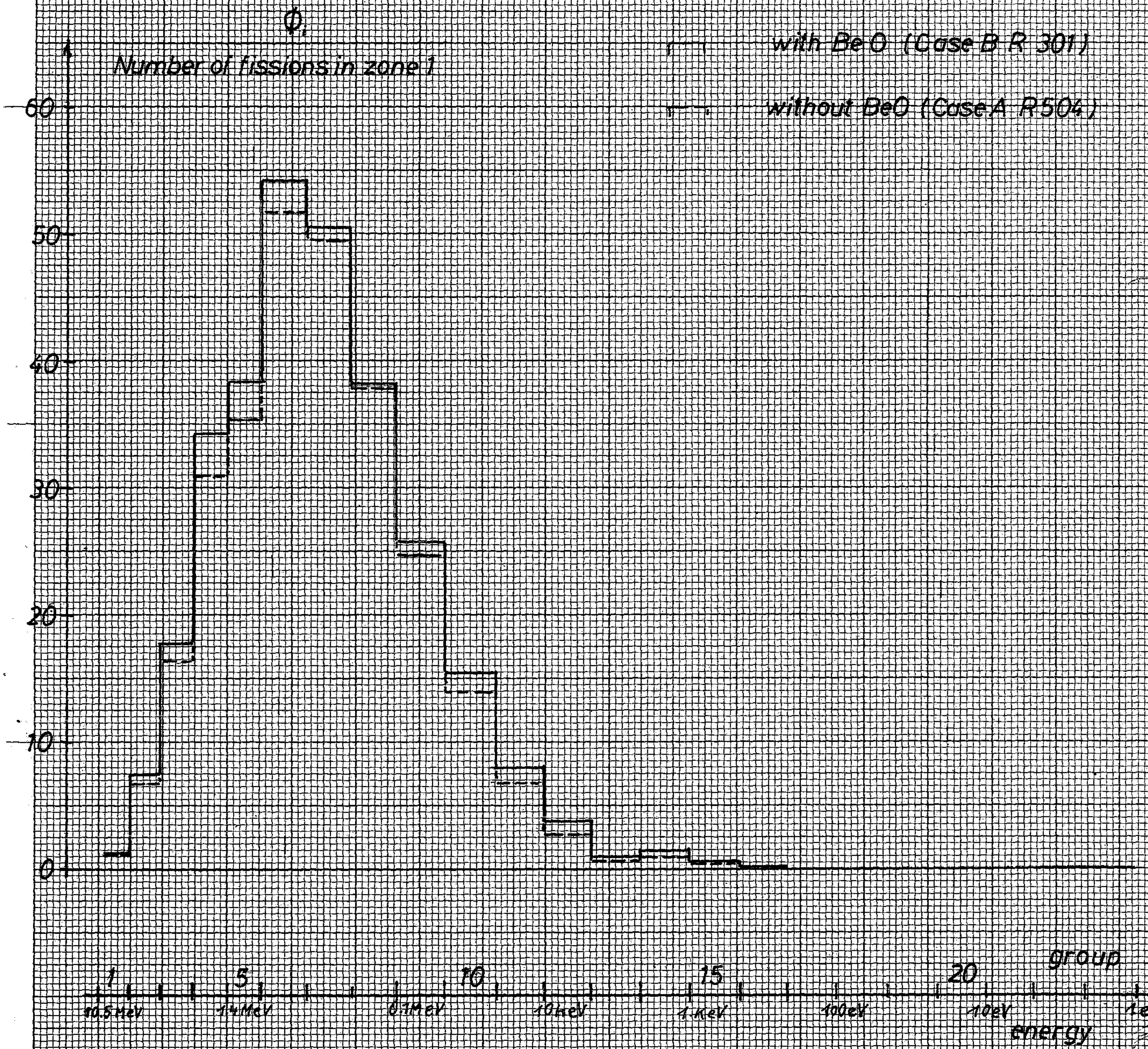
Fig. 28



SEFOR third core - Second design type flux spectrum at an intermediate point of zone 1

( r = 6.534 cm)

Fig. 29



SEFOR third core - Second design type flux spectrum at boundary of zone 1

($r = 10.89$ cm)

Fig. 30