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EUROPEAN ATOMIC ENERGY COMMUNITY - EURATOM

A METHOD FOR DETERMINATION OF CONVERTIBLE NUCLEAR HEATING DATA

by

H. KRÖCKEL

1970

Joint Nuclear Research Center
Petten Establishment - Netherlands

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Printed by Guyot, s.a.
Brussels, April 1970

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Numerical coefficients of this expression are given for materials C, Be, Mo and Fe as function of sample size.

A test rig, CADO-17 for measurements in the High Flux Reactor (HFR) at Petten is described; the chosen sample materials are C, Be and Mo.

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ABSTRACTS

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The energy distributions are approximated by expressions containing three unknown parameters which appear, after insertion, as three unknown linear constants in the heating equation.

By setting up this equation for three different materials, a system of three linear equations is obtained, the coefficients of which are computable functions.

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The known solution can be used for calculation of nuclear heating data for any desired sample size and material by the same linear expression.

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KEYWORDS

HEATING
GAMMA RADIATION
NEUTRONS
NUMERICALS
ENERGY
SPECTRA
INTEGRAL EQUATIONS
GRAPHITE
BERYLLIUM
MOLYBDENUM
IRON
CAPSULES
HFR

CONTENTS

A METHOD FOR DETERMINATION OF CONVERTIBLE NUCLEAR HEATING DATA*)

1.0. INTRODUCTION

Calculation of nuclear heat generation in non-fuel materials of the High Flux Reactor (HFR) at Petten is in general based on measured values, which are obtained by special calorimeter probes.

Although the presently available data are in themselves rather complete, there exists a considerable lack of means to apply them to conditions, which are different from the test conditions.

Particular difficulties are encountered, if the data are to be converted to objects having other geometry, size or material as the test sample.

These difficulties arise, because the nuclear heat generation, which is a result of several energy absorption processes of gamma and neutron radiation, is measured by calorimetric methods in integral form, which does not reveal the contribution of the individual process.

Data conversion however requires the knowledge of the contribution of each absorption process to the overall effect.

The functional dependency of a process on the sample parameters has the form of an energy integral of geometry and material dependent parameters, in which only the energy distributions (more correctly the "energy spectral densities of the number fluxes") of neutron and gamma particles appear as unknowns.

If these energy distributions are known, then the proportionate contributions of the absorption processes can be determined, so that the conversion problem can be solved.

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*) Manuscript received on 10 October 1969.

Since the gamma energy distribution, which is the more important one of the two, is not known for the HFR, some conversion relations had earlier been derived on basis of an assumed distribution.

Although by this evaluation, useful numerical results could be obtained, it is desirable to proceed to a method, in which no explicit assumptions on the energy distributions are needed and which also covers the influence of the neutron radiation.

Such a method must necessarily be based on a detailed analysis of the energy absorption processes involved and must be directed on determination of parameters, which are representative for the gamma and neutron energy distributions existing in the reactor.

The method described here, is laid out for determination of 3 constants, 2 representing the gamma and 1 the neutron distribution.

The description of these distributions by expressions containing 2 resp. 1 parameters is, of course, very approximate and will only be satisfactory for investigations of nuclear heating and similar effects.

The experimental principle of this method follows in some lines that of ref. 1, where 2 parameters are determined, which relate the gamma and neutron heating of a material to the corresponding values, measured in C.

2.0. SYNTHESIS OF NUCLEAR HEAT GENERATION

The main effects contributing to nuclear heat generation in non-fuel materials in the HFR are the following :

1. Core gamma radiation absorption, P_{γ}
2. Core neutron elastic scattering energy degradation, P_{nn}
3. Thermal neutron capture induced gamma absorption, $P_{n\gamma}$
4. Inelastic scattering (fast neutron) induced gamma absorption, $P_{ni\gamma}$
5. Activation product gamma and β absorption P_{ndecay}.

There are other minor sources of heat generation, such as effects of (n,α) and (n,p) reactions and others, which are however neglected here.

The 5 above mentioned heat sources are not equally important, and some of them have negligible contribution for some materials. In all cases, the dominant role is played by $P\gamma$.

The total effect is combined in the form :

$$P = P_{\gamma} + P_{n} \qquad (1)$$

$$P_{n} = P_{nn} + P_{n\gamma} + P_{ni\gamma} + P_{ndecay} \qquad (2)$$

2.1. Heat Generation by Core Gamma Absorption P_{γ}

The heat generation at a point with the local coordinate r in a sample due to gamma absorption is given in ref. 2 as :

$$P_{\gamma}(r) = \int_{0}^{\infty} \frac{\mu_a}{\rho}(E) \cdot N(E,r) \cdot E \, dE \qquad (3)$$

The spectral number flux density at r, $N(E,r)$ is obtained from the undisturbed flux density $N_o(E)$ by multiplication with a factor which is, according to ref. 3, equal to the escape probability p(r) from the same body for a homogeneous internal source distribution; if linear exponential attenuation is considered :

$$N(E,r) = N_o(E) \cdot p(r) \tag{4}$$

The average escape probability is :

$$p_o = \frac{1}{V} \int_V p(r)dV \tag{5}$$

The average heating is :

$$P_\gamma = \frac{1}{V} \int_V P_\gamma(r)dV = \int_o^\infty \frac{\mu_a}{\rho} \cdot E \cdot \frac{1}{V} \int_V N(E,r)dVdE \tag{6}$$

(7)

Herein :

$$\frac{1}{V} \int_V N(E,r)dV = \frac{N_o}{V} \int_V p(r)dV = N_o P_o \tag{8}$$

And finally :

$$P_\gamma = \int_o^\infty \frac{\mu_a}{\rho} \cdot N_o \cdot p_o \cdot E \, dE \tag{9}$$

Alternative Derivation

This result can be derived in an alternative way on basis of the total amount of incoming photons n_o (spectral) and the fraction of collisions F_c :

$$P_\gamma = \frac{1}{\rho V} \int_o^\infty \frac{\mu_a}{\mu} \cdot F_c \cdot n_o E dE \tag{10}$$

In ref. 3 one finds the relation :

$$n_o = N_o \cdot \frac{S}{4} \tag{11}$$

and the definition of the average chord R_{av}, which represents the mean of all possible penetrations through a body :

$$R_{av} = \frac{4V}{S} \tag{12}$$

Introduction of these terms in eq. (10) yields :

$$P_\gamma = \int_0^\infty \frac{\mu_a}{\rho} N_o \frac{F_c}{\mu R_{av}} E \, dE \qquad (13)$$

Eqs. (9) and (13) are equal if :

$$p_o = \frac{F_c}{\mu R_{av}} \qquad (14)$$

The proof that relation (14) holds, is given in ref. 6.

Since in eqs. (9) and (13) the effect of secondary gammas (scattering gammas) is neglected, these expressions give underestimated values for P_γ, which are corrected by introduction of the energy absorption build-up factor B_a, which is applied in the linear form proposed in ref. 4 :

$$B_a(E,\mu r) = 1 + (\frac{\mu}{\mu_a} - 1)\, \mu r \qquad (15)$$

With use of the mean value $r = \frac{1}{2} R_{av}$ in eq. (15), eq. (9) becomes:

$$P_\gamma = \int_0^\infty \frac{\mu_a}{\rho} \left[1 + \frac{1}{2}(\frac{\mu}{\mu_a} - 1)\mu R_{av}\right] p_o N_o E dE \qquad (16)$$

The average escape probability p_o is a function of photon energy and sample geometry. Calculations of p_o are rather extensive. For simple geometries, tabulated results can be found in ref. 3; among them are tables for slabs, spheres, half-spheres and infinitely long cylinders.

The result for infinite cylinders is reproduced in fig. 1. It can also be used with good accuracy for length to diameter ratios L/D >0.5, if one replaces χ by the parameter :

$$\chi = \frac{1}{2} \mu R_{av}, \qquad (17)$$

where R_{av}, defined by eq. (12), is for cylinders :

$$R_{av} = \frac{D}{1+\frac{1}{2}D/L} \tag{18}$$

Definition (17) permits the shorter form of eq. (16) :

$$P_\gamma = \int_o^\infty \frac{\mu_a}{\rho} \left[1+\left(\frac{\mu}{\mu_a}-1\right)\chi\right] .p_o(\chi).N_o.E.dE \tag{19}$$

Other geometries than cylinders can be treated in analogue form on the basis of ref. 3.

2.2. Heat Generation due to Core Neutron Radiation P_n

2.2.1. Heat Generation by Elastic Scattering P_{nn}

In ref. 2 the following expression is given for neutron heating by elastic scattering :

$$P_{nn}(r) = \int_o^\infty \frac{\overline{\Delta E}}{\rho}(E).\ \Sigma_s(E)\ \emptyset\ (E,r)\ dE, \tag{20}$$

where the mean energy degradation per collision $\overline{\Delta E}$ is :

$$\overline{\Delta E} = E\ .\ \frac{2A}{(A+1)^2} \tag{21}$$

Analogue to sect. 2.1., the local flux density can be expressed by the undisturbed flux density and a probability. The volume average has the form :

$$P_{nn} = \frac{2A}{(A+1)^2}\ .\ \frac{1}{\rho}\int_o^\infty \Sigma_s(E).\emptyset_o(E).p_o(\chi_T).E.dE \tag{22}$$

where in this equation :

$$\chi_T = \frac{1}{2}\Sigma_T R_{av} \tag{23}$$

and $p_o(\chi)$ is taken from fig. 1, R_{av} corresponding to eq. (18). Graphs of Σ_s and Σ_T are presented in ref. 4.

2.2.2. Heat Generation by Capture Gamma Radiation $P_{n\gamma}$

For the (n,γ) reaction following thermal neutron capture is assumed, that it has a spatial distribution in the sample producing a homogeneous gamma source distribution.

Under this condition the heating due to capture gammas can be expressed by

$$P_{n\gamma} = \frac{1}{\rho}.\Sigma_a.\phi_{oth}.p_o(\chi_n).\int_o^\infty B_a \frac{\mu_a}{\mu}.p_c(\chi).q_{n\gamma}(E).E\ dE \tag{24}$$

where

$$\phi_{oth} = \int_{E_{th}} \phi_o(E)dE \tag{25}$$

is the thermal neutron flux density. The build up factor B_a is:

$$B_a = 1 + (\frac{\mu}{\mu_a}-1).\ \chi \tag{26}$$

In view of the information available in ref. 2, the integral can better be expressed as a sum over discrete energy intervals ΔE_i in the form :

$$\int_o^\infty B_a \frac{\mu_a}{\mu}.p_c(\chi).q_{n\gamma}(E).EdE \approx \sum_{i=1}^{N} \frac{\mu_a}{\mu}(E_i).p_c(\chi).E_i.B_a \int_{\Delta E_i} q_{n\gamma}dE \tag{27}$$

In this expression, $p_c(\chi)$ is the collision probability

$$p_c(\chi) = 1-p_o(\chi) \ , \tag{28}$$

In the preceding equations, χ is defined by eq. 17 and χ_n by

$$\chi_n = \frac{1}{2} \Sigma_{thT} R_{av}. \tag{29}$$

The integrals

$$\int_{\Delta E_i} q_{n\gamma}(E_i)dE = S(E_i) \tag{30}$$

are tabulated in ref. 2 for 7 gamma energy intervals and for all important materials. Eq. (24) can therefore be written :

$$P_{n\gamma} = \frac{1}{\rho}\Sigma_a \cdot \phi_{oth} \cdot p_o(\chi_n) \cdot \sum_{i=1}^{7} B_a \frac{\mu_a}{\mu}(E_i).p_c(\chi).E_i.S(E_i) \tag{31}$$

$P_{n\gamma}$ is in general negligible for materials having comparably small absorption cross sections.

2.2.3. Heating by Fast Neutron Inelastic Scattering Gamma Radiation $P_{ni\gamma}$

In the few cases, where inelastic scattering (fast neutrons) induced gamma radiation contributes to the heating, one can treat the induced gammas as monoergetic with energy z_γ.

Under analogue conditions as in sect. 2.2.2, the heating can then be expressed as :

$$P_{ni\gamma} = \frac{B_a}{\rho} \frac{\mu_a}{\mu}(E_\gamma).p_c(\chi).E_\gamma . \int_o^\infty \Sigma_{ni\gamma}(E_\gamma, E_n)\phi_o(E_n)P_o(\chi_T)dE_n, \tag{32}$$

where B_a is defined by eq. 26. Furthermore :

$$p_c(\chi) = 1-p_o(\chi) \tag{33}$$

and

$$\chi = \frac{1}{2}\mu R_{av} \tag{34}$$

$$\chi_T = \frac{1}{2}\Sigma_T R_{av} \tag{35}$$

Cross section data are available in ref. 4 .

2.2.4. Heating by Activation Product Decay Radiation. P_{ndecay}

In some cases, thermal neutron capture generated nuclides contribute to the heating by their decay gamma and beta radiation.

For calculation, it is again assumed, that the gamma and beta source distributions are homogeneous. The decay radiation normally originates from a nuclide, which was generated by neutron capture in an isotope, the natural abundance of which in the material under consideration is y_n.

The source strength therefore is

$$y_n \cdot \Sigma_a \cdot \phi_{oth} \cdot p_o(\chi_n) \tag{36}$$

If the decay gamma and beta energies are E_γ and E_β, the partial heating terms are :

$$P_{ndecay\gamma} = \frac{B_a}{\rho}\,\frac{\mu_a}{\mu}\,(E_\gamma) \cdot p_c(\chi) \cdot E_\gamma \cdot y_n \cdot \Sigma_a \cdot \phi_{oth} \cdot p_o(\chi_n) \tag{37}$$

$$P_{ndecay\beta} = \frac{1}{\rho} \cdot p_c(\chi_\beta) \cdot E_\beta \cdot y_n \cdot \Sigma_a \cdot \phi_{oth} \cdot p_o(\chi_n) \tag{38}$$

where B_a is defined by eq. 26 and

$$\chi_n = \frac{1}{2} \Sigma_{thT} \cdot R_{av} \tag{39}$$

$$\chi = \frac{1}{2} \mu(E_\gamma) . R_{av} \tag{40}$$

$$\chi_\beta = \frac{1}{2} \cdot \mu_\beta \cdot R_{av} \tag{41}$$

The total decay radiation heating must be summed up from the partial heating terms according to the decay characteristics of the involved nuclides, so that

$$P_{ndecay} = \Sigma P_{ndecay\gamma} + \Sigma P_{ndecay\beta} \tag{42}$$

The relations derived above apply to equilibrium conditions, which are reached only after a time of several half lives of the decaying nuclide.

3.0 ENERGY DISTRIBUTIONS OF GAMMAS AND NEUTRONS

The three types of parameters of the preceding sections :

Attenuation coefficients or cross sections,
Geometry averaged reaction probabilities,
Particle energy distributions

are direct or indirect functions of particle energies; the energy distributions of neutrons and gammas therefore constitute the key to heating calculations.

Energy distributions of neutron flux densities in the HFR are in general available by 4 group computer codes of the neutron metrology group (RCN).

The -for heat calculations- more important gamma energy distributions are unknown in the operating reactor.

The calculations of gamma heating terms are therefore based on a double exponential approximation of the energy distribution with two unknown linear constants.

3.1 Approximation of the Gamma Energy Distribution

The gamma energy distribution of the operating reactor is a result of the interactions of the prompt fission spectrum and the fission product decay spectrum with the materials of the core region.

In general, this distribution is a rather complicated function of the configuration and can only very summarily be expressed by a two parameter approximation.

In the higher energy region (E>1MeV) the prompt and fission product spectra show an exponential form, approximated in ref. 5 by a function $e^{-1.1E}$. Other measurements, mentioned in ref. 5, which include also capture gammas, suggest a form $e^{-1.24E}$.

Since in the present case ^{28}Al decay will cause appreciable increases of a distribution in the range E<1.3, one can assume, that the exponent -1.24 will be more realistic for the HFR.

In the range E<1MeV ref. 5 suggests $e^{-2.3E}$ for the prompt gammas. However, a great contribution of degraded higher energy photons must be expected in this region; the actual spectrum can therefore be expected to have an exponent <-2.3. For convenience, -2.5 is chosen; the distribution is therefore approximated by the expression

$$N_o(E) = A_o \cdot \frac{\phi_s}{E_s} \cdot e^{-1.25E} + B_o \cdot \frac{\phi_s}{E_s} e^{-2.50E} \qquad (43)$$

The exponents -1.25 and -2.50 have the dimensions MeV^{-1}, if E is taken in MeV.
The multiplication with $\frac{\phi_s}{E_s}$ is applied in order to make A_o and B_o non-dimensional.
The gamma energy distribution could also be approximated by various other two parameter expressions, but in view of the presentation in ref. 5, the exponential form is preferred here.

3.2. Approximation of the Neutron Energy Distribution

For the approximation of the neutron energy distributions, results of the TEDDI-HFR 4 group code are used as a basis. These results refer to the integrated energy spectral densities of the neutron flux in the form

$$\phi_n = \int_{E_{Ln}}^{E_{Un}} \phi(E)dE \ , \quad n = 1...4 \qquad (44)$$

where the following energy limits are attributed to the group :

ϕ_1 : E_{L1} = 1.35 MeV E_{U1} = 10 MeV

ϕ_2 : E_{L2} = 67.4 keV E_{U2} = 1.35 MeV

ϕ_3 : E_{L3} = 0.625 eV E_{U3} = 67.4 keV

ϕ_4 : E_{L4} = 0 E_{U4} = 0.625 eV

One can derive from the TEDDI results, that the group fluxes ϕ_n are roughly equally related to each other in all central positions and also, but functionally slightly different, for peripheral positions of the HFR.

These two forms can be approximated by :

$$\frac{\phi_n}{\phi_1} = 1 + 0.70(n-1) - 0.05(n-1)^3 \qquad (45)$$

$$n = 1 \ldots 4$$

$$\frac{\phi_n}{\phi_1} = 1 + 0.75(n-1) \qquad (46)$$

for central (45) and peripheral (46) positions, respectively. The characteristic ratio

$$\frac{\phi_1 + \phi_2}{\phi_4} \qquad (47)$$

is by these approximations 1.51 for central positions and 0.85 for peripheral positions.

For a given core position, relation (45) or (46) can be used to approximate the neutron energy distribution in group representation by

$$\int_{E_{Ln}}^{E_{Un}} \phi_o(E)dE = C_o \cdot \frac{\phi_n}{\phi_1} \cdot \phi_s \ , \qquad (48)$$

where the factor ϕ_s is used for obtaining a non-dimensional form of C_o.

4.0 SOLUTION OF THE HEAT GENERATION EQUATION

4.1. Insertion of Gamma and Neutron Energy Distributions

The energy distributions of gammas and neutrons, represented by eqs. (43) and (48), can now be applied to solve the various heat generation expressions of sect. 2 up to the unknown factors A_o, B_o and C_o.

For this procedure the following insertions are made :

I) Eq. (43) in eq. (19) :

$$P_\gamma = A_o \cdot \frac{\phi_s}{E_s} \int_o^\infty \frac{\mu_a}{\rho} \left[1+\left(\frac{\mu}{\mu_a}-1\right)\chi\right] . p_o(\chi) . e^{-1.25E} . EdE \qquad (49)$$

$$+ B_o \cdot \frac{\phi_s}{E_s} \int_o^\infty \frac{\mu_a}{\rho} \left[1+\left(\frac{\mu}{\mu_a}-1\right)\chi\right] . p_o(\chi) . e^{-2.50E} . EdE$$

II) Eq. (48) in eq. (22) :

Eq. (22) is approximated by the sum :

$$P_{nn} = \frac{2A}{(A+1)^2} \cdot \frac{1}{\rho} \sum_{n=1}^{4} \cdot \overline{p_o(\chi_T)} . \overline{\Sigma_s} . \int_{E_{Ln}}^{E_{Un}} \phi_o(E) . EdE \qquad (50)$$

The integral of this expression can be solved by applying eq. (48) in the following form :

$$\phi_{on} = \frac{1}{E_{Un}-E_{Ln}} \cdot \int_{E_{Ln}}^{E_{Un}} \phi_o dE = \frac{C_o}{E_{Un}-E_{Ln}} \cdot \frac{\phi_n}{\phi_1} \cdot \phi_S \qquad (51)$$

which brings :

$$\int_{E_{Ln}}^{E_{Un}} \phi_o E dE = \frac{C_o}{E_{Un}-E_{Ln}} \cdot \frac{\phi_n}{\phi_1} \cdot \phi_s \cdot \frac{1}{2}(E_{Un}^2 - E_{Ln}^2) = \frac{1}{2} C_o (E_{Un}+E_{Ln}) \cdot \frac{\phi_n}{\phi_1} \cdot \phi_s \tag{52}$$

and

$$P_{nn} = C_o \cdot \frac{A}{(A+1)^2} \cdot \frac{1}{\rho} \sum_{n=1}^{4} \overline{p_o(\chi_T)} \cdot \overline{\Sigma_s} \quad (E_{Un}+E_{Ln}) \cdot \frac{\phi_n}{\phi_1} \cdot \phi_s \tag{53}$$

III) Eq. (48) in eq. (31):

The thermal neutron flux density ϕ_{oth} corresponds to the 4th energy group, and therefore :

$$\phi_{oth} = C_o \cdot \frac{\phi_4}{\phi_1} \cdot \phi_s \tag{54}$$

$$P_{n\gamma} = C_o \cdot \frac{\Sigma_a}{\rho} \cdot \frac{\phi_4}{\phi_1} \cdot p_o(\chi_n) \cdot \sum_{i=1}^{7} B_a \frac{\mu_a}{\mu}(E_i) \cdot p_c(\chi) \cdot E_i \cdot S(E_i) \cdot \phi_s \tag{55}$$

IV) Eq. (48) in eq. (32):

Eq. (32) is approximated by:

$$P_{ni\gamma} = C_o \frac{\mu_a}{\mu}(E_\gamma) \cdot p_c(\chi) \cdot E_\gamma \; B_a \sum_{m=1}^{4} \overline{p_o(\chi_T)} \frac{\Sigma_{ni\gamma}}{\rho} \cdot \frac{\phi_m}{\phi_1} \cdot \phi_s \tag{56}$$

V) Eq. (48) in eq. (37):

$$P_{ndecay\gamma} = C_o \frac{\mu_a}{\mu}(E_\gamma) \cdot p_c(\chi) \cdot E_\gamma \cdot y_n \cdot \frac{\Sigma_a}{\rho} \cdot \frac{\phi_4}{\phi_1} \cdot \phi_s p_o(\chi_n) B_a \tag{57}$$

VI) Eq. (43) in eq. (38):

$$P_{ndecay\beta} = C_o \cdot p_c(\chi_\beta) \cdot E_\beta \cdot y_n \cdot \frac{\Sigma_a}{\rho} \cdot \frac{\phi_4}{\phi_1} \cdot \phi_s \cdot p_o(\chi_n) \qquad (58)$$

4.2. Presentation of Heating as Linear Expression with 3 Unknown Constants

By summing up the terms of sect. 4.1. to the total heat generation (eq. 1), an expression for P is obtained, in which the unknown factors A_o, B_o and C_o appear in linear combination.

The resulting equation can be written:

$$P = A_o \cdot G + B_o \cdot F + C_o \cdot N \qquad (59)$$

G, F and N are short forms of the following expressions :

$$G = \frac{\phi_s}{E_s} \int_o^\infty \frac{\mu_a}{\rho} \left[1 + \left(\frac{\mu}{\mu_a} - 1\right)\chi\right] \cdot p_o(\chi) \cdot e^{-1.25E} \cdot E \cdot dE \qquad (60)$$

$$F = \frac{\phi_s}{E_s} \int_o^\infty \frac{\mu_a}{\rho} \left[1 + \left(\frac{\mu}{\mu_a} - 1\right)\chi\right] p_o(\chi) \cdot e^{-2.50E} \cdot E dE \qquad (61)$$

$$N = \frac{A}{(A+1)^2} \cdot \frac{1}{\rho} \cdot \sum_{m=1}^{4} \overline{p_o}(\chi_T) \cdot \overline{\Sigma_s} \cdot (E_{Um} + E_{Lm}) \cdot \frac{\phi_m}{\phi_1} \cdot \phi_s$$

$$+ \frac{\Sigma_a}{\rho} \cdot \frac{\phi_4}{\phi_1} \cdot \phi_s \cdot p_o(\chi_n) \cdot \sum_{i=1}^{7} B_a \frac{\mu_a}{\mu}(E_i) \cdot \overline{p_c}(\chi) \cdot \overline{E_i} \cdot S(E_i) \qquad (62)$$

$$+ \frac{B_a}{\rho} \frac{\mu_a}{\mu} (E_\gamma) . p_c(\chi) . E_\gamma \sum_{m=1}^{4} \overline{p_o}(\chi_T) . \overline{\Sigma_{ni\gamma}} . \frac{\phi_m}{\phi_1} . \phi_s$$

$$+ \frac{1}{\rho} . \sum_{E_{n.decay\gamma}} B_a \frac{\mu_a}{\mu} (E_\gamma) . p_c(\chi) . E_\gamma . y_n . \Sigma_a . p_o(\chi_n) \frac{\phi_4}{\phi_1} . \phi_s \qquad (62)$$

$$+ \frac{1}{\rho} . \sum_{E_{n.decay\beta}} p_c(\chi_\beta) . E_\beta . y_n . \Sigma_a . p_o(\chi_n) . \frac{\phi_4}{\phi_1} . \phi_s$$

For convenience, the different arguments of the probability factors are oncemore listed here :

$$\chi = \frac{1}{2} \mu R_{av}$$

$$\chi_T = \frac{1}{2} \Sigma_T R_{av} \qquad (63)$$

$$\chi_n = \frac{1}{2} \Sigma_{thT} R_{av}$$

$$\chi_\beta = \frac{1}{2} \mu_\beta R_{av}$$

The expressions G, F and N (60), (61) and (62) are functions of the sample material and the sample geometry and size; they can be determined theoretically.
For cylinder geometries, which are considered here, the influence of size is expressed by the dependency of G, F and N on R_{av}.
The dimensions of G, F and N are the same as the dimension of P, e.g. [Watt/g].

4.3. Determination of Unknowns A_o, B_o and C_o

The solution of eq. (59) for the total nuclear heat generation now depends on the knowledge of the constants A_o, B_o and C_o of the gamma and neutron energy distributions.

A_o and B_o are unknown; C_o can be obtained by the TEDDI code theoretically and by activation analysis experimentally; it is however not advisable to apply the so-found values, in view of the complete loss of self-correction within the further process.

It is therefore useful to consider all three constants as unknown and to determine them simultaneously in a common procedure.

For this purpose, the method applied in ref. 1 is used here in a modified form. It consists in a measurement of the heat generation in 3 materials and solution of the system of 3 linear equations (59) with the measured values P.

With the subscripts 1, 2 and 3 for the 3 materials, one has :

$$\begin{aligned} P_1 &= G_1 A_o + F_1 B_o + N_1 C_o \\ P_2 &= G_2 A_o + F_2 B_o + N_2 C_o \\ P_3 &= G_3 A_o + F_3 B_o + N_3 C_o \end{aligned} \tag{64}$$

The determinant of the coefficients is :

$$D_c = \begin{vmatrix} G_1 & F_1 & N_1 \\ G_2 & F_2 & N_2 \\ G_3 & F_3 & N_3 \end{vmatrix} \tag{65}$$

The solution can be presented in the following form :

$$A_o = D_c^{-1} \cdot \left[(F_2 N_3 - N_2 F_3) P_1 + (N_1 F_3 - F_1 N_3) P_2 + (F_1 N_2 - N_1 F_2) P_3 \right] \tag{66}$$

$$B_o = D_c^{-1} \cdot \left[(N_2 G_3 - G_2 N_3) P_1 + (G_1 N_3 - N_1 G_3) P_2 + (N_1 G_2 - G_1 N_2) P_3 \right]$$

$$C_o = D_c^{-1} \cdot \left[(G_2 F_3 - F_2 G_3) P_1 + (F_1 G_3 - G_1 F_3) P_2 + (G_1 F_2 - F_1 G_2) P_3 \right] \qquad (66)$$

Once these constants have been determined, one can express numerically the approximations for the gamma and neutron energy distributions (43) and (48) for the conditions of the measurement (core position, core configuration, etc.).

For the same conditions, the constants in combination with eq. (59) permit to calculate the nuclear heat generation in samples of any material, geometry and size, for which the coefficients G, F and N are known.

5.0. EXPERIMENTAL

5.1. Principle

The experimental determination of the constants A_o, B_o and C_o according to sect. 4.3. requires simultaneous measurement of the specific power for 3 different materials, which are exposed to the radiation at the same point of the reactor core.

Since this is, in the strict sense, impossible, it is necessary to apply a separation in either time or space.

The principle of time separation requires use of calorimeters, which can be moved to the measurement position in succession.

The principle of space separation can be realized with fixed calorimeters.

In view of the rather slow changes in the radiation at a given point of the core, the time separation introduces practically no mistake, whereas the space separation can be subject to errors caused by local differences in the radiation pattern. These errors are difficult to estimate and can only be kept at a minumum by minimum spacing of the calorimeters.

The practical realization of the time separation principle (movable calorimeters) however, is rather difficult and introduces special problems in view of the required sensitivity of the calorimeters.

Since construction of rigs with movable probe supports is presently an unproved technique for the HFR, preference is given to the somewhat less accurate solution with fixed calorimeters.

5.2. Sample Materials

In order to reduce the errors, which are introduced by local gradients of the radiation pattern (sect. 5.1.), and to make the sensitivity, expressed by the right sides of eqs. (66), a maximum, materials with sufficiently different gamma and neutron heating characteristics must be selected.

In numerical terms, the determinant D_c (eq. 65) should approach a maximum value.

On the other hand, the sample materials should be suitable for construction of geometrically equal calorimeters with good sensitivity and limited temperatures, which is an important requirement reducing the risk of thermo-couple failures.

On the above basis, the combination graphite-molybdenum-beryllium was chosen. Estimated heating ratios of these materials are approximately :

Gammas : C : Mo : Be ≈ 10 : 14 : 9
Neutrons: C : Mo : Be ≈ 1 : 0 : 2

The thermal characteristics of C and Be calorimeters are very similar, the temperatures in Mo are comparably high, due to the higher heating rate and the greater density,

Cross sections and absorption coefficients are well known for all 3 materials; the specific heats and their temperature derivatives (source : ref. 6) as defined by eq. (67) are listed in the following table :

$$c = c_o \left[1 + q(T - T_o)\right] \qquad (67)$$

Material	ρ [g/cm^3]	c_o [J/(gdeg)]	q [1/deg]	T_o [degC]	T [deg C]
Be	1.85	1.892	0.00178	35	0<T<150
C*	1.69	0.762	0.00332	35	0<T<200
Mo	10.21	0.253	0.00026	35	0<T<600

* graphite Carbone Lorraine type 3780 WEG

With the above figures, c is accurate within ± 2% in the temperature range indicated for T.

5.3. Test Rig

A test rig, which can be inserted into the relevant experimental core positions of the HFR, is designed on basis of the principles of the CADO series, being in use at Petten.

This test rig, CADO-17, is a carrier for isothermal calorimeters, which are arranged at the 4 vertical stations shown on the scheme of fig. 2: (1) two groups of 3 calorimeters (referred to as "group calorimeters") with graphite, molybdenum and beryllium samples and (2) two single calorimeters with graphite samples.

The group calorimeters have capsule diameters of 6 mm, the single ones of 10 mm. The single calorimeters serve for comparison with earlier measurements, for which the same types had been used.

The calorimeter capsules are of stainless steel with a wall thickness of 0.3 mm; the free space is helium filled.

The group arrangement is shown in fig. 2 too. The center radius of 10 mm is a compromise between minimum spacing (see sect. 5.1.) and the distance needed in order to reduce mutual influencing (shadowing) of the calorimeters.

The calorimeters are cooled by the primary coolant of the HFR, flowing in downward direction through the rig. The rig is inserted in a standard filler element.

The inner and outer thermo-couples of each calorimeter are connected in differential junction in the head of the rig.

The instrumentation is a Solartron digital data logger with punched tape recording equipment.

5.4. Calibration and Sensitivity

Calorimeters are calibrated out-of-pile by derivation of the temperature dependent time constant of the differential thermo-voltage, developped in response to a sudden decrease of the cooling temperature.

The first order approximation for this time constant reads

$$M = M_o \cdot (1+\beta\Delta T). \qquad (68)$$

With this, the differential equation of the calorimeter response

$$\frac{d\Delta T}{dt} = - \frac{\Delta T}{M}$$

has the solution

$$\frac{\Delta T}{\Delta T_o} = \exp \left[- \frac{t}{M_o} + \beta(\Delta T_o - \Delta T) \right] . \qquad (69)$$

Measured response curves of CADO calorimeters are perfectly represented by this relation, so that the parameters M_o and β, defining M by eq. (68), are easily determined from the measured response on basis of eq. (69).

A steady state calorimetric measurement is evaluated, the time constant being known, from the following equation:

$$P = \frac{f}{1-k} \cdot \frac{c}{M} \cdot \Delta T. \qquad (70)$$

The correction factors f and k, allowing for the influence of the inner thermo-couple mass and heat capacity and the heat loss by the sample supports, respectively, have been calculated; results are listed in the following table.

Calorimeters type	Sample material	f	k
single	C	0.985	0.043
group	C	0.985	0.024
"	Be	0.975	0.024
"	Mo	1.004	0.024

The following table shows predicted mean values of the time constant, the temperature difference developped per $^{W}/_{g}$ of heat generation and the sensitivity of the calorimeters, defined as the output in millivolts (thermo-voltage) per $^{W}/_{g}$ of heat generation.

Calori-meter type	sample mate-rial	capsule i.d. [mm]	mean time constant [sec]	related tem-perature [deg/(W/g)]	mean sen-sitivity [mV/(W/G)]
single	C	10	10.5	12	0.48
group	C	6	5.5	6.8	0.27
group	Be	6	14	7.5	0.30
group	Mo	6	11	41	1.64

5.5. Accuracy

According to an analysis made in connection with earlier experiments, the expected mean error of CADO measurements is of the order of 4%.

Since the same calorimeter type is used for the present method, it is reasonable to consider this value also as the mean error of the individual calorimeter output.

The total error of the method, which is the error attributed to the final result A_o, B_o, C_o, must be evaluated on basis of eq. (66), in which the calorimeter outputs are combined with the elements of the determinant D_c (eq. 65).

The accuracy of these elements is rather difficult to estimate, because it depends very much on the unknown quality of the approximations for the gamma and neutron energy distributions.

In view of these uncertainties, an analysis of the method accuracy requires experimental experience and can therefore only be made, after measured data results are available.

6.0. NUMERICAL CALCULATIONS

6.1. Expressions G, F and N

The expressions G, F and N of eq. (59), which are formulated in eqs. (60), (61) and (62), have been evaluated for the materials

C, Be, Mo, Fe

and for cylinders of the dimensions

$0 \leq R_{av} \leq 6$ cm.

Eqs. (60) and (61) were integrated graphically by means of a planimeter, with upper integration limits of 8 MeV for G and 4 MeV for F.

Absorption coefficients were taken from refs. 5, 7 and 8.

N has been determined on basis of the mean of the neutron group energy distributions (45) and (46), reading

$$\frac{\phi_n}{\phi_1} = 1 + 0.70\ (n - 1) - 0.03\ (n - 1)^3 \qquad (71)$$

Cross sections were taken from ref. 4.

The n,γ contributions were evaluated on basis of the 7 group capture gamma spectra of ref. 2.

Numerical results are presented for the standard values of

$E_s = 0.1$ MeV

$\phi_s = 10^{14}$ cm^{-2} sec^{-1}

Diagrammes of G, F and N, based on these calculations, are presented in figs. 3 through 6. Diagrammes for other materials will be communicated in a separate note.

It should be noted, that numerical values of A_o, B_o and C_o, which are obtained experimentally and by inversion of the linear system (64), are only valid for parameters G, F and N with the above mentioned standard values of E_s and ϕ_s.

6.2. Determinant D_c for CADO-17

The samples installed in experiment CADO-17 are cylinders of 3.2 mm diameter and 20 mm length; their corresponding value of R_{av} (eq. 18) is

$$R_{av} = 0.296 \text{ cm}$$

The determinant (65) is set up by coefficients G, F and N, which are read from figs. 3 through 5 for this R_{av}. The index correlation used here is 1 for C, 2 for Mo, 3 for Be :

$$D_c = \begin{vmatrix} 2.667 & 0.757 & 1.470 \\ 3.491 & 1.443 & 0.240 \\ 2.320 & 0.644 & 3.110 \end{vmatrix} \qquad (72)$$

The value of D_c is :

$$D_c = + 2.143 \ W^3 \ g^{-3} \qquad (73)$$

On basis of this figure, eqs. (66) are evaluated to (P in Watts/gram) :

$$\begin{aligned} A_o &= + 2.022 \ P_C - 0.657 \ P_{Mo} - 0.905 \ P_{Be} \\ B_o &= - 4.806 \ P_C + 2.279 \ P_{Mo} + 2.096 \ P_{Be} \qquad (74) \\ C_o &= - 0.513 \ P_C + 0.018 \ P_{Mo} + 0.563 \ P_{Be} \ , \end{aligned}$$

where the indices C, Mo and Be stand for the corresponding materials.

Since physically meaningful solutions require that $P_\gamma \geq 0$ and $P_n \geq 0$, there exist the conditions

$$\begin{aligned} A_o G + B_o F &\geq 0 \\ C_o &\geq 0 \end{aligned} \qquad (75)$$

By insertion of eqs. (74) into (75) and use of values G and F of (72), one finds a field of physically meaningful specific power ratios, which is shown in fig. 7 as the area limited by the straight lines (a), (b) and (c).

However, in view of the expected gamma energy distribution, only a part of this field can be realistic.

The actual gamma distribution of the HFR has in all probability a form, to which both terms of approximation (43) contribute with positive sign, so that the expected field of solutions has the sharper limits

$$A_o \geq 0, \quad B_o \geq 0, \quad C_o \geq 0 \; . \qquad (76)$$

This field is, on basis of eqs. (74), the triangle I-II-III (fig. 7), in which point I corresponds to a gamma energy distribution type $e^{-1.25E}$ (hard spectrum), point II to $e^{-2.50E}$ (soft spectrum) and point III to pure neutron energies.

Accordingly, on a line connecting two points, the contribution represented by the opposite point is zero.

It can be expected, that actual HFR results will fall close to the line I-II, because the neutron effects are relatively small.

The results of measurements at different points of the core combine to a curve or a field, the magnitude of which depends on the variation of the spectra over the core.

ACKNOWLEDGEMENT

Messrs. J. Vande Meutter and R. Metz substantially contributed to this work by performing the extensive numerical calculations.

7.0. DEFINITION OF SYMBOLS

A	atomic weight
A_o, B_o, C_o	constants of energy distributions, eqs. (43) and (48)
B_a	energy absorption build-up factor
D	diameter
D_c	determinant of coefficients, eqs. (65)
E	energy of gammas and neutrons
E_s	standard energy, arbitrary definition
F	defined by eq. (61)
F_c	fraction of collisions
G	defined by eq. (60)
L	length of cylinder
M	time constant
N	defined by eq. (62)
N	energy spectral density of gamma number flux (eqs. 3...8)
N_o	energy sp. dens. of gamma number flux, undisturbed
P	specific power of nuclear heating
R_{av}	average chord
S	total surface of sample
$S(E_i)$	integrated capture gamma spectrum, defined by eq. (30)
T	temperature
T_o	reference temperature
ΔT	temperature difference corresponding to U_T
U_T	differential thermo-voltage of calorimeter
V	total volume of sample

c	specific heat
c_o	reference value of specific heat
f	correction factor
k	correction factor
n_o	total amount of photons coming in
p	escape probability
$\bar{p}_o$	volume average of p
p_c	volume average of collision probability, eq. (28)
q	temperature derivative of specific heat
$q_{n\gamma}$	energy spectral density of capture gammas produced per capture
r	local coordinate
y_n	natural abundance
Σ_a	absorption cross section
Σ_s	scattering cross section
Σ_T	total cross section
Σ_{thT}	total cross section for thermal neutrons
$\Sigma_{ni\gamma}$	cross section for inelastic scattering gamma ray production
ϕ	energy spectral density of neutron number flux
ϕ_o	energy spectral density of neutron number flux, undisturbed
μ	gamma ray attenuation coefficient
μ_a	gamma ray energy absorption coefficient
μ_β	beta ray absorption coefficient
ρ	density
σ	sensitivity of calorimeter output

ϕ	neutron number flux
ϕ_o	neutron number flux, undisturbed
ϕ_{oth}	undisturbed thermal neutron number flux
ϕ_s	standard neutron flux, arbitrary definition
ϕ_n	neutron number flux in energy group n, eq. (44)
χ	defined by eqs. (63)
χ_T	defined by eqs. (63)
χ_n	defined by eqs. (63)
χ_β	defined by eqs. (63)

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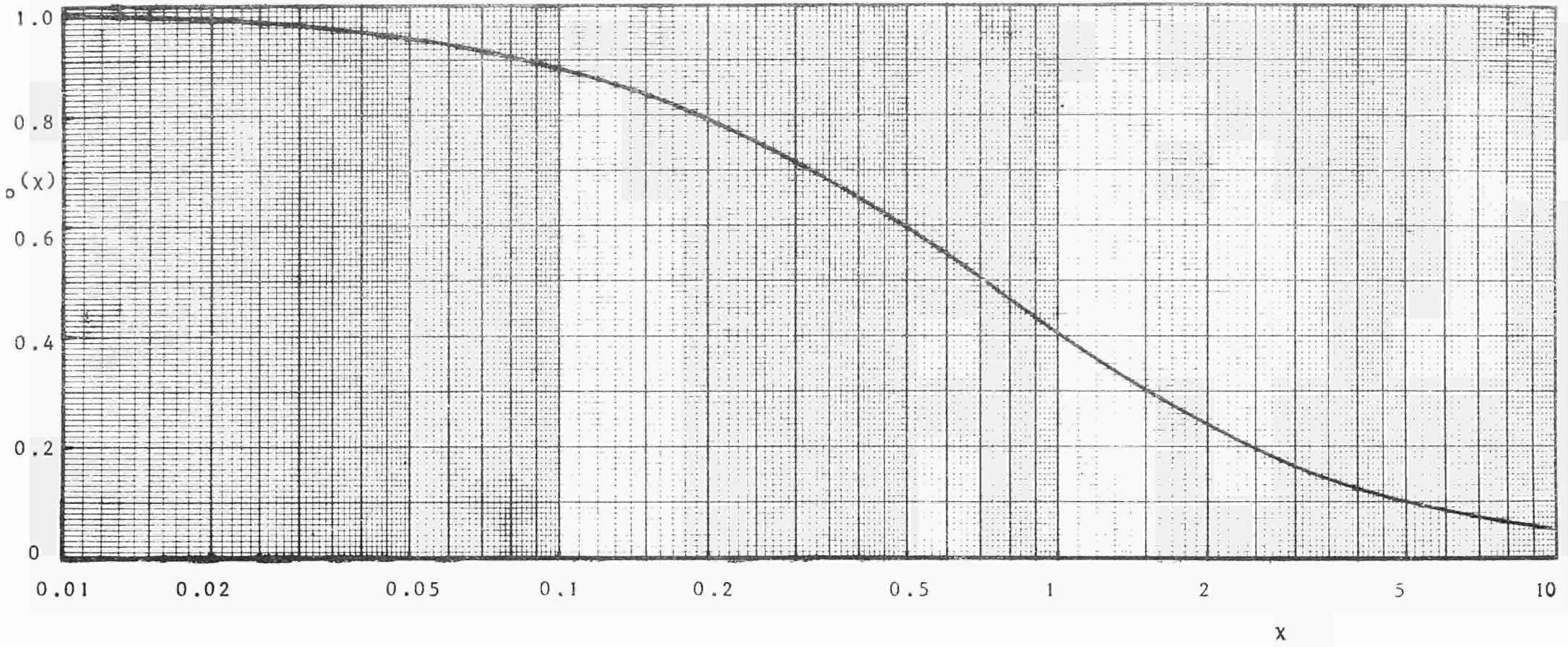


$$p_o = \frac{1}{2\chi} \quad \text{for } \chi > 10$$

$$p_o = 1 - \frac{4}{3}\chi \quad \text{for } \chi < 0.01$$

Fig. 1 : ESCAPE PROBABILITY OF CYLINDERS (from ref. 6)

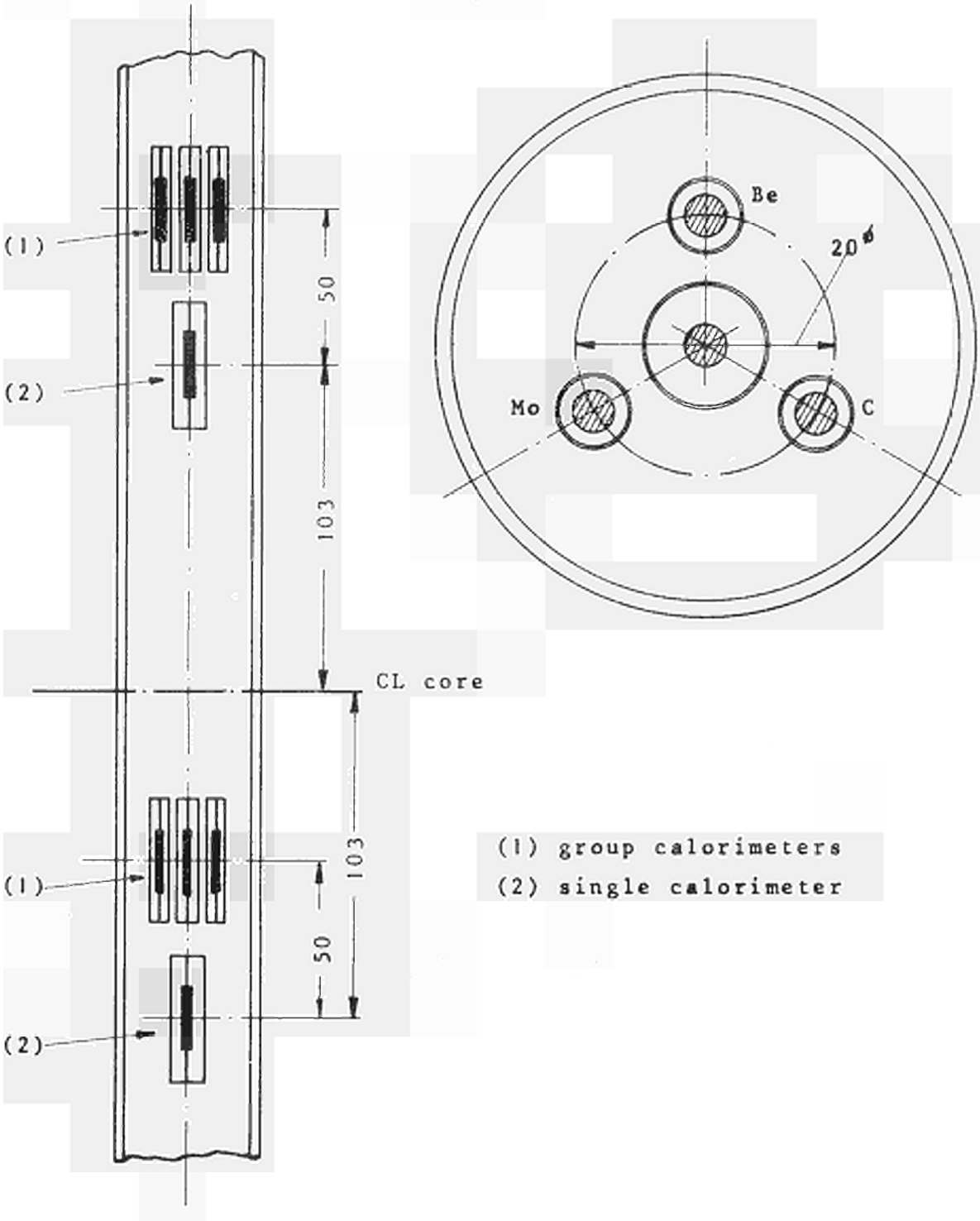
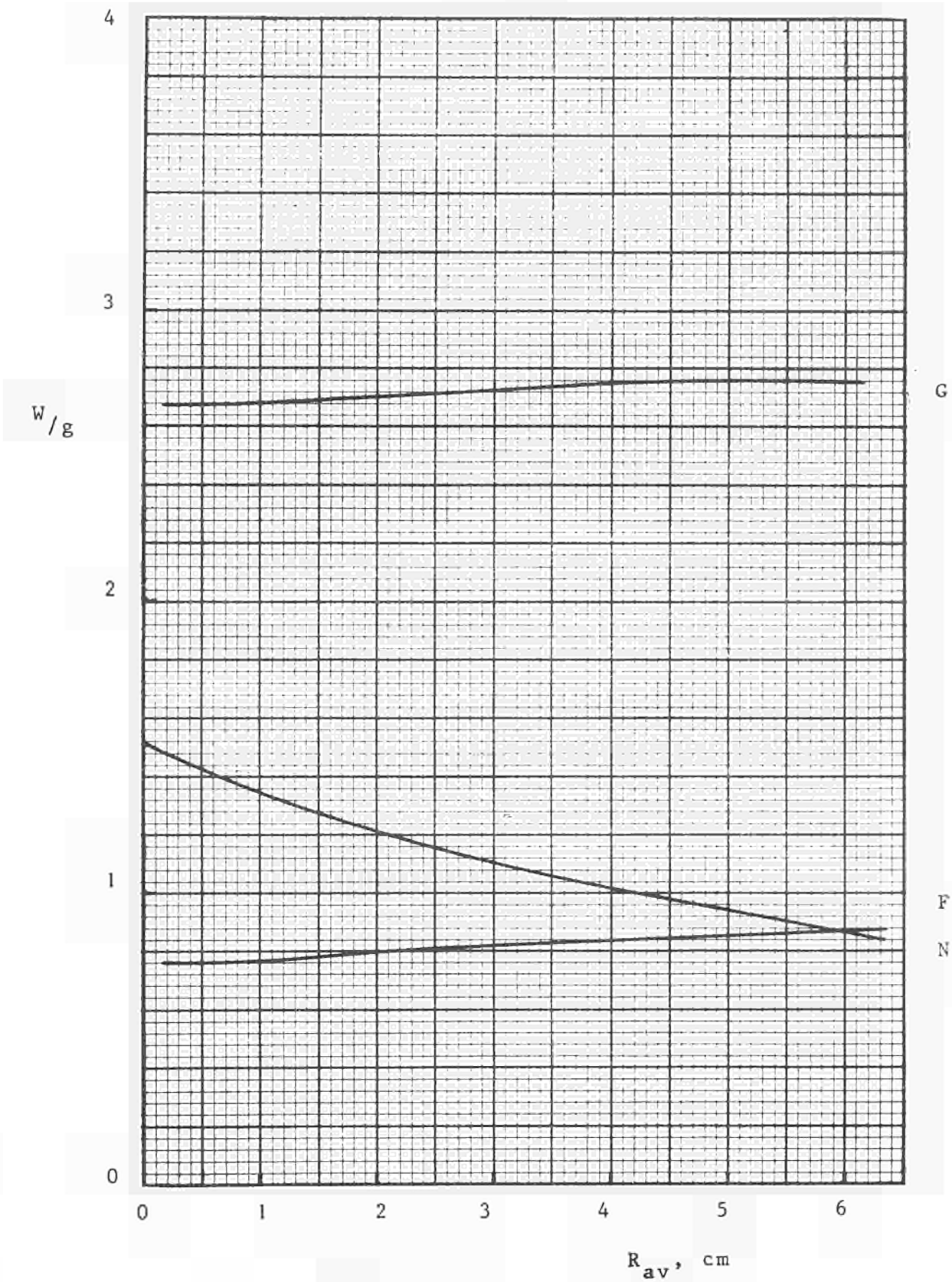


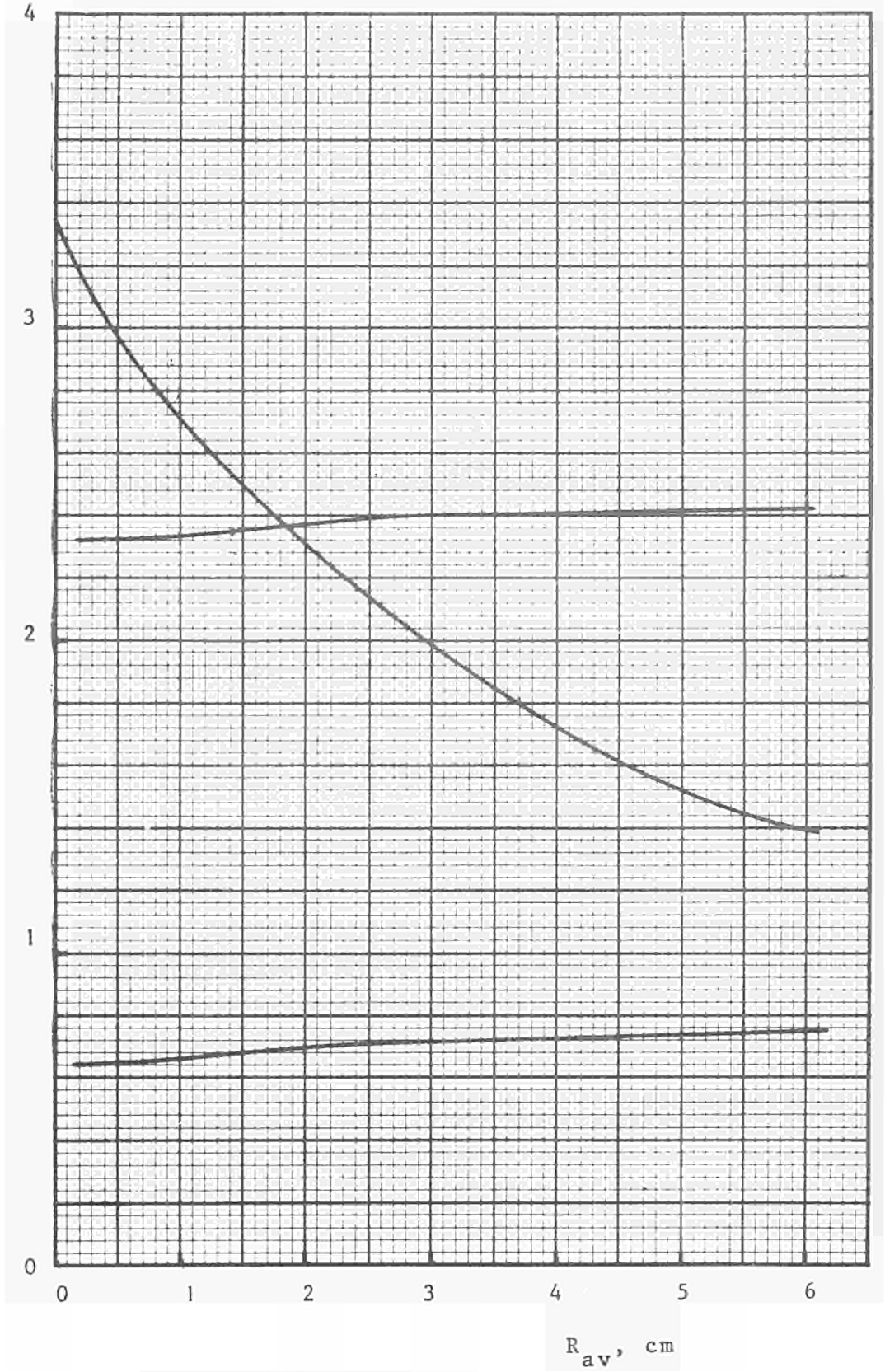
Fig. 2.: ARRANGEMENT OF CALORIMETERS IN TEST RIG CADO-17.



$\Phi_s = 10^{+14}\ cm^{-2}s^{-1}$

$E_s = 0.1$ MeV

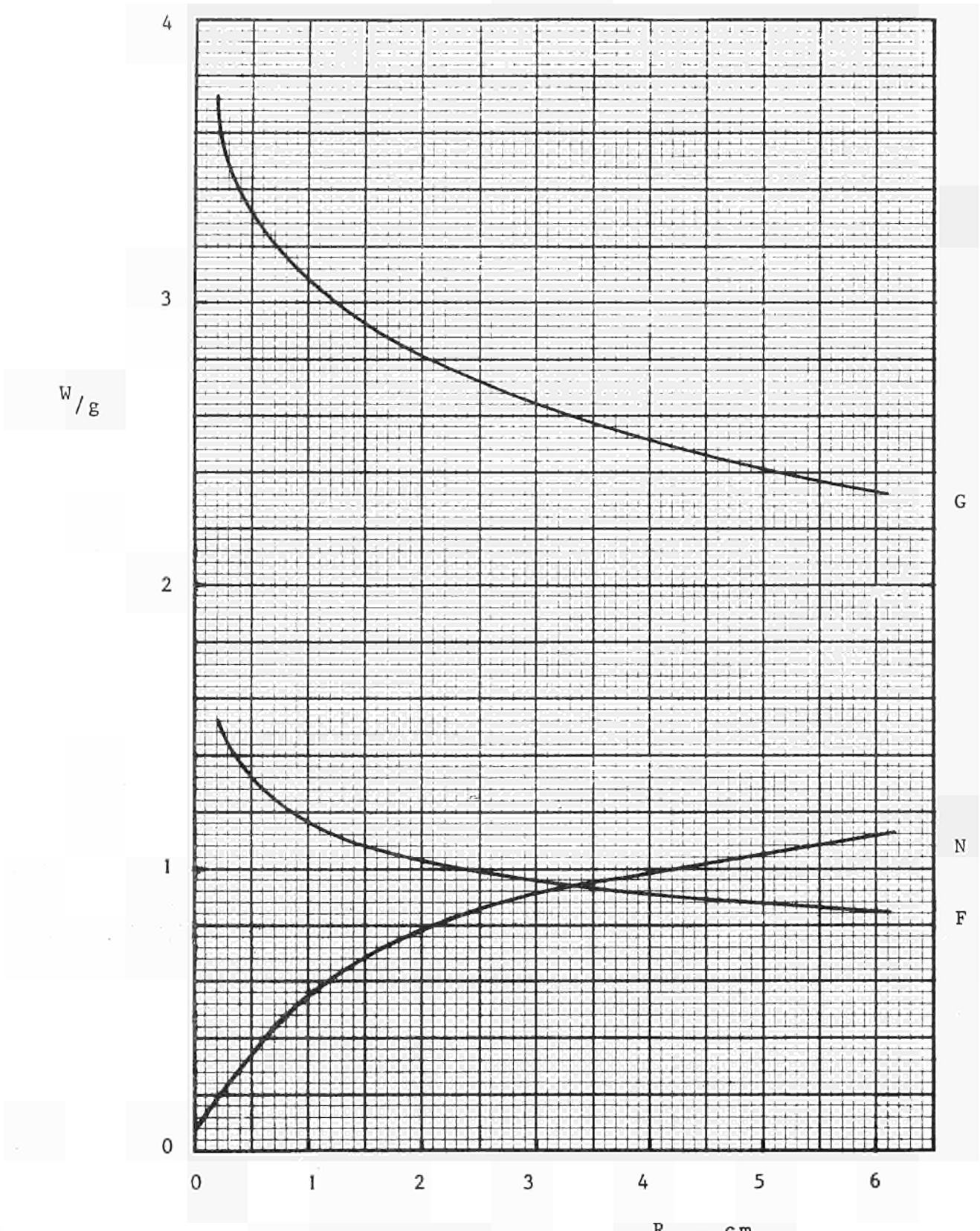
Fig. 3 : HEAT GENERATION COEFFICIENTS FOR C



$\phi_s = 10^{+14}\,cm^{-2}s^{-1}$

$E_s = 0.1$ MeV

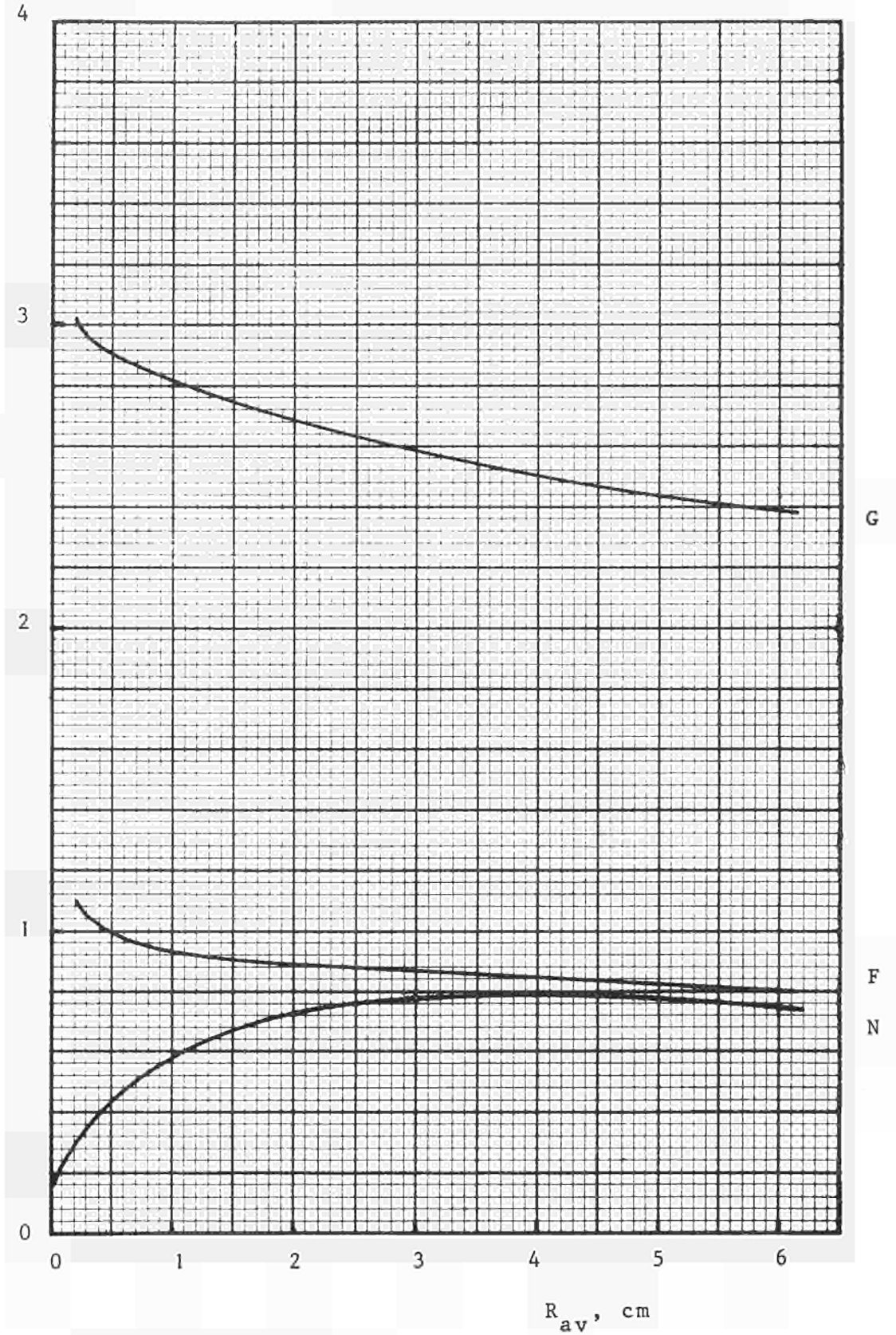
Fig. 4 : HEAT GENERATION COEFFICIENTS FOR Be.



$\phi_s = 10^{+14}\ cm^{-2}s^{-1}$

$E_s = 0.1$ MeV

Fig. 5 : HEAT GENERATION COEFFICIENTS FOR Mo.



$\phi_s = 10^{14} cm^{-2} s^{-1}$

$E_s = 0.1$ MeV

Fig. 6 : HEAT GENERATION COEFFICIENTS FOR Fe.

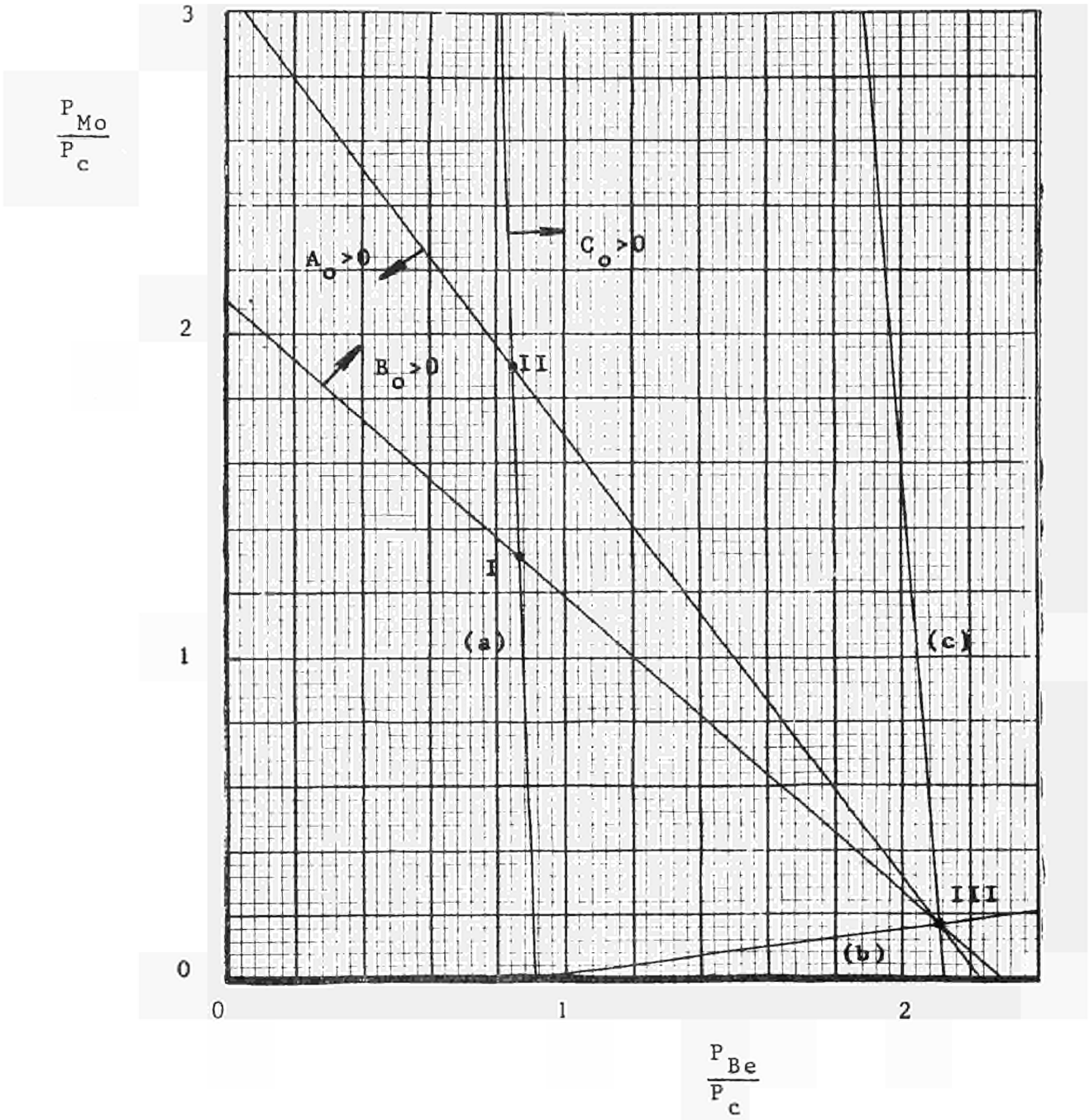


Fig. 7 : FIELD OF PHYSICALLY MEANINGFUL SPECIFIC POWER RATIOS.

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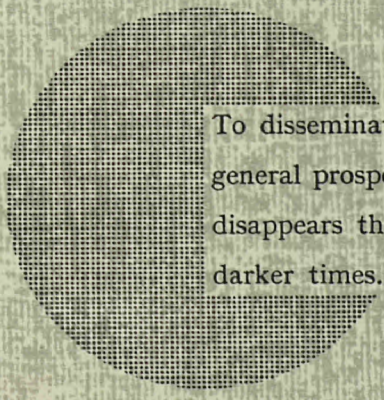

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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