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COSTANZA
A NUMERICAL CODE FOR THE STUDY OF THE REACTOR SPATIAL DYNAMICS IN TWO GROUPS

by

E. VINCENTI, R. MONTEROSSO
(Euratom)
and
A. AGAZZI (C. Gavazzi S.p.A. - Milan)

1964

Joint Nuclear Research Center
Ispra Establishment - Italy

Scientific Data Processing Center - CETIS
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LIST OF SYMBOLS

B_r = radial buckling

C = delayed neutrons' precursor density

c = core specific heat $\frac{cal}{cm^3\ °C}$

D_f = fast diffusion coefficient of core

D_f^r = fast diffusion coefficient of reflector

D_f^k = fast diffusion coefficient of the K_{th} region

D_t = thermal diffusion coefficient of core

D_t^r = thermal diffusion coefficient of reflector

D_t^k = thermal diffusion coefficient of the K_{th} region

F = heat released by one fission (7.66×10^{-12} cal)

K = infinite multiplication factor

K_{eff} = effective multiplication factor

L = diffusion length

l_o = life time of a thermal neutron in an infinite medium

l = life time of a thermal neutron in a finite reactor

n = neutron density

R^k = K_{th} region

T = temperature (Kelvin)

To = temperature of the cold reactor

V = thermal neutron velocity

w = fast neutron velocity

$\alpha = \frac{1}{T}$ = reciprocal of the reactor period

β = total fraction of delayed fission neutrons

Δt = time step

Δz^k = mesh increment in the K_{th} region

λ = precursor decay constant (weighted average)

ν = fission neutrons per fission

Σ_a^c , Σ_a^r = absorption cross section of core, reflector

Σ_p = absorption cross section of the rod equivalent poison

ϕ = thermal flux

Ψ = fast flux

τ = Fermi age of core

τ_r = Fermi age of reflector

PREFACE

This report describes a numerical code for the study of the spatio-temporal dynamics of a reactor. It is written for the reactor TESI in particular, which operates in conditions of prompt criticality. This example was chosen because the classical method of the kinetic eq. is based on the assumption that the reactor is very near criticality. The numerical method, based on the direct solution of the time-dependent diffusion equation, in condition of prompt criticality, should give more accurate results than the classical one.

Although a very special type of reactor is studied here, this work is meant to be a preliminary work for a more general code for power reactors.

The code described in this report is only for one space dimension.

The case of two space dimensions is being studied and will be the subject of another report.

We are indebted to Mr. Foggi and Mr. Ricchena (T.C.R.) for many informations on the core of the reactor TESI and on the point dynamics and for their valuable contribution during the discussions. We are also grateful to Mrs. Tamagnini (CETIS) for the calculation made with the Pineto Code and to Mr. Green and Mr. Caligiuri (CETIS) for the calculation on the analogue computer.

§ I. The power excursion reactor and its simplified geometrical configuration

This report contains the description of a numerical code written for the IBM 7090, and to be employed for the study of the spatio-temporal dynamics of the reactor TESI.

This reactor is meant for studying the destruction of a fuel element of any other reactor caused by a flash of high neutron flux. It operates in the following way: from being critical at a very low power, it is made prompt critical. The flux rises very rapidly, and, as the reactor is not cooled during the transient, the temperature in the core rises accordingly. The core has a large negative temperature coefficient and therefore when a certain value of the flux is reached, the reactor becomes undercritical and after a pulse of very short duration the flux decreases.

It is provided with a cooling system, which can bring the core to its initial temperature in two or three hours and prepares the condition for a new pulse. This cooling, however, has no effect during the transients of a few seconds which will be studied here. The temperature rises as the integral of the flux and tends to its final maximum value.

The core of reactor TESI is a vertical cylinder of 145 cm height made of a homogeneous mixture of fuel and graphite. There is a radial reflector and also an upper and lower reflector 60 cm thick. The control rods are of two types. The first type is placed at the interface between core and radial reflector. When they are completely introduced they separate the core from the reflector. The other type of rods are immersed from the top into the core. We will consider them as moving all together in the axial

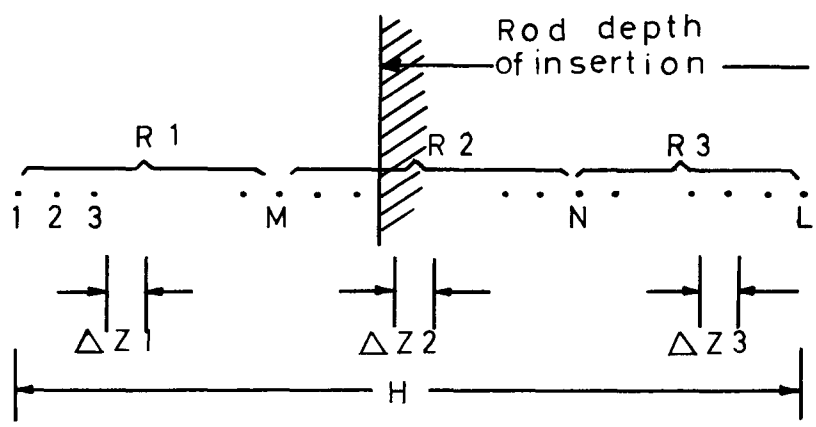
direction with the same depth of insertion. We shall consider substituting these rods by an equivalent poison which is homogeneously distributed in the rodded part of the reactor.

Since we dispose of a programme with one spatial dimension only i.e. the z vertical dimension, we shall consider, instead of the finite cylindrical core, a horizontal infinite slab with a thickness equal to the height of the core and with upper and lower reflectors. In the cylinder there is a horizontal neutron leakage, which does not take place in the infinite slab; to compensate this the absorption cross section is increased by the quantity B_r^2 D.

Along the z axis, see Fig. 1, we consider a mesh-points $\{z_i\}$ (i=1,...L); in the region R 1 (lower reflector) with a mesh increment $\Delta z1$; in the region R 2 (core), mesh increment $\Delta z2$; in the region R 3 (upper reflector) mesh increment $\Delta z3$. On each interface between core and reflector is a point of the lattice z_M, z_N, each region must contain at least one internal point.

The code can operate with a maximum number of 100 points.

Fig. 1.



§ II The physical equations and their transformation into a system of linear equations

One of the purposes of this code is to give a description of the flux distribution in the core and reflectors and of the deformation of this distribution during the transient, due to the movement of the control rods, to the temperature reaction and to the presence of reflectors. Although in reactor dynamics it is usual to adopt the one group approximation, two energy groups, fast and thermal, will be considered here. With one group there is no thermal source in the reflector, whereas with two groups there is a source of thermal neutrons also in the reflector due to the slowing down of the fast neutrons; this gives a much better spatial distribution of fluxes.

There is only one group of delayed neutrons with a decay constant λ equal to the properly weighed average for the six actual groups. This approximation is good enough because the reactor operates as prompt critical and the delayed neutrons have an effect only on the tail of the transient.

The heat balance equation contains only the term of the heat accumulation and that of heat production, which must be equal because, as said before, no heat is removed during the transient.

The following are the two groups' diffusion equations, the equation of the balance of precursors of the delayed neutrons and the equation of the heat balance.

$$(II\text{-}1)\quad D_f \frac{\partial^2 \Psi}{\partial z^2} - \left(\frac{D_f}{\tau} + D_f B_r^2\right)\Psi + k(1-\beta)\Sigma_a \phi + \lambda C = \frac{1}{w}\frac{\partial \Psi}{\partial t}$$

$$(II\text{-}2)\quad D_t \frac{\partial^2 \phi}{\partial z^2} - \left(\Sigma_a^c + D_t B_r^2 + \Sigma_p\right)\phi + \frac{D_f}{\tau}\Psi = \frac{1}{v}\frac{\partial \phi}{\partial t}$$

$$(II\text{-}3)\quad \frac{\partial C}{\partial t} = k\Sigma_a \beta \phi - \lambda C$$

$$(II\text{-}4)\quad \frac{\partial T}{\partial t} = \frac{F}{c}\frac{k}{\nu}\Sigma_a \phi \qquad \text{(see List of Symbols)}$$

The equations (II-1) and (II-2) are written for points in the core; in the reflectors they have the following form:

$$(II\text{-}5)\quad D_f^r \frac{\partial^2 \Psi}{\partial z^2} - \left(\frac{D_f^r}{\tau_r} + D_f^r B_r^2\right)\Psi = \frac{1}{w}\frac{\partial \Psi}{\partial t}$$

$$(II\text{-}6)\quad D_t^r \frac{\partial^2 \phi}{\partial z^2} - \left(\Sigma_a^r + \Sigma_p + D_t^r B_r^2\right)\phi + \frac{D_f^r}{\tau_r}\Psi = \frac{1}{v}\frac{\partial \phi}{\partial t}$$

The term B^2D which appears in the diffusion equations increases the cross-sections of a quantity equivalent to the radial leakage which is not considered in this slab geometry. In equations (II-2) and (II-6) the term Σ_p indicates the control rod equivalent poison, which is present only at those points of the lattice (Fig. 1 p. 4) which are in the rodded region. Equations (II-3) and (II-4) of the precursors of delayed neutrons and of heat balance respectively are to be considered only in the core region; the reflectors are thermically separated from the core and are always at 20 °C.

The fluxes Ψ and ϕ are supposed to be zero at the outer boundary of the reflectors (Points $z_1 = 0$, $z_L = H$)

$$\Psi(0,t) = \Psi(H,t) = 0 \qquad \text{(II-7)}$$
$$\phi(0,t) = \phi(H,t) = 0 \qquad (H = \text{height of reactor})$$

The system of the two diffusion equations is quasi-linear because the cross section, the neutron velocities and the quantities τ, k, c, which appear in their coefficients, are temperature-dependent and therefore they are indirect functions of the flux ϕ.

It is through these variable coefficients that the temperature feed-back takes place.

The cross sections and the neutron velocities are calculated according to

$$\Sigma_a^c(z,t) = \Sigma_{ao}^c \sqrt{\frac{T_o}{T(z,t)}} \quad ; \quad \Sigma_p(z,t) = \Sigma_{po} \sqrt{\frac{T_o}{T(z,t)}}$$

$$w(z,t) = w_o \sqrt{\frac{T(z,t)}{T_o}} \quad ; \quad v(z,t) = v_o \sqrt{\frac{T(z,t)}{T_o}}$$

where T_o is the uniform temperature of the cold reactor at the initial state, and Σ_{ao}^c, Σ_{po}, w_o, v_o are values corresponding to temperature T_o.

The quantities k, τ, c are obtained in this code by linear interpolation on tables given as input data.

We consider in a small time interval Δt the system of the two quasi-linear parabolic equations (II-1), (II-2) or (II-5), (II-6) as linear; in other words we suppose that

the coefficients remain constant during this interval. This is possible only when they change very slowly with time and for small Δt.

At every time step Δt, the coefficients are given new values, which are determined according to the temperature reaction and the position of the control rods.

§ III - The finite difference equations

The two diffusion equations can be written in the following form:

$$(III\text{-}1)\quad D_f^k \frac{\partial^2}{\partial z^2} \Psi - A^k \Psi + B^k \phi + C^k = \frac{1}{w^k} \frac{\partial \Psi}{\partial t}$$

$$(III\text{-}2)\quad D_t^k \frac{\partial^2}{\partial z^2} \phi - E^k \phi + F^k \Psi = \frac{1}{v^k} \frac{\partial \phi}{\partial t}$$

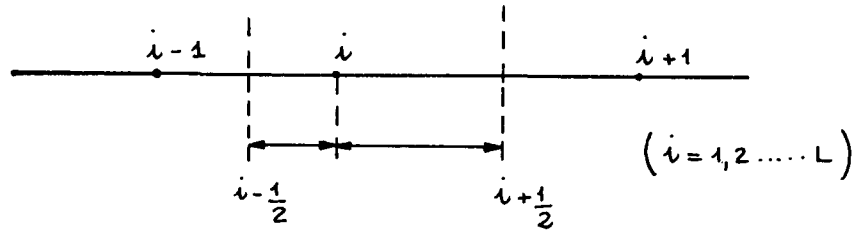
where $k(k = 1, 2, 3)$ is the index of the region: lower reflector, core and upper reflector respectively. The meaning of A^k, B^k, C^k, E^k, F^k is evident.

The height of the reactor has been divided into mesh-points $\{z_i\}$, $(i = 1,2,.....L)$ with $z_1 = 0$ and $z_L = H$ = height of the reactor.

On each interface between core and reflector is a point of the lattice, and each region contains at least one internal point; $\Delta_i = z_{i+1} - z_i = \Delta z^k$ is constant in each region R^k, and can vary from region to region.

Let us consider the i^{th} point of the lattice.

Fig.-2



The coefficients D_f, A, B, C, $\frac{1}{w}$ and D_t, E, F, $\frac{1}{v}$ depend on the temperature, and on the position of the control rods; therefore they vary from point to point of the lattice.

Let us make the integration in the space intervals

$z_{i-\frac{1}{2}} < z < z_i$ and $z_i < z < z_{i+\frac{1}{2}}$.

In these intervals the coefficients are not supposed to vary.

For the sake of brevity we will carry out the calculation only for eq.(III-1); for eq.(III-2) we will give the final expressions.

$$\int_{z_{i-\frac{1}{2}}}^{z_i} \frac{1}{w} \frac{\partial \Psi}{\partial t} \, dz = \left[D_f \frac{\partial \Psi}{\partial z} \right]_{z_i-} - \left[D_f \frac{\partial \Psi}{\partial z} \right]_{z_{i-\frac{1}{2}}} - \int_{z_{i-\frac{1}{2}}}^{z_i} (A\Psi - B\phi - C) dz \qquad \text{(III-3)}$$

$$\int_{z_i}^{z_{i+\frac{1}{2}}} \frac{1}{w} \frac{\partial \Psi}{\partial t} \, dz = \left[D_f \frac{\partial \Psi}{\partial z} \right]_{z_{i+\frac{1}{2}}} - \left[D_f \frac{\partial \Psi}{\partial z} \right]_{z_i+} - \int_{z_i}^{z_{i+\frac{1}{2}}} (A\Psi - B\phi - C) dz \qquad \text{(III-4)}$$

where

$$\left[f(z) \right]_{z_i-} \quad \text{and} \quad \left[f(z) \right]_{z_i+}$$

are respectively the left and right limit of $f(z)$ in $z = z_i$.

As fluxes and neutron currents are continuous throughout the reactor it is:

$$\left[D_f \frac{\partial \Psi}{\partial z} \right]_{z_i-} = \left[D_f \frac{\partial \Psi}{\partial z} \right]_{z_i+}$$

Adding (III-3) and (III-4) we obtain:

$$\int_{z_{i-\frac{1}{2}}}^{z_{i+\frac{1}{2}}} \frac{1}{w}\frac{\partial \Psi}{\partial t}\,dz = \left[D_f \frac{\partial \Psi}{\partial z}\right]_{z_{i+\frac{1}{2}}} - \left[D_f \frac{\partial \Psi}{\partial z}\right]_{z_{i-\frac{1}{2}}} - \int_{z_{i-\frac{1}{2}}}^{z_{i+\frac{1}{2}}} (A\Psi - B\phi - C)dz$$

(III-5)

The derivatives $\frac{\partial \Psi}{\partial z}$ are calculated with the central differences:

$$\left[\frac{\partial \Psi}{\partial z}\right]_{z_{i-\frac{1}{2}}} = \frac{\Psi_i^n - \Psi_{i-1}^n}{\Delta_{i-1}} \; ; \; \left[\frac{\partial \Psi}{\partial z}\right]_{z_{i+\frac{1}{2}}} = \frac{\Psi_{i+1}^n - \Psi_i^n}{\Delta_i}$$

The derivatives with respect to the time are approximated according to:

$$\left[\frac{\partial \Psi}{\partial t}\right]_{z_i} = \frac{\Psi(z_i,t_n) - \Psi(z_i,t_{n-1})}{t_n - t_{n-1}} = \frac{\Psi_i^n - \Psi_i^{n-1}}{\Delta t}$$

The integrals are approximated according to the formula:

$$\int_{z_{i-\frac{1}{2}}}^{z_{i+\frac{1}{2}}} f(z)dz = f_i^- \cdot \frac{\Delta_{i-1}}{2} + f_i^+ \frac{\Delta_i}{2}$$

equation (III-5) then becomes:

$$0 = \left[\frac{1}{w}\frac{\Psi^n - \Psi^{n-1}}{\Delta t}\right]_{z_{i-}} \cdot \frac{\Delta_{i-1}}{2} + \left[\frac{1}{w}\frac{\Psi^n - \Psi^{n-1}}{\Delta t}\right]_{z_{i+}} \cdot \frac{\Delta_i}{2} - D_{i+\frac{1}{2}} \frac{\Psi_{i+1}^n - \Psi_i^n}{\Delta_i} +$$

$$+ D_{i-\frac{1}{2}} \frac{\Psi_i^n - \Psi_{i-1}^n}{\Delta_{i-1}} + \left[A\,\Psi^n - B\,\phi^n - C\right]_{z_{i-}} \cdot \frac{\Delta_{i-1}}{2} + \left[A.\Psi^n - B\,\phi^n - C\right]_{z_{i+}} \cdot \frac{\Delta_i}{2}$$

(III-6)

If z_i is an internal point of region R_k (K = 1,2,3; -reflector; core, reflector) then $\left[D_f\right]_{i-\frac{1}{2}} = \left[D_f\right]_{i+\frac{1}{2}} = D_f^k$ and $\Delta_{i-1} = \Delta_i = \Delta z^k$. The functions A, B, C, w are continuous in z_i and equation (III-6) becomes:

$$- \frac{D_f^k}{\Delta z^k} \Psi_{i-1}^n + \left[\frac{2D_f^k}{\Delta z^k} + \left(\frac{1}{w^k . \Delta t} + A_i^k\right) \Delta z^k\right] \Psi_i^n - \frac{D_f^k}{\Delta z^k} \Psi_{i+1}^n -$$

$$- \Delta zk . B_i^k . \phi_i^n = \Delta z^k \left(C_i^k + \frac{\Psi_i^{n-1}}{w^k . \Delta t}\right) \qquad \text{(III-7)}$$

If z_i is a point on the interface between R_{k-1} and R_k then eq.(III-6) becomes:

$$- \frac{D_f^{k-1}}{\Delta z^{k-1}} \Psi_{i-1}^n + \left[\frac{D_f^{k-1}}{\Delta z^{k-1}} + \frac{D_f^k}{\Delta z^k} + \left(\frac{1}{w_i^{k-1} . \Delta t} + A_i^{k-1}\right) \frac{\Delta z^{k-1}}{2} +\right.$$

$$\left. + \left(\frac{1}{w_i^k . \Delta t} + A_i^k\right) \frac{\Delta z^k}{2}\right] \Psi_i^n - \frac{D_f^k}{\Delta z^k} \Psi_{i+1}^n - \left(\frac{B_i^{k-1} . \Delta z^{k-1}}{2} + \frac{B_i^k . \Delta z^k}{2}\right) \phi_i^n =$$

$$= \left[C_i^{k-1} + \frac{\Psi_i^{n-1}}{w_i^{k-1} . \Delta t}\right] \frac{\Delta z^{k-1}}{2} + \left[C_i^k + \frac{\Psi_i^{n-1}}{w_i^k . \Delta t}\right] \frac{\Delta z^k}{2} \qquad \text{(III-8)}$$

A similar result can be obtained with the integration of equation (III-2).

The two diffusion equations of the fast and thermal groups are then transformed into the system of 2 X (L-2) linear equations:

$$- r_{i1} \cdot \Psi_{i-1} + P_{i1} \Psi_i - t_{i1} \cdot \Psi_{i+1} - s_i \phi_i = q_{i1}$$

$$- m_{i1} \cdot \Psi_i - r_{i2} \phi_{i-1} + P_{i2} \cdot \phi_i - t_{i2} \phi_{i+1} = q_{i2} \qquad \text{(III-9)}$$

$$\left[i = 2, \ldots . (L-1)\right]$$

We have supposed that $\phi_1 = \phi_L = \Psi_1 = \Psi_L = 0$.
The coefficients depend on the temperature, on the position of the control rods and on the distribution ϕ_i^{n-1} and Ψ_i^{n-1} calculated at the preceding time interval.

A subroutine calculates the coefficients for every point of the lattice at every time step.

The solution of this system can be obtained with an iterative method using alternatively Ψ as source of ϕ and ϕ as source of Ψ, or with a direct method. Both methods were thoroughly described in another report (EUR - 596e "Comparison between the solution by an iterative and a direct method" by Monterosso and Vincenti).

The distribution Ψ_i and ϕ_i are calculated at every time step by another subroutine.

The coefficients (which must be calculated at every time step according to the temperature reaction and the position of the control rods) are presumed to be constant during the interval Δt which must therefore be sufficiently small. The choice of Δt is based on a compromise between the precision and the time of calculation.

§ IV The parts of the code and their function

This code consists of two parts:

a) Initial condition:

this section calculates for the cold reactor:

- the uniformly distributed poison Σ_p for which the reactor is overcritical with a required stable period
- a critical uniformly distributed poison Σ_{po}, or the critical depth of insertion of the control rods -
- the corresponding distribution $\Psi(z)$, $\phi(z)$, $C(z)$ at the steady state for a required power (this power must be sufficiently small for the reactor to be considered as remaining cold)

b) Dynamic calculation:

this section simulates the movement of the rods and calculates the evolution of flux and temperature in space and time during the power excursion.

§ V - Initial conditions

- Calculation of the uniformly distributed poison Σ_p corresponding to a desired stable period T

When the reactor is not critical, after an initial transient, the flux increases exponentially according to $\phi(t) = \phi_o \ e^{\alpha t}$, $(\alpha = \frac{1}{T})$, until the temperature reaction takes place.

A poison Σ_p, as a first approximation, is introduced in the diffusion equations; after a certain number of time steps, the code calculates $\alpha = \frac{1}{T}$, and corrects the value of Σ_p in the sense of reducing the error $(\alpha - \bar{\alpha})$, where $\bar{\alpha} = \frac{1}{\bar{T}}$. The calculation is repeated until $(\alpha - \bar{\alpha}) < \varepsilon$, where ε is an arbitrarily small quantity given as input data.

To avoid the temperature reaction, which perturbs the stable period, these calculations start from an initial arbitrary flux distribution at a very low power ($\phi \simeq 10^{10} \frac{n}{cm^2 sec}$); and the reactor is considered as remaining cold during the time of this calculation.

To calculate the first approximation of Σ_p we use the formula

$$\bar{\alpha} = \frac{1}{\bar{T}} = \frac{\delta k_{eff}}{l} \qquad (V-1)$$

even though this is valid only near criticality (in our case the reactor is prompt critical).

It is:

$$l = \frac{1}{(\Sigma_a^c + \Sigma_p).\ v} \cdot \frac{1}{(1+B^2\ L^2)} \qquad (V-2)$$

and

$$\delta k_{eff} = 1 - \frac{k_\infty \frac{\Sigma_a^c}{\Sigma_a^c+\Sigma_p}}{(1+B^2L^2)\ (1+B^2\tau)} \qquad (V-3)$$

where

$$L^2 = \frac{D_t^c}{\Sigma_a^c + \Sigma_p} \qquad (V-4)$$

substituting in (V-1) and rearranging:

$$\Sigma_p = \frac{k_\infty \Sigma_a^c}{(1+B^2\tau)} - B^2 D_t^c - \Sigma_a^c - \frac{\bar{\alpha}}{v} \qquad (V-5)$$

- <u>Calculation of the critical uniformly distributed poison Σ_{po}</u>

With the same iterative method it is possible to determine Σ_{po} taking $\bar{\alpha} = \frac{1}{\bar{T}} = 0$, starting from:

$$\Sigma_{po} = \frac{k_\infty \Sigma_a^c}{(1+B^2\tau)} - B^2 D_t^c - \Sigma_a^c \qquad (V-6)$$

It is interesting to remark that, for large values of $\bar{\alpha}$, the Σ_p, calculated by the code with the iterative method, is considerably different from the value obtained with formula (V-5); this is due to the fact that the deduction of the formulae (V-1) to (V-4) is based on simplifying assumptions valid only near criticality. For $\bar{\alpha} = 0$, however, the

Σ_{po} calculated with (V-6) is almost the same as the value calculated by the code with the iterative method. The small difference is due to the inexactitude of B^2 in (V-6). In fact TESI is a reflected reactor and B^2 is the buckling of an equivalent bare reactor, the dimensions of which are determined by a reflector saving calculation. By substituting in (V-6) the final value of Σ_p, it is possible to calculate a more exact value of the equivalent buckling B^2.

- Critical depth of insertion of the control rods

If the effect of the control rods is equivalent to a uniformly distributed poison Σ_{pB}, then it must be:

$$\Sigma_{pB} + \Sigma_p > \Sigma_{po}$$

When the control rods are inserted the reactor is undercritical; when they are completely withdrawn the flux evolves with the stable period $\bar{T}$ before the temperature reaction takes place.

At a certain depth of insertion of the bank of control rods, the reactor is critical. To find it, the code utilizes an iterative method (regula falsi): at every successive position of the rods, α is calculated and the iterations stop when $|\alpha| < \varepsilon$.

- The distribution of fluxes at steady state

After having obtained the critical Σ_{po}, or the critical position of the rods, the code repeats the calculation of the fluxes until the stable critical distribution $\Psi(z)$, $\phi(z)$, $C(z)$ is obtained. These distributions are symmetrical or asymmetrical accordingly.

The code can now reduce the fluxes to values corresponding to a desired power. This power, of course, must be sufficiently small to have a negligeable heat production.

The iterative calculations will be repeated a number of times. At every iteration the thermal flux $\phi(z)$ is multiplied by the factor

$$F = \frac{A \int_{core} dz}{\int_{core} \phi(z) dz}$$

where A is the average flux in the core corresponding to the desired power. At every iteration, the C(z) are calculated according to:

$$C(z) = \frac{k_\infty \beta \Sigma_a}{\lambda} \cdot \phi(z)$$

After a number of iterations the fast flux $\Psi(z)$ also reaches the value of steady state in equilibrium with its normalized source $\left[k(1-\beta)\,\Sigma_a \cdot \phi(z) + \lambda\, C(z)\right]$ (see p. 6 eq.(II-1)).

§ VI - Dynamic calculation

The programme reads an initial distribution $\Psi(z,t_o)$; $\phi(z,t_o)$; $C(z,t_o)$ and $T(z,t_o)$ at the time t_o and the control rod position $xz(t_o)$. Starting from these values it calculates their evolution in space and time according to the diffusion equations and the movement of the control rods.

The calculation can start from a critical distribution obtained by "Initial Conditions" at the time $t_o = 0$. It is also possible to reinitiate, from the last distribution at the time $t_o = t$, an interrupted calculation.

Control rods. The movement of the control rods is simulated in a special subroutine. They can be withdrawn instantaneously, or with a finite velocity which can be changed during the extraction, or reinsertion, according to any given law of movement.

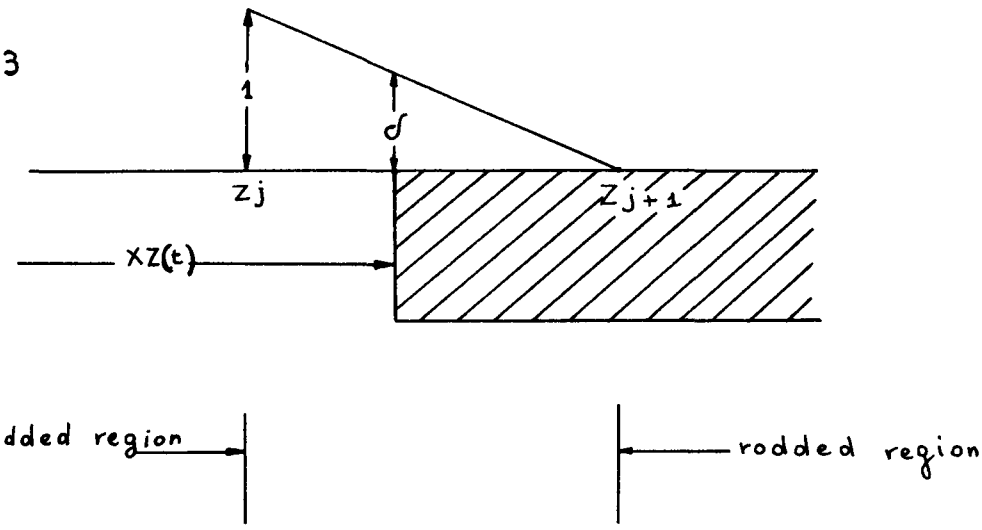
The coefficients p_{i2} of the thermal group equation are calculated with or without poison for all the points of the lattice. The subroutine decides which points are in the rodded or in the non rodded region and assigns to p_{i2} the poisoned or the non poisoned value.

The point z_i of the non rodded region, in the vicinity of the rod, will be partially poisoned and the total absorbtion cross-section is:

$$(\Sigma_{ao} + \delta \Sigma_{po}) \sqrt{\frac{To}{(T(z_{i,t})}} \qquad 0 \leq \delta \leq 1$$

where the factor δ is obtained by interpolation according to the position of the rods $xz(t)$ between the two points z_j and z_{j+1}, see Fig. 3.

Fig. - 3



In this way the total equivalent poison in the reactor is expressed as a continuous function of the position of the rod, independently of the subdivision of the space in mesh points.

Temperature reaction. Equation (II-4) of page 6 is transformed into the explicit system of L equations:

$$\frac{T_i^n - T_i^{n-1}}{\Delta t} = \frac{F}{c_i} \frac{k_i}{\nu} \Sigma_{ai} \phi_i^n \qquad (i = 1\ 2\ \ldots\ldots L)$$

The T_i^n are the unknown values of the temperature at each point z_i of the lattice at the time t_n; T_i^{n-1} are the known values calculated at the time $(t_n - \Delta t)$; Σ_{ai}, k_i, C_i are temperature dependent and therefore they have different values from point to point, their values were calculated according to the temperature distribution T_i^{n-1} at the time $(t_n - \Delta t)$; ϕ_i^n is the thermal flux corresponding to the lost calculation at time t_n.

The values of Σ_{ai}, k_i, C_i are therefore delayed with respect to the values of ϕ_i^n. The error due to this inconsistency can be reduced by diminishing Δt. Many tests were made using several Δt. The fluxes and temperatures calculated

converge to a final value for decreasing Δt. The experience has demonstrated that for $\Delta t \leqslant 10^{-3}$ sec no practical improvement can be obtained (see Report EUR-596 e).

With the temperatures T_i^n the new τ_i, c_i, k_i are calculated by interpolation between the tabulated values, and the new Σ_a, Σ_p, w, v are calculated with the formulae:

$$\Sigma_{ai} = \Sigma_{ao}\sqrt{\frac{To}{T_i^n}} \quad ; \quad \Sigma_{pi} = \Sigma_{po}\sqrt{\frac{To}{T_i^n}} \quad ; \quad w_i = w_o\sqrt{\frac{T_i^n}{To}} \quad ;$$

$$v_i = v_o\sqrt{\frac{T_i^n}{To}}$$

These values corresponding to the time t_n are introduced in the coefficients of the system (III-9) to calculate the new distribution of Ψ_i^{n+1}, ϕ_i^{n+1}, C_i^{n+1} at the time $t_{n+1} = t_n + \Delta t$.

§ VII - Comparison between the conventional method of the kinetic equations and the direct solution of the diffusion equations

The conventional method for studying the dynamics of a reactor is based on the kinetics equations

$$(VII\text{-}1) \qquad \frac{dn}{dt} = \frac{k_{eff}\,(1-\beta) - 1}{l} + e^{-B^2\tau} \cdot \lambda \cdot C$$

$$(VII\text{-}2) \qquad \frac{dC}{dt} = \frac{k_\infty \beta}{l_o} n - \lambda C$$

The following equation gives the law of the temperature variation

$$(VII\text{-}3) \qquad \frac{dT}{dt} = \frac{F}{c} \frac{k_\infty}{\nu} \Sigma_{ao} \cdot v_o \cdot n$$

These equations contain the space average values of n, c and T and do not consider the geometrical configuration of the reactor. From now on we will call this the point-method. The one used in our code will be called the spatial-method.

The value of k_{eff} is determined by the control rods' position and also by the values of k_∞, τ, L^2, which are known functions of the temperature. It is therefore possible to calculate the function $k_{eff}(T)$, which, introduced into equation (VII-1) gives the temperature reaction.

This set of equations, together with the function $k_{eff}(T)$

can be studied with the analogue computer, or with the digital code AIREC or PINETO.

However, this method is based on simplifying assumptions, which will be now explained:

a) The equations (VII-1) and (VII-2) are deduced from the one-group time-dependent diffusion equation. This deduction is possible only by supposing that the flux is separable relatively to the time and space variables, i.d. the flux

$$\phi(r,t) = R(r) \cdot T(t) \qquad \text{(VII-4)}$$

actually it should be:

$$\phi(r,t) = \sum_{n=1}^{\infty} Rn(r).Tn(t) \qquad \text{(VII-5)}$$

we consider only the first mode.

This is true only at criticality and can be assumed for states very close to criticality. The reactor TESI, however, operates in conditions of prompt criticality.

b) The expressions of k_{eff} and l appearing in (VII-1)

$$k_{eff} = \frac{k_\infty e^{-B^2\tau}}{(1+B^2L^2)} \qquad l = \frac{l_o}{(1+B^2L^2)}$$

contain B^2 (Buckling) or the first of the proper values of the solution (VII-5). As the reactor is reflected, B^2 can only be obtained considering an equivalent bare reactor, the dimensions of which are determined by a reflector saving calculation. As before this calculation has a meaning only at criticality or close to it.

c) The temperature reaction given by the function $k_{eff}(T)$ can be calculated only using a value of T averaged throughout the core. The temperature however is different from point to point and its spatial distribution changes according to the production of heat. This deforms the shape of the flux distribution and influences the reactivity. This effect can not be taken into account using this method.

d) The k_{eff} depends on the position of the control rods xz and on the temperature T. These two variables in the function $k_{eff}(T,xz)$ are non separable. However the only possible way of determining k_{eff} with the analogue computer or with the Airek Code is to consider their effect separately.

These simplifying assumptions and their consequent effects on the precision of the results can be avoided by the method of the direct solution of the time-dependent-diffusion-equation considered in each point of the reactor core and reflectors.

It is interesting to compare the results of both methods for the same case. The choice of a suitable example for this comparison is however rather difficult because the two methods have a completely different approach to the problem.

In this example, to avoid the deformation of the flux distribution due to the movement of the control rods, these are withdrawn instantaneously (which corresponds to a step of reactivity in the point-method). This instantaneous extraction of the rod avoid furthermore the difficulties explained in d) ; in fact only the temperature reaction on reactivity takes place during the power excursion.

The control rods at the interface between core and radial reflector are kept completely inserted. By this means it is possible to calculate exactly the radial buckling $B_r^2 = (\frac{2.405}{R})^2$, where R = radius of core. The error of the buckling determination [b) p. 24] is limited to the axial buckling.

Fixed a value of $\bar{\alpha}$, the Σ_p can be calculated with the iterative method of p. 15. Then using the formulae (IV-1) to (IV-4) it is possible to calculate the corresponding δk_{eff} to be used in the kinetic equations.

§ VIII - Some examples of calculation

The Code Costanza can plot automatically the curves by a CALCOMP DATA-PLOTTER. See Figures 7 to 11.

a) Control rods extracted with constant velocity

Fig. 7 shows the curves of $\bar{\Psi}(t)$ and $\bar{\phi}(t)$ obtained with an instantaneous expulsion of the control rods, and by extracting the rods with constant velocity in 0.15 sec. The poison left in the core is, in this case, $\Sigma_p = 0.00007$ cm^{-1}. At the time the control rods are completely extracted, the temperature reaction has not yet reached its effect, therefore the curves $\bar{\Psi}(t)$ and $\bar{\phi}(t)$ are almost the same in both cases, they are shifted forwards for the ramp extraction. In Fig. 8 are the curves of the average temperature $\bar{T}(t)$.

Figs. 9 and 10 are the spatial distributions $\Psi(z)$ and $\phi(z)$, when the control rods are extracted in 0.15 sec, at the time 0.075 sec when the rods are still in the core, and at the time 0.241 sec when the maximum of $\bar{\phi}(t)$ is reached.

Fig. 11 shows the temperature distribution of 0.501 sec.

Fig. 12 is a page of the listing of the IBM 7090 with the input data and the tables of k_∞ , τ and specific heat. In Fig. 13 are the initial distributions and Figs. 14 , 15 , 16 are the prints corresponding to the times 0.1 , 0.24 , 0.501 sec.

(For the meaning of the symbols see the WRITE-UP of the Code Costanza; some remarks and descriptions of symbols have been written with a type-writer on the listing itself).

If the rods are extracted with a low velocity, the oscillations take place. Fig. 17 reports the function $\bar{\phi}(t)$ corresponding to a rod velocity of 40 cm/sec. In Fig. 18 the non symmetrical flux and temperature distri-

bution and the control rods' positions are plotted, corresponding to the peaks of Fig. 17 at the times $t = 2.63$ sec and $t = 3.62$ sec.

b) Rod movements for constant power

One of the interesting operational conditions of TESI consists in reaching in a short time a certain power level and in maintaining it as lons as possible, according to the temperature reaction and to the total built-in reactivity.

The desired power can be reached in the shortest time by an extremely rapid expulsion of a certain number of control rods. Once the required power has been reached, the reactor must again become critical and some rods are shot into the reactor again. If in the meantime the temperature has reached a considerable level not all the extracted rods are reinserted. Some of them remain out to compensate the temperature reaction. After this first phase, the temperature reaction increases continuously and this will be compensated by again extracting the control rod at a reduced velocity. The total expulsion and reinsertion of the first phase are obtained with pneumatic devices, with a maximum permissible acceleration of 100 g. The movement at reduced velocity of the second phase is obtained by mechanical engines. An additional subroutine of the code simulates the expulsion and reinsertion of the rods. The reduced number of rods can easily be simulated by using a convenient value of Σ_{pB} in the rodded region. This subroutine determines continuously the position of the control rods according to the power wanted and the temperature reaction. The movements are kept within the limits of the maximum mechanical speed possible. Fig. 19 contains the curves of the rod position as function of time and of the average temperature $\bar{T}(t)$. Fig. 20 contains the $\bar{n}(t)$, average neutron density, as function of time.

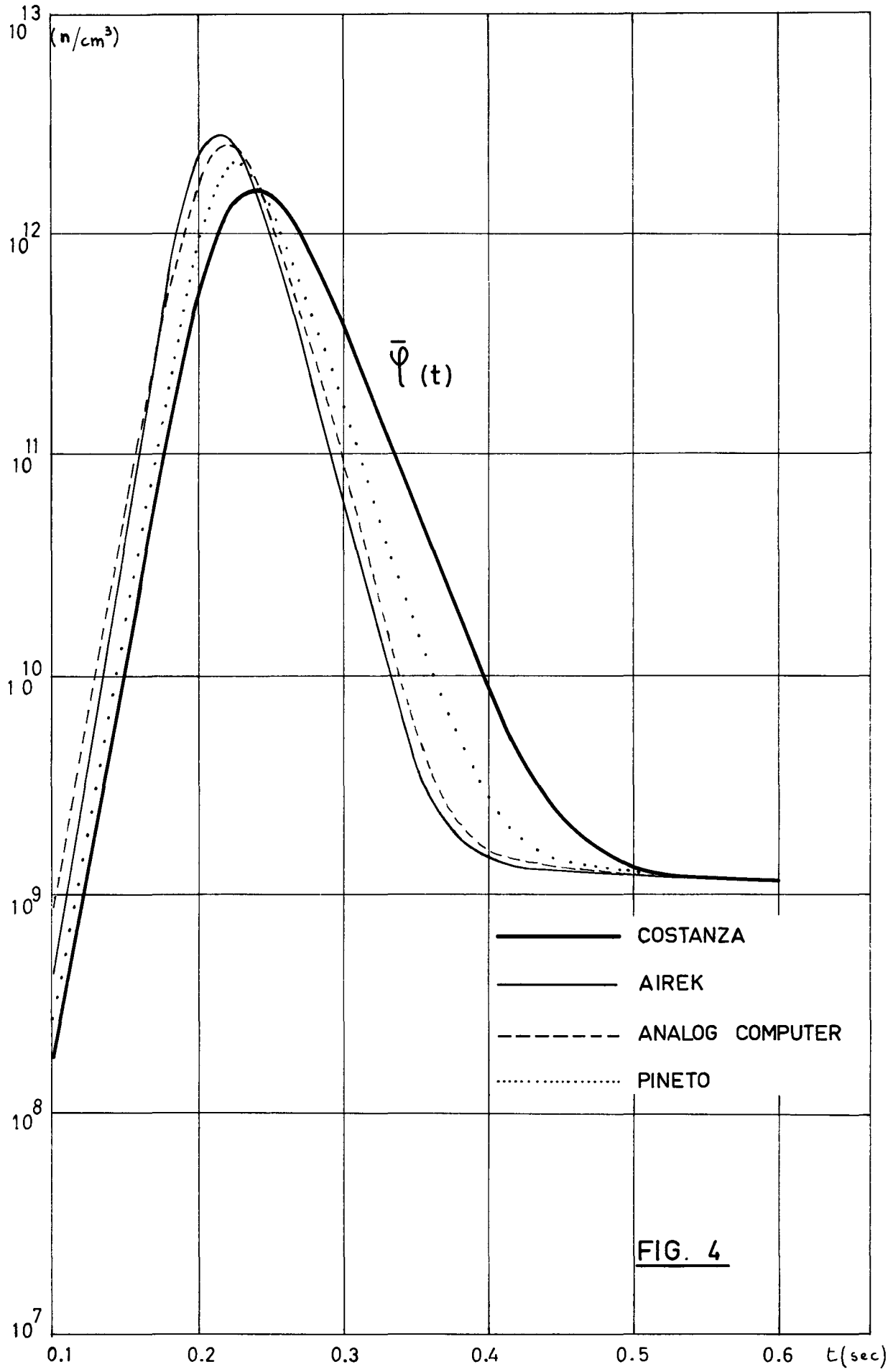

10^{13} (n/cm³)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
$\bar{\varphi}$ (t)
COSTANZA
AIREK
ANALOG COMPUTER
PINETO
0.1
0.2
0.3
0.4
0.5
0.6
t(sec)

FIG. 4

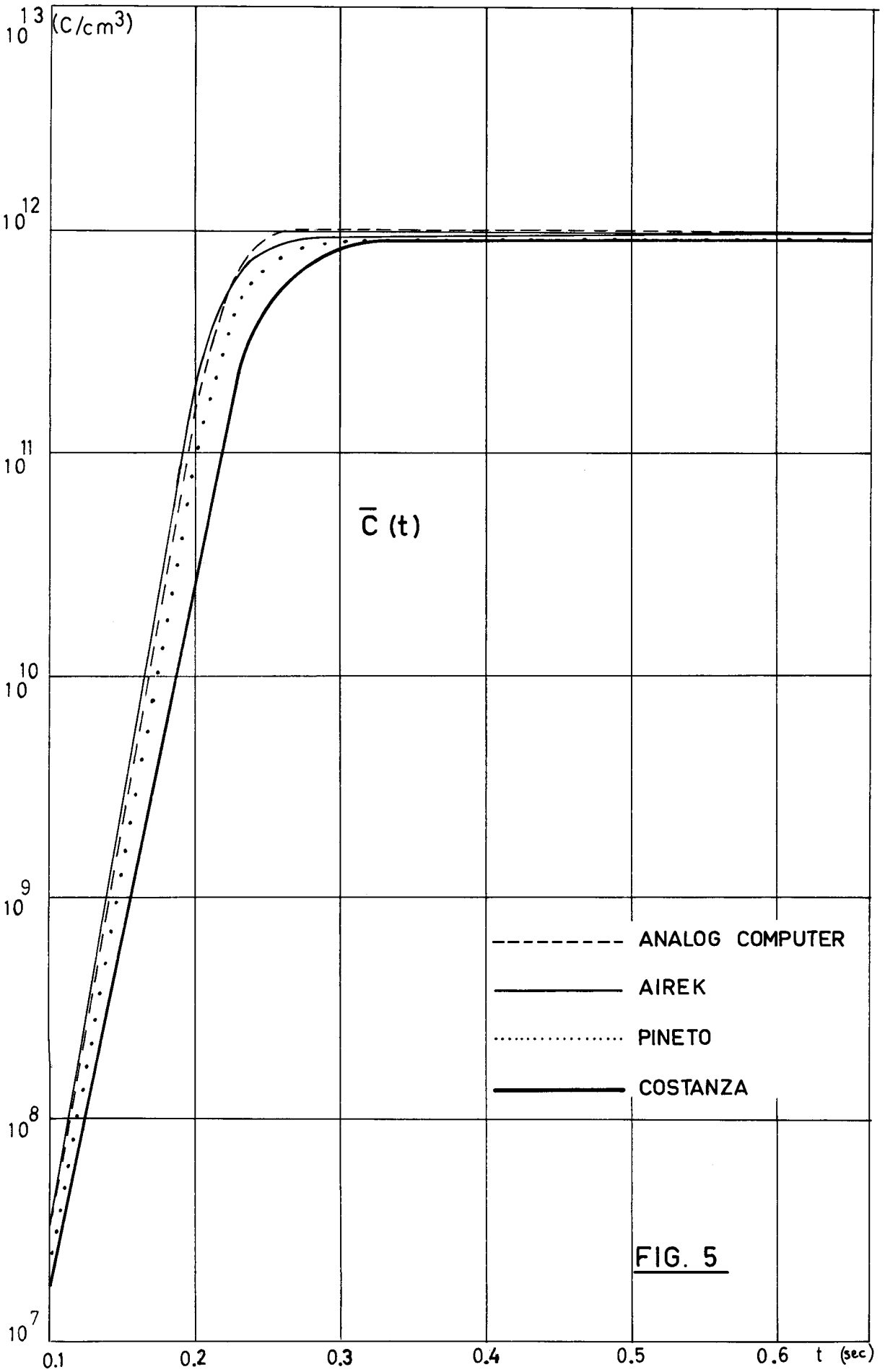

10^{13} (C/cm^3)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
$\bar{C}$ (t)
ANALOG COMPUTER
AIREK
PINETO
COSTANZA
0.1
0.2
0.3
0.4
0.5
0.6
t (sec)

FIG. 5

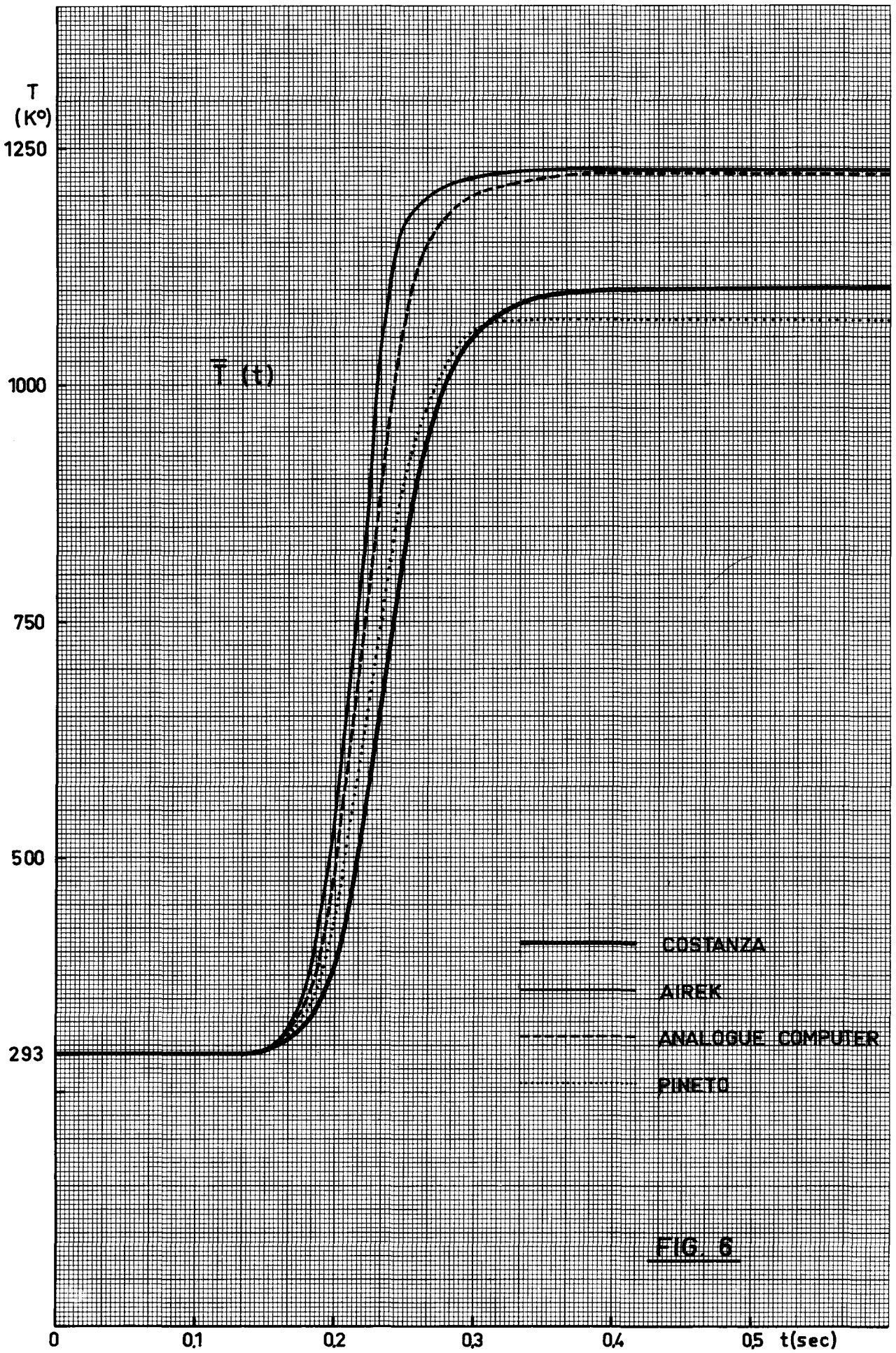
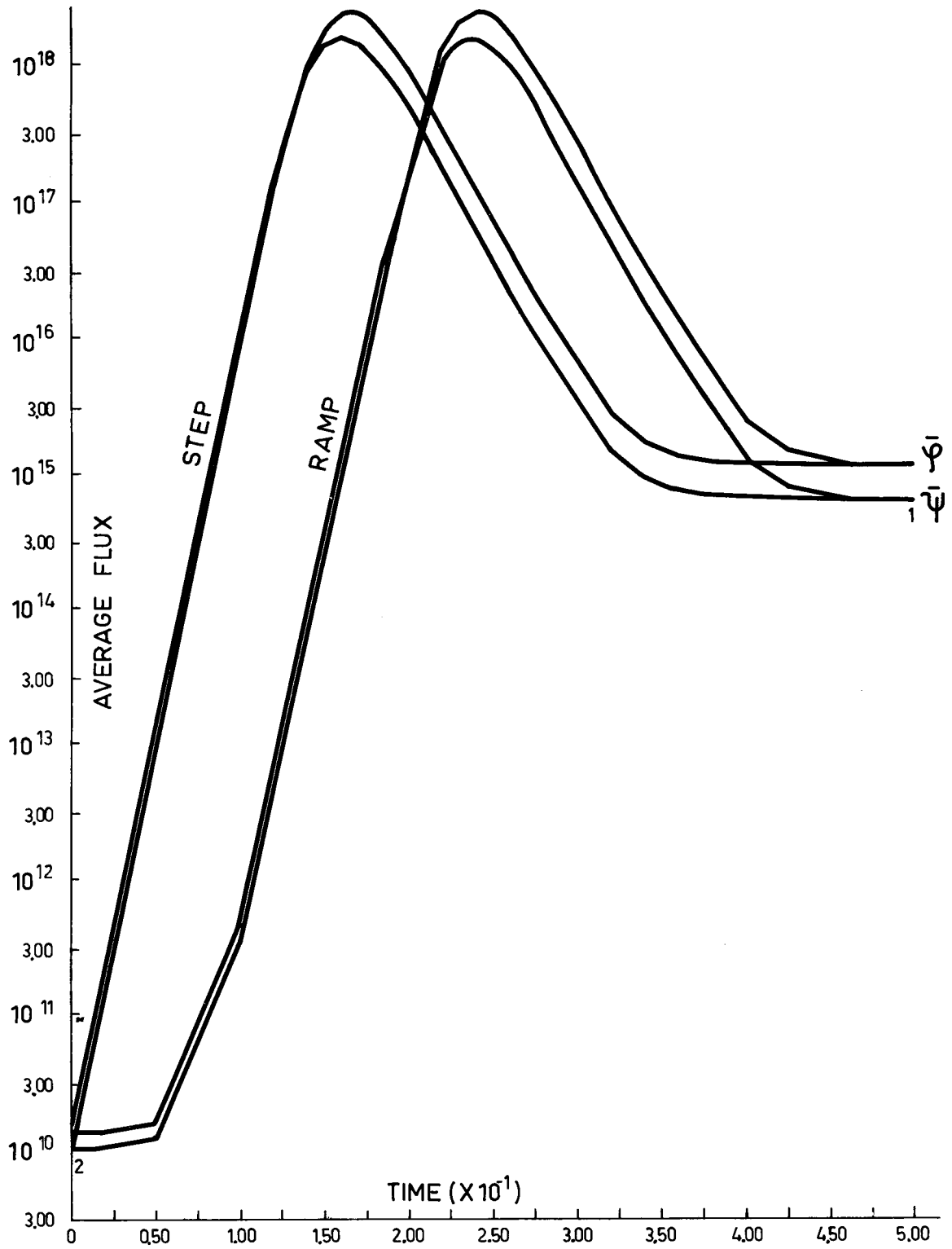

T
(K°)
1250
1000
750
500
293
T (t)
COSTANZA
AIREK
ANALOGUE COMPUTER
PINETO
0
0,1
0,2
0,3
0,4
0,5
t(sec)

FIG. 6

FIG. 7



CODE COSTANZA I 60.5414

FIG. 8

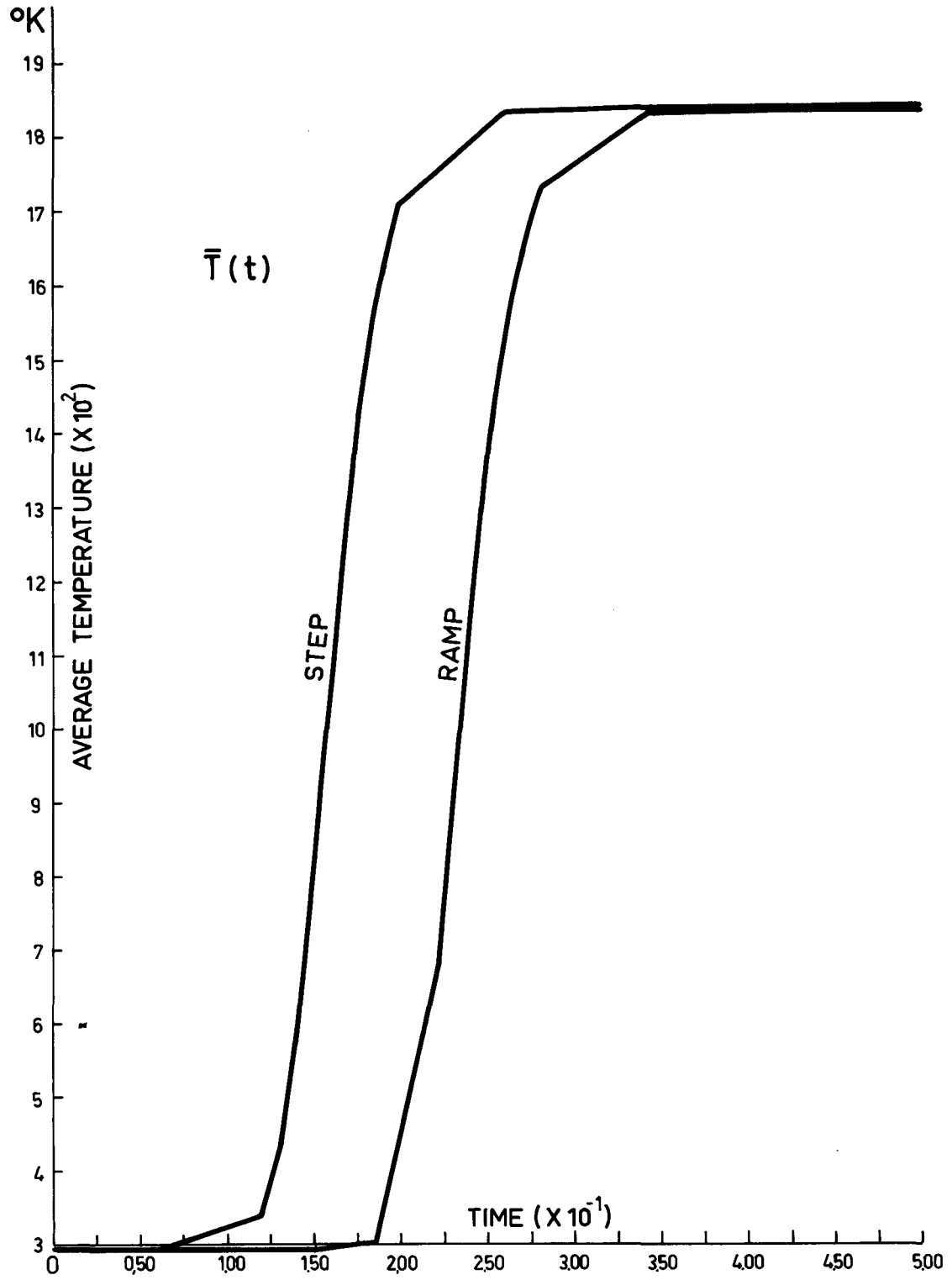
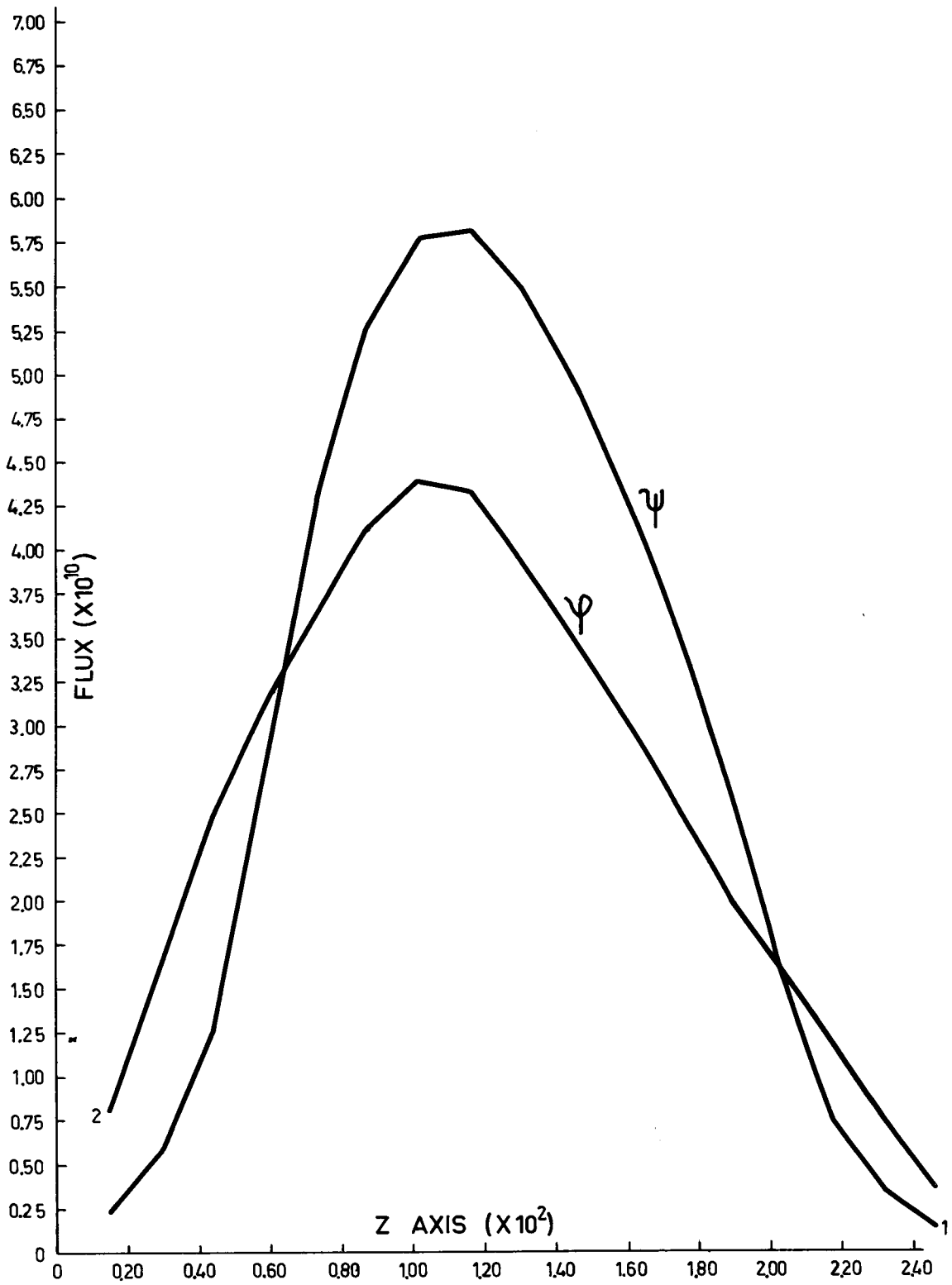

°K
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
$\bar{T}(t)$
AVERAGE TEMPERATURE (X 10^2)
STEP
RAMP
TIME (X 10^{-1})
0
0,50
1,00
1,50
2,00
2,50
3,00
3,50
4,00
4,50
5,00

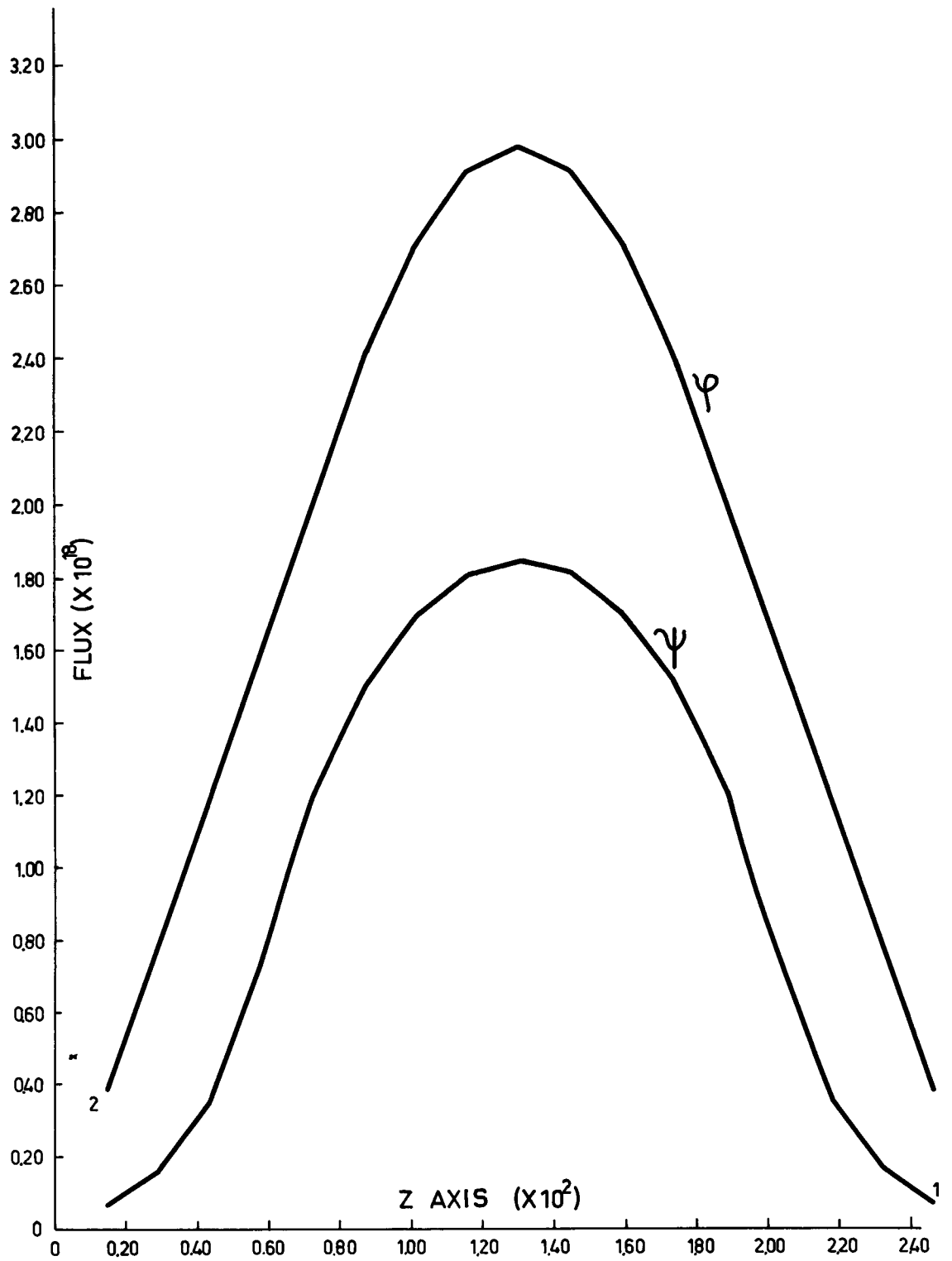
FIG. 9



SPATIAL DISTRIBUTION TIME – 0.07499

CODE COSTANZA I 60.5414

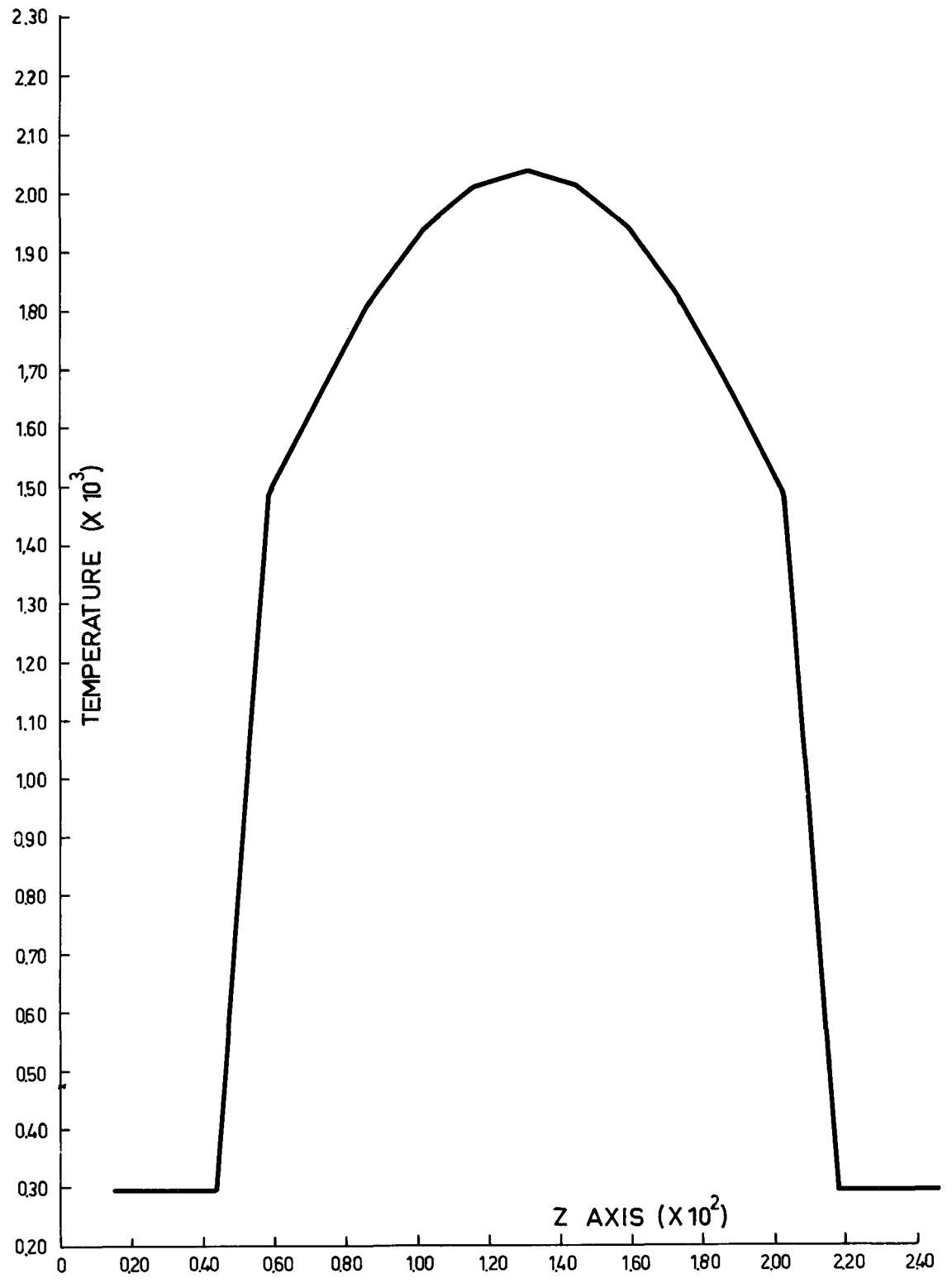
FIG. 10



SPATIAL DISTRIBUTION TIME - 0.24099

CODE COSTANZA I 60.5414

FIG. 11



TIME -0.50099

COSTANZA - CONTROL RODS EXTRACTED IN 0.15 SEC - SPR=0.00007

DZ1	DZ2	DZ3	DRF	DCF	DRT	DCT
0.14500E 02	0.14500E 02	0.14500E 02	0.11000E 01	0.10660E 01	0.98600E 00	0.95500E 00
DT	SARZ	SACZ	WZ	VZ	SPZ	TZ
1.00000E-03	0.26350E-03	0.24770E-02	0.30800E 07	0.24860E 06	0.58338E-03	0.29300E 03
BU	B	DL	SPR	PREC	VNU	FC
0.34400E-03	0.67600E-02	0.76790E-01	0.70000E-04	1.00000E-04	0.24700E 01	0.76600E-11
XZ	TF	VKP	TRP	TCP	CSP	
0.	0.50000E 00	-0.55500E 00	0.	0.50200E-04	-0.57500E-02	

M = 5	N = 15	L = 19	INT = 6	KL = 20	KI = 0	KS = 0

T	VK	TAUR	TAUC	CS
0.29300E 03	0.18315E 01	0.42600E 03	0.40200E 03	0.25200E-00
0.39300E 03	0.18255E 01	0.42600E 03	0.39700E 03	0.35000E-00
0.49300E 03	0.18195E 01	0.42600E 03	0.39350E 03	0.44000E-00
0.59300E 03	0.18145E 01	0.42600E 03	0.39080E 03	0.51000E 00
0.69300E 03	0.18100E 01	0.42600E 03	0.38850E 03	0.55500E 00
0.79300E 03	0.18055E 01	0.42600E 03	0.38680E 03	0.60000E 00
0.89300E 03	0.18022E 01	0.42600E 03	0.38500E 03	0.63000E 00
0.99300E 03	0.17995E 01	0.42600E 03	0.38300E 03	0.66000E 00
0.10930E 04	0.17970E 01	0.42600E 03	0.38180E 03	0.68000E 00
0.11930E 04	0.17950E 01	0.42600E 03	0.38050E 03	0.70000E 00
0.12930E 04	0.17933E 01	0.42600E 03	0.37900E 03	0.72000E 00
0.13930E 04	0.17915E 01	0.42600E 03	0.37800E 03	0.73500E 00
0.14930E 04	0.17900E 01	0.42600E 03	0.37700E 03	0.75000E 00
0.15930E 04	0.17890E 01	0.42600E 03	0.37640E 03	0.76000E 00
0.16930E 04	0.17880E 01	0.42600E 03	0.37550E 03	0.77000E 00
0.17930E 04	0.17870E 01	0.42600E 03	0.37450E 03	0.78000E 00
0.18930E 04	0.17865E 01	0.42600E 03	0.37400E 03	0.78600E 00
0.19930E 04	0.17855E 01	0.42600E 03	0.37350E 03	0.79200E 00
0.20930E 04	0.17850E 01	0.42600E 03	0.37300E 03	0.79800E 00
0.21930E 04	0.17845E 01	0.42600E 03	0.37250E 03	0.80000E 00

Fig. I2

T = temperatures $[^{\circ}K]$

VK = K_{∞} infinite multiplication factor

TAUR = Fermi-Age in the reflectors $[cm^2]$

TAUC = Fermi-Age in the core $[cm^2]$

CS = Specific heat of core $\left[\frac{cal}{cm^3 \cdot {}^{\circ}C}\right]$

RISOLUZIONE CON METODO ITERATIVO INT = 6

CONDIZIONI INIZIALI

TO = 0. XZ = 0.

Z	TR	TC	C	PH1	PH2	N
0.	0.29300E 03			0.	0.	0.
0.14500E 02	0.29300E 03			0.54178E 09	0.15561E 10	0.62595E 04
0.29000E 02	0.29300E 03			0.13901E 10	0.32396E 10	0.13031E 05
0.43500E 02	0.29300E 03			0.30251E 10	0.50483E 10	0.20307E 05
0.58000E 02	0.29300E 03	0.29300E 03	0.26334E 07	0.63719E 10	0.65938E 10	0.26524E 05
0.72500E 02		0.29300E 03	0.32161E 07	0.10538E 11	0.80529E 10	0.32393E 05
0.87000E 02		0.29300E 03	0.38662E 07	0.13544E 11	0.96809E 10	0.38942E 05
0.10150E 03		0.29300E 03	0.43997E 07	0.15676E 11	0.11016E 11	0.44312E 05
0.11600E 03		0.29300E 03	0.47409E 07	0.16968E 11	0.11871E 11	0.47751E 05
0.13050E 03		0.29300E 03	0.48577E 07	0.17403E 11	0.12164E 11	0.48930E 05
0.14500E 03		0.29300E 03	0.47409E 07	0.16968E 11	0.11871E 11	0.47751E 05
0.15950E 03		0.29300E 03	0.43997E 07	0.15676E 11	0.11016E 11	0.44312E 05
0.17400E 03		0.29300E 03	0.38662E 07	0.13544E 11	0.96809E 10	0.38942E 05
0.18850E 03		0.29300E 03	0.32161E 07	0.10538E 11	0.80529E 10	0.32393E 05
0.20300E 03	0.29300E 03	0.29300E 03	0.26334E 07	0.63719E 10	0.65938E 10	0.26524E 05
0.21750E 03	0.29300E 03			0.30251E 10	0.50483E 10	0.20307E 05
0.23200E 03	0.29300E 03			0.13901E 10	0.32396E 10	0.13031E 05
0.24650E 03	0.29300E 03			0.54178E 09	0.15561E 10	0.62595E 04
0.26100E 03	0.29300E 03			0.	0.	0.
VALORI MEDI		0.29300E 03	0.39937E 07	0.13723E 11	0.99999E 10	0.40225E 05

Fig. I3 The calculation is made with the iterative method, with a maximum of 6 inner iterations.

TO = 0.10000 ITER = 100

XZ = 173.99998 VB = 0.174000E 04 REP = 0.114054E 03 DP = 0.379130E 14 PHI = 0.427778E 10 VM = 0.248600E 06

Z	TR	TC	C	PH1	PH2	N
0.	0.29300E 03			0.	0.	0.
0.14500E 02	0.29300E 03			0.20561E 11	0.67748E 11	0.27252E 06
0.29000E 02	0.29300E 03			0.52886E 11	0.13968E 12	0.56186E 06
0.43500E 02	0.29300E 03			0.11547E 12	0.21450E 12	0.86282E 06
0.58000E 02	0.29300E 03	0.29300E 03	0.27129E 07	0.24814E 12	0.27497E 12	0.11061E 07
0.72500E 02		0.29300E 03	0.33090E 07	0.40034E 12	0.32873E 12	0.13223E 07
0.87000E 02		0.29300E 03	0.39729E 07	0.50560E 12	0.38651E 12	0.15547E 07
0.10150E 03		0.29300E 03	0.45149E 07	0.57201E 12	0.42897E 12	0.17256E 07
0.11600E 03		0.29300E 03	0.48577E 07	0.60189E 12	0.44855E 12	0.18043E 07
0.13050E 03		0.29300E 03	0.49688E 07	0.59595E 12	0.44259E 12	0.17803E 07
0.14500E 03		0.29300E 03	0.48400E 07	0.55595E 12	0.41112E 12	0.16537E 07
0.15950E 03		0.29300E 03	0.44823E 07	0.48585E 12	0.35576E 12	0.14310E 07
0.17400E 03		0.29300E 03	0.39319E 07	0.39266E 12	0.27887E 12	0.11218E 07
0.18850E 03		0.29300E 03	0.32667E 07	0.28848E 12	0.21340E 12	0.85842E 06
0.20300E 03	0.29300E 03	0.29300E 03	0.26722E 07	0.16864E 12	0.16340E 12	0.65728E 06
0.21750E 03	0.29300E 03			0.79733E 11	0.11872E 12	0.47754E 06
0.23200E 03	0.29300E 03			0.36505E 11	0.73270E 11	0.29473E 06
0.24650E 03	0.29300E 03			0.14188E 11	0.34318E 11	0.13805E 06
0.26100E 03	0.29300E 03			0.	0.	0.
VALORI MEDI		0.29300E 03	0.40837E 07	0.46025E 12	0.35137E 12	0.14134E 07

Fig. I4

TO = time
ITER = number of time steps
XZ = position of the control rods
VB = control rod velocity
REP = reciprocal of the reactor period = $\frac{I}{T}$
DP = $\frac{d\bar{\varphi}}{dt}$

PHI = $\int_0^t \bar{\varphi}(t)\, dt$

VM = neutron velocity of the thermal group

TR = temperature in reflector °K
TC = temperature in core °K
C = precursor density c/cm^3
PHI = fast flux $\frac{n}{cm^2 \cdot sec}$
PH2 = thermal flux "
N = neutron density n/cm^3

Under each column are reported the corresponding average values.

TO = 0.24000 ITER = 240

XZ = 260.99996 VB = 0. REP = 0.274671E 01 DP = 0.675901E 19 PHI = 0.562321E 17 VM = 0.499579E 06

Z	TR	TC	C	PH1	PH2	N
0.	0.29300E 03			0.	0.	0.
0.14500E 02	0.29300E 03			0.63720E 17	0.37724E 18	0.15175E 13
0.29000E 02	0.29300E 03			0.16347E 18	0.77519E 18	0.31182E 13
0.43500E 02	0.29300E 03			0.35563E 18	0.11975E 19	0.48170E 13
0.58000E 02	0.29300E 03	0.97205E 03	0.69883E 12	0.74886E 18	0.16000E 19	0.43805E 13
0.72500E 02		0.10748E 04	0.83910E 12	0.12176E 19	0.20030E 19	0.42068E 13
0.87000E 02		0.11711E 04	0.97482E 12	0.15220E 19	0.23990E 19	0.48267E 13
0.10150E 03		0.12440E 04	0.10800E 13	0.17190E 19	0.27141E 19	0.52984E 13
0.11600E 03		0.12885E 04	0.11453E 13	0.18314E 19	0.29137E 19	0.55890E 13
0.13050E 03		0.13034E 04	0.11674E 13	0.18681E 19	0.29818E 19	0.56868E 13
0.14500E 03		0.12885E 04	0.11453E 13	0.18314E 19	0.29137E 19	0.55890E 13
0.15950E 03		0.12440E 04	0.10800E 13	0.17190E 19	0.27141E 19	0.52984E 13
0.17400E 03		0.11711E 04	0.97482E 12	0.15220E 19	0.23990E 19	0.48267E 13
0.18850E 03		0.10748E 04	0.83909E 12	0.12176E 19	0.20030E 19	0.42068E 13
0.20300E 03	0.29300E 03	0.97205E 03	0.69883E 12	0.74886E 18	0.16000E 19	0.43805E 13
0.21750E 03	0.29300E 03			0.35563E 18	0.11975E 19	0.48170E 13
0.23200E 03	0.29300E 03			0.16347E 18	0.77519E 18	0.31182E 13
0.24650E 03	0.29300E 03			0.63720E 17	0.37724E 18	0.15175E 13
0.26100E 03	0.29300E 03			0.	0.	0.
VALORI MEDI		0.11832E 04	0.99446E 12	0.15622E 19	0.24641E 19	0.49909E 13

Fig. I5

TO = 0.50100 ITER = 501

XZ = 260.99996 VB = 0. REP = -0.330473E-00 DP = -0.384903E 15 PHI = 0.137855E 18 VM = 0.623441E 06

Z	TR	TC	C	PH1	PH2	N
0.	0.29300E 03			0.	0.	0.
0.14500E 02	0.29300E 03			0.25244E 14	0.17073E 15	0.68676E 09
0.29000E 02	0.29300E 03			0.64772E 14	0.35199E 15	0.14159E 10
0.43500E 02	0.29300E 03			0.14095E 15	0.54797E 15	0.22042E 10
0.58000E 02	0.29300E 03	0.14884E 04	0.14859E 13	0.29689E 15	0.74478E 15	0.17183E 10
0.72500E 02		0.16630E 04	0.17641E 13	0.48322E 15	0.94576E 15	0.15969E 10
0.87000E 02		0.18230E 04	0.20249E 13	0.60364E 15	0.11358E 16	0.18317E 10
0.10150E 03		0.19439E 04	0.22245E 13	0.68125E 15	0.12848E 16	0.20065E 10
0.11600E 03		0.20180E 04	0.23476E 13	0.72536E 15	0.13785E 16	0.21130E 10
0.13050E 03		0.20428E 04	0.23891E 13	0.73973E 15	0.14104E 16	0.21486E 10
0.14500E 03		0.20180E 04	0.23476E 13	0.72536E 15	0.13785E 16	0.21130E 10
0.15950E 03		0.19439E 04	0.22245E 13	0.68125E 15	0.12848E 16	0.20065E 10
0.17400E 03		0.18230E 04	0.20249E 13	0.60364E 15	0.11358E 16	0.18317E 10
0.18850E 03		0.16630E 04	0.17641E 13	0.48322E 15	0.94576E 15	0.15969E 10
0.20300E 03	0.29300E 03	0.14884E 04	0.14859E 13	0.29689E 15	0.74478E 15	0.17183E 10
0.21750E 03	0.29300E 03			0.14095E 15	0.54797E 15	0.22042E 10
0.23200E 03	0.29300E 03			0.64772E 14	0.35199E 15	0.14159E 10
0.24650E 03	0.29300E 03			0.25244E 14	0.17073E 15	0.68676E 09
0.26100E 03	0.29300E 03			0.	0.	0.
VALORI MEDI		0.18427E 04	0.20597E 13	0.62475E 15	0.11645E 16	0.18963E 10

Fig. I6

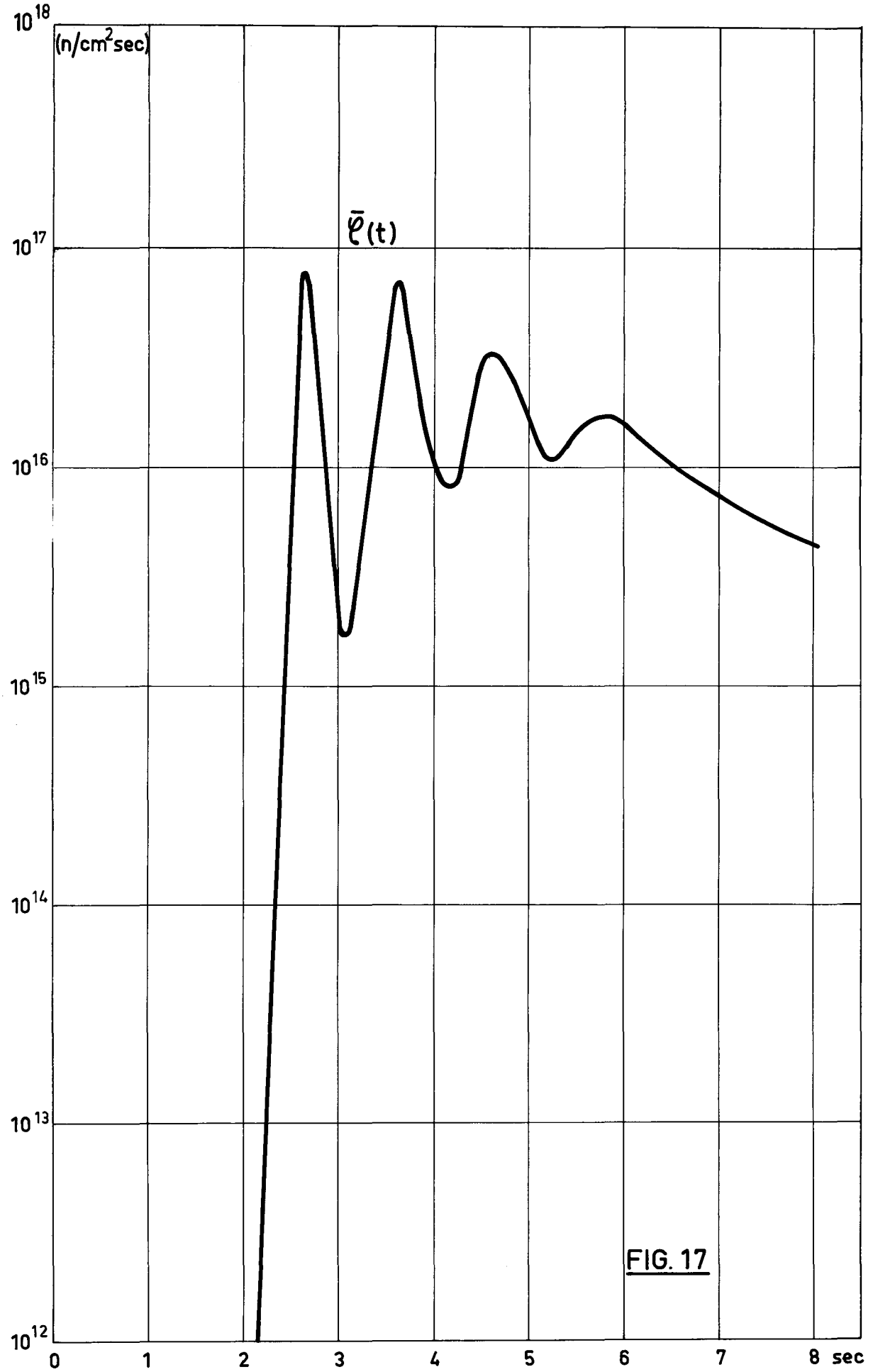

10^{18}
(n/cm^{2}sec)
$\bar{\varphi}(t)$
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
0
1
2
3
4
5
6
7
8 sec

FIG. 17

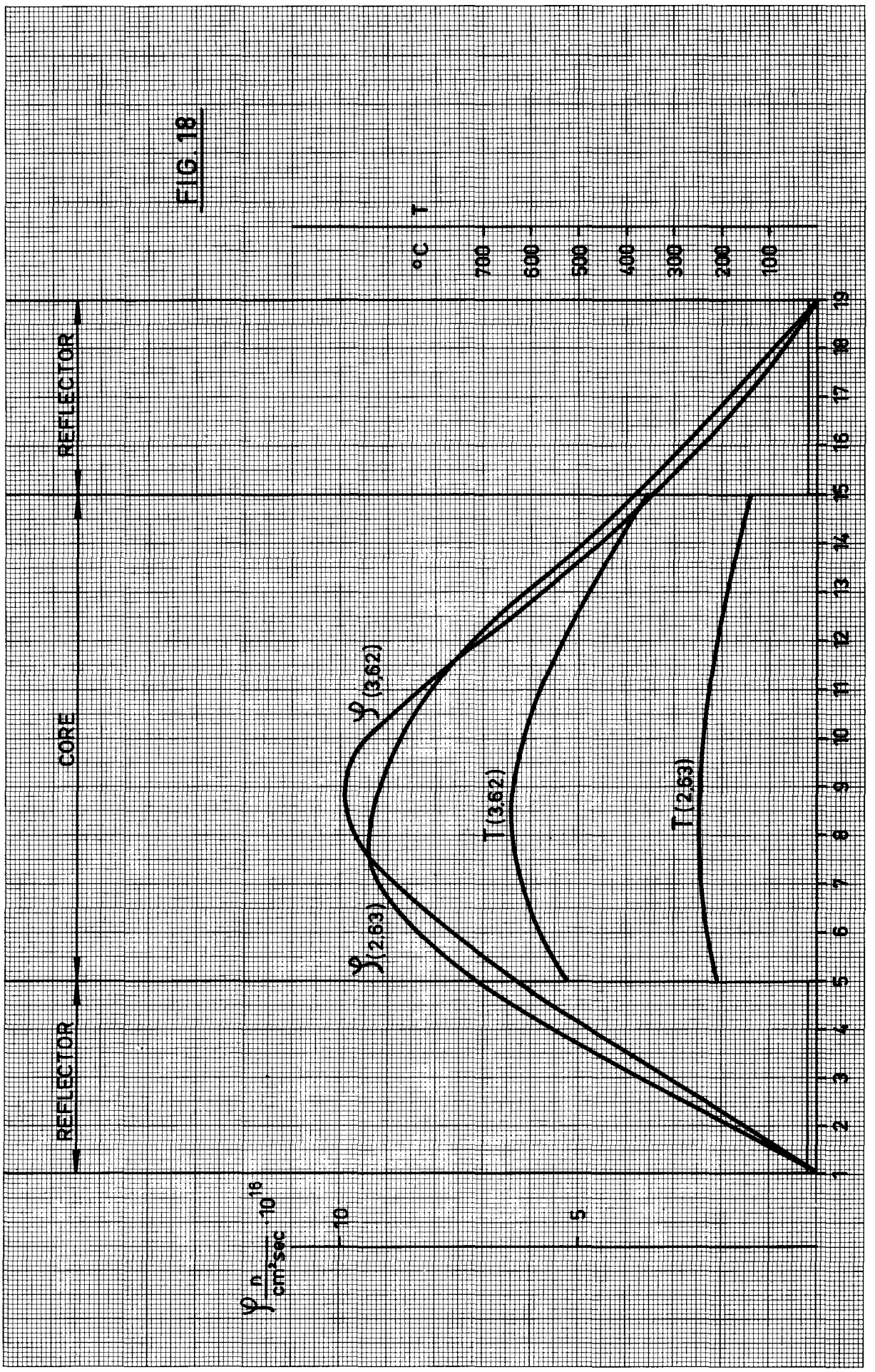

REFLECTOR
CORE
REFLECTOR
T °C
700
600
500
400
300
200
100
T(3,62)
T(2,63)
φ(3,62)
φ(2,63)
10
5
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

FIG. 18

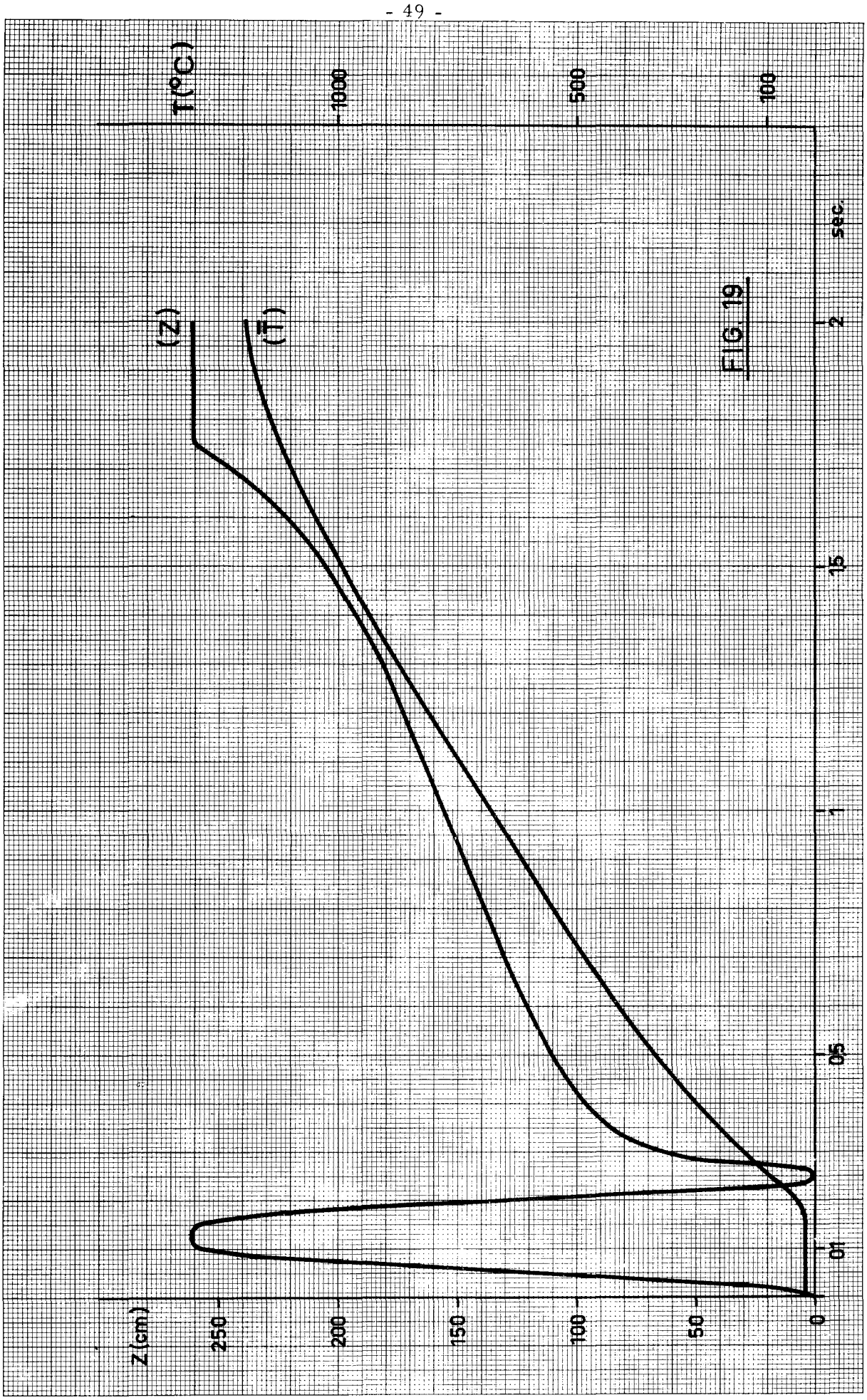


FIG. 19

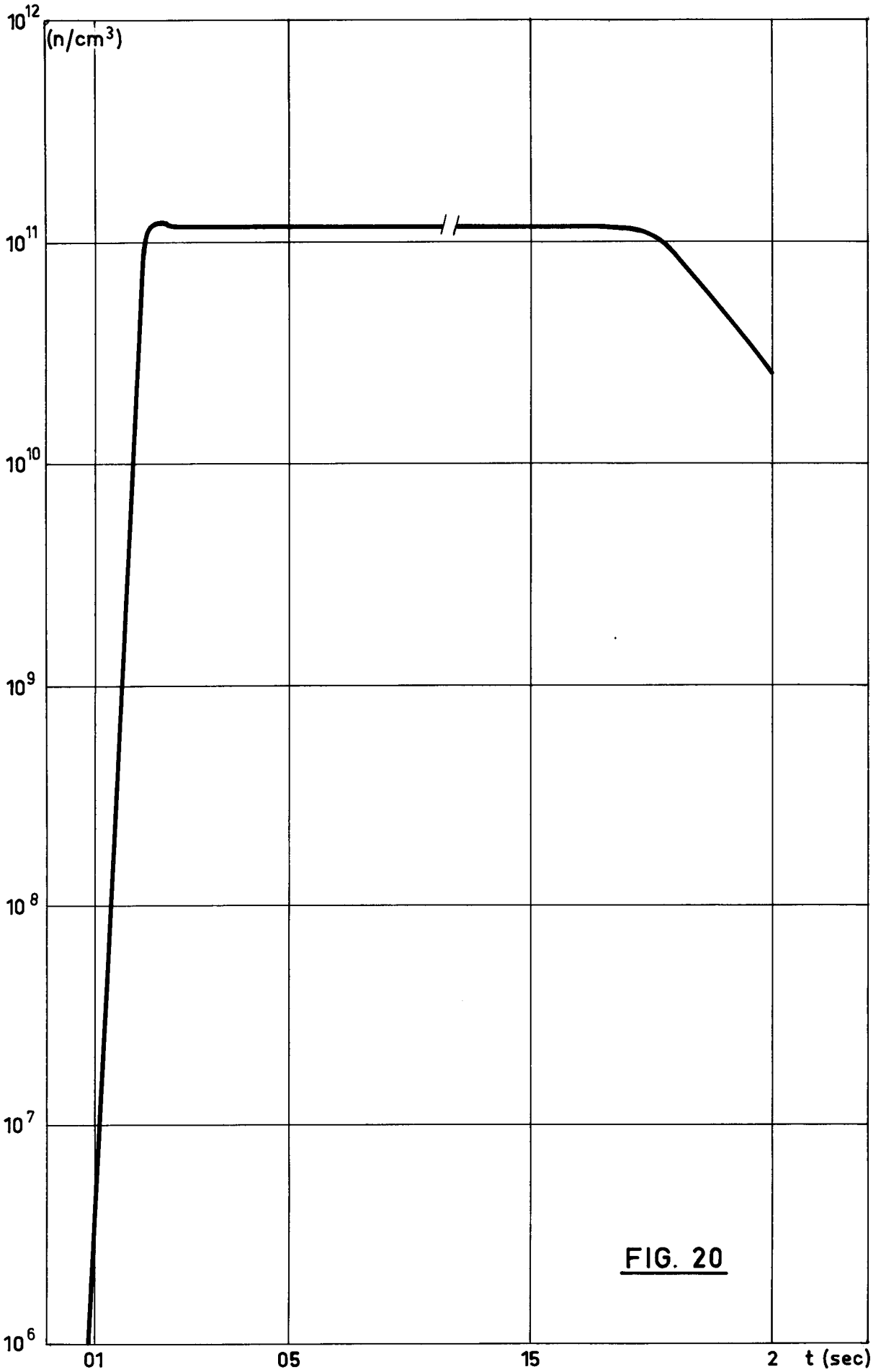


FIG. 20

References

AIREK: "Generalized Reactor Kinetics Code"; Atomics International, No.4980.

COHEN, E.R.: "Some Topics in Reactor Kinetics"; Geneva Conference 1958, Volume 11,P/629 USA.

FOX, L: "Numerical Solution of Ordinary and Partial Differential Equations"; Pergamon Press - 1962

KAPLAN, S.: "Some New Methods of Flux Synthesis"; N.S.&E. 13 - 1962.

P.D.Q.: "An IBM-704 Code to Solve the Two-dimensional Few-Group Neutron Diffusion Equations"; WAPD-TM-70

RICHTMYER, R.D.: "Difference Methods for Initial-Value Problems"; Interscience Publishers, Inc., New York.

SCHECHTER, S.: "Quasi-Tridiagonal Matrices and Type-insensitive Difference Equations"; AEC Computing and Applied Mathematics Center - TID-4500, NYO-2542.

STAB: "A Kinetic, Three-Dimensional, One-Group Digital Computer Program"; AEEW-R.77.

VARGA, R.S.: "Matrix Iterative Analysis"; Prentice-Hall, Inc.

WACHSPRESS, E.L.: "Digital Computation of Space-Time Variation of Neutron Fluxes"; KAPL - 2090.

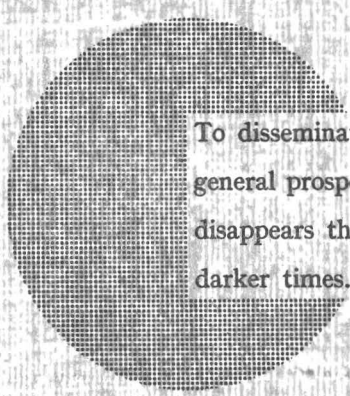
WANDA: "A One-dimensional Few-Group Diffusion Equation Code for the IBM-704".

R.MONTEROSSO and E.VINCENTI "Finite Difference Method for Solving the Spatio-Temporal Diffusion Equation in the Two-Group Approximation" EUR 596.e

References

C.BONA, C.TAMAGNINI — PINETO - A Fortran Code for Systems of Quasi-Linear Differential Equations, Particularly Suitable for Nuclear Reactor Dynamics.

To be published.



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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