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A SIMPLIFIED VISCO-ELASTIC ANALYSIS OF GRAPHITIC BODIES SUBJECTED TO EXTERNAL LOADS, TEMPERATURE GRADIENTS AND NEUTRON IRRADIATION

by

J. DONEA and S. GIULIANI

1971

Joint Nuclear Research Centre
Ispra Establishment - Italy

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Printed by Van Muysewinkel, Brussels
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ABSTRACT

Within the frame of the finite-element method, the solution of some visco-elastic problems governing the behaviour of graphite structures under irradiation can be obtained by a conventional elastic analysis.
Numerical examples are included to illustrate the method of analysis suggested in the present report.

KEYWORDS

IRRADIATION
GRAPHITE
ELASTICITY
MATERIALS TESTING
PRESSURE
TEMPERATURE
MATHEMATICS
TENSORS
STRAIN

CONTENTS

1. Introduction. *)

This note is concerned with a special application of linear visco-elasticity to the stress analysis of graphitic bodies when subjected to boundary loads, temperature gradients and dimensional changes due to neutron irradiation .

The special treatment presented in this paper is based on some hypotheses which simplify very much the stress analysis [1] :

a) The creep function for graphite under irradiation which includes an elastic response, a primary creep term and a secondary creep contribution is assumed to have a constant value over the body . This means that the secondary creep coefficient corresponds to some mean temperature and that the fast-neutron flux is considered as uniform .

b) For transversely isotropic graphites, the three creep functions that are necessary to define the material behaviour are assumed to be all proportional to a single function .

c) Poisson's ratio of graphite remains constant during irradiation and at a low value of about 0.2 .

The preceding assumptions have recently been applied to the analysis of graphitic bodies using a biharmonic computer code [2] .

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*) Manuscript received on March 13, 1971

The result was that any two-dimensional visco-elastic problem could be solved from the sum of four elastic solutions which are multiplied by appropriate functions of the neutron dose.

The formulation of the same problem is presented here within the frame of the finite-element method.

It will in particular be shown how the original visco-elastic problem can be reduced to an elastic one introducing the concept of equivalent forces acting at the nodes of the idealized structure.

If the displacements within the structure are sought, the equivalent forces are derived from the boundary loads. For the stress problem they result from the nodal loads due to the thermal and irradiation strains.

Once the appropriate equivalent forces have been applied at the nodal points, the stress or displacement picture at any given neutron dose is obtained from a single computer run. A great saving in computational time can thus be achieved, since the original problem has been reduced to an elastic one.

If the preceding hypotheses cannot be accepted, the problem has to be solved using either an incremental procedure [3] or the Laplace Transform method suggested in reference [4] .

2. Basic equations.

Although the considerations developed hereafter are valid for two or three dimensional stress analysis, the formulation of the visco-elastic problem will be illustrated for a situation of plane stress with an isotropic material.

It could be objected that many graphites are transversely isotropic so that three creep functions are necessary to characterise the material behaviour. It can however be shown that the assumption (b) makes it very easy to extend the approach presented here for the isotropic case to deal with transversely isotropic materials. The problem presents in fact no more difficulty than the corresponding elastic case.

Since the relationship between an uniaxial normal stress σ_x and a normal strain ε_x is assumed to be linear, the principle of superposition holds. It follows that the total normal strain $\varepsilon_x(D)$ at some neutron dose (D) due to a variable normal stress $\sigma_x(D)$ can be represented by the convolution integral :

$$\varepsilon_x(D) = \int_0^D J(D-D') \frac{\partial}{\partial D'} (\sigma_x(D')) \, dD' \qquad (1)$$

The creep function J for graphite can be written in the form [2] :

$$J(D) = \frac{1}{E_o} + \frac{1}{2E_o} (1 - e^{-A_o D}) + K(T) D \qquad (2)$$

where D is the fast-neutron dose and T the temperature.

The creep function (2) includes an elastic term as well as a primary and a secondary creep part.

For convenience of notation the integral operator appearing in Eq. (1) is written as

$$\int_0^D J(D-D') \frac{\partial}{\partial D'} dD' \equiv C^* \qquad (3)$$

Therefore Eq. (1) can be written in analogy with elastic behaviour in the form

$$\varepsilon_x (D) = C^* \sigma_x(D) \qquad (4)$$

The stress can be expressed in terms of strain as

$$\sigma_x (D) = \int_0^D G(D - D') \frac{\partial}{\partial D'}(\varepsilon_x(D'))\, dD' = R^* \varepsilon_x(D') \qquad (5)$$

where G(D) is the relaxation function related to the creep function J(D) by

$$\int_0^D G(D - D') \frac{\partial}{\partial D'} J(D')\, dD' = H(D) \qquad (6)$$

in which H(D) is the Heaviside step function.

As can be seen the operators C^* and R^* are related by the identity

$$C^{*\,-1} = R^* \qquad (7)$$

It can be shown [2] that the relaxation function which corresponds to the creep function given by Eq. (2) has the following expression

$$G (D) = \frac{E_0}{\left((E_o K + 1.5 A_o)^2 - 4 E_o K A_o\right)^{\frac{1}{2}}} \left[(K_1 + A_o)\, e^{K_1 D} - (K_2 + A_o)\, e^{K_2 D}\right] \qquad (8)$$

with

$$K_1 = -0.5\,(E_oK + 1.5\,A_o) + 0.5\,\left((E_oK + 1.5\,A_o)^2 - 4\,E_oK\,A_o\right)^{\frac{1}{2}}$$

$$K_2 = -0.5\,(E_oK + 1.5\,A_o) - 0.5\,\left((E_oK + 1.5\,A_o)^2 - 4\,E_oK\,A_o\right)^{\frac{1}{2}} \qquad (9)$$

For an isotropic material in which Poisson's ratio ν remains constant during creep, the stress-strain relations for linear visco-elasticity are for the case of plane stress

$$\{\varepsilon(D)\} = \begin{bmatrix} 1 & -\nu & 0 \\ -\nu & 1 & 0 \\ 0 & 0 & 2(1+\nu) \end{bmatrix} C^{*}\{\sigma(D')\} + \{\varepsilon^{th}(D)\} + \{\varepsilon^{w}(D)\} \qquad (10)$$

where, denoting by T the transposition

$$\{\varepsilon\}^T = (\varepsilon_x, \varepsilon_y, \gamma_{xy}) \quad ; \quad \{\sigma\}^T = (\sigma_x, \sigma_y, \tau_{xy})$$

$$\{\varepsilon^{th}\}^T = \alpha T\,(1\,,1\,,0) \quad ; \quad \{\varepsilon^{w}\}^T = W\,(1\,,1\,,0) \qquad (11)$$

αT and W represent the thermal and irradiation strains , respectively. The stress vector can in turn be defined as

$$\{\sigma(D)\} = [E]\; R\,\left(\{\varepsilon(D')\} - \{\varepsilon^{th}(D')\} - \{\varepsilon^{w}(D')\}\right) \qquad (12$$

where $$R = R^{*}/E_o = \frac{1}{E_o}\int_0^D G(D - D')\,\frac{\partial}{\partial D'}\,dD' \qquad (13.a)$$

$$\left[E\right] = \frac{E_0}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \qquad (13.b)$$

is the conventional elasticity matrix for plane stress with a constant Young's modulus E_o .

3. Finite-element formulation.

If triangular finite-elements with nodal points at the corners are used in the idealization of the body, the simplest way of representing the displacement field within an element is given by two linear polynomials with the nodal point displacements as parameters.

Following the notations of reference [5] , the total strain at any point within an element (i,j,k) can be defined as

$$\left\{\varepsilon\,(D)\right\}^e = \left[B\right]\left\{\delta\,(D)\right\}^e \qquad (14)$$

The (3x6) matrix $\left[B\right]$ contains geometric coefficients, while the six components of nodal displacements are listed as

$$\left\{\delta^e\right\}^T = (u_i, v_i, u_j, v_j, u_k, v_k) \qquad (15)$$

3.1 The Stress Distribution.

In view of Eqs (10) and (12), the stiffness matrix of the element can be written in the form

$$\left[K\right]^{e} = \left[B\right]^{T} \left[E\right] \; R \; \left[B\right] \Delta^{e} \qquad (16)$$

with Δ^{e} representing the area of triangle (i,j,k).

The nodal forces due to the thermal and irradiation strains are given by

$$\left\{\overline{F_{\varepsilon}}\right\}^{e} = \left[B\right]^{T} \left[E\right] \; R \; \left(\left\{\varepsilon^{th}(D')\right\}^{e} + \left\{\varepsilon^{w}(D')\right\}^{e} \right) \Delta^{e} \qquad (17)$$

while the nodal forces balancing the surface pressures actually present at dose D are denoted by $\left\{F_{p}\right\}^{e}$.

Using these results, the nodal point equilibrium equations for element (i,j,k,) are found to be at neutron dose D

$$\left[B\right]^{T} \left[E\right]\left[B\right] \Delta^{e} \; R \; \left\{\delta(D')\right\}^{e} = \left\{\overline{F_{\varepsilon}}\right\}^{e} + \left\{F_{p}\right\}^{e} \qquad (18)$$

The next step in the finite-element procedure is the assembly of the equilibrium equations (18) for the whole structure. Since it was assumed that the scalar operator R is a common factor in all the elements we find that the nodal point equilibrium equations for the complete structure are at neutron dose D

$$\left[K\right] \; R \left\{\delta(D')\right\} = \left\{\overline{F_{\varepsilon}}\right\} + \left\{F_{p}\right\} \qquad (19)$$

In Eq. (19) the stiffness matrix $\left[K\right]$ is based on the elastic properties E_{o}, ν appearing in the elasticity matrix $\left[E\right]$.

As can be seen from Eq. (17), the first vector in the right-hand side of Eq. (19) can be interpreted as equivalent nodal forces due to the thermal and irradiation strains. In other words, these forces can be generated by considering an elastic structure on which equivalent thermal and irradiation strains of magnitude

$$\left\{\overline{\varepsilon^{th}}\right\} = R \left\{\varepsilon^{th}(D')\right\} \quad ; \quad \left\{\overline{\varepsilon^{w}}\right\} = R \left\{\varepsilon^{w}(D')\right\} \qquad (20)$$

are applied .

The vector $\left\{F_p\right\}$ in Eq.(19) represents the nodal forces due to the actual surface pressures existing at neutron dose D .

Now, solving the system (19) for equivalent nodal displacements of magnitude

$$\left\{\overline{\delta}\right\} = R \left\{\delta(D')\right\} \qquad (21)$$

we find, looking at Eq.(12) , that the stress components in all the elements can be evaluated elastically using the relation

$$\left\{\sigma\right\} = \left[E\right] \left(\left\{\bar{\varepsilon}\right\} - \left\{\varepsilon^{th}\right\} - \left\{\varepsilon^{w}\right\} \right) \qquad (22)$$

The equivalent visco-elastic strains $\left\{\bar{\varepsilon}\right\}$ are obtained on the basis of Eq.(14) from the equivalent displacements $\left\{\bar{\delta}\right\}$ which satisfy the system (19)

One may therefore conclude from Eqs.(19) to (22) that when the stresses are caused by external pressures only, their distribution can be calculated by a purely elastic procedure for the prescribed boundary loads actually existing at the specified neutron dose.

In presence of thermal and irradiation strains, the stress picture is obtained considering an elastic structure on which equivalent strains defined by Eq.(20) are applied.

3.2 The displacement field.

A complementary problem must be solved to find the displacements in the structure at any given neutron dose.

It will be immediately obvious that the equations governing the displacement field are obtained by multiplying both sides of Eq.(19) by the scalar operator

$$C = E_o \int_0^D J(D - D') \frac{\partial}{\partial D'} dD' = R^{-1} \qquad (23)$$

The result is that the nodal point displacements at a neutron dose D satisfy the system

$$\left[K\right] \left\{\delta (D)\right\} = \left\{F_\varepsilon\right\} + C \left\{F_p\right\} \qquad (24)$$

where the stiffness matrix $\left[K\right]$ is again based on the elastic properties E_o , ν .

The vector $\left\{F_\varepsilon\right\}$ is constructed by a summation taken over all the elements of contributions of the type

$$\left\{F_\varepsilon\right\}^e = \left[B\right]^T \left[E\right] \left(\left\{\varepsilon^{th}(D)\right\}^e + \left\{\varepsilon^{w}(D)\right\}^e \right) \Delta^e \qquad (25)$$

which represents the forces acting at the nodes of an elastic triangular element due to the thermal and irradiation strains actually present at the neutron dose D .

The second vector in the right-hand side of Eq.(24) is due to the surface pressures and it may be interpreted as a set of equivalent nodal forces of magnitude

$$\left\{ \overline{F_p} \right\} = C \left\{ F_p (D') \right\} \tag{26}$$

applied on an elastic structure.

If there are no prescribed surface pressures, the conclusion is that the displacements and the strains within the structure at any given neutron dose can be obtained by performing a conventional elastic analysis with the thermal and irradiation strains actually existing at that dose .

In presence of surface pressures, the displacements and the strains are again obtained elastically if the structure is supposed to be loaded with the equivalent nodal forces defined by Eq.(26) .

3.3 Evaluation of the equivalent strains and nodal forces.

Expressions such as (20) and (26) have to be evaluated in order to calculate the equivalent sollicitations to be applied on the elastic structure.

If the loading history is known analytically, the required integrations can be carried out analytically using the expressions (2) and (8) for J(D) and G(D) .

The frequent case of surface pressures $\left\{ F_p^o \right\}$ applied at a given dose D_o and maintained constant thereafter will be investigated first Such a situation can be written mathematically as

$$\left\{ F_p (D') \right\} = \left\{ F_p^o \right\} \; H (D' - D_o) \qquad (27)$$

in which H is the unit step function.

After substitution of Eq.(27) into (26) we find for the equivalent loads

$$\left\{ \overline{F_p} \right\} = E_o \left\{ F_p^o \right\} \int_0^D J(D-D') \frac{\partial H(D'-D_o)}{\partial D'} dD' = E_o \, J(D-D_o) \left\{ F_p^o \right\} \qquad (28)$$

Consider now Wigner strains W having as in ref. [2] a quadratic dependence on the neutron dose D and expressed as

$$W = A(T) \left[D^2 + B(T) \, D \right] \qquad (29)$$

where A(T), B(T) are functions of the temperature .

The equivalent strains for the stress problem are obtained from Eq.(20) as

$$\overline{W} = \frac{A(T)}{E_o} \int_0^D G(D-D') \, 2D' \, dD' + \frac{A(T) \, B(T)}{E_o} \int_0^D G(D-D') \, dD' \qquad (30.a)$$

i.e.

$$\overline{W} = \frac{A(T)}{E_o} \left\{ B(T) \, F_1(D) + F_2(D) \right\} \qquad (30.b)$$

Writing for convenience the expression (8) for G(D) in the form

$$G(D) = \alpha_1 \left(\alpha_2 \, e^{K_1 D} - \alpha_3 \, e^{K_2 D} \right) \qquad (31.a)$$

we find after integration

$$F_1(D) = \alpha_1 \left[\frac{\alpha_3}{K_2} (1 - e^{+K_2 D}) - \frac{\alpha_2}{K_1} (1 - e^{+K_1 D}) \right] \qquad (31.b)$$

$$F_2(D) = 2\,\alpha_1 \left(\frac{\alpha_3}{K_2} - \frac{\alpha_2}{K_1} \right) D - \frac{\alpha_2}{K_1^2} (1 - e^{+K_1 D}) + \frac{\alpha_3}{K_2^2} (1 - e^{+K_2 D}) \qquad (31.c)$$

The equivalent Wigner strains are thus readily evaluated .

4. Illustrative Problems.

A computer program named VELAG (Visco ELastic Analysis of Graphite) has been developed for solving two-dimensional problems, i.e. , problems with plane stress, plane strain, generalized plane strain or axisymmetric deformations. A general flow chart of the computer code is given in Fig. 1 .

The solution of two illustrative problems will be presented in order to demonstrate the accuracy and the versatility of the solution technique presented in this paper.

4.1 Circular cylinder with temperature gradients and Wigner strains.

The first problem is the generalized plane strain solution of a thick-walled circular cylinder on which temperature gradients and Wigner strains are applied.

The closed form solution of this problem is given in ref. [2] where all the input data can be found.

Because of the axial symmetry, a two-dimensional finite-element analysis was made of a narrow segment of the cylinder. The numerical resul are shown in Fig.(2) , (3) and (4) . The circles represent the numerical values while the solid lines show the theoretical results.

The radial distribution of the circonferential strain is presented in Fig. 2 for $D = 3 \times 10^{22}$ nvt. Figure 3 is a plot of the circonferential strain existing at the outer surface of the cylinder as a function of the neutron dose. The variation with the neutron dose of the axial stress at the outer radius is shown in Fig. 4 .

As can be seen, the numerical results are in good agreement with the analytical solution.

4.2 Fuel rod with Teledial design.

A fuel element with teledial design (Fig. 5) has been analysed. It was subjected to steady-state thermal strains applied at $D = 0$ and to variable Wigner strains.

The stress field was assumed to be repetitive within the symmetric sectors of the element, so that the finite element grid could be limited to the symmetric sector, as shown in Fig. 5 .

The steady-state temperature distribution has been obtained using a finite element code [6] .

The heat generation within the fuel zone was assumed to be uniform and the same coefficient of heat transmission has been used for both coolant holes. No gaseous gap was considered between the fuel and the graphite sleeve.

The temperature distribution within the symmetric sector of the fuel element is presented in Fig. 6 .

For the stress analysis a generalized plane strain situation was assumed, with a net resultant force in the axial direction equal to zero. The graphite was taken as isotropic and the creep function of Eq.(2) was used with

$E_o = 770$ kg/mm^2 ; $\nu = 0.2$; $A_o = 2 \times 10^{-22}$neut^{-1}-cm^2 ; $K = 0.286 \times 10^{-23}$ (kg/mm^2)$^{-1}$(cm^2-neut^{-1}) .

The Wigner strains have a quadratic dependence on the neutron dose as in Eq.(29). They depend from the temperature as in ref. [2] .

The axial stress picture can be seen from Fig. 7 for $D = 0$ and from Fig. 9 for $D = 1.2 \times 10^{22}$nvt. Figures 8 and 10 give a plot of the maximum principal stress for the same values of the neutron dose.

The distribution of σ_θ and σ_z along the edge AB (see Fig. 5) is given in Fig. 11 and 12, respectively. These results are compared with those obtained using the incremental procedure suggested in ref. [3] for the solution of general creep problems.

5. Conclusions.

When some simplifications are available, the visco-elastic behaviour of graphite structures in presence of external loads, thermal field and neutron irradiation can be investigated assuming an elastic structure on which appropriate equivalent sollicitations are applied.

If the finite-element method is used as a numerical technique, the stress or displacement picture within the body at any given neutron dose is obtained from a single run of the computer code.

Stresses and displacements are, in fact, derived from an overall stiffness matrix based on elastic properties, and from appropriate nodal forces which account for dose dependent surface pressures or variable thermal and irradiation strains.

As a consequence, any two or three-dimensional computer code for elastic structures could readily be adapted to deal with such visco-elastic problems .

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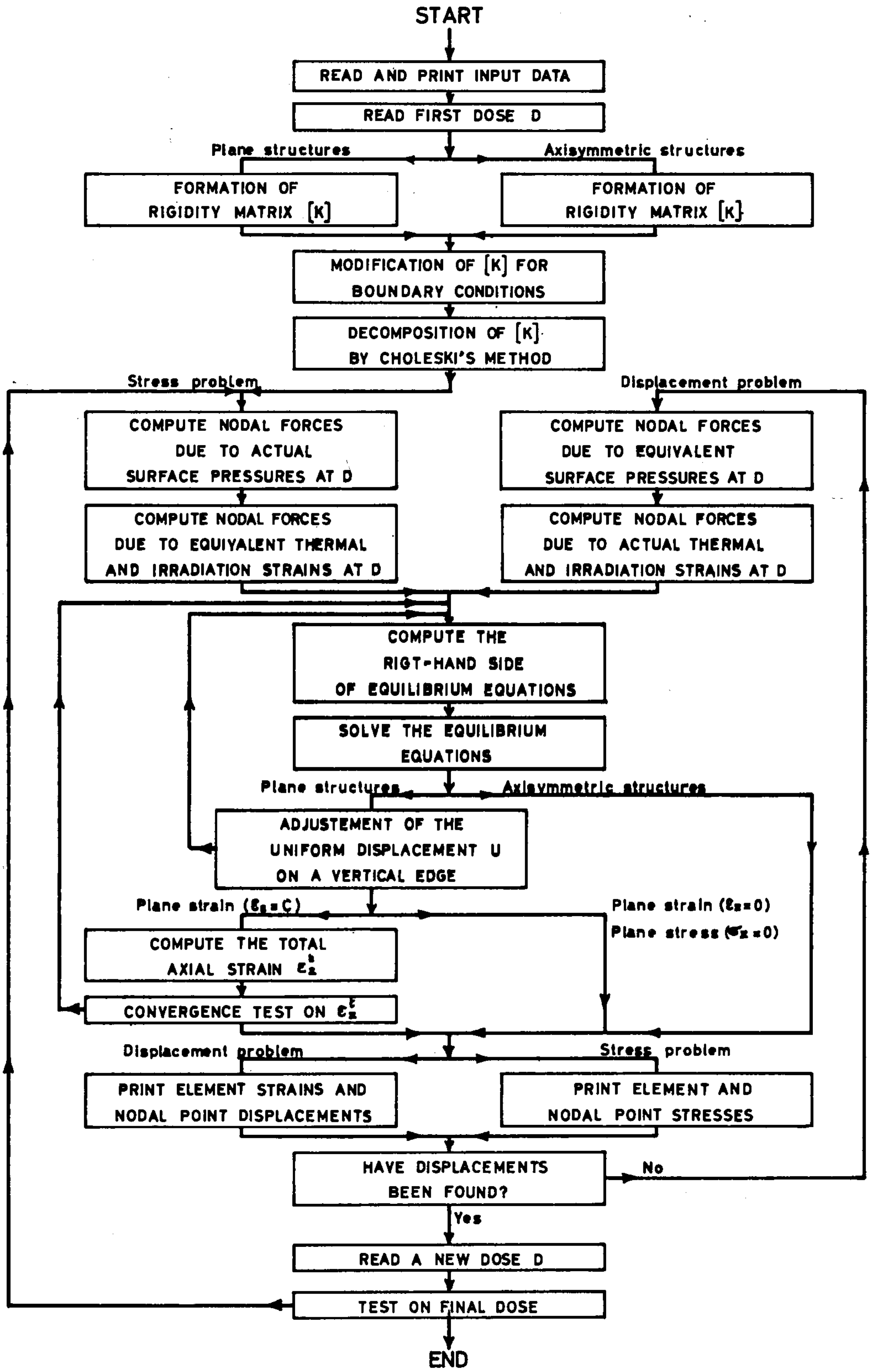


Fig. 1 General flow chart of "VELAG"

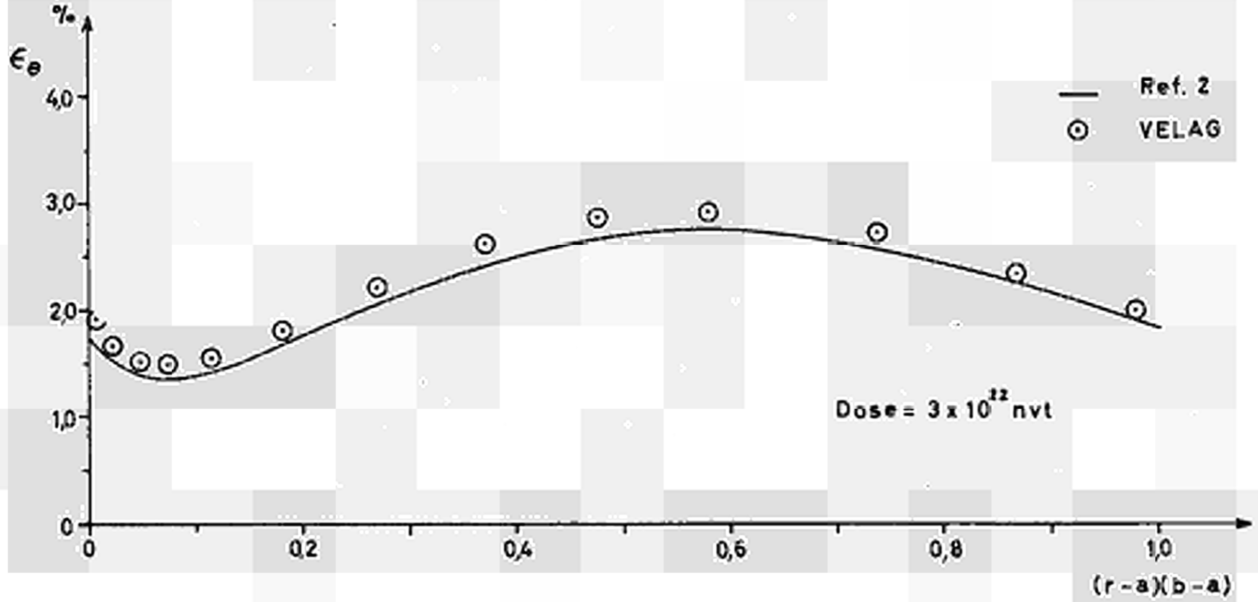


Fig. 2 ϵ_θ as a function of the radial position.

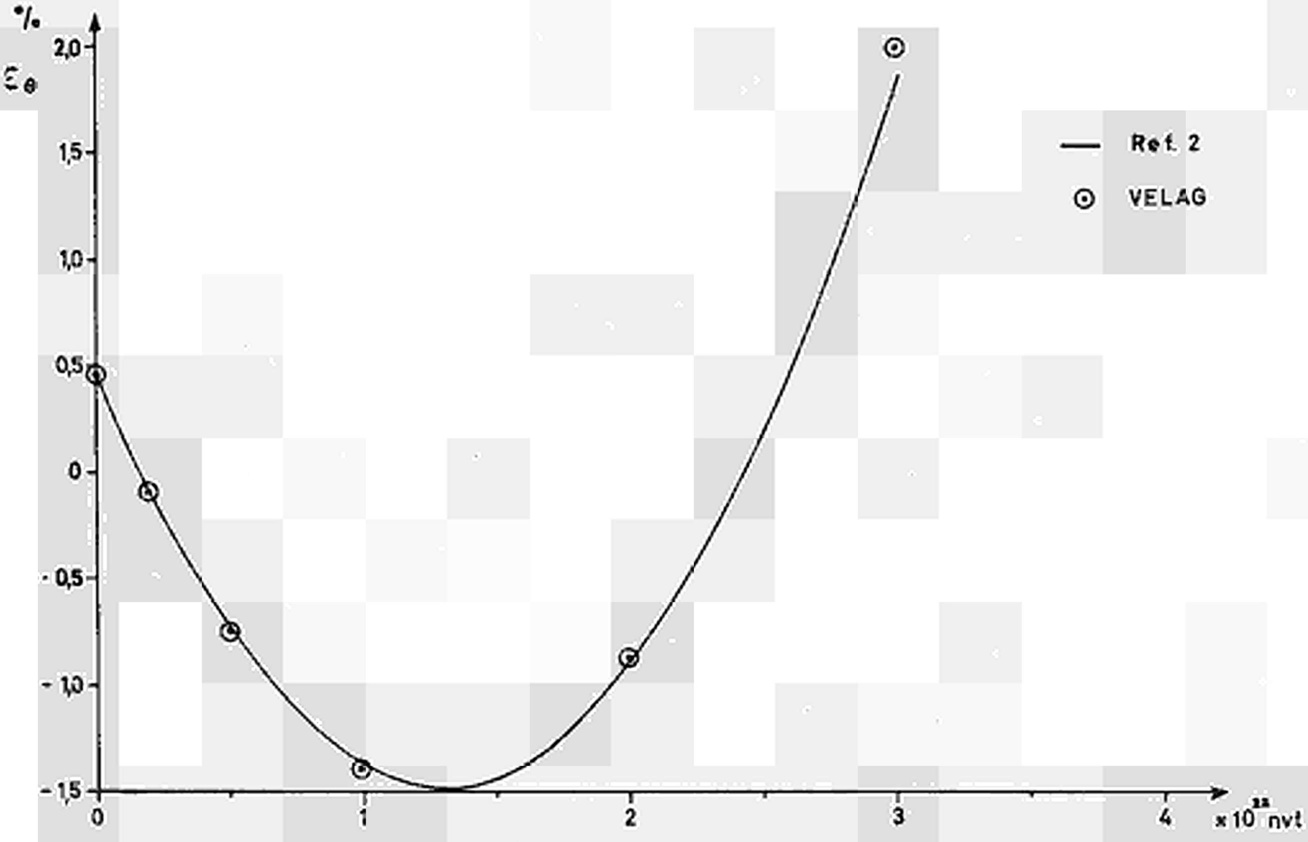


Fig. 3 $(\epsilon_\theta)_{\text{Outer surface}}$ as a function of D.

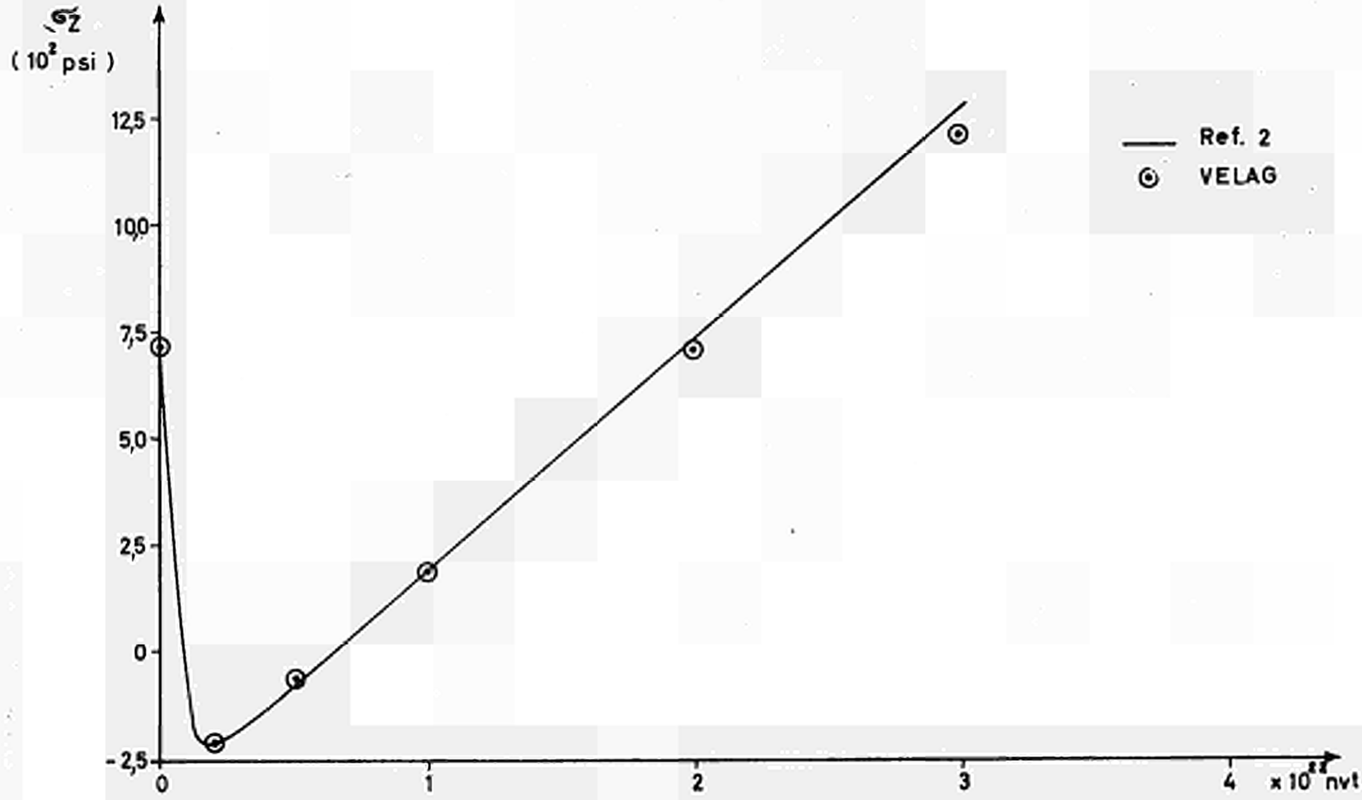
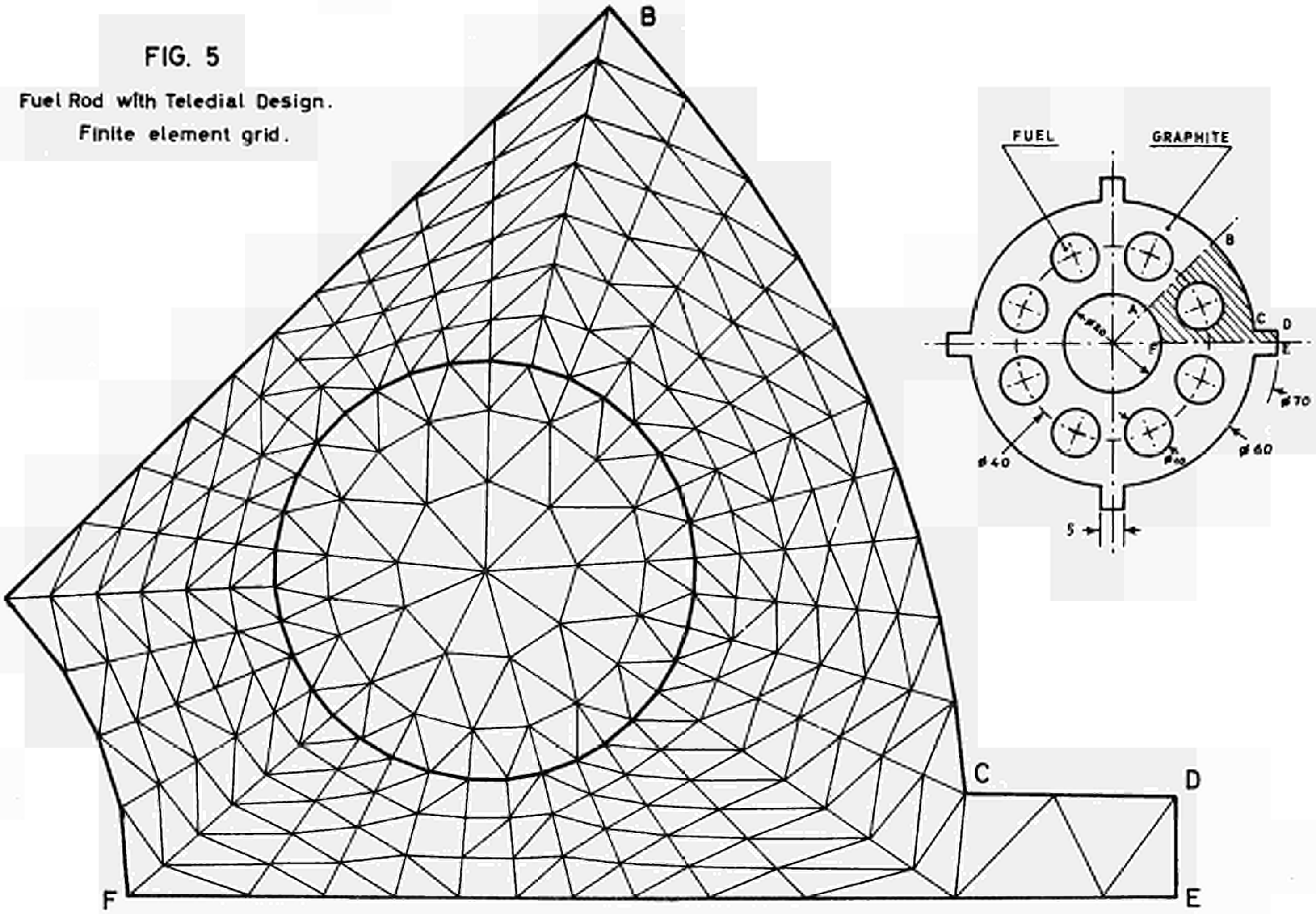


Fig. 4 $(\sigma_z)_{\text{Outer surface}}$ as a function of D.

FIG. 5

Fuel Rod with Teledial Design.
Finite element grid.



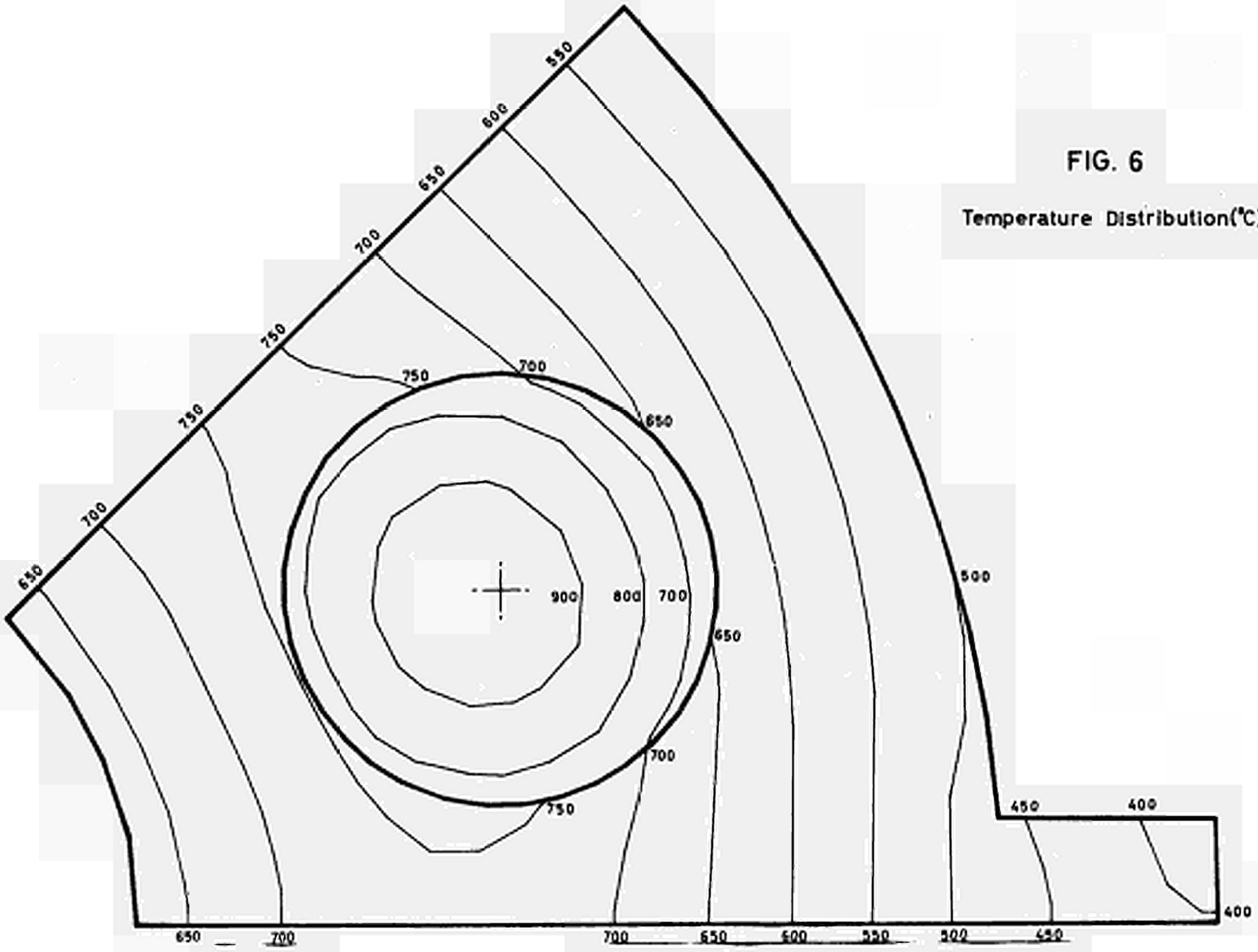


FIG. 6

Temperature Distribution(°C)

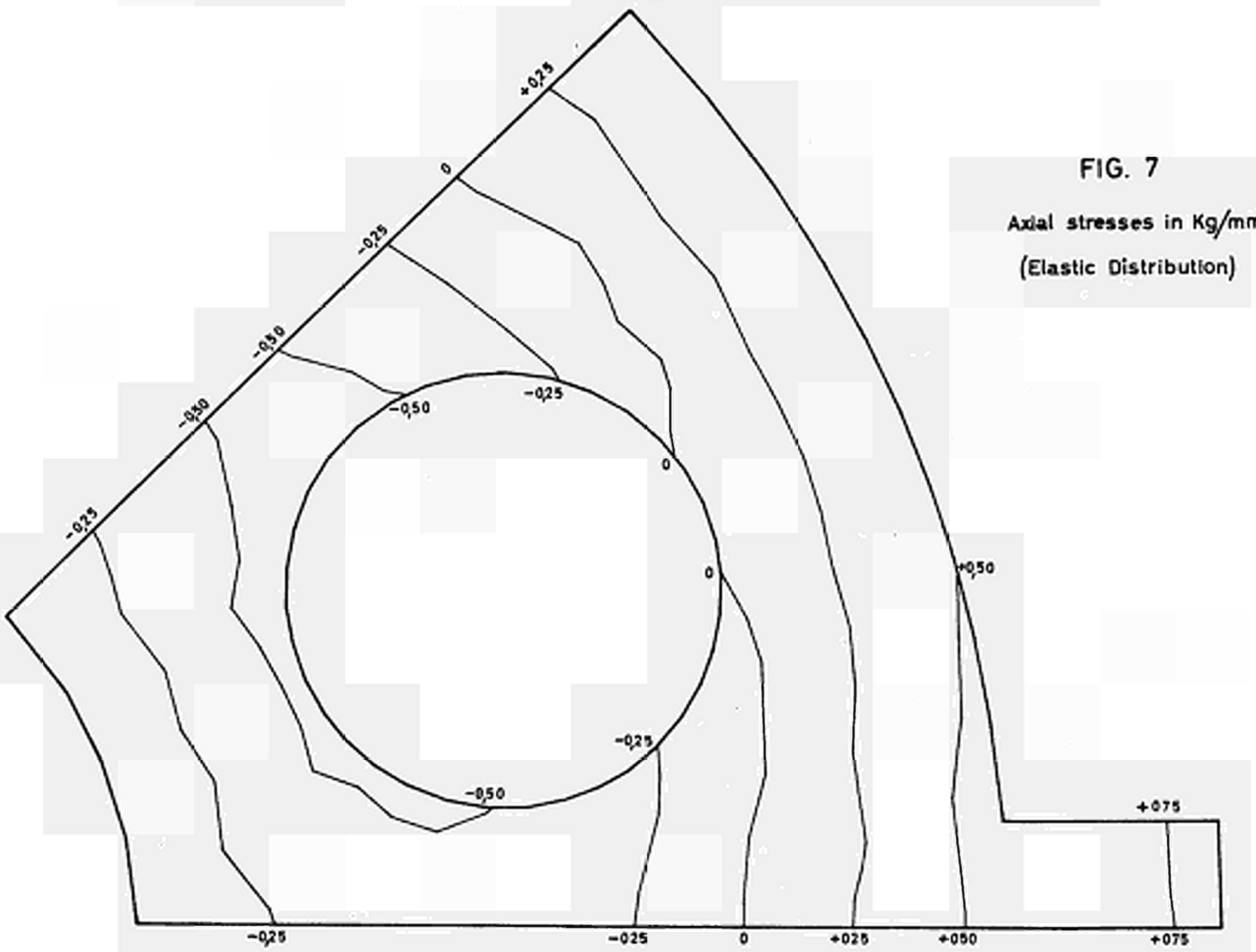


FIG. 7

Axial stresses in Kg/mm²

(Elastic Distribution)

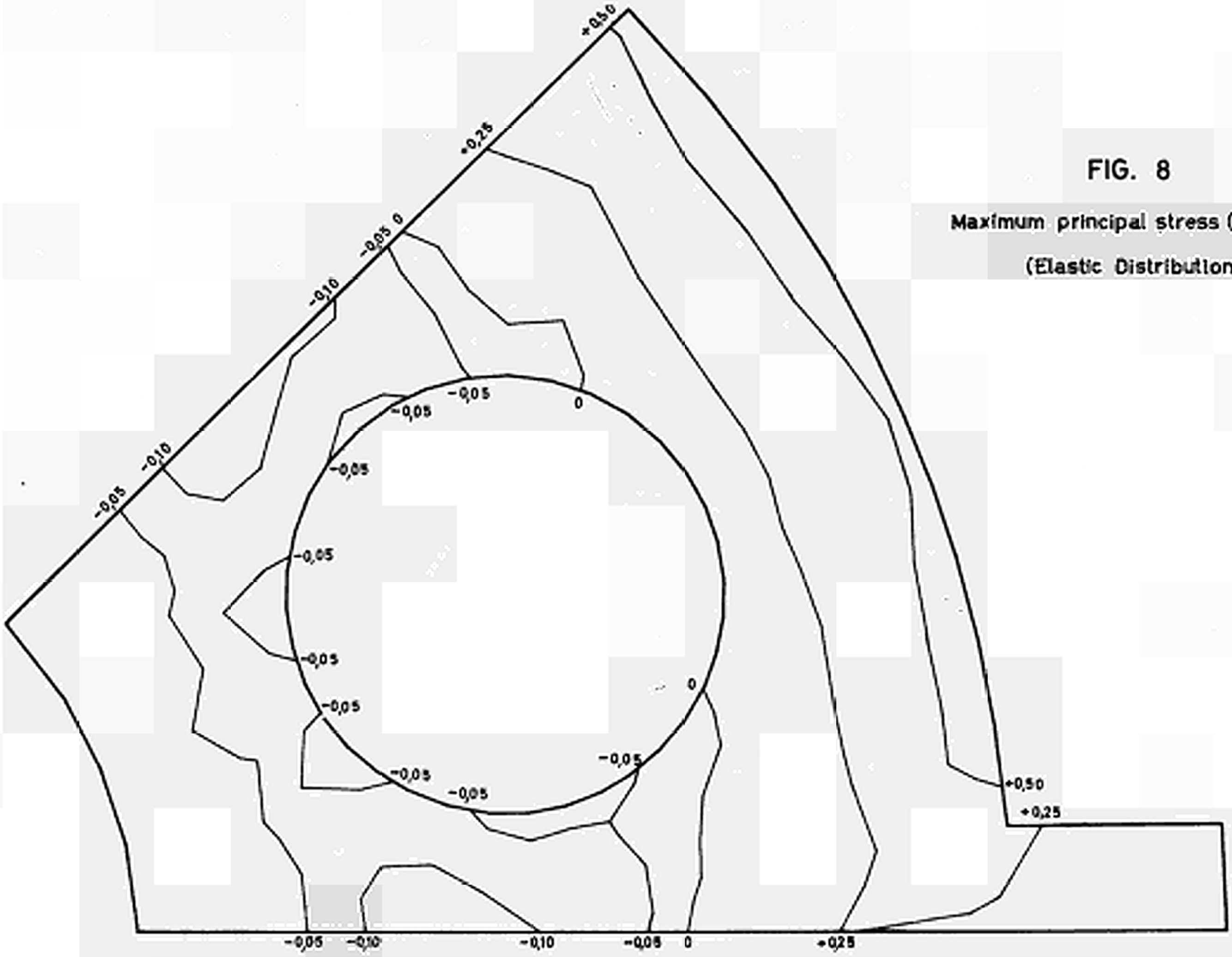


FIG. 8

Maximum principal stress (Kg/mm²)

(Elastic Distribution)

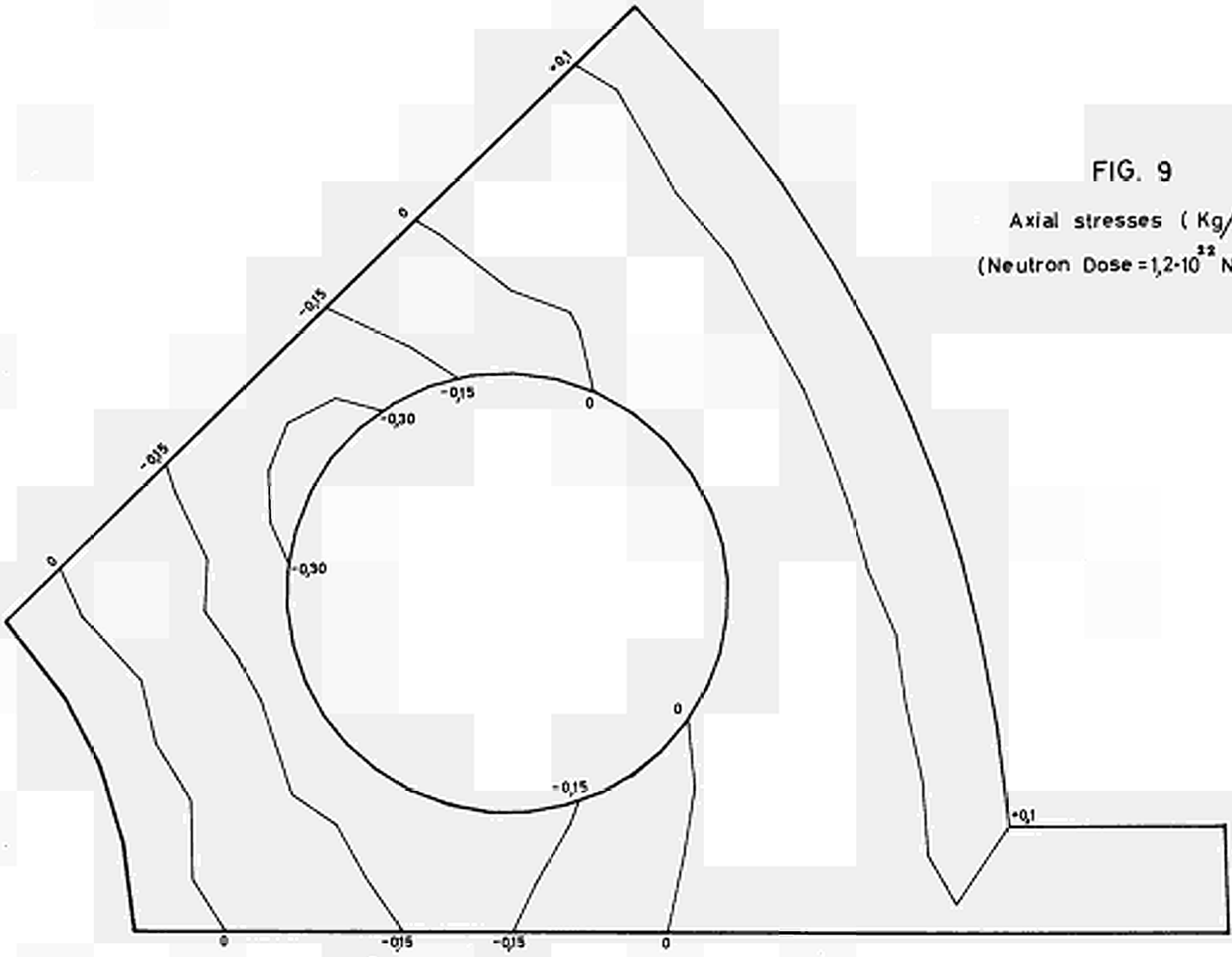


FIG. 9

Axial stresses (Kg/mm²)

(Neutron Dose = 1,2·10²² NVT)

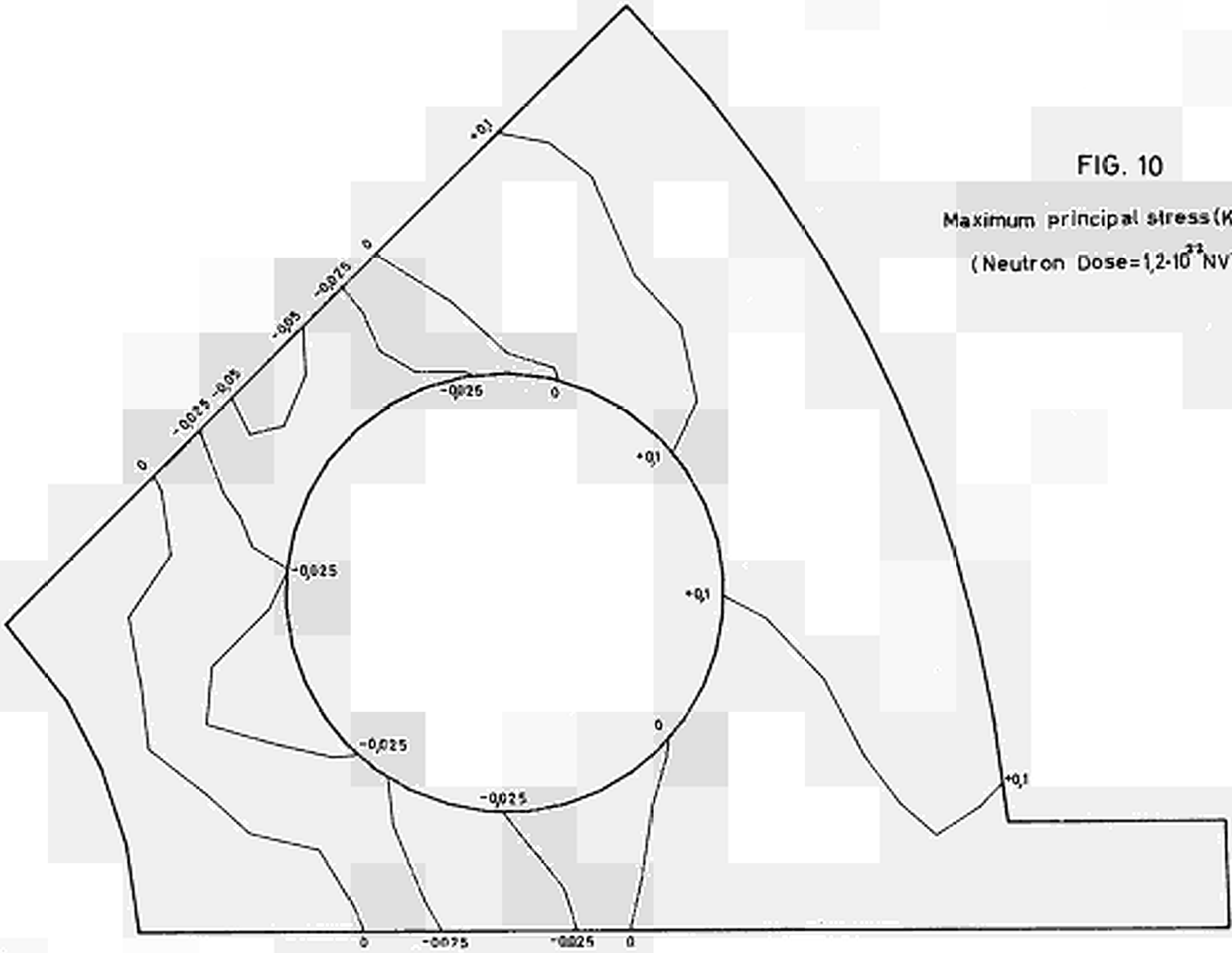


FIG. 10

Maximum principal stress (Kg/mm²)

(Neutron Dose = 1,2·10²² NVT)

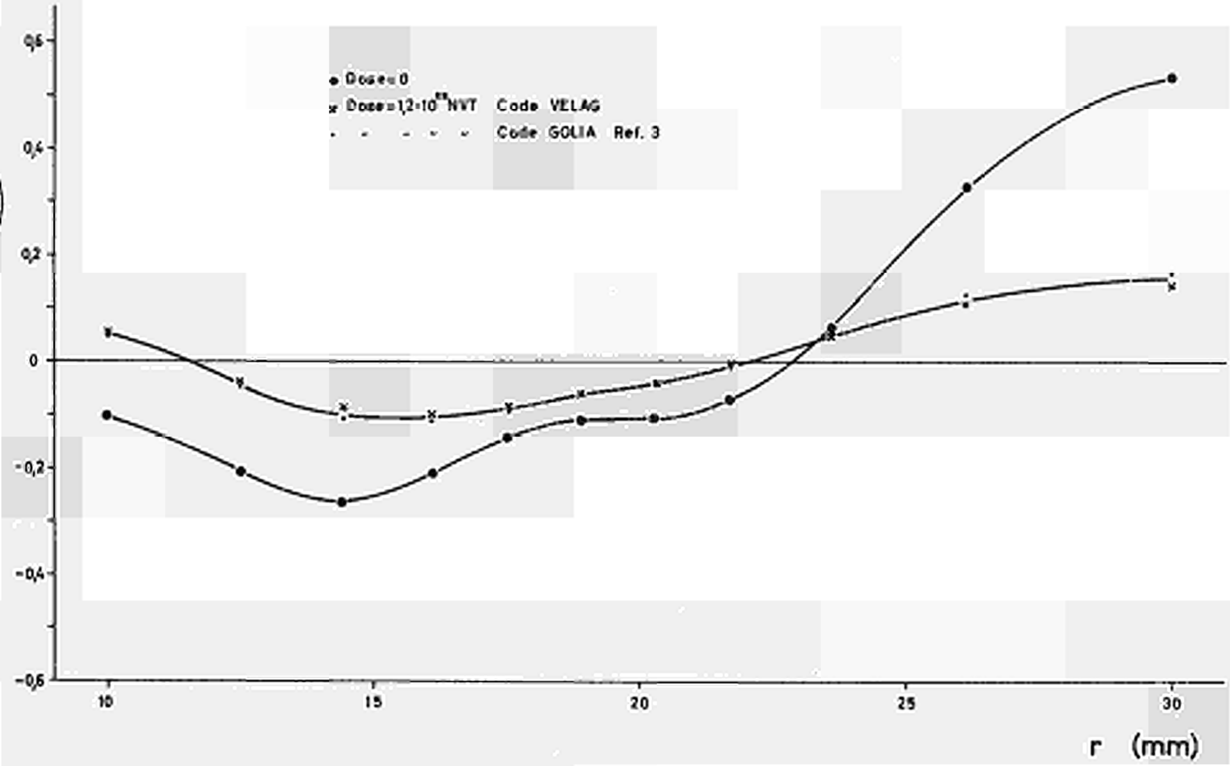


Fig. 11 Circonferential stress (Edge AB)

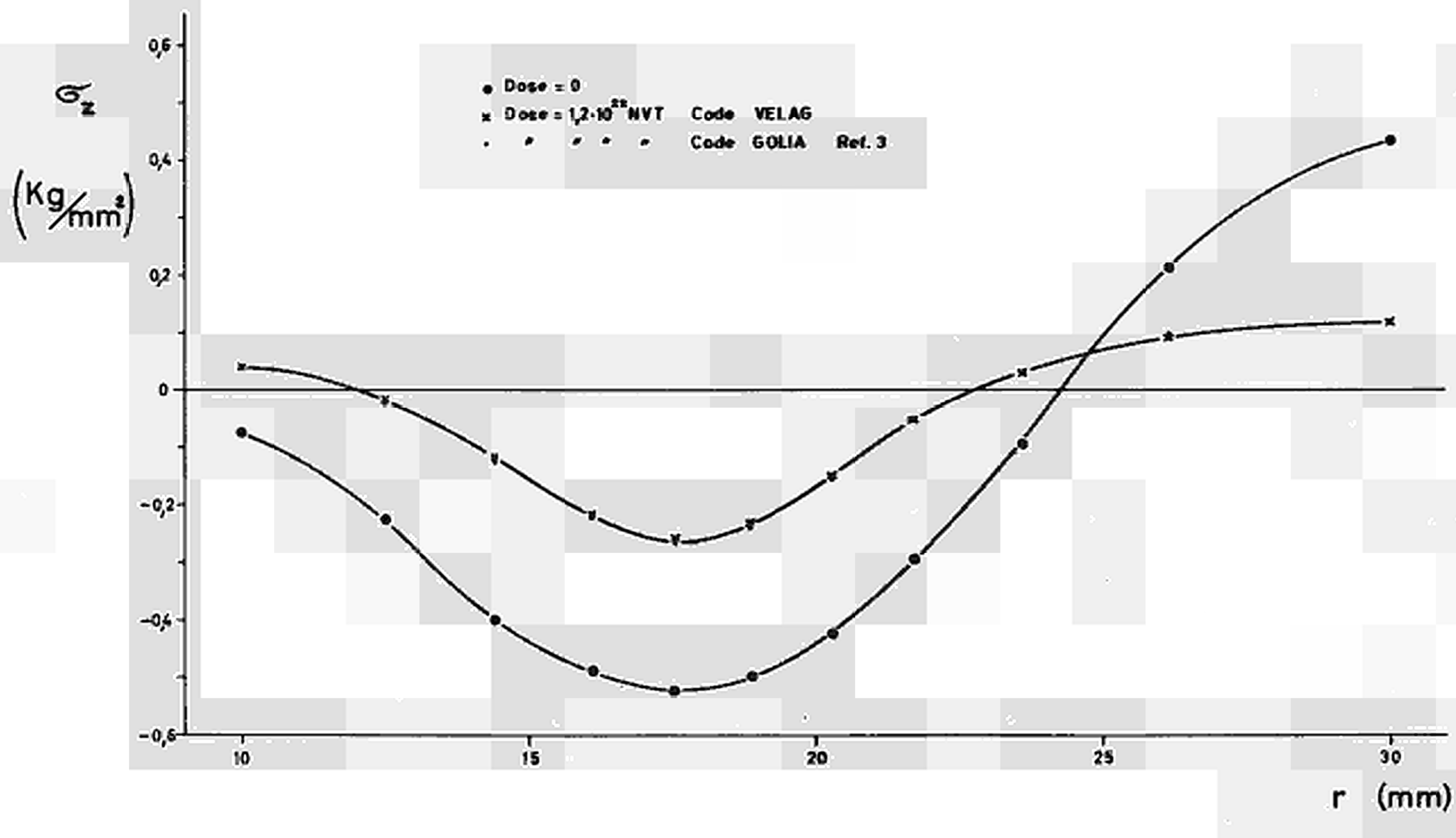


Fig. 12 Axial stress (Edge AB)

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