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TECHNICAL SESSIONS

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J. SPENCE, University of Strathclyde, Glasgow, SCOTLAND, and G. THOMSON, Ferranti, Edinburgh, SCOTLAND

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M. UEDA, Hitachi Zosen Corp., Sakai, JAPAN, T. KANO, Power Reactor and Nuclear Fuel Development Corporation, Tokyo, JAPAN, and A. YOSHITOSHI, Power Reactor and Nuclear Fuel Development Corporation, Ibaraki-ken, JAPAN

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J. KUNIYA, I. MASAOKA, and R. SASAKI, Hitachi Research Laboratory, Hitachi Ltd., Ibaraki-ken, JAPAN, H. ITOH, Hitachi Works, Hitachi Ltd., Ibaraki-ken, JAPAN, and T. OKAZAKI, Kure Works, Babcock Hitachi Ltd., Hiroshima-ken, JAPAN

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K. YAMAUCHI, I. HAMADA, and A. NISHIOKA, Kure Research Laboratory, Babcock-Hitachi K. K., Kure, JAPAN, T. YOKONO and T. OKAZAKI, Kure Works, Babcock-Hitachi K. K., Kure, JAPAN

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INTEGRITY ASSESSMENT FOR A ZIRCALOY-2 PRESSURE TUBE WITH FRETTING CORROSION DEFECTS

F. ALICINO **G. ZAMPINI**

ABSTRACT

In pressure tubes for heavy water reactors, fretting corrosion defects can rise owing to the contact with the fuel cladding bearing pads.

These defects, which may be "single" or "multiple" in a tube belt, could significantly enhance the stresses in the pressure tube.

For this reason, to have high confidence in tube reliability, a specific tube integrity assessment should be performed taking into account the different modes of failure which the component can undergo, i.e.:

- static collapse (bursting)
- buckling
- creep
- non-ductile fracture
- fatigue

To complete such an assessment, an evaluation for the changes in the safety factors throughout the life of the plant may be performed. This evaluation can permit plant operators to define suitable surveillance and in-service inspection programs with greater reliability.

NOMENCLATURE

a_d = Depth of each defect constituting a circumferentially eroded zone

$\bar{a}$ = Depth of the uniformly eroded zone equivalent to a set of circumferentially distributed defects ("multiple" defects case)

a = Depth of a continuous eroded zone (in general)

$a(N)$ = Depth of the fretting defect after N refuelings

A = Area of the cross section of the pressure tube

C_c = $(2\pi^2 E/\sigma Y)^{1/2}$

C_s = KL/R

d = Width of the fuel cladding bearing pads

D = Diameter (in general)

$D_i(o)$ = Inner (outer) diameter of the pressure tube

e = Neperian basis

E = Elasticity modulus

F_c = Material parameter = $[0.25/(n+0.227)]\cdot(e/n)^n$

F_s = Safety factor (PB/PD)

F_z = Axial shape factor

H = Axial coordinate

J = Moment of inertia

K = Material constant or slenderness ratio (see expression of C_s)

L = Length of the tube

L_p = Fuel cladding bearing pads length

M = Folias' factor

n = Number of prints left by the pads on the tube or strain hardening exponent (see expression F_c)

N = Number of refuelings already occurred ($N = o \ldots.$)

P = Applied pressure

P_B = Burst pressure for undefected or defected tube

P_D = Design pressure

P_L = Local primary membrane stress intensity

P_m = General primary membrane stress intensity

q_e = Number of circumferential defects ($q_e \leq Q$)

Q = Minimum number of defects around a circumference which are necessary to obtain an equivalent continuous defect

r = Inertia radius of section ($= \sqrt{J/A}$)

R_a = Ratio for axial buckling ($R_a = \xi\tau/\tau_{crit}$)

R_m = Mean radius of the pressure tube

R_t = Ratio for shear buckling ($R_t = \xi\tau/\tau_{crit}$)

S_m = Allowable stress intensity

S_u = Ultimate strength of the material of the pressure tube

t = Thickness of the pressure tube wall

T = Temperature

Z = Ratio between depth and thickness of the fretting defect ($Z = a/t$)

$Z(N)$ = Increased length due to creep after N refuelings

β = Axial anisotropic creep parameter

δ = Height of fuel cladding bearing pads

Δ_{ai} = Increase in fretting defect depth after each refueling ($i = 1 + N$)

Δ_{zi} = Increase in defects length due to each refueling ($i = 1 - N$)

ϵ_z = Creep axial strain

ϕ_{max} = Maximum neutron flux

$\phi(z)$ = Fast neutron flux (E > 1 M e V)

ν = Poisson's ratio

σ_a = Applied axial stress

σ_{crit} = Critical axial stress

σ_θ = Hoop stress

$\sigma_{\theta,L}$ = Local hoop stress

$\sigma_{\theta,d}$ = Hoop stress for a defective pressure tube

σ_y = Yield strength of the material

σ_a^* = Modified applied axial stress

σ_{crit}^* = Modified critical axial stress

$\Delta\tau$ = Interval of time between two refuelings

τ = Applied shear stress or interval of time from one refueling to another

τ_{crit} = Critical shear stress

τ^* = Modified applied shear stress

ξ = Safety factor (depending on loading conditions: normal, upset, emergency, faulted)

ξ_A = Ratio between defective and undefective cross sectional areas

ξ_{Jx} = Ratio between defective and undefective axial moments of inertia

ξ_{Jp} = Ratio between defective and undefective polar moments of inertia

INTRODUCTION

Owing to the contact with the fuel cladding bearing pads, heavy water reactor pressure tubes may be subjected to the rise of fretting corrosion defects (see the sketch of a pressure tube cross section shown in Fig. 14).

These defects in general increase the state of stress in the pressure tube, and therefore can cause its failure. The failure may be due to the following failure modes with respect to which a pressure tube is designed:

- static collapse (bursting)
- buckling
- creep
- non-ductile fracture
- fatigue

So, to perform a complete structural verification of a pressure tube, it is necessary to evaluate how fretting corrosion defects can influence the above failure modes.

According to the ASME Boiler and Pressure Vessel Code definition, such defects have to be classified as "gross discontinuities."

On the other hand, they differ from the "gross discontinuities" of the components covered by the Code, because their dimensions normally increase throughout the life of the plant.

Therefore, a specific tube integrity assessment which addresses the effects of fretting corrosion defects should be performed according to the following guidelines:

(*a*) Application of the ASME Code, Section III Class I, design methodology, with some suitable modifications to account the different behavior of the considered material (Zircaloy-2) compared with materials adopted by the ASME Code itself;

(*b*) conservative theoretical evaluation of defect sizes and shapes and their change vs time, on the basis of both short term experimental tests and analytical considerations;

(*c*) identification of the failure modes – among those normally considered in designing pressure tubes – which are greatly influenced by the presence of such defects;

(*d*) definition of suitable "reference" or "design" defects, from the point of view of both shape and size;

(*e*) execution of the structural verification according to the ASME Code.

Furthermore, the reliability aspect for nuclear components being of primary importance, the proposed integrity assessment will address also the changes of safety factors throughout the life of the plant, to demonstrate that the plant can operate with sufficient safety margins.

The approach followed to pursue the above items is illustrated in the flow chart of Fig. 1.

GENERAL METHOD

In the Fig. 1 flow chart the method followed to perform the integrity assessment of fretting corrosion defected pressure tubes is shown.

The steps shown in Fig. 1 are briefly described below:

(*a*) The first step consists in identifying all the possible shapes and sizes of defects which the fretting corrosion phenomenon is able to develop.

It is not possible to define these parameters on an exact basis, since long term experimental results are not available. Furthermore, real types and dimensions of these defects have a probabilistic nature, depending on normal forces between fuel cladding bearing pads and pressure tube, frequency of the relative motion, etc.

Therefore, a theoretical conservative assumption, for shapes and sizes, is the only possible and promising approach.

(*b*) The next step consists of evaluating what failure modes are influenced by such defects.

(*c*) Then a structural verification according to ASME Code Section III [1] has to be performed. "Reference" or "design" defects are assumed for this scope.

(*d*) Eventually, it is convenient to show that the very high reliability of nuclear components, assured by the high Code safety factors, is not diminished by the presence of such defects.

DETERMINATION OF TYPOLOGIES AND DIMENSIONS OF FRETTING CORROSION DEFECTS

It has already been outlined that shapes and dimensions of fretting corrosion defects can be estimated only on a theoretical basis, owing to lack of long term experimental results and the large number of different parameters which can produce these defects.

Two families of defects can after all be recognized: "single" and "multiple" defects.

This means that two different situations can be imagined: one which produces only one defect which becomes deeper during the life of the plant, and another in which many defects, close enough to each other so that they may be considered interacting[1], are able to arise.

Keeping in mind that the aim is to evaluate in a conservative way the maximum possible dimensions of fretting corrosion defects, it is important that the events which lead to one or the other of the above situations are conservatively taken into account and their effects are not overestimated.

In such a way a methodology will be defined to evaluate the defect's dimensions, taking into account crack growth, even if this effect is really negligible due to the defect's shape and the number of cycles.

SITUATION PRODUCING A "SINGLE DEFECT"

To conservatively evaluate the "single" defect type dimensions, the following hypothesis may be used:

(a) Erosion velocity is assumed to be very high, so that immediately during each refueling a print on the pressure tube is left.

(b) Fuel cladding bearing pads maintain the same position during each refueling[2].

(c) Bearing pads and pressure tube are equally consumed by erosion. The amount of erosion after each refueling is assumed to be equal to the actual half height of the pads.

(d) The effects due to the contact between pressure tube and fuel cladding are not considered.

(e) Refuelings follow each other at constant intervals of time.

EVALUATION OF THE "SINGLE" DEFECT TYPE DIMENSIONS

Depth and length have to be calculated.

On the basis of the previous hypothesis, it is possible to write the following expression about depth:

$$a(N) = \Delta a_0 + \Delta a_1 + \cdots + \Delta a_N = \frac{\delta}{2} + \frac{\delta}{4} + \cdots = \frac{\delta}{2}\left[2 - \left(\frac{1}{2}\right)^N\right] \quad (1)$$

When examining length, it has to be considered that Zircaloy pressure tubes are subjected to creep, so that its effects on length must be taken into account. Therefore, the following equation for the "single" defect length may be written:

$$L = Lp + Z(N) \quad (2)$$

This equation states that the actual defect length (L), after the N refueling, is equal to the pad's length (L_p) plus the increase ΔZ_N in defect length due to creep times the number N of refuelings $[Z(N) = N \cdot \Delta Z_N]$. The term ΔZ_N has the following expression:

$$\Delta Z_N = \int_o^H \epsilon_z \, dZ = A \int_o^H \phi(z)\, dZ = A \phi_{max} F_z \cdot H \quad (3)$$

with[3]:

$$\epsilon_Z = \beta \sigma_\theta K (T - 160)\, \phi(Z)\, \Delta\tau \quad (4)$$

Parameters a and L vs time assume the trends qualitatively shown in Figs. 2 and 3, respectively.

SITUATION PRODUCING A "MULTIPLE" DEFECT

To conservatively evaluate the "multiple" defect type dimensions, the following hypothesis may be used (for clarification, see Fig. 14):

(*a*) a set of defects lying on different meridional planes, but in correspondence to the same transverse plane, is considered;

(*b*) erosion velocity is very high, just as for single defects;

[1] Interaction may be defined on the basis of ASME Section III Code requirements.

[2] This is a very pessimistic assumption.

[3] For the meaning of the other amounts, see Nomenclature.

(*c*) a uniform corrosion around the circumference is taken into account. Such a situation can be caused by:

(1) a real uniform erosion around the circumference;

(2) a set of many prints very close to each other, so that it is possible to consider them as interacting on a structural basis.

By means of a uniform erosion, shallower defects than those of the second situation may be obtained.

For this reason, reference will be made in the following to this last situation.

Then it will be assumed as uniform erosion depth, the depth due to a set of defects lying on the same transverse pressure tube belt.

(*d*) It is assumed that initially, all the defects around a circumference are formed and afterwards their dimensions begin to increase.

(*e*) Finally, it is assumed that not only one pad is in contact with the pressure tube during each refueling, so that more than one print is formed. Two prints of identical depth are assumed as a consequence of each refueling.

EVALUATION OF THE "MULTIPLE" DEFECT TYPE DIMENSIONS

At first it is necessary to state when more defects lying on different meridional planes can be considered as interacting.

In this context, reference is made to ASME III criteria regarding local stresses (Art. NB-3213). On the basis of this criterion, two local stressed zones can be considered as interacting if their circumferential distance is less than $1.0\sqrt{R_{mt}}$.

This criterion permits us to calculate the minimum number Q of defects around the circumference which causes the development of a uniform eroded zone. Then:

$$Qd + Q\sqrt{R_{mt}} = \pi \phi_i \qquad (5)$$

$$Q = \pi\phi_i/(d + \sqrt{R_{mt}}) \qquad (6)$$

When the number of circumferential defects is $q_e < Q$, each having depth a_d, an equivalent uniform eroded zone may be defined. This has a depth $\bar{a}$ equal to the depth a_d of each defect averaged on the circumference:

$$\bar{a} = q_e a_d / Q \qquad (7)$$

Since it has been assumed that each refueling produces two prints upon the tube, when N refuelings have occurred the number of defects is:

(*a*) $q_e = 2n$ if $n < Q/2$

(*b*) $q_e = Q$ if $n > Q/2$

Since each defect has the depth:

$$a_d = \frac{\delta}{2}\,[2 - (\tfrac{1}{2})^N],$$

then:

$$(a)\quad \bar{a} = \frac{2n}{Q}\cdot\frac{\delta}{2}\,[2 - (\tfrac{1}{2})^n] \qquad \text{if } n < Q/2 \qquad (8)$$

$$(b)\quad \bar{a} = \frac{\delta}{2}\,[2 - (\tfrac{1}{2})^n] \qquad \text{if } n > Q/2 \qquad (9)$$

For simplicity finally it may be assumed that the length for "multiple" defects grows following the same law of the "single" defect.

In Fig. 4 the qualitative variation of parameter $\bar{a}$ vs time is shown for the "multiple" defect type.

STRUCTURAL VERIFICATION BASED UPON ASME SECTION III CODE

"REFERENCE" DEFECTS

To perform the structural verification of a defective pressure tube, it is convenient to introduce the concept of a "reference" defect.

Such a "reference" or "design" defect will have its dimension and shape referenced at the time of verification.

Thus, the verification in the initial condition, before variation of mechanical characteristics caused by neutron fluence, shall be conducted referring to a "single" defect with a dimension not greater than the initial one (Fig. 2). To verify, instead, the defective pressure tube subjected to irradiated conditions, it is most proper to consider a circumferential (continuous) defect, supposing that a "single" defect grows in length rather than in depth during the life of the component. In fact it is most probable that a set of close defects can rise, leading to a situation of continuous defect only after several cycles.

From the structural point of view, such a defect has to be considered as a "gross geometrical discontinuity", according to ASME Section III (Art. NB-3220).

MODES OF FAILURE TO CONSIDER

Fretting corrosion defects can mainly influence the following failure modes:

- static collapse
- buckling
- non-ductile fracture
- creep[4]

[4] Creep has been taken into account by increasing the defects length and diminishing the tube thickness.

STATIC COLLAPSE

To verify that a defective pressure tube cannot fail by static collapse in both initial and end-of-life conditions, it is necessary to determine the state of stress induced by mechanical loads and pressure. The most significant load is pressure; therefore, in the following discussion, only pressure will be considered.

It has been mentioned already that the "reference" defect in the initial condition is "single" while the defect in end-of-life conditions is "multiple." Nevertheless, the state of stress induced by pressure on a defective pressure tube is most conveniently and easily determined assuming continuous defects which have a depth corresponding to the life considered.

Applying the pressure as load, stress intensities vs axial coordinate diagrams can be obtained, as shown in Fig. 5.

On the basis of Article NB-3210-13 of ASME Section III, a "gross geometrical discontinuity" will be such that:

(*a*) membrane stresses can be considered as local if $Pm > 1.1\ Sm$ through a meridional length not greater than $\sqrt{R_{mt}}$;

(*b*) bending stresses always have to be considered as 10 cal.

Generally the maximum membrane stress is less than the value obtained, considering the thickness of the tube less the defect depth:

$$\sigma_{\theta,L} = \frac{pD}{2(t-a)} \qquad (10)$$

Then, assuming $P_L = \sigma_{\theta,L}$ and 1.5 Sm being the limit for P_L, the local primary membrane stress intensity always satisfies this limit, if in the regions far from the discontinuity the general primary membrane stress intensity Pm is verified, providing that: $a/t = 0.33$.

In fact:

$$\sigma_{\theta,L} = \sigma_\theta \frac{t}{t-a} \qquad (11)$$

$$P_L = P_m \quad \frac{t}{t-a} = P_m \frac{1}{1-\frac{a}{t}} \qquad (12)$$

when:

$$P_L < 1.5\ Sm$$

$$P_m < Sm$$

it follows:

$$a/t < 0.33.$$

Therefore, the static collapse of the defected tube is verified in accordance with the Code if the undefective tube is verified and if the maximum expected defect depth is less than 0.33 t.

BUCKLING

A pressure tube can buckle due to the combined effects of shear (torsional moment) and axial stress (axial load). For an undefective tube, the condition which the component shall satisfy will be:

$$R_a + R_t^2 < 1.0 \qquad (13)$$

when:

$$R_a = \xi \frac{\sigma_a}{\sigma_{crit}} \qquad (14)$$

$$R_t = \xi \frac{\tau}{\tau_{crit}} \qquad (15)$$

In a defective tube the critical and applied stresses are charged by the defects, because geometrical properties of cross sections are changed (Fig. 12). When evaluating the influence of the defects on critical and applied stresses, the main conclusions which can be reached are[5]:

(*a*) In the case of "single" defect, the defective pressure tube is verified against buckling, if the undefective one is verified in regions far from discontinuities with a margin:

$$\Delta = 1 - \frac{1}{\xi B} \qquad (16)$$

ξB being a parameter depending on:

- geometry of defective and undefective pressure tube
- applied axial and shear stresses[6]
- critical axial and shear stresses[7]

(*b*) The same conclusion may be obtained for the multiple defect.

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[5] These conclusions are valid only in the case where the pressure tube has dimensions such that torsional buckling falls in the plastic field (Fig. 13).

[6] Applied axial stress is enhanced by the presence of the defect in the amount $1/\xi_A$ (see Nomenclature); applied shear stress is enhanced in the amount $1/\xi_{Jp}$ (see Nomenclature).

[7] Critical axial stress given by (see [5] and [7]):

$$\sigma_{CR} = \begin{cases} \sigma_y\,[1 - C_s^2/4C_c^2] & \text{if } C_s < C_c \\ \pi^2 E/C_s^2 & \text{if } C_s > C_c \end{cases} \qquad (17)$$

is reduced, due to the defect, to the value:

$$\sigma_{CR}{}^x = \sqrt{\xi J_x/\xi_A}\ \sigma_{CR} \qquad (18)$$

For critical shear stress see Fig. 13 [6-8]; it can be observed that in the plastic field critical shear stress is left unchanged by the defect.

NON-DUCTILE FRACTURE

This failure mode is influenced only by a "single" defect and it refers essentially to a pressure load.

Analytical approaches to define critical loads in the past have not furnished acceptable results, so that load experimental tests performed on different sizes and material conditions have been used.

In such a way the tube critical defect lengths at different pressure stress conditions can be obtained.

Figure 6 shows the critical stress trend vs temperature for a defined length and the hoop stress to temperature correlation for a typical heavy water reactor, with hoop stress depending on saturated steam pressure.

Curve 1 shows the correlation between the hoop stress and the temperature of the cooling, based upon the fact that in the saturation condition, pressure, and then hoop stress, are related to temperature.

Curve 2 outlines how the critical hoop stress changes vs temperature in the case of a defect of assigned length. It is emphasized the transition from the ductile behavior (the largest critical hoop stress) to the brittle one (the smallest critical hoop stress) which has been experienced at a value of 200°C for temperature, in the case of irradiated and hydrided Zr-2 tubes.

Figure 7 shows the critical length vs hoop stress.

The tube integrity will be satisfied if, for the maximum "reference" defect length, the critical stress will be adequately greater than the applied one.

CONSIDERATIONS ABOUT VARIATION OF SAFETY FACTORS

GENERAL

The approach to take fretting corrosion defects' structural effects into account has been shown. However, even if the defects satisfy the structural verifications, a difference in strength of a defective tube vs an undefective one will arise.

It is therefore useful and meaningful to calculate the real safety margins of a defective tube, especially against the pressure burst mode of collapse.

In addition, because the fretting corrosion defects can change their dimensions with time, the variation of safety factors vs time is of interest. In fact, such an evaluation permits:

(*a*) addressing the safety margins vs tube burst for the life of the plant;

(*b*) defining a periodic in-service inspection to check fretting corrosion defect growth, if necessary.

The burst analysis will be performed with regard to pressure, which is the most significant load. In such a case, the safety factors are defined as:

$$F_s = P_B/P_D \tag{19}$$

Furthermore, to take into account safety factor changes during the life of the plant, variations in mechanical characteristics of Zr-2 have to be considered.

BURST PRESSURE FOR AN UNDEFECTIVE PRESSURE TUBE

The PVRC [3] equation for isotropic materials has been considered:

$$P_B = S_u F_c \frac{2t}{Di} \left(1 - \frac{t}{Di}\right) \tag{20}$$

This equation is valid for $D_o/D_i \leq 1.4$ and it gives the lower bound of P_B among other correlations.

This correlation would not be applicable to Zr-2 pressure tubes, due to the anisotropy of the latter material.

However, using for S_u the lowest value between axial and transverse directions, Eq. (20) gives a conservative evaluation of P_B [4].

BURST PRESSURE FOR A DEFECTIVE TUBE WITH SINGLE AXIAL DEFECT

The burst pressure for a partial through thickness defect can be evaluated as follows:

$$\frac{\sigma_{\theta,d}}{\sigma_\theta} = \frac{1 - Z}{1 - Z/M} \tag{21}$$

with:

$$M = \text{Folias' factor} = \sqrt{1 + 1{,}61 \, \frac{L_c^2}{4R_{mt}}} \tag{22}$$

This law has been confirmed by experimental results.

Substituting Eq. (20) in Eq. (21), the burst pressure for a single defective tube can be found:

$$P_{B,d} = P_B \left(\frac{1 - Z}{1 - Z/M}\right) =$$

$$S_u F_c \frac{2t}{Di} \left(1 - \frac{t}{Di}\right) \left(\frac{1 - Z}{1 - Z/M}\right) \tag{23}$$

BURST PRESSURE FOR A MULTIPLE-DEFECT TUBE

This situation can be conservatively estimated using the Eq. (20), where for t the corroded uniform thickness is assumed.

SAFETY FACTORS EVALUATION DURING THE LIFE OF THE PLANT

To consider the variation of safety factors through the life of the plant, at least the following three different situations have to be considered:

(*a*) initial life with unirradiated material;
(*b*) intermediate life with irradiated material;
(*c*) end-of-life with irradiated material.

For these different situations and for the two types of defects, intermediate and end-of-life defect dimensions (from Figs. 2, 3 and 4) are associated.

On this basis, assuming a known embrittlement of Zr-2 due to neutron fluence, curves as those shown in Figs. 8 and 9 can be found.

NUMERICAL RESULTS

The above procedure has been applied to a referenced pressure tube characterized by:

inner diameter	$D_i = 106.1$ mm	
nominal thickness	$t = 3.15$ mm	
fuel bearing pads height	$\delta = 1.10$ mm	
fuel bearing length	$L = 25$ mm	
strain hardening coefficient	$n = 0.120$	unirradiated material
ultimate strength	$S_u = 370$ MPs	unirradiated material
strain hardening coefficient	$n = 0.06$	irradiated material at end-of-life fluence
ultimate strength	$S_u = 480$ MPa	irradiated material at end-of-life fluence

The numerical results are shown in Figs. 8 and 9 for "single" and "multiple" (uniform eroded tube) defects, respectively.

To realize how safety factors change with respect to the undefective situation, the safety factors curves vs time for the undefective situation are shown, in Figs. 10 and 11.

CONCLUSIONS

A general methodology to account for fretting corrosion defects in a pressure tube for heavy water reactors has been outlined.

Verification according to ASME Code Section III has been shown, considering the defects as gross discontinuities, particularly addressing buckling due to axial and torsional stresses.

A main point is that, if the defect dimensions are within defined limits, the satisfaction of Code rules far from the discontinuities automatically assures meeting the allowable limits in the local defective region.

Safety margins against burst pressure have been defined, also taking into account irradiation embrittlement. On this basis, considerations can be made about the surveillance program to control the embrittlement of the material, and the in-service inspection program to check the fretting crack growth can be done.

Additionally, indications regarding the minimum safety factor at end-of-life can be obtained.

REFERENCES

(1) *ASME Boiler and Pressure Vessel Code, Section III* – Nuclear Power Plant Components."

(2) R. B. Maxwell – CRNL, "Mechanical Properties and Corrosion Resistance – Zirconium Alloys," Part 2, Rev. 1 – Dec. 1970.

(3) *WRC Bulletin M95*, "PVRC Interpretative Report of Pressure Vessel Research."

(4) *ASME Boiler and Pressure Vessel Code, Section III* – "Nuclear Power Plant Components," Division 1, Appendix XVII.

(5) Timoshenko, G., *Theory of Elastic Stability*, Second Edition, McGraw Hill Book Company, 1961.

(6) Brush, Almoroth, *Buckling of Bars, Plates and Shells*, McGraw Hill Book Company, 1975.

(7) Column Research Committee of Japan, *Handbook of structural stability*, 1971.

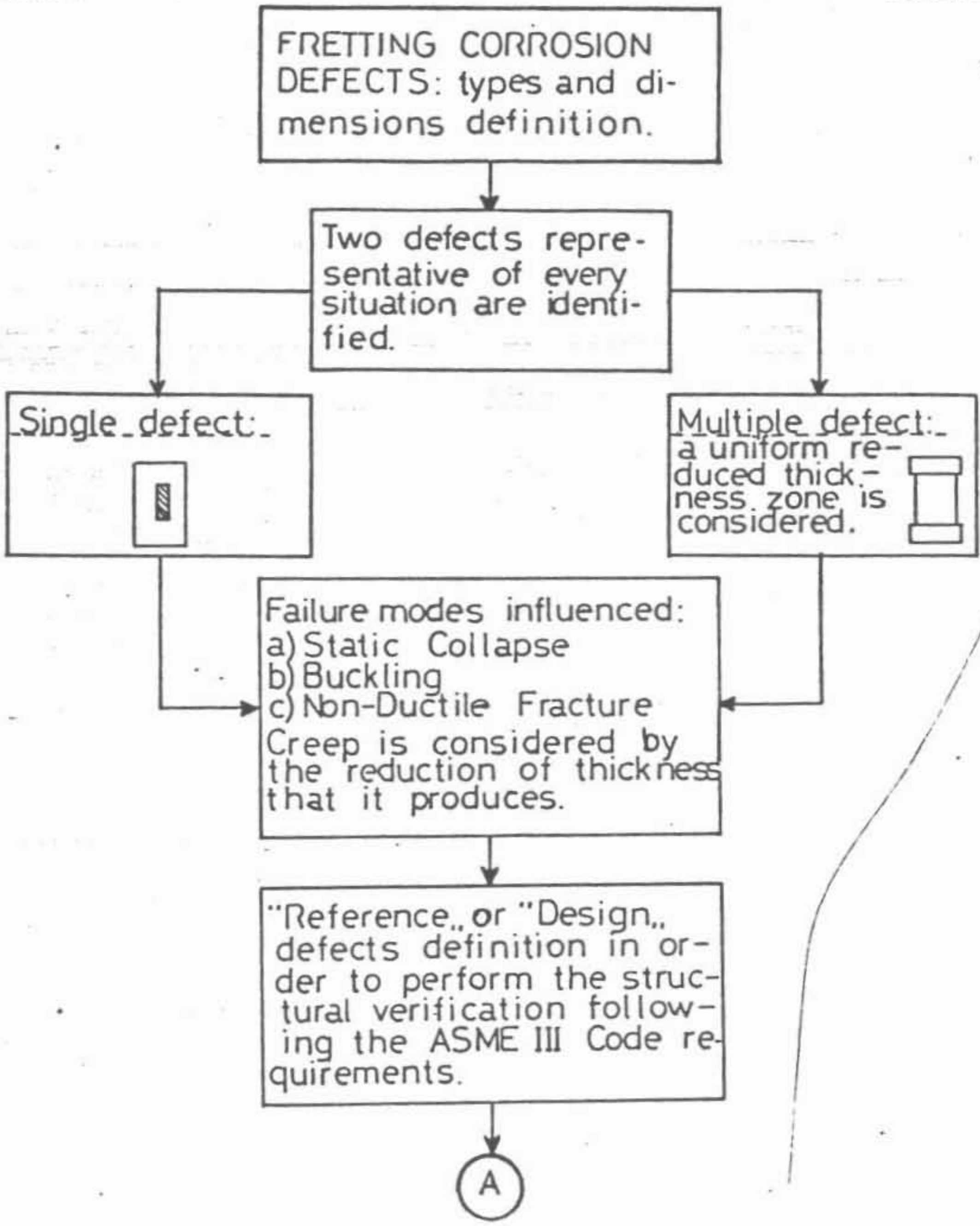

FIG. 1 FLOW CHART ILLUSTRATING THE APPROACH TO PURSUE INTEGRITY ASSESSMENT FOR A PRESSURE TUBE WITH FRETTING CORROSION DEFECTS

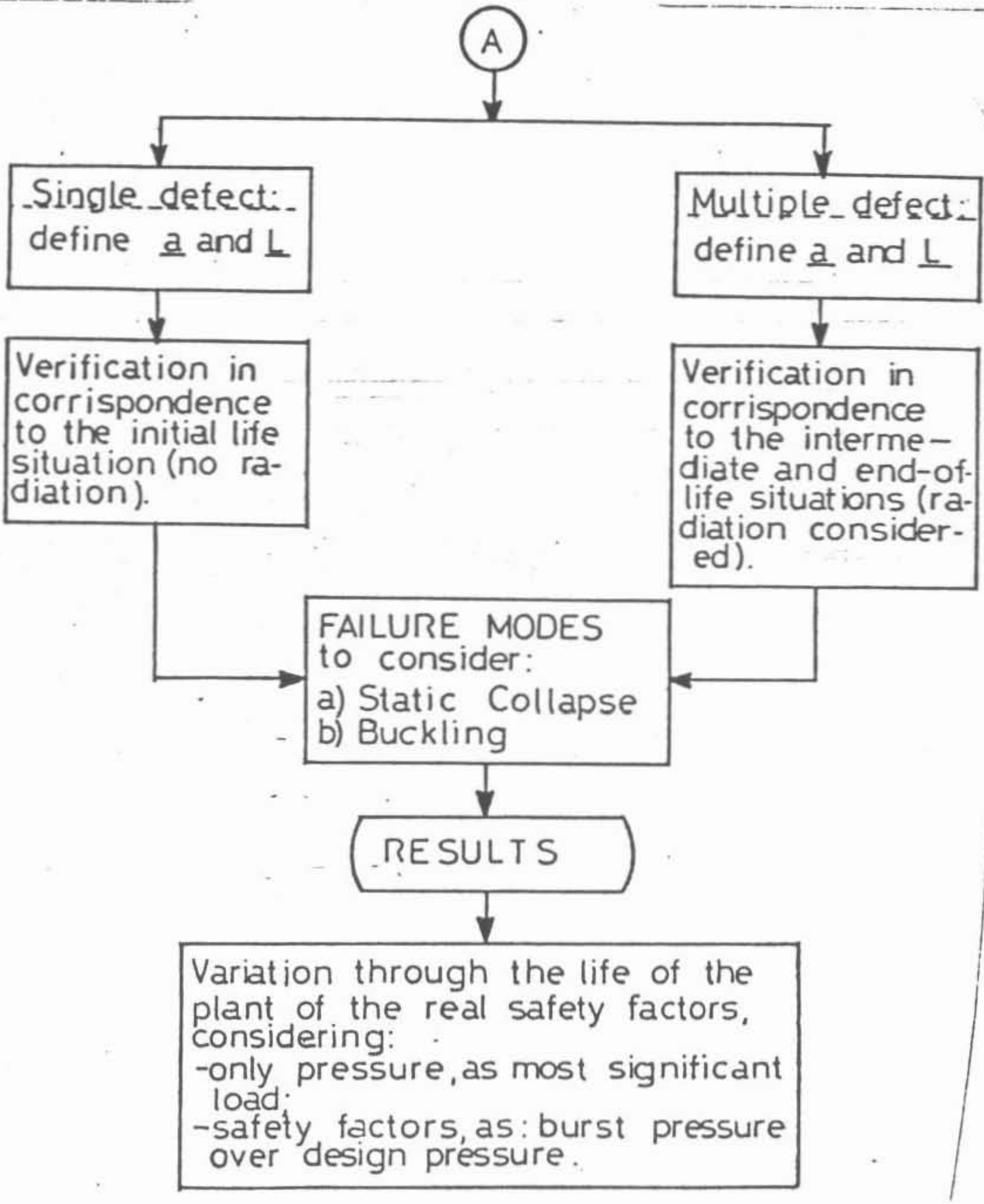
A
Single defect: define a and L
Multiple defect: define a and L
Verification in corrispondence to the initial life situation (no radiation).
Verification in corrispondence to the intermediate and end-of-life situations (radiation considered).
FAILURE MODES to consider:
a) Static Collapse
b) Buckling
RESULTS
Variation through the life of the plant of the real safety factors, considering:
-only pressure, as most significant load;
-safety factors, as: burst pressure over design pressure.

FIG. 1 (CON'T)

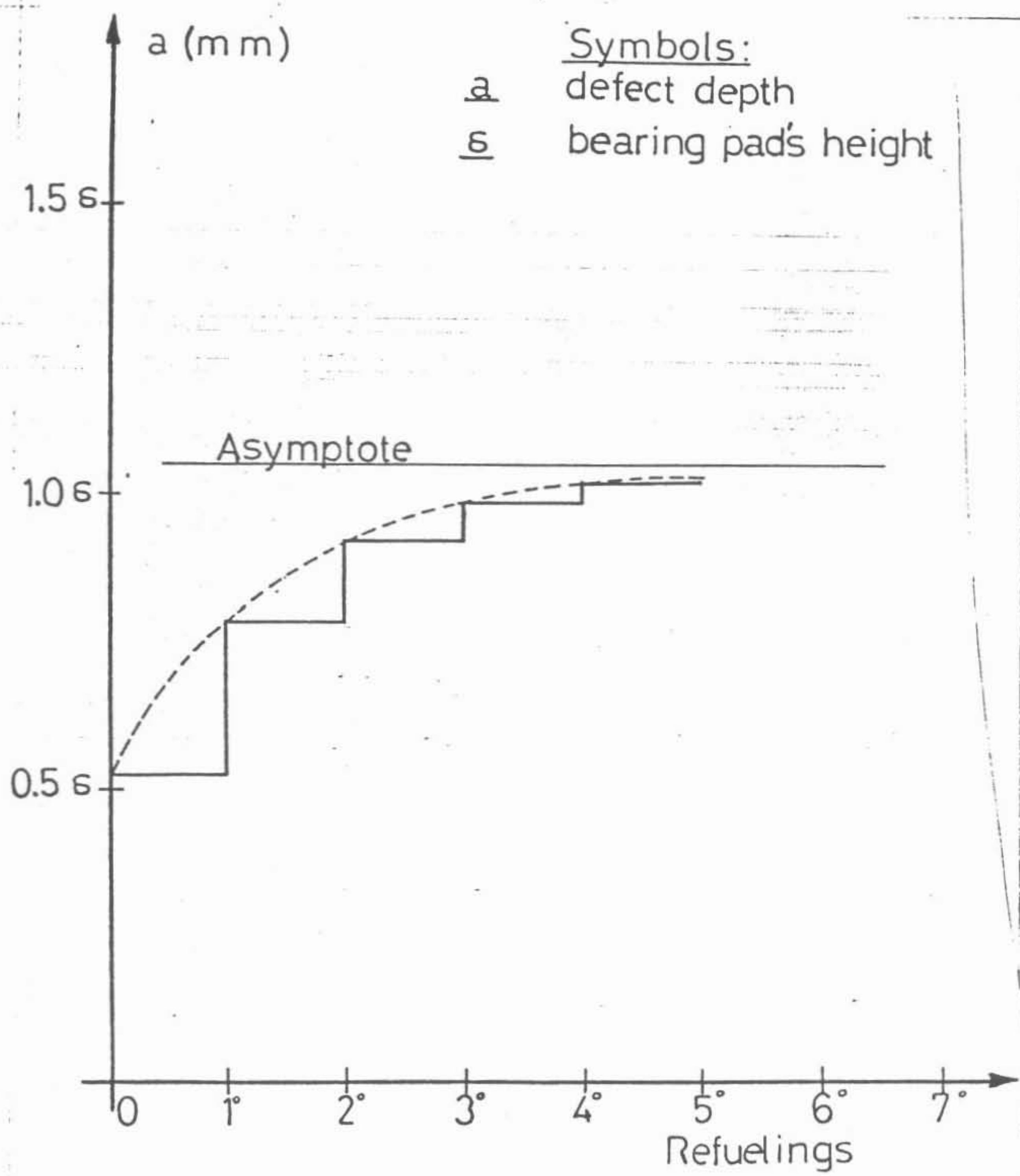

FIG. 2 QUALITATIVE TREND VS TIME OF THE DEPTH FOR THE CASE OF SINGLE DEFECT

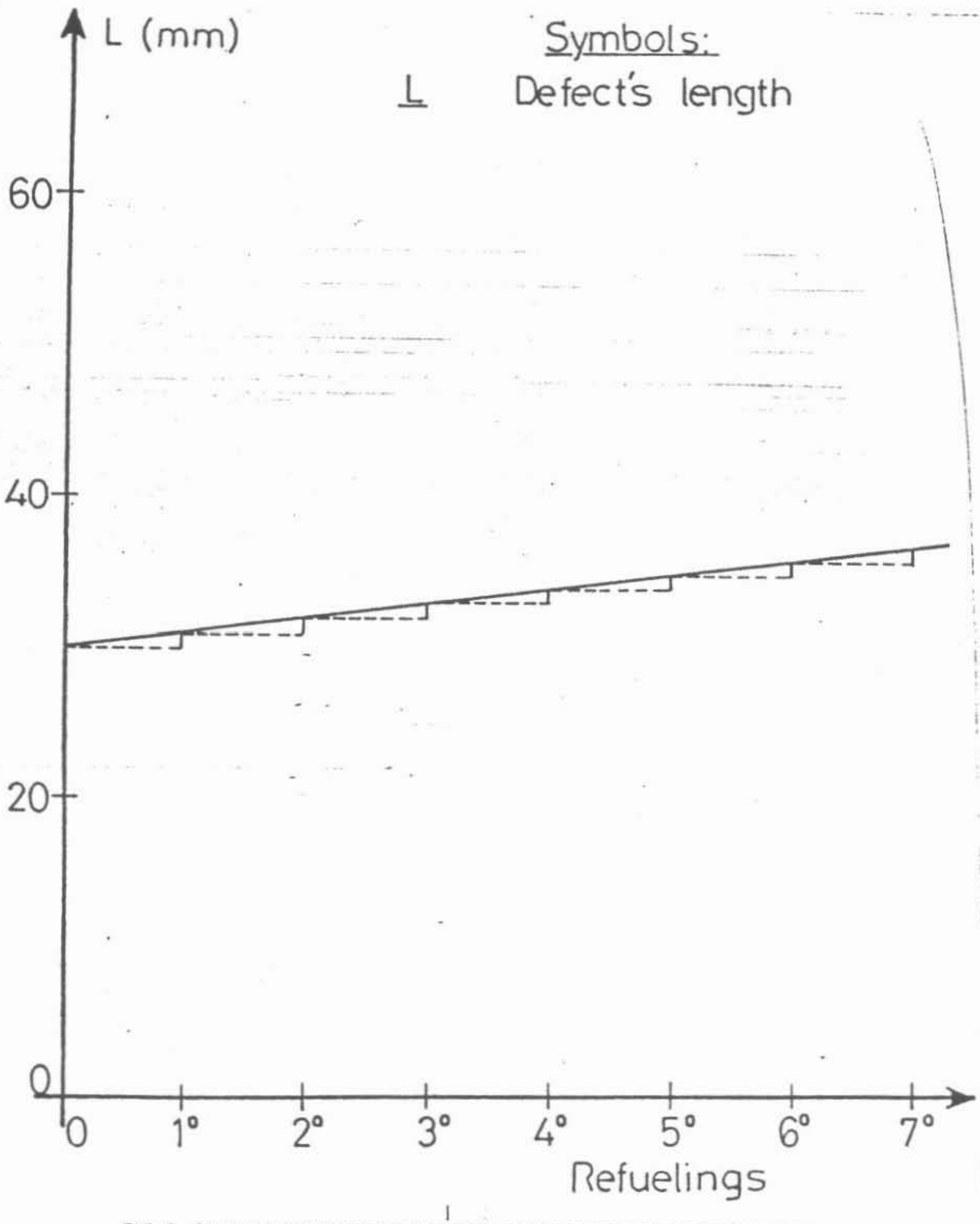

FIG. 3 QUALITATIVE TREND VS TIME OF THE LENGTH FOR THE CASES OF SINGLE AND MULTIPLE DEFECTS

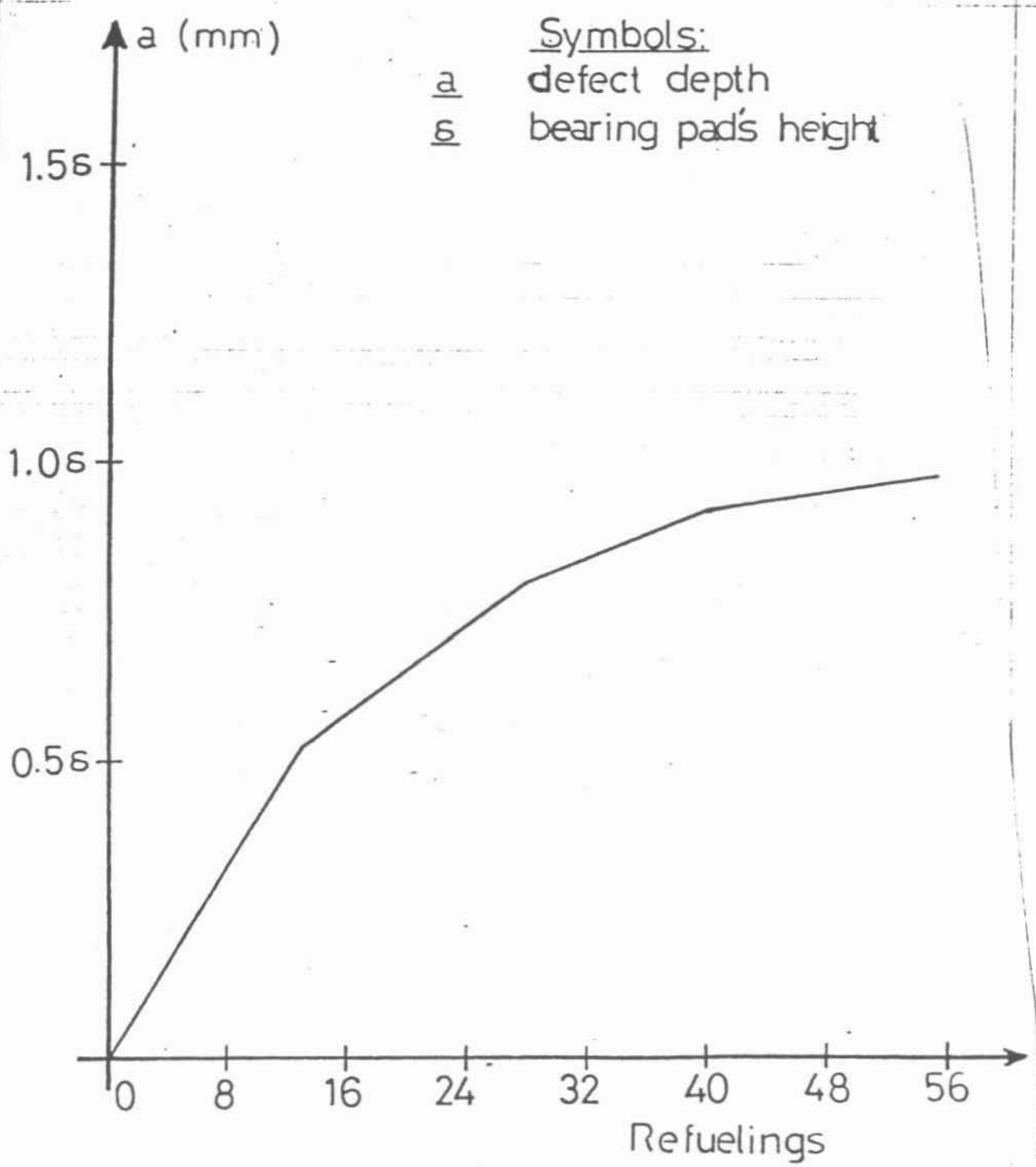

FIG. 4 QUALITATIVE TREND VS TIME OF THE DEPTH FOR THE CASE OF MULTIPLE DEFECTS

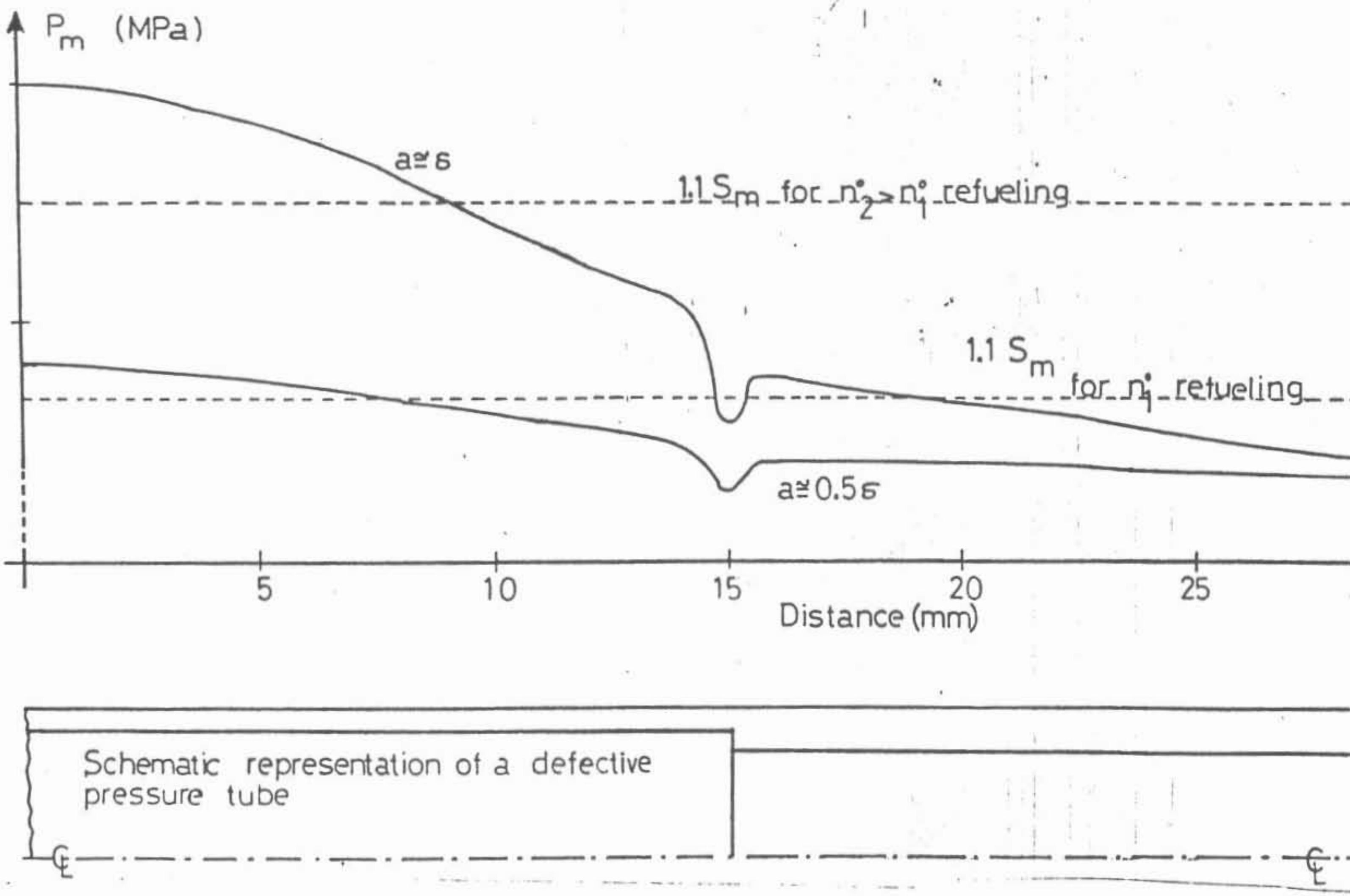

FIG. 5 MEMBRANE STRESS INTENSITY PATTERN IN A DEFECTIVE TUBE AFTER DIFFERENT REFUELINGS

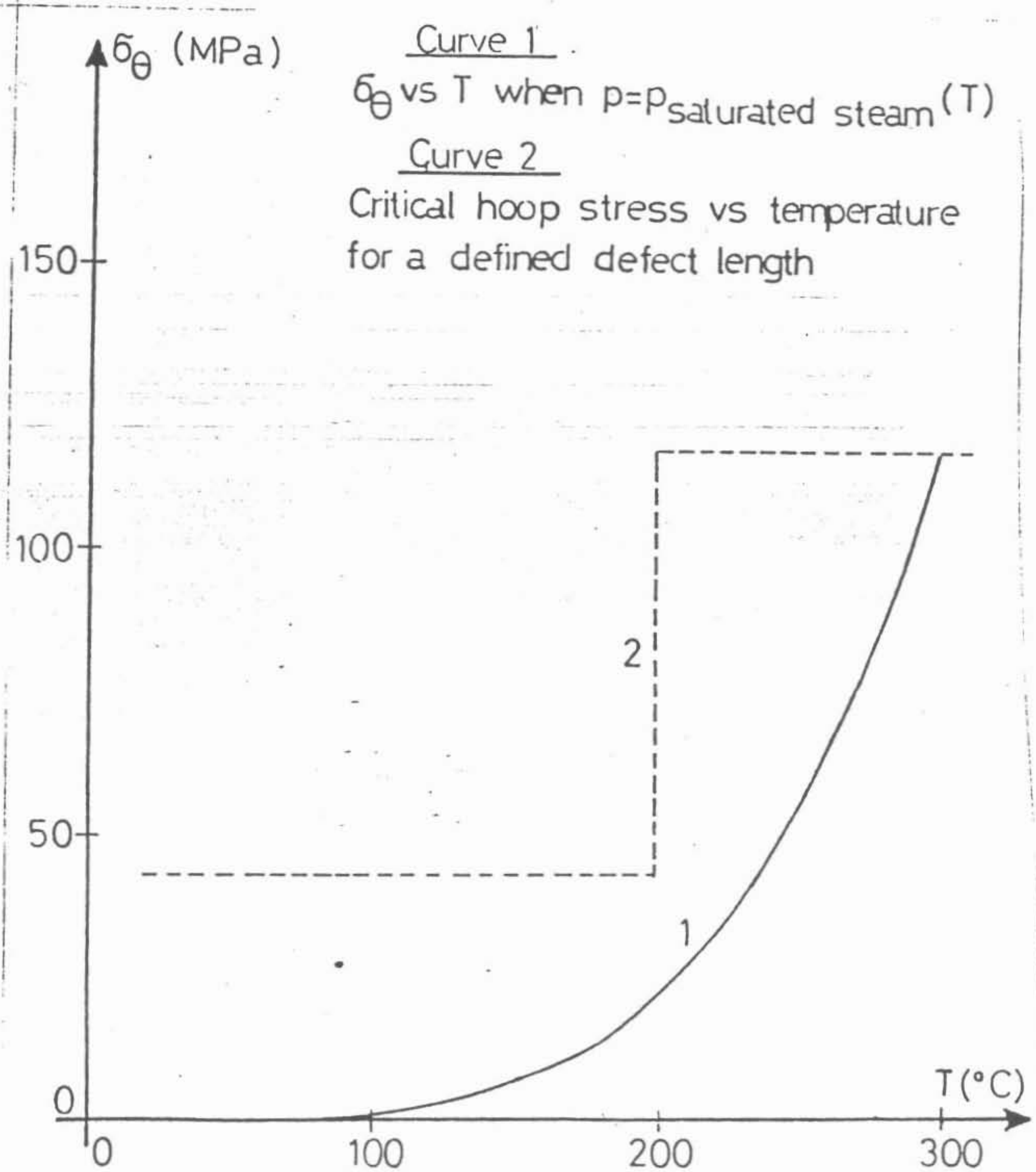

FIG. 6 CORRELATION BETWEEN HOOP STRESS AND TEMPERATURE FOR A TYPICAL HEAVY WATER REACTOR

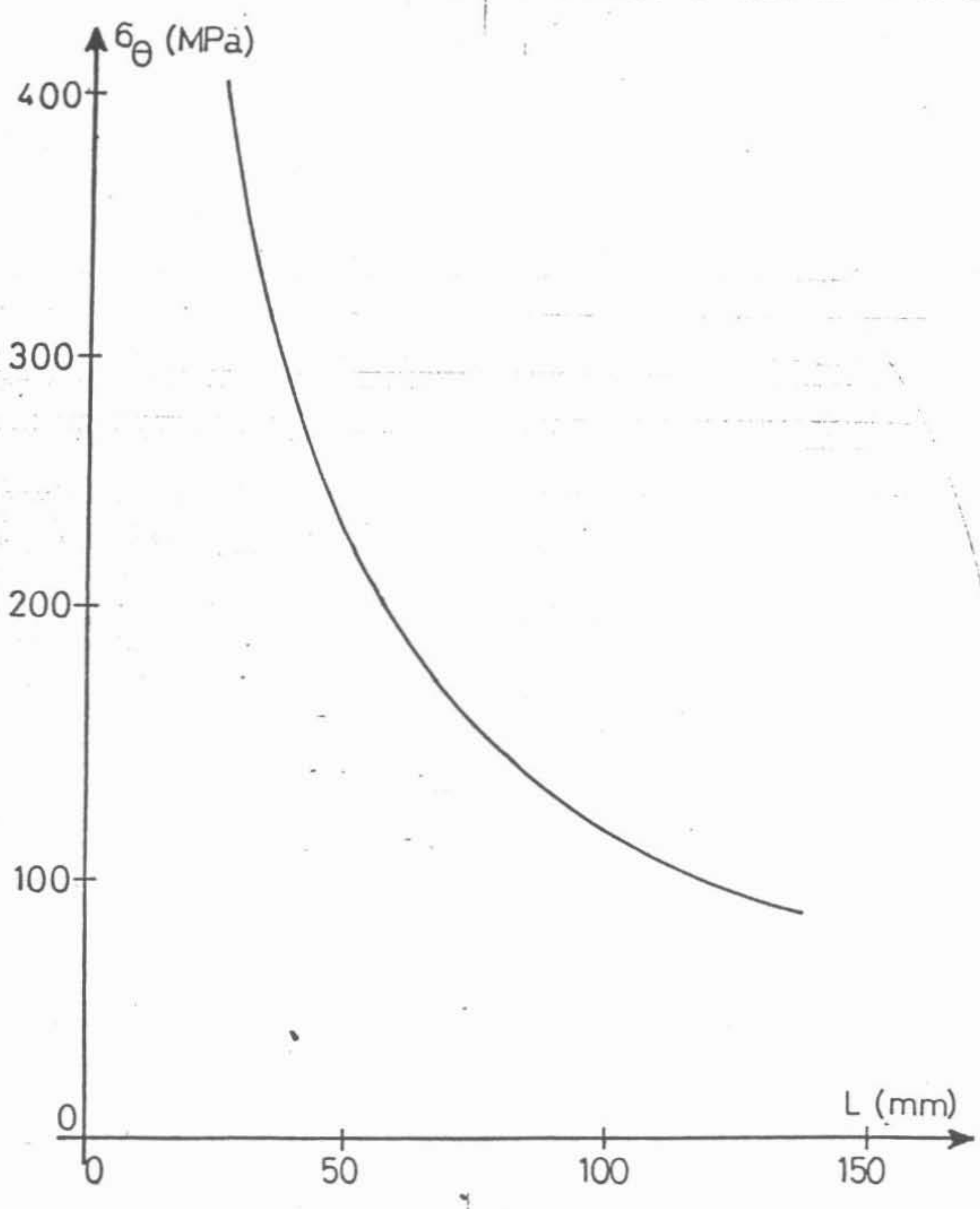

FIG. 7 CORRELATION BETWEEN HOOP STRESS AND THE CRITICAL LENGTH OF THROUGH THICKNESS DEFECTS (200°C ≤ T ≤ 300°C)

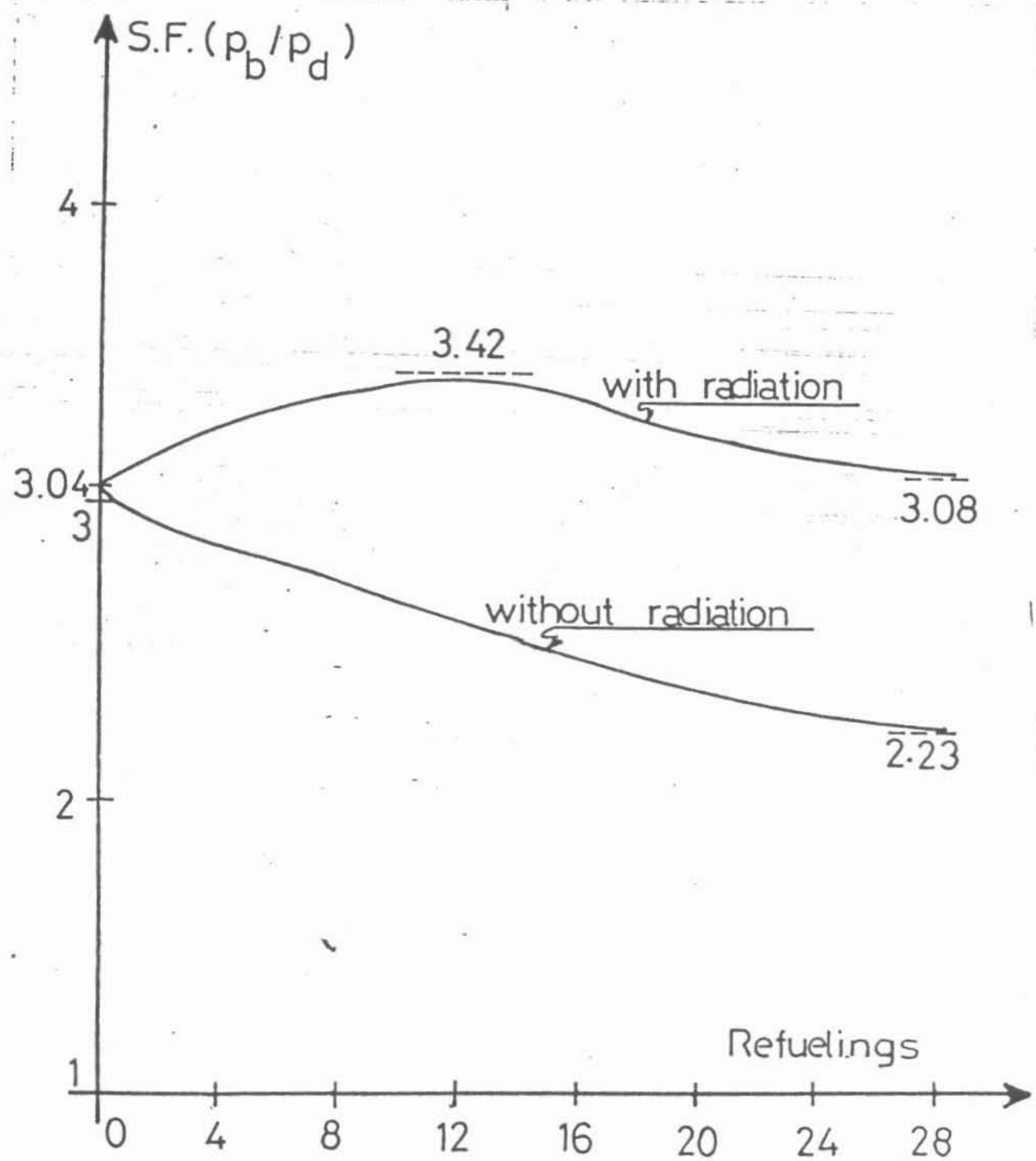

FIG. 8 QUALITATIVE TREND OF THE SAFETY FACTOR FOR THE CASE OF A PRESSURE TUBE WITH A SINGLE DEFECT (VS TIME)

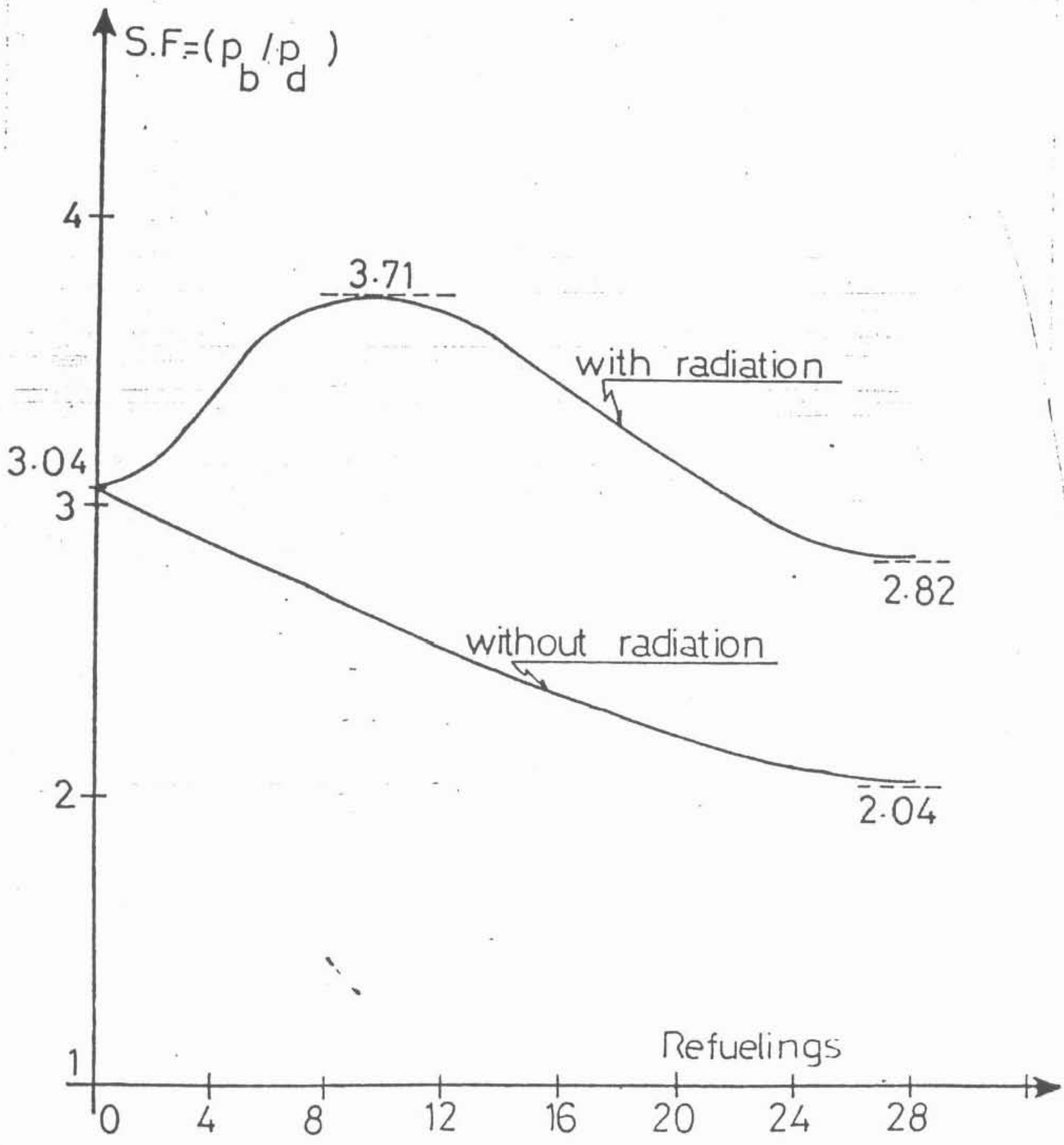

FIG. 9 QUALITATIVE TREND OF THE SAFETY FACTOR FOR THE CASE OF A PRESSURE TUBE WITH A CONTINUOUS DEFECT (VS TIME)

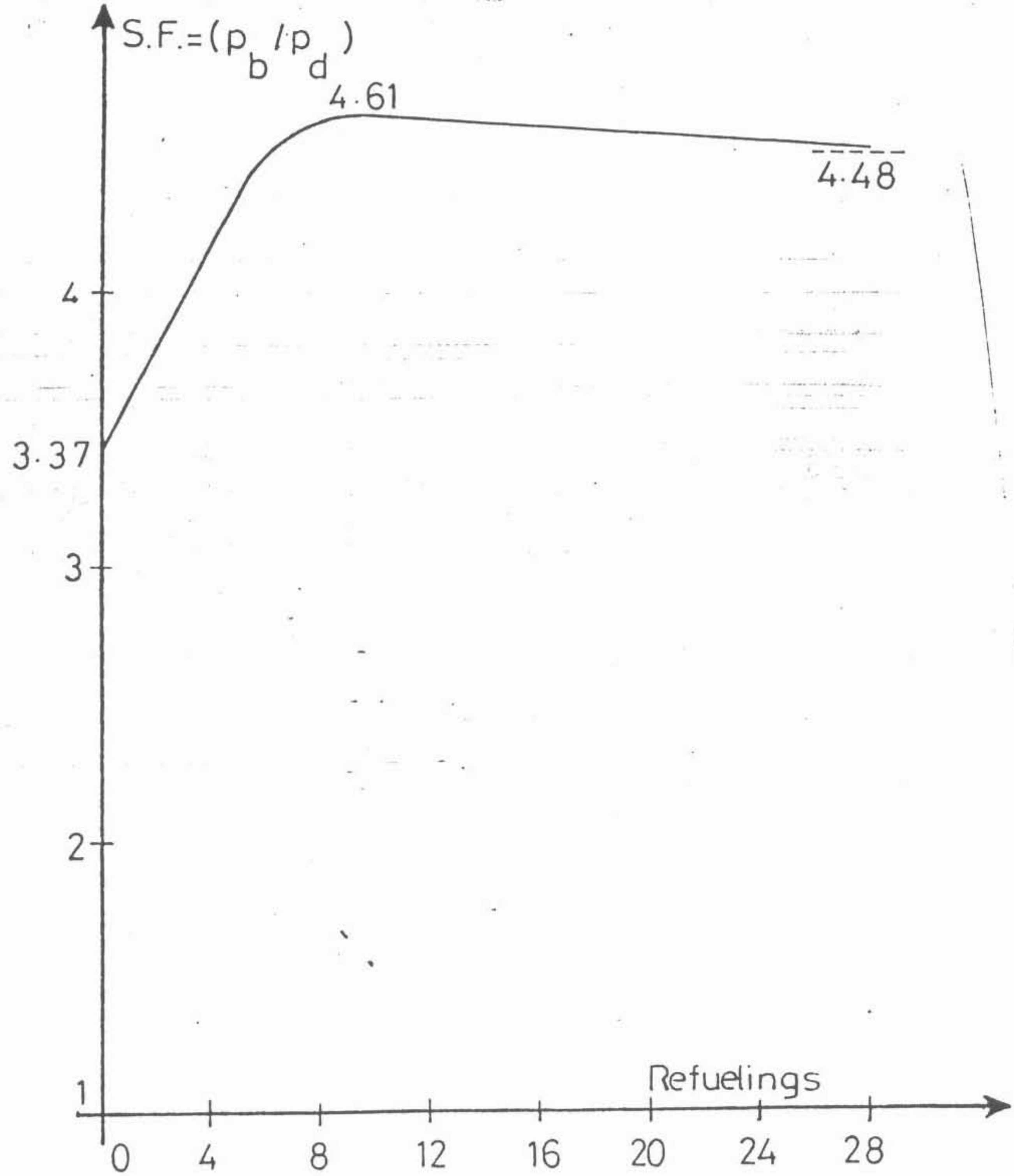

FIG. 10 QUALITATIVE TREND VS TIME OF THE SAFETY FACTOR OF AN UN-DEFECTIVE PRESSURE TUBE SUBJECTED TO NEUTRON FLUX

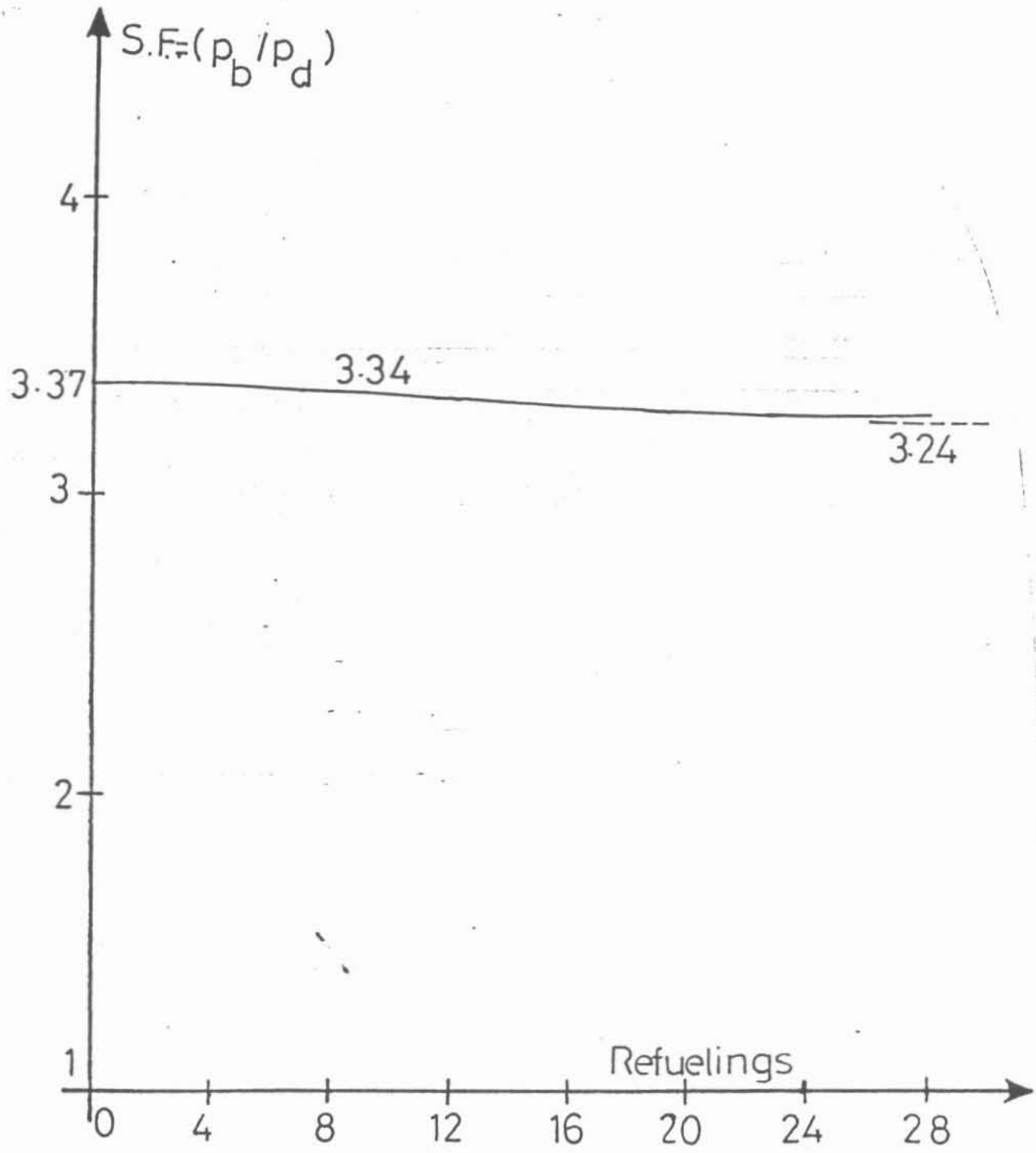

FIG. 11 QUALITATIVE TREND VS TIME OF THE SAFETY FACTOR FOR AN UNDEFECTIVE PRESSURE TUBE WHICH IS NOT SUBJECTED TO NEUTRON FLUX

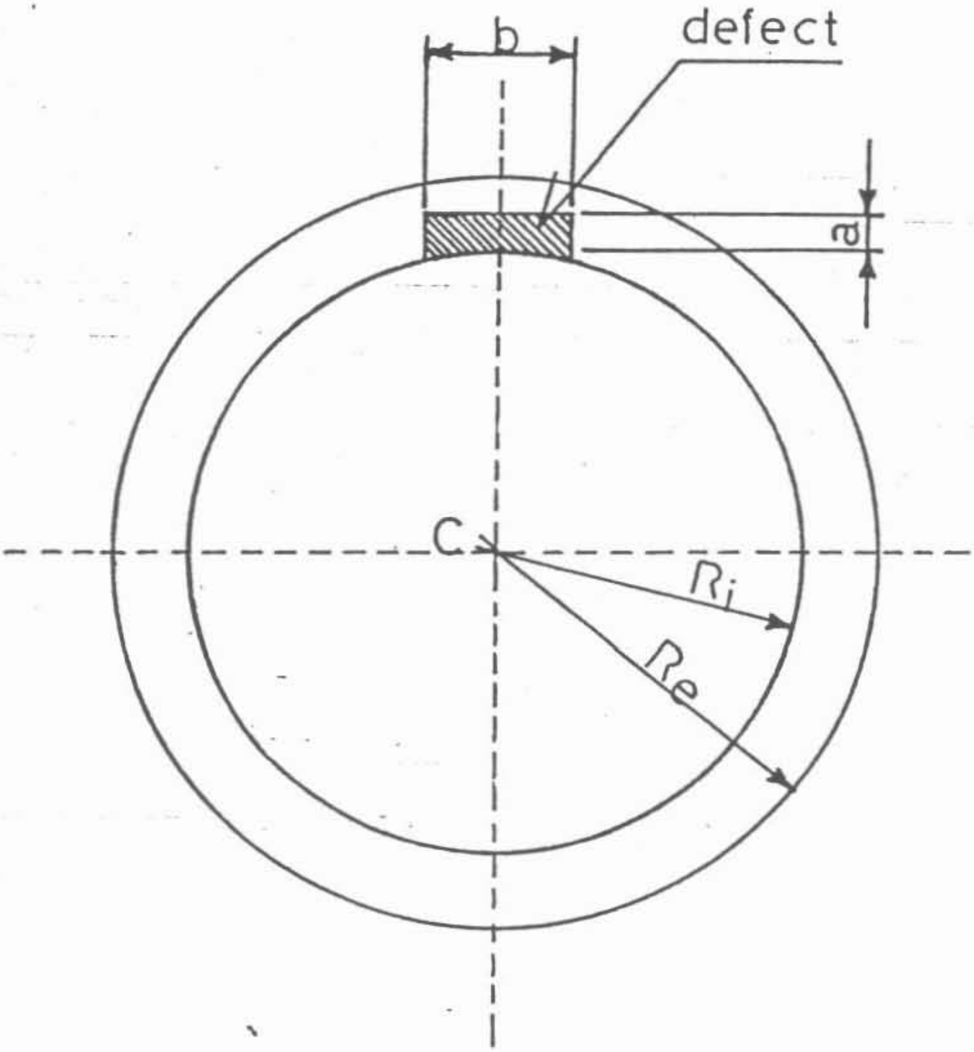

FIG. 12 GEOMETRY OF A HOLLOW CIRCULAR CROSS SECTION WITH A SINGLE iFRETTING CORROSION DEFECT

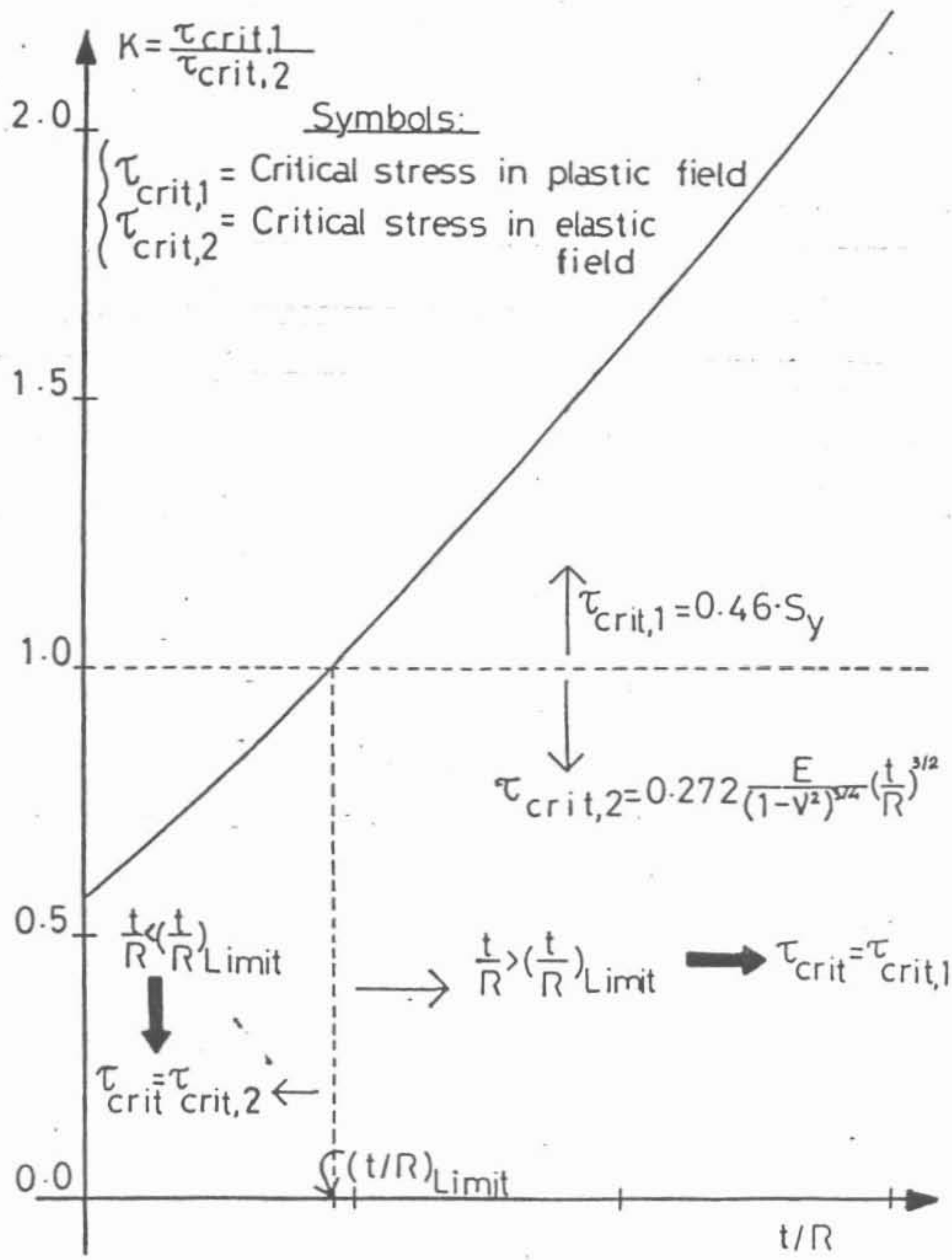

FIG. 13 BUCKLING DUE TO SHEAR STRESS: QUALITATIVE TREND OF THE FACTOR K = $\tau_{crit,1}/\tau_{crit,2}$ VS (1/R)

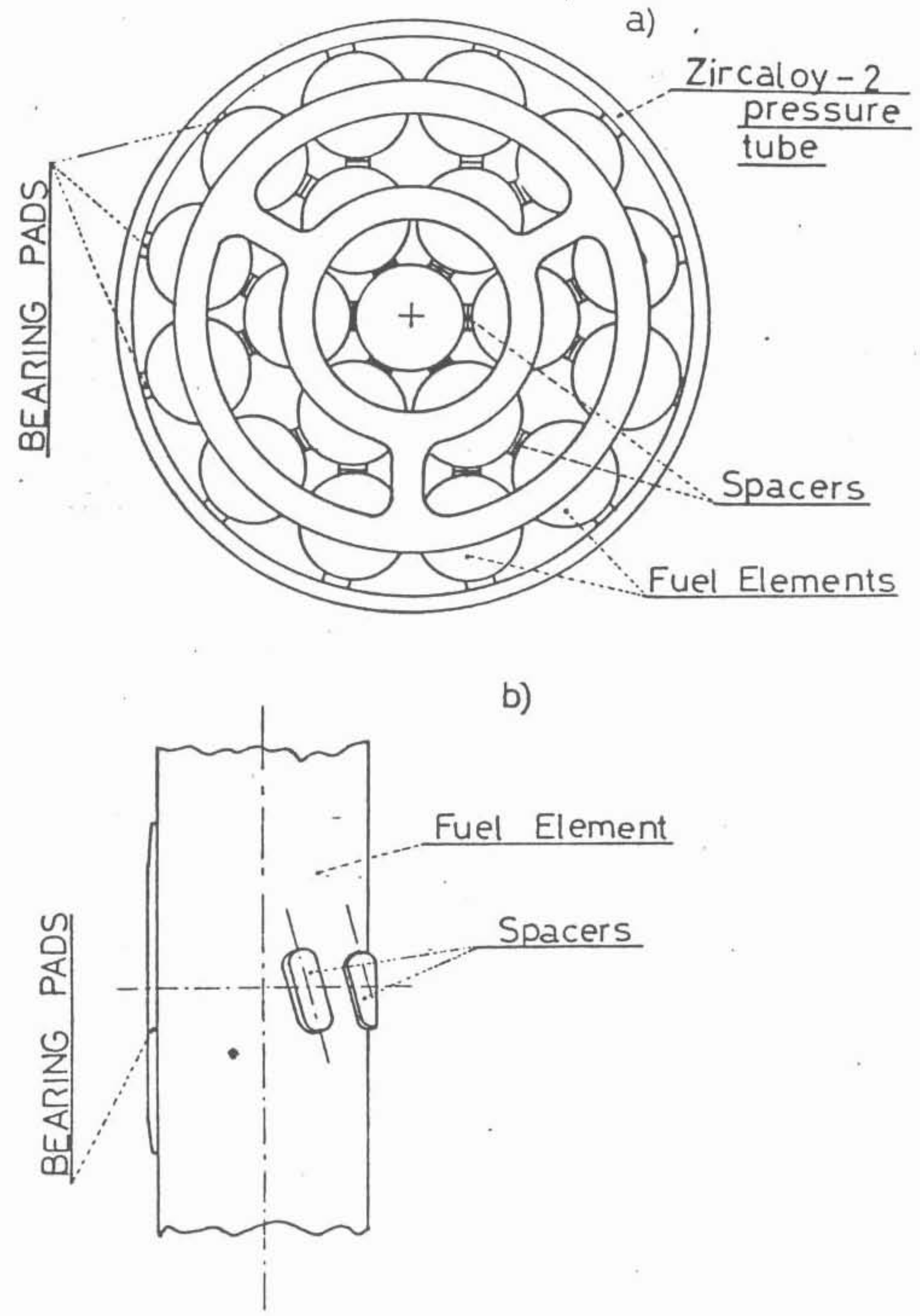

FIG. 14 a) SKETCH OF A GENERIC FUEL ELEMENTS ASSEMBLY (TRANSVERSAL)
b) SKETCH OF A FUEL ELEMENT (LONGITUDINAL)