A preliminary model for estimating the first wall lifetime of a fusion reactor

W. Dänner

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Abstract

The estimation of the first wall lifetime is a necessary basis for predicting the availability of a fusion power plant. In order to do this, an analytical model was prepared and programmed for the computer which calculates the temperature and stress load of the first wall from the principal design parameters and quotes them against the relevant material properties. Neither the analytical model nor the information about the material performance is yet complete so that the answers obtained from the program are very preliminary. This situation is underlined by the results of sample calculations performed for the CTRD blanket module cell. The results obtained for vanadium and vanadium alloys show a strong dependence of the lifetime on the irradiation creep and the ductility of these materials. Completion of this model is envisaged as soon as the missing information becomes available.

Contents:

1. Introduction

The information about the first wall lifetime was recognized as important for predicting the frequency of shut-down periods for routine replacement. Together with the length of these periods which results from considerations of the feasibility and sequence of the replacement operations envisaged, this information should subsequently permit conclusions concerning the availability of a fusion power plant.

The purpose of this study was to provide the means for estimating the useful life to be expected for the first wall by means of an analytical model. This model should allow

- evaluation of the temperature, stress and radiation loads from the principal design parameters of a reactor
- quotation of these loads against the material performance and hence derivation of an estimated lifetime.

This model was developed in the course of the European Collaborative Tokamak Reactor Design study (CTRD). Its first part is therefore strongly related to this special design. Parametric studies by means of this model should already aid the design at an early stage of its development and provide a background against which the final decisions could be weighed. To meet these requirements, the analytical model as hitherto elaborated was programmed for the IBM 360/91 computer at IPP using basic FORTRAN-IV language.

2. Principal design features of the module cell

The present study is concerned with a modular cell (see Fig. 1) as proposed by J.T.D. Mitchell and J.A. Booth [1] and J.R. Stanbridge et.al. [2]. As a first guess it is assumed that the cross-section of this cell will be circular and that the material composition inside this cell is in close agreement with the blanket proposed by J. Darvas [3]. This implies the use of helium as a coolant.

To describe the geometrical environment of a single cell, the analytical model allows of two options: the arrangement in a square (see fig. 2a) or haxagonal (see fig. 2b) matrix.

In addition, the specification of a pitch ratio p is possible, this being the ratio of the distance d between the axes of two adjacent cells and their outer diameter D_C:

$$p = \frac{d}{D_C} \tag{1}$$

These options permit the definition of a package density ρ_p, which is the ratio of the cell cross-section A_C and that of a matrix element A_M. A simple calculation leads to the expression

$$\rho_p = \frac{\pi}{4} \cdot \frac{1}{\alpha p^2} \tag{2}$$

with $\alpha = 1.0$ for the square matrix and $\alpha = \frac{\sqrt{3}}{2} = 0.866$ for the hexagonal matrix.

3. Input quantities to the analytical model

Before beginning with the analytical treatment of this problem it first had to be decided which quantities shall be treated as independent variables. To gain the greatest possible flexibility it seemed realistic to choose those quantities about which information is most probably provided by other areas of reactor design:

- neutron wall loading P_{Wn} [W/cm^2]

— bremsstrahlung power. Although there is a difference in the temperature dependence of the neutron and the bremsstrahlung wall loading it is assumed in this model that they are proportional to each other. Therefore, a constant factor f_{Wbr}

$$f_{Wbr} = \frac{P_{Wbr}}{P_{Wn}} \quad [\,-\,] \qquad (3)$$

has been introduced. This factor describes the dependence exactly only if changes in the neutron wall loading are obtained by changing the ion density. In the case the ion temperature is changed it is only an approximation.

— The power multiplication factor M of the blanket, defined as the ratio of the total nuclear power of the blanket and the power carried by the 14 MeV neutrons from the plasma to the blanket.

— the structure material volume fraction ε_W permitted for the outer cell wall. This figure does not include further structure material inside the beryllium, lithium or graphite regions.

— a factor f_{HW} which relates the average power density $\bar{q}$ in the first wall to the neutron wall loading. This factor can be derived from the results of a neutronics analysis. Knowing the power density profile q(x) across the first wall with the thickness s_W for a given neutron wall loading P_{Wn}, f_{HW} becomes

$$f_{HW} = \frac{\bar{q}}{P_{Wn}} = \frac{\frac{1}{s_W}\int_0^{s_W} q(x)\,dx}{P_{Wn}}$$

— a factor f_{dpa} which relates the annual displacement rate in the first wall to the neutron wall loading.

— the outer cell diameter D_C [cm]

— the radial length of a cell L_C [cm]

— the helium pressure level p_c [bar]

— the helium inlet temperature to the blanket $t_{c_{in}}$ [C]

— the helium outlet temperature from the blanket $t_{c_{out}}$ [C]

— the width of the helium duct δ [cm]

— the actual helium temperature at the first wall t_{cx} [C]
The choice of t_{cx} has to be made within the limits of $t_{c_{in}}$ and $t_{c_{out}}$.

— a factor f_{HTC} [-]
allowing for input of an enhanced heat transfer coefficient at the first wall. In the course of the calculation a heat transfer coefficient h is calculated for the annular duct in the straight section of the cell. Inside the spherical cup, however, the heat transfer may deviate from that. It depends on the amount of coolant which is diverted into the beryllium region along the path from the straight section to the bottom of the spherical cup as indicated in Fig. 1. The factor f_{HTC} has been introduced to take account of this fact. Actually it has to be determined by the thermal design of the cell.

4. Analysis of the temperature and stress load of the first wall

4.1 Determination of basic quantities

From the quantities defined in sections 2 and 3 the following general quantities can be derived:

The ratio of the cell wall thickness s_W and the outer cell diameter D_C can be calculated from the structure material volume fraction ξ_W and the package density ρ_p by

$$\frac{s_W}{D_c} = \frac{1}{2} \left(1 - \sqrt{1 - \frac{\varepsilon_W}{\varrho_p}} \right) \quad [-] \qquad (4)$$

The actual wall thickness s_W is

$$s_W = D_C \cdot \frac{s_W}{D_C} \quad [cm] \qquad (5)$$

The cell cross-section area A_c follows directly from

$$A_C = \frac{\pi}{4} D_C^2 \quad [cm^2] \qquad (6)$$

and the cross-sectional area of a matrix element from

$$A_M = \frac{A_C}{\varrho_p} \quad [cm^2] \qquad (7)$$

For the investigation of heat transfer it is necessary to know the coolant duct cross-section area A_{CD}

$$A_{CD} = \pi \cdot \delta \cdot (d_C - \delta) \quad [cm^2] \qquad (8)$$

with the inner diameter of the cell d_C

$$d_C = D_C - 2 s_W \quad [cm] \qquad (9)$$

The hydraulic diameter of the duct is

$$d_h = 2 \cdot \delta \quad [cm] \qquad (10)$$

To calculate the helium flow rate necessary for cooling the cell within the indicated temperature limits, first the total power produced inside a single cell, P_C, has to be evaluated. It is assumed that the entire energy incident on the area of one matrix element is converted to heat inside the corresponding cell. This means that

$$P_C = [P_{Wn} (M + f_{Wbr})] \cdot A_M \quad [W] \qquad (11)$$

From this the coolant mass flow rate $\dot{m}_c$, volume flow rate $\dot{v}_c$ and velocity w_c can be calculated by using the following equations:

$$\dot{m}_c = \frac{P_C}{c_p \, (t_{cout} - t_{cin})} \qquad [g/s] \qquad (12)$$

$$\dot{v}_c = \frac{\dot{m}_c}{\rho_c} \qquad [cm^3/s] \qquad (13)$$

$$w_c = \frac{\dot{v}_c}{A_{CD}} \qquad [cm/s] \qquad (14)$$

The specific heat at constant pressure, c_p, and the density ρ_c of the coolant are thereby taken at the mean coolant temperature t_c

$$t_c = \frac{t_{cin} + t_{cout}}{2} \qquad [C] \qquad (15)$$

4.2 Heat transfer from the wall to the coolant

The inner cell wall temperature t_{Wi} is determined by the actual helium temperature t_{cx} and the temperature difference Δt_{cW} between the wall and coolant. The latter depends on the real heat flux density q_W at the wall and the heat transfer coefficient h of the coolant flow:

$$\Delta t_{cW} = \frac{q_W}{h} \qquad [C] \qquad (16)$$

The heat flux density q_W is calculated from the brems-strahlung wall loading and the power density inside the wall by the following equation:

$$q_W = P_{Wn} \cdot (f_{Wbr} + s_W \cdot f_{HW}) \qquad [W/cm^2] \qquad (17)$$

The calculation of the heat transfer coefficient h is based on the Kraussold-Nusselt equation for a circular pipe flow presented by U. Grigull et al. [4]:

$$Nu = 0.032 \cdot Re^{0.8} \cdot Pr^{0.37} \cdot \left(\frac{L_c}{d_h} \right)^{-0.054} \qquad (18)$$

with Nu, Re, and Pr being the Nusselt, Reynolds and Prandtl numbers. Introducing the coolant properties and the layout parameters into equ. (18) we arrive at the following expression for h:

$$h = \frac{k}{d_h} \cdot Nu =$$

$$h = 0.032 \cdot f_c (\vartheta, p_c) \cdot w_c^{0.8} \cdot L_c^{-0.054} \cdot d_h^{-0.146} \ [W/cm^2 \ grd] \qquad (19)$$

$f_c (\vartheta, p_c)$ summarizes the coolant properties which, in general, are dependent on the coolant pressure p_c and the average film temperature ϑ:

$$f_c (\vartheta, p_c) = \varrho_c^{0.8} \cdot c_o^{0.37} \cdot k^{0.63} \cdot \eta^{-0.43} \qquad (20)$$

Equation (20) yields the results in appropriate units for direct use in equ. (19), if the coolant properties are expressed in the following units:

density	ϱ_c	$[g/cm^3]$
specific heat	c_p	[J/g grd]
thermal conductivity	k	[W/cm grd]
dynamic viscosity	η	[g/cm s]

To yield h in W/cm^2 grd , the coolant velocity w_c, coolant duct length L_c, and hydraulic diameter d_h have to enter in the following units:

w_c [cm/s] L_c [cm] d_h [cm]

In the analytical model the heat transfer coefficient and the quantities depending on it are evaluated in a iterative way, so that the temperature difference between the wall and coolant is obtained with an accuracy of $\pm$ 1 C.

4.3 Temperatures inside the first wall

Having evaluated the inner wall temperature t_{W_i} by

$$t_{W_i} = t_{cx} + \Delta t_{cW} \quad [C] \tag{21}$$

the next step is to determine the outer and the mean wall temperatures t_{W_o} and t_{W_m}. To solve this problem, the differential equation describing the process of heat conduction was applied to the case of plane geometry, which should be a sufficiently good approximation. As boundary conditions the temperature gradient resulting from the heat transfer to the coolant was used at the inner side, while the bremsstrahlung wall loading treated as an external heat source was used at the outer side. This procedure yields the temperature difference across the wall:

$$\Delta t_W = \frac{P_{W_n} \cdot s_W}{k_W} \left(f_{W_{br}} + \frac{1}{2} \; s_W \cdot f_{HW}\right) \quad [C] \tag{22}$$

The outer and mean wall temperatures t_{W_o} and t_{W_m} then become

$$t_{W_o} = t_{W_i} + \Delta t_W \quad [C] \tag{23}$$

$$t_{W_m} = t_{W_i} + \frac{1}{2} \Delta t_W \quad [C] \tag{24}$$

The thermal conductivity k_W of the wall material is thereby taken at the mean wall temperature. Therefore, in this case as well the analytical model provides an iterative procedure, yielding Δt_W with an accuracy of $\pm$ 0.5 C.

4.4 Stresses inside the first wall

Whereas the temperature load of the first wall has already been determined by the procedure described above, the problem of stress loading remains to be solved. At present, three sources of stress can be identified:

- tensile stresses due to the static coolant pressure
- thermal stresses due to the temperature gradients across the wall
- additional stresses due to differential swelling in the wall.

From these sources the contribution of stresses due to differential swelling has not yet been included in the analysis.

For calculating the tensile stresses the equation

$$\sigma_1 = \frac{p_c}{2\,(\frac{s_W}{D_C})} \qquad [kp/cm^2] \qquad (25)$$

is used, yielding the maximum tangential stress at any point along the straight section of the cell wall. This should also be the maximum stress in that part of the wall which is directly exposed to the neutron and bremsstrahlung radiation, at least at the point where the straight section is joined to the spherical cup.

The thermal stresses are calculated using the formula given by J.R. Stanbridge et al. [2]:

$$\sigma_2 = \frac{1}{2} \cdot \frac{\Delta t_W \cdot \alpha \cdot E}{1 - \nu} \qquad [kp/cm^2] \qquad (26)$$

Here α is the thermal expansion coefficient, E the Young's modulus and ν the Poisson ratio of the wall material considered.

Since the thermal stress has a tensile characteristic at the colder side of the wall, the maximum total stress

$$\sigma = \sigma_1 + \sigma_2 \qquad [kp/cm^2] \qquad (27)$$

appears at the inner side of the cell wall.

5. Material properties and wall lifetime

Before any statement about the lifetime of the first wall can be made, the temperature and stress loads have to be quoted against the relevant material properties. As far as we are aware these are:

- the time rupture strength
- the creep strength
- the fatigue strength
- the ductility

In comparing the temperature and stress loads evaluated according to the procedure described in section 4 with those four properties, their variation with the radiation dose also has to be taken into account. As far as the fatigue strength is concerned, information about the thermal cycling should also be available. At the present stage only the time rupture behaviour, excluding the influence of irradiation, thermal creep and irradiation creep have been included in the analysis.

5.1 Time rupture strength

In the current literature (see, for example, H. Böhm, M. Schirra [5]) data for the time rupture strength σ_{tr} are presented as a function of the Larson-Miller parameter P. This parameter is defined as

$$P = T \cdot (C + \log t_1) \qquad (28)$$

C being a material constant, T [K]the operating temperature and t_1 [h] the useful life.

The analytical model presented here makes use of information of this kind in the following way. If σ_{tr} is known as a function of P, the reverse procedure must yield a certain value for P when σ_{tr} is replaced by the total stress load σ evaluated in equ. (27). Introducing the working temperature T

(in the present case the inner wall temperature t_{Wi} as the point of maximum stress), equ. (28) can be solved for t_1 yielding

$$t_1 = 10^{\left(\frac{P}{T_{Wi}} - C\right)} \quad [h] \qquad (29)$$

An interative procedure could be provided in the event of knowledge about the changes of σ_{tr} with the neutron dose becoming available.

5.2 Thermal creep

Literature on thermal creep, e.g. M. Schirra [6] or G. Schmidt [7], presents the dependenc of the creep rate $\dot{\varepsilon}_t$ due to Norton's relationship:

$$\dot{\varepsilon}_t = k \cdot \sigma^n \quad [h^{-1}] \qquad (30)$$

Using σ in $[kp/mm^2]$ yields $\dot{\varepsilon}$ in $[h^{-1}]$. M. Schirra [6] also presents an equation with which it is possible to calculate the lifetime t_2 due to thermal creep:

$$\log t_2 + m \log \dot{\varepsilon}_t = \ell \qquad (31)$$

Therefore, if the materials characteristics k, n, m, and ℓ are known, it is possible to arrive at a second figure t_2 for the expected lifetime due to

$$t_2 = 10^{(\ell - m \cdot \log \dot{\varepsilon}_t)} \quad [h] \qquad (32)$$

The analytical model makes use of this procedure and evaluates t_2 besides t_1.

5.3 Irradiation creep

The importance of irradiation creep is outlined by J.R. Stanbridge et al. [2]. The equation given in this report can be transformed in such a way that a creep rate $\dot{\varepsilon}_i$ can be obtained.

$$\dot{\varepsilon}_i = C_i \cdot f_{dpa} \cdot P_{Wn} \cdot \sigma \qquad [h^{-1}] \qquad (33)$$

Information has, however, to be provided about the materials constant C_i, which is presented in this report only for stainless steel.

5.4 Open problems

As mentioned above, the analytical model for an estimation of the first wall lifetime as described so far is not yet complete. There is especially a lack of information about the irradiation effects. This becomes immediately obvious if the creep rates for both thermal and irradiation creep are quoted against any permissible limit. Equation (32) defines an expected lifetime only for the case of absence of irradiation and is therefore not necessarily true if $\dot{\varepsilon}_t$ is replaced by the total creep rate $\dot{\varepsilon}$:

$$\dot{\varepsilon} = \dot{\varepsilon}_t + \dot{\varepsilon}_i \qquad [h^{-1}] \qquad (34)$$

The analytical model nevertheless makes use of this assumption to calculate a third lifetime t_3.

$$t_3 = 10^{(\ell - m \cdot \log (\dot{\varepsilon}_t + \dot{\varepsilon}_i))} \qquad [h] \qquad (35)$$

To obtain a precise picture, obviously the total creep rate and the static elongations due to thermal and stress effects have to be quoted against the ductility of the

special material, which, in general, is strongly affected by irradiation embrittlement. This step in the analysis has not yet been done. Instead of this a fourth time t_4 describing the time in which a total of 1 % creep is reached is calculated:

$$t_4 = \frac{0.01}{\dot{\varepsilon}_t + \dot{\varepsilon}_i} \quad [h] \qquad (36)$$

Summarizing the status of the development of the analytical model, it must be emphasized that further refinements and additions are necessary. This is especially true as far as the material properties are concerned. It is in this area that a lot of work will have to be done if this model is to be further developed to become a useful tool in reactor design.

6. Computer program

In order to have a convenient means of performing parameter studies, it was decided to program this model for the IPP computer. Figure 3 shows a flow diagram of this program, which shall be briefly explained in this section.

The program consists of a main program and 12 sub-programs, 8 of which exclusively provide material properties. These latter routines are written in such a way that they can easily be corrected and extended to any number of materials.

6.1 Description of the single programs

MAIN is a multi-purpose input/output program which can be applied to any calculation routine. It offers great flexibility for the following reasons:

- the number of input quantities is, in principle, unlimited.
- each input quantity can be varied in equal steps between two limits. In the present version, however, only the first two quantities with varying input are accepted to be changed.
- it provides either total output or selected output of special quantities.
- it provides additional plot output of selected quantities. In the present version, however, the plot routines have been removed to save storage location during the test period.

Communication with the first level subroutines (in this case WLOAD and LIFE) is ensured by COMMON statements. To adjust this program to any subroutine, only the COMMON and part of the DIMENSION statements have to be changed. In addition, the names of the input and output quantities have to be put to two DATA statements to provide a self-explanatory print output.

WLOAD performs all calculations described in section 4 of this paper. It makes use of two further subroutines for calculation: HTCOF and WALLTM.

HTCOF evaluates the heat transfer coefficient, the temperature difference between the wall and coolant and the inner wall temperature itself. The coolant properties needed for this calculation are supplied by the subroutine COOLNT.

WALLTM calculates the temperature difference within the wall using the thermal conductivity provided by COND.

LIFE finally takes over the figures for the temperature and stress load evaluated by WLOAD and quotes them against the material properties as described in sections 5 and 6.

COOLNT calculates the coolant properties for helium which are needed in WLOAD and HTCOF. Dependent on temperature and pressure, it yields the density, specific heat at constant pressure, thermal conductivity, and dynamic viscosity. The equations contained in this subroutine are taken from W. Zimmerer [8].

The remainder of the routines are concerned with properties of the wall materials. Each property needed is supplied by a special subprogram which may contain the data of various metals and alloys. Which of these data are used is decided by a material identification number.

COND supplies the thermal conductivity dependent on the temperature. At present this FUNCTION subprogram contains only data for vanadium and vanadium-titanium alloys. Data for pure vanadium and for the alloys V-3 Ti and V-20 Ti have been calculated according to H. Böhm et al. [9]. For any other titanium content these data are linearly interpolated. The actual titanium content which will be taken into account is supplied to this and any further routine by the material identification number.

EXPN calculates the thermal expansion coefficient dependent on the temperature. This FUNCTION subprogram at present contains only the data for pure vanadium which are also used for vanadium alloys. They are taken from F. Sperner [10].

EMOD supplies Young's modulus. Provision is made for taking into account a temperature dependence. At present, however, only the value for vanadium is supplied as a constant figure which is due to F. Sperner [10].

POIS supplies the Poisson ratio. For this the same is valid as for Young's modulus, the figure for vanadium being taken from Kieffer [11].

LARSON supplies the material constant C (see equ. (28)) and calculates the Larson-Miller parameter P for a given stress. As yet only data for two vanadium alloys, V-5 Ti and V-20 Ti, which were taken from H. Böhm, M. Schirra [5], have been evaluated. The curves given there were approximated by polynomials and interpolation is provided to obtain results for any reasonable titanium content.

CIC supplies the material constant C_i for irradiation creep (see equ. (33)). At present only the figure for stainless steel is known from the publication of J.R. Stanbridge et al. [2]. This figure is therefore also used for vanadium.

CREEP supplies the parameters for secondary creep, i.e. the creep constant k and the stress exponent n for Norton's equation (equ. (30)) and the material constants m and ℓ which are needed to solve equ. (32) and (35) respectively. This subroutine contains at present k and n for stainless steel according to G. Schmidt [7] dependent on temperature. Since m and ℓ are unknown, the same data as for vanadium are used here.

Data of k and n for vanadium and vanadium alloys were derived from the publication of H. Böhm and M. Schirra [5]. Because of the somewhat different definition of Norton's equation close agreement can only be expected for pure vanadium and the alloys V-2.8 Ti, V-5 Ti, and V-20 Ti. The constants m and ℓ were also taken from this publication.

Complete lists of all programs are included in the Appendix.

6.2 Description of the input

1st card (format: 8X, 4I4)

NA	number of input quantities	= 17 (fixed)
NR	number of results (total)	= 34 (fixed)
NPR	number of results to be printed	
	NPR $\leq$ NR	
	NPR = 0 : total output	
NPL	number of results to be plotted	= 0 (fixed)

2nd card ff. (format: 8X, 3F12.5)

A1	lower limit of variable range
A2	upper limit of variable range
DA	increment of variable variation

There have to be NA cards defining the input variables in the following sequence:

PWNU	neutron wall loading P_{Wn}	[W/cm^2]
FWBR$^+$	bremsstrahlung factor f_{Wbr}	[-]
PMUL	power multiplication factor M	[-]
STRU	structure material volume fraction ε_w	[-]
PRES	coolant pressure P_c	[bar]
TCI	coolant inlet temperature t_{cin}	[C]
TCO	coolant outlet temperature t_{cout}	[C]
TCX	coolant temperature at first wall t_{cx}	[C]
ARR	option for cell arrangement	
	= 1.0 cylindrical cells in square matrix	
	> 1.0 cylindrical cells in hexagonal matrix	
DCO	outer cell diameter D_C	[cm]
CHAN	coolant duct width δ	[cm]
XLEN	cell or coolant duct length L_C	[cm]
PITC	cell pitch ratio p	[-]

FHW^{+} power density factor f_{HW} [cm^{-1}]

FHTC factor for enhanced heat transfer f_{HTC} [-]

XMAT^{++} material identification number [-]

FDPA^{+} displacement rate factor f_{dpa} [-]

$^{+}$ The factors f_{Wbr}, f_{HW}, and f_{dpa} have to be normalized to P_{Wn} = 100 W/cm^2 = 1 MW/m^2.

$^{++}$ The material identification number is of the following type:

XMAT = xx.yyzz

xx = charge number of the basic element

yy = percentage of the first alloying element

zz = percentage of the second alloying element

Examples:

Pure vanadium:	XMAT =	23.0000
V-5 Ti :	XMAT =	23.0500
V-10 Ti-10 Cr:	XMAT =	23.1010

3rd card ff. (format: 8X, 9I4)

KPR identification numbers of the results to be printed.
There have to be NPR identification numbers.
The numbers correspond to the order in the DATA NAMER statement of MAIN. Their meaning can be looked up in the comment cards in WLOAD and LIFE.
This card can be omitted if NPR = 0

4th card ff. (format: 8X, 9I4)

KPL identification numbers of the results to be plotted.

This card has to be omitted since plot-output is not possible in the present version.

7. Sample calculations

7.1 Input specifications

To demonstrate the runnability of the program some sample calculations were performed. The following input parameters were chosen:

neutron wall loading	P_{Wn}	= 83 W/cm^2
bremsstrahlung factor	f_{Wbr}	= 2.7 10^{-4}
power multiplication factor	M	= 1.2
structure material volume fraction	ε_W	= 0.02
coolant pressure	P_c	= 10 to 50 bar
coolant inlet temperature	t_{cin}	= 350 C
coolant outlet temperature	t_{cout}	= 750 C
coolant temp. at first wall	t_{cx}	= 350 to 750 C
arrangement option (see section 2)		= 1.0
cell outer diameter	D_C	= 30 cm
cell length	L_C	= 100 cm
pitch ratio	p	= 1.0
heat source density factor	f_{HW}	= 0.04
heat transfer factor	f_{HTC}	= 1.0
material identific. number		see below
displacement rate factor	f_{dpa}	= 0.319

Four runs were performed for four different vanadium alloys:

pure vanadium	XMAT = 23.0000
V-2.8 Ti	XMAT = 23.0300
V-5 Ti	XMAT = 23.0500
V-20 Ti	XMAT = 23.2000

The neutron wall loading, the bremsstrahlung factor and the power multiplication factor are in agreement with the CTRD outline specifications stated at the 1st General Meeting of the CTRD team in May 1974 at Garching. The characteristic data of the cell, i.e. D_c, L_c and ε_w correspond to the Culham design [1], while the arrangement of the cells and their pitch ratio were chosen arbitrarily. The heat source density factor and the displacement rate factor were derived from Steiner's publication [12]. For the thermodynamic cycle the temperature boundaries were taken from an equivalent fission reactor helium cycle [13].

The aim of the sample calculation was to see the influence of the coolant pressure level P_c and the actual helium temperature at the first wall t_{cx}. Therefore, P_c was varied between 10 and 50 bar, and t_{cx} within the limits of the blanket inlet and outlet temperatures, i.e. between 350 and 750 C.

7.2 Results for pure vanadium

From the four runs made for different materials here only the results for pure vanadium shall be reported in some detail. The influences of titanium additions to the basic material are summarized below.

Figure 4 shows the results obtained for t_1, which is the useful life due to the time rupture strength. As was to be expected, the life decreases as temperature and pressure increase.

The same is true of t_2, which is the useful life due to thermal creep, as can be seen from the solid lines in fig. 5. Two differences, however, can be observed:

- the temperature dependence shows a steeper slope in the case of thermal creep as compared to the time rupture behaviour.
- the pressure dependence shows an increasing slope in the time rupture behaviour but a decreasing slope in the creep behaviour.

As far as the absolute figures are concerned, it can be clearly stated that the limits set by the time rupture strength are more stringent than those set by thermal creep. This is more obvious from table I, in which the temperature limits are summarized as dependent on the pressure level for three different lifetimes, namely 1, 5, and 20 years. From this table it can be concluded that the first wall could last the whole life of the reactor, if the helium pressure does not exceed about 40 bar and the wall temperature remains in the range of 400 C, as was anticipated in the first guess of the blanket thermal design.

Figure 5 also shows the influence of irradiation creep, which is represented by the dotted lines. At this point it should be repeated, however, that two assumptions are involved in this consideration:

- the irradiation creep constant C_i is the same for vanadium as for stainless steel.
- the lifetime due to the sum of thermal and irradiation creep obeys the same law as the lifetime due to thermal creep alone.

This figure shows that irradiation creep limits the lifetime at lower temperatures whereas at higher temperatures thermal creep is the limiting effect. As is already expressed by equ. (33), there is only a dependence on pressure, not on temperature. The absolute values of the lifetime where irradiation creep becomes important, however, are far from being realistic. Therefore strong doubts should be cast on this line of reasoning.

A more realistic picture of the material performance can most probably be achieved if the actual creep rates, i.e. the sum of thermal and irradiation creep, are considered. In Fig. 6 the total creep rates are plotted versus the temperature t_{cx} with the pressure level as the parameter. The zero slope at low temperatures is again due to the irradiation creep, whereas the strong increase at higher temperatures is due to thermal creep. The straight lines in this diagram designate those creep rates which can be allowed to reach a certain amount of total creep in a certain time. This picture clearly shows that irradiation creep may become very important from this point of view.

At this stage again the question arises what amount of total creep or, to be more precise, of total elongation including static elongation and creep can be permitted from the ductility point of view. No relevant information is available at present. Therefore, the amount of total creep has to be treated as a variable in the following considerations.

Figures 7 to 9 now show the limits for the first wall lifetime of 1, 5, and 20 years respectively, within the parameter fields of both pressure and temperature. Common to all the three figures is that the limit of thermal creep is irrelevant in all cases. Whether or not the time rupture strength will be a limiting property ultimately depends on the change of this limit due to irradiation and on the total permissible creep.

If a useful life of 1 year (see Fig. 7) is envisaged, then the time rupture strength should become a limit only if helium pressures above 40 bar are chosen. At lower pressure levels the ductility should always present the significant limitation. This is the more true the longer the lifetimes expected are (see Figs. 8 and 9). The reason for this is

the shift of the curves for equal total creep to lower levels of temperature and pressure with increasing time, and the most probable shift of the total permissible creep to lower values with increasing time and neutron fluence.

The most interesting information from these three pictures, however, is the cut-off of the smooth curves characterizing the constant amounts of total creep at certain pressures. This is a consequence of the effect of irradiation creep. As can be seen from Figs. 7 to 9, these pressure limits are dependent on the lifetime chosen. Assuming a helium temperature at the first wall close to the inlet coolant temperature (to be precise, $t_{cx} \leq 420$ C for $t_{c_{in}} = 350$ C), the choice of the helium pressure level is exclusively determined by the lifetime desired and the total permissible creep. This relationship is shown in Fig. 10. This picture can be interpreted in the following way:

If the ductility loss during 5 years of operation should allow for 5 % creep during this period, then the helium pressure should not exceed 34 bar. If, however, the helium pressure chosen were to be only 20 bar, then a lifetime of about 10 years could be expected.

7.3 Influence of titanium as alloying element

In this section it is not intended to repeat the entire procedure once more for the three vanadium-titanium alloys. The results of the equivalent calculations shall only be summarized with regard to their tendency.

As compared to pure vanadium the V-2.8 Ti alloy offers a higher lifetime due to its time rupture strength. This, however, can only be considered as an advantage, as was stated in section 7.2, if the total creep rates are smaller and/or if the irradiation effects on the ductility are of less importance than in the case of pure vanadium. Indeed, the total creep rate has to be expected to be higher at

low temperatures but very much smaller at higher temperatures. The reason for this is that the thermal creep behaviour is somewhat more balanced, yielding higher lifetimes at high temperatures and lower, but still sufficiently high lifetimes at low temperatures. This, in turn, means that the irradiation creep becomes more important at low temperatures than in the case of pure vanadium. Since the model does assume identical irradiation creep constants for all the alloys considered there should be no significant consequence for the choice of the helium pressure if a low first wall temperature is envisaged. Under these circumstances the choice of this alloy would only be profitable if higher temperatures should occur.

Similar conclusions can be drawn about the two remaining alloys V-5 Ti and V-20 Ti. These, however, again show very disadvantageous behaviour of the thermal creep rate at higher temperatures. At present no necessity can therefore be seen for using alloys with a high titanium content unless significant differences in the ductility and irradiation creep behaviour should be detected.

8. Conclusions

The work done up to now shows that the analytical model and the computer program based on it is able to derive statements concerning the material performance and especially the first wall lifetime. The reliability of these statements mainly depends, however, on the accuracy and reliability of the material data. In this respect the model is far from being complete.

At present only some data on vanadium and a few vanadium alloys are included. Already the sample calculations show that the information about these materials is insufficient to arrive at reasonably credible estimates of the lifetime. As far as these alloys are concerned, neither the time rupture nor the

thermal creep behaviour seem to be properties governing the first wall life. It is far more probable that especially at the low temperatures envisaged the irradiation creep and the ductility under neutron irradiation will be the properties that will impair operation of the wall. It is in these very fields, however, that information is lacking.

It is hoped by the author that the work performed hitherto can be completed to some extent by incorporating the information arising in the field of material investigation. It will then surely be possible to arrive at somewhat more credible statements about the first wall lifetime to be expected for this special design.

It should also be mentioned that neither the method applied nor the computer program is restricted to the blanket design of the CTRD. In the same way as was done here, it could be applied to any other design now existing or arising in the future. In this case modifications of the program will be necessary especially in the subroutine WLOAD. The amount of work entailed, however, should not be prohibitive.

Besides this, the program could be sustained in an operable mode if the stress, temperature and irradiation loads were used as the only input quantities. With this modification performed the program could be made a module of a more comprehensive systems analysis program system.

9. Acknowledgements

The author gratefully acknowledges his nomination to the CTRD study group by K.H. Schmitter in that it enabled him to deal with this interesting problem. He is also indebted to Dr. A. Knobloch, member of der Coordinating Committee, for providing him with useful information. He also thanks Dr. S. Förster (KFA Jülich), Dr. G. McCracken and Mr. J.T.D. Mitchell (Culham Laboratory) for many helpful discussions and some valuable hints during the progress of this work. He finally thanks A. Nicol for reading the manuscript.

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TABLE I: Temperature limits ϑ for the first wall coolant to reach a lifetime t for a certain coolant pressure p_c for pure vanadium.

ϑ [C]; p_c [bar]

ϑ_{TR}: limit due to time rupture strength

ϑ_{CR}: limit due to thermal (+ irradiation) creep

p_c	t = 1a		t = 5a		t = 20a	
	ϑ_{TR}	ϑ_{CR}	ϑ_{TR}	ϑ_{CR}	ϑ_{TR}	ϑ_{CR}
10	650	780	615	760	585	750
20	640	690	600	670	575	655
30	590	640	560	625	540	610
40	520	610	495	590	460	580
50	410	585	380	570	360	560

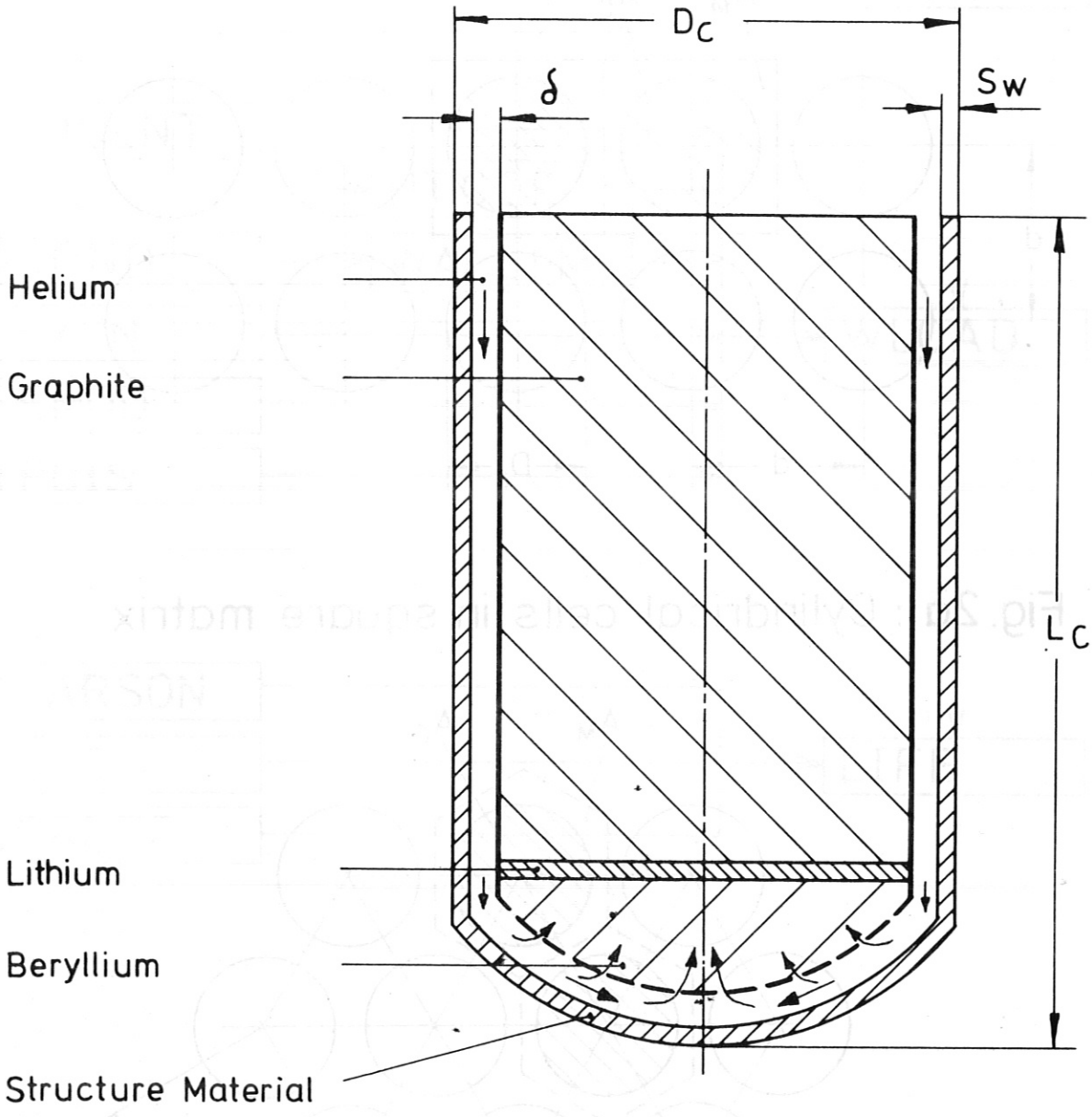


Fig. 1.: Scheme of a blanket module cell

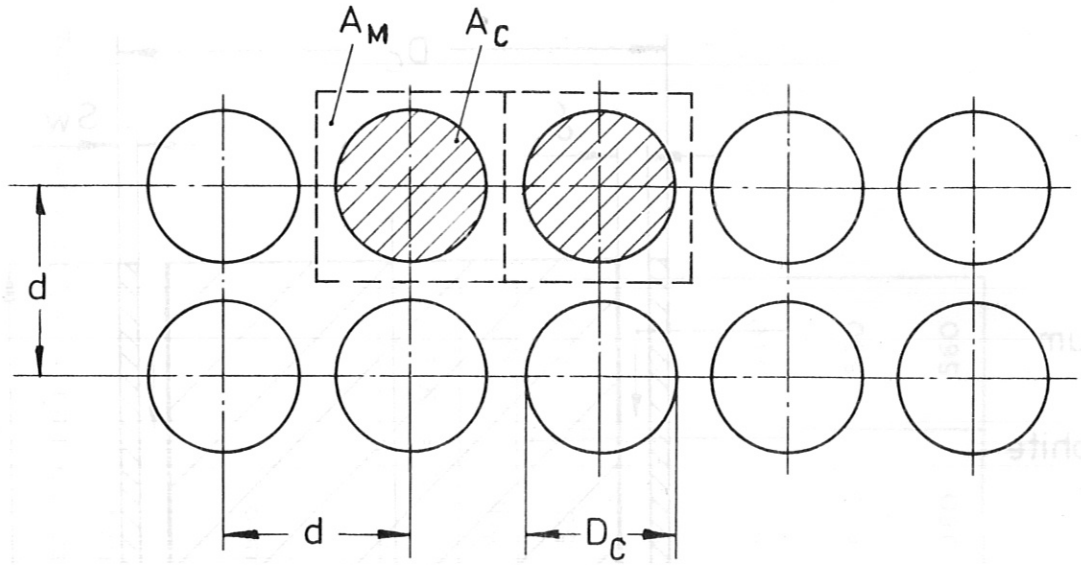


Fig. 2a : Cylindrical cells in square matrix

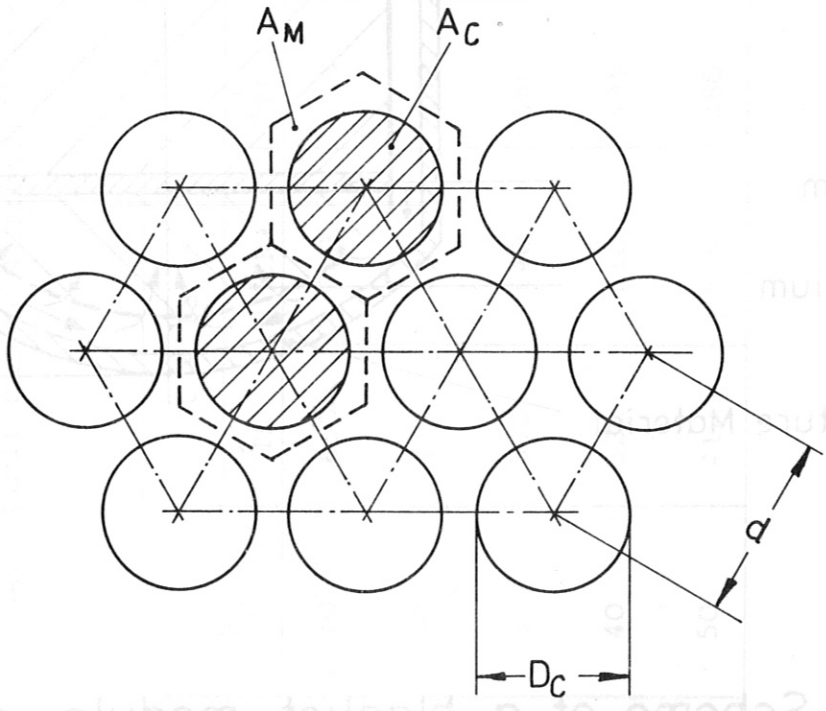


Fig. 2b : Cylindrical cells in hexagonal matrix

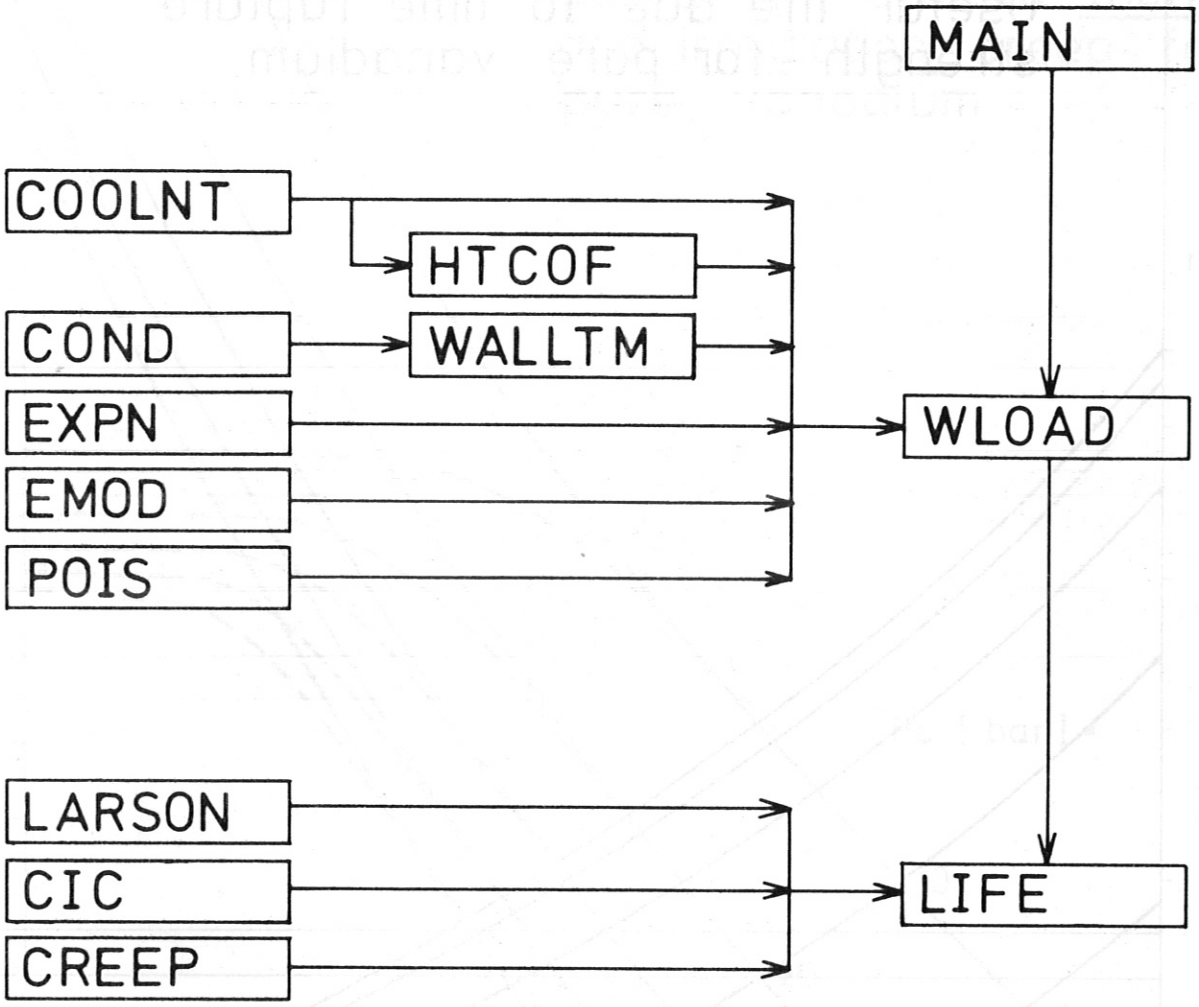
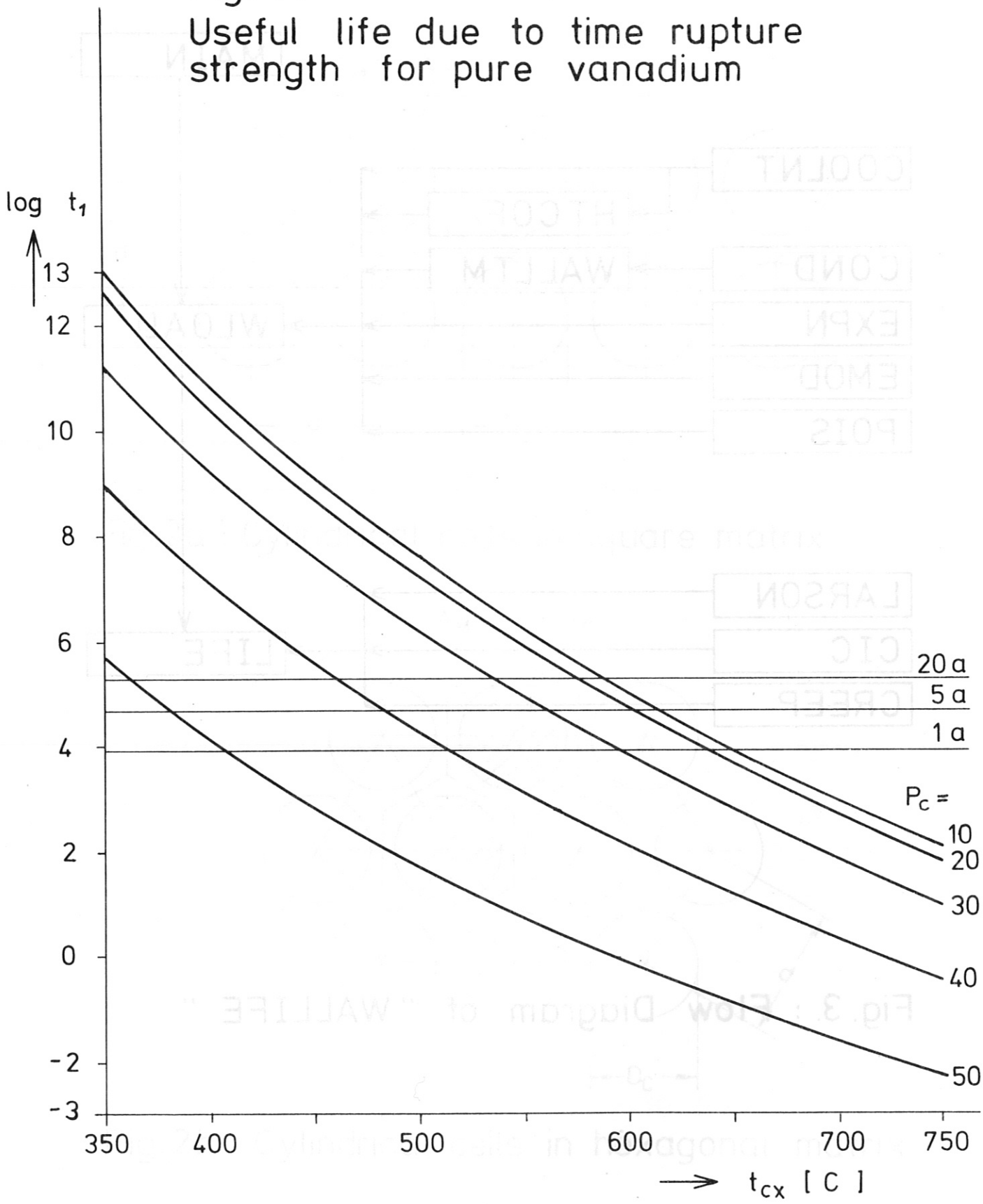


Fig. 3. : Flow Diagram of "WALLIFE "

Fig. 4 :
Useful life due to time rupture strength for pure vanadium



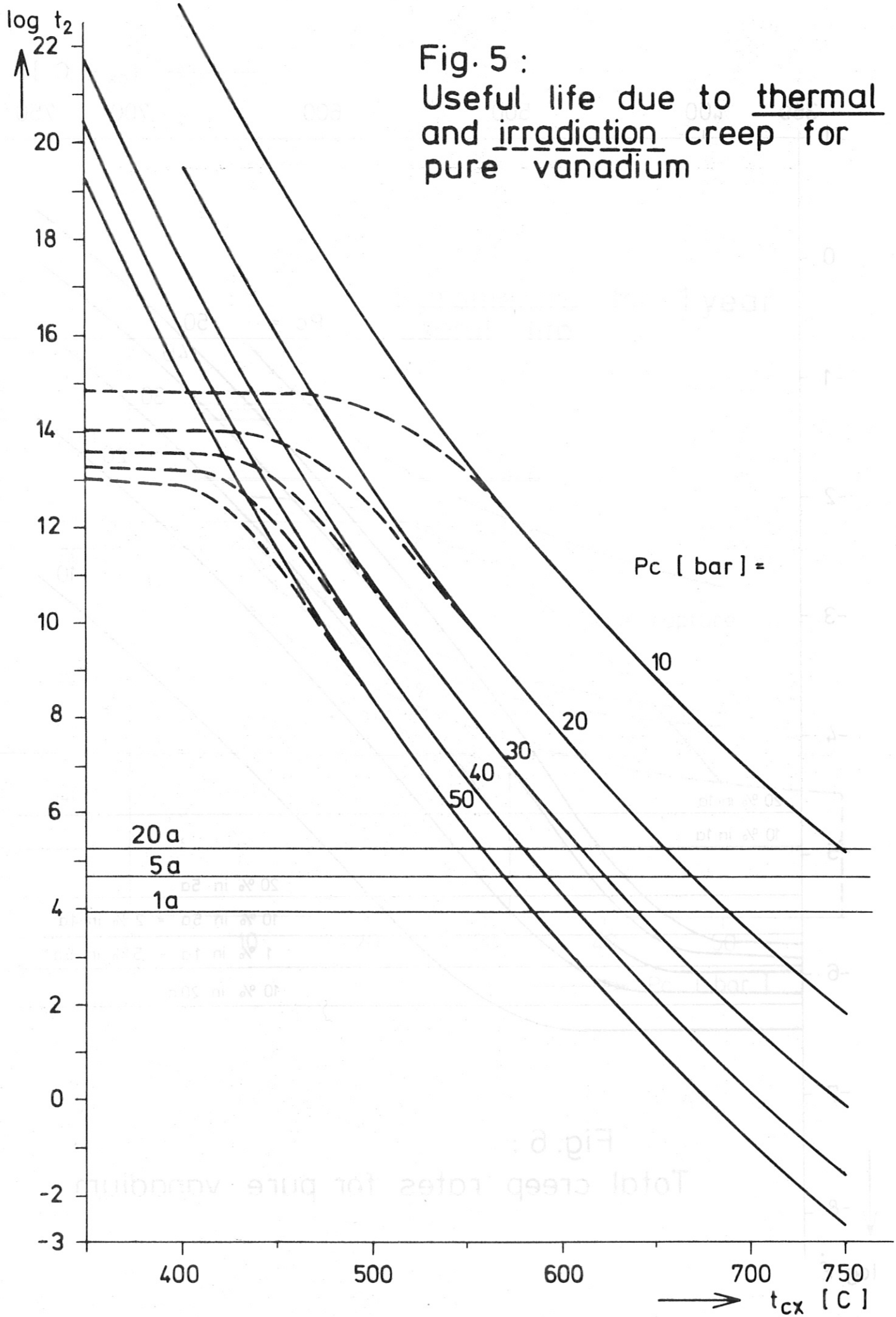


Fig. 5 :
Useful life due to thermal and irradiation creep for pure vanadium

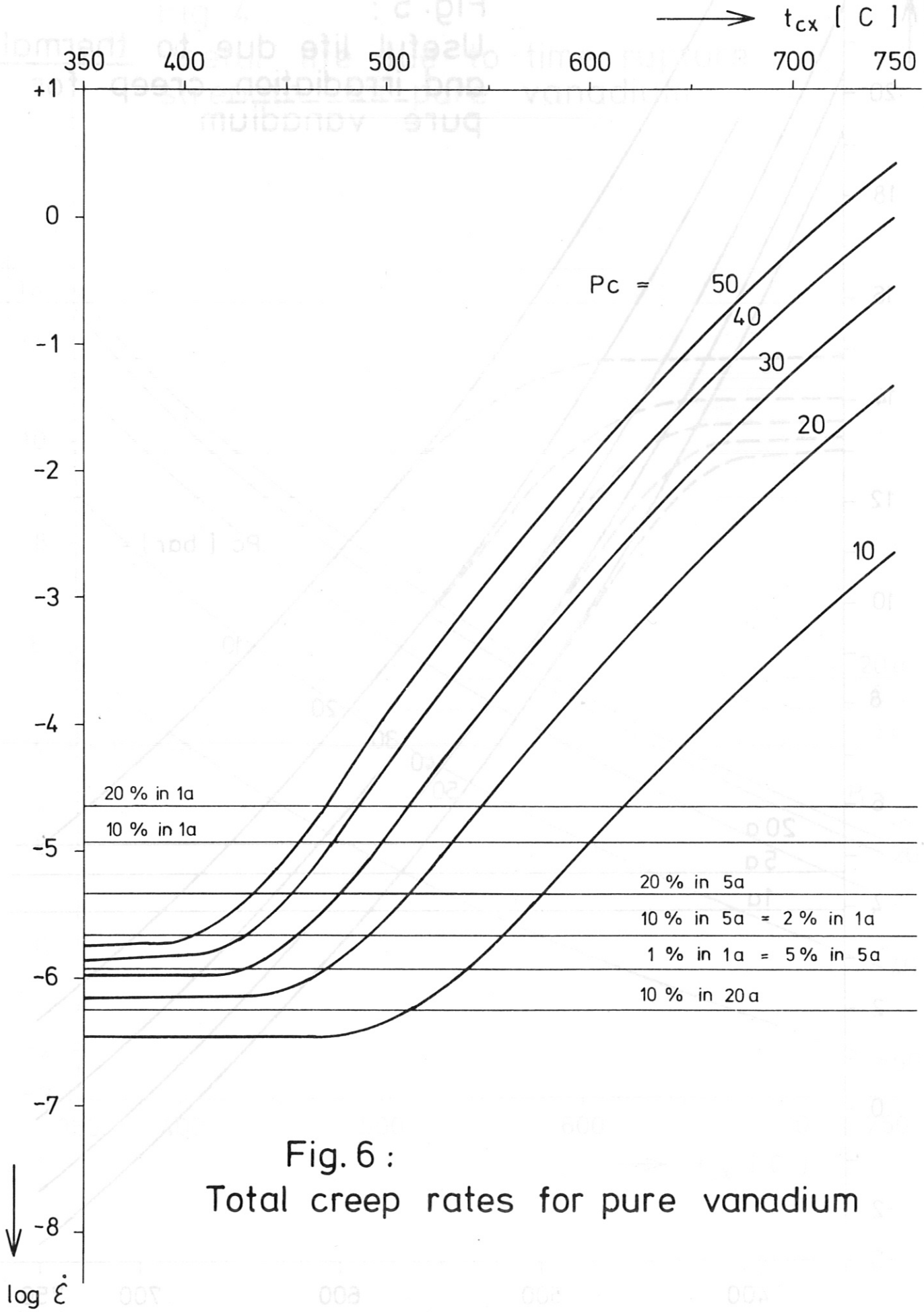
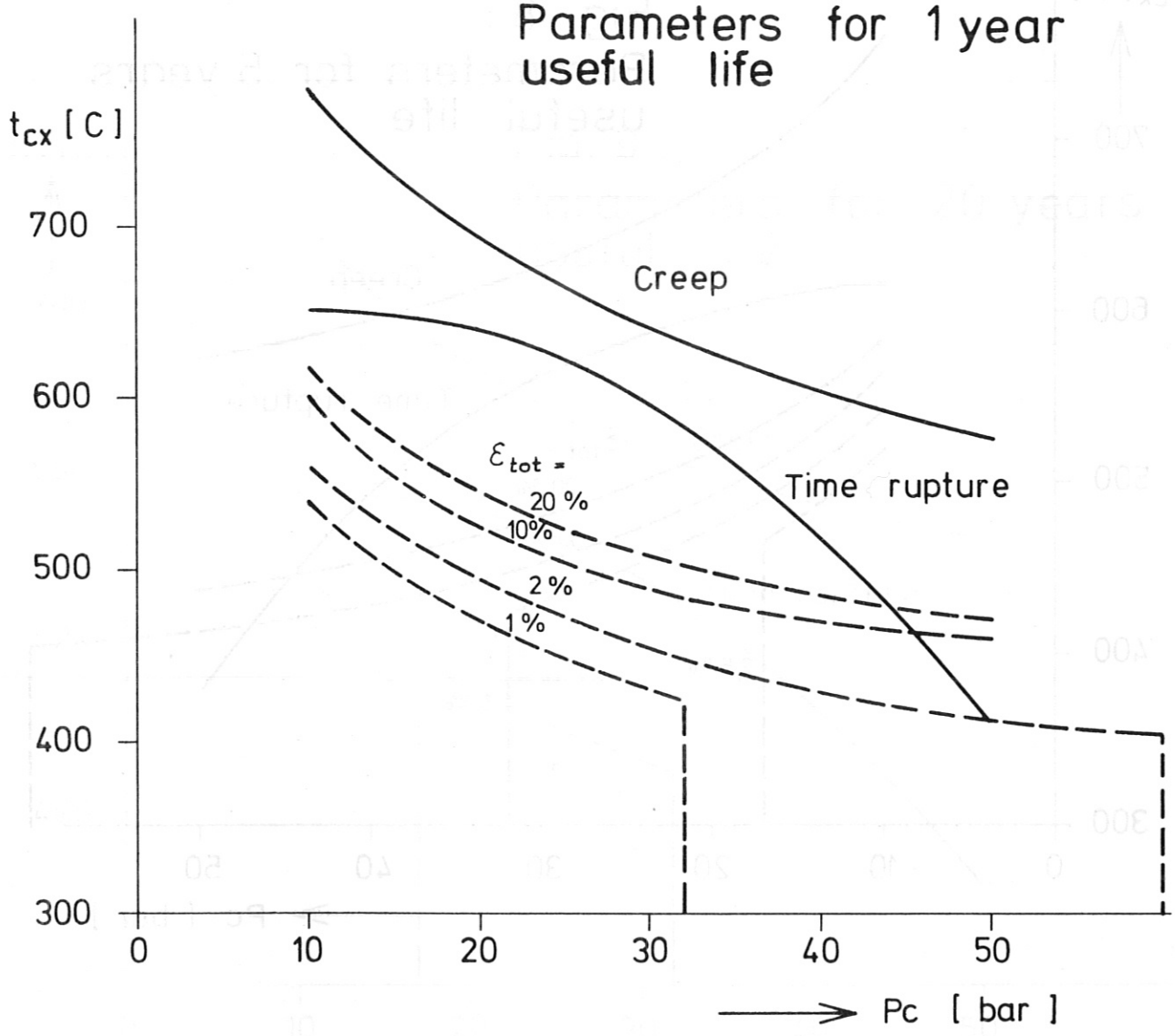


Fig. 6 :
Total creep rates for pure vanadium

Fig. 7 :
Parameters for 1 year useful life



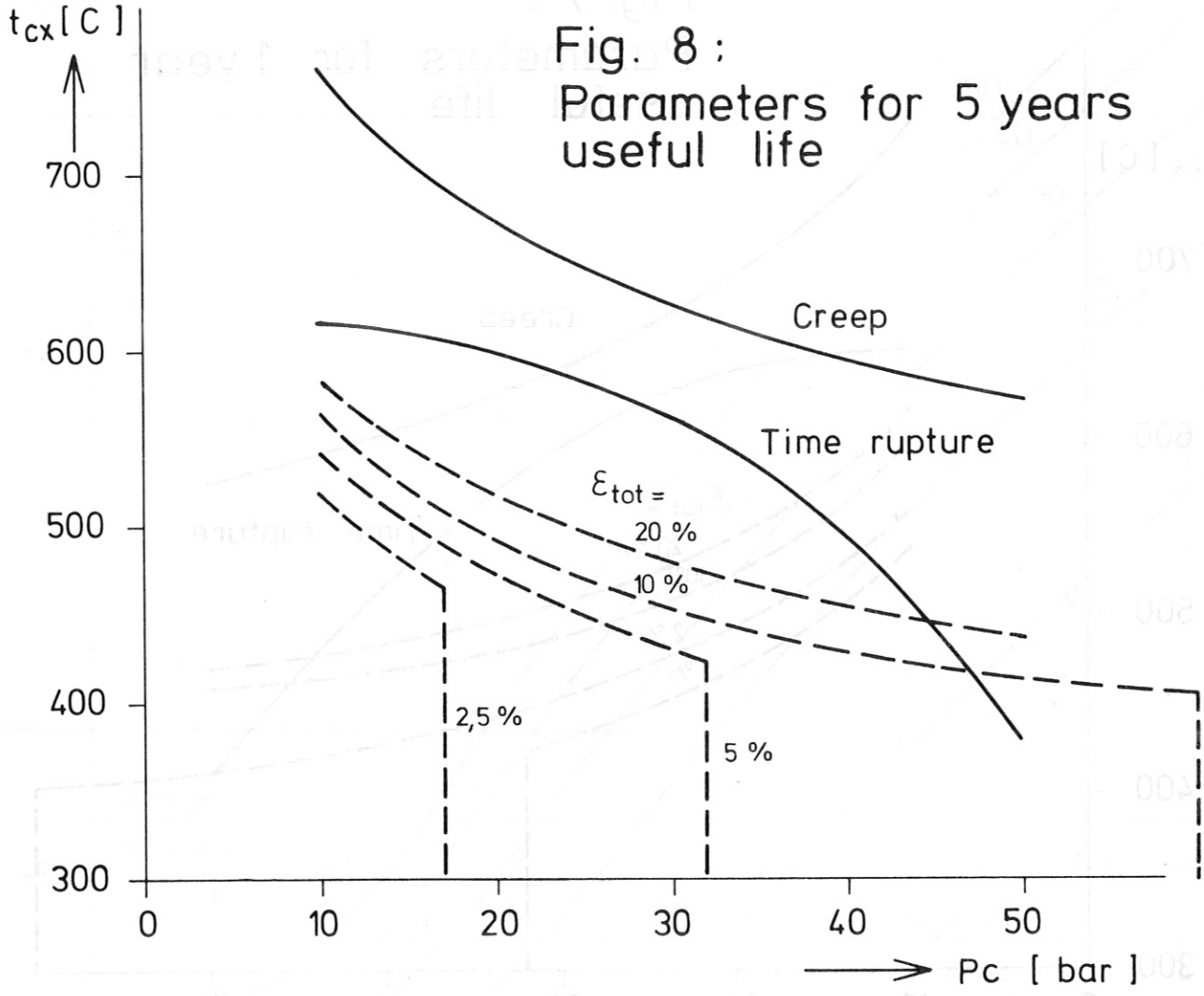


Fig. 8 :
Parameters for 5 years useful life

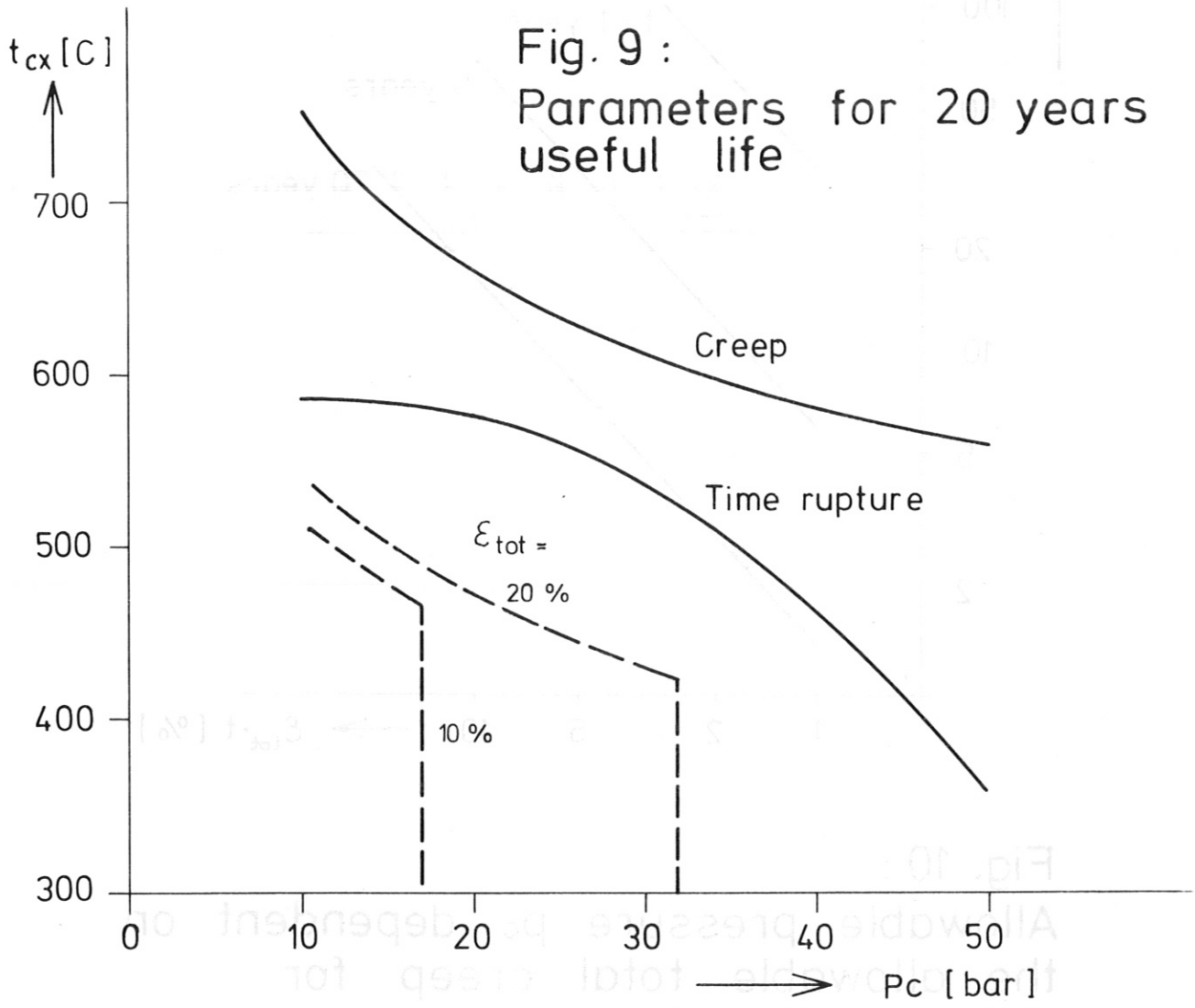


Fig. 9 :
Parameters for 20 years useful life

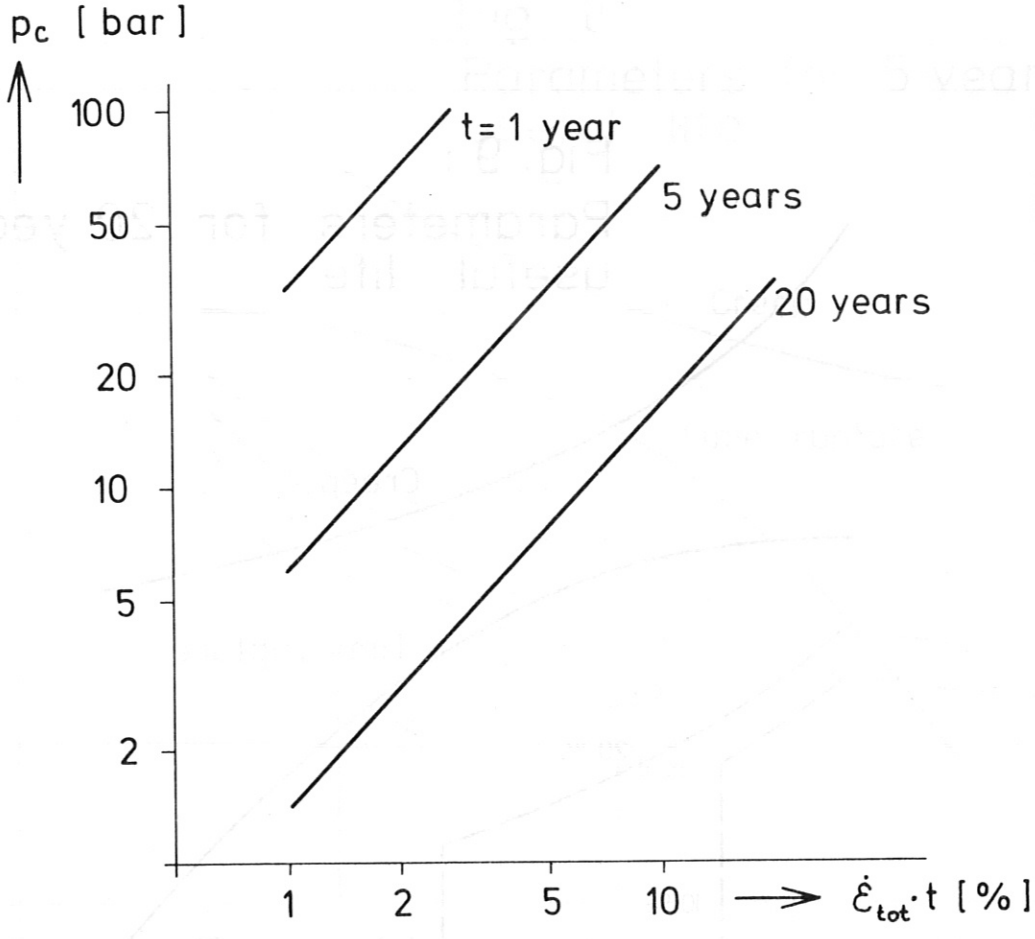


Fig. 10 :
Allowable pressure p_c dependent on the allowable total creep for different life times

APPENDIX

```
C*************** M A I N ***************                                  10
C                                                                         20
C*****THIS IS A MULTI-PURPOSE INPUT/OUTPUT PROGRAM WHICH CAN BE           30
C     ADJUSTED TO A NUMBER OF SUBROUTINES BY CHANGING ONLY A FEW          40
C     STATEMENTS.                                                         50
C                                                                         60
C*****IN THIS VERSION IT IS APPLIED TO THE PROBLEM OF EVALUATING          70
C     THE LIFETIME EXPECTED FOR THE FIRST WALL OF A CTRD BLANKET          80
C     MODULE CELL.                                                        90
C                                                                        100
C***** AUTHOR: DR.W.M.DAENNER, IPP GARCHING                             110
C                                                                        120
C***** INPUT DESCRIPTION:                                               130
C       CARD 1   NA   NUMBER OF ARGUMENTS TO BE READ AND TRANSFERRED     140
C                     TO THE CALCULATION SUBROUTINE(S)                   150
C                NR   NUMBER OF RESULTS TO BE TRANSFERRED FROM THE       160
C                     SUBROUTINE(S) AND SHIFTED TO OUTPUT                170
C                NPR  NUMBER OF RESULTS TO BE PRINTED (NPR.LE.NR)        180
C                     NPR = 0  TOTAL OUTPUT                              190
C                     NPR > 0  SELECTIVE OUTPUT                          200
C                NPL  NUMBER OF RESULTS TO BE PLOTTED (MAXIMUM = 10)     210
C                     IN THIS VERSION NO PLOT-OUTPUT IS POSSIBLE,        220
C                     THEREFORE NPR = 0 HAS TO BE USED.                  230
C       CARD 2   A1   LOWER LIMIT OF ARGUMENT RANGE                      240
C                A2   UPPER LIMIT OF ARGUMENT RANGE                      250
C                DA   INCREMENT TO BE USED FOR THE VARIATION OF THIS     260
C                     ARGUMENT BETWEEN THE LIMITS A1 AND A2              270
C                     THIS CARD HAS TO BE REPEATED FOR EACH OF THE       280
C                     NA ARGUMENTS.                                      290
C       CARD 3   KPR  IDENTIFICATION NUMBER(S) OF THE RESULTS TO BE      300
C                     PRINTED (MAXIMUM NPR)                              310
C                     THIS CARD CAN BE OMITTED IF NPR = 0.               320
C       CARD 4   KPL  IDENTIFICATION NUMBER(S) OF THE RESULTS TO BE      330
C                     PLOTTED (MAXIMUM 10, BUT EQUAL NPL)                340
C                     THIS CARD CAN BE OMITTED IF NPL = 0.               350
C                                                                        360
      DIMENSION APR1(10),APR2(10),KPL(10),RPL(10,10,10),ZZ(6)           370
C                                                                        380
C***** THE FOLLOWING CARDS HAVE TO BE ADJUSTED TO THE SPECIAL PROBLEM.   390
C                                                                        400
C***** THE LENGTH OF THE ARRAYS IN THIS DIMENSION STATEMENT HAS TO BE    410
C       EQUAL TO 'NA':                                                   420
C                                                                        430
      DIMENSION A1(17),A2(17),DA(17),NAMEA(17)                          440
C                                                                        450
C***** THE LENGTH OF THE ONEDIMENSIONAL ARRAYS AND THAT OF THE LAST      460
C       DIMENSION IN THE THREEDIMENSIONAL ARRAY HAS TO BE EQUAL TO 'NR'. 470
C                                                                        480
      DIMENSION NAMER(34),KPR(34),RPR(10,10,34)                         490
C                                                                        500
C***** THE LENGTH OF THE FOLLOWING COMMON ARRAYS HAS TO BE               510
C       'NA' AND 'NR' RESPECTIVELY.                                      520
C                                                                        530
      COMMON ARG(17)                                                    540
      COMMON RES(34)                                                    550
C                                                                        560
C***** THE FOLLOWING DATA STATEMENTS SHOULD CONTAIN THE 'NA' VARIABLE    570
```

```
C       NAMES OF THE INPUT QUANTITIES AND THE 'NR' VARIABLE NAMES OF THE
C       OUTPUT QUANTITIES. THEY ARE ONLY USED TO IDENTIFY THE DIFFERENT
C       COLUMNS IN THE PRINT OUTPUT LIST.
C
      DATA NAMEA/'PWNU','FWBR','PMUL','STRU','PRES','TCI ','TCD ',
     1           'TCX ','ARR ','DCO ','CHAN','XLEN','PITC','FHW ',
     2           'FHTC','XMAT','FDPA'/
      DATA NAMER/'PCK ','SOD ','SW  ','DCI ','DHY ','TCM ','ACH ',
     1           'AC  ','AM  ','PWBR','PC  ','DTC ','XMC ','XVC ',
     2           'WC  ','QW  ','HFW ','HTC ','DTCW','TWI ','TWO ',
     3           'TWM ','DTW ','STTH','STTN','STTO','PLM ','ULTR',
     4           'CRIC','CRSC','ULSC','CRTO','ULC ','UL1C'/
C
C***** IF THIS ADJUSTMENT IS DONE IN THE RIGHT WAY THE PROGRAM IS NOW
C       READY FOR USE. THE OUTPUT IS SELFEXPLAINING.
C
      CALL DATE (ZZ)
      WRITE(6,206) ZZ
      WRITE(6,200)
      READ(5,100) NA,NR,NPR,NPL
      DO 1 N=1,NA
      READ(5,101) A1(N),A2(N),DA(N)
    1 WRITE(6,201) NAMEA(N),A1(N),A2(N),DA(N)
      IF(NPR) 2,3,2
    2 READ(5,100) (KPR(K),K=1,NPR)
    3 IF(NPL) 4,5,4
    4 READ(5,100) (KPL(K),K=1,NPL)
    5 I=0
      DO 6 N=1,NA
      IF(DA(N)) 7,6,7
    7 I=I+1
      IF(I-2) 8,9,6
    8 I1=N
      GO TO 6
    9 I2=N
    6 CONTINUE
      DO 10 N=1,NA
   10 ARG(N)=A1(N)
      LOOP1=1+IFIX((A2(I1)-A1(I1))/DA(I1))
      LOOP2=1+IFIX((A2(I2)-A1(I2))/DA(I2))
      DO 11 L1=1,LOOP1
      ARG(I1)=A1(I1)+FLOAT(L1-1)*DA(I1)
      APR1(L1)=ARG(I1)
      DO 12 L2=1,LOOP2
      ARG(I2)=A1(I2)+FLOAT(L2-1)*DA(I2)
      APR2(L2)=ARG(I2)
C
C***** AT THIS PLACE INSERT YOUR CALCULATION SUBROUTINE(S). ***********
C
      CALL WLOAD
      CALL LIFE
C
      IF(NPR) 13,14,13
   13 DO 15 L3=1,NPR
      LPR=KPR(L3)
   15 RPR(L1,L2,L3)=RES(LPR)
      GO TO 17
```

```
   14 DO 16 L3=1,NR                                                    1150
   16 RPR(L1,L2,L3)=RES(L3)                                            1160
   17 IF(NPL) 18,12,18                                                 1170
   18 DO 20 L4=1,NPL                                                   1180
      LPL=KPL(L4)                                                      1190
   20 RPL(L1,L2,L3)=RES(LPL)                                           1200
   12 CONTINUE                                                         1210
   11 CONTINUE                                                         1220
      IF(NPR) 19,21,19                                                 1230
   19 NTAB=1+(NPR-1)/8                                                 1240
      GO TO 22                                                         1250
   21 NTAB=1+(NR-1)/8                                                  1260
   22 DO 23 L1=1,LOOP1                                                 1270
      WRITE(6,202) NAMEA(I1),APR1(L1)                                  1280
      DO 24 NT=1,NTAB                                                  1290
      WRITE(6,203)                                                     1300
      IF(NPR) 26,25,26                                                 1310
   25 NT2=8*NT                                                         1320
      NT1=NT2-7                                                        1330
      IF(NT-NTAB) 28,27,27                                             1340
   27 NT2=NR                                                           1350
   28 WRITE(6,204) NAMEA(I2),(NAMER(NN),NN=NT1,NT2)                    1360
      WRITE(6,207)                                                     1370
      DO 29 L2=1,LOOP2                                                 1380
   29 WRITE(6,205) APR2(L2),(RPR(L1,L2,L3),L3=NT1,NT2)                 1390
      GO TO 24                                                         1400
   26 NT2=8*NT                                                         1410
      NT1=NT2-7                                                        1420
      IF(NT-NTAB) 30,32,32                                             1430
   32 NT2=NPR                                                          1440
   30 WRITE(6,204) NAMEA(I2),(NAMER(KPR(NN)),NN=NT1,NT2)               1450
      WRITE(6,207)                                                     1460
      DO 31 L2=1,LOOP2                                                 1470
   31 WRITE(6,205) APR2(L2),(RPR(L1,L2,L3),L3=NT1,NT2)                 1480
   24 CONTINUE                                                         1490
   23 CONTINUE                                                         1500
      STOP                                                             1510
  100 FORMAT(8X, 9I4)                                                  1520
  101 FORMAT(8X,3F12.5)                                                1530
  200 FORMAT(/' INPUT PARAMETERS'//)                                   1540
  201 FORMAT(' VARIATION OF ',A4,' FROM ',F12.5,' TO ',F12.5,' BY STEPS 1550
     1OF ',F12.5)                                                      1560
  202 FORMAT(//'1R E S U L T S  F O R  ',A4,' = ',F12.5)                1570
  203 FORMAT(//5X,'ARGUMENT',7X,'R E S U L T S  F O R'/)                1580
  204 FORMAT(5X,A4,11X,8(A4,8X))                                       1590
  205 FORMAT(' ',F12.5,5X,8(1PE12.4))                                  1600
  206 FORMAT('1DATE = ',2A4/' TIME = ',2A4/' JOB  = ',2A4///)           1610
  207 FORMAT(' ')                                                      1620
      END                                                              1630
```

```
C*************** W L O A D ***************                                  10
C                                                                          20
C**** SUBPROGRAM FOR EVALUATING THE TEMPERATURE AND STRESS LOAD OF THE      30
C     FIRST WALL OF THE CTRD MODULE CELL                                   40
C                                                                          50
C***** AUTHOR: DR.W.M.DAENNER, IPP GARCHING                                60
C                                                                          70
C***** INPUT  PWNU  (W/CM2)   NEUTRON WALL LOADING                         80
C             FWBR  (-)       BREMSSTRAHLUNG FACTOR                        90
C             PMUL  (-)       POWER MULTIPLICATION FACTOR OF THE BLANKET  100
C             STRU  (-)       STRUCTURE MATERIAL VOLUME FRACTION FOR      110
C                             THE CELL WALL                               120
C             PRES  (BAR)     COOLANT PRESSURE                            130
C             TCI   (C)       COOLANT INLET TEMPERATURE                   140
C             TCO   (C)       COOLANT OUTLET TEMPERATURE                  150
C             TCX   (C)       COOLANT TEMPERATURE AT THE FIRST WALL       160
C             ARR   (-)       ARRANGEMENT OPTION                          170
C                             = 1.0 : CYL. CELLS IN SQUARE MATRIX         180
C                             > 1.0 : CYL. CELLS IN HEXAGONAL MATRIX      190
C             DCO   (CM)      OUTER CELL DIAMETER                         200
C             CHAN  (CM)      COOLANT DUCT WIDTH                          210
C             XLEN  (CM)      CELL OR COOLANT DUCT LENGTH                 220
C             PITC  (-)       CELL PITCH RATIO                            230
C             FHW   (1/CM)    HEAT SOURCE DENSITY FACTOR                  240
C             FHTC  (-)       FACTOR FOR ENHANCED HEAT TRANSFER           250
C             XMAT  (-)       WALL MATERIAL IDENTIFICATION NUMBER         260
C             FDPA  (DPA*CM2/W*A) DISPLACEMENT RATE FACTOR                270
C                                                                         280
C**** OUTPUT  PCK   (-)       PACKAGE DENSITY                             290
C             SOD   (-)       RATIO OF WALL THICKNESS AND OUTER CELL      300
C                             DIAMETER                                    310
C             SW    (CM)      FIRST WALL THICKNESS                        320
C             DCI   (CM)      INNER CELL DIAMETER                         330
C             DHY   (CM)      COOLANT DUCT HYDRAULIC DIAMETER             340
C             TCM   (C)       MEAN COOLANT TEMPERATURE                    350
C             ACH   (CM2)     COOLANT DUCT CROSS-SECTION AREA             360
C             AC    (CM2)     CELL CROSS-SECTION AREA                     370
C             AM    (CM2)     CROSS-SECTION AREA OF MATRIX ELEMENT        380
C             PWBR  (W/CM2)   BREMSSTRAHLUNG WALL LOADING                 390
C             PC    (W)       TOTAL POWER PER CELL                        400
C             DTC   (C)       COOLANT TEMPERATURE RISE                    410
C             XMC   (G/SEC)   COOLANT MASS FLOW RATE                      420
C             XVC   (CM3/SEC) COOLANT VOLUME FLOW RATE                    430
C             WC    (CM/SEC)  COOLANT VELOCITY                            440
C             QW    (W/CM3)   HEAT SOURCE DENSITY INSIDE THE FIRST WALL   450
C             HFW   (W/CM2)   HEAT FLOW FROM WALL TO COOLANT              460
C             HTC   (W/CM2*C) HEAT TRANSFER COEFFICIENT                   470
C             DTCW  (C)       TEMPERATURE DIFFERENCE WALL -> COOLANT      480
C             TWI   (C)       INNER WALL TEMPERATURE                      490
C             TWO   (C)       OUTER WALL TEMPERATURE                      500
C             TWM   (C)       MEAN WALL TEMPERATURE                       510
C             DTW   (C)       TEMPERATURE DIFFERENCE INSIDE THE WALL      520
C             STTH  (KP/CM2)  MAXIMUM THERMAL STRESS INSIDE THE WALL      530
C             STTN  (KP/CM2)  TENSILE STRESS INSIDE THE WALL              540
C             STTO  (KP/CM2)  MAXIMUM TOTAL STRESS INSIDE THE WALL        550
C                                                                         560
C***** SUBPROGRAMS NEEDED: COOLNT                                         570
```

```
C                          HTCOF                                              580
C                          WALLTM                                             590
C                          EXPN                                               600
C                          EMOD                                               610
C                          POIS                                               620
C                                                                             630
      SUBROUTINE WLOAD                                                        640
      COMMON PWNU,FWBR,PMUL,STRU,PRES,TCI,TCO,TCX,ARR,DCO,CHAN,XLEN,          650
     1       PITC,FHW,FHTC,XMAT,FDPA                                          660
      COMMON PCK,SOD,SW,DCI,DHY,TCM,ACH,AC,AM,PWBR,PC,DTC,XMC,XVC,WC,         670
     1       QW,HFW,HTC,DTCW,TWI,TWO,TWM,DTW,STTH,STTN,STTO                   680
C     CHARACTERISTIC MATRIX AREA FIGURE 'ALPHA'                               690
      IF(ARR-1.0) 1,1,2                                                       700
C     'ALPHA' FOR CYLINDER IN SQUARE MATRIX                                   710
    1 ALPHA=1.0                                                               720
      GO TO 3                                                                 730
C     'ALPHA' FOR CYLINDER IN HEXAGONAL MATRIX                                740
    2 ALPHA=0.866                                                             750
    3 PCK=0.7854/(ALPHA*PITC*PITC)                                            760
      SOD=0.5*(1.0-SQRT(1.0-STRU/PCK))                                        770
      SW=SOD*DCO                                                              780
      DCI=DCO-2.0*SW                                                          790
      DHY=2.0*CHAN                                                            800
      TCM=0.5*(TCI+TCO)                                                       810
      ACH=3.14159*CHAN*(DCI-CHAN)                                             820
      AC=0.7854*DCO*DCO                                                       830
      AM=AC/PCK                                                               840
      PWBR=PWNU*FWBR                                                          850
      PC=(PWNU*PMUL+PWBR)*AM                                                  860
      DTC=TCO-TCI                                                             870
      CALL COOLNT (TCM,PRES,DENM,CAPM,CONM,VISM)                              880
      XMC=PC/(CAPM*DTC)                                                       890
      XVC=XMC/DENM                                                            900
      WC=XVC/ACH                                                              910
      QW=FHW*PWNU                                                             920
      HFW=PWBR+QW*SW                                                          930
      CALL HTCOF (HFW,WC,XLEN,DHY,TCX,PRES,FHTC,HTC,DTCW,TWI)                 940
      CALL WALLTM (TWI,QW,PWBR,DCO,DCI,XMAT,TWO,TWM,DTW)                      950
      STTH=0.5*DTW*EXPN(XMAT,TWM)*EMOD(XMAT,TWM)/(1.0-POIS(XMAT,TWM))         960
      STTN=0.50986*PRES/SCD                                                   970
      STTO=STTH+STTN                                                          980
      RETURN                                                                  990
      END                                                                    1000
```

```
C*************** L I F E ***************                                    10
C                                                                          20
C     SUBPROGRAM FOR EVALUATING THE USEFUL LIFE OF THE FIRST WALL          30
C     OF THE CTRD MODULE CELL                                              40
C                                                                          50
C*****  AUTHOR: DR.W.M.DAENNER, IPP GARCHING                               60
C                                                                          70
C***** INPUT  PWNU  (W/CM2)   NEUTRON WALL LOADING                        80
C             FWBR  (-)       BREMSSTRAHLUNG FACTOR                      90
C             PMUL  (-)       POWER MULTIPLICATION FACTOR OF THE BLANKET 100
C             STRU  (-)       STRUCTURE MATERIAL VOLUME FRACTION FOR     110
C                             THE CELL WALL                              120
C             PRES  (BAR)     COOLANT PRESSURE                           130
C             TCI   (C)       COOLANT INLET TEMPERATURE                  140
C             TCO   (C)       COOLANT OUTLET TEMPERATURE                 150
C             TCX   (C)       COOLANT TEMPERATURE AT THE FIRST WALL      160
C             ARR   (-)       ARRANGEMENT OPTION                         170
C                             = 1.0 : CYL. CELLS IN SQUARE MATRIX        180
C                             > 1.0 : CYL. CELLS IN HEXAGONAL MATRIX     190
C             DCO   (CM)      OUTER CELL DIAMETER                        200
C             CHAN  (CM)      COOLANT DUCT WIDTH                         210
C             XLEN  (CM)      CELL OR COOLANT DUCT LENGTH                220
C             PITC  (-)       CELL PITCH RATIO                           230
C             FHW   (1/CM)    HEAT SOURCE DENSITY FACTOR                 240
C             FHTC  (-)       FACTOR FOR ENHANCED HEAT TRANSFER          250
C             XMAT  (-)       WALL MATERIAL IDENTIFICATION NUMBER        260
C             FDPA  (DPA*CM2/W*A) DISPLACEMENT RATE FACTOR               270
C                                                                        280
C***** OUTPUT PLM   (-)        LARSON-MILLER-PARAMETER                   290
C             ULTR  (H)        USEFUL LIFE DUE TO TIME-RUPTURE-STRENGTH  300
C             CRIC  (H-1)      IRRADIATION CREEP RATE                    310
C             CRSC  (H-1)      THERMAL CREEP RATE                        320
C             ULSC  (H)        USEFUL LIFE DUE TO THERMAL CREEP          330
C             CRTO  (H-1)      TOTAL CREEP RATE                          340
C             ULC   (H)        USEFUL LIFE DUE TO TOTAL CREEP            350
C             UL1C  (H)        TIME TO REACH 1% TOTAL CREEP              360
C                                                                        370
C***** SUBPROGRAMS NEEDED:  LARSON                                       380
C                          CIC                                           390
C                          CREEP                                         400
C                                                                        410
      SUBROUTINE LIFE                                                    420
      COMMON PWNU,FWBR,PMUL,STRU,PRES,TCI,TCO,TCX,ARR,DCO,CHAN,XLEN,     430
     1       PITC,FHW,FHTC,XMAT,FDPA                                     440
      COMMON PCK,SOD,SW,DCI,DHY,TCM,ACH,AC,AM,PWBR,PC,DTC,XMC,XVC,WC,    450
     1       QW,HFW,HTC,DTCW,TWI,TWO,TWM,DTW,STTH,STTN,STTO,PLM,ULTR,    460
     2       CRIC,CRSC,ULSC,CRTO,ULC,UL1C                                470
      CALL LARSON(XMAT,STTO,PLM,C)                                       480
      ULTR=10.0**(PLM/(TWI+273.15)-C)                                    490
      CRIC=CIC(XMAT)*FDPA*PWNU      *STTO                                500
      CALL CREEP(XMAT,TWM,CCO,CEX,CL1,CL2)                               510
      CRSC=CCO*(0.01*STTO)**CEX                                          520
      ULSC=10.0**(CL1  -CL2*ALOG(CRSC))                                  530
      CRTO=CRIC+CRSC                                                     540
      ULC=10.0**(CL1  -CL2*ALOG(CRTO))                                   550
      UL1C=0.01/CRTO                                                     560
      RETURN                                                             570
      END                                                                580
```

```
C**************  H T C O F  **************                                  10
C                                                                          20
C**** SUBPROGRAM FOR EVALUATING THE HEAT TRANSFER COEFFICIENT FOR A        30
C     HELIUM GAS FLOW                                                      40
C                                                                          50
C***** AUTHOR: DR.W.M.DAENNER, IPP GARCHING                                60
C                                                                          70
C***** INPUT   HFW   (W/CM2)   HEAT FLUX DENSITY AT THE WALL               80
C              WC    (CM/SEC)  COOLANT VELOCITY                            90
C              XLEN  (CM)      COOLANT DUCT LENGTH                        100
C              DHY   (CM)      HYDRAULIC DIAMETER OF THE COOLANT DUCT     110
C              TX    (C)       COOLANT TEMPERATURE                        120
C              PR    (BAR)     COOLANT PRESSURE                           130
C              FHTC  (-)       FACTOR FOR ENHANCED HEAT TRANSFER          140
C***** OUTPUT  HTC   (W/CM2*C) HEAT TRANSFER COEFFICIENT                   150
C              DTCW  (C)       TEMPERATURE DIFFERENCE BETWEEN WALL AND    160
C                              COOLANT                                    170
C              TW    (C)       WALL TEMPERATURE                           180
C                                                                         190
C***** SUBPROGRAM NEEDED:  COOLNT                                         200
C                                                                         210
      SUBROUTINE HTCOF (HFW,WC,XLEN,DHY,TX,PR,FHTC,HTC,DTCW,TW)           220
      FWLD=WC**0.8 / (XLEN**0.054 * DHY**0.146)                           230
      IT=1                                                                240
      TF=TX                                                               250
    3 CALL COOLNT (TF,PR,DEN,CAP,CON,VIS)                                 260
      FTP=DEN**0.8 * CAP**0.37 * CON**0.63 / VIS**0.43                    270
      HTC=0.032*FTP*FWLD*FHTC                                             280
      IF(IT-1) 1,1,2                                                      290
    1 DT1=HFW/HTC                                                         300
      TF=TX+0.5*DT1                                                       310
      IT=IT+1                                                             320
      GO TO 3                                                             330
    2 DT2=HFW/HTC                                                         340
      DDT=ABS(DT2-DT1)                                                    350
      IF(DDT-1.0) 4,4,5                                                   360
    5 DT1=DT2                                                             370
      IT=IT+1                                                             380
      TF=TX+0.5*DT1                                                       390
      GO TO 3                                                             400
    4 DTCW=DT2                                                            410
      TW=TX+DTCW                                                          420
      RETURN                                                              430
      END                                                                 440
```

```
C*************** W A L L T M ***************                                10
C                                                                           20
C**** SUBPROGRAM FOR EVALUATING THE TEMPERATURE DIFFERENCE WITHIN THE        30
C     FIRST WALL OF THE CTRD MODULE CELL                                    40
C                                                                           50
C***** AUTHOR: DR.W.M.DAENNER, IPP GARCHING                                 60
C                                                                           70
C***** INPUT   TW1   (C)       INNER WALL TEMPERATURE                       80
C              QW    (W/CM3)   HEAT SOURCE DENSITY INSIDE THE WALL          90
C              PWBR  (W/CM2)   HEAT FLUX DENSITY FROM OUTSIDE THE WALL      100
C              DCO   (CM)      OUTER WALL DIAMETER                          110
C              DCI   (CM)      INNER WALL DIAMETER                          120
C              XMAT  (-)       WALL MATERIAL IDENTIFICATION NUMBER          130
C***** OUTPUT  TW2   (C)       OUTER WALL TEMPERATURE                       140
C              TWM   (C)       MEAN WALL TEMPERATURE                        150
C              DTW   (C)       TEMPERATURE DIFFERENCE ACROSS THE WALL       160
C                                                                           170
C***** SUBPROGRAM NEEDED:  COND                                             180
C                                                                           190
      SUBROUTINE WALLTM (TW1,QW,PWBR,DCO,DCI,XMAT,TW2,TWM,DTW)              200
      SW=0.5*(DCO-DCI)                                                      210
      FTW=SW*(0.5*SW*QW+PWBR)                                               220
      IT=1                                                                  230
      TW=TW1                                                                240
    3 CON=COND(XMAT,TW)                                                     250
      IF(IT-1) 1,1,2                                                        260
    1 DT1=FTW/CON                                                           270
      TW=TW1+0.5*DT1                                                        280
      IT=IT+1                                                               290
      GO TO 3                                                               300
    2 DT2=FTW/CON                                                           310
      DDT=ABS(DT2-DT1)                                                      320
      IF(DDT-0.5) 4,4,5                                                     330
    5 DT1=DT2                                                               340
      TW=TW1+0.5*DT1                                                        350
      IT=IT+1                                                               360
      GO TO 3                                                               370
    4 TW2=TW1+DT2                                                           380
      TWM=0.5*(TW1+TW2)                                                     390
      DTW=TW2-TW1                                                           400
      RETURN                                                                410
      END                                                                   420
```

```
C*************** H E L I U M ***************                                10
C                                                                           20
C**** A SUBROUTINE PROGRAM FOR EVALUATING THE THERMAL PROPERTIES OF         30
C     HELIUM AS A COOLANT                                                   40
C                                                                           50
C*****  AUTHOR: DR.W.M.DAENNER, IPP GARCHING                                55
C                                                                           56
C**** INPUT    T    (C)              TEMPERATURE                            60
C              P    (BAR)            PRESSURE                               70
C**** OUTPUT   DEN  (G/CM3)          DENSITY                                80
C              CAP  (W*S/G*K)       SPECIFIC HEAT AT CONSTANT PRESSURE     90
C              CON  (W/CM*K)        THERMAL CONDUCTIVITY                   100
C              VIS  (G/CM*S)        DYNAMIC VISCOSITY                      110
C                                                                           120
C*****  THE INDICATED PROPERTIES ARE CALCULATED USING FORMULAS              121
C       PRESENTED BY W.ZIMMERER: MAPLIB-FUNKTIONEN ZUR BERECHNUNG DER       122
C       ZUSTANDSGROESSEN VON HELIUM, LUFT, KOHLENDIOXID UND WASSER.         123
C       KFK 1403 (1971)                                                     124
C                                                                           125
      SUBROUTINE COOLNT (T,P,DEN,CAP,CON,VIS)                               130
      TA=T+273.15                                                           140
      PA=1.0E5*P                                                            150
C     DENSITY 'DEN'                                                         160
      D=2076.2*(TA/PA+1.13E-5/TA**0.3333-2.37E-2/(TA*TA))                   170
      DEN=1.0E-3/D                                                          180
C     SPECIFIC HEAT AT CONSTANT PRESSURE 'CAP'                              190
      C=5196.0-1043.0*(1.0/TA**1.3333-28300.0/TA**3.0)*1.0E-5*PA            200
      CAP=1.0E-3*C                                                          210
C     THERMAL CONDUCTIVITY 'CON'                                            220
      CON=1.44E-3*(TA/273.15)**0.7*(1.0+2.0E-9*PA)                          230
C     DYNAMIC VISCOSITY 'VIS'                                               240
      V=1.855E-5*(TA/273.16)**0.68                                          250
      VIS=10.0*V                                                            260
      RETURN                                                                270
      END                                                                   280
```

```
C*************** C O N D ***************                                  10
C                                                                        20
C     FUNCTION SUBPROGRAM FOR PROVIDING THE THERMAL CONDUCTIVITY OF      30
C     STRUCTURAL METALS AND ALLOYS                                       40
C                                                                        50
C*****  AUTHOR: DR.W.M.DAENNER, IPP GARCHING                             60
C                                                                        70
C*****  INPUT   XMAT  (-)  MATERIAL IDENTIFICATION NUMBER                80
C               T     (C)  TEMPERATURE                                   90
C                                                                       100
C*****  OUTPUT  COND  (W/CM*C)  THERMAL CONDUCTIVITY                    110
C                                                                       120
C*****  CURRENT CONTENTS:                                               130
C       ================                                                140
C       XMAT = 23.XX00   V-XXTI  ALLOYS                                 150
C                        FOR PURE VANADIUM AND THE ALLOYS V-3TI AND     160
C                        V-20TI POLYNOMIAL APPROXIMATION OF THE DATA    170
C                        FROM H.BOEHM E.A., 6. PLANSEE-SEMINAR.         180
C                        LINEAR INTERPOLATION FOR OTHER TI-CONTENTS.    190
C                                                                       200
      FUNCTION COND (XMAT,T)                                            210
      IF(IFIX(XMAT)-23) 1,1,1                                           220
    1 TIC=XMAT-FLOAT(IFIX(XMAT))                                        230
      IF(TIC) 2,2,3                                                     240
    3 IF(TIC-0.03) 2,4,5                                                250
    2 C1=0.2899+1.0312E-4*T-2.1875E-8*T*T                               260
      IF(TIC) 6,6,4                                                     270
    6 COND=C1                                                           280
      RETURN                                                            290
    4 C2=0.255+1.8E-4*T-1.0E-7*T*T                                      300
      IF(TIC-0.03) 8,7,9                                                310
    7 COND=C2                                                           320
      RETURN                                                            330
    8 COND=C1-TIC*(C1-C2)/0.03                                          340
      RETURN                                                            350
    5 IF(TIC-0.2) 4,9,9                                                 360
    9 C3=0.14375+2.175E-4*T-5.625E-8*T*T                                370
      IF(TIC-0.2) 11,10,10                                              380
   10 COND=C3                                                           390
      RETURN                                                            400
   11 COND=C2-(TIC-0.03)*(C2-C3)/0.17                                   410
      RETURN                                                            420
      END                                                               430
```

```
C***************  E X P N  ***************                                  10
C                                                                          20
C     FUNCTION SUBPROGRAM FOR EVALUATING THE THERMAL EXPANSION COEFFI-     30
C     CIENT OF STRUCTURAL MATERIALS                                        40
C                                                                          50
C*****  AUTHOR: DR.W.M.DAENNER, IPP GARCHING                               60
C                                                                          70
C*****  INPUT   XMAT    (-)      MATERIAL IDENTIFICATION NUMBER            80
C               TC      (C)      TEMPERATURE                               90
C*****  OUTPUT  EXPN    (CM-1)   THERMAL EXPANSION COEFFICIENT            100
C                                                                         110
C*****  CURRENT CONTENTS:                                                 120
C       ================                                                  130
C       XMAT = 23.0000  PURE VANADIUM                                     140
C                       IN 3 TEMPERATURE RANGES LINEAR INTERPOLATION OF   150
C                       DATA FROM F.SPERNER, METALL 15,10(1961),988-994   160
C                                                                         170
      FUNCTION EXPN(XMAT,TC)                                              180
      IF(IFIX(XMAT)-23) 1,1,1                                             190
    1 IF(TC-500.0) 2,2,3                                                  200
    2 EXPN=7.975E-6+3.25E-9*TC                                            210
      RETURN                                                              220
    3 IF(TC-900.0) 4,4,5                                                  230
    4 EXPN=9.6E-6+2.0E-9*(TC-500.0)                                       240
      RETURN                                                              250
    5 EXPN=10.4E-6+2.5E-9*(TC-900.0)                                      260
      RETURN                                                              270
      END                                                                 280
```

```
C*************** E M O D ***************                                  10
C                                                                        20
C     FUNCTION SUBPROGRAM FOR PROVIDING THE YOUNG'S MODULUS OF           30
C     STRUCTURAL MATERIALS                                               40
C                                                                        50
C*****  AUTHOR: DR.W.M.DAENNER, IPP GARCHING                             60
C                                                                        70
C*****  INPUT   XMAT   (-)      MATERIAL IDENTIFICATION NUMBER           80
C               TC     (C)      TEMPERATURE                              90
C*****  OUTPUT  EMOD   (KP/CM2) YOUNG'S MODULUS                          100
C                                                                        110
C***** CURRENT CONTENTS:                                                 120
C      ================                                                  130
C      XMAT = 23.0000   PURE VANADIUM                                    140
C                       CONSTANT VALUE DUE TO F.SPERNER, METALL 15,10    150
C                       (1961),988-994                                   160
C                                                                        170
      FUNCTION EMOD(XMAT,TC)                                             180
      IF(IFIX(XMAT)-23) 1,1,1                                            190
    1 EMOD=1.5E6                                                         200
      RETURN                                                             210
      END                                                                220
```

```
C***************  P O I S  ***************                                10
C                                                                         20
C     FUNCTION SUBPROGRAM FOR PROVIDING THE POISSON RATIO OF              30
C     STRUCTURAL MATERIALS                                                40
C                                                                         50
C*****  AUTHOR: DR.W.M.DAENNER, IPP GARCHING                              60
C                                                                         70
C*****  INPUT   XMAT    (-)       MATERIAL IDENTIFICATION NUMBER          80
C               TC      (C)       TEMPERATURE                             90
C*****  OUTPUT  POIS    (-)       POISSON RATIO                          100
C                                                                        110
C***** CURRENT CONTENTS:                                                 120
C      ================                                                  130
C      XMAT = 23.0000    PURE VANADIUM                                   140
C                        CONSTANT VALUE DUE TO KIEFFER, JANG, ETTMAYER:  150
C                        SONDERMETALLE, SPRINGER-VERLAG WIEN/NEW YORK    160
C                        1971                                            170
C                                                                        180
      FUNCTION POIS(XMAT,TC)                                             190
      IF(IFIX(XMAT)-23) 1,1,1                                            200
    1 POIS=0.35                                                          210
      RETURN                                                             220
      END                                                                230
```

```
C*************** L A R S O N ***************                              100
C                                                                        190
C     SUBPROGRAM FOR PROVIDING THE ALLOY CONSTANT C AND THE              200
C     LARSON-MILLER PARAMETER PLM NECESSARY FOR A GIVEN SRESS            300
C                                                                        400
C*****  AUTHOR: DR.W.M.DAENNER,IPP GARCHING                              401
C                                                                        402
C*****  INPUT   XMAT    (-)       MATERIAL IDENTIFICATION NUMBER         403
C               STR     (KP/CM2)  STRESS LOAD                            404
C*****  OUTPUT  PLM     (-)       LARSON-MILLER-PARAMETER REQUIRED       405
C               C       (-)       MATERIAL CONSTANT                      406
C                                                                        407
C***** CURRENT CONTENTS:                                                 408
C      ================                                                  409
C      XMAT = 23.XX00     V - XX TI  ALLOYS                             410
C                         CONSTANT VALUE FOR ALLOY CONSTANT C.           411
C                         POLYNOMIAL APPROXIMATION FOR V-5TI AND V-20TI  412
C                         CORRESPONDING TO DATA OF H.BOEHM, M.SCHIRRA:   413
C                         J.LESS-COMM.MET.,12(1967),280-293. LINEAR      414
C                         INTERPOLATION FOR OTHER TITANIUM CONTENTS.     415
C                                                                        416
      SUBROUTINE LARSON(XMAT,STR,PLM,C)                                  500
      IF(IFIX(XMAT)-23) 1,1,1                                            600
    1 C=15                                                               700
      TIC=XMAT-FLOAT(IFIX(XMAT))                                         800
      P5=18143.0+5.206E-2*STR-2.837E-4*STR*STR                           900
      P20=19933.0-2.402*STR+4.436E-4*STR*STR-2.658E-8*STR*STR*STR       1000
      PLM=P5+(P20-P5)*(TIC-0.05)/0.15                                   1100
      RETURN                                                            1200
      END                                                               1300
```

```
C***************  C I C  ***************                                  10
C                                                                        20
C     FUNCTION SUBPROGRAM FOR SUPPLYING THE IRRADIATION CREEP CONSTANT   30
C     OF A STRUCTURAL METAL OR ALLOY                                     40
C                                                                        50
C*****  AUTHOR: DR.W.M.DAENNER, IPP GARCHING                             60
C                                                                        70
C*****  INPUT   XMAT    (-)      MATERIAL IDENTIFICATION NUMBER          80
C*****  OUTPUT  CIC     (-)      IRRADIATION CREEP CONSTANT              90
C                                                                       100
C*****  CURRENT CONTENTS:                                               110
C       ================                                                120
C       XMAT = 26.0000    STAINLESS STEEL 316SS                         130
C                         CONSTANT VALUE DUE TO J.R.STANBRIDGE E.A.:    140
C                         CLM-R 127 (1974)                              150
C                                                                       160
      FUNCTION CIC(XMAT)                                                170
      IF(IFIX(XMAT)-26) 1,1,1                                           180
    1 CIC=1.679E-11                                                     190
      RETURN                                                            200
      END                                                               210
```

```
C*************** C R E E P ***************                                  10
C                                                                          20
C     SUBROUTINE FOR EVALUATING THE SECONDARY CREEP PARAMETERS FOR         30
C     STRUCTURAL METALS AND ALLOYS                                         40
C                                                                          50
C*****  AUTHOR: DR.W.M.DAENNER, IPP GARCHING                               60
C                                                                          70
C*****  INPUT   XMAT   (-)      MATERIAL IDENTIFICATION NUMBER             80
C               TC     (C)      TEMPERATURE                                90
C*****  OUTPUT  C      (-)      CREEP CONSTANT FOR NORTON'S EQUATION       100
C               EX     (-)      STRESS EXPONENT FOR NORTON'S EQUATION      110
C               C1     (-)      MATERIAL CONSTANT                          120
C               C2     (-)      MATERIAL CONSTANT                          130
C                               C1 AND C2 ARE FOR LIFE CALCULATION         140
C                               DUE TO M.SCHIRRA: KFK 1925 (1974).         150
C                                                                          160
C***** CURRENT CONTENTS:                                                   170
C      ================                                                    180
C      XMAT = 26.0000   STAINLESS STEEL                                    190
C                       C1 AND C2 ARE ARBITRARILY TAKEN TO BE THE SAME     200
C                       AS FOR VANADIUM (SEE BELOW). C AND EX TEMPER-      210
C                       ATURE DEPENDENT DUE TO G.SCHMIDT: KFK 808 (1968)   220
C      XMAT = 23.XX00   V - XX TI  ALLOYS                                  230
C                       CONSTANT VALUES FOR C1 AND C2. EVALUATION OF       240
C                       C AND EX FOR PURE VANADIUM AND THE ALLOYS          250
C                       V-2.8TI, V-5TI, AND V-20TI FROM DATA PRESENTED     260
C                       BY H.BOEHM, M.SCHIRRA: J.LESS-COMM.METALS 12       270
C                       (1967), 280-293. NO INTERPOLATION FOR OTHER        280
C                       TITANIUM CONTENTS.                                 290
C                                                                          300
      SUBROUTINE CREEP(XMAT,TC,C,EX,C1,C2)                                 310
      TK=273.15+TC                                                         320
      IF(IFIX(XMAT)-26) 2,1,2                                              330
    1 C1=-1.55                                                             340
      C2=1.1                                                               350
      C=1.0E-12**(923.15/TK) * 10.0**(15.0*(1.0-923.15/TK))                360
      EX=5538.0/TK                                                         370
      RETURN                                                               380
    2 C1=-1.55                                                             390
      C2=1.1                                                               400
      TIC=XMAT-FLOAT(IFIX(XMAT))                                           410
      IF(TIC) 3,3,4                                                        420
    3 EX=4.4                                                               430
      C=9.3E6*EXP(-6.5E4/(1.987*TK))                                       440
      RETURN                                                               450
    4 IF(TIC-0.03) 5,5,6                                                   460
    5 EX=9.3                                                               470
      C=3.65E-10*EXP(-3.1E4/(1.987*TK))                                    480
      RETURN                                                               490
    6 IF(TIC-0.05) 7,7,8                                                   500
    7 EX=8.4                                                               510
      C=4.5E-4*EXP(-5.1E4/(1.987*TK))                                      520
      RETURN                                                               530
    8 EX=4.2                                                               540
      C=7.0E22*EXP(-13.6E4/(1.987*TK))                                     550
      RETURN                                                               560
      END                                                                  570
```