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DESIGN CRITERIA FOR THE CALCULATION OF A HOT CHANNEL IN A PRESSURE TUBE NUCLEAR REACTOR

J. BERNARD, J. DUFRESNE, F. FARFALETTI-CASALI, J. PUTZEYS,

Commission of the European Communities,
Euratom Joint Nuclear Research Center, Ispra, Italy

ABSTRACT

In this paper, pressure tube materials, characteristics and life-time expectancy in function of nominal and accidental operating conditions are considered.

A great part of this work has been done on the basis of statistical interpretation of creep tests, that have given results allowing to appreciate the cumulative material damage. Subsequently, calculations of the wall thickness of a hot pressure tube have been carried out. These results give the lower limit of the pressure tube wall thickness excluding wear and fabrication tolerances.

1. INTRODUCTION

This report aims at formulating a calculation method which could be used as a basis for the design of nuclear reactor core components. The structure considered as example is the hot pressure tube of a heavy water moderated nuclear reactor and some design criteria for the determination of its thickness are presented on the following basis:

- Operating conditions of the reactor and related power station, including accident conditions
- Evaluation of allowable stresses for the material in order to assure an acceptably low fracture probability or a tolerable maximum deformation, taking into account the cumulative damage that the various operating conditions produce on the material
- Determination of a criterion correlating effective stresses with allowable stresses.

1.1. Generalities concerning the pressure tube design

1.1.1. Operating conditions

The operating conditions of a reactor can only be determined when the power station is exhaustively specified.

In general the nominal operating conditions of a nuclear reactor vary periodically during its life-time, more so than it occurs in a conventional plant. Thus the total damage sustained by a hot pressure tube during its life-time may include also some important damage due to operating conditions of short duration but inducing high-stress levels. It can thus be understood how a particular design philosophy can help to evaluate dangerous operating conditions and therefore, as feed-back information, may influence the design concepts. The analysis of the different operating conditions, nominal and accidental, with their associated design criteria aims at attaining assigned life-times for the pressure tubes, taking into account the uncertainty of the operating conditions.

1.1.2. Evaluation of allowable stresses

Standard codes cannot always be applied for the design of nuclear reactor pressure tubes since often the material utilized for the construction of nuclear pressure tubes is generally a new alloy whose long term behaviour is not very well known.

Two extreme cases are considered, i.e. brittle type material and ductile type material. In both cases a material may be considered as belonging to one category in a specific operating range of temperature and eventually to the other under different temperature conditions.

As far as materials of the brittle class are concerned, the allowable stresses must be defined in terms of failure probability, since there is a wide scattering in the results of the destructive tests. However, it is possible, on the basis of the available results, to establish design criteria with a reasonably high confidence level. Since working conditions may vary considerably according to the particular operating conditions (power variations, reactor shut-down, scram, etc.) it is necessary to know as well as possible the behaviour of this type of material under cyclic or dynamic sollicitations. Relating total life-time to various sollicitations during the structure life is based on a cumulative damage theory of materials. As an example of these materials, design criteria for pressure tubes utilizing SAP material (Sintered Aluminium Powder) will be given.
SAP being a material endowed with mechanical peculiarities, one cannot use standard design codes neither standard correlations between effective and allowable stresses.

The ductile type materials must satisfy the standard codes criteria, but however some particular conditions may even be more restrictive. One must verify, for example, if the allowed creep deformation of 1% in 100.000 hrs doesnot lead to radial deformations of a pressure tube during the reactor life-time that are incompatible with satisfactory operating conditions. When the design criteria are defined in terms of failure probabilities, the chosen criteria must depend on the implications and consequences of a pressure tube burst on the surrounding structures, such as the calandria tube, other pressure tubes, safety rods, control rods, vessel. Evidently, replacement of damaged pressure tubes requires costly and time-consuming interventions. Therefore all effects, due to accidental conditions such as seismic waves, overpressure, etc. must also be taken into account and these considerations can weigh heavily in the overall reliability of the pressure tube.

Rupture probability of a pressure tube must be kept very low because of the consequent economical damage, there is however another factor i.e. the neutron economy, that puts a limit to a significant increase of the pressure tube thickness with consequent decrease of failure probability especially for natural uranium reactors. The optimization of the reactor as a whole, thus finally the overall economy balance, will therefore define a reasonable value for the rupture probability of a component.

1.1.3. Determination of a criterion to calculate effective stresses

For the determination of the pressure tube thickness, difficulties appear in the formulation of the correlation between effective stresses under the various operating conditions and the allowable stresses (i.e. accurate definition of an adequate materials strength theory). Different flow criteria, used in multiaxial stress conditions, are discussed in former works (see e.g. Wahl [1] and Marin [2]). The criterion to be used for a particular material may be defined based on the results of tests performed in mono- and biaxial stress conditions. Odquist [3] and Finie [4] studied the creep behaviour of thin walled tubes under internal pressure utilizing the Von Mises flow rule. J. Marin [3] suggests that the Tresca criterion be used if no experimental results are available.

2. OPERATING CONDITIONS AND ASSOCIATED DESIGN CRITERIA

Operating conditions will be split into three groups: nominal, transient and accidental:

- Nominal conditions are those normally foreseen for the power station operation and are defined with a certain range of daily, weekly or yearly fluctuation
- Transient conditions are defined by the variation of nominal conditions, and by special operating conditions expected within a reactor life-time (fuel handling, coolant loadings, maintenance stop, start-up, etc.).
  These conditions can therefore be defined only on the basis of a detailed design and of systematic tests on the various sub-assemblies.
- A list of accidental conditions can be established a priori for different channel designs, but the assessment of the accident probability, and the consequences thereof, require statistical testing of each component under nominal operating conditions.

To each operating conditions, design criteria must take into account nominal operating conditions and general operating economy besides consequences of failure.

Design of all major components will be carried out on the basis of the criteria just defined.

The simultaneous occurence of accidental conditions have not been considered because of the negligible probability of such events and because provisions have been taken in the design to avoid them.

3. CHARACTERIZATION OF MATERIALS

The ductility of the materials that can be utilized for the fabrication of pressure tubes must satisfy the ASME code. Limitations of the allowable working stresses for these materials, besides those deriving from the standard codes, may also derive from two different design criteria, i.e. an ultimate stress type criterion or a deformation criterion.

A preliminary study of the material must ascertain the valid design criteria for the material under nominal operating conditions. Therefore, one must first determine the elongation corresponding to ultimate strength under nominal operating conditions, such as temperature, fast neutron flux, etc.

If the material properties are such that the pressure tube's radial deformations, under nominal load, become relevant the limitation of the working stresses will be set by a deformation criterion, compatible with satisfactory operating conditions.
A to important radial deformation may allow vibrations of the fuel elements, create poor hydrodynamic conditions, i.e. the coolant could partially bypass the fuel on its periphery, and reduce the insulating gap between the pressure tube and the calandria tube up to allowing contact between the two tubes.
If the elongation of the material at ultimate stress is small and cannot cause such thermodynamic problems then stress limitations will derive from other factors such as pressure tube burst, due to its brittleness that requires special attention.

3.1. Materials with high elongation at ultimate stress

Mechanical testing of these materials allow to determine their creep velocity, under nominal operating conditions, such as mechanical sollicitations, temperature, fast neutron flux, etc. The velocity of the deformation can be expressed as follows:

$$\dot{\varepsilon} = f\,(\sigma,\ \phi,\ T) \qquad (1)$$

where:

$\dot{\varepsilon}$ = the strain rate
σ = the primary stress
ϕ = neutron flux
T = operating temperature

Ross Ross [5] and Watkins [6] suggest similar laws for Zircaloy 2.

3.2. Brittle materials

Determination of permissible working stress is quite delicate. Creep tests conducted on these materials often give scattered results. It is therefore necessary to analyse statistically the data obtained, and the results would then be given under the form of stresses causing rupture after a certain time and with a certain probability, at a given temperature.

The size effect (see E.Y. Robinson [7]), has not been considered in the example (brittle type material), since neither the temperature nor the stress conditions are constant along the pressure tube. Creep tests, at a certain temperature allow to define a law: [8] [9]

$$\log t_\sigma = k_1 - k_3\sigma - \alpha \cdot s \cdot k_2 \qquad (2)$$

or

$$\sigma = \frac{k_1 - \log t_\sigma - \alpha \cdot s \cdot k_2}{k_3} \qquad (3)$$

where:

t_σ = expected life-time of structure under stress σ
k_1 and k_2 are constants
s = standard deviation
α = is defined by the probability of rupture
k_2 = is dependent of the number of tests performed

In order to determine admissible stresses at various temperature levels, the following method is proposed:

- The stress causing rupture after a certain time with a certain probability is defined for the maximum nominal operating temperature
- The criterion of ultimate strength at room temperature is applied accordingly to the standard code (the stresses thus calculated correspond to a very low rupture probability)
- The admissible stresses in between these two extreme cases is assumed to vary linearly. Such a hypothesis is conservative since relatively the diminution of the allowable stress of the material increases with temperature (fig. 1).

In this hypothesis the admissible stress can be expressed by the relation:

$$\sigma(T) = \sigma_0 + \frac{T - T_0}{T_f - T_0} \cdot \left[\frac{k_1 - \log t_\sigma - \alpha \cdot s \cdot k_2}{k_3} - \sigma_0 \right] \qquad (4)$$

where:

$\sigma(T)$ = admissible stress at temperature T
σ_0 = allowable stress at temperature T_0
T_0 = room temperature
T_f = maximum nominal operating temperature

The influence of variations of temperature or stress conditions during creep have been studied by Oding [10], Robinson [11], Kennedy [12], Manson [13], Shinn [14] and Shuji Taira [15]. The autors propose a law that defines for each operating condition a damage of the material that is a function of the duration t_i of the sollicitation and of its life-time t_{σ_i} under an identical stress and at the same temperature.
Any one of these damaging effects may be expressed by a term $(t_i/t_{\sigma_i})^m$, and rupture of the material should occur for the condition:

$$\sum_{i=1}^{N} (t_i/t_{\sigma_i})^m = 1$$

Some autors consider that the exponent m is equal to unity.

4. CALCULATION METHODS

4.1. Ductile materials

The conventional standard codes may be utilized, but at the criterion for creep, which defines the allowable stress as being the smallest between the 3/5 of the stress causing rupture after 100.000 hours and the stress inducing a deformation of 1% in 100.000 hrs, must be added a deformation condition, since for pressure tubes the allowable radial dilatation is determined by hydrodynamic factors that characterize the behaviour of the fuel element under vibration and optimum cooling conditions.

4.2. Brittle materials

For the design with brittle materials or materials that fail in a brittle fashion, the classical design safety factors must be redefined in terms of reliability.

To obtain reliable information from creep rupture tests it is necessary to analyse the experimental data by statistical methods because of the scatter of the results.

The following equation allows to calculate the expected lifetime $t_{\sigma_i}(T)$ of a structure under a stress σ_i at a temperature T.

$$\log t_{\sigma_i} = K_3 \left[\sigma_f - \sigma_o - (\sigma_i - \sigma_o) \frac{T_f - T_o}{T - T_o} \right] + K_4 \qquad (6)$$

σ_o allowable stress at temperature T_o
σ_f allowable stress at temperature T_f
$K_4 = \log t_{\sigma_f}$

The "Oding" formula which takes into account the cumulative damage in materials then becomes:

$$\sum_{i=1}^{N} \left(\frac{t_i}{t_{\sigma_i}(T)}\right)^m = 1 \qquad (7)$$

where:

t_i = effective time of operation under stress σ_i and at temperature T

$t_{\sigma_i}(T)$ = defined by equation (6)

m = coefficient determined in creep tests (see Annex)

For the various operating conditions the equivalent stress is calculated as a function of the pressure tube wall thickness and the minimum expected life-time of the tube under each stress condition is determined by equation (6).

The stresses that yield equation (7) ate the allowable stresses from which the wall thickness can be defined.

Besides those considerations also different particular operating conditions must be checked such as:

- buckling of the pressure tube under external pressure
- local stresses e.g. near the junctions between the pressure tube and its prolongation
- particular conditions such as seismic phenomena etc.

CONCLUSION

The previous presented calculation method allows to take into account the different operating conditions that may occur during the reactor life time. A quantitative estimate of the damage caused by each operation condition is calculated and permits to reconsider eventually the most dangerous ones and thus to improve the overall design.

ANNEX

EXAMPLE ORGEL

The calculations performed for a pressure tube of an ORGEL type reactor are given as example.

The ORGEL, i.e. Organic Cooled, Heavy Water Moderated Natural Uranium Reactor with pressure tubes is characterized by a bundle of parallel vertical channels. Each channel consists of a hot pressure tube, containing the fuel elements that are cooled by a downwards flowing organic liquid, and of a concentric cold calandria tube that isolates the pressure tube from the moderator. The insulating gas between both tubes is pressurized to reduce the hoop stresses in the pressure tube.

The material of the pressure tube is a sintered aluminium powder (SAP) containing 10% of Al_2O_3. This material has the peculiar property of having a decreasing elongation in function of temperature.

1. OPERATING CONDITIONS

The operating conditions that have been considered are as follow:

1.1. Nominal conditions with boundary conditions:
  - tolerances of the vessel
  - assembly
  - local conditions

1.2. Transient operation
  - power variation and power control at constant set level
  - scream
  - fuel handling
  - filling with hot coolant

1.3. Accidental conditions
  - channel rupture /16/
  - closure of isolating valves
  - overpressure of isolating gaz and depressurisation of primary circuit
  - depressurisation of insulating gaz
  - blocking of fuel element
  - fall of a fuel element
  - blocking of the handling machine
  - seismic stresses

2. CHARACTERIZATION OF MATERIAL

The SAP material may be considered as a ductile type of material at room temperature, its elongation at rupture being about 20%, but at normal operating temperature in the reactor, SAP has a brittle behaviour, its elongation at rupture under creep conditions being 0,5%. In a former publication (see M. Montagnani /17/) have been presented the results of creep tests on SAP performed at 420°C under monoaxial stress conditions.

Equation (2) then becomes:

$$\log t_{\sigma} = 12{,}6 - 2{,}09\,\sigma - \alpha \cdot 0{,}796 \cdot 1{,}27$$

Further creep tests performed on pressurised SAP tube sections, in biaxial stress conditions and at 400°C, lead to the following relation:

$$\log t_{\sigma} = 15{,}1 - 2{,}29\,\sigma - \alpha \cdot 0{,}344 \cdot 1{,}41$$

The results of these tests did show that the von Mises flow criterion may be used for the SAP material.
The determination of m, (cfr. eq. (7)) for SAP material has been determined, based on a series of tests utilizing tubular sections submitted to different pressures at a constant temperature of 400°C.

The dispersion that was observed during creep tests under constant load has been found also for the tests under variable load conditions, therefore the determination of m must be done usign a

statistical approach.
If one admits that the cumulative damage theory is applicable for this material, then one may write for a test under two different pressure conditions:

$$\left(\frac{t_1}{t_{\sigma_1}}\right)^m + \left(\frac{t_2}{t_{\sigma_2}}\right)^m = 1$$

where

t_1 = duration of test for a stress σ_1
t_{σ_1} = life-time at rupture for the same stress σ_1
t_2 = duration of test for a stress σ_2
t_{σ_2} = life-time at rupture for same stress σ_2

If one considers a reference stress σ_a in the σ_1, σ_2 region at the same temperature, one can write:

$$t^*_{\sigma_a} = \left[\left(t_1 \frac{t_{\sigma_a}}{t_{\sigma_1}}\right)^m + \left(t_2 \frac{t_{\sigma_a}}{t_{\sigma_2}}\right)^m\right]^{1/m} \qquad (2)$$

The ratios $\frac{t_{\sigma_a}}{t_{\sigma_1}}$ and $\frac{t_{\sigma_a}}{t_{\sigma_2}}$ are material characteristics and do not present a dispersion since the values of $\frac{t_{\sigma_a}}{t_{\sigma_1}}$ and $\frac{t_{\sigma_a}}{t_{\sigma_2}}$ are determined considering average values.

It is therefore possible to determine for each test a value for $t^*_{\sigma_a}$ with formula (2).

If the "Oding" law is applicable then the average value for $t^*_{\sigma_a}$ calculated must be equal to the average value t_{σ_a} obtained from creep tests under constant load.

$$t^*_{\sigma_a} = t_{\sigma_a} = f(m) \qquad \text{which defines m}$$

The value chosen for σ_a is 5,3 kg/mm^2 corresponding to

$$t^*_{\sigma_a} = t_{\sigma_a} = 900 \text{ hrs}$$

The value of m has been found on the curve given on fig. 2 and equals

$$m = 0{,}7$$

3. DETERMINATION OF PRESSURE TUBE WALL THICKNESS

The different operating conditions are divided into two categories. To the first group belong the long and medium term conditions that require an analysis based on the "creep damage" criterion. In the second group are assembled the conditions that may induce high stress levels of short duration and therefore require to be verified on the basis of particular design criteria. Table 1 summarizes the different working conditions for the most loaded sections of the pressure tube.

3.1. Long and medium term conditions

The equivalent stresses versus the pressure tube wall thickness are calculated on the basis of the Von Mises flow law. The allowable stress at a temperature T is calculated by equation (6). The minimum life-time for the pressure tube must be 100.000 hrs and the rupture probability has been fixed at 1‰, taking into account the requirements of safety and neutron economy. To account for the cumulative damage in the SAP material one used the relation

$$\sum_{i=1}^{N} \left(\frac{t_i}{t_{\sigma_i}}\right)^{0,7} = 1 \qquad (7)$$

The estimated values for the duration t_i, of the temperature and of the equivalent stress for each working condition are given in table 1, group 1. The minimum wall thickness of the pressure tube thus defined is 1,8 mm.
The most severe operating condition is the depressurization of the insulating gas between the pressure tube and the calandria tube. The most loaded part of the pressure tube is its upper section.

3.2. Short term conditions

For particular operating conditions that are given in Table 1, group 2, the smallest allowable wall thickness is calculated on the basis of short term design criteria. The minimum thickness of the pressure tube wall to avoid radial buckling under external pressure of 10 atmospheres, that is the most severe condition, is 2,5 mm.

3.3. Pressure tube thickness

It results from the above calculations that the minimum allowable tube wall thickness will be 2,5 mm. This value must be increased to account for wear caused by vibrations of the fuel element and by fuel handling, for fabrication tolerances and junction allowance.

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TABLE 1 TYPICAL CALCULATION FOR AN ORGEL TYPE REACTOR

HYPOTHESIS : RUPTURE PROBABILITY OF SAP MATERIAL UNDER BIAXIAL STRESSES AT 420 °C :

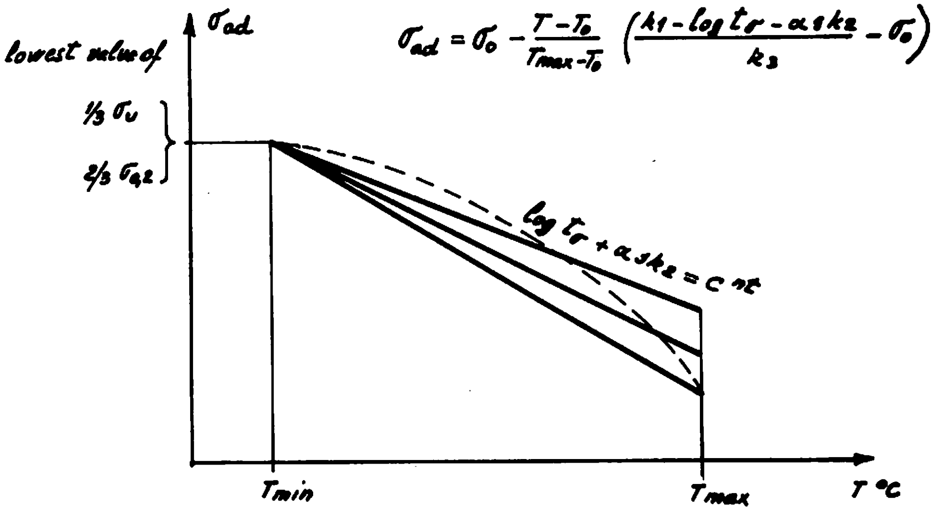
$$\mathrm{Log}\,[t_{\sigma_{ad}}]_{420\,°C} = 15{,}86 - 2{,}44\,(\sigma_{ad})_{420\,°C} - \alpha \cdot 0{,}65$$

WHERE $\alpha = 3{,}09$ FOR RUPTURE PROBABILITY OF 1 ‰

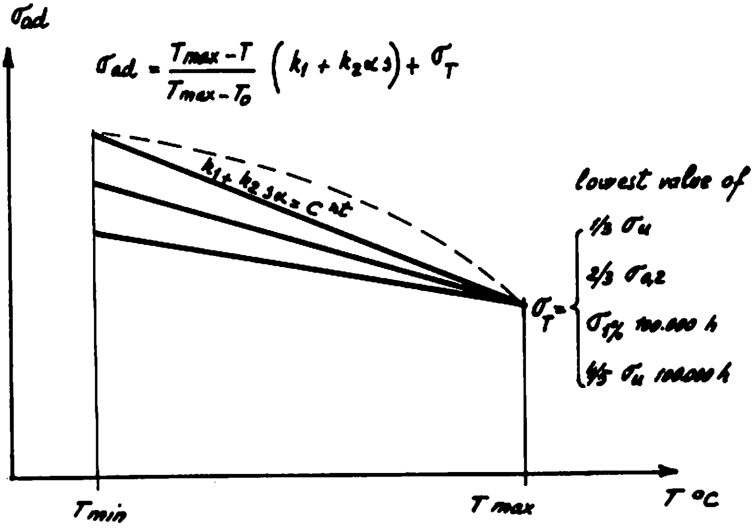
ALL CALCULATIONS BASED ON FORMULA (6)

OPERATING CONDITIONS	MOST-STRESSED LEVEL OF CHANNEL (TOP LEVEL)			$D = \left(\frac{t}{t_\sigma}\right)^{0,7}$
GROUP 1	Temp. (°C)	duration (h)	equiv. stress	WALL-THICKNESS $W = 1{,}80$ mm.
– Normal power operation	290	75.000	$\sqrt{\frac{34{,}35}{W^2} + \frac{1{,}21}{W} + 0{,}04}$	$7{,}92 \cdot 10^{-3}$
– Reduced power operation	310	25.000	$\sqrt{\frac{34{,}35}{W^2} + \frac{1{,}21}{W} + 0{,}04}$	$9{,}79 \cdot 10^{-3}$
– Fuel unloading	290	200	$\sqrt{\frac{14{,}54}{W^2} + \frac{1{,}05}{W} + 0{,}04}$	$1{,}40 \cdot 10^{-6}$
– Depressurization of insulating gas	290	10	$\sqrt{\frac{133{,}83}{W^2} + \frac{2{,}82}{W} + 0{,}04}$	$974 \cdot 10^{-3}$
– Overpressure of primary circuit	290	10	$\sqrt{\frac{106{,}75}{W^2} + \frac{2{,}9}{W} + 0{,}04}$	$8{,}11 \cdot 10^{-3}$

GROUP 2	TOP LEVEL		BOTTOM LEVEL		$\Sigma\left(\frac{t}{t_\sigma}\right)^{0,7} \cong 1000 \cdot 10^{-3}$
	Temp. (°C)	equiv. stress	Temp (°C)	equiv. stress	
– Depressurization of primary circuit or overpressure of insulating gas	290	$\sigma_t = -\frac{5{,}3}{W}$	420	$\sigma_t = -\frac{5{,}3}{W}$	
– Fuel blocking	290	$\sigma_a = \frac{8{,}6}{W}$	290	$\sigma_a = \frac{6{,}7}{W}$	



Material brittle at high temperature



Material brittle at low Temperature

Fig. 1 ALLOWABLE STRESS VERSUS TEMPERATURE

t_1 operating time at σ_1 and T_1
t_2 " " " σ_2 and T_2
t_{σ_1} life time expectancy at σ_1 and T_1
t_{σ_2} " " " " σ_2 and T_2
t_{σ_0} " " " " σ_0 and T_0

$$\left(\frac{t_1}{t_{\sigma_1}}\right)^m + \left(\frac{t_2}{t_{\sigma_2}}\right)^m = 1$$

$$t_{\sigma_0} = \left[\left(t_1 \frac{t_{\sigma_0}}{t_{\sigma_1}}\right)^m + \left(t_2 \frac{t_{\sigma_0}}{t_{\sigma_2}}\right)^m\right]^{1/m} = f(m)$$

$$t_{\sigma_{0_{med}}} = \sqrt{\frac{\sum_{i=1}^{i=m} t^2_{i\sigma_0}}{m}} = F(m)$$

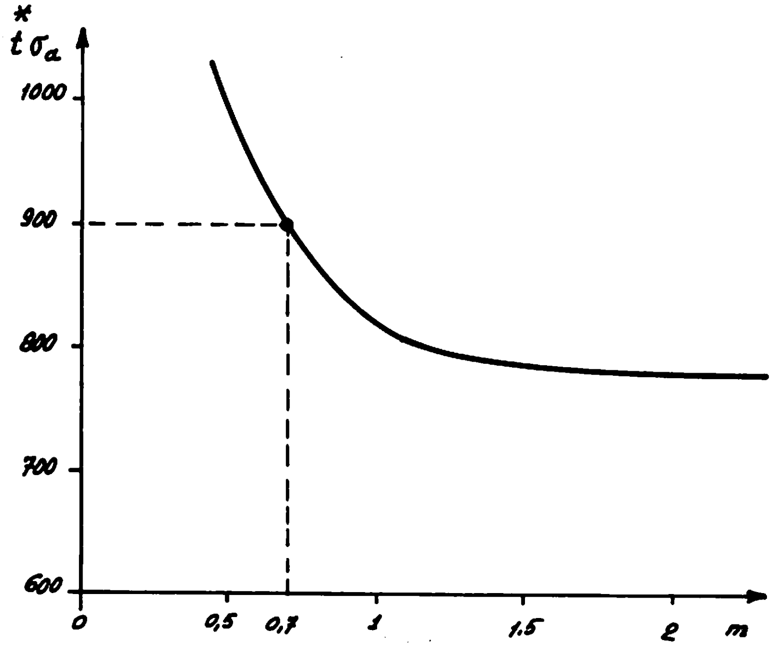


Fig. 2 EVALUATION OF m

DISCUSSION

Q R. L. ROCHE, France

Ma question montrera que je n'ai peut être pas bien suivi l'exposé. Je ne connais pas bien les propriétés du SAP, mais j'ai cru comprendre que vous considériez deux possibilités de rupture : rupture fragile ou rupture ductile. Vous avez évoqué que le critère de Von Mises représente bien le comportement du SAP. Je crois me souvenir que le critère de Von Mises détermine l'apparition de phénomènes plastiques. Ma question est: "Quel critère doit-on adopter pour la rupture et, en particulier, pour la rupture fragile ?".

A J. DUFRESNE, JRC Ispra, Italy

Le critère de Von Mises a été à l'origine un critère de plasticité. Ce critère a été étendu, dans certains cas, à la rupture des matériaux. En ce qui concerne le fluage, différents auteurs (réf. 1, 2, 3, 4) ont montré que ce critère s'appliquait également à la rupture.
En tout état de cause le critère de rupture par fluage doit, pour un matériau considéré, être vérifié expérimentalement au moyen d'essais effectués en condition mono- et bioxides, par exemple tube sous pression avec et sans compensation de l'effet des fonds.

Q P. A. ROSS-ROSS, Canada

With respect to creep strain and pressure tube lifetime, how do you define damage and how do you determine damage due to irradiation ? Was your analysis based on results from irradiated material and in particular material which was strained in reactor ?
Is the creep behaviour of SAP pressure tubes in reactor the same as the creep behaviour out of reactor ?

A J. DUFRESNE, JRC Ispra, Italy

Les essais d'irradiation effectués sur des échantillons de SAP ont montré que ce matériau n'était pas sensible à l'effet de l'irradiation. Ce qui a permis, pour ce matériau, de limiter les essais sur tronçons à des essais hors pile.