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ECCC RECOMMENDATIONS - VOLUME 9 Part II [Issue 1]

HIGH TEMPERATURE COMPONENT ANALYSIS OVERVIEW OF ASSESSMENT & DESIGN PROCEDURES

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HIGH TEMPERATURE COMPONENT ANALYSIS OVERVIEW OF ASSESSMENT & DESIGN PROCEDURES

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FORWARD

Volume 9 Part II provides an overview of assessment and design procedures. It has been developed by members of the ECCC-WG4 (Components) working group.

WG4 aims to review model component/features test data and produce harmonised assessment methods. More specifically, the overall objectives of WG4 can be listed as follows:

i) Explore multiaxial effects in components and feature tests
ii) Explore component design vs. in-service behaviour
iii) Review current assessment procedures for components (rupture, crack growth)
iv) Explore the transfer of design and assessment of component behaviour
v) Consider implications for standardisation of design and assessment.

This document deals with (iii) the review of current assessment procedures for components. It has been produced to show the various design and assessment procedures that are currently available to assess the time to rupture of vessels and crack growth.

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SCOPE

There are a number of assessment and design procedures which are currently used to assess the time to rupture of vessels. These are listed below:

1.	R5 (RUPTURE)	(Assessment procedure)
2.	R5 TDFAD APPROACH	(Assessment procedure)
3.	R5 (CRACK GROWTH)	(Assessment procedure)
4.	R5 CREEP-FATIGUE CRACK INITIATION	(Assessment procedure)
5.	σ_d	(Assessment procedure)
6.	Two Criteria Diagram	(Assessment procedure)
7.	EN 12952-4 & ISPESL	(Assessment procedure)
8.	TRD 508, VGB-R 509L	(Assessment procedure)
9.	EN 12952-3	(Design procedure)
10.	RCC-MR	(Design procedure)
11.	ASME III SUBSECTION NH	(Design procedure)
12.	TRD 300/301	(Design procedure)

The Assessment procedure aims to predict a test accurately, whereas a Design procedure assesses a test/component with in-built conservatisms. Therefore a difference in the results would occur purely due to the differences in the two types of procedure.

The twelve procedures that are described here have been developed by various companies. For example, R5 is a UK procedure developed by British Energy, and TRD are the Technical Rules for Steam Boilers (TRD), prepared and updated by “Deutscher Dampfkesselausschuß” (DDA).

The following pages give a description of each of the procedures in turn. Firstly the assessment procedures are described followed by the design procedures.

1. R5 (RUPTURE) – ASSESSMENT PROCEDURE

Nomenclature

P_L	Plastic collapse load
P_W	Working load
t	Time
t_f	Failure time at rupture reference stress
T_{ref}	Reference temperature
U	Creep usage factor
$\overline{\sigma}_{E,max}$	Maximum elastic equivalent stress
σ_{ref}	Reference stress
σ_{ref}^{R}	Rupture reference stress
σ_y	Yield stress
χ	Stress concentration factor

1.1 Brief Overview

This is a UK assessment procedure. The basic steps involved in evaluating the time to rupture are shown below in section 1.2.

1.2 Basic steps of R5 (RUPTURE) assessment procedure

1.2.1 Primary load reference stress

The first objective is to evaluate the primary load reference stress, σ_{ref}. For an isothermal structure or feature σ_{ref} is calculated from:

$$\sigma_{ref} = P_W \frac{\sigma_y}{P_L}$$

where P_L is the lower bound limit or plastic collapse load for the yield stress σ_y and is in proportion to the working loads P. The ratio of σ_y/P_L is not dependent on the use of a real yield stress and any convenient value may be used for σ_y for the purpose of calculating this ratio.

For isothermal structures, the reference temperature T_{ref} is equal to the temperature of the structure during the creep dwell; a history of varying temperature is permissible.

1.2.2 Rupture reference stress for creep ductile materials

The rupture reference stress, σ_{ref}^{R} , for creep ductile materials should then be evaluated from:

$$\sigma_{ref}^{R} = \{1 + 0.13[\chi - 1]\}\sigma_{ref}$$

where σ_{ref} is the primary load reference stress as calculated in step 1.2.1. χ is a stress concentration factor for the adjustment of reference stress, which is evaluated in step 1.2.3.

1.2.3 Stress concentration factor for adjustment of reference stress

The reference stress, σ_{ref}, from step 1.2.1 should be adjusted according to step 1.2.2 for local strain concentrations to provide the rupture reference stress σ_{ref}^{R}. The relevant stress concentration factor χ should be calculated from:

$$\chi = \frac{\overline{\sigma}_{E,max}}{\sigma_{ref}}$$

Here, $\overline{\sigma}_{E,max}$ is the maximum elastically calculated value of the equivalent stress in the structure or feature from an elastic analysis for the same set of loadings that were used to obtain σ_{ref}. The elastic stresses shall not be linearised for this purpose. This evaluation is acceptable for $\chi \leq 4.0$; for larger values of χ it must be considered that the stress raiser is sufficiently sharp to require treatment as a crevice or crack-like defect using the provisions of Volume 4 or Volume 5 of R5.

1.2.4 Assessment of creep rupture

A creep usage factor U is obtained from the expression:

$$U = \sum_{r=1}^{k} \left[\frac{t}{t_f(\sigma_{ref}^{R}, T_{ref})} \right]_r$$

where:

r	denotes the cycle type.
t	is the duration of steady load operation during which creep is significant totalled over all cycles of type r.
k	is the number of cycle types.
t_f	is the allowable time read from rupture curves for the rupture reference stress σ_{ref}^{R} at the reference temperature T_{ref}.

A single value of U is obtained for each structural feature, and it should be shown that:

$$U \leq 1$$

1.3 Material model - used in R66

Creep rupture strength – used to estimate time to failure:

$$P(\sigma) = \frac{\log(t_f) - F}{(T - G)^H} = a + b(\log\sigma) + c(\log\sigma)^2 + d(\log\sigma)^3 + e(\log\sigma)^4$$

Lower bound is –20% of the mean stress

2. R5 TDFAD APPROACH – ASSESSMENT PROCEDURE

Nomenclature

E	Young's modulus
K	Stress intensity factor
K^c_{mat}	Material creep toughness corresponding to a given crack extension in a given time
K_r	K / K^c_{mat}
L_r	$\sigma_{ref} / \sigma^c_{0.2}$
L_r^{max}	Cut-off on the R5 TDFAD; minimum of $\sigma_R / \sigma^c_{0.2}$ and $\overline{\sigma} / \sigma_{0.2}$
σ_{ref}	Reference stress
σ_R	Rupture stress for the time and temperature of interest
σ_u	Ultimate tensile strength
$\sigma_{0.2}$	0.2% proof stress; stress corresponding to 0.2% plastic strain
$\sigma^c_{0.2}$	0.2% inelastic strength; stress corresponding to 0.2% inelastic (plastic plus creep) strain
$\overline{\sigma}$	Short term flow stress $(= (\sigma_{0.2} + \sigma_u)/2)$
ε_{ref}	Total strain at the reference stress
ε^e_{ref}	Elastic strain at the reference stress
$\varepsilon^e_{0.2}$	Elastic strain at a stress of $\sigma^c_{0.2}$

2.1 Brief Overview

This is a UK assessment procedure to assess creep crack initiation. The basic steps involved in assessing creep crack initiation is shown below in section 2.2.

2.2 Basic steps of R5 TDFAD Approach

The TDFAD is based on the Option 2 FAD specified in R6 [2.1] and involves a failure assessment curve relating the two parameters K_r and L_r, which are defined in equations (1) and (2) below, and a cut-off L_r^{max}. For the simplest case of a single primary load acting alone

$$K_r = K / K^c_{mat} \tag{1}$$

where K is the stress intensity factor and K^c_{mat} is the appropriate creep toughness value.

$$L_r = \sigma_{ref} / \sigma^c_{0.2} \tag{2}$$

where σ_{ref} is the reference stress and $\sigma^c_{0.2}$ is the stress corresponding to 0.2% inelastic (plastic plus creep) strain from the average isochronous stress-strain curve for the temperature and assessment time of interest, see Figure 1, below:

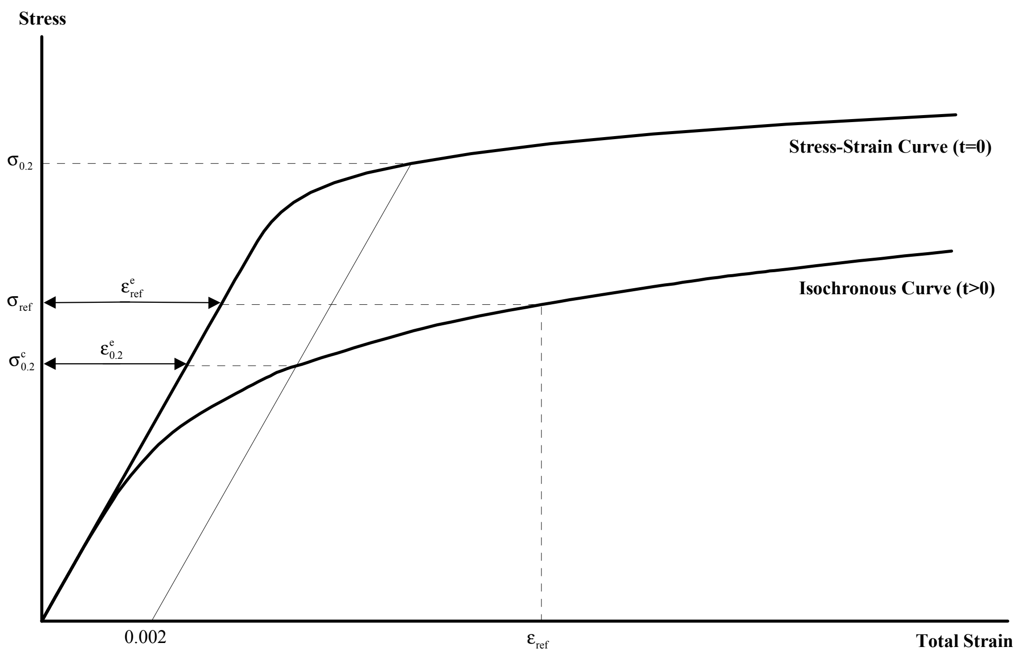


Figure 1 Schematic isochronous stress-strain curves

The failure assessment diagram is then defined by the equations

$$K_r = \left[\frac{E\varepsilon_{ref}}{L_r\sigma^c_{0.2}} + \frac{L_r^3\sigma^c_{0.2}}{2E\varepsilon_{ref}} \right]^{-1/2} \qquad L_r \le L_r^{max} \qquad (3)$$

$$K_r = 0 \qquad L_r > L_r^{max} \qquad (4)$$

In equation (3), E is Young's modulus and ε_{ref} is the total strain from the average isochronous stress-strain curve at the reference stress, $\sigma_{ref} = L_r\sigma^c_{0.2}$, for the appropriate time and temperature. Thus, equation (3) enables the TDFAD to be plotted with K_r as a function of L_r, as shown schematically in Figure 2.

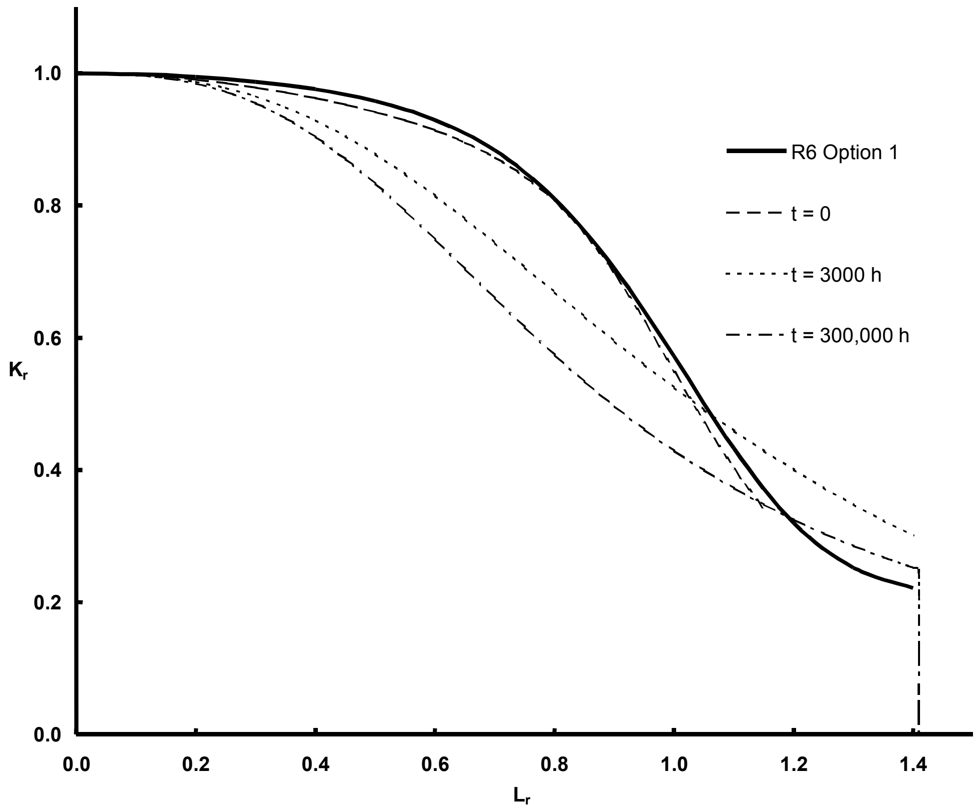


Figure 2 Schematic failure assessment diagrams based on data from an austenitic type 316 steel at 600°C

The cut-off, L_r^{max}, is defined as

$$L_r^{max} = \sigma_R / \sigma_{0.2}^c \tag{5}$$

where σ_R is the rupture stress for the time and temperature of interest. However, for consistency with R6 [2.1], the value of L_r^{max} should not exceed $\overline{\sigma} / \sigma_{0.2}$ where $\overline{\sigma}$ is the short term flow stress and $\sigma_{0.2}$ is the conventional 0.2% proof stress. As in R6 [2.1], $\overline{\sigma}$ may be taken as $(\sigma_{0.2} + \sigma_u)/2$ where σ_u is the ultimate tensile strength.

The TDFAD approach relies on the definition of an appropriate creep toughness, K_{mat}^c, which, when used in conjunction with the failure assessment diagram, ensures that crack growth in the assessment period is less than a value Δa.

The assessment point (L_r, K_r), from equations (1) and (2), using the current values of stress intensity factor and reference stress respectively, is plotted on the failure assessment diagram. If the point lies within the failure assessment curve of equation (3) and the cut-off of equation (4), then the crack extension is less than Δa and creep rupture is avoided. Alternatively, the TDFAD approach can be used to predict the time required for the crack to extend by Δa. This requires the time locus of (L_r, K_r) points to be constructed and the time for crack extension, Δa, is given by the intersection of this locus with the failure assessment curve of equation (3) for the corresponding time. This calculation may be simplified by noting that the failure assessment curve may be a weak function of time; this allows the time for the crack to extend by Δa to be estimated using a failure assessment curve for a single time.

3. R5 (CRACK GROWTH) – ASSESSMENT PROCEDURE

Nomenclature

A, A'	Constants in creep crack growth laws
a	Defect size including any crack growth
a_0	Initial defect size
$\dot{a}$	Creep crack propagation rate
$\dot{a}_c, \dot{a}_R$	Creep crack propagation rate for coarse and refined microstructures
$C^*, C(t), C_h^*$	Creep crack growth parameters
da/dN	Crack growth per cycle
$(da/dN)_c$	Creep crack growth per cycle
$(da/dN)_f$	Fatigue crack growth per cycle
D	Constant in creep deformation law
E	Young's modulus
K	Stress intensity factor
K_{min}, K_{max}	Minimum and maximum values of K in cycle
ΔK	Stress intensity factor range
ΔK_{eff}	Effective stress intensity factor range
ℓ	Exponent in fatigue crack growth law
n	Creep stress exponent, not necessarily the steady state value
P, P_o	Applied loading, value at start of displacement hold
P_L	Plastic collapse load
q, q'	Constants in creep crack growth laws
q_o	Crack closure parameter
r_p^{crack}	Cyclic plastic zone size at crack tip
R	Load or stress intensity factor ratio
R'	Geometrical parameter
t	Time
$t_h, t_{h,j}$	Hold time, hold time in cycle j
t_{red}	Redistribution time
β	Constant in creep crack incubation law; exponent in the stress-strain law
ε_c	Creep strain
ε_{ref}^c	Accumulated creep strain at the reference stress
ε_{ref}^e	Elastic strain at the reference stress
$\dot{\varepsilon}^c$	Creep strain rate
$\dot{\varepsilon}_{ref}^c$	Creep strain rate from uniaxial data at the reference stress
σ, σ_{ij}	Stress, stress tensor
σ_{ref}	Reference stress
σ_y	Yield stress

3.1 Brief Overview

This is a UK assessment procedure to assess crack growth. The basic steps involved in assessing crack growth is shown below in section 3.2.

3.2 Basic steps of R5 (CRACK GROWTH) assessment procedure

The background to the defect assessment procedures in R5 and BS 7910 has been set out in [3.1]. Here, the basic R5 Volume 4/5 procedures [3.2] for creep-fatigue loading of homogeneous components are briefly presented. The procedures use approximate techniques based on a reference stress related to the applied load, P, by

$$\sigma_{ref} = P\sigma_Y / P_L(\sigma_Y, a) \tag{1}$$

where P_L is the plastic collapse load for a yield stress σ_Y and crack size, a. For creep-fatigue conditions, creep crack growth during the dwell period and fatigue crack growth during the cycle are evaluated separately.

In order to estimate creep crack growth during dwell periods, the C^* parameter is estimated using reference stress techniques as

$$C^* = \sigma_{ref}\dot{\varepsilon}^c_{ref}R' \tag{2}$$

where $\dot{\varepsilon}^c_{ref}$ is the creep strain rate from uniaxial data at the reference stress (equation (1)) calculated for the current defect size, a, and the characteristic length, R' is defined by

$$R' = (K/\sigma_{ref})^2 \tag{3}$$

where K is the stress intensity factor. As both K and σ_{ref} are directly proportional to the loading P, the value of R' is independent of the magnitude of P. However, R' does vary with crack size and, when creep crack growth is being considered, both K and σ_{ref} should be calculated for the defect size equal to the size of the original crack plus the amount of creep crack growth. The parameter C^* characterises the crack tip stress and strain rate fields for times in excess of the redistribution time, t_{red}. This is the time required for stress redistribution due to creep from the initial elastic state, which may be expressed conveniently in terms of the reference stress [3.3] as

$$\varepsilon_c[\sigma_{ref}(a_0), t_{red}] = \sigma_{ref}(a_0)/E \tag{4}$$

where a_0 is the initial crack size and $\varepsilon_c[\sigma_{ref}, t]$ is the accumulated creep strain at the reference stress for time, t, from uniaxial creep data.

Prior to the attainment of widespread creep conditions, the crack tip stress and strain rate fields are characterised by a parameter usually denoted C(t). For times in excess of the redistribution time, C(t) approaches C^*. An interpolation formula for C(t) during the transition between initial elastic loading and steady state secondary creep has been derived by Ainsworth and Budden [3.4] as

$$\frac{C(t)}{C^*} = \frac{(1 + t/t_{red})^{n+1}}{(1 + t/t_{red})^{n+1} - 1} \tag{5}$$

for a material obeying a Norton state secondary creep law of the form

$$\dot{\varepsilon}^c = D\sigma^n \tag{6}$$

For more generalised application, equation (5) may be expressed as

$$\frac{C(t)}{C^*} = \frac{(1 + \varepsilon^c_{ref}/\varepsilon^e_{ref})^{1/(1-q)}}{(1 + \varepsilon^c_{ref}/\varepsilon^e_{ref})^{1/(1-q)} - 1} \tag{7}$$

where ε^c_{ref} is the accumulated creep strain at the reference stress after time t, ε^e_{ref} is the elastic strain at the reference stress and q (≈ n/(n+1)) is the exponent in the creep crack growth law (equation (15) below).

In order to estimate cyclic crack growth under conditions of shakedown to elastic conditions, an effective stress intensity factor, ΔK_{eff}, is used to make an allowance for compressive stresses at the extreme of the cycle. ΔK_{eff} is related to the total stress intensity factor range, ΔK, by:

$$\Delta K_{eff} = q_o \Delta K \tag{8}$$

where q_o is the fraction of the total load range for which a crack is judged to be open [3.3, 3.5], and ΔK is given by

$$\Delta K = K_{max} - K_{min} \tag{9}$$

where K_{max} and K_{min} are the values of the total stress intensity factor at times during the cycle where K has its extreme values.

For a structure, q_o may be estimated conservatively from:

$$\begin{aligned} q_o &= 1 && R \geq 0 \\ q_o &= (1 - 0.5R)/(1 - R) && R < 0 \end{aligned} \tag{10}$$

where:

$$R = K_{min}/K_{max} \tag{11}$$

It should then be determined whether or not creep behaviour is unperturbed by cyclic behaviour. This test should be performed both for the overall structural response and for stresses local to the crack tip. The test for the overall structural response may be demonstrated by satisfying the uncracked body requirements of R5 Volume 2/3 [3.6]. The test for stresses local to the crack tip may be made by demonstrating that, for the most severe fatigue cycle, the cyclic plastic zone at the crack tip is small. Under cyclic loading, the allowable elastic stress range is $2\sigma_y$ in the absence of cyclic hardening or softening, and the cyclic plastic zone size at the crack tip is given by

$$r_p^{crack} = \beta(\Delta K / 2\sigma_y)^2 \tag{12}$$

where β is typically $1/2\pi$ in plane stress and $1/6\pi$ in plane strain. More generally, the cyclic plastic zone size at the crack tip should be calculated using the cyclic yield or 0.2% offset stress. This cyclic plastic zone size should be shown to be much less than the crack size or any other dimension characteristic of the structure, such as section thickness or remaining ligament ahead of the crack. If these tests are satisfied, cyclic loading and creep-fatigue interaction can be considered to be insignificant. In this situation, creep-fatigue crack growth rates can be obtained as a simple sum of the contributions due to fatigue and creep crack growth rates as

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_f + \left(\frac{da}{dN}\right)_c \tag{13}$$

In situations where creep-fatigue interaction is shown to be significant, it may be necessary to use cyclic crack growth rates in equation (13), which are higher than those obtained from pure fatigue tests.

The creep crack growth per cycle, $\left(\frac{da}{dN}\right)_c$, is determined using C(t) or C^* depending whether or not widespread creep conditions have been attained in the component. In either case,

$$\left(\frac{da}{dN}\right)_c = \int_0^{t_h} \dot{a}_c dt \tag{14}$$

where $\dot{a}_c$ is the creep crack growth rate and t_h is the duration of the dwell period. For widespread creep conditions, the creep crack growth rate is obtained from creep crack growth data in the form

$$\dot{a} = AC^{*q} \tag{15}$$

where A and q are material and temperature dependent constants. To allow for transient creep and the increased amplitude of the crack tip fields at short times estimated using equation (7), it is assumed that for times less than the redistribution time ($t<t_{red}$), equation (15) may be generalised to

$$\dot{a} = A[C(t)]^q \tag{16}$$

For situations where creep crack growth calculations are being performed for a period in excess of the redistribution time, the effects of the redistribution period can be allowed for by using the crack growth rates of equation (15) multiplied by a factor of 2 for $t<t_{red}$, i.e.

$$\begin{aligned} \dot{a} &= 2A(C^*)^q \quad \text{for } t < t_{red} \\ \dot{a} &= A(C^*)^q \quad \text{for } t \geq t_{red} \end{aligned} \tag{17}$$

The fatigue crack growth rate, $(da/dN)_f$, is given by

$$\left(\frac{da}{dN}\right)_f = C(\Delta K_{eff})^{\ell} \tag{18}$$

where the coefficient C and index ℓ are material and temperature dependent.

4. R5 CREEP-FATIGUE CRACK INITIATION – ASSESSMENT PROCEDURE

4.1 Brief Overview

Within the UK, parts of the R5 high temperature assessment procedures address creep-fatigue crack initiation in initially defect-free components. The procedures were developed some time ago and included a number of novel features such as: the shakedown reference stress approach for structural assessment; the ductility exhaustion method for estimating creep damage; and, the inclusion of size effects in fatigue damage calculations to enable assessments of thin in-reactor components. Recently, the R5 creep-fatigue initiation procedures have undergone a major revision. In the revision the above novel features have been retained but other parts of the procedure have been modified. These include: a restructuring of the document with an associated new step-by-step procedure to enable easier application of the procedures; modifications to the ductility exhaustion model to address multiaxial stresses including the triaxial stresses which may be present in regions of high welding residual stress; additional advice for assessment of weldments including fatigue strength reduction factors based on experimental data on austenitic weldments; generalized hysteresis loop construction methods for complex non-isothermal cycles, supported by laboratory data collected under non-isothermal conditions; and, advice on inelastic analysis when simplified shakedown methods are inapplicable. This section describes in outline the new R5 creep-fatigue crack initiation assessment procedures.

4.2 Introduction

Creep-fatigue life prediction methods generally employ separate calculations of creep damage and fatigue damage. These are then combined according to an interaction rule to evaluate the time, or number of cycles, to lead to creep-fatigue failure. Creep damage has traditionally been calculated using a time fraction rule and this approach is incorporated in the American Society of Mechanical Engineers (ASME) and French RCC-MR Codes [4.1, 4.2]. However, there are detailed differences in the application of the time-faction rule in different codes in terms of safety factors on creep rupture curves and the interaction rules for combining the calculated creep damage with fatigue.

An alternative to the time-fraction approach is the ductility exhaustion method. Early developments of this [4.3] led to incorporation of the method in the R5 assessment procedure [4.4]. As with the time-fraction rule, there were detailed differences with other ductility exhaustion methods in terms of the definition of creep ductility and the associated interaction rules [4.5]. This has led to further developments which suggest that the method is capable of greater accuracy than the time fraction rule [4.6].

4.3 R5 Procedures

The R5 Procedure provides an assessment of the continuing integrity of a defect-free component, where the operating lifetime might be limited by one of the following mechanisms:

(1) excessive plastic deformation

(2) creep rupture
(3) ratchetting or incremental collapse
(4) initiation of cracking due to combined creep and fatigue damage
(5) creep deformation enhanced by cyclic load

These mechanisms are assessed by simplified approaches which are less restrictive than those based on elastic calculations, without requiring the complexity of full inelastic computation. The simplified approaches use reference stress and shakedown concepts and incorporate some conservatism. Within these simplified approaches there are a number of options for performing some of the calculations. The first option presented is the simplest; other options may require additional calculations or data but give less restrictive results. An alternative approach is not to use the simplified approaches but to use detailed inelastic calculations to demonstrate the continuing integrity of a component.

The aims of the procedure are to estimate, by a simplified approach based on elastic stress analysis, the steady cyclic stresses and strains (the steady cyclic state) in a defect free structure under creep-fatigue loading, and to use these parameters to determine creep-fatigue crack initiation in the structure. Several limits are included in the procedure to ensure the validity of the approach adopted. In the event of failure to satisfy these limits, advice is provided on the determination of creep-fatigue crack initiation by detailed inelastic finite element analysis. The steps of the procedure, which are summarised below, illustrate a simple conservative route through the procedure and indicate where a higher level of assessment is required.

The procedure is not intended to provide an estimate of the number of cycles to failure of a component although the crack initiation endurance is a lower bound to this. Following initiation, or for components containing cracks or crack like defects, an assessment may be supported by separate calculations using other procedures in R5.

4.3.1 Step 1: Resolve load history into cycle types

The complete load history of a component is required to define the cyclic conditions in the region under investigation. The history needs to be broken down into well defined cyclic events or service cycles. Each different service cycle has an associated cyclic load, a steady state load which operates during a dwell period and a characteristic temperature. This simplifies the actual loading history so that it is reduced to a well defined number of different service cycles. Detailed advice on defining and constructing cycles types is given in R5 and is similar to other codes.

4.3.2 Step 2: Perform elastic stress analysis

Elastic stress analyses are performed, assuming a homogeneous body of parent material, to determine the variation, with position x and time t, of the multiaxial stress field $\tilde{\sigma}_{el}(x,t)$ throughout the component, for each different service cycle. The zones which give the most critical regions for the lifetime limiting mechanisms which are considered (i.e. plastic collapse, creep rupture, ratchetting, creep-fatigue initiation and cyclically enhanced creep deformation) are then selected taking note of the presence of weldments, the maximum stress levels, stress ranges, maximum temperature levels and time at these temperatures. For each type of cycle, the von Mises equivalent elastic stress and strain, $\bar{\sigma}_{el}(t)$ and $\bar{\varepsilon}_{el}(t)$, and equivalent elastic stress and strain ranges, $\Delta\bar{\sigma}_{el}(t)$ and $\Delta\bar{\varepsilon}_{el}(t)$, at the chosen locations (x), are calculated from the multi-axial stress field history $\tilde{\sigma}_{el}(x,t)$.

4.3.3 Step 3: Demonstrate sufficient margins against plastic collapse

These tests are standard and are specified in R5 to ensure that the component does not suffer plastic collapse on the first application of load, that excessive plastic deformation is not accumulated before the steady cyclic state is reached and that it is possible for the steady cyclic state to be within global shakedown (see Step 7 below).

4.3.4 Step 4: Determine whether creep is significant

The effects of creep may be neglected if the sum of the ratios of the hold time t to the maximum time t_m, at the maximum temperature in the dwell, T_{ref}, for the total number of cycles n_j of each cycle type j, is less than one:

$$\sum_j n_j [t / t_m (T_{ref})]_j < 1 \tag{1}$$

Curves of t_m as a function of temperature are provided in R5 for ferritic and austenitic steels based on criteria in [4.2].

4.3.5 Step 5: Demonstrate that creep rupture endurance is satisfactory

Creep rupture is assessed using a rupture reference stress, which is calculated using the primary load reference stress, σ_{ref}, which may be calculated from the elastic stress resultants or more generally from

$$\sigma_{ref} = P\sigma_y / P_L \tag{2}$$

where P represents the magnitude of the primary loads and P_L is the corresponding value at plastic collapse for a rigid plastic material with yield stress σ_y. For creep ductile materials the rupture reference stress is then calculated from:

$$\sigma^R_{ref} = \{1 + 0.13[\chi - 1]\}\sigma_{ref} \tag{3}$$

For all other materials the rupture reference stress is calculated from:

$$\sigma^R_{ref} = \{1 + (1/n)[\chi - 1]\}\sigma_{ref} \tag{4}$$

where n is the secondary creep stress exponent. This expression may also be used for creep ductile materials with n>7. In both cases the stress concentration factor χ is calculated from:

$$\chi = \bar{\sigma}_{el,max} / \sigma_{ref} \tag{5}$$

where $\bar{\sigma}_{el,max}$ is the maximum elastically calculated value of equivalent stress, at the chosen section. This evaluation is acceptable for $\chi \le 4.0$; for larger values of χ it must be considered that the stress raiser is sufficiently sharp to require treatment as a crevice or crack-like defect using the procedures elsewhere in R5. Where very high triaxial stresses occur, such as in notches, further consideration of their effect on creep rupture is required.

It should then be shown that the creep usage factor U, summed for the total number of cycles, n_j, of each cycle type j, is less than one:

$$U = \sum_j n_j \left[\frac{t}{t_f(\sigma^R_{ref}, T_{ref})} \right]_j < 1 \qquad (6)$$

where t_f is the allowable time, determined from the creep rupture curve, corresponding to the rupture reference stress σ^R_{ref}, with a suitable safety factor at the reference temperature T_{ref}.

4.3.6 Step 6: Perform a simple test for shakedown and check for insignificant cyclic loading

The demonstration of shakedown ensures the avoidance of ratchetting or incremental collapse. R5 first provides a simple test which may be used to obviate the need for a detailed shakedown analysis. If it is further possible to demonstrate insignificant cyclic loading, the need to complete Steps 7 to 14 is removed and the assessment continues at Step 15.

In many cases, with the satisfaction of the primary stress limit of Step 3, the elastic stress solutions of Step 2 for the most severe cycle is within global shakedown. For these cases, a simple test for shakedown is provided by assuming the residual stress field, Step 7, is null, and demonstrating that the equivalent elastic stresses determined from linearised stresses, at all the points x on the structural section for all times t, denoted $\bar{\sigma}_{el,lin}(x,t)$ are within a modified yield limit:

$$\bar{\sigma}_{el,lin}(x,t) \leq K_s S_y \qquad (7)$$

Here, the product K_sS_y is a measure of the ability of the material to develop a steady cyclic behaviour, S_y is the minimum 0.2% proof stress for the material for the temperature at point x and time t, and values of K_s are obtained from figures in R5 for the same material and temperature.

The extent of the length of the stress classification line, at the inner and outer surfaces, $(r_p)_i$ and $(r_p)_o$ respectively, over which $\bar{\sigma}_{el}(x,t)$ exceeds K_sS_y is identified, and it should be demonstrated that:

$$(r_p)_i + (r_p)_o \leq 0.2 \text{ x section thickness} \qquad (8)$$

Then, a detailed shakedown analysis, Step 7, to find a residual stress field and a steady cyclic stress history is not required and the cyclic plastic zone size, r_p, is taken as $(r_p)_i$ or $(r_p)_o$ as appropriate.

At this stage, if inequality (7) has been satisfied, it may also be possible to demonstrate that the section under assessment is within strict shakedown, fatigue is insignificant and creep behaviour is unperturbed by cyclic loading. Demonstration of insignificant cyclic loading removes the requirement to perform Steps 7 to 14 inclusive. The necessary criteria for insignificant cyclic loading are;

- the most severe cycle is within the elastic range of the material,

$$\Delta\bar{\sigma}_{el,max} \leq (K_s S_y)_c + (K_s S_y)_{nc} \qquad (9)$$

where subscripts c and nc refer to values during the creep dwell and at the end of the cycle in the direction of the stress change during creep,

- the total fatigue damage for all cycles, is less than 0.05,

$$D_f \le 0.05 \tag{10}$$

where the fatigue damage, D_f, is calculated using the maximum elastic strain range, $\Delta\bar{\varepsilon}_{el,max}$, for each cycle,

$$D_f = \sum_j \frac{n_j}{N_{0j}} \tag{11}$$

where N_0 is the fatigue endurance at strain range, $\Delta\bar{\varepsilon}_{el,max}$

- creep behaviour is unperturbed by cyclic loading. If the creep dwell is at the tensile peak stress, this criterion is satisfied by demonstrating

$$\Delta\bar{\sigma}_{el,max} \le \sigma_{ss} + (K_s S_y)_{nc} \tag{12}$$

where σ_{ss}, the steady state creep stress, is equal to the rupture reference stress, σ^R_{ref}, of Eq.(4). Satisfaction of these criteria ensures that the steady state for all cycles is within strict shakedown, fatigue is insignificant and does not perturb creep behaviour.

4.3.7 Step 7: Perform a global shakedown check and calculate the cyclic plastic zone size

R5 assesses the ability of the structure to attain global shakedown to nearly elastic behaviour after the first few cycles of loading, so that avoidance of plastic ratchetting or incremental collapse is ensured. The state of shakedown is brought about by the action of residual stresses left by the early cycles of load and an estimate of the residual stress field is needed. Any number of estimates of residual stress fields may be generated, but only one field, $\tilde{\rho}$ (x), which is constant with respect to time throughout all loading cycles is used for the assessment of shakedown. It is necessary to obtain equivalent stresses $\bar{\sigma}_s$(x,t) applying during the steady cyclic state for each type of loading cycle, at least for the extremes of stress occurring during the cycle at the locations of maximum cyclic stress range. This is done by first forming the steady cyclic stresses $\tilde{\sigma}_s$(x,t) by the addition of the elastically calculated stress $\tilde{\sigma}_{el}(x,t)$ to the residual stress field $\tilde{\rho}$ (x):

$$\tilde{\sigma}_s(x,t) = \tilde{\sigma}_{el}(x,t) + \tilde{\rho}(x) \tag{13}$$

The equivalent stress history, $\bar{\sigma}_s$(x,t), is determined from $\tilde{\sigma}_s$(x,t). If the elastically calculated stresses have been linearised, all values of $\bar{\sigma}_s$(x,t) should be shown to satisfy the short term shakedown criterion

$$\bar{\sigma}_s(x,t) \le K_s S_y \tag{14}$$

If elastic stress distributions have not been linearised, the extent of the regions, at the inner and outer surfaces, $(r_p)_i$ and $(r_p)_o$ respectively, over which inequality (14) is violated should be identified.

Limited regions of the structure may be exempted from the strict shakedown requirement if at least 80% of the thickness of every section consists of a ligament over which the criterion is continuously satisfied. If this requirement is satisfied for all types of load cycle for all points in the structure apart from the stated exemptions and for all instants of time during each cycle, then the structure is within global shakedown. In this event, no further tests are necessary for plastic ratchetting or incremental collapse. If global shakedown cannot be demonstrated, then the Procedure given here for the assessment of creep-fatigue and strain limits cannot be applied directly and it may be necessary to consider detailed inelastic analysis in order to substantiate the component.

4.3.8 Step 8: Calculate the shakedown reference stress, reference temperature and start of dwell stress

This step also involves determining the combination of shakedown reference stress and temperature which results in the shortest rupture life. For the period of each type of cycle during which loadings are constant with time, the value of $\overline{\sigma}_s(x,t)$ calculated in Step 7 using linearised stresses, is selected which, in combination with the temperature T at the same point during the same period, gives the shortest rupture time read from minimum stress rupture curves. This value of $\overline{\sigma}_s(x,t)$ is then defined as the shakedown reference stress σ^s_{ref} for the structure during this period and the corresponding temperature T is the shakedown reference temperature T^s_{ref}. The residual stress field may be chosen to minimise the shakedown reference stress σ^s_{ref} at any point while continuing to satisfy the shakedown test of Step 7. Where the full elastic stress field has been considered and peak F-stresses have been included, the estimated shakedown reference stress and temperature, σ^s_{ref} and T^s_{ref}, provide a conservative estimate.

If the loadings or temperatures vary slowly over long periods it is permissible to divide the time interval concerned into blocks during which the variation is small and assign a shakedown reference stress and temperature to each block. A pessimistic assessment is achieved by using the highest values of σ^s_{ref} and T^s_{ref} from any block.

If the initial elastic solution satisfies the requirements of the shakedown tests in Step 7, then the residual stress is null and $\overline{\sigma}_s(x,t)$ is identical to $\overline{\sigma}_{el}(x,t)$. In this case the structure is well within strict shakedown and the stress at the start of creep may be expected to diminish with repeated relaxations. It is then permissible to adjust the mean stress in the cycle to minimise the shakedown reference stress, provided the maximum stress which occurs at any point in the cycle, where there is no creep, does not exceed $(K_sS_y)_{nc}$.

It is also necessary to calculate a start-of-dwell stress, σ_0. This can be taken equal to a revised shakedown reference stress with F-stresses included in the shakedown calculations. The greatest elastically calculated equivalent stress range, $\Delta\overline{\sigma}_{el,max}$, between the stress level at the start of a creep dwell and any stress level in the load cycle at which creep does not occur is established and a revised steady state stress at the start of the creep dwell, σ_0 is estimated from

$$\sigma_0 = \overline{\sigma}_s(x,t)_{rev} = \Delta\overline{\sigma}_{el,max} - (K_sS_y)_{nc} \tag{15}$$

For tensile dwells at the peak of a cycle, if Eq. (15) gives a negative value, σ_0 is set equal to 0. For complex cycles, for example when the dwell is not at the hysteresis loop tip, it may be necessary to consider the elastic stress range between the stress level at the start of the creep dwell and the stress level at a number of points in the cycle where creep does not occur.

The derivation of the start-of-dwell stress, σ_0, from $\bar{\sigma}_s(x,t)$ uses elastic calculations of stress throughout. If the point of interest is outside strict shakedown, then the resulting value for σ_0 may be unrealistically above yield. A less pessimistic value may be estimated following detailed procedures in R5.

4.3.9 Step 9: Estimate the elastic follow-up factor and associated stress drop during the creep dwell

The loadings applied to high temperature structures often consist of severe cyclic thermal stresses, possibly beyond yield, and relatively smaller, steadier mechanical loads. Under these circumstances, behaviour during periods of steady operation at high temperature results in the relaxation of initially high stresses as creep strain replaces elastic strain. The process may lead to an increase in the total strain as a result of elastic follow-up and can be described by

$$\frac{d\bar{\varepsilon}_c}{dt} + \frac{Z}{\bar{\bar{E}}} \cdot \frac{d\bar{\sigma}}{dt} = 0 \qquad (16)$$

where $\bar{\varepsilon}_c$ is equivalent creep strain, E is Young's modulus, $\bar{E} = 3E/2(1+\nu)$ where ν is Poisson's ratio, $\bar{\sigma}$ is equivalent stress and Z is called the elastic follow-up factor. Three options are available for the evaluation of this factor, which needs to be evaluated separately for each type of load cycle. The simplest option is to neglect any stress relaxation which may occur during a dwell prior and evaluate creep damage using forward creep data. This is equivalent to taking Z as ∞ and results in a conservative estimate of creep damage in any situation. Note, however, that it is still necessary to take account of any stress relaxation which does occur in the evaluation of total strain range (see Step 10).

The second option may be applied if the structure is isothermal, to the extent that the temperature nowhere varies by more than 10°C and primary loads are small compared with secondary loads, so that

$$(P_L + P_B) < 0.2\sigma_0 \qquad (17)$$

is satisfied everywhere, where P_L and P_B are the ASME [4.1] primary stress resultants. For these conditions, the factor may be conservatively bounded by the value Z=3.

The third option is to calculate Z from an inelastic computation, but it is not necessary to consider alternating plasticity and creep nor to analyse large numbers of cycles to obtain a steady state, and the option therefore remains much simpler than assessment by full inelastic analysis. This represents the most effective way of estimating the change in kinematics due to creep. Simple power-law creep is used with a typical value of creep exponent n, and allowing for any temperature dependence of creep for non-isothermal loadings. A monotonic elastic-creep computation is then performed, starting from the elastically calculated state corresponding to the maximum elastic stress in the cycle. The computation is continued until either stresses have become constant or have reduced to the level $\sigma_0 - \Delta\sigma_{rD}$ where σ_0 is the value calculated in Step 8 and $\Delta\sigma_{rD}$ is the stress drop in a laboratory relaxation test starting from the stress σ_0 at temperature T^s_{ref} for the hold time of interest. $\Delta\sigma_{rD}$ is treated as a material property. In this latter case, Z is then estimated from integration of Eq. (16) as

$$Z = (\Delta\bar{\varepsilon}_t + \Delta\sigma_{rD} / \bar{E}) / (\Delta\sigma_{rD} / \bar{E}) \tag{18}$$

where $\Delta\bar{\varepsilon}_t$ is the increase in total strain in the computation. As values Z > 1 slow the rate of stress reduction, $\Delta\sigma_{rD}$ may be replaced by a value $\Delta\sigma'$ in Eq. (18) where $\Delta\sigma'$ is obtained from cyclic relaxation data allowing for the value of Z. Iteration is needed to obtain consistent values of $\Delta\sigma'$ and Z in Eq. (18).

4.3.10 Step 10: Calculate the total strain range

A simplified method can be used for calculating the total strain range if creep effects can be neglected (Step 4) or the creep dwell starts at the hysteresis loop tip, and if the elastic follow-up is estimated to be moderate, defined as Z < 5. In other cases, detailed routes are provided in R5 but the estimate of strain range obtained from the simplified treatment described here exceeds that obtained following these detailed routes and hence leads to a more conservative assessment.
The total strain range is obtained by enhancing the maximum elastically calculated stress range, $\Delta\bar{\sigma}_{el} = \Delta\bar{\sigma}_{max}$, from Step 2, by the stress relaxation drop $\Delta\sigma_{rD}$. The increased elastic stress range $\Delta\bar{\sigma}_{el,r}$ is then given by

$$\Delta\bar{\sigma}_{el,r} = \Delta\bar{\sigma}_{el} + \Delta\sigma_{rD} \tag{19}$$

In situations where creep effects can be neglected, $\Delta\bar{\sigma}_{el,r} = \Delta\bar{\sigma}_{el}$. It should be noted that here $\Delta\sigma_{rD}$ should not be adjusted for any influence of elastic follow-up, and should not be replaced by $\Delta\sigma'$ calculated in Step 9.

If the conventional uni-axial cyclic stress-strain curve is represented by a Ramberg-Osgood relation of the form

$$\Delta\varepsilon = \Delta\sigma / E + (\Delta\sigma / A)^{1/\beta} \tag{20}$$

the total stress range, $\Delta\bar{\sigma}$, is obtained by solving the Neuber relationship:

$$\Delta\bar{\sigma}_{el,r}\Delta\bar{\varepsilon}_{el,r} = (\Delta\bar{\sigma}_{el} + \Delta\sigma_{rD})^2 / \bar{E} = \Delta\bar{\sigma}\left[\Delta\bar{\sigma} / \bar{E} + (\Delta\bar{\sigma} / A)^{1/\beta}\right] \tag{21}$$

which gives the total strain range, $\Delta\bar{\varepsilon}_t$, for use in the fatigue assessment, as:

$$\Delta\bar{\varepsilon}_t = \left[\Delta\bar{\sigma} / \bar{E} + (\Delta\bar{\sigma} / A)^{1/\beta}\right] + \Delta\bar{\varepsilon}_{vol} \tag{22}$$

The quantity $\Delta\bar{\varepsilon}_{vol}$ is the enhancement due to constant volume deformation during plasticity and is estimated from:

$$\Delta\bar{\varepsilon}_{vol} = (K_v - 1)\Delta\bar{\varepsilon}_{el,r} \tag{23}$$

where

$$K_v = [(1+\bar{\nu})(1-\nu)] / [(1+\nu)(1-\bar{\nu})] \tag{24}$$

and

$$\bar{\nu} = \nu E_s / \bar{E} + 0.5(1 - E_s / \bar{E}) \tag{25}$$

The secant modulus, E_s, is obtained from the relationship,

$$E_s = \Delta\bar{\sigma} / [\Delta\bar{\sigma} / \bar{E} + (\Delta\bar{\sigma} / A)^{1/\beta}] \tag{26}$$

4.3.11 Step 11: Check limits on cyclically enhanced creep

Although the demonstration of shakedown ensures there will be no plastic ratchetting, an additional check is needed to ensure that there is no excessive accumulation of forward creep strains due to the cyclic loading.

The shakedown reference stress and temperature, σ^s_{ref} and T^s_{ref} calculated in Step 8 provide a conservative estimate of the stress and associated temperature controlling creep deformation. The shakedown reference temperature T^s_{ref} remains the temperature to be used in all cases but for situations involving constant primary loads combined with secondary loads producing essentially through-wall bending stresses across the section of interest, a lower value of σ^s_{ref} for assessing cyclically enhanced creep may be obtained as follows. First, the load parameters X and Y are defined for each type of loading cycle as:

$$X = \sigma_{ref} / S_y \tag{27}$$

and

$$Y = Q_{range} / S_y \tag{28}$$

where σ_{ref} is the primary load reference stress calculated in Step 5 and Q_{range} is the maximum elastically calculated range of the linear thermal stresses Q for the structural section on which the shakedown reference stress σ^s_{ref} has been calculated in Step 8. The proof stress S_y used to non-dimensionalise X and Y is obtained for the temperature T^s_{ref}. The reduced value of σ^s_{ref} is then calculated from:

$$\sigma^s_{ref} = \{Y - 2\sqrt{Y(1-X)} + 1\} S_y \qquad Y(1-X) < 1 \tag{29}$$

$$\sigma^s_{ref} = XYS_y \qquad Y(1-X) \geq 1 \tag{30}$$

for this specific loading application.

The shakedown reference stress of either Eqs (29) and (30) for the specific loading case or more generally that from Step 8 is then used to calculate a creep usage factor W which must satisfy :

$$W = \sum_j n_j \left[\frac{t}{t_f(\sigma^s_{ref}, T^s_{ref})} \right]_j < 1 \tag{31}$$

similar to Eq. (6). In practice, t_f is defined both from minimum creep rupture data and from creep strain data so that inequality (31) limits creep deformation resulting from the enhancement of creep strains by cyclic thermal loads, and ensures that this process does not result in accelerated creep rupture in the case of brittle materials.

4.3.12 Step 12: Summarise the assessment parameters

The above steps lead to the determination of all the parameters required for the basic assessment of a component. Where a more detailed analysis is warranted, this is undertaken by use of appropriate appendices in R5. The identified parameters are summarised as follows:

r_p The cyclic plastic zone size is determined in Step 6 or 7 and is required in the choice of initiation crack size, a_0, which is used to calculate the fatigue damage per cycle in Step 14.

T^s_{ref}, σ_0 The shakedown reference temperature and start-of-dwell stress are determined in Step 8; the shakedown reference temperature is used to calculate the total strain range in Step 10 and both parameters are required to calculate the creep damage per cycle in Step 15.

$Z, \Delta\sigma'$ The elastic follow-up factor and the stress drop in the creep dwell are determined in Step 9; they are used to calculate the total strain range in Step 10 and the creep damage per cycle in Step 15.

$\Delta\bar{\varepsilon}_t$ The total equivalent strain range is determined in Step 10 and is used to calculate the fatigue damage per cycle in Step 14.

W The creep usage factor is determined in Step 11; although it is necessary to demonstrate that $W < 1$ over the service history of the component, W is not required in the calculation of creep damage per cycle in Step 15.

4.3.13 Step 13: Treatment of weldments

Modifications are needed to Steps 3-11 for welded structures. Complications include:

- potential mismatch of materials properties
- the introduction of welding defects
- the presence of high local residual stress
- the effect of surface finish creating the difference between 'dressed' and 'undressed' welds.

Due to these factors, R5 separates the treatment of weldments from that of parent material. This treatment is not described in detail here but some background information is provided below.

4.3.14 Step 14: Calculate the fatigue damage per cycle

The process of fatigue damage is considered to consist of two stages. The first corresponds to the nucleation of a defect of size, a_i = 0.02mm. The second stage is the growth of this defect to a specified depth, a_0, which corresponds to the initiation criterion. This separation enables assessments to be made for thin sections in which a_0 must be specified to be smaller than the crack size, a_ℓ, corresponding to failure in a laboratory specimen. The separation also enables allowance to be made for the order in which cycles are applied and for the different effects of multiaxial stress state on the nucleation and growth processes [4.7].

For thick section components, a_0 is set equal to a_ℓ. For thin-section components, a_0 is set equal to a small fraction (typically less than 10%) of the cross-section so that uncracked body stress analysis is appropriate. A convenient choice is often the extent of the cyclic plastic zone, r_p.

The fatigue damage per cycle, d_f, corresponding to the cyclic strain range $\Delta\bar{\varepsilon}_t$ as calculated in Step 10, is defined as

$$d_f = 1/N_0 \tag{32}$$

where N_0 is the number of cycles to initiate a crack of size a_0 under continuous cycling conditions at strain range $\Delta\bar{\varepsilon}_t$. The method for calculating N_0 may be summarised as follows:

Obtain the relevant fatigue endurance data. Partition the endurance data into curves describing the number of cycles for nucleation, N_i, and growth, N_g, of a defect as functions of total strain range using:

$$\ln(N_i) = \ln(N_\ell) - 8.06 N_\ell^{-0.28} \tag{33}$$

and

$$N_g = N_\ell - N_i \tag{34}$$

Calculate the number of cycles $N'_g = MN_g$ to grow the crack from size a_i to a_0 where M is given by

$$M = \frac{a_{min}\ln(a_0/a_{min}) + (a_{min} - a_i)}{a_{min}\ln(a_\ell/a_{min}) + (a_{min} - a_i)} \quad \text{for } a_0 > a_{min} \tag{35}$$

or

$$M = \frac{a_0 - a_i}{a_{min}\ln(a_\ell/a_{min}) + (a_{min} - a_i)} \quad \text{for } a_0 < a_{min} \tag{36}$$

and a_{min} is taken to be 0.2 mm [4.8]. If $a_0 < a_\ell$, this modifies the growth curve to take account of size effects and $N'_g < N_g$. If $a_0 \geq a_\ell$, N'_g is set equal to N_g and $N_0 = N_\ell$.

4.3.15 Step 15: Calculate the creep damage per cycle

For cases where there is insignificant cyclic loading according to the criteria of Step 6, the creep damage, d_c, per cycle is defined as

$$d_c = t_h / t_f(\sigma_{ss}) \tag{37}$$

where t_h is the duration of the creep dwell and $t_f(\sigma_{ss})$ is the rupture time of the material at the steady state creep stress σ_{ss} equal to the rupture reference stress, σ^R_{ref} of Eq. (4). More generally, a ductility exhaustion model is used to assess creep damage. The creep damage per cycle, d_c, is then given by

$$d_c = \int_0^{t_h} \frac{\dot{\bar{\varepsilon}}_c}{\bar{\varepsilon}_f(\dot{\bar{\varepsilon}}_c)} dt \tag{38}$$

where $\dot{\bar{\varepsilon}}_c$ is the instantaneous equivalent creep strain rate during the dwell period and $\bar{\varepsilon}_f(\dot{\bar{\varepsilon}}_c)$ is the appropriate creep ductility taking account of the effects of stress state and strain rate. This method for determining d_c is applicable to all situations; however, inelastic finite element analyses would be required to fully take account of the variation of creep ductility with instantaneous values of creep strain rate and stress state throughout the dwell period. The calculation of creep damage per cycle can be simplified by assuming the most onerous stress state during the dwell period applies at all times, and assuming that the creep ductility is independent of strain rate and equal to a lower shelf ductility, ε_L, suitably factored to take account of stress state and denoted $\bar{\varepsilon}_L$. Both of these simplifications lead to a pessimistic assessment of creep damage per cycle. For a case involving a tensile dwell where both of these simplifying assumptions have been made, the creep damage per cycle is given by

$$d_c = Z\Delta\bar{\sigma}' / \bar{E}\bar{\varepsilon}_L \tag{39}$$

where $\Delta\bar{\sigma}'$ is the equivalent stress drop in the dwell. However, if the dwell occurs in the compressive part of the cycle, an upper shelf uniaxial creep ductility, $\bar{\varepsilon}_U$, is used to estimate the creep damage as

$$d_c = Z\Delta\bar{\sigma}' / \bar{E}\varepsilon_U \tag{40}$$

Modelling of the transition from first cycle to steady cyclic behaviour leads to an associated time or number of cycles. If creep damage in this transition phase is judged to be significant then it must be separately calculated and added to the value calculated above for steady state operation.

4.3.16 Step 16: Calculate the total damage

The total damage D over the creep-fatigue history is the linear sum of a fatigue component, D_f, and a creep component D_c, that is:

$$D = D_f + D_c \tag{41}$$

where

$$D_f = \sum_j \frac{n_j}{N_{0j}} = \sum_j n_j d_{fj} \tag{42}$$

and

$$D_c = \sum_j n_j d_{cj} \tag{43}$$

Here n_j is the number of service cycles of type j and N_{0j}, d_{fj} and d_{cj} are the values of N_0, d_f and d_c corresponding to that cycle type, as calculated by Eqs. (32-40). If $D<1$, then crack initiation will be avoided. If $D\geq 1$, then crack initiation is assessed to have occurred and creep or creep-fatigue crack growth calculations should be performed using the procedures elsewhere in R5.

4.3.17 Step 17: Assess significance of results and perform a sensitivity analysis

Further action is required if the criterion for safe operation of the component defined in terms of initiation of a crack of specified depth is not met. Possible courses of action include:

(i) use more detailed methods of stress analysis, for example, inelastic computations;
(ii) perform a sensitivity analysis;
(iii) improve the input data, for example use cast specific ductility and/or endurance;
(iv) use the multiaxial fatigue route, particularly if significant components of compressive stress are present;
(v) assess subsequent crack growth;
(vi) develop a safety case based on alternative arguments, such as leak before break or features tests;
(vii) refine the operating history or revise future allowable operating conditions;

(viii) repair, replace or re-design (for example, change of material).

The initiation of a crack does not necessarily imply that the structure is unsafe. Under some circumstances a crack may propagate sub-critically for the planned remaining life of the component, or might arrest and become dormant. The extension of the safe life to include crack propagation can be made by using the initiation crack depth, a_0, as the starting depth for a crack growth assessment.

A sensitivity analysis will identify those parameters which have the most significant effect on the results. For example, at high cyclic strain ranges the fatigue damage contributes most to crack initiation, whereas at low cyclic strain ranges and moderate to long dwell times creep damage dominates. However, changes in one parameter may promote or demote the importance of other parameters in the analysis. For example, using lower bound yield stresses in the analysis will maximise the strain range, $\Delta\bar{\varepsilon}_t$, but may minimise the stress at the start of the dwell, σ_0, and hence the creep damage accumulated in a cycle. Sensitivity analyses with respect to materials data which are known to be significantly affected by operating conditions are advised. The use of cast specific data will generally lead to a less pessimistic assessment, as these data will normally have properties better than the lower bound of the data set. However, the procurement of cast specific data may involve conducting mechanical property tests on material removed from plant.

4.3.18 Step 18: Report results

The results and methods employed in an assessment must be properly reported so that the data and procedures used can be scrutinised and verified. Any pessimisms must be clearly identified. If a weldment is being considered, the information should include the weldment type and whether the weldment is treated as dressed or undressed. The materials data employed at all stages of the procedure including its source and justification for any assumptions or extrapolations made, and whether bounding or best-estimate data have been used should be reported. In particular, it should be recorded if strain-rate dependent creep ductility data are used to assess cyclic creep damage and then the details of the necessary adjustments reported. If weldments are being assessed the appropriate Fatigue Strength Reduction Factors (FSRFs) should be recorded.

4.4 Background information

4.4.1 Treatment of weldments

Weldments are assessed using the step-by-step procedure described above but with some modifications as indicated in Step 13. In particular, FSRFs are used to modify the strain range in order to estimate fatigue damage. Recommended FSRFs are given in R5 for different types of dressed and undressed weldments and these have recently been the subject of a review for both austenitic and ferritic weldments.

4.4.2 Multiaxial ductility

In order to apply Eq.(38) it is necessary to have an estimate of the effect of stress state on creep ductility. As creep-fatigue initiation assessments are generally performed at a surface, relationships were developed by Spindler [4.10] from biaxial creep data on Type 316 and Type 304 stainless steels. An empirical expression of the form

$$\bar{\varepsilon}_f/\varepsilon_f = \exp[p(1-\sigma_1/\bar{\sigma})]\exp[q(1/2-3\sigma_p/2\bar{\sigma})] \tag{44}$$

was developed where $\bar{\varepsilon}_f$ and ε_f are the von Mises equivalent and uniaxial ductilities, respectively, and $\sigma_1, \bar{\sigma}$ and σ_p are the maximum principal, equivalent and hydrostatic stresses. Values p=2.38, q=1.04 were obtained for materials where ε_f decreased with decreasing stress and values p=0.15, q=1.25 were obtained for materials with a ductility sensibly independent of stress.

5. σ_d – ASSESSMENT PROCEDURE

Nomenclature

a	crack size
B	specimen thickness
C*	steady state creep integral
d	characteristic distance in sigma-d method
D	parameter in creep rupture expression
E	Young's modulus
E'; $\overline{E}$	plane strain modulus, $E/(1-\nu^2)$; adjusted modulus, $3E/[2(1+\nu)]$
I_n, I_m	functions in HRR fields
J, J_{el}	J-contour integral, elastic J
K	stress intensity factor
K^c_{mat}	time-dependent fracture toughness, a function of Δa and t
K_r	R6/TDFAD parameter, K/K^c_{mat}
L_r	R6/TDFAD parameter, P/P_L
$L_r^{(1)}, L_r^{(2)}, L_r^{(3)}$	limiting values of L_r for models 1,2,3
m	parameter in stress-strain expression
n	parameter in creep deformation expression
p	parameter in creep rupture expression
P, P_L	load, limit load
r_c	characteristic distance
R_1,R_2,R_3	incubation time ratios
R'	length scale in reference stress J-estimation scheme
t	time
t_i	incubation time
t_r	rupture time
t_{red}	redistribution time
w	section width
α	parameter in stress-strain expression
Δa	crack growth
ε	strain
ε_o	normalising strain in stress-strain expression
$\varepsilon_f, \varepsilon_{fo}$	uniaxial creep ductility, uniaxial creep ductility at stress σ_o
$\varepsilon_f^*, \varepsilon_{fo}^*$	multiaxial creep ductility, multiaxial creep ductility at stress σ_o
$\dot{\varepsilon}$	strain rate
$\dot{\varepsilon}_o$	strain rate at stress σ_o
$\varepsilon_{yy,el}$	strain, $\sigma_{yy,el}/\overline{E}$
λ	ductility ratio, $\varepsilon_f/\varepsilon_f^*$
ν	Poisson's ratio
σ	stress
σ_{ref}	reference stress, $L_r\sigma_{0.2}$

$\sigma_{0.2}$	0.2% proof stress
σ_o	normalising stress, taken equal to $\sigma_{0.2}$
σ_d	sigma-d stress
σ_{yy}	elastic-plastic stress normal to crack plane
$\sigma_{yy,el}$	elastic stress normal to crack plane
$\tilde{\sigma}_{yy}$	dimensionless function in HRR field

5.1 Brief Overview

This is a UK assessment procedure, set down in the French design code RCC-MR [5.1], which provides a practical method for estimating incubation of fatigue crack growth from notch or crack-like defects. The method is based on the evaluation of a stress σ_d at a short distance (d = 50μm) in front of the crack tip. The incubation of fatigue crack growth is then conceded when the endurance limit is reached at the distance d = 50μm.

The method was extended by Moulin et al [5.2] to the assessment of incubation of pre-existing defects under creep and combined creep-fatigue loading. The rationale for the application of the method to creep crack incubation is similar to that for fatigue, where it is considered that a finite volume of the material must be at a stress level equal to the rupture limit before creep crack extension will occur. The specific advantage of this method, over other methods for the assessment of crack incubation, is that the material data required can be obtained from experiments on smooth specimens.

Recent developments within the UK have led to Appendix A10 to Volume 4 of R5 [5.3] for austenitic steels.

5.2 The sigma-d method

The first step in the sigma-d approach is to calculate, for the given loading and geometry, the leading-order, singular, term in the expansion of the elastic stress normal to the crack plane at the distance d ahead of the crack tip:

$$\sigma_{yy,el} = \frac{K}{(2\pi d)^{1/2}} \tag{1}$$

where, following [5.1, 5.3], $d = 50\mu m$. A corresponding elastic strain at stress $\sigma_{yy,el}$ is then evaluated from:

$$\varepsilon_{yy,el} = \frac{\sigma_{yy,el}}{\overline{E}} \tag{2}$$

where $\overline{E} = 3E/2(1+\nu)$ accounts for the difference in Poisson's ratio between elasticity and plasticity in the definition of equivalent strain. The elastic strain is then enhanced by the plastic strain at the reference stress level

$$\sigma_{ref} = \frac{P\sigma_{0.2}}{P_L(a, \sigma_{0.2})} \equiv L_r \sigma_{0.2} \tag{3}$$

with P the load and P_L the plastic collapse load at crack size a and yield stress $\sigma_{0.2} = \sigma_o$, to give the total strain, prior to plastic redistribution, as $\varepsilon_{yy,el} + \alpha\varepsilon_o(\sigma_{ref}/\sigma_o)^m$.

The Neuber procedure defines σ_d as the solution of

$$\frac{K}{(2\pi d)^{1/2}}\left(\frac{K}{(2\pi d)^{1/2}\overline{E}} + \alpha\varepsilon_o\left(\frac{\sigma_{ref}}{\sigma_o}\right)^m\right) = \sigma_d\left(\frac{\sigma_d}{\overline{E}} + \alpha\varepsilon_o\left(\frac{\sigma_d}{\sigma_o}\right)^m\right) \tag{4}$$

where $\alpha\varepsilon_o$=0.002.

The predicted initiation time is then estimated from conventional creep rupture data as the rupture time for a stress, σ_d:

5.3 Material model - used in R66

Creep rupture strength – used to estimate time to failure:

$$P(\sigma) = \frac{\log(t_r) - F}{(T - G)^H} = a + b(\log\sigma) + c(\log\sigma)^2 + d(\log\sigma)^3 + e(\log\sigma)^4$$

Lower bound is –20% of the mean stress.

6. TWO CRITERIA DIAGRAM - ASSESSMENT PROCEDURE

Nomenclature

Symbol	Definition	Unit
R_K	Stress intensity-(crack tip) ratio	-
K_I	Stress intensity factor	MPa √m
K_{Imax}	Maximum stress intensity (crack tip situation)	MPa √m
K_{IA}	Stress intensity (denotes the creep crack initiation value of the material)	MPa √m
K_{Iid0}	Fictitious elastic K-value at time zero	MPa √m
R_σ	stress-(far field) ratio	-
σ_{npl}	Ligament stress	MPa
R_{mt}	Creep rupture strength	MPa
r_a	Outer radius of a pipe bend	mm
s_{vi}	Wall thickness intrados	mm
s_{va}	Wall thickness extados	mm
R	Bending radius	mm
a_0	Initial depth of notch	mm
c_0	Initial half length of notch	mm
p_i	Internal constant pressure	MPa
T	Temperature	°C
$\overline{\sigma}_a$	Mean stress in pipe bend wall	MPa
$Y\sigma$	Stress intensity factor correction function	MPa
σ_{max}	Maximum value of the absolute stress level (max. tensile stress)	MPa
P_m	Primary membrane stress	MPa
k_t	Stress concentration factor	-
k_m	Membrane stress concentration factor	-
M	Stress magnification factor	-
M_m	Stress intensity magnification factor	-
f_w	Correction terms in stress intensity for elliptical flaws	-

6.1 Brief Overview

The two-criteria-diagram distinguishes between the two main damage modes (ligament damage and crack tip damage) and is able to show the influence of combination of both modes on creep crack initiation. So it is possible to determine the initiation time of different short and long cracked specimens regarding the loading situation at the crack tip and in the fare field (ligament) [6.1-6.5].

The stress intensity- (crack tip) ratio $R_K = K_{Imax}/K_{IA}$ and the stress- (far field) ratio $R_\sigma = \sigma_{npl} / R_{mt}$ are used. The two parameter stress intensity at the defect (K_{Imax}, to consider the crack tip situation) and the nominal stress ($\sigma_{npl,}$ to consider the ligament stress) have to be determined. Then they are compared with corresponding time dependent values for creep crack initiation (stress intensity K_{IA}) and for creep rupture strength ($R_{m,t,T}$) (Figure 1).

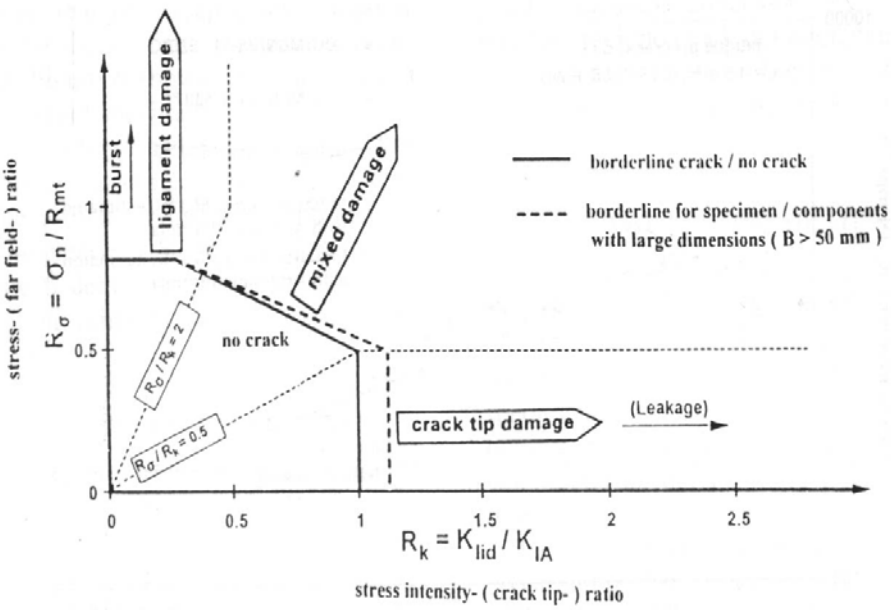


Figure 1 Two-criteria-diagram for creep crack initiation, 1% CrMoV [6.1]

6.2 Calculation example

<u>Estimation of crack initiation for pipe bend P22/B2</u> [6.4]:
Material P22 according to ASTM A335

<u>Diametrical data:</u>

Outer radius:	78 mm
Wall thickness intrados s_{vi}:	22.2 mm
Wall thickness extrados s_{va}:	16.5 mm
Bending radius R:	468 mm
Initial depth of the notch a_0:	7.6 mm
Initial length of the notch 2 c_0:	40.0 mm

<u>Loading conditions:</u>

Inner pressure p_i:	25 MPa
Temperature:	565 °C

The ovality of the pipe bend is neglected. The orientation of notch Y is longitudinal (axial surface crack).

CALCULATION STEPS:

6.2.1 Calculation of mean stress in the pipe wall at the extrados according to TRD 301 [6.6]:

$$\overline{\sigma}_a = \frac{\mathrm{p}*(2*\mathrm{r_a} - s_{vi} - s_{va})}{2*s_{va}} * \frac{2*\mathrm{R} + \mathrm{r_a} + 0{,}5*s_{vi} - 1{,}5*s_{va}}{2*R + 2*r_a - s_{va}} + \frac{\mathrm{p}}{2}$$

$$\overline{\sigma}_a = 95MPa$$

6.2.2. Calculation of stress intensity factor KI (acc. to [6.7] chapter J.4.2.5, level 1)

Parameters for table J8 of [6.7], J.4.2.5:

$$\frac{a_0}{B} = \frac{a_0}{s_{va}} = 0{,}46 \qquad \frac{a_0}{c_0} = 0{,}38 \qquad \frac{B}{r_i} = \frac{s_{va}}{r_i} = 0{,}28$$

Quantity $M_m(d)$ of Table J8 [6.7]: $M_m(d) = 1{,}16$

Stress intensity factor according to [6.7], equation J1 to J7 for fracture assessment, level 1:

$$(Y\sigma) = k_t * M * f_w * M_m\left[\sigma_{\max} + (k-1)*P_m\right]$$

with k_t=1; M=1; f_w=1 and k_m=1

$$(Y\sigma) = 1{,}16*95MPa \qquad K_I = (Y\sigma)*\sqrt{\pi * a_0} \qquad K_I = 17.03MPa\sqrt{m}$$

6.2.3 Calculation of stress ratio R_σ for the two-criteria-diagram:

$$R_\sigma = \frac{\sigma}{R_{mt}}$$

Table 1

Time in h	R_m (565°C) in MPa	σ in MPa	R_σ
100	≈ 156 *)	95	0,61
1000	≈ 125 *)	95	0,76

*) data from ENEL data base [6.2]

6.2.4 Calculation of stress intensity ratio R_K for the two-criteria-diagram:

$$R_K = \frac{K_I}{K_{IA}}$$

The K_{IA} data are gained from CCG tests on lab specimens [6.2].

Table 2

Time in h	K_I in MPa√m	K_{IA} in MPa√m	R_K
100	17,03	≈ 24	0,71
1000	17,03	≈ 15	1,13

Two-criteria diagram for estimation of crack initiation time

The prediction of crack initiation time is demonstrated in Figure 2.

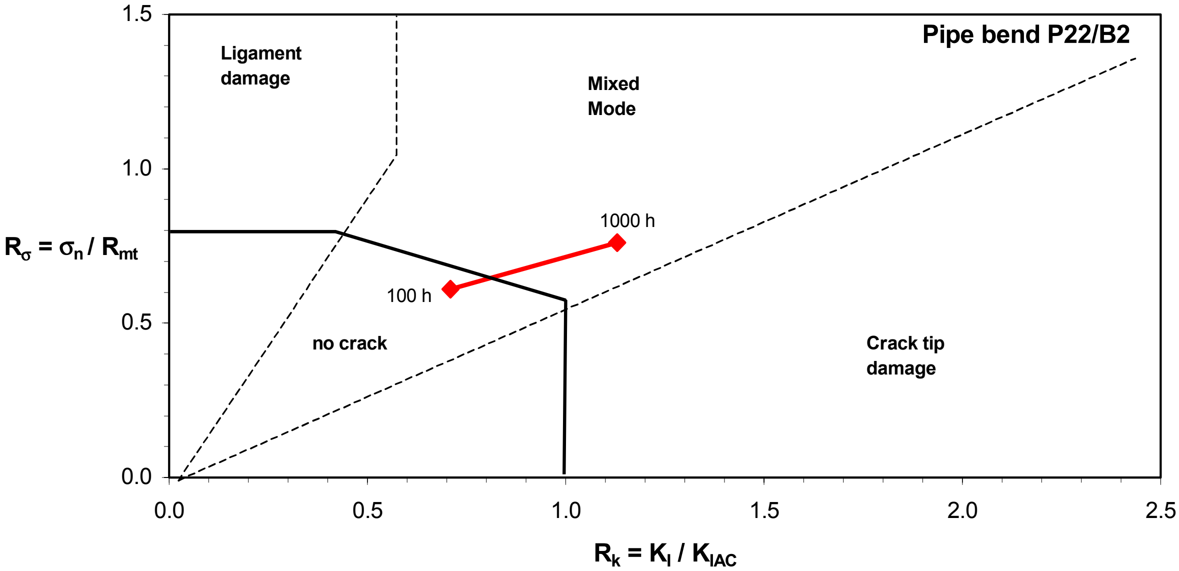


Figure 2 Prediction of the crack initiation for notch Y of the pipe bend P22/B2 [6.4]

The predicted initiation time for notch Y of the pipe bend P22/B2 is about 100 h. The crack growth measurement showed immediate crack growth without significant incubation period. The estimation is in good accordance with the measured data as a short initiation time is predicted on the basis of the two-criteria-diagram [6.4].

In a MPA-proposal a method was given to estimate crack initiation for creep fatigue loading also. A modification was made, by evaluation K_{Iid} and R_m at a corrected time, which is reduced by 40%, taking into account the influence of load cycles on damage [6.3, 6.8].

7. EN 12952-4 & ISPESL - ASSESSMENT PROCEDURE

7.1 Brief overview of EN 12952-4

The procedure of calculation showed in EN 12952-4 regards in-service boiler life expectancy. This procedure includes life calculation using the diagram 0,8*R_{mTtc} vs. T, where R_{mTtc} is creep rupture strength at tc temperature (main temperature of each temperature increment) and T is time to reach theoretical rupture by creep. This calculation can be used to determine a guideline for the decision to inspect for creep by replica method or any other suitable method.

If necessary, more detailed assessment method may be used (the standard suggest PD6539). The pressure component under investigations can be used even if the ratio operating time/time to theoretical rupture exceeds the value of 1.

7.2 Brief overview of ISPESL P.T. 15/92

The procedure regards calculations, examinations and controls to perform on pressure parts designed to work in creep conditions.
This evaluations includes the following steps:

1. preliminary analysis of design parameters, history and previous controls of the component to inspect; preliminary calculation of life to determine places to control by NDT;
2. NDT examination plan;
3. NDT execution including replicas;
4. calculation of life in real operating condition, using results of NDT (i.e. real thickness of pressure parts);
5. final evaluation of pressure equipment based on the results of all performed analysis; it very important to verify congruence within these results.

The procedure imposes the use of a method to calculate life expectancy of pressure component (the method is the same of EN12952-4); it imposes also the use of mandatory NDT tests.

7.3 ISPESL method

Since 1989 ISPESL has emanated dispositions for pressure equipment designed in the creep range according to time dependent mechanical properties.. During the years, on the base of the results of in-field examinations, the original procedure has been improved and sharpened through a series of new provisions.

During the last two years ISPESL has proceeded to revise and update the emanated regulations,. Now a new entire legislation covers all the subject and it is set as an advanced mean of investigation for equipment working in the creep range.

The legislation in matter has been elaborated by keeping in mind the previous experience, the indications of users and , the European and international standards. ISPESL technical procedures n. 15/92 (of February 27th 1992) established the verifications to perform on steam boilers and steam or gas pressure vessels, operating in creep range. After over ten years of successful application of the same procedures and after the issue of further explication on the matter (Circ. 11/93 - 11.2.1993, Circ. 12/93 - 15.2.1993, Circ. 24/94 - 14.2.1994, Circ. 139/94 - 19/12/1994, Circ. 20/97 - 19.2.1997, Circ. 100/98 - 29.9.1998) ISPESL decided, in order to clarify, to proceed to summarize the contributions of the above list in an unique document. Furthermore, the new technical procedure, (synthetically denominated PT) adjusts the dispositions to the state of the art on the matter.

The new PT is a modular procedure. Close to the technical procedure, that establishes the general criterions to follow for the examination on component, a guideline has been compiled to supply an operational tools to effect the evaluation of the residual life. This guideline is synthetically indicated as LG. The new technical procedure includes, with the limitations specified, the equipment manufacturing according to the Directive 97/23/CE (PED). A new version of LG must subsequently be completed inserting some integrations in the section related to the conventional creep temperature. The new document introduces all the new concepts of modern philosophy of the life-extension is marking, as risk analysis, “Fitness for service" and “Risk Based Inspection."

7.3.1 Structure of the PT

The structure of the procedure is the following: a procedure core, to point out the fundamental footsteps to follow to achieve the authorization for pressure equipment that has overcome design theoretical life, and nine annexes working as guidelines, to drive the investigation on life consumption.
The annexes treat of the followings matters:
1. Conventional temperature of creep initiation
2. Computational methods for creep
3. Computational methods for fatigue
4. Combined damage creep-fatigue
5. Non destructive testing
6. Metallographic examination by replicas
7. Reinspection intervals
8. Numerical examples
9. Summarized report on design and service

The presence of annexes separated by the procedure core allows periodic updating, on the base of the state of the art, without modifying the fundamental principles of the document. It has been easy to ascertain that, in this field, the technical evolution and legislation updating (world wide) is continuous, and it is therefore necessary to foresee the possibility to integrate or to modify, if necessary, the technical dispositions contained in the same text.

The technical procedure not only introduces itself as a simple legislative disposition but also as a real" manual" for residual life evaluation, susceptible of continuous improvements and updating in relationship to technique progress.

7.3.2 The basic text of the document

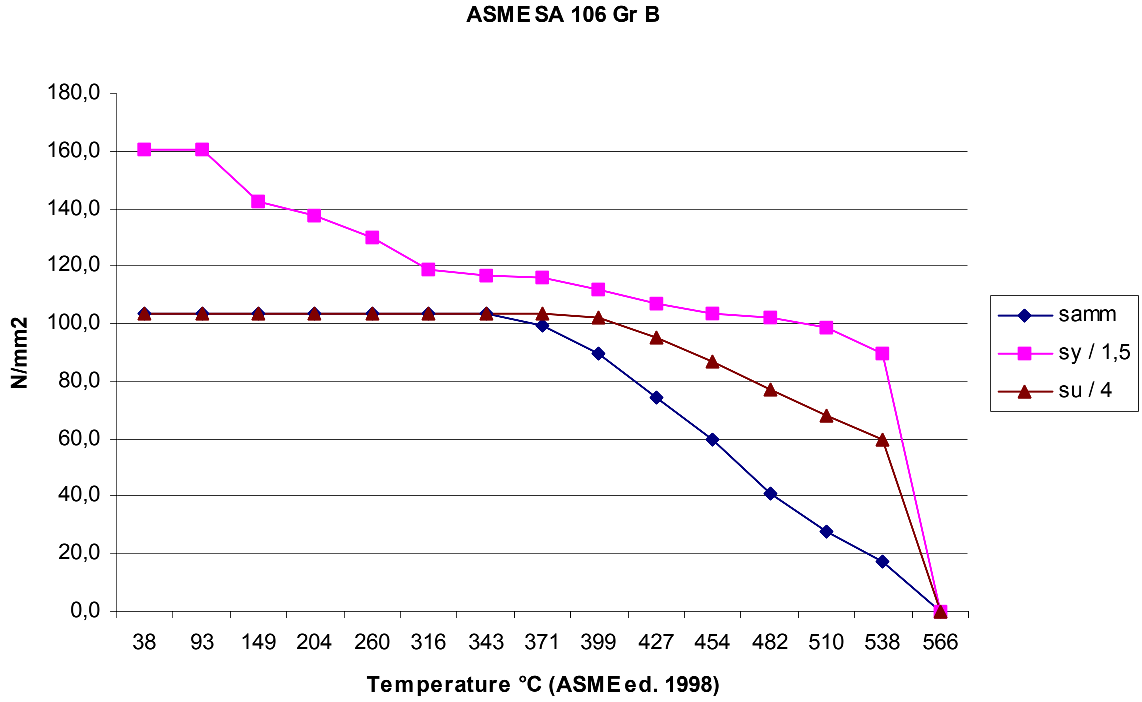
The central body of the document is structured on the model of the technical procedure attached to ISPESL former disposition (n.15/92), introducing however some substantial novelties.
In first place the new PT has widened the scope of 15/92 Circular to equipments built according to Directive PED, to fill a legislative gap connected to the new dispositions in pressure vessels manufacturing.

It is also been introduced the concept of "risk analysis", in a way similar to other European directives of the “new approach”, with the purpose of identifying the most remarkable parts, according to safety principles, to consider in the evaluation of consumed life.

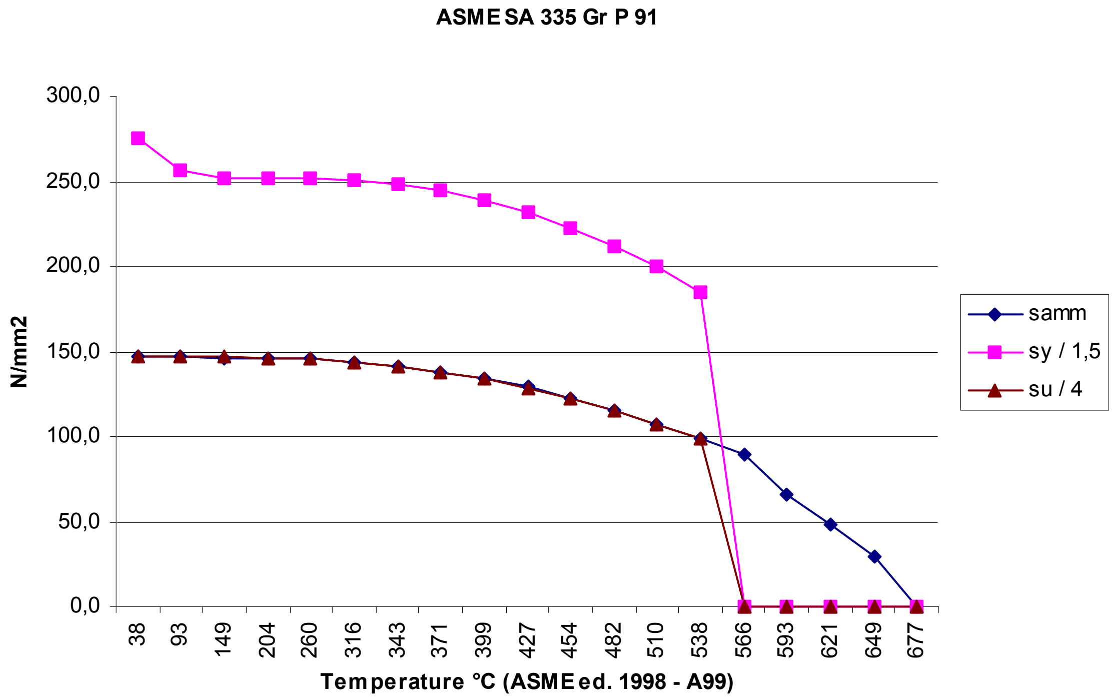
Whereas, in national and international standards, already exists some valid and consolidated normative references (for instance ISO, CEN, UNI, BSI, CTI, etc.), the revision has been limited to an indication of the limitations in the use, avoiding so an excessive weighting of the document.

Annex 1: Conventional temperatures of creep initiation

A notable job has been carried out with the purpose to individualize the conventional temperatures of creep initiation. For some materials objective difficulties exist in the determination of the value of such temperature. Anyway the new PT proceeds, where possible for well known materials (e.g. ISPESL Raccolta M materials), to determine the point of intersection among $R_{p(0.2)}$ and $\sigma_{r/100000/T}$, through interpolations e/o graphic linear extrapolations . At the moment it is under investigation a procedure that allows the determination of the conventional temperature for ASME materials. It must be underlined that ASME ed. 2001 does not give exhaustive details about this value, as well: the only point that has been fixed is the point from which allowable stresses are surely obtained by time dependent properties.



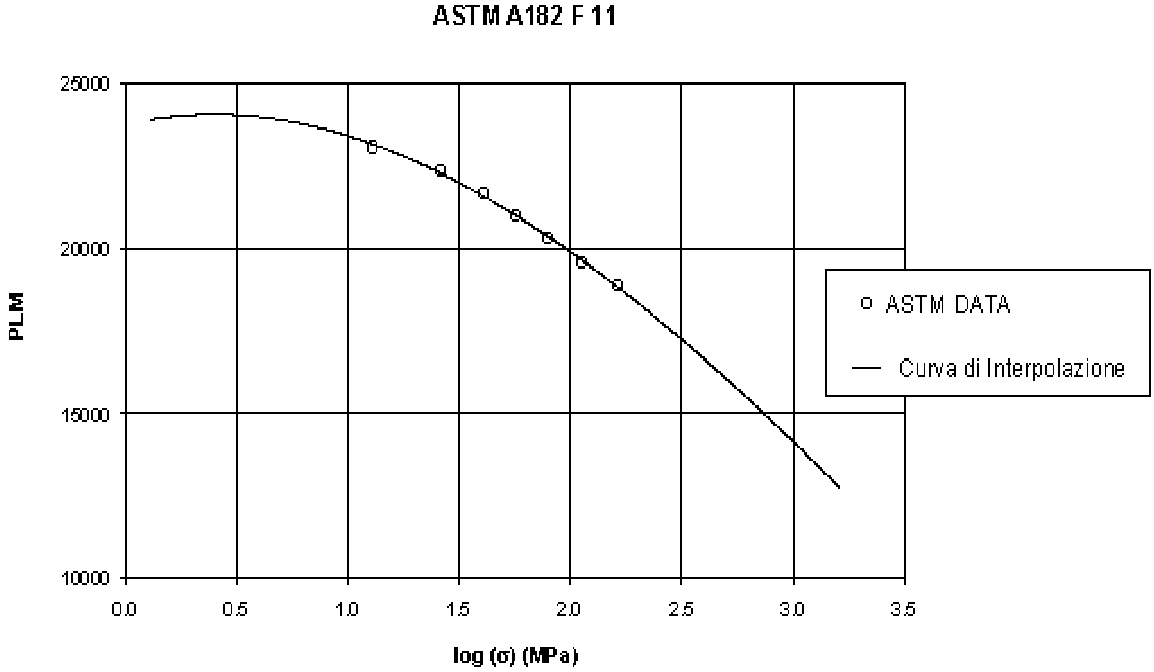
Conventional temperature of creep initiation (SA106 Gr. B)



Conventional temperature of creep initiation (SA335 P91)

Annex 2: Calculation of consumed life under creep conditions

Having ascertained, by several hundred examples and simulations, that the role of life calculation rarely leads to absolute results, it has been held opportune to consider such parameter as further information to individualize risk degree in the equipment, rather than an indicative value of the life really consumed by the equipment. Experience has shown that consumed life is deducible by results of calculation, metallographic replicas and non-destructive testing. It is held opportune to leave greater flexibility to the Designer in the choice of computational methods, giving the possibility to choose among more computational methods. Particularly, on the base of the acquired experience in international field, it is suggested to pass through the construction of one" master curve" by PLM parameter - interpolating the available points; from " master curve", it can easily be traced creep curve for various temperatures in the bi-logarithmic diagram stress vs. time. The validity of the interpolation can be checked through criterions of" Post Assessment Test" according to the ECCC Recommendations Vol. 5": Guidance for the assessment of creep rupture, creep strain and stress relaxation dates".



Master curve

Annex 3: Calculation of consumed life under fatigue conditions

Even if till now there have been few cases of equipments subject to fatigue damage, it is also true that power plants (due to a market submitted to" deregulation") work according to flexible regimes of "two-shift" or "load-follow" in which fatigue cycles become often remarkable. It has been considered that in a next future, due to different ways of working of power plants, the influence of the fatigue on the consumed life for steam boilers cannot be neglected anymore; so we decided to adopt, in annex 3, the procedure derived by the European norm EN 12952 "water tube boilers", in which it is foreseen that the fraction of consumed life for fatigue is the sum of single cycles contribution and of relative extremes contribution.

Annex 4: Calculation of consumed life under combined creep-fatigue conditions

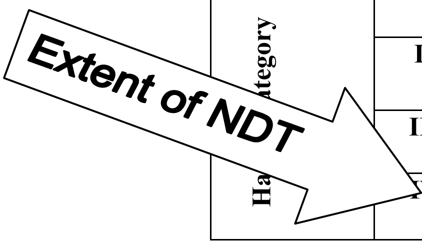
The criterion adopted for esteeming the damage due to the interaction creep-fatigue is the widely used method based on the linear overlap of the damage according to the rule of Miner and Robinson. The cumulative damage D is estimated by graphic methods through available diagrams in the specialized literature.

Annex 5: Recommended procedure for NDT planning

In order to rationalize the planning of NDT (type and extension), a new recommended procedure on "risk based" procedure developed by ISPESL has been introduced a. By this procedure it is possible to make reference to a parameter (shortly defined PEC) function of risk category of the equipment, according to directive 97/23/CE, of the level of consumed life and of the type of welding. Associated to a specific value of PEC is a specific extension of NDT and a specific inspection technique, for every welded joint.

Table 2. Extension of NDT

		Level of Expended Life fraction			
		α	**β**	**γ**	**δ**
Ha[illegible]ategory	**I**				
	II				
	III				
	[illegible]V				



The introduced parameter constitutes a fundamental footstep to tie, in systematic way, the extension of the non-destructive testing to the connected risk to the specific structure investigated.

For the specific case of steam generators with "multiple" headers an NDT plan has been proposed to cover, in cyclical way, all the headers during subsequent periodic controls, using PEC discriminating parameter, indicative of the state of connected risk of the equipment and the consumed life deduced by the calculation.

Annex 6: Metallographic replicas

Annex 6 concerns some guidelines to drive collecting and observation of morphological and cavitative replicas; it brings also indicative charts for the classification. In comparison to the former versions the annex has nearly been unchanged.

Annex 7: Recommended procedure for the determination of reinspection intervals

Coming back to Risk Based Inspection, it has been proposed an innovative method that, starting from already existing procedures (RBI type), as API 579, 580 and 581, individualize through of the matrixes of risk reinspection intervals. In such method, beginning from the results of non-destructive testings and metallographic replicas, damage degree of component is characterized and consequently its level of risk is assessed. Time durations individualized through such procedure can be increased adopting a more severe control plan, respect to that expected.

Adoption of this methodology allows to overcome the "personal opinion of the planner and/or designer" in the choice of time duration between two subsequent investigations and facilitates the role of the ISPESL, like independent control body, guaranteeing greater uniformity of behavior towards final user companies.

Annex 8: Numerical Examples (annex 1 to this file)

In order to clarify the application of the procedure for NDT planning and for individualization of NDT techniques, a relative numerical example has been brought to a practical case. The applied procedure is the recommended one in annexes 5 and 7. Nevertheless the Planner can choose to apply other procedures, if more suitable to the specific case.

Annex 9: Summarized report on design and service

Annex 9 synthetically illustrates the operational data that has to be included in the final report of the investigation. ISPESL is collecting a lot of data based on files checked during last ten years. The summarized report help ISPESL to collect this kind of data. The report lists in systematic way all the information of interest that will be inserted in ISPESL database and whose statistic anonymous results will periodically be divulged for the benefit of interested subjects.

Annex 1 (numerical example)

ISPESL	Recommended Guide Lines for life assessment of pressure equipment under creep conditions ***Numerical Examples***	***Section 8*** **LG v.1**

Example: Superheater header

Below you can find a practical example to plan NDT and reinspection intervals, according to recommended practice for section 5 and 7.

MAIN DATA
We took under examinations an SH header of the following steam boiler:

- Consumed life = 24.8%
- Service hours: 120'000
- Equipment category (PED): IV
- Header length L=4000
- Outer diameter: 350

PRELIMINARY NDT PLAN
This kind of component requires the following criticality levels (Fig. 1):

- Very low level (A) for non-pressure part welding;
- Low level (B) for welding between header and nozzles to heat exchanger pipes (De<100);
- High level (C) for welding between header and big nozzles to connection tubes (De≥100);
- Very high level (D) for circumferential welding of headers or tubes.

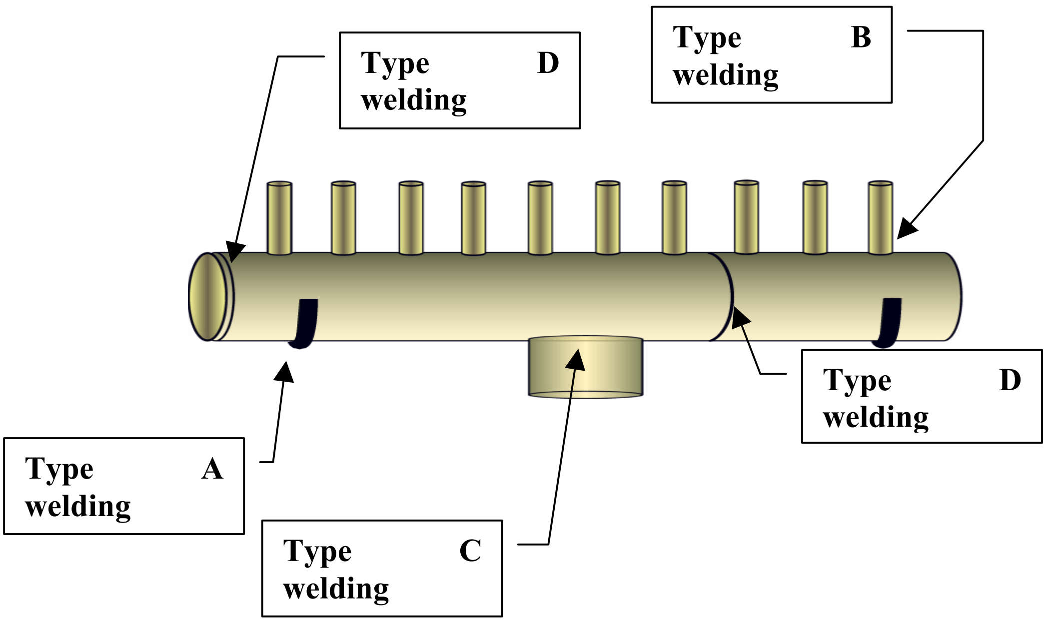


Figure 1 Welding joints classification

From Table 1 it is possible to obtain NDT to perform, introducing the right criticality level.

Table 1 NDT methods determination

Weld criticality level	NDT to perform	
	Mandatory	**others**
A	VT, PT (or MT)	ST
B	VT, ST, MT (or PT)	ET
C	VT, ST, UT, MT (or PT)	RT
D	VT, ST, UT, MT (or PT)	RT
E (base material)	VT, UTS	DM

In next table you can find a specific level taking into account consumed life: for the header shown above we find consumed life level α.

Table 2 Consumed life level determination

Level	**α**	**β**	**γ**	**δ**
Consumed life	0 ÷ 25%	25% ÷ 60%	60% ÷ 90%	90% ÷ 100%

By next table it is possible to individuate, for each welding, PEC values (Preliminary NDT Extension Parameter).

Table 3 PEC individuation

	PEC_p	**Consumed life level**			
		α	**β**	**γ**	**δ**
PED hazard category	**I**	**1**	**1**	**2**	**2**
	II	**1**	**2**	**2**	**3**
	III	**2**	**2**	**3**	**4**
	IV	**2**	**3**	**4**	**5**

Regarding above header the parameter PEC is 2.

NDT extension can be find in the following table (this table is only for steam boiler headers):

Table 4 NDT extension versus PEC and versus criticality of the welding

Criticality of the welding	NDT method		PEC: Low PEC 1	Moderate PEC 2	Medium PEC 3	High PEC 4	Very High PEC 5
A: Header/non-pressure parts	**Basic**	**VT**	100%	100%	100%	100%	100%
		PT (o MT)	60%	70%	80%	90%	100%
	additional	**ST**	*	*	*	*	*
B: Header/little nozzles	**Basic**	**VT**	100%	100%	100%	100%	100%
			1% welded joints (max 2, min 1)	1,5% welded joints (max 2, min1)	2% welded joints (max 2, min 1)	3% welded joints (min 2)	5% welded joints (min 2)
			10% welded joints	20% welded joints	30% welded joints	40% welded joints	50% welded joints
		ET	*	*	*	*	*
C: Header/big nozzles	**Basic**	**VT**	100%	100%	100%	100%	100%
		ST	1	1	1	2	2
		UT	70%	80%	90%	100%	100%
		MT (o PT)	70%	80%	90%	100%	100%
	additional	**RT**	*	*	*	*	*
D: Circumferential welded joints	**Basic**	**VT**	100%	100%	100%	100%	100%
			1	1	2	2	2
			80%	90%	100%	100%	100%
			70%	80%	90%	100%	100%

	additional	**RT**	*	*	*	*	*
E: Base material	**Basic**	**VT**	100%	100%	100%	100%	100%

			**	**	**	**	**

	additional	**DM**	*	*	*	*	*
Internal surface	**Basic**	**VTE**	20%	30%	50%	80%	100%

<u>Note:</u>
* according to designer/inspector evaluations
**map yet to define

Table calculated according to above SH header data:

Table 5 – Preliminary NDT Planning

Weld		**NDT**	**PEC 2**
A: Header/non-pressure parts	**Mandatory**	**VT**	100%
		PT (o MT)	70%
	Additional	**ST**	-
B: Header/little nozzles	**Mandatory**	**VT**	100%
		ST	1.5% welded j. (max 2)
		MT (o PT)	20% welded j.
	Additional	**ET**	-
C: Header/big nozzles	**Mandatory**	**VT**	100%
		ST	1
		UT	80%
		MT (o PT)	80%
	Additional	**RT**	-
D: Circumferential welded joints	**Mandatory**	**VT**	100%
		ST	1
		UT	90%
		MT (o PT)	80%
	Additional	**RT**	-
E: Base material	**Mandatory**	**VT**	100%
	Additional	**DM**	-
Internal surface	**Mandatory**	**VTE**	30% (***)

(***) if it is possible to reach internal surface

<u>DEFECTS CLASSIFICATION</u>

We suppose that after NDT examination we have found:

- Creep damage level 3 according Neubauer
- Three superficial cracks on type B welded j., 4 mm deep

The defect classes (CD) according to this damage are the following:

- CD creep=3 (lined up microcavities, see section 6)
- CD cracks: CD_1=4 (see table 6)

Table 6 Superficial defects classification (p=deep, n=number of defects)

				Defect Class (CD)
$p < 2$ $n \leq 2$	$p < 2$ $n \leq 2$	$p < 1$ $n \leq 2$	$p < 1$ $n \leq 2$	**1**
$p < 2$ $n > 2$	$p < 2$ $n > 2$	$p < 1$ $n > 2$	$p < 1$ $n > 2$	**2**
$p \geq 2$ $n \leq 2$	$p \geq 2$ $n \leq 2$	$p \geq 1$ $n \leq 2$	$p \geq 1$ $n \leq 2$	**3**
$2 \leq p < 5$ $n > 2$	$2 \leq p < 5$ $n > 2$	$2 \leq p < 5$ $n > 2$	$2 \leq p < 5$ $n > 2$	**4**
$p \geq 5$ $n > 2$	$p \geq 5$ $n > 2$	$p \geq 4$ $n > 2$	$p \geq 4$ $n > 2$	**5**
A	**B**	**C**	**D**	
Criticality of the weld				

INTENSIFICATION OF NDTs

Applying the procedure brought in section 5 (figure 1 and table 4) it is deduced that, in relationship to the defects found on the welding header/little nozzles, inspection planner must have intensified the control by liquid penetrant (or MT/ET) and metallographic examination.

Particularly, in this example, it is assumed to extend the control to a level equal to the class of the found defect (therefore according to this hypothesis the new value of the PEC has to be at least equal to the numerical value of CD).

The new extension of the controls on the welding header/little nozzles is therefore deducible from the following table:

Table 7 Controls to be intensified on the welding header/little nozzles

	LP (or MT or ET)	ST
Preliminary extension	**PECp=2** 20% welded joints	**PECp=2** 1.5% welded joints (max 2, min1)
New extension	**PECa=4** 40% welded joints	**PECa=3** 2% welded joints (max 2, min 1)

If so performed new controls lead to notice some other defects, it will need to repeat the procedure described for determining further additional controls.
INSPECTION CATEGORY

The general controls performed on the component are those of the following table, where the corresponding extension is suitable.

Table 8 Final Extension of the controls altogether performed

Welded Joint	**NDT method**		**Extension**
A: Header/non-pressure parts	**Mandatory**	**VT**	PEC2
		PT (o MT)	PEC2
B: Header/little nozzles	**Mandatory**	**VT**	PEC2
		ST	**PEC3 (intensification)**
		MT (o PT)	**PEC4 (intensification)**
C: Header/big nozzles	**Mandatory**	**VT**	PEC2
		ST	PEC2
		UT	PEC2
		MT (o PT)	PEC2
D: Circumferential welded joints	**Mandatory**	**VT**	PEC2
		ST	PEC2
		UT	PEC2
		MT (o PT)	PEC2
E: Base material	**Mandatory**	**VT**	PEC2
		UTS	PEC2
Internal surface	**Basic**	**VTE**	PEC2

As it is evident, the extension of controls is level PEC2, except for two controls for which PEC3 and PEC4 are respectively applied.
The category of the inspection can consider level 2 (see section 5).

INDIVIDUALIZATION OF RISK LEVEL

With the purpose to determine the level of risk reference it can be followed a simplified procedure in which probability of breakup and consequences of breakup are expressed in simplified way.

Breakup Probability

Instead of breakup probability it has been here considered (for simplicity) the index of damage (PID. indicative parameter of the damage) defined as function of defect class (number, depth, length etc) and creep damage class (see table 9).

Table 9 Indicative Parameter of damage (PID) as function of the result of NDT and replicas

DEFECT CLASS	5	II	III	IV	V	(*)
	4	II	III	IV	V	(*)
	3	II	II	III	IV	(*)
	2	I	II	III	IV	(*)
	1	I	II	III	IV	(*)
PID		1	2	3	4	5
		CLASS MICROSTRUCTURAL DAMAGE				

(*) Whole welding reparation.

In the example under examination in which the class of the defect is equal to 4 and the class of the micro-structural damage is equal to 3, it is deduced, from the table 9, a PID equal to IV in the welding type B (the most damaged).

Consequences of breakup

Once defined the indicative parameter of the damage (PID), correspondent to the probability of breakup of the component, it is necessary to hold in consideration what consequences can derive from the same breakup. For the specific case in consideration in which the fluid is neither toxic neither explosive, this is tightly dependent from the type of welding and from the criticality level associated. For instance the breakup of a circumferential welding of an SH header can certainly have more serious consequences some breakup of a welding between header and a little nozzle.

Risk Index Parameter

It is possible to define a simplified correlation between index of damage and criticality level of the welding introducing a further parameter (PIR: Risk Indicative Parameter). This correlation is brought in the following table:

Table 10 Risk indicative parameter (PIR) versus index of damage and criticality level of the welding

PID					
	V	PIR 4	PIR 5	PIR 5	PIR 5
	IV	PIR 4	PIR 4	PIR 5	PIR 5
	III	PIR 3	PIR 3	PIR 4	PIR 5
	II	PIR 2	PIR 2	PIR 3	PIR 3
	I	PIR 1	PIR 1	PIR 1	PIR 1
		A	B	C	D
		Criticality level of the welding			

From table 10 it is possible to deduce, for the example in examination, that the welding type B has a level of elevated risk identified by a parameter PIR equal to 4, while the other joints have a level very low, equal to 1, without any other indications (see following table).

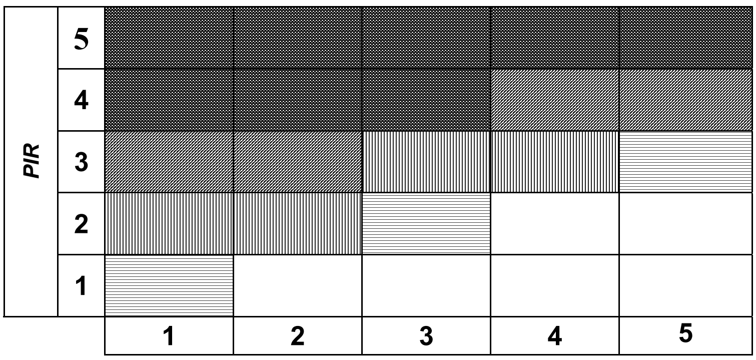
Table 11 Index of damage (PID) and index of risk (PIR) for various welded joints

Welded joint	Defect Class	Micro-structural Class	PID	PIR
A: Header/non-pressure parts	1	1	I	1
B: Header/little nozzles	4	3	IV	4
C: Header/big nozzles	1	1	I	1
D: Circumferential welded joints	1	1	I	1
E: Base material	1	1	I	1

RE-INSPECTION INTERVALS

The number of hours of operation before the following control can be determined as function of maximum PIR value and the Category of the inspection with reference to the following table.

Table 12 Calculation of re-inspection intervals



Category of inspection

To every area of preceding diagram it is possible to associate a re-inspection interval according to the following correspondence :

5.000 hours

7.000 hours

12.000 hours

25.000 hours

40.000 hours

50.000 hours

Nevertheless it is possible, adopting a superior PEC, to increase the interval before following reinspection. In the specific case in examination being the PIR maximum equal to 4 and the Category of inspection equal to 2, an interval 5000 hours is necessary.

Increasing NDT extension a bigger reinspection interval can be admitted (ΔI=7000 hours), increasing from 2 to 4 the inspection Category. Such Category of inspection could be obtained, for instance, increasing from 2 to 4 PEC value on every welding.

The real reinspection interval is the lowest one among that determined by the preceding considerations, 50'000 hours and 60% of the residual life:

$$\text{Reinspection Interval} = \min\,[\Delta I,\ 50.000,\ (60\%\ Hr)]$$

That is, in the specific case under examination:

$$\text{Reinspection Interval}_1 = \min[5000,\ 50.000,\ 218322]=5000 \text{ hours (PEC 2)}$$

or:

$$\text{Reinspection Interval}_2 = \min[7000\ ,\ 50.000,\ 218322]=7000 \text{ hours (PEC 4)}$$

8. TRD 508, VGB-R 509L - ASSESSMENT PROCEDURE

Nomenclature

Symbol	Design Value	Unit
e	Calculated total usage factor $(e = e_z + e_w)$	%
e_w	Calculated usage factor due to cyclic loading	%
$e_{w,i}$	Increase in usage factor (usage factor for single cycle)	%
$e_{w,k}$	Increase in usage factor due to load cycles per rating for the evaluated period	%
e_z	Calculated usage factor for creep	%
$e_{z,k}$	Increase in usage factor for creep per rating for the evaluated period	%
$\hat{n}_i$	Number of load cycles for crack initiation for one range	-
n_k	Number of load cycles obtained in rating k	-
$\hat{n}_k$	Number of load cycles for crack initiation, obtained in rating k	-
p	Working pressure	bar
$\overline{R}_{m/10000/\vartheta}$	Mean value for creep rupture strength for 10,000 hours at operating temperature ϑ	N/mm²
$\overline{R}_{m/100000/\vartheta}$	Mean value for creep rupture strength for 100,000 hours at operating temperature ϑ	N/mm²
$\overline{R}_{m/z/\vartheta}$	Mean value for creep rupture strength for Z hours at operating temperature ϑ	N/mm²
Z	Time	h
Z_0	Operating time until beginning of special inspection measures	h
Z_B	Design lifetime of component	h
$Z_{\vartheta/p}$	Operating time at operating temperature ϑ and working gauge pressure p	h
$Z_{B/\vartheta/p}$	Design lifetime of component at operating temperature ϑ and working gauge pressure p	h
ϑ	Wall temperature (Fluid temperature plus allowance for temperature asymmetries)	°C
ϑ_i	Temperature at inner wall	°C
ϑ_M	Fluid temperature	°C
ϑ_m	Mean wall temperature	°C
$2\sigma_a$	Range of load cycles to be compared	N/mm²
$\overline{\sigma}$	Mean stress due to internal pressure	N/mm²
σ_{gB}	Working stress	N/mm²

8.1 Assessment according to TRD 508 and VGB-R 509L

The inspection measures on creep damage should be planned and stared depending on evaluation of the exhaustion degree. According to the German Codes VGB-R 509L [8.1] and TRD 508 [8.2] the start or extended material inspection is required at the earliest data determined as follows:

- Calculated total exhaustion e= 60% (or fatigue e_w = 50%)
- about 70.000 h for 14MoV6 3, about 100.000 h for the other heat-resistant steels.

Therefore, stress analysis and calculation of exhaustion are required in any case.

- Calculation according to the technical rules, e.g. TRD 301 and ASME-Code Section III, NB 3685 using the real geometrical data and the creep strength neglecting stress relaxation
- numerical calculation of the consumed creep and fatigue life (e.g. the German code TRD 508)
- destructive material testing, non-destructive examinations and strain measurements, e.g. the VGB-Guideline VGB-R 509L
- FE-analysis including equations describing the creep behaviour.

According to VGB-R 509L the intersection point between the time-independent deformation and the time-dependent deformation results from the overlapping of the curves of minimum values of thermal yield strength $R_{p/0,2/\vartheta}/1,5$ with the creep-rupture strength $0,8 * R_{m/200000/\vartheta+5°C}$ (Figure 1).

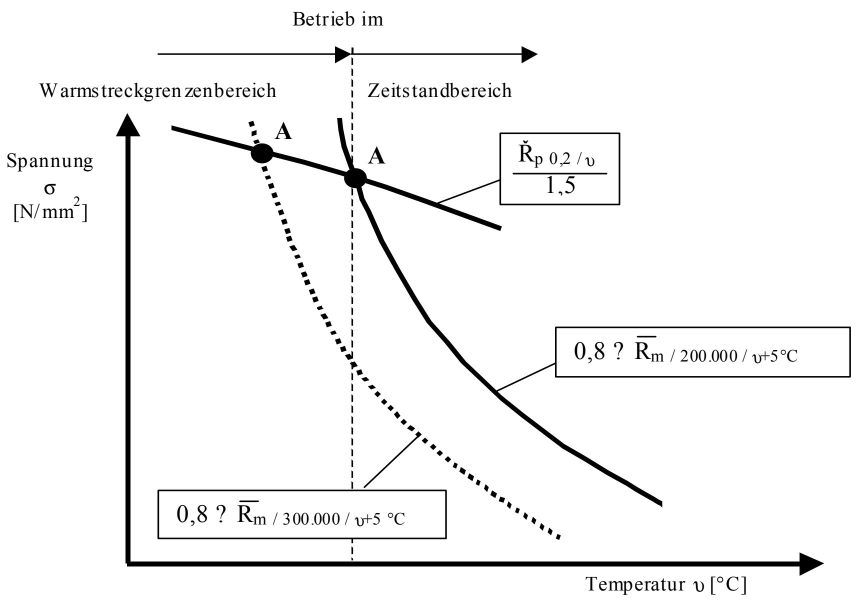


Figure 1 Intersection points of design for different plant materials [8.1]

The intersection point is dependent on the material (Table 1).

Table 1 Limiting temperature according to VGB-R 509L [8.1]

Material	Temperature limit with dominant time-dependent deformation at static loading (°C)
unalloyed steel	400
Mo-alloyed steel	410
17 MnMoV 6 4	420
15 NiCuMoNb 5	420
15 Mo 3	470
13 CrMo 4 4	480
10 CrMo 9 10	470
14 MoV 6 3	500
X 20 CrMoV 12 1	480

The service life analysis contains the comprehensive assessment of the results concerning:

- re-calculation of life time and exhaustion according to TRD 508, Annex 1
- measurement of distension
- testing methods on welds, pipe bends, T- and Y-sections
- other examinations, e.g. creep-rupture tests to determine the creep damage [8.1].

Measurements to be provided for highly loaded components [8.2]

The following measures may be used:

(1) Recording measurement for the evaluation of the loading due to the pressure and temperature,

(2) Recording measurement of temperature differences within the wall thickness of the components which will probably determine the allowable rate of temperature change,

(3) Establishing the possibility for the inspection of temperature measuring points using temperature measuring points that are additionally provided for this propose and that are located in close vicinity to the operational measuring points,

(4) Non-destructive examinations in the manufacture and at the same points for periodic inspections,

(5) Measurements for establishing the geometry, e.g. wall thickness and out-of-roundness measurements,

(6) Measurements for establishing the permanent set,

(7) Examination of the surface texture (microstructure),

(8) Design prosecution of the exhaustion due to fatigue and creep.

8.2 Special examination according to TRD 508

Measures to be taken after the total cumulative usage (exhaustion) e = 60% or e_w = 50% respectively has been attained

i) Non-destructive examinations, such as magnetic particle method, penetration method, ultrasonic and surface texture examination as well as internal inspections by means of appropriate devices (endoscopes and others) shall be taken into consideration. As far as these examinations have been carried out by the manufacturer or user, the inspector may restrict himself to spot-checks.

ii) The examination shall be performed within the scope or periodic inspections, until damages or cases of 1% permanent set have been found, taking into consideration the results of previously performed inspections.

Measures to be taken upon attainment of total usage factor e = 100%

The same examinations as mentioned above apply however, the extent ox examination shall be increased accordingly. A reduction of the inspection period is not required if the usage factor due to creep e_z or the usage factor due to cyclic loading e_w is less than 100% or no damage is detected.

A reduction of the inspection period shall not be required upon a attainment of usage factor e_Z and/or $e_w \geq 100\%$, even if, at that time, the components have been operating over 15 years, which is the normal case, and the inspector decides not to reduce inspection periods upon evaluation of the following examinations.

i) Examination of the respective components with regards to creep damage and damage due to cyclic loading (Surface structure or equivalent examinations must be considered in this case)

ii) Evaluation of the mode of operation intended for the operating period to follow, with respect to the previous operating mode.

This applies to high-temperature ferritic steels.

Measures to be taken after a measured 1% permanent set has been attained.

The same examinations as above mentioned shall apply. The test periods shall be reduced as agreed with the user, unless special operational precautions are taken.

Furthermore the requirements concerning replacement of component are described.

8.3 Methods for the calculation of components having time-dependent design strengths values according to TRD 508, Annex 1 [8.2]

8.3.1 Calculation of service life with regards to creep

The calculation of service life with regards to creep gives preliminary information on the component lifetime. The calculation is based on the pressures and temperatures measured in service and, as far as possible, on the smallest wall thickness that is decisive for component design, and it reveals weak points.

The times Z_0 and Z_B are to be calculated. According to Figure 2 Z_B is obtained at the intersection of the working stress line σ_{gB} and the lower limit curve of the scatter band for creep rupture strength at operating temperature $\left(0{,}8 * \overline{R}_{m/Z/\vartheta}\right)$ and designates the time from which on damage is to be expected.

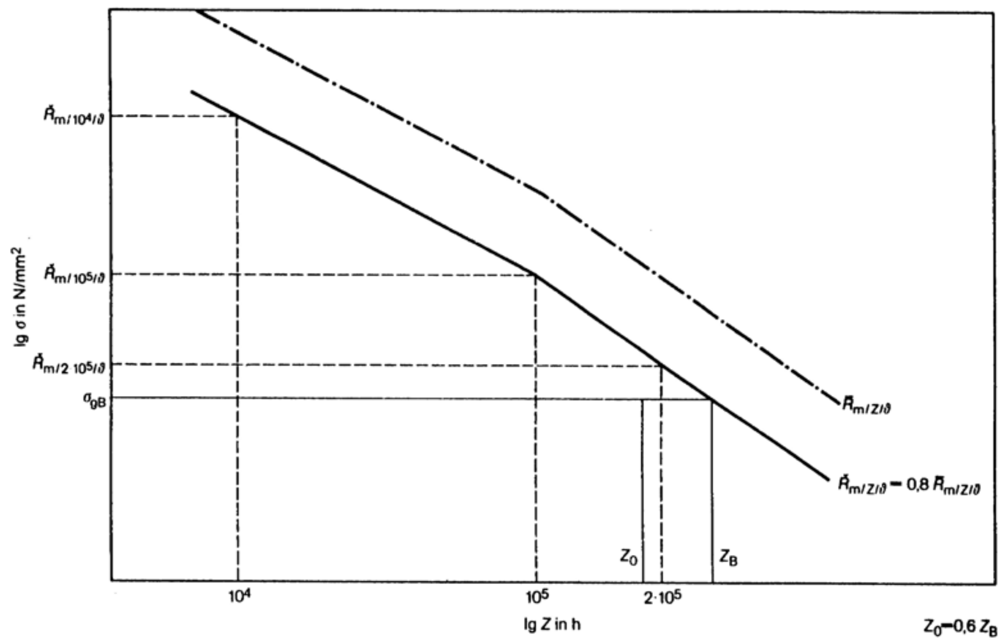


Figure 2 Diagram for the determination of Z_0 and Z

8.3.2 Calculation of usage due to creep

The calculation of the usage factor due to creep is a method that retrospectively takes into consideration the previous mode of operation. It is carried out for highly loaded components on the basis of the operating temperatures and gauge pressures measured.

Using the method a statement is possible whether the pervious mode of operation in relation to the given operation conditions will lead to an increase or decrease of the service life, and when special inspections or a replacement of the components are required.

The usage factor e_z is based on the elapsed operating times $Z_{\vartheta / p}$ and the periods of the component design lifetime, Z. To this end, the user shall compile a summary of the operating times with the pertinent temperature and pressure ratings. To each temperature rating a representative mean temperature is assigned as mean wall temperature in due consideration of a temperature allowance for measuring uncertainties and temperature asymmetries.
From this mean wall temperature and the stress obtained the time Z_B shall be determined.

The usage increase is

$$e_{z,k} = \frac{Z_{\vartheta / p}}{Z_{B / \vartheta / p}} * 100$$

The usage factor due to creep during the evaluated period is obtained from the linear damage rule regarding the portion of service life by summing up the values Δe_z
for all temperature ratings and, if any, pressure ratings

$$e_z = \sum_k e_{z,k}$$

8.3.3 Calculation of usage due to cyclic loading

The calculation of the usage factor of components being subject to cyclic loading shall be carried out in accordance with the TRD sheets of the 300 series.

The usage factor due to cyclic loading is determined from the course of the working gauge pressures, operating temperatures and differences in wall temperature. For all stress cycles being substantial to usage the reduced cyclic stress range $\Delta\sigma_1$ and the cyclic stress range $2\sigma_a$ shall be determined in accordance with TRD 301, Annex 1. Along with the temperature ϑ^* the number of stress cycles being decisive for crack initiation $\hat{n}_i$ shall be taken from TRD 301, Annex 1 or be calculated with the set of formulas describing the group of curves.

The increase in usage factor (usage factor of single cycle) will be, in percent

$$e_{w,i} = \frac{1}{\hat{n}_i} * 100$$

and the sum of factors of usage due to cyclic loading, at the time of the confirmatory calculation, will be

$$e_w = \sum_i e_{w,i} \qquad \text{with i=1,2,..., number of evaluated load cycles.}$$

The increase in usage factor due to cyclic loading (partial usage factor $e_{w,k}$) of the load cycle range considered will be, in percent

$$e_{w,k} = \frac{n_k}{\hat{n}_k} * 100$$

The calculated usage factor due to cyclic loading e_w will be obtained according to the linear damage rule from the sum of partial usage factors $e_{w,k}$ as follows.

$$e_w = \sum_k e_{w,k}$$

For time being, the total usage factor is calculated by summing up the usage factors due to creep and cyclic loading respectively

$$e = e_z + e_w$$

9. EN 12952-3 – DESIGN PROCEDURE

9.1 Brief Overview of EN 12952-3

Below is a summary of the euronorm for creep design:

6.3.2 Design stress for fully load carrying welds operating under creep conditions

Where creep properties for fully loaded joints are not available, the base material values must be reduced by 20% when applied for the design of welded construction for fully load carrying welds (e.g. longitudinal welded tube).

Table 6.3-1: Material strength value K and related safety factor S for rolled and forged steels in accordance with the requirement of Part 2 of this standard

Material strength value K	Safety factor S
	under internal pressure
R_m at 20 °C	2,4
$R_{p\,0,2/t_c}$	1,5
$R_{m/T/t_c}$ [1], [2]	1,25

[1]) T is the minimum specified operational lifetime with a minimum of 100 000 h. If no lifetime is specified 200 000 h shall be taken.

In exceptional cases, where pressure parts are operated in the creep range for short duration (less than 10 000 h) e.g. discharge, relief lines, T may be reduced to 10 000 h with the safety factor 1,25.

Should creep rupture strength values for times in excess of 100 000 h not be available, 100 000 h data may be used with S = 1,5 for internal pressure.

[2]) Creep rupture strength values for intermediate lifetimes shall be obtained by linear interpolation in a double-logarithmic system.

Table 6.3-2: Material strength value K and related safety factors S for cast steel and cast iron in accordance with the requirement of Part 2 of this standard

Material strength value K	Safety factor S		
	Cast steel	Nodular graphite cast iron	
		annealed	non-annealed
R_m at 20 °C	3,2	4,8	5,8
$R_{p\,0,2/t_c}$	2,0	3,0	4,0
$R_{m/T/t_c}$	2,0	–	–

10. RCC-MR – DESIGN PROCEDURE

10.1 Brief Overview

The third edition of the French RCC-MR Code for Fast Reactors (FRs) which includes design rules for elevated temperatures (> 425°C) has been issued by AFCEN (French Society for Design and Construction Rules for Nuclear Island Components).

The aim of this overview is to update the status of RCC-MR code emphasising the progress made since the May 1993 edition in the fields of design rules and material design data :

- Revision of the complete set of material data for French austenitic stainless steel 316L(N),
- Confirmation and revision of, respectively, fatigue and creep weld factors for 316L(N) austenitic stainless steel,
- Extension to plain carbon steels of RCC-MR fatigue assessment with associated design data,
- Completion of the set of material design data for high chromium alloy steel 9Cr 1MoVNb,
- Modification of some Reference Material Specifications to take into account approved European standards,
- Modification of sections related to welding procedure qualification and qualification of welders and operators taking into account European standards,
- Introduction of less conservative ratchetting rules and extension to the case of overstress of short duration and of significant secondary membrane stresses,
- Harmonisation of design rules between class 1 and 2 piping
- For buckling analyses, definition of imperfection and extensions added concerning buckling with significant creep and buckling under cyclic loading,
- Improvements of appendices A10 and A11 (recommendations for inelastic analyses) taking into account recent models,
- Introduction of appendix A16 as a guide for Leak Before Break analysis and associated defect assessment.

10.2 Introduction

The 2002 edition of RCC-MR Code (Design and Construction Rules for Mechanical Components of FBR Nuclear Island) is now available. This new edition available in French and English covers improvements resulting from more than ten years R&D activities in the domain of Fast reactors. The rules and requirements provided by this Code are however not limited to FRs and RCC-MR is therefore the most consistent set of rules applicable in the high temperature domain.

The modifications of this new edition are of different nature:

- Improvement of sets of material properties for base metal and associated welded joints taking into account the latest test results from R&D European activities,

- Larger use of references to European standards,
- Modification of design rules taking into account the feedback from design studies and recent improvements resulting from R&D work,
- Extension of the scope of the RCC-MR by the introduction of a guide for Leak Before Break analysis (Appendix A16).

The aim of this overview is to update the status of RCC-MR code emphasising the progress made since the May 1993 edition [10.1].

10.3 Structure of the RCC-MR Code

Table 1 illustrates the general presentation of the RCC-MR code. The RCC-MR is split into five sections defined as follows:

- Section I provides sets of design rules for various types of components,
- Section II contains procurement specifications for parts and products which can be used for components designed and manufactured according to RCC-MR,
- Section III is devoted to rules for applying the various destructive and non destructive examination methods,
- Section IV gives the rules relating to the various qualifications for welding operations and welding procedures,
- Section V provides rules relating to manufacturing operations other than welding.

Table 1. Table of contents of the RCC-MR code

	Title	Reference symbol
SECTION I	NUCLEAR ISLAND EQUIPMENT	
	Subsection "A": General	RA
	Subsection "B": Class 1 components	RB
	Subsection "C": Class 2 components	RC
	Subsection "D": Class 3 components	RD
	Subsection "H": Supports	RH
	Subsection "K": Examination and handling mechanisms	RK
	Subsection "Z": Technical appendices	RZ
SECTION II	MATERIALS	RM
SECTION III	EXAMINATION METHODS	RMC
SECTION IV	WELDING	RS
SECTION V	FABRICATION	RF

Subsection Z contains a certain number of appendices referenced in the other subsections of SECTION I. Table 2 provides the table of contents of this subsection.

Table 2. Table of contents of subsection Z – Appendices

Appendix	Title
A3	Characteristics of materials
A6	Design of bolted assemblies
A7	Analyses taking account of buckling
A9	Characteristics of welded joints
A10	Elastoplastic analysis of a structure subjected to cyclic loading
A11	Elasto-visco-plastic analysis of a structure subjected to cyclic loading
A12	Design rules for shells of revolution subject to external pressure and cylinders under axial compression
A14	Design rules for linear type supports
A15	Design rules for dished heads subject to internal pressure
A16	Guide for Leak Before Break analysis and defect assessment
A17	Design of flat tubeplates

10.4 Improvement of sets of material properties

The RCC-MR code provides in Appendix A3 consistent sets of material properties which are needed for the application of the design rules of Section I. Appendix A3 covers in particular the following groups of materials:
- Austenitic stainless steels: 316 or 316L(N), 304, 316L, 304L,
- Nickel Iron alloy (alloy 800),
- Carbon manganese steels,
- Chromium molybdenum steels: 2.25 Cr 1 Mo and 9 Cr 1 Mo V Nb grades,
- Precipitation hardened austenitic steel for bolting (25 Ni 15 Cr Mo V Ti Al).

The material properties of Appendix A3 are applicable to the base material. The allowable stresses of the welded joints depend on the quality of the weld (type of joint, extent of control) and on the material properties of the base and weld metal. Appendix A9 provides weld factors which can be used to determine the material properties of the welded joints on the basis of the properties of the base material.

10.5 Revision of the complete set of material data for 316L(N) austenitic stainless steel

The set of material data for 316 L(N) material (A3.1S) has been revised taking into account the most recent results of the European R&D work on this material. This led to the modification of the following material properties:
- Conventional yield strength at 0.2% offset: Rp0.2
- Ultimate tensile strength: Rm
- Values of allowable stresses: Sm and S
- Values of time dependent allowable stress: St
- Creep rupture stress: Sr
- Creep-strain laws.

10.6 Revision of weld factors for 316L(N) austenitic stainless steel

Appendix A9.1J provides weld factors applicable to 19 Cr 12 Ni 2 Mo and 16 Cr 8 Ni 2 Mo filler metals. Following the revision of time dependent allowable stress St and creep rupture stress Sr for 316L(N) steel, the creep weld factors Jt and Jr which are aimed at correcting respectively St and Sr stresses have been also revised. These factors which are temperature and time dependent, are shown (for a given temperature) to decrease with time, which means that the strength of the weld is all the more low compared to the base metal that the hold time is high.
As far as fatigue weld factor is concerned, test results have confirmed that the fatigue curves for the welded joints should be obtained from those for the parent metal by dividing the strain range by the coefficient Jf = 1.25.

10.7 Revision of the set of material data for plain carbon steels

The 1993 edition of the RCC-MR code provided two sets of material data for carbon steels corresponding to A42 and A48 materials (A3.11S and A3.12S respectively).
These sets of material data have been revised following European R&D work and this led to the modification of the following material properties:

- Conventional yield strength at 0.2% offset: Rp0.2
- Ultimate tensile strength: Rm
- Values of allowable stresses: Sm and S. The new values take into account not only the changes of yield strength and tensile strength but also the new definition of Sm and S for ferritic steels which considers at temperature θ a margin on Rm(θ) of respectively 2.7 and 3.6 instead of 3 and 4 in the previous edition.

In addition, these sets of material data have been completed by the addition of all the data needed for design against fatigue:

- Cyclic stress-strain curves and associated parameters Kε and Kν
- Design fatigue curves.

Furthermore, a new set of material data has been added in the new edition of the RCC-MR code for A37 type materials. This set of material data contains the following properties:

- Coefficient of thermal expansion
- Young's modulus
- Poisson's ratio
- Minimum and average yield strength at 0.2% offset
- Minimum and average tensile strength
- Values of allowables stresses Sm and S.

10.8 Completion of the set of material design data for high chromium alloy steel 9Cr 1MoVNb

The material 9Cr 1MoVNb known as modified 9 Cr 1 Mo has been extensively studied in the past year for application to Steam Generator Units for Fast Reactor (in particular in the frame of the European Fast Reactor project) and is presently one candidate for vessel material of HTRs (High Temperature Reactors). The new edition of the RCC-MR provides updated values for the following properties based on the most recent test results:

- Average yield strength at 0.2% offset
- Average tensile strength
- Values of time dependent allowable stress: St
- Creep rupture stress: Sr
- Cyclic stress-strain curves and associated parameters $K\varepsilon$ and $K\nu$
- Design fatigue curves
- Creep-strain laws.

In addition, test results have indicated that this material presented at high temperature an elastic-relaxation behaviour and this could be used to define a value of the symmetrisation factor Ks (used to calculate the stress at the beginning of the hold time, $\sigma k = Ks\ \Delta\sigma^*$ when there is no primary stress, where $\Delta\sigma^*$ is the elastoplastic stress range) significantly lower than that used in the RCC-MR for austenitic stainless steels (see figure 1).

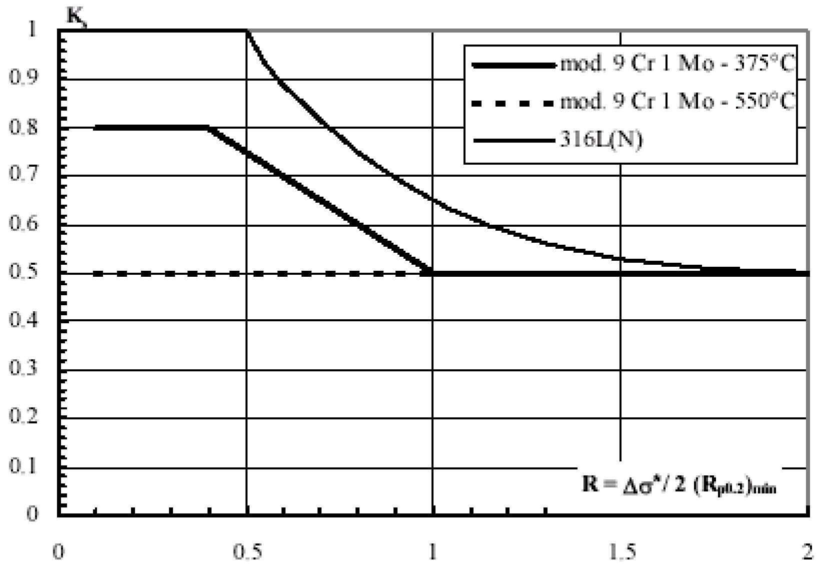


Figure 1 Symmetrisation factor for modified 9 Cr 1 Mo steel

10.9 Modification of reference material specifications

In the 1993 edition of the RCC-MR, references were made to AFNOR standards in some Reference Material Specifications (RMS) in particular for ferritic steels. The corresponding RMS have been modified to take into account European Standards NF EN 10028-2 for pressure vessel steels and NF EN 10025 for supports.

Modification of Sections Related to Welding Procedure Qualification and Qualification of Welders and Operators.

RS 3000 sets out the requirements relating to the qualification testing of welding procedures. This chapter contains the conditions for the execution of welding procedure approval tests and the limits of validity of an approved welding procedure. This chapter has been completely revised in the new edition of the RCC-MR code to refer to European standards NF EN 288-1, NF EN 288-2 and NF EN 288-3.

RS 4000 covers the rules to be applied for qualifying welders and operators. It has been modified in this new edition to refer to European standards NF EN 287-1 for steels and NF EN ISO 9606-4 for Ni-based alloys.

The new RCC-MR chapters are in agreement with corresponding RCC-M [10.2] chapters and the main differences between both codes are linked to the peculiarities of the RCC-MR in particular for what concerns tests at elevated temperature and requirements related to type of welded joints specific to Fast Reactors.

10.10 Improvement of design rules

10.10.1 Improvement of ratchetting rules

Ratchetting (progressive deformation) rules (RB 3260) have been significantly modified to include the most recent results from R&D work. The rules are still based on the efficiency diagram method but modifications are introduced to cover:

- the special case of an overstress of short duration (as in the case of a seismic overstress or of an overstress due to rapid drain-out, to a sodium-water reaction, or to a steam hammer). In this case, correction factors based on [10.3] are introduced making the ratchetting assessment less conservative than if the overload was considered as permanent.
- the special case of structures presenting secondary membrane stresses (e.g. cylinders subjected to axial thermal gradients that vary with time and in space). In this case, primary stresses are calculated not only on the basis of dead weight, pressure or moment loads but also taking into account that a fraction of the secondary membrane stresses acts as a primary stress [10.4].

The new edition of the RCC-MR introduces also less conservative criteria in the efficiency diagram method. In the negligible creep regime, the effective primary membrane stress intensity should not exceed 1.3 times the value of allowable stress Sm whereas the effective primary membrane + bending stress intensity should not exceed 1.95 times the value of Sm in the case of plates or shells (the limits were originally 1.2 and 1.8 respectively). These criteria are equivalent to limiting the strain to respectively 1% and 1.7%. In the significant creep regime, the efficiency diagram method is not any more based on the calculation of a creep usage fraction. The new criteria require that the strain associated to 1.25 times the effective primary membrane and membrane + bending stress intensity is limited to 1% and 2 % respectively. These limits should be divided by 2 in welded joints.

10.10.2 Harmonisation of design rules between class 1 and 2 piping

A new sub-section had been added in the 1993 edition of the RCC-MR code concerning design rules for class 1 piping (RB 3600). These rules were based on class 2 piping rules and the most significant differences between class 1 and 2 rules [10.1] concerned the introduction of elastic follow-up factors and the addition of new criteria related to plastic instability and buckling (RB 3651.113 - Limitation of stresses due to pressure, to load-controlled moments and displacement-controlled moments) in replacement of buckling rules of RC 3670 paragraph.

In the 2002 edition of the RCC-MR, it has been decided to harmonise the two set of rules on the basis of former RB 3600 rules. On the other hand, rules have been modified in order to simplify the determination of elastic follow-up factors.

10.10.3 Improvement of buckling analyses rules

An important parameter of buckling analyses is the value of imperfection. In the new edition of the RCC-MR code, the definition of imperfection for buckling analysis can be based either on tolerances indicated on drawings (as before) or tolerances defined in chapter RF 4200 (maximum values of shape tolerances for typical components).

The new edition of RCC-MR gives a design method for creep buckling analysis of 316 austenitic stainless steel components (A7.5000). This method, which is detailed in reference [10.5], allows critical creep loading or time to be assessed for a shell under mechanical loading. It was first studied and validated on electro-deposited nickel cylinders under external pressure. It is based on a ring model including an initial geometrical imperfection. The material is assumed to be elastic perfectly plastic.

For 316 steel, a set of diagrams has been established giving a reduction factor to Euler instantaneous buckling load which is a function of temperature, hold time, thinness of the structure and geometrical imperfection amplitude. Therefore, knowing this set of parameters, an operating point can be located in the selected diagram, which must be under the curve corresponding to the hold time value (see figure 2).

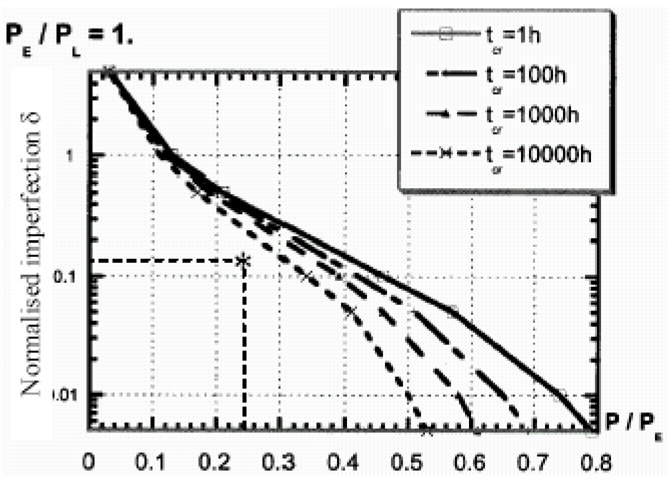


Figure 2 Creep buckling diagram

Another modification of Appendix A7 is linked to the coherence between A7.4000 (buckling under cyclic loading) and the new ratcheting rule of RB 3261.11. The two methods of A7.4200 and A7.4300, where the efficiency diagram is used with modified stresses, are still valid, but they consider in the new edition the primary character of membrane thermal stresses and the influence of primary overloads.

The last improvement of the RCC-MR in relation to buckling concerns Appendix A12 which provides rules to determine minimum thicknesses for shells submitted to external pressure or cylinders under axial compression. The main change is linked to the modification of diagrams necessary for the method (B factor), these diagrams being in the new edition identical to the corresponding ones in RCC-M code [10.2]. In addition, the method for evaluating B factor from any particular tensile curve has been provided.

10.10.4 Improvements of appendices A10 and A11 (recommendations for inelastic analyses)

Appendices A10 and A11 related to elastoplastic and elasto-viscoplastic analysis of a structure subjected to cyclic loading have been rewritten to provide recommendations for Inelastic Analyses.

These appendices provide information on general principles for modelization (Von Mises' plasticity criterion, plastic or creep flow rule, strain hardening law) and give a description of the most commonly used constitutive laws, from the most simple one (perfectly plastic material, isotropic strain hardening material, kinematic strain hardening material) to the most sophisticated one with combined strain hardening (Chaboche model, Burlet-Cailletaud model, Guionnet model, Chaboche-Ohno-Wang model).

They also provide recommendations to engineers on the use of models according to the failure mode analysed. In addition, Appendix A10 provide rules against progressive deformation using simplified elastoplastic methods. Two methods are proposed based on [10.3] and [10.4].

10.11 Guide for leak before break analysis (Appendix A16)

Appendix A16 provides a guide for Leak Before Break (LBB) analysis and defect assessment. The purpose of LBB analysis is to determine if it is possible to detect under in-service conditions the leak flow of a structure containing a fluid (vessel, pipe) prior to the defect that is at the origin of the leak provocates the rupture of this structure.
The LBB approach initially based on [10.6] has been revised since then to include the most recent improvements resulting from R&D work carried out in the frame of a cooperative program between CEA, EdF and Framatome. An extensive test program enabled in particular to validate the A16 procedures on the following aspects [10.7] [10.8]:

- crack propagation and instability under high cyclic load,
- leak rate and crack opening area,
- crack shape evolution up to and after wall penetration

Appendix A16 provides also a comprehensive set of formula for defect assessment and give in particular stress intensity and reference stress solutions for a wide range of geometry. The defect assessment rules and associated material data are consistent with those of the RSE-M Code [10.9].

10.12 Conclusions

The RCC-MR code is a complete set of design and construction rules for nuclear components. The modifications of the RCC-MR in its 2002 edition are supported by more than ten years R&D work in France and Europe and this new edition provides therefore to the engineers a modern set of rules applicable not only to Fast Reactors but more generally to components either operating at elevated temperature or having geometrical features close to those of FRs (thin shells).

11. ASME III SUBSECTION NH – DESIGN PROCEDURE

11.1 Brief Overview

Subsection NH of ASME III [11.1] contains rules for the design of Class 1 nuclear components operating at elevated temperatures, defined as 700°F (371°C) for ferritic steels and 800°F (427°C) for austenitic steels. The procedure allows design assessments to be performed for defect-free components operating in the creep regime. Limits on primary and secondary stresses are provided to demonstrate

(a) margins against plastic collapse
(b) margins against creep rupture
(c) that the component is operating within shakedown

Rules are then given to assess whether creep-fatigue initiation will occur during the component lifetime. Creep damage, D_c, is evaluated using a life fraction rule as

$$D_c = \sum (t/t_r)_j$$

and the fatigue damage, D_f, is evaluated using a Miner's rule as

$$D_f = \sum (n/N)_k$$

Creep rupture and fatigue endurance properties used to evaluate damage are design values, which incorporate inherent conservatisms. The total damage, D, is taken as the sum of the creep and fatigue components

$$D = D_c + D_f$$

Allowable values of the total damage D are shown in Figure 1, noting that the bi-linear interaction used for 304 and 316 steels differs from that recommended for Alloy 800H and 2.25Cr1Mo steel. The effects of stress state on creep damage are incorporated by using an effective stress derived by Huddleston [11.2].

For weldments, weld strength reduction factors are used to account for the inferior creep rupture strength of the weldment compared to the parent material. Similarly, a Fatigue Strength Reduction Factor (FSRF) of 2.0 is used to account for the inferior fatigue strength of the weldment compared to the parent material. It is also required that creep-fatigue initiation calculations for weldments use stress and strain concentration factors appropriate to the worst surface geometry. This is to take account of the potential for welds to exhibit limited ductility and should preclude locating welds in severely loaded regions of components.

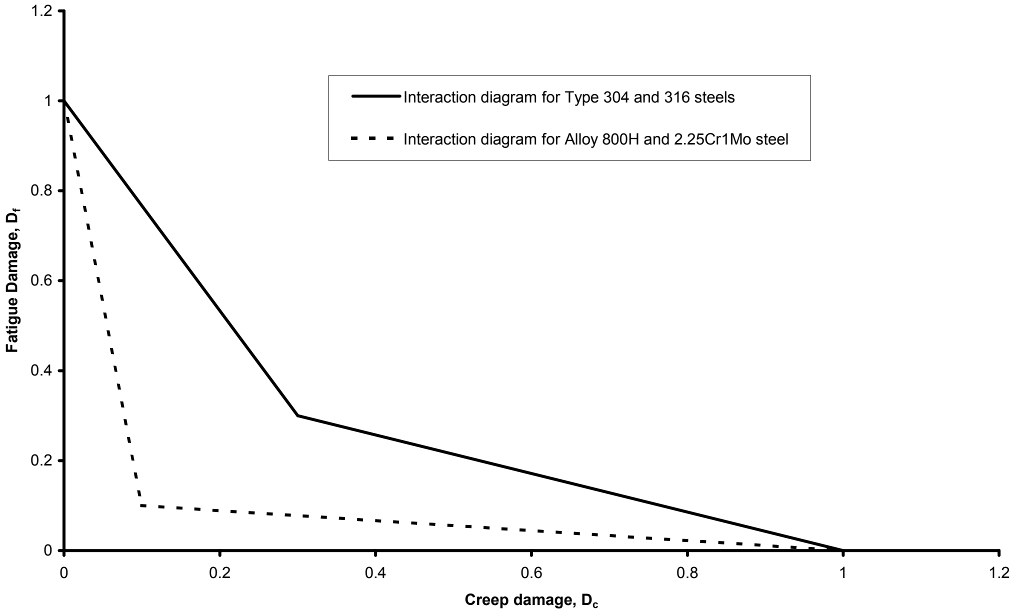


Figure 1 Creep-fatigue damage diagrams used in ASME III subsection NH

12. TRD 300/301 – DESIGN PROCEDURE

Nomenclature

Symbol	Design Value	Unit
d_a	Outer diameter of cylindrical shell	mm
d_i	Inside diameter of cylindrical shell	mm
d_m	Mean diameter	mm
d_{Aa}	Outside diameter of a branch	mm
d_{Ai}	Diameter of openings or inside diameter of branches	mm
e_A	Maximum length of a branch which is effective as compensation	mm
e_G	Maximum length of a main body which is effective as compensation	mm
l_0	Die-out length on main body	mm
l_{A0}	Die-out length on branch	mm
l_{A1}	Die-out length or reinforcement on branch	mm
s_v	Wall thickness of main body, with openings, without allowances	mm
s_A	Required wall thickness of branches, without allowances	mm
s_{A0}	Wall thickness of branches, without allowances	mm
s_{Ae}	Actual wall thickness of branches, without allowances	mm
ϑ	Design temperature	°C
ϑ^*	Governing temperature for calculation in accordance with annex 1 to TRD 301	°C
$\overline{\sigma}_{B/100000/\vartheta}$	Mean value for creep rupture strength for 100,000 hours at design temperature ϑ	N/mm²
$\breve{\sigma}_{B/100000/\vartheta}$	Minimum value for creep rupture strength for 100,000 hours at design temperature ϑ $(\breve{\sigma}_{B/100000/\vartheta} = 0.8 * \overline{\sigma}_{B/100000/\vartheta})$	N/mm²
$\overline{\sigma}_{B/200000/\vartheta}$	Mean value for creep rupture strength for 200,000 hours at design temperature ϑ	N/mm²
$\breve{\sigma}_{B/200000/\vartheta}$	Minimum value for creep rupture strength for 200,000 hours at design temperature ϑ $(\breve{\sigma}_{B/200000/\vartheta} = 0.8 * \overline{\sigma}_{B/200000/\vartheta})$	N/mm²
t_φ	Distance between centres of adjacent openings, offset by angle φ, referred to wall centre, without allowances	mm
v_N	Weld joint factor	-
A_p	Pressure loaded area, without consideration of allowances	mm²
A_σ	Cross-sectional area, effective as compensation without consideration of allowances	mm²
φ_A	Angle of connecting line between two openings, relative to axis of main body	°
σ_i	Ideal-elastic total hole edge stress	N/mm²
$\Delta\sigma_i$	Allowable reduced stress range, or true stress range of σ_i, respectively	N/mm²

12.1 Introduction

This is a German design procedure. The Technical Rules for Steam Boilers (TRD) reflect the present state of safety requirements for the material, manufacture, design, equipment, erection, inspection and testing as well as the operation of steam boilers.

The design rules of the TRD sheets of the 300 series apply to steam boilers and to feedwater heaters, isolatable superheaters, reheaters, desuperheaters as well as steam and hot-water pipes including their valves considered part of the steam boiler plant under § 2(4) of the Steam Boiler Decree (DampfkV).

The design rules of the TRD 301 apply to cylindrical shells with and without openings (tubes, drums, separating vessels, headers, shells, sections, etc.) under internal pressure, for which the ratio $d_a/d_i \leq 1.7$. In addition, diameter ratio of d_a/d_i up to 2.0 shall be acceptable where the wall thickness $s_v \leq 80$ mm.

The design rules only consider loadings caused by internal pressure. Additional forces and moments of significant magnitude shall be considered separately. In Table 1 of TRD 301 the design values are mentioned.

The result of service life calculations is essentially influenced by the wide scattering range of the creep strength value of a certain material. The design rules of TRD demand the use of the lower bound of the ±20 % scatter band of the material specific creep rupture values.

12.2 Calculation example TRD 301: T-joint

For calculation of a T-joint the software programme DIMy (RWTÜV) was used.

Stress calculation according to TRD 301:
Material P22 according to ASTM A335

Input data:

pressure p:	250 bar
temperature T:	585 °C
strength pipe:	60 MPa
strength branch:	60 MPa
safety factor:	1
Outer diameter pipe d_a:	390 mm
Wall thickness pipe s_v:	69 mm
Outer diameter branch d_{Aa}:	178 mm
Wall thickness branch s_{A0}:	31.5 mm
Die-out length on branch l_{a0}:	150 mm
weld joint factor v_N:	1

<u>Output data (in parts):</u>

required wall thickness for branches s_A:	67.24 mm
calculated max. length of branch l_S:	84.9 mm
cross-sectional area, effective as compensation without consideration $A\sigma$:	15139 mm²
pressure loaded area, without consideration of allowances A_p:	38816 mm²
calculated stress:	76.6 MPa

According to TRD Code the stress shall be compared to base material data with a safety factor or 1.5. Than, often the calculated value seems to be very conservative.

In TRD 301 the following calculation examples regarding calculation for predominantly static loading due to internal pressure are specified:

Cylindrical shells without opening
Cylindrical shells with oblique single branch
Cylindrical shells with isolated opening and single vertical branch
Cylindrical shells with multiple openings and branches
Cylindrical shells with non-radial branch
Cylindrical shells with Y-shaped branch.

Further the calculation for cyclic loading due to pulsating internal pressure or combined changes of internal pressure and temperature is described.

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