EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-M

European Project for the development of HTR Technology - Materials for the HTR

CONTRACT N°
FIKI-CT-2000-00032
FIKI-CT-2001-00135

Recommendations for RPV design, choice of material, defect assessment and leak before break methodology

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Dissemination level : CO
Document Number: HTR-M-02/08-D-1.1.40
Deliverable No 1.3

DIRECTION DE L'ENERGIE NUCLÉAIRE
DIRECTION DU CEA/CADARACHE

DÉPARTEMENT D'ÉTUDES DES RÉACTEURS
SERVICE D'ÉTUDES DES RÉACTEURS INNOVANTS
LABORATOIRE DE CONCEPTION DES SYSTEMES INNOVANTS

NT	SERI	LCSI	02/4017	0	5H62	A-RCGMA-02-02	DDIN/SF/P5	1/34
NATURE	SERVICE	LABORATOIRE	NUMÉRO DOC.	INDICE	IDENT. UNITÉ	ÉLÉMENT D'OTP	CLASSEMENT UNITE	PAGE

Note Technique

TITRE : European Project for the Development of HTR Technology – Materials for the HTR - HTR-M Project – WP1 Task 1.5 : Design Rule Check

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RESUME : The development of advanced HTR concepts requires material data information and an understanding of material behaviour under reactor operating conditions.
In the framework of HTR-M, WP1 is devoted to the study of the RPV (Reactor Pressure Vessel) material. Improvements are necessary in the areas of design analysis, structural integrity analysis and material properties data. The aim of this WP is to confirm the choice of a material for the RPV of different HTR concepts.
Several tasks have been identified. The aim of task 1.5 is to check if the existing design rules are suitable and validated for HTR RPV loading conditions and for the corresponding materials.
The present document is a contribution from CEA and Empresarios Agrupados to the task 1.5 : check of design rules. We examine if the design rules recommended by ASME and RCC-MR codes are suitable for this purpose and identify the developments or improvements which are necessary.
We conclude that these rules are appropriate, but some improvements are necessary and some material data are missing or are available elsewhere and have to be codified. One important point to investigate is the behaviour of weld joints.
Other points are also examined such as: irradiation effect and defect nocivity analyses. For that, rules are available in the design codes, they have to be validated for the HTR conditions and experimental programs are necessary to obtain the corresponding material data.

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MOTS CLES : HTR RPV – DESIGN CODES – ASME – RCC-MR

(04/02 - mtc-Document4)

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Date	08/07/02	09/07/02	2/10/2002	09/07/02

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Cadre de réalisation du document.	
DOB	DDIN
Domaine	SF
Projet	P5
Contrat	HTR-M PCRD 5

Classification				
DR	CC	CD	SD	SANS
				X

Indice	OBJET DES REVISIONS	DATE	NUMÉRO DOC.
0	Emission initiale	04/07/02	02/4017

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1. INTRODUCTION

The development of advanced HTR concepts requires material data information and an understanding of material behaviour under reactor operating conditions. Specific studies have been undertaken to identify suitable materials for the different components of the reactor and mainly for the RPV (Reactor Pressure Vessel), the internal structures and the turbine.

In the framework of HTR-M, WP1 is devoted to the study of the RPV material. Validations and improvements are necessary in the areas of design analysis, structural integrity analysis and material properties data. Complementary informations are also needed on manufacturing of products and parts, influence of environment (neutron-irradiation fluence, temperature, helium) and welding.

The purpose of WP1 is to investigate all these points. The final objective is to confirm the choice of a material for the RPV of different HTR concepts, accounting for normal and accidental conditions but also environmental conditions, and to compile the design properties, including the presence of weld joints.

To reach this objective, different tasks have been defined [1]. Different points are investigated such as: identification of sensitive zones to analyse and damage mechanisms to consider, evaluation of the validity of the existing design rules, influence of welds, influence of environment, and review of the existing data base. These different studies allow to identify the missing data and the developments which are necessary to perform the design of RPV.

The present document is a contribution from CEA and EA (Empresarios Agrupados) to the task 1.5 : check of design rules. In previous documents [2,3], an identification of damage mechanisms to consider for the RPV design has been proposed.
Different design codes can be used for RPV design, mainly ASME [4] or RCC-MR [5] codes. In this report we examine if the design rules recommended by these two codes are suitable for this purpose and identify the developments or improvements which are necessary.
We also give indications on complementary analyses, which are not included in the design codes, for instance allowance for the influence of irradiation and structural integrity analyses. Specific developments have been performed concerning these items for other applications. It is necessary to check their applicability in this specific case and to identify the points to improve.

Contribution from CEA is also presented in [14] and contribution from EA in [12].

2. DESIGN OF THE RPV FOLLOWING RCC-MR CODE

Following the RCC-MR procedures [5], we have to perform the analyses hereafter:

- primary stresses limitation or limitation of type P damage
- cyclic stresses limitation or limitation of type S damage

for structures without defects: see §2.1 and 2.2.

Type P damage verification has to be done for level A, C and D conditions. Level B, which exists in ASME code, is not considered in RCC-MR.
Type S damage limitation has to be done for level A conditions.

These analyses do not account for fast rupture, defect nocivity analyses and irradiation influence. These points will be treated in § 2.3.

2.1 LIMITATION OF PRIMARY STRESSES

In [2] we presented the RCC-MR design rules for primary stresses limitation, taking into account the presence of welds and the allowance for creep.

2.1.1 Level A limits

With: P_m : membrane primary stress
P_L : local membrane primary stress
P_b : bending primary stress

the corresponding rules for level A conditions are:

$P_m \le S_m(\theta_m)$ and $P_L + P_b \le 1.5S_m(\theta_m)$

and: $U_{A,C}(\Omega P_m) \le 1$ and $U_{A,C}(P_L + \phi P_b) \le 1$ if creep is not negligible.

$U_{A,C}$ means that this condition has to be verified for all loading situations corresponding to level A and C criteria.

When the primary stress is constant during the whole time, the previous equations are equivalent to:

$\Omega P_m < S_t(\theta_m)$ and $P_L + \phi P_b < S_t(\theta_m)$

where θ_m is the maximal value of the mean temperature in the thickness

S_m allowable stress, independent of time

S_t allowable stress depending of time

U creep damage evaluated as a time fraction using the S_t curves

Ω is a parameter which is introduced to account for the stress redistribution effect due to creep. If all membrane stresses are considered as primary membrane stresses, then Ω=1. If not, $\Omega = \Omega_1 * \Omega_2$ with:

$\Omega_1 = 1 + 0.2\dfrac{P_L - P_m}{P_m}$ if $P_L > P_m$ and $\Omega_1 = 1$ if $P_L < P_m$

$\Omega_2 = \text{Max}\left\{\dfrac{\sigma_1}{P_m}, 1\right\}$ where σ_1 is the maximal principal stress component associated to the equivalent membrane stress P_m

> ϕ is a parameter introduced to account for influence of creep on bending stresses. The value of ϕ depends on the geometry of the section. For instance, for plates and thin shells with a rectangular section ϕ =0.8

In presence of weld joints these rules become:

$$P_m \leq nJ_m S_m(\theta_m) \qquad P_L + \phi P_b \leq 1.5 nJ_m S_m(\theta_m)$$

and $$\Omega P_m \leq nJ_t S_t(\theta_m) \qquad P_L + \phi P_b < nJ_t S_t(\theta_m)$$

where n is a coefficient which depends on the type of joint considered and on the controls performed on the weld during and after realisation, and J_m and J_t are joint coefficients introduced to account for the difference of behaviour between base metal and weld metal.

2.1.2 Level C limits

For level C conditions and when creep is not significant, the rules are similar to the previous ones but $S_m(\theta_m)$ is replaced by Min(1.35*$S_m(\theta_m)$, $R_{p0.2\%min}$) where $R_{p0.2\%min}$ is the minimal yield stress.
In creep situations, the condition is the same as in level A conditions:

$$U_{A,C}(\Omega P_m) \leq 1 \quad \text{and} \quad U_{A,C}(P_L + \phi P_b) \leq 1$$

2.1.3 Level D limits

For level D conditions and when creep is not significant, the rules are similar to the level A conditions but $S_m(\theta_m)$ is replaced by Min(2.4*$S_m(\theta_m)$, 0.7$R_{m\ min}$) where $R_{m\ min}$ is the minimal tensile stress to rupture.
In creep situations, we must check:

$$W_{A,C,D}(1.35 * \Omega * P_m) \leq 1 \quad \text{and} \quad W_{A,C,D}(1.35 * (P_L + \phi P_b)) \leq 1$$

where W is the creep damage to rupture. W is evaluated as a time fraction using the creep time to rupture curves: S_r curves.

2.1.4 Material data

These rules on primary stresses can be used for the design of the HTR RPV. In RCC-MR, the material data necessary for base metal (S_m, S_t, $R_{p0.2\%min}$, $R_{m\ min}$ and S_r) in 2¼Cr and mod 9Cr1Mo are given in Appendix A3-16S and A3-18S respectively. These data are available up to 550°C for 2¼Cr and up to 600°C (S_m, $R_{p0.2\%min}$, $R_{m\ min}$) or 650°C (S_t, S_r) for mod 9Cr1Mo.

Values of n are given in the RCC-MR RB 3300.

A specific Appendix (Appendix A9) is dedicated to joint coefficients, but J_m and J_t values are not available for 2¼Cr and mod 9Cr1Mo at the present time.

2.2 LIMITATION OF CYCLIC STRESSES

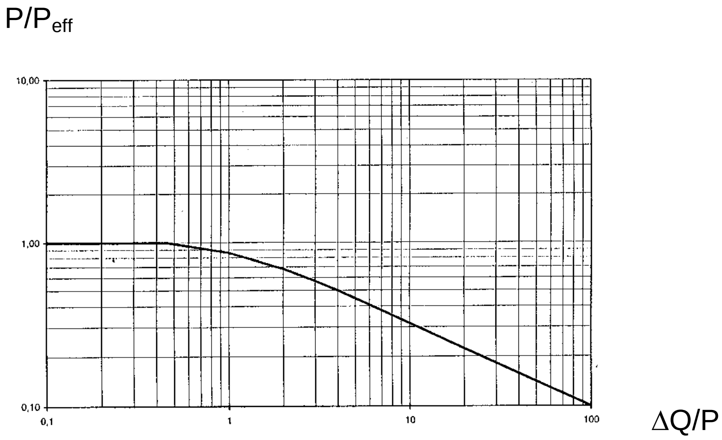
For cyclic stresses, we must check rules to prevent from ratcheting and from fatigue or creep-fatigue, for level A situations. These rules can be applied only when limitations for prevention of type P damage are verified.

2.2.1 Ratcheting

In RCC-MR code, 2 rules are proposed to verify that there will be no ratcheting: efficiency diagram rule and $3S_m$ rule.

2.2.1.1 Efficiency diagram rule

Considering the primary stress P and the secondary stress range ΔQ, an efficient primary stress P_{eff} is evaluated as follows using the efficiency diagram :



Then the rule consists in limiting the value of P_{eff}.

Two efficient primary stresses are evaluated and the limitations depend on the working conditions.

- if creep is negligible:
    - efficient primary membrane stress P_1, considering P_m and ΔQ. In this case we have to check: $P_1 < 1.2S_m$.
    - efficient primary membrane + bending stress P_2, evaluated with P_L+P_b and ΔQ. The rule is: $P_2 < 1.2 *1.5\ S_m$.
- in the creep range, P_1 and P_2 are evaluated in the same manner as before. There is an additive verification to check: $U(P_{eff}/1.2)<1$.

2.2.1.2 3 S_m rule

An alternative rule is:

$$\mathrm{Max}(\overline{P_L + P_b}) + \overline{\Delta Q} < 3S_m$$

This rule can be applied only when creep is not significant.

2.2.1.3 Application to HTR RPV

The previous rules have been developed mainly for austenitic steels, which are cyclically hardening materials. The limitations imposed in the efficiency rule for instance guarantee that the cumulated membrane plastic strain will be lower than 0.45% and the cumulated plastic membrane + bending strain lower than 0.8%. A new issue of RCC-MR is in preparation, in which these limits have been extended to 1% and 2% respectively, as in other design codes.

But mod 9Cr1Mo steel has a specific behaviour: it softens cyclically, mainly in the temperature range 500-600°C. It is not clear at the moment if this behaviour has an influence on ratcheting. Very few experimental results are available.

In the framework of a European research program [6], studies were undertaken in order to make recommendations for the design of components in mod 9Cr1Mo steel under cyclic loading.

A specific task was devoted to the validation of ratcheting rules for this steel. In this study, we showed that for mod 9Cr1Mo, S_m value is determined as a fraction of UTS (Ultimate Tensile Stress or R_m) rather than by a multiple of yield stress $R_{p0.2\%}$. As a result, S_m value is very low when compared to $R_{p0.2\%}$ (see figure 1).

We have the following data:

Temperature °C	450	500
S_m MPa	163	146
$R_{p0.2\%}$ MPa	320	292
$S_m/R_{p0.2\%}$	0.51	0.5
$1.2S_m/R_{p0.2\%}$	0.61	0.6
$3S_m/2R_{p0.2\%}$	0.76	0.75

We concluded that, concerning efficiency diagram rule, the limitation of P_{eff} to $1.2S_m$ is probably very conservative, even when considering the cyclic softening effect. In the same way, the 3Sm rule is thought to be conservative, $3S_m$ value being lower than twice the yield stress. But to be able to improve these rules, experimental results are necessary. No suitable tests were found at this moment to go further.

In this study, other rules were examined: Shakedown method, Bree diagram, Brussels diagram. In all cases the same conclusion was reached: there are insufficient data to test the rules adequately.

For the RPV, we can suspect that ratcheting risk is probably low. In nominal situations, secondary stress ranges are thought to be low, nevertheless primary stresses are not negligible (about half the yield stress value) and emergency or faulted conditions have to be taken into account. In order to solve this problem, and to propose validated rules, it appears necessary to perform a limited number of experimental tests for mod 9Cr1Mo steel.

Concerning 2¼Cr steel, S_m value is determined either by a fraction of R_m or by the $R_{p0.2\%}$ value (see figure 2 for data tabulated in RCC-MR). The monotonic tensile curves are not tabulated in RCC-MR, so it is not possible at the moment to estimate the plastic strain value corresponding to a stress equal to $1.2S_m$, nevertheless we can suspect that it will be very low due to the fact that $1.2S_m < R_{p0.2\%}$.

For this steel it will be interesting to analyse experimental results in order to evaluate the conservatism of the ratcheting rules and possibly to improve them.

2.2.2 Fatigue

The following rules can be applied only when rules to prevent from ratcheting are verified.
Fatigue damage is evaluated in a classical way:

$D_f = \sum_i \frac{n_i}{N_i}$ and we must check: $D_f<1$

where: i indicates the different types of cycles supported by the analysed structure

n_i number of cycles of type i supported by the structure for the whole life

N_i number of allowable cycles of type i

N_i is evaluated using the fatigue curve for the elastoplastic strain range $\Delta\varepsilon_i$ estimated for cycle i.

RCC-MR developed an original rule in order to estimate the elastoplastic strain range $\Delta\varepsilon_i$.

$$\Delta\varepsilon_i = \Delta\varepsilon_1 + \Delta\varepsilon_2 + \Delta\varepsilon_3 + \Delta\varepsilon_4$$

Starting from the elastic stress range $\Delta\sigma_i$, the different strain components are evaluated as:

$\Delta\varepsilon_1$: elastic strain range $\Delta\varepsilon_1 = \frac{2(1+\nu)}{3}\frac{\Delta\sigma_i}{E}$ E: Young modulus

$\Delta\varepsilon_2$: plastic amplification due to primary stress. Generally $\Delta\varepsilon_2=0$

$\Delta\varepsilon_3$: strain amplification to take account of plastic behaviour of material

$\Delta\varepsilon_3 = (K_\varepsilon - 1)\Delta\varepsilon_1$ in the general case

$\Delta\varepsilon_4$: strain amplification to account for stress triaxiality (variation of Poisson coefficient with plasticity) $\Delta\varepsilon_4 = (K_\upsilon - 1)\Delta\varepsilon_1$

K_ε and K_ν coefficients are evaluated using the cyclic curve, the Young modulus, and the Poisson coefficient. The procedure to calculate them is explicited in RCC-MR. But K_ε and K_ν values are also tabulated for different materials. The local temperature is considered for these evaluations.

For mod 9Cr1Mo and 2¼Cr steels, all data necessary for fatigue damage evaluation are available in RCC-MR A3-18S and A3-16S respectively: fatigue curves, K_ε and K_ν values.

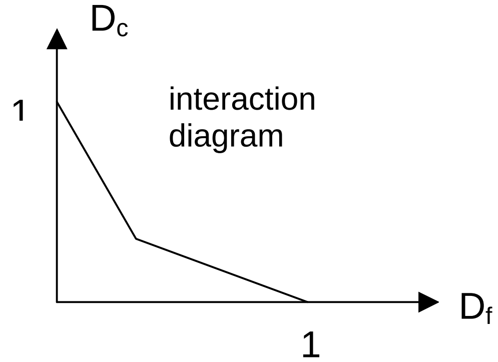
Concerning the specific case of HTR RPV, normal situations will probably cause very low fatigue damage but we must consider emergency and faulted conditions on one hand and the presence of a constant primary stress due to pressure on an other hand.

For this last point, it is necessary to check if there is an influence of the mean stress value on the fatigue life. Experimental results have to be analysed. If it is concluded that, in the loading conditions of the RPV, mean stress has an influence on the fatigue life, it will be necessary either to propose fatigue curves accounting for mean stress or to validate a fatigue method including mean stress effect.

2.2.3 Creep-fatigue

If the structure works in the creep range it must be designed against creep-fatigue damage.
In RCC-MR, a negligible creep curve is proposed. It allows to determine if creep must be considered or not.

When creep must be considered, fatigue damage D_f and creep damage D_c are evaluated separately, then they are combined using the interaction diagram.
The point corresponding to D_f, D_c must be inside the diagram.



- To evaluate creep damage, it is first necessary to estimate the stress value σ_k during hold time.
σ_k is evaluated in the following way:

- $\Delta\sigma^*$ is the stress corresponding to the elastoplastic strain range $\Delta\varepsilon_i$ (evaluated as explained in 2.2.2) on the cyclic curve
- $\sigma_k = P + k_s \Delta\sigma^*$

where P is the primary stress value and k_s is the symmetrisation factor.

k_s varies between 1 for low strain range cycles to 0.5 for large strain range cycles. It is introduced to take into account the fact that large strain range cycles will become symmetric rapidly, while low strain range cycles will remain unsymmetrical.
k_s values depend on the ratio $\Delta\sigma^*/R_{p0.2\%}$.

Creep damage for one cycle is then evaluated considering that the stress σ_k is maintained during the time t with:

$$D_{c1} = \frac{t}{T(\sigma_k)}$$

where $T(\sigma_k)$ is the time to creep rupture corresponding to the stress σ_k at the temperature considered. The local temperature is considered for these evaluations.

For n_i cycles of type i, the corresponding creep damage will be: $D_{ci}=n_i D_{c1}$, and for the different types of cycles: $D_c = \sum_i D_{ci}$

Concerning creep damage evaluations, many improvements have been introduced in RCC-MR:

- allowance for stress relaxation during hold time
- less conservative formulation for the combination of primary stress and secondary stress range

We do not give the complete formulation in this document. It is available in RCC-MR [5].

- Fatigue damage is evaluated as explained in 2.2.2 but strain range is increased to take into account creep strain ε_c during hold time.
ε_c is evaluated with the creep strain laws considering that the stress σ_k is imposed during the hold time at high temperature.
A less conservative estimation of ε_c is also possible if we consider stress relaxation.

- Data necessary for creep-fatigue damage evaluation

In the previous paragraph, we said that all data necessary for fatigue damage evaluations are available in RCC-MR for mod 9Cr1Mo and 2¼Cr steels.

For creep-fatigue damage, additive data are necessary:

- negligible creep curve
- creep-fatigue interaction diagram
- symmetrisation coefficient k_s
- creep strain laws
- creep rupture stress curves

For mod 9Cr1Mo, all these data, except negligible creep curve, are available in A3.18S in the next edition of RCC-MR (issue planned in 2002).

For 2¼Cr, some data are missing in RCC-MR: negligible creep curve, creep strain laws, creep-fatigue interaction diagram. Nevertheless, many of these data are available and they will have to be codified.

- In nominal situations the RPV temperature will be low enough to avoid significant creep damage. Hence again we'll have to consider the emergency and faulted conditions and mainly the situations where the pressure is maintained at a high level while there is an increase of temperature: pressurised cool down transients.

2.2.4 Allowance for welds

In the presence of welds, the same analyses are performed. Joint coefficients are introduced to take into account the difference of behaviour and of resistance between base metal and weld metal.

- For ratcheting evaluation, the allowable stresses S_m and S_t are replaced by nJ_mS_m and nJ_tS_t (see §2.1)
- For fatigue damage evaluation, elastic stress range $\Delta\sigma$ is replaced by f. $\Delta\sigma$, where f depends on the type of joint and on the controls performed. f is a fatigue strength reduction factor. It is introduced to account for local strain concentrations in the joint. Its values are given in RCC-MR. They vary between 1 and 4.
  Moreover the fatigue curve of the joint is deduced from the fatigue curve of base metal using a fatigue joint coefficient J_f.
- For creep damage evaluation, the creep rupture stress curve of the joint is deduced from that of the base metal using a creep joint coefficient J_r.

f values are given in RCC-MR RB 3300.

A specific Appendix (Appendix A9) is dedicated to joint coefficients, but their values are not available for 2¼Cr and mod 9Cr1Mo at the present time.

2.3 OTHER POINTS TO EXAMINE

The previous analyses concern the design of structures without defects, and they don't account for irradiation effect. It will be necessary to examine these situations.

One important point to study is the case of "Fast Rupture".
In RCC-MR, there is no verification against fast rupture at the design stage. It is considered that, for the specific case of FBR structures, the limitation of plastic strains and the choice of steels will allow to avoid this kind of fracture.
In RCC-M (French design code for PWR) [7], it is asked to check that there is no risk of fast rupture, and a procedure is given for ferritic steels.
For HTR, the RPV is a part of the reactor coolant boundary. Its temperature varies between 300°C ("cold vessel" option – ferritic steels) and 440°C ("warm vessel" option – mod 9Cr1Mo or 2¼Cr steels). Its integrity is of prime importance for the safety. Verification against fast rupture will have to be done.

The methods used for verification against Fast Rupture are methods based on defect nocivity analyses. But these analyses are also used for other purposes such as:

- To demonstrate that the component respects the LBB (Leak Before Break) concept
- To evaluate the evolution of a realistic defect during the life and demonstrate that its size remains limited compared to the section thickness and to the critical defect size.

A second point which must be evaluated is the irradiation effect.

In following paragraphs, we give indications on:

- o "Fast rupture" evaluation §2.3.1
- o Other defect nocivity analyses §2.3.2
- o Irradiation effect §2.3.3

2.3.1 Fast rupture

In RCC-MR, there is no verification against fast rupture at the design stage, while RCC-M prescribes this verification and a specific procedure is proposed for ferritic steels.

For HTR RPV situations, the RCC-M procedure can be applied with some modifications to account for the possibility of working in the creep range. In RCC-M, it is asked to check that there will be no fast rupture of the component, in the different loading situations, considering the defects presumed to exist.

Two different methods are proposed.

- The first one is a simplified method, which presents important margins relatively to fast rupture. It postulates a reference defect, which is « envelope » of the defects presumed to exist, for the whole life of the component, in the considered zone. The corresponding analysis is divided in several steps:
  - Definition of the reference defects to consider. The reference defect is a semi-elliptic surface flaw, normal to the direction of the maximal stress and on the most stressed skin. The size of the flaw is a function of the section thickness. Far from geometric discontinuities, for instance, and for ferritic steels, the size is defined as :

section thickness t mm	flaw depth	flaw length
< 100	25 mm	150 mm
100 to 300	¼ t	1.5 t
> 300	75 mm	450 mm

  - Evaluation of the stress intensity factors K_{im} and K_{Ib} in mode I situations for membrane and bending stresses respectively, and combination of these factors in order to obtain the total stress intensity factor K_I . In this combination, a coefficient 2 is applied to the stress intensity factor corresponding to primary membrane and bending stresses. Stress intensity factors corresponding to thermal loadings are not amplified.
  - Comparison of these stress intensity factors with the critical or reference mode I stress intensity factor K_{IR}. K_{IR} values are function of the temperature in the analysed zone and of the ductile-to-brittle transition temperature RT_{NDT}. Influence of irradiation must be considered if necessary. Values of K_{IR} are given in RCC-M Appendix ZG (figure ZG 3410), for ferritic steels. Indications are also given to evaluate the evolution of RT_{NDT} with the fluence.

    For other steels, it is indicated that the same methodology can be used for steels whose yield stress at room temperature is in the range 400 - 620 MPa, with the condition that toughness tests are performed for base metal, weld metal and HAZ (Heat Affected Zone) and that the results obtained are higher than the curve ZG 3410.

    For the case of HTR RPV, the influence of thermal ageing on toughness values will also have to be evaluated.
- The second method considers more realistic defects, in relation with the fabrication and the associated controls. Detailed fracture mechanics analyses have to be performed in order to estimate the size of the flaw at a given time in the life considering all the loading situations from the beginning of the life. The possibilities of fatigue or creep-fatigue propagation will be estimated. The stress intensity factors are then evaluated for that flaw size and the values so obtained are compared with the admissible toughness values.

The material data necessary for these verifications are mainly the admissible toughness values, and their evolution with irradiation and with thermal ageing. If the second method is used, fatigue and creep crack initiation and propagation curves are needed.
Defects being generally in the vicinity of weld joints, these data will have to be available for base metal and weld joints.

Concerning crack initiation and propagation in the creep range, methods are available in [11] and will be included in the next issue of RCC-MR 2000. These rules have been developed mainly for austenitic steels, for the FBR structures. It is necessary to validate them for the application to mod 9Cr1Mo and 2¼Cr.

2.3.2 Defect nocivity analyses

Defect nocivity analyses are necessary in addition to classical design rules to assess the integrity of the RPV. They are used for different purposes:

- To check the assessment relatively to fast rupture (see §2.3.1)
- To demonstrate that the component respects the LBB (Leak Before Break) concept
- To evaluate the evolution of a realistic defect during the life and demonstrate that its size remains limited compared to the section thickness and to the critical defect size.

2.3.2.1 Leak Before Break analyses

It is possible to use the LBB (Leak Before Break) concept as early as in the design phase. This possibility will have to be discussed in order to decide whether it will be applied for future HTR vessels.

Specific rules have been developed for FBR or PWR components [10], [11]. It will be necessary to evaluate if these methods are suitable and validated for HTR RPV and corresponding materials.

The aim of this approach is to check if a through wall defect will be detected before it becomes unstable under emergency or faulted conditions (see figure 3).

The procedure is applied in several steps:

- ➢ select the zones to study: zones where stresses are maximal (geometrical discontinuities, welds…)
- ➢ evaluate the detectable defect length: $2C_L$. This length depends on the methods used to detect the leak. The minimal detectable leak flow is Q_{min}. The detectable flow for the evaluation is $Q_{det}=m_q Q_{min}$, m_q being a margin
- ➢ evaluate the critical defect size, under the emergency and faulted loading conditions, i.e. the defect size which leads to fast rupture or ligament instability in these loading conditions
- ➢ check that the following condition is respected:

$$2C_L + 2C_S \le 2C'_G \quad \text{with:} \quad C'_G = C_G / m_g$$

m_g being a margin on the critical defect size

Material data necessary for this evaluation are: fatigue and creep crack initiation and propagation curves, toughness, for the base metal but also for the weld metal, and their evolution with irradiation.

Some of these data are available. They have to be compiled. Complementary characterisation must be undertaken.

Moreover we need to be able to evaluate the detectable leak flow, which depends on the leak detection methods. Investigations will have to be performed in this field.

Emergency and faulted conditions have to be considered in the evaluation of the critical defect size. So it is necessary to identify these situations, and to evaluate the corresponding stresses.

Application of this procedure will be performed on HTR RPV conditions, to check if it is valid in these loading conditions and for the materials concerned, with the aim of identifying the lack of material data and the points to improve.

2.3.2.2 Evolution of a realistic defect

Analyses will be performed in order to check that realistic defects due to fabrication or evidenced during the life will reach a limited size (relatively to the section thickness and to the critical defect size) at the end of life, considering normal, emergency and faulted conditions.

The same material data as in §2.3.1 are needed for these evaluations.

2.3.3 Irradiation effect

An important point to study is the influence of irradiation on the RPV. Due to the irradiation, the material microstructure is modified by complex mechanisms. From a macroscopic view point, three phenomena are important and must be considered: swelling, irradiation-induced creep and modification of material properties: mainly loss of ductility, loss of strain hardening capability and reduction of fracture toughness.
Irradiation level also has an influence on the ductile-to-brittle transition temperature. This later increases with fluence level.
Creep and fatigue behaviour may be modified by irradiation.
Weld joints are sensitive to neutron irradiation.

It is first necessary to evaluate the minimal level of fluence (in the RPV loading conditions: effect of irradiation temperature) for which there is a significant influence on material behaviour. For fluence lower than this level, classical design rules for non irradiated structures will be valid. For fluence higher than this level, specific rules will have to be used.

Design codes have been developed to account for irradiation effect for FBR or fusion reactor applications [8], [9]. It will be necessary to check if these rules are valid and validated for HTR structures, and to identify if the required data are available for materials of interest. This work has not been performed at the moment. It needs an important time investment.

The main features of these design codes are as follows:

- Swelling is considered as an additive strain controlled loading. A test of negligible swelling effect is proposed. If this test is verified, it is not necessary to evaluate stresses induced by swelling.
- Irradiation-induced creep is considered as being non damaging and is not limited by ductility. Nevertheless, the strains caused by irradiation-induced creep affect the stress distribution and can influence some damage mechanisms. A test for negligible irradiation-induced creep is proposed, allowing to neglect this effect.
- Additional verifications have to be made on stress values to account for the loss of ductility, the loss of strain hardening and the decrease of fracture toughness:

- limitation on membrane primary + secondary stress
- limitation on total stress, including peak stress
- verification relatively to fast fracture (see §2.3.1)

For these verifications, allowable stress values including evolution of material data with fluence are defined.

- Developments of the rules are necessary in the creep range.

Specific material data are necessary, mainly evolution of yield stress, ultimate tensile stress, ductility, toughness with fluence, for base metal and weld joints. It will also be necessary to evaluate if there is an effect on fatigue (cyclic behaviour) and creep behaviour.

For HTR RPV, due to the presence of graphite structures, it is thought that the cumulated fluence during the whole life will be limited. For the GT-MHR vessel, an estimation of the expected cumulated fluence for 60 years is 8.E18n/cm^2 for neutrons with an energy E>0.1Mev and 4.E18n/cm^2 for E>0.5Mev. It is necessary to quantify the modifications in material behaviour for such a fluence level, considering the operating temperature.

The main point to examine will be the evolution of toughness in the operating conditions, and the influence on the ductile-to-brittle transition temperature DBTT. The change in DBTT is higher for irradiation temperature lower than 400°C.

Due to the working temperature of the RPV, it is expected that swelling and irradiation-induced creep will be negligible in base metal. Nevertheless it will be necessary to examine the behaviour of the weld joints.

Some data are already available and must be compiled and analysed. Moreover, specific tests will be performed on mod 9Cr1Mo allowing to obtain complementary indications.

2.4 CONCLUSIONS

RCC-MR design rules are suitable for HTR RPV, but some improvements or some verifications appear to be necessary and some material data are missing or are available elsewhere and have to be codified.
We have identified the following points to investigate:

- ratcheting: experimental results on mod 9Cr1Mo and 2¼Cr steels must be analysed in order to fully validate and possibly improve the rules. Mod 9Cr1Mo is a cyclically softening material. Moreover, the monotonic tensile curves are not codified for 2¼Cr.
- fatigue: study the influence of a mean stress value on the fatigue life
- creep-fatigue: some material data are not codified in RCC-MR:
  - mod 9Cr1Mo: negligible creep curve
  - 2¼Cr: negligible creep curve, creep strain laws, creep-fatigue interaction diagram
- allowance for welds : joint coefficients are not tabulated in RCC-MR. We'll have to search whether experimental results are available and to perform tests to complete them.

Other points also have to be examined

- verification relatively to fast rupture. This verification is performed for PWR vessels, but not for FBR vessels. For this verification, the procedures developed for PWR, and codified in RCC-M, can be used.
  They require to know the toughness of the base metal and of the weld joints and their evolution with thermal ageing and irradiation. For more refined analyses, fatigue or creep-fatigue propagation of the defects are considered. Consequently the same data as for the defect nocivity analyses are necessary (see below).
- influence of irradiation on mechanical properties. Design rules have been proposed for other applications. We have to check their validity for HTR RPV conditions, to improve

them if necessary, to compile the existing data and to conduct experimental programs to obtain the missing ones, mainly the toughness values for the base metal and the weld joints.

- defect nocivity analyses. Specific procedures exist for that purpose. We have to check their validity for the HTR RPV loading conditions and materials, improve them if necessary, compile the existing data and undertake programs to complete them.
- a LBB procedure is available in next issue of RCC-MR. It must be validated for HTR conditions.

3. DESIGN OF THE RPV FOLLOWING ASME CODE

The aim of the following chapter is to examine the ASME Code (2001 Edition, [4]) in order to carry out an initial approach for the evaluation of the applicability of the Code to the design of the HTR RPV [12]. Aspects not covered by this ASME Code Edition will be identified in order to see whether they are covered by other pressure vessel design codes or could be included in future improvements and developments of the existing rules.

The objective of the ASME Code rules is to provide protection of life and property and to provide a margin for deterioration in service to provide a reasonably long, safe period of use. Therefore, the rules will ensure the integrity of the pressure barrier even though local and global deformations have to be allowed for in all foreseen design conditions (normal operation, emergency, faulted and upset conditions). Advances in design and materials and the evidence of experience have been recognised.

The ASME Code contains mandatory requirements, specific prohibitions, and non-mandatory guidance for construction (comprising materials, design, fabrication, examination, inspection, testing, certification and pressure relief), and in-service inspection and testing activities. The Code does not address all aspects of these activities and the aspects which are not specifically addressed should not be considered prohibited. The Code is not a handbook and cannot replace formation, experience and the use of engineering judgements, which must be consistent with the philosophy of the Code and must never be used to overrule mandatory requirements or specific prohibitions of the Code.

3.1 CLASSIFICATION OF THE HTR RPV WITHIN ASME CODE

Within the ASME Code, the chapters that are applicable for the HTR RPV design are the following:

- Section II, Part A
- Section III, Division 1
- Section V
- Section IX
- Section XI

The RPV houses the reactor core and contains pressurised primary coolant. The RPV is therefore typically classified due to safety reasons as nuclear Class 1 component, thus within ASME Section III, Division 1.

ASME Code Section III gives rules and requirements for the design, construction, inspection, testing, stamping and overpressure protection of nuclear power plant components. The rules of this section apply for new construction items and include considerations of mechanical and thermal effects due to cyclic operation.

Division 1 of Section III is focused on the design and construction of Class 1, 2 and 3 components. Within Division 1, Subsection NB is centred on Class 1 components and Subsection NH on Class 1 components in elevated temperature service.

Subsection NB contains rules for the material, design, fabrication, examination, testing, overpressure relief, marking and stamping of Class 1 components which are to be subjected to metal temperatures where creep and relaxation effects are negligible, that is, temperatures for which design stress intensity values are given in Section II, Part D, Subpart 1, Tables 2A, 2B and 4. Fatigue design curves and specific methods for fatigue analysis are not applicable above 371 ºC for materials covered by Figs. I-9.1 and I-9.4, and above 427 ºC for materials covered by Figs. I-9.2 and I-9.3. Above those temperatures, the creep and stress rupture characteristics of allowed materials become significant factors which are not covered by the rules of Subsection NB.

The rules of Subsection NB only guard against the time-independent failure modes – ductile rupture, gross distortion (buckling and incremental collapse) and fatigue.

Subsection NH contains rules for materials, design, fabrication, examination, testing and overpressure relief of Class 1 components, parts and appurtenances which are expected to function even when metal temperatures exceed those covered by the rules of Subsection NB. However, the rules of Subsection NH shall not be used for structural parts which will be subjected either to metal temperatures or to times greater than those values associated with the S_{mt} data given in Appendix I-14.3 for the specified material (for instance, limits for 2 ¼ Cr – 1 Mo are 649ºC over 10^3 hours or 593 ºC over 300 x 10^3 hours).

The rules of Subsection NH are applicable no matter the type of contained fluid (water, steam, sodium, helium or any other process fluid). Moreover, Subsection NH also considers time-dependent material properties and structural behaviour by guarding against the following modes of failure:

- ductile rupture due to short-term loadings
- creep rupture due to long-term loadings
- creep fatigue failure
- gross distortion due to incremental collapse and ratcheting
- loss of function due to excessive deformation
- buckling due to short-term loadings
- creep buckling due to long-term loadings

On the other hand, the rules of Subsections NB and NH do not provide methods to evaluate deterioration which may occur as a result of corrosion, mass transfer phenomena, radiation effects, or other material instabilities. However, ASME Section III, Appendix G ‘Protection against non-ductile failure’ and Section XI, Appendix H ‘Evaluation of flaws in ferritic materials’, provide methods to prevent non-ductile fracture based on inspection.

Regarding HTR RPV, two possible design options are being considered [13]:

- ‘Cold’ Vessel option, like the South African PBMR, where the RPV wall temperature is limited to 350 ºC. Candidate materials for this vessel option are carbon steels and low alloy steels (like SA 508, Grade 3, Class 1 and SA 533, Grade B, Class 1). For this temperature and materials, creep and relaxation effects are likely to be negligible. The ASME Code, Section III, Division 1, Subsection NB is therefore fully applicable and the required data for candidate materials being considered is also available within the Code
- ‘Warm’ Vessel option, like the Russian GT-MHR, where the RPV wall temperatures are limited to 440 ºC. Candidate materials being considered are Chrome and Molybdenum alloy steels, such as Modified 9 Cr – 1 Mo (Grade 91), 2 ¼ Cr – 1 Mo (SA 182-F22, SA 335-P22, SA 387-Gr22) and 12 Cr Mo V (X20). Temperatures exceed those covered by rules of Subsection NB, and therefore the rules of Subsection NH should be applied in order to guard against both time-independent and time-dependent failure modes

ASME Code, Subsection NB is fully applicable for the design of the HTR ‘cold’ RPV option. There is large experience designing nuclear RPVs with Subsection NB since it has been used extensively for many years. Therefore, there is no point in describing Subsection NB here.

This chapter is focused on the examination of ASME Code, Section III, Division 1, Subsection NH, Class 1 components in elevated temperatures, to evaluate whether it is applicable directly to the design of the HTR 'warm' RPV option or whether improvements and developments of the rules are necessary.

3.2 DESIGN RULES AND LIMITS FOR LOAD CONTROLLED STRESSES (PRIMARY STRESSES)

NH-3220 sets out the rules for the design against failure due to load controlled stresses. Design conditions and Level A, B, C and D Service conditions are considered (see NCA-2142 for conditions definitions). ASME Figure NH-3221-1 presents the analysis flow diagram for elevated temperatures and gives stress limits for all design and service conditions.

3.2.1 Design limits

The calculated stress intensity values based on a linearly elastic material model shall satisfy the following limits:

– The general primary membrane stress intensity, derived from P_m, shall not exceed S_o:
$P_m \leq S_o$

– The combined primary membrane plus bending stress intensity, derived from P_L and P_b, shall not exceed 1.5 S_o:
$(P_L + P_b) \leq (1.5)\ S_o$

Where, S_o is the maximum allowable value of general primary membrane stress intensity given in ASME Table I-14.2. This table includes values for 2 ¼ Cr – 1 Mo (SA 182-F22, SA 335-P22, SA 387-Gr22) but no data is available for Modified 9 Cr – 1 Mo and 12 Cr Mo V

3.2.2 Level A and B service limits

The calculated stress intensity values based on a linearly elastic material model for Level A and B service loads shall satisfy the following limits:

– The general primary membrane stress intensity, derived form P_m, shall not exceed S_{mt}:

$P_m \leq S_{mt}$

– The combined primary membrane plus bending stress intensities, derived from P_L and P_b, shall satisfy the following:

$P_L + P_b \leq K\ S_m$

$P_L + (P_b/K_t) \leq S_t$

Where,

– S_{mt} is the allowable limit of general primary membrane stress intensity for time t, corresponding to the total duration of the particular loading, and for temperature T, corresponding to the maximum average wall temperature during such particular loading. The value shall be taken as the lower of the S_{mt} values from ASME Table I-14.3, or as 0.8 S_r x R, being:

- S_r the expected minimum stress-to-rupture strength given in ASME Table I-14.6

- R the appropriate ratio of the weld metal creep rupture strength to the base metal creep rupture strength from Table I-14.10

The referenced tables include values for 2 ¼ Cr – 1 Mo, but no data is available for Modified 9 Cr – 1 Mo and 12 Cr Mo V

– S_m is the lowest stress intensity value at a given temperature among the time-dependent strength quantities which are defined in Section II, Part D, and extended to elevated temperatures in Subsection NH.

– K is the section factor for the cross section being considered. It is the ratio of the load set producing a fully plastic section to a load set producing initial yielding of the extreme fibre of the cross section. Values of K for various sections are in Section III, Appendix A, Table A-9521(b)-1

– K_t factor accounts for the reduction in extreme fibre bending stress due to the effect of creep. The factor is given by: $K_t = (K + 1) / 2$

– S_t is the temperature and time-dependent stress intensity limit at a weldment, and shall be taken as the lower of tabulated S_t values from ASME Table I-14.4, or as 0.8 S_r x R, being S_r and R as previously defined. This table includes values for 2 ¼ Cr – 1 Mo, but no data is available for Modified 9 Cr – 1 Mo and 12 Cr Mo V

3.2.3 Level C service limits

The calculated stress intensity values based on a linearly elastic material model shall fulfil the following conditions:

– The general primary membrane stress intensity, derived from P_m for Level C Service loadings, shall not exceed the smaller of 1.2 S_m and 1.0 S_t:

$P_m \leq 1.2\ S_m$ and

$P_m \leq 1.0\ S_t$

– The use-fraction sum associated with the general primary membrane stresses for all increments of primary loadings during levels A, B and C loadings shall meet the following requirement:

$$\sum_i \left(\frac{t_i}{t_{im}} \right) \leq 1.0$$

– The combined primary membrane plus bending stress intensities, derived from P_L and P_b for Level C Service loadings, shall comply with:

$P_L + P_b \leq K\ S_m$ (with 1.0< K<1.5)

$P_L + (P_b/K_t) \leq S_t$

– The sum of the use-fractions associated with the primary membrane plus bending stresses for all increments of primary loadings during levels A, B and C loadings shall meet the following requirement:

$$\sum_i \left(\frac{t_i}{t_{ib}} \right) \leq 1.0$$

Where,

– t_i is the total duration of the specific loading, P_{mi}, at elevated temperature, T (the above values are governed by Subsection NB), during the entire service life of the component

– t_{im} and t_{ib} are the maximum allowed times under P_m and P_L+P_b/K_t stress intensities respectively, for the loading condition and temperature in question. t_{im} and t_{ib} are determined from a graph of S_t vs time (ASME Figure I-14.4)

3.2.4 Level D service limits

The following rules (and those of Section III, Appendix F) may be used in the evaluation of components subjected to Level D service loadings:

– The general primary membrane stress intensity, derived from P_m for Level D, shall not exceed the smaller limit for P_m in Appendix F, 0.67 S_r and 0.8 R S_r:

$P_m \leq$ limit in Appendix F for P_m, and

$P_m \leq 1.2\ S_m$, and

$P_m \leq 1.0\ S_t$

– The use-fraction sum associated with the general primary membrane stresses derived from all service loadings shall meet the following requirement:

$$\sum_i \left(\frac{t_i}{t_{ir}} \right) \leq 1.0$$

– The combined primary membrane plus bending stress intensities, derived from P_L and P_b for Level D service loadings, shall meet the following requirement and limits in Appendix F:

$P_L + P_b \leq$ limits in Appendix F for P_L+P_b, and with 1.0< K<1.5 both

$P_L + (P_b/K_t) \leq 0.67\ S_r$, and

$P_L + (P_b/K_t) \leq 0.8\ R\ S_r$

– The sum of the use-fractions associated with the primary membrane plus bending stresses that arise from all service loadings shall meet the following requirement:

$$\sum_i \left(\frac{t_i}{t_{ibr}} \right) \leq 1.0$$

Where,

– t_{ir} is the maximum allowed time under 1.5 P_m for base metal. For weldments, the higher of 1.5 P_m and (1.25/R) P_m. t_{ir} is determined from a graph of S_r vs time (ASME Figure I-14.6)

– t_{ibr} is the maximum allowed time under 1.5 (P_L+P_b/K_t) for base metal. For weldments, the higher of 1.5 (P_L+P_b/K_t) and (1.25/R) (P_L+P_b/K_t). t_{ibr} is determined from a graph of S_r vs time (Figure I-14.6)

– For the purpose of Section III, Appendix F calculations, the yield strength and tensile strength values shall be obtained as the S_y value shown in ASME Table I-14.5 and the S_u value shown in Table NH-3225-1 respectively, multiplied by the strength reduction factor shown in Tables NH-3225-3A and NH-3225-3B. The referenced tables include values for 2 ¼ Cr – 1 Mo, but no data is available for Mod. 9 Cr – 1 Mo and 12 Cr Mo V

3.3 DESIGN RULES AND LIMITS ON DEFORMATION CONTROLLED QUANTITIES

The strains and deformations resulting from the specific operating conditions shall be evaluated, including the effects of ratcheting, the interaction of creep and fatigue and the possibility of buckling and structural instability. ASME Code NH-3250 states that the acceptability criteria and material properties contained in Appendix T may be used.

ASME Appendix T sets out rules for strain, deformation and fatigue limits at elevated temperatures. ASME Figure NH-3221-1 shows the analysis flow diagram. Strains and deformation limits are summarised below. Note that Design and Level D Service conditions are exempted from this analysis.

3.3.1 Deformation and strain limits for structural integrity

In regions where elevated temperatures are expected, the maximum accumulated inelastic principal strain over the expected lifetime of the element under consideration shall not exceed the following limits (T-1310):

– Strains averaged through the thickness ≤ 1 %

– Strains at the surface, due to an equivalent linear distribution of strain through the thickness ≤ 2 %

– Local strains at any point ≤ 5 %

In order to evaluate whether the previous strain limits are met, two methods are proposed. These methods are an alternative to the purely inelastic analysis and are based on elastic analyses and simplified inelastic analyses respectively.

To evaluate strains, two definitions are required to establish the appropriate cycle:

$$X = \left(P_L + \frac{p_b}{K_t}\right)_{max} \times \frac{1}{S_y^{'}}$$

$$Y = \frac{(Q_R)_{max}}{S_y^{'}}$$

Where,

– $(Q_R)_{max}$ is the maximum range of secondary stress intensity during the cycle being considered

– S'_y is:

- for the elastic analysis, the average of the S_y values in ASME Table I-14.5 at the maximum and minimum average wall temperatures during the cycle

- for the simplified inelastic analysis, the average value of S_y, corresponding to the lower (S_{yL}) and the higher (S_{yH}) of the average wall temperatures for the stress extremes defining the secondary stress range Q_R.

3.3.1.1 Elastic analysis

The inelastic strain limits given above are considered to have been satisfied if the limits of any of the following requirements are met:

– Test No. A-1: $X+Y \leq S_a/S'_y$

Where S_a is the lesser of:

– S_t using the highest average wall temperatures during the cycle and a time value of 10^4 hours, and

– the average of the two S_y values associated with the maximum and minimum average wall temperatures during the cycle

S_t and S_y values for 2 ¼ Cr – 1 Mo are available in ASME Tables I-14.4 and I-14.5 respectively.

– Test No. A-2: $X+Y \leq 1$

For those cycles during which the average wall temperature at one of the stress extremes defining the maximum secondary stress range $(Q_R)_{max}$ is below the applicable temperature of ASME Table T-1323 (427 ºC for 2 ¼ Cr – 1 Mo). No data is available in this table for Modified 9 Cr – 1 Mo and 12 Cr Mo V.

3.3.1.2 Simplified inelastic analysis

The proposed tests B-1 and B-2 are successful if the inelastic strain limits given before are not reached. These tests can be used if the average wall temperature at one of the stress extremes defining each secondary stress intensity range Q_R is below the applicable temperature of ASME Table T-1323.

Test B-1 can be used only for axisymmetric structures subjected to axisymmetric loading and general structures in which peak through-the-wall thermal stress is negligible. Test B-2, which is more conservative, is applicable to any structure and loading.

The requirements presented hereafter restrict the amount of inelastic creep strain that can be accumulated over the service life of the component, including Levels A, B and C service loadings so that the strain limits are not exceeded.

The effective creep stress σ_c is defined as:

$\sigma_c = Z\ S_{yL}$

Z is the dimensionless effective creep stress parameter, obtained using the elastically calculated primary and secondary stress intensities to enter in:

- Figure T-1332-1 for Test No. B-1, and
- Figure T-1332-2 for Test No. B-2

Data is available for 2 ¼ Cr – 1 Mo in ASME Figures T-1332.

The total ratcheting creep strain is obtained entering the isochronous stress-strain curves of T-1800 with the 1.25 σ_c stress throughout the temperature-time history of the entire service life. The total service life may be subdivided into temperature-time blocks. The creep strain increment for each block can be calculated separately and added to obtain the total ratcheting creep strain. The resulting value shall be limited to:

- For parent metal: total ratcheting creep strain ≤ 1 %
- For weld metal: total ratcheting creep strain ≤ 0.5 %

Data is available for 2 ¼ Cr – 1 Mo in ASME Figures T-1800, but there is no data for Modified 9 Cr – 1 Mo and 12 Cr Mo V.

3.3.2 Creep – fatigue evaluation

The combination of Levels A, B and C service loadings shall be evaluated for accumulated creep and fatigue damage, including hold time and strain rate effects. T-1400 states that for a design to be acceptable the creep and fatigue damage shall comply with the following Damage Equation:

$$\sum_{j=1}^{P}\left(\frac{n}{N_d}\right)_j+\sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k \leq D$$

Where,

- *D* is the total creep-fatigue damage, given in ASME Figure T-1420-2. This figure includes values for 2 ¼ Cr – 1 Mo, but there is no data for Modified 9 Cr – 1 Mo and 12 Cr Mo V
- n_j is the number of type *j* cycles
- Δt_k is the time duration of interval *k*

- $(N_d)_j$ is the number of design allowable cycles for cycle type *j*, determined from the design fatigue curves (ASME Figure T-1420-1) corresponding to the maximum metal temperature occurring during the cycle. Data is available for 2 ¼ Cr – 1 Mo
- $(T_d)_k$ is the allowable time duration for a given stress and the maximum temperature at the point of interest during the time interval *k*. The allowable time duration is determined by entering ASME Figure I-14.6 at the stress value obtained by dividing the maximum stress (at the point of interest during interval *k*) by the safety factor k' from ASME Table T-1411-1. K' equals 0.67 for 2 ¼ Cr – 1 Mo, but there is no data for Modified 9 Cr – 1 Mo and 12 Cr Mo V.

The two terms of the Damage Equation (the fatigue term and the creep term) have to be evaluated separately and the creep-fatigue relation satisfied.

To evaluate the fatigue term, the maximum equivalent strain range $\Delta\varepsilon_{max}$ is required. $\Delta\varepsilon_{max}$ is obtained from the strain components for each point in time for the complete cycle. The history of the change in such strain components shall be calculated and the equivalent strain range ($\Delta\varepsilon_{equiv}$) for each point obtained. $\Delta\varepsilon_{max}$ is therefore the maximum of the above calculated equivalent strain ranges.

3.3.2.1 Limits using inelastic analysis

Both fatigue and creep terms of the Damage Equation shall be evaluated with results from inelastic analysis, and the creep-fatigue relation satisfied.

- The fatigue term is evaluated by entering the design fatigue curve (ASME Figure T-1420-1) at the strain range ε_t given by:

  $\varepsilon_t = \Delta\varepsilon_{max}$

  $\Delta\varepsilon_{max}$ is the maximum strain range, calculated as described before and using calculated inelastic strains.
- The creep term is obtained evaluating Δt_k and $(T_d)_k$, the latter considering the inelastic stress level and the maximum temperature at the point of interest in ASME Figure I-14.6.

3.3.2.2 Limits using elastic analysis

The elastic analysis rules given hereafter may be used to evaluate both fatigue and creep terms of the Damage Equation only when:

- the deformation and strain limits for structural integrity (ratcheting) rules, with $Z \leq 1$, have been satisfied,
- the 3 S_m limit in NB-3222.2 is met ,and
- the pressure induced membrane, bending stresses and thermal induced membrane stresses are classified as primary (load control) stresses.

The fatigue term is evaluated using a modified maximum equivalent strain range $\Delta\varepsilon_{mod}$, that accounts for the underestimation of the actual strain range incurred during plastic or creep deformation when using linearly elastic methods (T-1432). The strain range ε_t used to enter the design fatigue curve is obtained by:

$\varepsilon_t = k_v \, \Delta\varepsilon_{mod} + K \, \Delta\varepsilon_c$

Where,

- K is either the equivalent stress concentration factor, as determined by test or analysis, or the maximum value of the theoretical elastic stress concentration factor in any direction for the local area under consideration

– $k_v = 1 + f\,(k_v' - 1)$

– Since k_v' is the plastic Poisson ratio adjustment factor from ASME Figure T-1432-3, and *f* the factor determined from ASME Figure T-1432-2

– $\Delta\varepsilon_c$ is the creep strain increment and is obtained from the isochronous stress-strain curve (ASME Figure T-1800) for the maximum metal temperature during the stress cycle time-temperature block of the stress cycle. The $\Delta\varepsilon_c$ equals the sum of the creep strain increment accumulated in one stress cycle time. Data is available for 2 ¼ Cr – 1 Mo in Figure T-1800.

The creep term evaluation requires the obtainment of the envelope stress-time history, accounting for the stress relaxation (T-1433). Therefore, the stress-time histories for each type *j* cycle should be defined before. To do so, the corresponding initial stress level S_j and the stress relaxation history shall be determined by entering the appropriated stress-strain curve of ASME Figure T-1800 for $T_{HT,}$ at a strain level equal to εt and determining the corresponding stress levels for the time-independent curve and at varying times. This stress relaxation process shall not be permitted to proceed to a stress level lower than S_{LB}. The obtained stress-time history may require modification by a simple translation in time if $(S_{TRAN})_j$ exceeds the stress relaxation history within the time duration $(t_{TRAN})_j$.

Where,

– T_{HT} is the hold temperature, defined as the local metal temperature that occurs during sustained normal operation

– ε_t is the strain range as calculated to evaluate the fatigue term

– S_{LB} is the lower bound stress level defined to be equal to 1.25 σ_c, with σ_c as defined previously for ratcheting simplified inelastic analysis

– $(t_{TRAN})_j$ is that portion of the average cycle time of type *j* cycle that represents the time during elevated temperature transients conditions.

– $(S_{TRAN})_j$ is the load controlled stress intensity at the time point during $(t_{TRAN})_j$ for which the load controlled stresses are at maximum conditions

Superimposing the stress-time histories obtained for all cycles types will lead to the aimed envelope stress-time history. The envelope is divided into time intervals during D_t. For each *k* interval, the stress $(S)_k$ and temperature $(T)_k$ are assumed to be constant and are selected to represent the most damaging stress/temperature combination that could exist during that time interval.

Finally, the allowable time duration $(Td)_k$ of the Damage Equation is obtained by entering the expected minimum stress-to-rupture curve (Figure I-14.6) at $(T)_k$ and $(S)_k$ / k', (k' being the factor given in ASME Table T-1411-1). This table includes values for 2 ¼ Cr – 1 Mo, but there is no data for Modified 9 Cr – 1 Mo and 12 Cr Mo V.

3.4 ALLOWANCE FOR WELDS

The presence of welds has already been considered in the rules and limits for load controlled stresses when including the appropriate ratio of the weld metal creep rupture strength to the base metal creep rupture strength given in ASME Table I-14.10.

In order to meet the analysis requirements on deformation controlled quantities at elevated weld temperature regions, the assumed weld surface should be based on the most severe strain concentration expected on the actual weld placed in service (NH-3353). This geometry may be prescribed on a drawing or may be recorded by prior observation (visual, ultrasonic or radiographic).

3.5 MATERIAL DATA

For the HTR 'cold' RPV option, all required data for the candidate materials (carbon steels and low alloy steels like SA 508, Grade 3, Class 1 and SA 533, Grade B, Class 1) is available within the ASME Code and therefore the Code is fully applicable.

For the 'warm' Vessel option, the candidate materials are Chrome and Molybdenum alloy steels, such as Modified 9 Cr – 1 Mo (Grade 91), 2 ¼ Cr – 1 Mo (SA 182-F22, SA 335-P22, SA 387-Gr22) and 12 Cr Mo V (X20). For 2 ¼ Cr – 1 Mo all required data is available within the ASME Code (Subsection NH) and therefore the Code is fully applicable.

No data is available for Modified 9 Cr – 1 Mo and 12 Cr Mo V. The required data is:

- S_o - Maximum allowable stress intensity for design conditions
- S_{mt} and S_t - Allowable stress intensity values
- S_r - Expected minimum stress-to-rupture
- R - Stress rupture factors for material A welded with material B
- S_y - Yield strength values
- S_u - Tensile strength, YS and TS reduction factors
- D - Creep-Fatigue damage envelope
- N_d vs ε_t – Design fatigue strain range
- Average isochronous stress-strain curves
- k' – Correction/safety factor for evaluating allowable time duration

3.6 IRRADIATION EFFECT

The HTR RPV material will suffer the collision of the fast neutrons with its atomic lattice and will develop microstructural defects that would increase the yield strength (hardening) and the ductile-to-brittle transition temperature of the material. This material damage mechanism is known as irradiation embrittlement [2, 3].

The rules of ASME Code, Section III, Appendix G 'Protection against nonductile failure', provides a recommended procedure for obtaining the allowable loadings for ferritic pressure retaining materials in components.

This procedure is based on the principles of linear elastic fracture mechanics and consists of calculating at each important location the mode I stress intensity factor K_I, assuming a maximum postulated defect at that location.

The maximum postulated defect used is a sharp, surface crack normal to the direction of maximum stress. For section thicknesses of 102 mm to 305 mm, it has a depth of ¼ of the section thickness and a length of 1½ times the section thickness.

For Level A and B Service Loadings, the summation of the K_I values for the specified loadings shall meet the following requirements:

- At shell and heads remote from discontinuities:

  $2\,K_{Im} + K_{It} < K_{Ia}$

  Where,

  - K_{Im} is the mode I stress intensity factor corresponding to primary membrane tension for the postulated defect. K_{Im} = M_m x primary membrane stress, with M_m given in ASME Figure G-2214-1 for ferritic materials

- K_{It} is the mode I stress intensity factor produced by a radial thermal gradient across a wall thickness for the postulated defect. K_{It} = M_t x temperature difference through the wall, with M_t given in ASME Figure G-2214-2 for ferritic materials
- K_{Ia} is the critical or reference mode I stress intensity factor, that is, the maximum K_I that can be ensured for the material and temperature involve. For ferritic materials (SA-508 Grade 3 Class 1 and SA-533 Grade B Class1) K_{Ia} could be obtained from ASME Figure G2210-1, a curve showing the relationship that can be conservatively expected between K_{Ia} and the working temperature T, depending on the ductile-to-brittle transition temperature RT_{NDT} of the material. ASME Section XI, Division 1, Appendix A-4400 states that for materials that are subjected to fast neutron fluence, the degradation of the material fracture toughness due to irradiation must be accounted for. The degree of degradation depends upon the neutron fluence, the irradiation temperature, and the relative sensitivity of the particular steel. Radiation induced changes in fracture toughness should be determined from surveillance specimens of the actual material and product form, irradiated according to the surveillance techniques of ASTM E 185, Standard Recommended Practice for Effects of High-Energy Irradiation on the Mechanical Properties of Metallic Materials.

  Where surveillance data are not available, the effects of neutron irradiation should be considered for K_{Ia} by shifting the reference ductile-to-brittle transition temperature RT_{NDT} as a function of irradiation.

  RT_{NDT} should be obtained for base material, the heat affected zone and the weld material by drop weigh and Charpy V-Notch tests (NB-2330).

– At shell regions near geometric discontinuities, at nozzles and flanges:

  $2\ K_{Im} + K'_{Im} + 2\ K_{Ib} + K'_{Ib} < K_{Ia}$

  Where,

  - K'_{Im} is the mode I stress intensity factor corresponding to secondary membrane tension for the postulated defect. K_{Im} = M_m x secondary membrane stress
  - K_{Ib} is the mode I stress intensity factor corresponding to primary bending stress for the postulated defect. K_{Ib} = M_b x primary bending stress, where M_b is 2/3 of M_m given in ASME Figure G-2214-1
  - K'_{Ib} is the mode I stress intensity factor corresponding to secondary bending stress for the postulated defect. K_{Ib} = M_b x secondary bending stress
  - Thermal stresses shall be considered as secondary since K_{It} is not recommended when thermal stress distributions are more complicated.

For Level C and D Service Loadings, the possible combinations of loadings, defect sizes and material properties are too diverse to allow the application of definitive rules, and it is recommended that each situation be studied on an individual case basis.

3.7 DEFECT NOCIVITY ANALYSIS

ASME Code, Section XI, Division 1, Subsection IWB ‘Requirements for Class 1 components’ provides rules based on inspection to evaluate the harmfulness of defects on nuclear pressure retaining components. It establishes the examination and inspection requirements (IWB-2000) and sets the defect acceptance standards (IWB-3000).

Subsection IWB gives in ASME Tables IBW-3510 for vessel welds of ferritic material allowable dimensions for planar, laminar and linear flaws. For welds in vessel nozzles and piping of ferritic material the allowable flaws dimensions are given in ASME Tables IBW-3514.

IWB-3600 ‘Analytical evaluation of flaws’, provides rules to evaluate flaws which dimensions exceed the size of allowable flaws defined in IBW-3500 (tables IBW-3510 and IBW-3514 for ferritic materials). Flaws can be classified within five categories for evaluation by analysis, and when examination results do not permit accurate determination of the flaw category, the more conservative category shall be selected.

The component containing a flaw is acceptable for continued service during the evaluation time period if:

– the design rules and limits for load controlled stresses (primary stresses) are satisfied, considering the local reduction of the pressure retaining membrane that is equal to the area of the detected flaw(s) as determined by the flaw characterisation rules of IWA-3000.

– and one of the following acceptance criteria for ferritic materials is satisfied:

- Acceptance criteria based of flaw size:

  $a_f < 0.1\ a_c$

  $a_f < 0.5\ a_i$

  Where,

  – a_f is the maximum size to which the detected flaw is calculated to grow in a specific time period, which can be the next scheduled inspection of the component, or until the end of vessel design lifetime

  – a_c is the minimum critical flaw size of the flaw under normal operating conditions

  – a_i is the minimum critical flaw size of the flaw for initiation of nonarresting growth under postulated emergency and faulted conditions

- Acceptance criteria based of applied mode I stress intensity factor:

  For normal operating conditions: $K_I < \frac{K_{Ic}}{\sqrt{10}}$

  For emergency and faulted conditions: $K_I = \frac{K_{Ic}}{\sqrt{2}}$

  Where,

  – K_I is the maximum applied stress intensity factor for normal and emergency faulted conditions respectively, for the flaw size a_f as defined before.

  – K_{Ia} is the available fracture toughness based on crack arrest for the corresponding crack tip temperature

  – K_{Ic} is the available fracture toughness based on fracture initiation for the corresponding crack tip temperature

3.8 CONCLUSIONS

ASME Code, Section III, Division 1, Subsection NB is fully applicable for the design of the HTR ‘cold’ RPV option.

ASME Code, Section III, Division 1, Subsection NH ‘Class 1 components in elevated temperature’ shall be applied for the ‘warm’ vessel option, and all required data is available for 2 ¼ Cr – 1 Mo. Therefore if the selected material for the HTR RPV is 2 ¼ Cr – 1 Mo the ASME Code is fully applicable.

The two other candidate materials for the HTR ‘warm’ RPV option are Modified 9 Cr – 1 Mo and 12 Cr Mo V. No data is available for these two materials within ASME Code, Edition 2001, Subsection NH. Therefore, if any of these two materials is selected for the HTR ‘warm’ RPV option, ASME Code could not be applied as it is since the following data will be required:

- S_o - Maximum allowable stress intensity for design conditions
- S_{mt} and S_t - Allowable stress intensity values
- S_r - Expected minimum stress-to-rupture
- R - Stress rupture factors for material A welded with material B
- S_y - Yield strength values
- S_u - Tensile strength, YS and TS reduction factors
- D - Creep-Fatigue damage envelope
- N_d vs ε_t – Design fatigue strain range
- Averaged Isochronous stress-strain curves
- k’ – Correction/safety factor for evaluating allowable time duration

Regarding irradiation effect, ASME Code, Section III, Appendix G “Protection Against Nonductile Failure” provides a recommended procedure to prevent nonductile failure of the RPV. Test data of mode I stress intensity factor K_I versus temperature is required for the RPV base material, heat affected zone and weld material. This procedure may be used to prevent against irradiation effect if fracture toughness test data on irradiated material is provided:

- K_{Ia} – Critical or reference Mode I stress intensity factor

4. GENERAL CONCLUSIONS

We have examined RCC-R and ASME design rules in order to check if the existing rules are suitable for the design of HTR RPV.
We reach the following conclusions:

- RCC-MR design rules are applicable for HTR RPV design, but some improvements and verifications are necessary and some material data are missing or not codified at the moment.
  The following points have been identified:
  * ratcheting: mod 9Cr1Mo is a cyclically softening material. Experimental results must be analysed in order to fully validate the rules
  * fatigue: study the influence of a mean stress on the fatigue life
  * creep fatigue: some material data are missing in RCC-MR, mainly for 2¼Cr. For mod 9Cr1Mo, the negligible creep curve is missing.
  * weld: joint coefficients are not available in RCC-MR
  * verification against fast rupture: the procedure codified in RCC-M can be used. It must be validated for mod 9Cr1Mo and 2¼Cr.
    If necessary, some developments will be performed to account for the creep effect, for the crack initiation and propagation. For that, methods are already available, they will be included in the next issue of RCC-MR.
  * influence of irradiation and of thermal ageing on toughness values has to be considered. For that, experimental programs are necessary to complete the data.
  * influence of irradiation on mechanical properties: we have to check if the expected cumulated fluence level for the whole life has an influence on the mechanical properties, mainly on ductility. In this case it will be necessary to apply, validate and improve, if necessary, specific design rules developed for other applications.
  * a LBB procedure is available in next issue of RCC-MR. It must be validated for HTR conditions.

- ASME Code, Section III, Division 1, Subsection NB is fully applicable for the design of the HTR 'cold' RPV option.

  ASME Code, Section III, Division 1, Subsection NH 'Class 1 components in elevated temperature' shall be applied for the 'warm' vessel option, and all required data is available for 2 ¼ Cr – 1 Mo. Therefore if the selected material for the HTR RPV is 2 ¼ Cr – 1 Mo the ASME Code is fully applicable.

  The two other candidate materials for the HTR 'warm' RPV option are Modified 9 Cr – 1 Mo and 12 Cr Mo V. No data is available for these two materials within ASME Code, Edition 2001, Subsection NH. Therefore, if any of these two materials is selected for the HTR 'warm' RPV option, ASME Code could not be applied as it is since all material data are missing.

  Regarding irradiation effect, ASME Code, Section III, Appendix G "Protection Against Nonductile Failure" provides a recommended procedure to prevent nonductile failure of the RPV. Test data of mode I stress intensity factor K_I versus temperature is required for the RPV base material, heat affected zone and weld material. This procedure may be used to prevent against irradiation effect if fracture toughness test data on irradiated material is provided.

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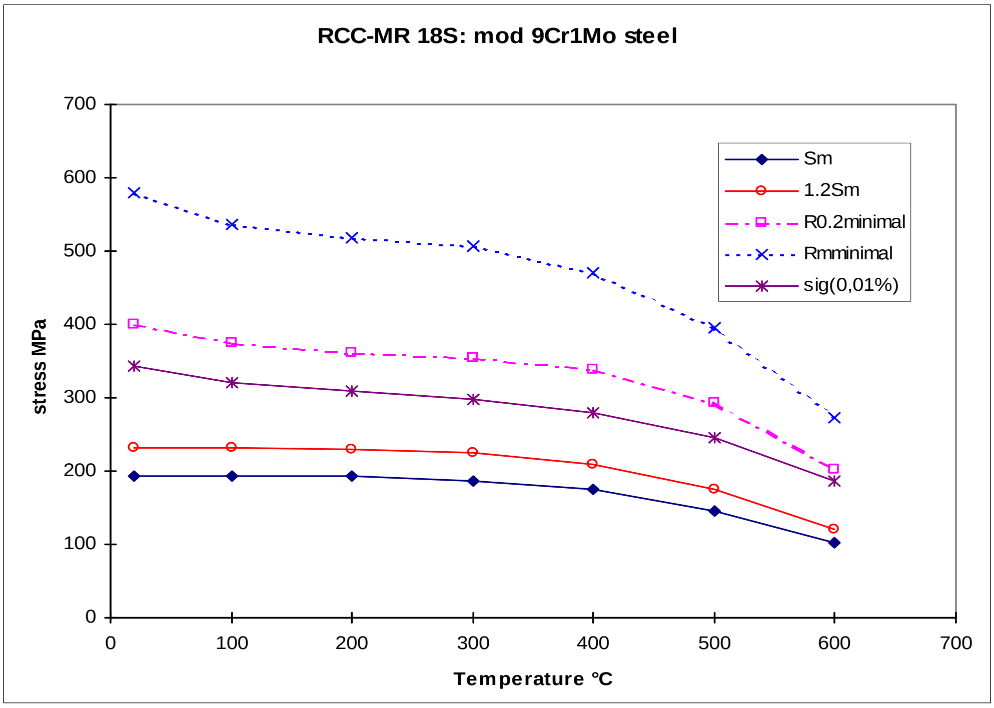
6. FIGURES

FIGURE 1 : RCC-MR ratcheting rule



Sig (0.01%): stress corresponding to a plastic strain equal to 0.01% on the minimal monotonic tensile curve

Figure 2: RCC-MR 16S - 2¼Cr steel

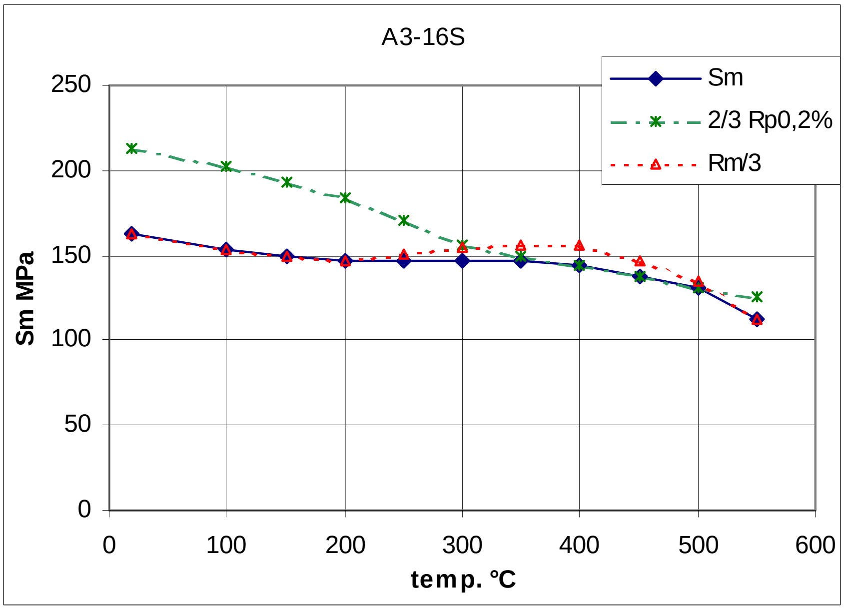
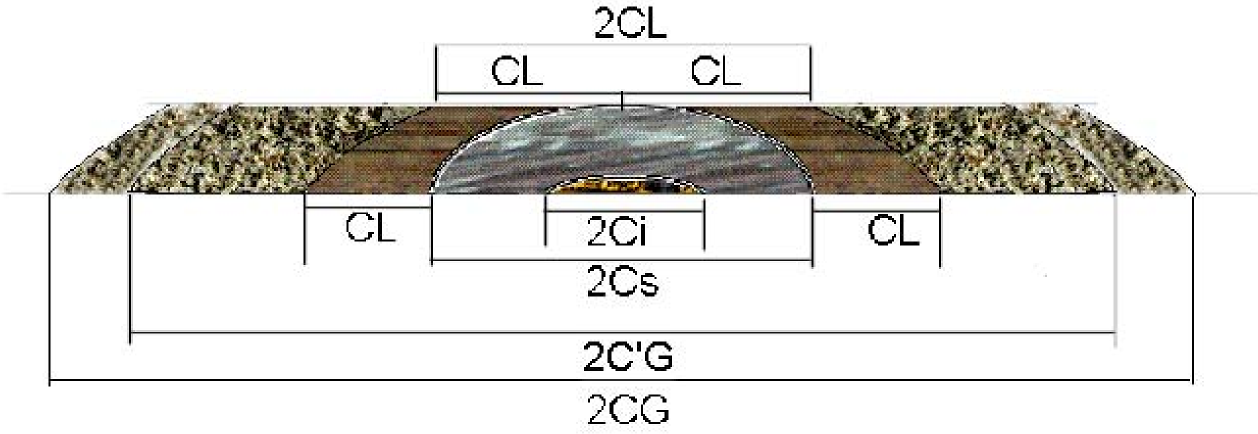


Figure 3: Leak Before Break Procedure



$2C_G$: unstable defect under emergency or faulted conditions
$2C_L$: detectable crack (corresponding to a leak flow Q_{det})
$2C_S$: through wall defect
$2C_i$: initial defect

Condition to check: $2C_S + 2C_L < 2C'_G$

$Q_{det} = m_q Q_{min}$

$C'_G = C_G/m_g$

m_g : margin on critical defect length

m_q : margin on minimal detectable leak flow