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RCC-MR code : presentation emphasizing recent design improvements

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ABSTRACT

The second edition of the French code for Liquid Metal Fast Reactor (RCC-MR) has been issued in May 1993 by AFCEN (Association Française pour les règles de conception et de construction des matériels des chaudières électro-nucléaires).
The aim of this contribution is to present the status of the RCC-MR code emphasizing the recent developments in the fields of design rules and material design data :
- design rules for class 1 piping,
- design rules for heat exchangers and tubeplates,
- new material specifications,
- updating of material data using the different data bases collected by the Research and Development organizations for EFR,
- welded joint factors.

1. INTRODUCTION

In 1978, CEA, EDF and NOVATOME decided to draw up a complete set of design and construction rules for LMFR components. The preparation of the design rules used largely the experience gained in Superphenix components analysis and the results of the large R & D programme performed as a support for the design of this plant.
This RCC-MR code issued first in June 1985 and reissued in May 1993 [1] has the same organization as the RCC-M code for pressurized water reactors :
- SECTION I : nuclear components, subdivided into
  A : general requirements
  B : class 1 components
  C : class 2 components
  D : class 3 components
  H : supports
  K : mechanisms for handling and reactor controlling
  Z : appendices.

Whenever necessary, subsections B, C and D of section I make specific and accurate reference to the rules and technical references contained in subsection Z and in sections II to V. For application of the RCC-MR to a given equipment, the manufacturer will find in the subsection of section I corresponding to this equipment all the applicable requirements either directly in the text, or via references to other parts of the RCC-MR. This section I constitutes the key to enter the code.

- SECTION II contains the procurement specifications for parts and products which can be used for components designed and manufactured with the rules of the RCC-MR section I. The sets of design material data are tabulated in subsection Z appendix A3 in close relationship with section II specifications.
- SECTION III supplies the rules for applying the various destructive tests and non destructive examination methods.
- SECTION IV supplies the rules relating to the qualifications for welding operations.
- SECTION V supplies the rules relating to manufacturing operations other than welding.

The scope of the RCC-MR exclusively covers mechanical components of the nuclear power plant considered to be important from a safety or availability point of view. These are : tanks, containers, vessels, reactor internals, heat exchangers, pumps, valves, pipes, box structures, supports, mechanisms for handling and reactor controlling.
The first edition of the RCC-MR and the two first addenda [1] of the RCC-MR have been early presented [2, 3] and since 1988 companies participating in the next European Fast Reactor (EFR) project have agreed to use RCC-MR as a sound basis with extensions and modifications reflecting the experience in the field of FR design and construction gained in the collaborating European countries and supported by the large cooperative R and D European programme.
Thanks to the modification procedure of the RCC-MR instituted by AFCEN, many proposals concerning design rules have been examined by the Tripartite Committee in charge of the elaboration of the design rules of RCC-MR (CEA, EDF, NOVATOME). Some of them are issued from the Design and Construction rules Committee in charge of the harmonization of the rules to be used for EFR. A tight link between the Tripartite Committee and the DCR Committee has been established.

The aim of this contribution is to present major modifications which have been included in the second edition May 1993 of the RCC-MR [1]. Special attention is given to :
- design rules for class 1 piping and heat exchangers,
- material specifications and design material data,
- welded joint factors.

2. DESIGN RULES

2.1 Design rules for class 1 piping

In the first edition of the RCC-MR only design rules for class 2 (RC 3600) and 3 (RD 3600) pipings were available. It was mainly due to the fact that for Superphenix 1, main pipes (secondary circuits and normal decay heat removal systems) are classified in class 2. The set of RCC-MR class 2 piping rules has been adapted from the B 3600 rules of ASME section III and extended to the creep regime according to the general design rules of RCC-MR RB/RC 3200.

2.1.1 Elastic follow-up

The rules governing the classification of the elastically calculated stresses into several categories (primary, secondary) are not easy to use, particularly when slightly loaded parts of a piping system act as a spring (elastic follow-up) on the heavily stressed parts. In that case, two effects appear and can be important for the designer :

- strain ranges under cyclic thermal expansion are higher than calculated assuming a linear and reversible behaviour of the material,
- the second effect appears in piping system operating at elevated temperature where creep is significant : undesirable accumulation of creep occurs in the weak zones which could result in fracture.

Class 2 practice (RCC-MR class 2 pipe rules) does not give practical method to determine whether the elastic follow-up is important or not. It is therefore recommended conservatively to classify any expansion stresses as primary stresses when, due to a bad design, some elastic follow-up can occur. This method is too conservative and it was decided to introduce in the new class 1 piping rules (RB 3600) the practical method developed by R.L. Roche [4].

- For cyclic thermal expansions, the effect of elastic follow-up is quantified by the elastic follow-up factor r_c. This factor represents the difference between the stress and strain ranges $\Delta\sigma_R$ and $\Delta\varepsilon_R$ given by elastic analysis and the "real" ranges $\Delta\sigma$ and $\Delta\varepsilon$ ($\Delta\sigma$ and $\Delta\varepsilon$ are on the cyclic curve) (figure 1) :

  $$r_C = - E \,.\, (\Delta\varepsilon - \Delta\varepsilon_R) / (\Delta\sigma - \Delta\sigma_R)$$

  It has been proven that for small values of the cyclic elastic follow-up factor ($r_C < 3$), enhancement of the strain range is covered by the present class 2 RCC-MR piping fatigue rules. Therefore, in order first not to complicate the fatigue analysis and second to avoid bad design, class 1 piping rules require to verify that r_C, calculated as above, remains smaller than 3 for the normal thermal expansions.

- For piping system operating at elevated temperature where creep is significant, present RCC-MR class 2 piping rules limit the creep usage fraction associated with the primary stresses for all loading related to level A and C criteria :

  $$U_{A,C}\,(P) < 1$$

  where $U = \Sigma\, t_i/t_p$; t_i : duration of P ; t_P : allowable duration under P.

  If the elastic follow-up is significant, stresses due to thermal expansions (σ_E) have to be conservatively classified as primary stresses. This practice is too conservative. The new RCC-MR class 1 piping rules propose now a practical method to take into account these expansion stresses. Based on elastic calculations of thermal expansion stresses σ_E, a relaxed strain value is estimated using a strain redistribution factor r_r calculated from a reference stress σ_R for the piping system. Assuming that the creep usage fraction is proportional to the creep strain, it is then possible to estimate the reduction of the creep usage fraction ΔU_A due to thermal expansion stresses (figure 2) :

  $$\Delta U_A = r_r \,.\, [\sigma_E / E\, \varepsilon_a]$$

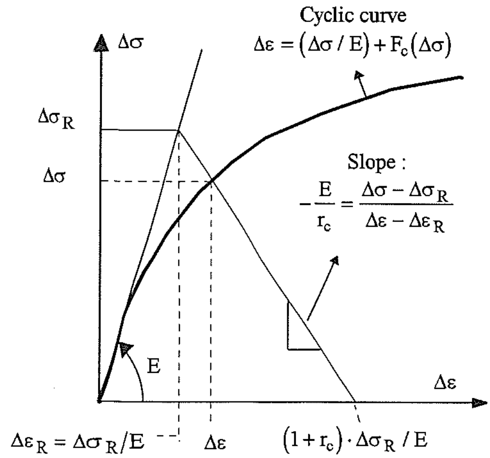
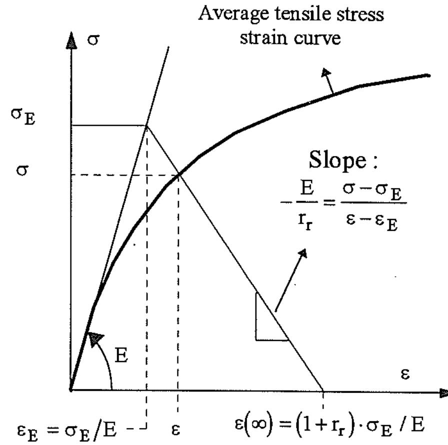


Figure 1 : cyclic elastic follow-up factor r_c



$$\Delta U_A = \frac{\varepsilon(\infty) - \varepsilon_E}{\varepsilon_a} = r_r \cdot \frac{\sigma_E}{E\varepsilon_a} \quad (\varepsilon_a = 1\%)$$

Figure 2 : strain redistribution factor r_r

2.1.2 Instability

Besides, based on a large data base of experimental results on straight parts and elbows representative of the pipes used in LMFR, rules against instability (collapse and buckling) have been improved and presented for the class 1 piping rules in a more practical form (RB3650), based on experimental results described in reference [5].

2.2 Design rules for heat exchangers

The second edition of the RCC-MR (Ref.1) proposes in a specific chapter (RB 3900 or RC 3900) all the design rules applicable to the design of the different parts of these components :

- stress classification,
- minimum thickness of exchange tubes and flat tubeplates,
- types of allowable welded joints,
- elastic route design method for tubeplates with holes arranged in an equilateral triangular pattern or a constant circular pattern.

3. NEW MATERIAL SPECIFICATIONS

Part and product procurement specifications included in section II of RCC-MR must cover the semi-finished metallurgical products corresponding to the design of each component which must comply with the rules of RCC-MR. New material specifications in RCC-MR 93 [1] concern two products necessary to the design of LMFR components :

- RM 4123 for bars in Nickel base alloy Ni 9 Cr Fe Nb Mo Ti (alloy 718) for mechanical parts of handling mechanisms,
- RM 2432 for plates in 9 Cr 1 Mo VNb grade for steam generator's shells.

4. MATERIAL DATA IN RCC-MR

4.1 Appendix A3

The purpose of this appendix is to provide all the material data necessary in order to perform the design assessments according to the rules of other sections of the code (mainly section 1). Appendix A3 comprises a general subsection which gives :

- the route from specified material to the relevant material properties group,
- the definitions of the properties included in the different material properties groups.

The other subsections (material properties group) of appendix A3 are numbered from 1S to 18S for the "structural" materials and from 1B to 11B for the bolting materials.

4.2 Materials covered by appendix A3

The different material properties groups cover in particular the following materials :

- Austenitic stainless steels :
  - low carbon 17 Cr 12 Ni 2 Mo with controlled nitrogen content (316L(N)),
  - 18 Cr 10 Ni (304)
  - low carbon 17 Cr 12 Ni 2 Mo (316L),
  - low carbon 18 Cr 10 Ni (304L)
- Nickel Iron alloy (alloy 800)
- Carbon Manganese steels with different levels of ultimate tensile strength (UTS) :
  - A42 (UTS $\geq$ 410 MPa)
  - A48 (UTS $\geq$ 450 MPa)
- Chromium molybdenum steels including 2,25 Cr 1 Mo grade and 9 Cr 1 MoVNb.
- Precipitation hardened austenitic steel for bolting 25 Ni 15 Cr MoVTi Al.

4.3 Content of each material properties group

Each material properties group should in principle content all the data which are listed hereafter. But due to lack of data, several material properties groups are still uncomplete. Are almost complete those which correspond to materials selected for actions by the Research and Development organizations involved in European Fast Reactor project (EFR) or by the Working Group Code and Standard (WGCS) of the European Union. It is one of the targets of the successive addenda of RCC-MR code to extend and to revise the material data taking into account the progress of the experimental data files on the different materials.

When complete, the group of material properties of appendix A3 comprises material data particularly involved in high temperature rules :

- extension of tensile properties to elevated temperatures,
- stress to rupture and allowable stress limit taking creep properties into account,
- data for strain evaluations (tensile curves and creep strain rate laws),
- cyclic stress strain curves and related parameter K_ε and K_v which are used in fatigue analysis according to section I of RCC-MR,
- fatigue endurance curves at elevated temperatures,
- symetrisation factor and creep-fatigue interaction diagramme which are used in the rules for creep-fatigue assessment.

A negligible creep curve is also provided in material properties groups of appendix A3 : it is a time temperature curve which is the lower bound of the domain where creep effects are significant. In design studies, this curve is used to select the design route with account of creep or the standard low temperature design route.
Mean and minimum values are provided for the strength properties (yield strength, tensile strength, stress to rupture). They are derived by statistical analyses when specific data bases are available from R and D works. When the values are extracted from various National or European standards, the minimum values are derived from mean values using a factor equal to 0.8.
The endurance curves for design against fatigue are derived from mean curves using the classical factors of 20 and 2 respectively on the number of cycles and on the strain range.
The data which describe the stress strain behaviour (monotonic tensile curves, cyclic curves, creep strain rates) correspond to mean curves.

4.4 Recent changes in RCC-MR for material data

4.4.1 Changes in material properties group A3.1S for 316L(N) steel

The physical properties data available for the partners of EFR project were reviewed and the most relevant data were selected for thermal expansion coefficient and Young modulus. The thermal conductivity density, thermal diffusivity, specific heat were included as complementary data in the RCC-MR 93 (Ref.1).
Based on average strain controlled fatigue curves established by R and D organizations by statistical analysis from low cycles data ($N \leq 10^5$) in one hand and from high cycles ($N > 10^5$) in the other hand, new fatigue curves were established.
The curves have been lowered by a coefficient equal to 1.3/1.5 (for a Poisson's ratio ν equal to 0.3) at 10^9 cycles, to be consistent with the use in design of the Von Mises equivalent strain range. These curves do not include possible mean stress effects at the high numbers of cycles.

4.4.2 Changes in material properties group A3.18S for 9 Cr 1 Mo VNb steel

The Young modulus, the thermal expansion coefficient and the thermal properties were revised for inclusion in RCC-MR 93 (Ref.1) as it was done for 316L(N) steel.
All the data needed for design against fatigue according the rules of section I of RCC-MR were also included in the RCC-MR 1993 (Ref.1) :

- cyclic stress strain curves and parameters K_ε and K_ν,
- design fatigue curve.

5. WELDED JOINT FACTORS

5.1 General

In the case of elastic analysis, the response of the structure is calculated without taking explicitely into account the mechanical properties of the welded joints. However the allowable values which are used are specific to the joints.

The allowable stresses of the welded joints depend on the quality of the weld and its mechanical characteristics. The design requires time dependent allowable stress limits such as S_t and S_r which can be satisfactorily derived only from a laboratory characterization. The limits are obtained by multiplying them by :

- the efficiency coefficient n which takes account of the type of joint and the extent of the examination made,
- and the allowable stresses in the weld which may be either directly tabulated or deduced from those of the base metal by multiplying each allowable stress by the corresponding coefficient J_m, J_t or J_r.

The allowable stresses of the welded joints become $n.J_m.S_m$, $n.J_t.S_t$ or $n.J_r.S_r$. For welded joints, the rules to be checked are thus those without welded joints, provided the allowable stresses of the base metal are replaced by the values thus calculated for the allowable stresses in the welded joint. For fatigue analysis of welds a multiplicative factor J_f ($J_f \geq 1$) is applied to the strain range.

In the appendix A9 of the RCC-MR, austenitic welds and nickel alloy welds are documented.

5.2 Austenitic welds with 19 Cr/12 Ni/2 Mo and 16 Cr/8 Ni/2 Mo filler metals

- J_r values should be obtained by comparing the mean values of the stress to rupture of the weldments with those of the base metal. For austenitic weldments, stress to rupture tests on the weld metal produced the most conservative ratio and these have been used instead of weldments results. These J_r values were extended in the RCC-MR 93, to low temperatures and short times. These values have to be revised from time to time taking account of up to date data on stress to rupture of 19 Cr/12 Ni/2 Mo and 16 Cr/8 Ni/2 Mo weld metals.
- J_f values were not in the appendix A9 issued before 1993. For 316L(N) welds fabricated with Superphenix weld metal (19 Cr/12 Ni/2 Mo) and welding procedure (manual electrode), a J_f value of 1 is used for fully penetrated welds on the basis of some representative tests on multipass weldments of about 25 mm thickness.

Other experiments on type and 316 steels in thermal shocks or in 3 mm to 25 mm thick sections under bend loading indicated J_f values from 1.1 to 1.5. In view of sparsity of experimental data and of the difficulty in treating these results, a J_f value of 1.25 has been adopted for the RCC-MR 93.

5.3 Butt welds of tubes in Ni Cr Fe Mo Nb Ti alloy (alloy 800)

For the particular case of TIG butt welds made on alloy 800 tubes before manufacturing the helicoïdal tube bundle, specific stress controlled fatigue tests with a mean stress have been performed by R and D in representative loading conditions.

A specific curve for the butt welds in alloy 800 was derived from these tests and introduced in A9 in 1987.

6. FUTURE WORKS

Works are also in progress :

- to write the criterion documents on design rules : ratchetting, fatigue without or with significant creep, buckling, pipes material data and type P damages,
- to improve ratchetting rules for axial thermal gradients,
- to revise the guideline to perform inelastic analysis (appendix X and XI),

- to improve the guide on fracture mechanic assessments,
- to take into account the recent developments of European standardization in material specifications,
- to update material data (by treatment of an extended 316 L(N) data base of more than 2500 tensile tests and 700 creep tests).

7. CONCLUSION

The RCC-MR code is a complete set of design and construction rules for LMFR mechanical components which evolves since the first edition in 1985. A second edition has been issued in 1993. This paper describes the main modifications included in this second version :

- design rules for class 1 piping, with practical rules taking into account elastic follow-up and rules against instability (collapse and buckling),
- values of the welded joint factors J_m, J_t, J_r and J_f for austenitic welds,
- specific chapter for the heat exchangers and steam generator components completed with an appendix for the analysis of flat tubeplates,
- design fatigue curves revised for 316L(N) and new for modified 9 Cr 1 Mo and a revised set of physical properties for each of these two grades.

This evolution is supported by the European R and D programme on LMFR and by the companies participating in the European Fast Reactor project.

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