AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE,
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RCC-MRx DESIGN CODE FOR NUCLEAR COMPONENTS

DOMENICO DE MEIS

ENEA - Dipartimento Fusione e Tecnologie per la Sicurezza Nucleare
Divisione Fisica della Fusione
Laboratorio Sorgenti, Antenne e Diagnostica
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D. DE MEIS

Sommario
Il codice francese RCC-MRx consiste in un unico documento che copre in modo coerente la progettazione e la costruzione di componenti per reattori ad alta temperatura, reattori di ricerca e a fusione (ITER) ed annessi ausiliari, i meccanismi per l'ispezione e la manipolazione e le apparecchiature di irraggiamento.
Le regole di progettazione sono state adattate per verificare la resistenza meccanica di strutture vicine a sorgenti neutroniche che possono operare anche in condizioni di creep significativo.

Parole chiave: Reattore a fusione, criteri di progettazione, integrità strutturale, codice RCC-MRx, creep, danno da irraggiamento

Abstract
The French RCC-MRx design and construction code constitutes a single document that covers in a consistent manner the design and construction of components for high temperature reactors, research reactors and fusion reactors (ITER) and the associated auxiliaries, examination and handling mechanisms and irradiation devices.
The design rules were adapted to cover the mechanical resistance of structures close to neutron sources that can also operate in significant creep conditions.

Keywords: *Fusion reactor, design criteria, structural integrity, RCC-MRx code, creep, irradiation damage*

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1. Introduction

The verification of the structural components of a fusion power reactor requires design criteria developed specifically for those components at the unique conditions at which they are operated. Therefore a creation of a body of structural design criteria appropriate for a fusion power plant is an important activity.
The French RCC-MRx design code (1) covers in a consistent manner all the above requirements. It is the result of the merger of the RCC-MX (2), developed in the context of the research reactor Jules Horowitz Reactor project, and RCC-MR (3) which set up rules applicable to the design of components operating at high temperature and to the Vacuum Vessel of ITER.

2. RCC-MRx design rules and corresponding stress limits

RCC-MRx is the selected C&S for the design of in-vessel components because of the following reasons:

- it provides an ensemble of consistent design, manufacturing and materials rules, revised in 2013, in order to implement, in particular, regulation requirements related to PED directive (4) and French ESPN order (5);
- it provides rules for high temperature operation;
- it provides rules for the design of irradiated components;
- eurofer97 is already included in the material properties tables given by the code, although these tables must be completed;
- it is the reference C&S selected for the design and construction of the test blanket for ITER. The code will continue to be developed in the framework of the TBM programme for fusion relevant aspects (6).

The RCC-MRx code has three quality classes in the design and construction rules:

- Class 1 N1Rx;
- Class 2 N2Rx;
- Class 3 N3Rx.

They correspond from 1 to 3 to a decreasing confidence in the security level regarding the different mechanical damage modes to which the equipment could be submitted due to the loading induced by operating conditions.
The use of the RCC-MRx design and construction code in the context of contractual relations between customer and supplier is based on a list of the components to which the code applies and their “entrance keys” which make it possible to determine what rules are applicable (table 1). The “entrance keys” are quoted in the Equipment Specifications:

- Key 1. This key is applicable to:

 1) Components of nuclear reactor and its auxiliary systems,
 2) or examination, handling or drive mechanisms,
 3) or components of irradiation devices.

- Key 2. This key gives the required RCC-MRx class:

 1) Class N1Rx

2) Class N2Rx
3) Class N3Rx.

For Safety classified components, the relations between “Safety Classes” and “RCC-MRx classes” that must be applied are defined before the application of the Code. The Manufacturer must apply the required class to each type of component and its support. It may however apply a higher class, if needed, to simplify parts manufacturing for example. It must inform the Contractor of working to higher class as an exception. It must apply all the provisions of the higher class.

- Key 3. This key indicates the type of component to which the component is attached:

-Vessels, tanks, containers;
- Pumps;
- Valves;
- Piping;
- Bellows;
- Box structures;
- Heat exchangers.

- Key 4. This key indicates, for irradiation devices, class 3 components, whether it is "Catalogue

Component" or not.

- Key 5. This key indicates whether component is subjected to pressure equipment regulations applicable in France (ESP Decree (7)/ESPN Order (5)).

- Key 6. Based on the value of keys 2 and 3, this key indicates all applicable rules among the following (Table 1):

- Section III;
- Section II REC 2200 as part of applying standard NF EN 13445;
- Section II REC 2300 as part of applying standard NF EN 13480;
- Section II REC 2400 as part of applying standard NF EN 1993-1-1.

As well as the following, based on the value of key 5:
- Section II REC 3200 if the component is subject to pressure equipment regulations - decree ESP/order ESPN.
The list of all applicable rules is defined in the Equipment Specification.

Key 1 **= Reactor components and associated auxiliaires** **= Examination or handling mechanisms** **= Irradiation devices**	**Applicable sets of rules**		**Key 5 = ESP/ESPN Special instructions**
Key 2 = Class $N1_{rx}$	Section III - **RA 4000**		Section II **REC 3200**
Key 2 = Class $N2_{Rx}$	Section III - **RA 4000**		Section II **REC 3200**
Key 2 = Class $N3_{Rx}$	Section III - **RA 4000**	Section II **REC 2200** (vessels) Section II **REC 2300** (piping) Section II **REC 2400** (metallic frameworks)	Section II **REC 3200**

Table 1 - Sets of applicable rules and special instructions.

The following table 2 shows the rules applicable according to keys 2 to 5 for ESP/ESPN component.

Table 1.3a: sets of applicable rules and specific provisions for an ESP or ESPN

	Specific design and manufacturing provisions	Key 2 $N1_{Rx}$	Key 2 $N2_{Rx}$	Key 2 $N3_{Rx}$
ESP Cat. I to IV	Arts. 3 to 6 and EES Annex 1 of ESP Decree.	Subsection B + REC 3231	Subsection C + REC 3231	Subsection D or REC 2000 + REC 3231
ESP art.7	Art.7 of ESP Decree. Best practices.	Subsection B + REC 3232	Subsection C + REC 3232	Subsection D or REC 2000 + REC 3232
ESPN (1) $N1_{ESPN}$ Cat. I to IV	EES Annex 1 ESP Art. 7, 8 and Annex 1 ESPN Order. Art. 9 and ER Annex 4 of ESPN Order.	Subsection B + REC 3233	Subsection B + REC 3233	Subsection B + REC 3233
ESPN (2) $N2_{ESPN}$ Cat. I to IV	EES Annex 1 ESP Art. 7, 8 and Annex 2 ESPN Order. Art. 9 and ER Annex 4 of ESPN Order.	Subsection B + REC 3234	Subsection C + REC 3234	Subsection C + REC 3234
ESPN $N3_{ESPN}$ Cat. I to IV	EES Annex 1 ESP Art. 7, 8 and Annex 3 ESPN Order. Art. 9 and ER Annex 4 of ESPN Order.	Subsection B + REC 3235	Subsection C + REC 3235	Subsection D or REC 2000 + REC 3235
ESPN $N1_{ESPN}$ Cat. 0	Art.6-II of ESPN Order. Best practices: trade manual submitted to applicable ministry. Art. 9 and ER Annex 4 of ESPN Order.	Subsection B + REC 3236	Subsection B + REC 3236	Subsection B + REC 3236
ESPN $N2_{ESPN}$ Cat. 0	Art.6-II of ESPN Order. Best practices: trade manual submitted to applicable ministry. Art. 9 and ER Annex 4 of ESPN Order.	Subsection B + REC 3237	Subsection C + REC 3237	Subsection D or REC 2000 + REC 3237
ESPN $N3_{ESPN}$ Cat. 0	Art.6-II of ESPN Order. Best practices. Art. 9 and ER Annex 4 of ESPN Order.	Subsection B + REC 3238	Subsection C + REC 3238	Subsection D or REC 2000 + REC 3238

(1) does not include pipes with NPS less than or equal to 100.
(2) includes Category I and II pipes from level $N1_{ESPN}$ with NPS less than or equal to 100.

Table 2 - Sets of applicable rules and specific provisions for an ESP or ESPN component.

As illustrated in the following table 3, Tome 1 Volume B-C-D L 3000 and Appendix A3 contain the design and analysis rules.

Moreover table 3 shows the outline of RCC-MRx code (RDG 1200) and provides the acronyms used to identify the Sections, Tomes and Subsections.

Sections	Tomes	Titles	Acronyms
• **Section I**		**General provisions**	RDG
• **Section II**		**Additional requirements and special instructions**	REC
• **Section III**		**Rules for nuclear installations mechanical components**	
	• **Tome 1**	• ***Design and Construction rules***	
		- *Subsection A: general provisions for Section III*	RA
		- *Subsection B: class $N1_{Rx}$ reactor components, its auxiliary systems and supports*	RB
		- *Subsection C: class $N2_{Rx}$ reactor components, its auxiliary systems and supports*	RC
		- *Subsection D: class $N3_{Rx}$ reactor components, its auxiliary systems and supports*	RD
		- *Subsection K: examination, handling or drive mechanisms*	RK
		- *Subsection L: irradiation devices*	RL
		- *Subsection Z: technical appendices*	A1, ...
	• **Tome 2**	• ***Part and product procurement specifications***	RM
	• **Tome 3**	• ***Destructive tests and non-destructive examination methods***	RMC
	• **Tome 4**	• ***Welding***	RS
	• **Tome 5**	• ***Manufacturing operations other than welding***	RF
	• **Tome 6**	• ***Probationary Phase Rules***	RPP

Table 3 - Outline of RCC-MRx code and acronyms to identify the Sections, Tomes and Subsections.

2.1 Design by analysis

The general analysis rules are provided in chapter RB 3200 (Class N1Rx), RC 3200 (Class N2Rx), RK 3200 (Examination and handling mechanisms) and RL 3200 (Irradiation devices) of Section III. In addition the specific design rules for box structures (RB3800) are well adapted to the Divertor cassette structural layout.

These general analysis rules are applicable to structures made of material whose properties are listed in one of the Properties Groups in Appendices A3 and A9 for the specified operating conditions. In the case of a new product or new grade purchased under a Particular Procurement Specification, it must be accompanied by a new Properties Group as shown in Appendices A3 and A9.

In addition to the negligible creep test (RB 3216.1) a negligible irradiation test, based on ductility criteria, has been added in RB 3216.2. This test makes it possible to disregard the effects of irradiation if the fluence received by the component in question remains below a value specified in Appendix A3 (Properties Group) at the service temperature in question. If the test is meeting, the fluence is considered to be negligible and the rules "without irradiation" apply unrestrictedly.

The structure of RB 3200 is as follows:

	Negligible creep	Significant creep
Negligible irradiation	RB 3251.1 (Type P damages) RB 3261.1 (type S damages) identical to RCC-MR	RB 3252.1(Type P damages) RB 3262.1 (Type S damages) Identical to RCC-MR
Significant irradiation	RB 3251.2 (Type P damages) RB 3261.2 (Type S damages) New rules	RB 3252.2(Type P damages) RB 3262.2 (Type S damages) New rules

Table 4 - RB structure.

They aim of RB3000 rules is to ensure that the components are sufficiently safe under the various mechanical damages to which they could be exposed under loads in specified operating conditions:

-damages called **"P-type damages"** are those which could result from applying constantly increasing loads to a structure:

- excessive deformation,
- plastic instability,
- fracture.

-damages called **"S-type damages"** are those which could only result by repeatedly applying loads:

- progressive deformation,
- fatigue.

- buckling.

- fast fracture; usually two types of fast fracture are considered:

- from ductile tearing,
- from fragile or semi-fragile tearing.

These rules do not cover all measures to be taken to avoid other types of deterioration that could occur, for example from erosion or corrosion.
These rules also do not cover the measures to be taken to ensure proper operation of component with moving parts such as pumps and valves, because they are essentially aimed at confinement and support functions.

RB 3000 includes general design rules (RB 3100) and general analysis rules (RB 3200) as well as specific design rules for particular components (RB 3300 through 3900).

When these specific rules lead to configuration conditions more restrictive than allowed in the general rules, the specific rules must be used.
The Equipment Specification (RB 3170) and the set of additional reference notes (operating condition notes, notes defining limit conditions, interface notes, load definition notes) include all the data needed to check the rules according the specified criteria levels.
All calculations made to check the rules contained in the chapters 3000 of Tome 1 shall be written in design calculation. These notes constitute the Design Report (RB, RC, RD, RK, and RL 3180).
The Design Report justifies that the requirements of the chapters 3000 of Tome 1 are satisfied when the component is subject to all the loading conditions specified in the Equipment Specification. This report also covers compliance with any additional requirements likely to appear in the Equipment Specification.

In the following we will explain only RB rules for level N1Rx. In fact design by analysis rules for RC 3200 is identical to those in RB 3200. RD 3200 is not supplied.
For irradiation devices RL 3000 rules, depending on the class, rules in RB 3200 (Class N1Rx) or RC 3200 (Class N2Rx) shall be applied.

2.2 Damages (RB 3120)

2.2.1 Type P damages (RB 3121)

Types of damage referred to by the expression "type P damages" are those which can result from the application to a structure of a steadily and regularly increasing loading or a constant loading.

Type P damages have the same meaning as in ASME code; P means Primary, damages that are to be considered in first, because they could lead to the burst or the collapse of the structure if they are not limited. These damages are caused by primary loads (like constant pressure, forces, etc.) and not by displacement controlled loads (like temperature gradients), for ductile and hardening materials. Of course, it is well known that any displacement corresponds to a force, so that controlled displacement can be neglected in Type P damage analyses if the produced plasticity is not important.
Type P damages for the level A criteria will cover excessive strain, plastic instability and rupture. They are divided in two parts:
- instantaneous, i.e. damages due to plastic strains;
- differed, i.e. damages due to creep strains.

2.2.1.1 Immediate excessive deformation RB 3121.1

For a structure made of elastic, ductile material to which is applied a loading multiplied by a gradually increasing coefficient, the following behaviour can be observed: with lower coefficient values, the structure behaves elastically and deformation is reversible. At higher values, irreversible plastic deformations occur such that if the loading were to be cancelled, the structure would not return to its original dimensions or shape. These plastic deformations are firstly contained by elastic zones which limit them and then, the plastic zones being sufficiently extended, yielding takes place easily. The overall permanent deformation of the structure thus increases faster the higher the loading coefficient. It is when the overall permanent deformation begins to increase rapidly that it is said to be excessive.

2.2.1.2 Immediate plastic instability (RB 3121.2)

When, in the previous case, the loading continues to increase, the behaviour of the structure depends on any variations in its shape and the strain hardening increase of the yield strength of the material. These two effects rapidly become counteracting: any change in shape tends to weaken the structure whereas an increase in the yield strength of the material tends, on the contrary, to reinforce it. As long as the first effect is dominated by the second, the structure is deformed in a stable manner, when the first becomes dominant, deformation is unstable and fracture is not far behind if the loading is maintained.
Plastic instability considered here is an overall phenomenon. It must be distinguished from ductile tearing which is a form of fast fracture and must be examined separately.

2.2.1.3 Time-dependent excessive deformation (creep) (RB 3121.3)

When a structure is subjected to loadings maintained for a sufficiently long time at high temperatures, deformations evolve with time and can consequently produce excessive deformation. This type of damage is called a time-dependent excessive deformation.

2.2.1.4 Time-dependent plastic instability (RB 3121.4)

Although inducing no immediate damage when applied, a loading can, because of creep, induce plastic instability over a certain period of time. This type of damage is called time-dependent plastic instability.

2.2.1.5 Time-dependent fracture (RB 3121.5)

In certain conditions, changes in shape prior to fracture can be small. The sometimes considerable reduction in the elongation at the time of rupture means that this phenomenon must be taken into account both globally (under the effect of external forces) and locally (fracture before complete release of internal stresses).

2.2.1.6 Elastic or elastoplastic instability (RB 3121.6)

Apart from the instabilities described above, other elastic or elastoplastic instabilities may occur, in which elastic deformation, by the changes in shape it induces, considerably weakens the strength of a structure and its ability to withstand the applied loading. The typical case of this type of damage is buckling as raised in RB 3123.

2.2.2 Type S damages (RB 3122)

Types of damage described by the expression "type S damages" are those which can only result from repeated application of loadings.

2.2.2.1 Progressive deformation (or ratcheting) (RB 3122.1)

When we consider a structure subjected to cyclic loading, at the end of the first cycle, the structure may show signs of permanent deformation. During the following cycles, two cases may arise:
- After a few cycles, the overall permanent deformation is stable;
- The permanent overall deformation continues to increase as every loading cycle induces additional deformation and the structure gradually changes from its original shape. This behaviour is called

progressive deformation.

2.2.2.2 Fatigue (progressive cracking) (RB 3122.2)

When the loading applied to a structure evolves with time, in particular in a cyclic fashion, the material is subjected to deformation variations. These variations, if sufficiently numerous and if of large amplitude are capable of causing cracking. The damage here is defined by the appearance of small macroscopic cracks which do not compromise the strength of the structure with regard to the other types of damage to be considered. When the temperature is sufficiently high, creep deformation occurs during each cycle thus accelerating the appearance of cracking.

2.2.3 Buckling damages (RB 3123)

The Buckling correspond to the behaviour of some slim or slender structures which are subject to compression stresses. For a certain level of loads (critic load), the deformed shape of the structure change suddenly.

2.2.4 Fast fracture damages (non-ductile damage modes) (RB 3124)

Fast fracture is any fracture initiated from an existing defect or defects under monotonic loading which occurs without being preceded by an appreciable global plastic deformation. Fast fracture is generally caused by unstable propagation of a crack.
Two types of fast fracture are generally considered, one by ductile tearing, the other by fragile or semi-fragile tearing:

- ductile tearing: the material cracks with local detectable plastic strain;
- brittle tearing: the material cracks without local plastic deformation (plastic deformation within a microscopic volume of material).

2.3 Operating conditions and criteria level

2.3.1 Operating conditions (RB 3130)

During operation a component may be subjected to a number of different operating conditions which are classified under four categories according to considerations which do not necessarily concern only the problems posed by its mechanical strength as a structure.
The operating conditions for each component are classified as follows:

- the 1st category operating conditions (SF1) and 2nd category operating conditions (SF2) are the conditions to which component may be subjected in the course of normal operation, including normal operating incidents, start-up and shutdown.
- the 3rd category operating conditions (SF3), emergency conditions, corresponding to very low probability of occurrence but which must nonetheless be considered, and which imply shut down and appropriate inspection of the component or of the plant.
- the 4th category operating conditions (SF4), which are highly improbable but whose consequences on component are studied among others for safety reasons.

The list and classification of operating conditions must be defined in the Equipment Specification (RB 3170).

2.3.2 Loading considerations (RB 3140)

There is a set of environmental effects (pressures, forces, heat flux, irradiation, corrosion) corresponding to each operating condition. Some of these effects, which may produce mechanical work depending on the component deformation, are referred to as loads. Sets of simultaneous loads are referred to as “loadings”.
The loads include the following:
- Internal and external pressures,
- The weight of the component and its contents, and the static and dynamic loads produced by liquids under each condition analysed;
- Forces resulting from weight, thermal expansion, and pressure and dynamic loads which originate outside the zone studied and which are applied at its boundaries;
- Loads resulting from earthquakes and vibrations;
- Reactions of supports;
- Temperature effects, either constant or transient;
- Forces resulting from non-free swelling in irradiation conditions.

2.3.3 Criteria levels (RB 3150)

The level (A, C and D) of criteria to be met must be defined in the Equipment Specification (RB 3170) for each loading associated with an operating condition or set of operating conditions.

These criteria levels have been established according to the objective defined in RB 3110 and they aim at the prevention of a certain number of damages for the component in question.
Table 5 below shows the level of Criteria and relative damages.

- Criteria of level A
  - Type P damage:
    - Fracture
    - Excessive deformation
    - Plastic instability / Failure
  - Type S damage:
    - Progressive deformation
    - Fatigue
  - Elastic or elastoplastic instability
  - The respect of the level A criteria ensures the security beside these damages
- Criteria of level C
  - Type P damage:
    - Excessive deformation
    - Plastic instability / Failure
  - Elastic or elastoplastic instability
  - There is not type S damage analysis. The number of cycle must be less than 10.
- Criteria of level D
  - Type P damage:
    - Plastic instability / Failure
  - Elastic or elastoplastic instability

Table 5 - Level Criteria and relative damages (8).

2.3.3.1 Level A criteria (RB 3151)

The aim of level A criteria is to protect the component against the following types of damage:

- Immediate or time-dependent excessive deformation;
- Immediate or time-dependent plastic instability;
- Time-dependent fracture;

- Elastic or elastoplastic instability, immediate or time-dependent;
- Progressive deformation;
- Fatigue.

The respect of level A criteria guarantees the level of safety required with regard to these types of damage throughout the life of the component, for operation as specified.

2.3.3.2 Level C criteria (RB 3153)

The aim of level C criteria is to protect the component against the following type of damages:

- Immediate or time-dependent excessive deformation;
- Immediate or time-dependent plastic instability;
- Time-dependent fracture;
- Elastic or elastoplastic instability, immediate or time-dependent.

2.3.3.3 Level D criteria (RB 3154)

The aim of level D criteria is to protect the component against the following types of damage:
- Immediate or time-dependent plastic instability,
- Time-dependent fracture,
- Elastic or elastoplastic instability, immediate or time-dependent.

But with lower safety margins than those with level C criteria.

2.3.4 Minimum criteria levels (RB 3160)

The level A criteria shall be met for the first and second category operating conditions (SF1 and SF2).
The criteria to be met for third category operating conditions (SF3) shall be at least as severe as those of level C.
The criteria to be met for fourth category operating conditions (SF4) shall be at least as severe as those of level D (table 6).

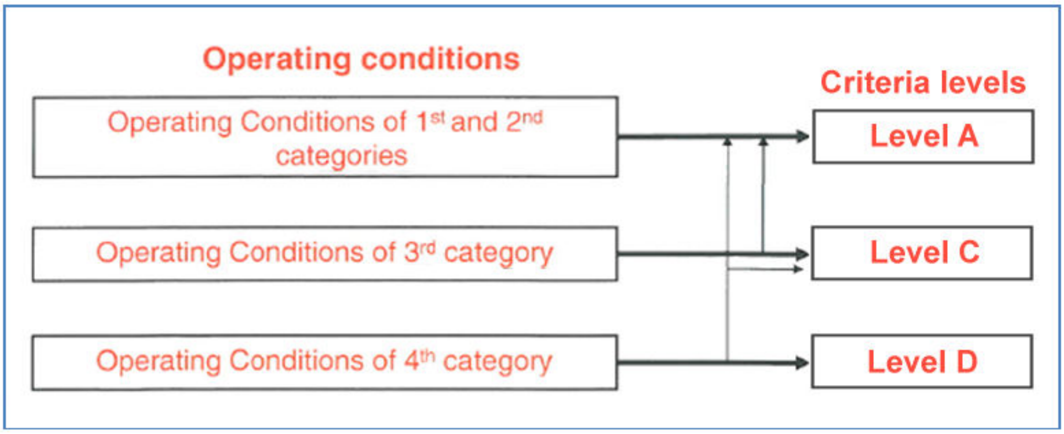


Table 6 - Category operating conditions and criteria levels (8)

In the following of this report only Level A criteria is considered since it is both the most conservative and comprehensive of all possible damage modes.
Limits for Level C and Level D criteria are usually derived from those of Level A using lower safety factors.

2.3.5 Equipment specification (RB 3170)

The Equipment Specification comprises at least:
- Description of the component with plans needed for calculation and providing functions, shapes, dimensions of component parts, limits and interconnections with other components;
- The list and definitions of conditions and corresponding loads;
- Identification of materials as well data for design;
- Levels of criteria A, C or D;
- Type and extent of maintenance and inspection actions;
- Provisions associated with seismic and fast fracture analysis.

2.3.6 Design report (RB 3180)

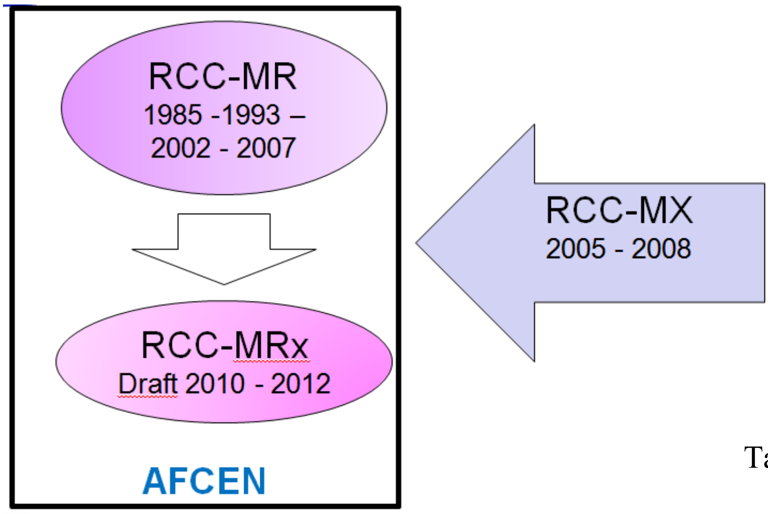
The Manufacturer shall prepare a Design Report for all components manufactured in accordance with this Code.
This report shall demonstrate:
-That the rules of this RB 3000 are respected for all loadings specified in the Equipment Specification;
-Demonstrate that any additional design requirements contained in the Equipment Specification are met.

The stress report has containing a design computation report.

The typical organization of these Design and Calculation Reports is:
- Introduction;
- Basic data;
- Materials;
- specified criteria;
- Calculations;
- Results and analysis;
- Conclusions.

2.4 General Analysis rules: RB 3200

The RB 3200 rules apply to structures made from materials whose properties are given in Section III (Appendix A3) (table 7) of RCC-MRx for the specified operating conditions.
The purpose of mechanical analyses is to demonstrate that a component does not undergo certain types of damage when subjected to the loadings associated with the conditions specified in the Equipment Specification.
Analyses consist in verifying compliance with criteria selected on the basis of the method of analysis and the level of criteria and the type of damage.



Tab. 7 RCC-MRx genesis

Three methods of analysis can be used in the code:
- Elastic analysis,
- Inelastic analysis,
- Experimental analysis.

The term elastic analysis designates analyses carried out on the assumption that the behaviour of the material is elastic and linear; that the displacements are small (geometrical linearity) and that there is no initial stress (or residual stress).
The term inelastic analysis designates all the other methods except for experimental analysis.
Experimental analysis consists in subjecting models representing the component or some of its elements to loadings in order to determine the deformation and stresses or margins with regard to the damage under study.

Elastic analysis should be the most commonly used method, the other methods of analysis only when some criteria associated to the elastic methods are not verified.

In the following thesis only elastic analysis will be pointed out. This means:
-the behaviour of the material is elastic and linear,
-the material is isotropic,
-the displacements and strains are small,
-the initial stresses are nil.

It may be necessary for technical reason to break a component up into several zones of calculation (RB3214) in order to analyse a single type of damage. In this case, an overall analysis of the component shall be made.

2.4.1 Applicable rules (RB 3216)

The rules to be respected differ according to:

- Level of criteria: A, C or D;
- Method of analysis: elastic, inelastic or experimental;
- Damage envisaged: type P or type S damages.

These rules also depend on three parameters: temperature, time and irradiation:

- Temperature because the properties of the material (allowable stresses, fatigue curves, etc.) often depend upon it;
- Time because its influence on the behaviour of the materials shows up in phenomena which can often be neglected at moderate temperatures but which, on the other hand, must be taken into account at high temperatures. These phenomena due to the effect of time are generally designated by the term creep;
- Irradiation because neutrons could, at moderate temperature, generates movement of atoms and transmutation that could lead to changes in the material’s properties. At high temperature, irradiation could influence the behaviour of materials over time and thus contribute to creep ("irradiation" creep combined with "thermal" creep). At high temperature, neutrons could also cause gas swelling, coming from the formation and growth of cavities due to the vacancies created by irradiation.

2.4.2 Negligible creep tests (RB 3216.1)

The first step to apply in any case is the negligible creep rule. It is generally better to keep a structure in the negligible creep domain. Here it is necessary to consider the maximum temperature of the structure. The reason is that the negligible creep rule covers both Type P damages (related to mean stresses and strains in the thickness) and Type S damages (taking care of local stresses and strains).
For the first ones, the mean temperature could be sufficient to describe the effect of creep. But for the second, it is necessary to have the maximum local temperatures. To keep the rules in the RCC-MRx code in a simple form, the maximum temperature has been defined for a conservative approach.
The negligible creep rule is divided in two tests.
Test 1 - is defined with two parts:
- is the maximum temperature in the thickness during the whole life of the shell less than the negligible creep temperature of the material?
- does the structure respect $\sum_{i=1}^{N} \frac{t_i}{T_i} \leq 1$? Which means that for any operating situation i to be analysed with level A, C, D criteria, and corresponding to a precise maximum temperature in the thickness, the sum of the ratio of the operating time t_i to the allowed time T_i is limited to 1. The T_i is read on the negligible creep curve, given in the A3 appendix.

Test 2 - the same approach of test 1 but without considering situations analysed with level D criteria.

2.4.3 Negligible irradiation test (RB 3216.2)

For a component the irradiation is said to be negligible or insignificant for the entire duration of its operational life if the fluence received during entire operational life is lower than the value defined in chapter A3.32 (table 8) at the maximum operating temperature for the material involved.

θ (°C)	20°C to 375°C	375°C to 400°C	400°C to 425°C	425°C to550 °C
D_{lneg} (dpa)	2.75	2.6	2	2
D_{lmax} (dpa)	53	40	30	24

Table 8 - Irradiation damages for X2CrNiMo17-12-2(N) austenitic stainless steel (from A3.1S.32).

2.5 Stresses (RB 3224)

It is possible to build the following table 9 that summarizes all possible combinations of loading and rules to be applied with negligible or significant creep and irradiation.

	NEGLIGIBLE CREEP	SIGNIFICANT CREEP
NEGLIGIBLE IRRADIATION	RB 3251.1 (Type P damage) RB 3261.1 (Type S damage) RB 3271.1 (Buckling)	RB 3252.1 (Type P damage) RB 3262.1 (Type S damage)
SIGNIFICANT IRRADIATION	RB 3251.2 (Type P damage) RB 3261.2 (Type S damage)	RB 3252.2 (Type P damage) RB 3262.2 (Type S damage)

Table 9 - All possible combinations of loading and rules to be applied with negligible/significant creep and negligible/significant irradiation (8).

2.5.1 Classification of stresses (RB 3224.3)

Primary, secondary and peak stresses are defined.

The primary stress is defined as the fraction of the total stress which does not disappear after small permanent deformation (stresses that balance the mechanical efforts: e.g. pressure, etc.).

Secondary stress is the fraction of the total stress which can disappear as a result of small permanent deformation, minus the peak stresses (e.g. thermal stresses, due to imposed displacements, etc.).

The peak stress is the fraction of the total stress which meets the following two conditions:

- It is the additional stress applied by a geometrical discontinuity of the structure or by non-linearity in the distribution of stresses within the thickness;
- This additional stress cannot cause deformation of the whole structure.

2.5.2 Negligible creep and negligible irradiation

In the following only rules for Level A criteria will be outlined.

2.5.2.1 Type P damages (RB 3251.1)

Two modes of failure directly related to the primary stress intensity in the material are the immediate plastic collapse and immediate plastic instability (9). If a structure is loaded above the yield strength of the material, plastic deformation occurs until the structure collapses either because of excessive deformation or necking.
We have to verify the classical limitation of primary stresses:

$$\overline{P_m} \leq S_m$$

$$\overline{P_L} \leq 1.5\ S_m$$

$$\overline{P_L + P_b} \leq 1.5\ S_m$$

Where:
P_m= primary membrane stress
P_b= primary bending stress
P_L= local membrane stress
S_m = Allowable stress given in A3.43 of the code with $R^t_{p0.2}$ and R_m

The explanation for the 1.5 coefficient multiplying bending P_b and local primary stress P_L is that these kinds of stresses cannot lead to necking and rupture but they can produce large strains, and they must be limited. But the limitation is not so severe compared to the limitation of the general primary membrane stress P_m. The temperature Θ_m to be considered here is the mean temperature in the thickness, since the load is sustained by the whole thickness of the component.

There is no limitation of secondary stresses.

Moreover we have to verify the measuring defect susceptibility.

$$J(a, C) \leq J_{IC}$$

Where:
C= the mechanical or thermal load;
a= the depth of conventional defect;
J_{IC}= characteristic value of the initiation;
J= driving force.

2.5.2.2 Type S damage (RB 3261.1)

2.5.2.2.1 Ratcheting damage (RB 3261.111)

Ratcheting is the accumulation of plastic deformation in structures subjected to cyclic stressing with a non-zero primary stress. When a structure is subjected to cyclic loading, the structure may show signs of permanent deformation at the end of the first cycle. During subsequent cycles, two cases may arise:

a) After a few cycles, the overall permanent deformation is stable. The subsequent structural response is elastic or elastoplastic and progressive incremental inelastic deformation is absent;
b) The permanent overall deformation continues to increase as every loading cycle induces additional deformation and the structure gradually changes from its original shape until it eventually collapses. This behavior is called progressive deformation or ratcheting.

With ratcheting, there is a risk that a structure could malfunction. Also, the rules to prevent fatigue damage are not valid if ratcheting occurs. Ratcheting rules require the definition of a period, which is considered as the assembly of all the situations to be analyses with level A criteria: here, this period is the sum of all the cycles, and the corresponding time is the total time life of the structure.

The criterion is based on efficiency diagram.

The objective is to calculate the equivalent of primary stress giving the same damages of the combination of a constant primary stress and a secondary stress range. This equivalent stress is compared to S_m.

The approach used in RCC-MRx to prevent ratcheting is based on the concept of the ''effective primary stress'' (P_{eff}), that is an equivalent stress that would give the same immediate deformation as the actual cycling load combination. Values of P_{eff} are determined experimentally. Limits are then defined in terms of this effective primary stress. Before obtaining the effective primary stress intensity, it is necessary to calculate the relative variation of secondary stress in relation to the primary stress considered. This introduces the notion of secondary ratio (SR):

$$SR_1 = \frac{\overline{\Delta Q_{max}}}{\max(\sigma_m)}$$

$$SR_2 = \frac{\overline{\Delta Q_{max}}}{\max(\sigma_L + \sigma_b)}$$

Where max (σ_m) and max (σ_l+ σ_b) are stresses depending of the type of loadings:
- Presence of the secondary membrane stressQ_m;
- Short term overstress.

Four methods exist for the calculation of $Max(\sigma_m)$ and $Max(\sigma_L + \sigma_b)$.

Once the values of the secondary ratios are known, the corresponding effective primary stresses can be obtained by means of the efficiency diagram (Fig. 1):

$$P_1 = \frac{Max(\sigma_m)}{V_1}$$

$$P_2 = \frac{Max(\sigma_L + \sigma_b)}{V_2}$$

Where V_1 and V_2 are the efficiency indexes obtained from SR1 and SR2 using the efficiency diagram.

The following limits need then to be verified:

$$P_1 \leq 1.3\ S_m$$
$$P_2 \leq 1.3 \text{ x } 1.5 \text{ x } S_m$$

This means that the effective primary membrane stress intensity P_1, calculated on the basis of a period covering all the events with loadings for which compliance with level A criteria is required, should not exceed 1.3 times the value of S_m.
The effective primary stress intensity of the sum of primary stresses P_2, calculated over the same period as previously, should not exceed 1.3 x 1.5 times the value of S_m.

Or as alternative rule (RB3261.1118)

$$\text{Max } \overline{P_L + P_b} + \overline{\Delta Q} \leq 3\ S_m$$

It must be noted that while 3Sm rule is extremely conservative for Eurofer (and 9%Cr steel in general); the present efficiency diagram in the code is not suited for this type of steel.

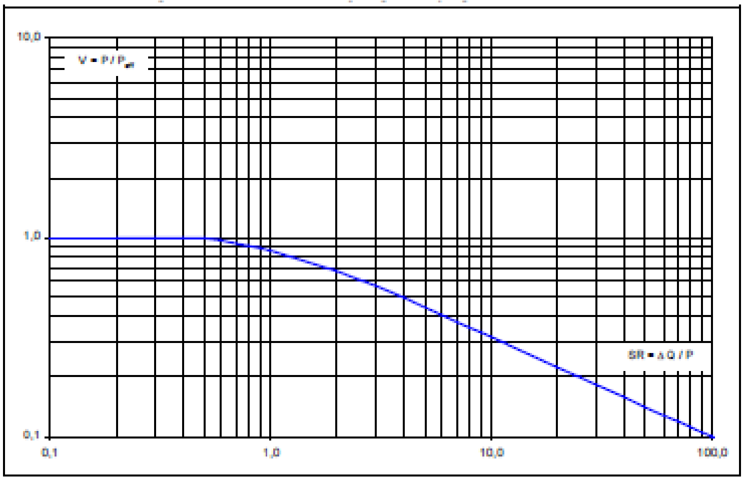


Fig. 1 - Typical efficiency diagram for progressive deformation.

2.5.2.2.2 Rule for fatigue damage (RB 3261.112)

Fatigue is a damaging mode that may appear under repeated loading. If the cyclic loads are too high, cracks can appear, propagate, and lead to the rupture of the component. Such cracks will appear most of the time at the surface of the component, where the stresses are higher. The total stress variation has to be considered everywhere in the structure, and more precisely, the total strain variation during a cycle.
The rules of RB 3261.112 only apply if the rules of RB 3261.111 (progressive deformation) are satisfied.

Use of fatigue curves (given in A3.47, fig. 2) and calculation of fatigue usage factor V= specified N_{cycles} /allowable N_{cycles} that must be lower than 1: V ≤ 1

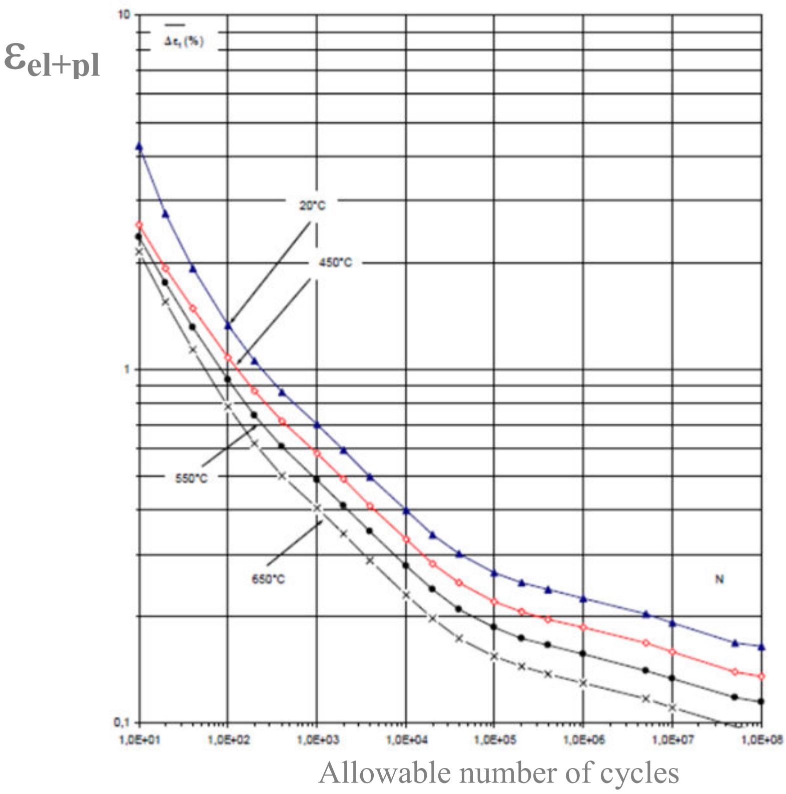


Fig. 2 - Typical fatigue curve

2.5.3 Negligible creep and significant irradiation

2.5.3.1 Type P damage (3251.2)

Primary stresses being limited by S_m, conventional design codes rely on sufficient ductility of the materials to simplify the analyses, ignoring secondary and peak stresses (apart from their effect on cyclic loadings like ratcheting and fatigue) since they are intrinsically self-limiting and cannot cause, by themselves, the failure of the structure. When the ductility of the material is reduced (intrinsically or because of neutron irradiation), it is however necessary to insure that the combined strain due to primary plus secondary stresses does not exceed the remaining elongation of the material.

Two different modes of potential failure due to the limited ductility of the materials can be defined: immediate plastic flow localization and immediate local fracture due to exhaustion of ductility (which is associated with a low total elongation). Given that irradiated Eurofer97 retains considerable ductility after necking, as is shown by the high values of the total elongation and reduction of area, the latter is not an issue. Immediate plastic flow localization is instead a concern for Eurofer97 (6).

We have to verify the rules for non-irradiated material (RB 3251.1) and limitation of primary, secondary and peak stresses:

$$\overline{P_m + Q_m} \leq S_{em}^A$$

$$\overline{P_L + P_b + Q + F} \leq S_{et}^A$$

And also the defect of susceptibility:

$$J(a, C) \leq J_{IC} \text{ (irradiated)}$$

Where:

$\overline{P_m + Q_m}$ = general membrane primary and secondary stress

$\overline{P_L + P_b + Q + F}$ = total primary and secondary equivalent stress

S_{em}^A = the allowable elastic membrane stress (in A3.63)

S_{et}^A = the allowable elastic total stress (in A3.63)

2.5.3.2 Type S damage (RB 3261.2)

2.5.3.2.1 Ratcheting

Apply rules with non-irradiated material (RB 3261.111) if irradiated properties are not available. Criterion is based on efficiency diagram. Calculate the “equivalent primary stress” P1 and P2 that are then compared to Sm. Or in alternative the “3Sm rule” (conservative).

2.5.3.2.2 Fatigue

Fatigue curves under irradiation. If these curves are not given in appendix A3.67 it is possible to use fatigue curves without irradiation. Calculate the fatigue usage factor V= specified Ncycles/allowable Ncycles.

As rule: V≤1

2.5.4 Significant Creep and Negligible Irradiation

2.5.4.1 Type P damage (3252.111)

First the rules of 3251(negligible creep) must be checked (9).

Then calculate the creep usage fraction (defined in RB 3226.1) associated with primary membrane stresses multiplied by a creep correction factor Ω:

Rules:

$$U_{A,C}(\Omega\overline{P_m})\leq 1$$

Where Ω is determinate as following:
If all membrane stresses, whatever the cause, are classified under general primary membrane stresses, Ω is then equal to 1;

If not $\Omega = \Omega_1 + \Omega_2$

With $\Omega_1 = 1 + 0.2\,(\frac{\overline{L_m}}{P_m})$ if $\overline{P_L} > \overline{P_m}$ and $\Omega_1 = 1$ if $\overline{P_L} < \overline{P_m}$

Calculate the creep usage faction (RB 3226.1) associated with the sum of the primary membrane stresses and primary bending stresses multiplied by coefficient Φ (depending of the geometry of cross section concerned)

And

$$U_{A,C}(\overline{P_L + \Phi\,P_b}) \leq 1$$

The primary bending stress is multiplied by factor Φ that takes into account the effect of creep on this stress category. Coefficient Φ depends on the geometry of the cross-section concerned; it is equal to 0.8 for plate elements and thin-wall shells with a rectangular cross-section.

$U_{A,C}$ is calculated by a linear damage rule summation:

$$U_{A,C}(\bar{\sigma}) = \Sigma_{i\varepsilon A,C}\frac{t_i}{T_i}$$

Where t_i is the time of duration of loading situation i, T_i the allowed time under a given stress, the latter being calculated on the S_t creep stress curves at the mean temperature in the thickness Θ_m. S_t has the same meaning as in ASME code and is given inside A3 appendix.

Figure A3.1S.53: minimum creep rupture stress S_r

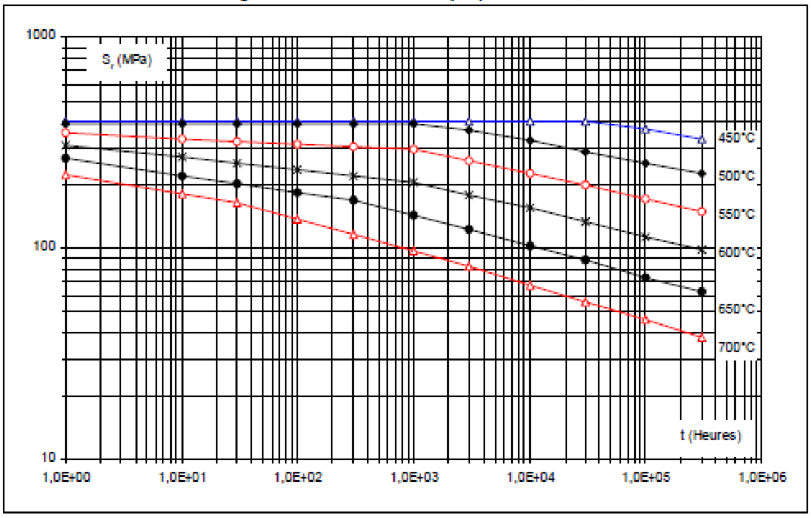


Fig. 3 - S_t curves from A3.53.

2.5.4.2 Type S damage (RB 3262.1)

2.5.4.2.1 Ratcheting

1) Verification of negligible creep rule (RB 3262.11)
2) The following limits must be checked at all points of the structure:

- Plastic strain + associated creep strain at 1.25 times the effective primary membrane stress intensity P_1 (RB 3262.1114) should not excide 1%;
- Plastic strain + associated creep strain at 1.25 times the effective primary stress intensity of the sum of primary stresses corrected by a factor of creep P_3 (RB 3262.1116) should not excide 2%

These rules are for austenitic stainless steels. No rules for the other steel for ratcheting (study in progress).

2.5.4.2.2 Fatigue-creep

Fatigue is a damaging mode that may appear under repeated loading. If the cyclic loads are too high, cracks can appear, propagate, and lead to the rupture of the component. Such cracks will appear most of the time at the surface of the component, where the stresses are higher. The total stress variation has to be considered everywhere in the structure, and more precisely, the total strain variation during a cycle. Moreover, the mechanical properties have to be taken at the local temperature, in the potentially damaged zone.
The design rules of RCC-MRx propose to avoid crack initiation by mean of the fatigue usage factor V_A for all possible cycles among level A:

$$V_A = \Sigma_i \frac{n_i}{N_i(\overline{\Delta\mathcal{E}})}$$

n_i being the number of cycles really applied to the structure, and N_i being the allowed number of cycles for the strain variation $\overline{\Delta\mathcal{E}}$. This strain variation is the addition of the elastic plus plastic strain variation $\overline{\Delta\mathcal{E}_{el+pl}}$ *and* of the creep strain variation $\overline{\Delta\mathcal{E}_{fl}}$: these latter accounts for the fact that creep or relaxation will increase the fatigue damage.

Limitation of creep-fatigue damage are reported in RB3262.1122:

-Calculate the fatigue usage factor V = specific number of cycles/allowable number of cycles;
-Calculate the creep fracture usage fraction (W = specific holding time/ allowable holding time with relaxation stress).

As criteria we have that all points V, W are located within an allowable area defined in creep-fatigue interaction diagrams in A3.55 (fig. 4).

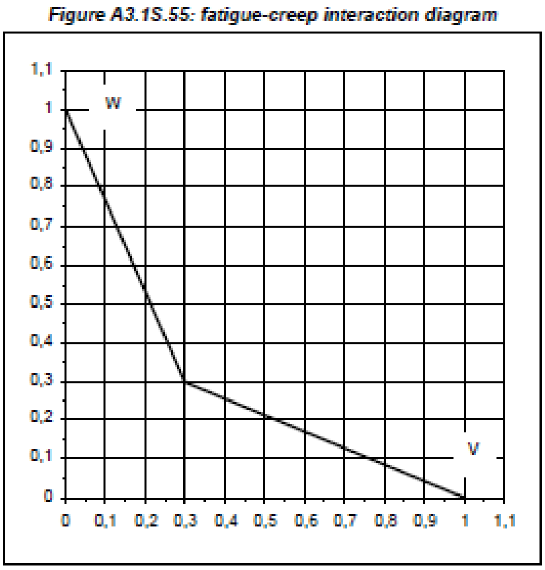


Fig. 4 - Creep-fatigue diagram.

2.5.5 Significant Creep and significant irradiation

For solution annealed or work –hardened austenitic stainless steel type of 316 and 316 L:
-The temperature domain is less than 625 °C;
-The irradiation damage remains less than the maximum allowable dpa number (A3.33)

2.5.5.1 P damage (RB 3252.2)

As a rule we have:

The rules of 3252.1 (significant creep and negligible irradiation) must be checked using the limits on usage fractions U and W equal to 0.1 instead of 1.

2.5.5.2 S damage (RB 3262.2)

Rules for austenitic stainless steel.
The rule of 3262.11 (significant creep and negligible irradiation) must be checked multiplying the

creep rupture usage fraction W by 10.

2.5.6 Rules for Buckling RB 3270

Buckling is a phenomenon which can occur in structures with an average centerline or average surface area. It consists in the development of deformations different from those which manifest themselves at low loading levels.
Buckling is not strictly speaking a type of damage but its appearance generally induces damage such as elastoplastic instability or excessive deformation or fatigue.

2.5.6.1 Negligible creep and negligible irradiation RB 3271.1

No elastic nor elastoplastic instability under a loading equal to 2.5 the specific loading.

2.5.6.2 Negligible creep and significant irradiation RB 3271.2

Later

2.5.6.3 Significant creep and negligible irradiation RB 3272.2

No elastic or elastoplastic instability under a loading equal to 1.5 the specific loading.

2.5.6.4 Significant creep and significant irradiation RB 3272.2

Later

2.6 Equipment subject to French regulations ESP/ESPN and RCC-MRx

According to French regulations, Pressure Equipment (ESP) and Nuclear Pressure Equipment (ESPN) (see Annex 2) are classified into categories based on pressure, by type of equipment (vessels, pipes and accessories), by type of fluid (gas or liquid) and by fluid group (group 1: explosive, dangerous – group 2: other fluids). On the other hand, Nuclear Pressure Equipment (ESPN) are classified into three levels (from $N1_{ESPN}$ to $N3_{ESPN}$), based on the amount of radiation released if they fail.
For equipment subject to both RCC-MRx and French ESP/ESPN regulations, all RCC-MRx rules and specific minimum provisions are therefore a function of the specified RCC-MRx classes (N1Rx, N2Rx or N3Rx) and of the ESPN levels ($N1_{ESPN}$, $N2_{ESPN}$, $N3_{ESPN}$) as shown in table 2.
REC 3200 of section II of RCC-MRx lists the specific mandatory provisions for design and manufacturing, matching all the applicable rules of RCC-MRx to those in the ESP decree and the ESPN order.
For example the requirements for the values for acceptance of material for the pressure parts and the requirements for regulatory hydraulic pressure test are:

-the minimum acceptance values for percentage elongation after fracture A at ambient temperature and the average values of the energy KV absorbed by breakage on three Charpy V-notch test specimens used in manufacturing level $N1_{ESPN}$, $N2_{ESPN}$ and $N3_{ESPN}$ pressure equipment are shown in table 10; they can be found under REC 3254.1, REC 3264 and REC 3274, as well as in Tome 2 in RM 012-1.

-the French regulatory hydrostatic pressure test is covered specifically in REC 3257.4 because the test is performed differently in each country. Based on the ESP decree and the harmonized standard

NF EN 13445, the hydrostatic pressure test is performed on each equipment. It is deemed satisfactory if the pressure is reached without leakage or visible deformation based on direct visual examination. For class 1 (N1Rx) or 2 (N2Rx) vessels sized under RB 3000 or RC 3000, Pressure Test(PT) is defined by the following formula:

$$PT = \mathrm{Max}\left[\left\{1.25 \cdot PD \cdot \frac{S_{mA}(T_{test})}{S_{mA}(T)}\right\};\{1.43 \cdot PS\}\right]$$

The purpose of the pressure test is not to dimension pressure equipment, the test pressure PT shall therefore be limited so as not to cause a higher membrane stress than is allowed for level C:

$$S_{mC}(Ttest) = \mathrm{Min}[\ 1.35 x S_{mA}(T_{test})\ ;\ R_{p0.2}(T_{test})\ ].$$

Where:

-PS: maximum allowable pressure. PS cannot be less than the pressure in the equipment for 1st category (SF1) and 2nd category (SF2) operating conditions to which the equipment would be subjected during normal operation conditions, including normal operating incidents, start up and shut down;

-PD: Design pressure (RB 3324.2)

-T: temperature associated with PD

-T_{test}: test temperature

-$S_{mA}(T_{test})$: allowable stress at the test temperature T_{test} (A3.43)

$S_{mA}(T)$: allowable stress at the temperature T (A3.43)

The ratio between $S_{mA}(T_{test})/S_{mA}(T)$ depends on the material used for the section in question. The value of the ratio used when calculating PT must not be less than the smallest ratio obtained by assuming different materials for the main pressurized sections (e.g. shells, heads, exchanger tube sheets, tube bundles, main body flanges, but ignoring the bolts associated with the main body flanges).

For Class N3 vessels sized using RD 3000, test pressure is defined by the same formula except for replacing S_{mA} by the allowable stress SA (A3.43), provided that the test pressure PT is limited so as not to cause a higher membrane stress than this allowed for level C: $SC(T_{test}) = 1.5\ SA(Tt_{est})$.

Table 1.3b: acceptance values for steels of Nuclear Pressure Equipment ESPN

Acceptance values for $N1_{ESPN}$ Nuclear Pressure Equipment		
Ferritic steels	A ≥ 20 % at room temperature	KV ≥ 40 J at 0 °C, if R_m < 600 Mpa KV ≥ 60 J at 0 °C, if 600 MPa ≤ R_m ≤ 800 MPa (R_m at A at room temperature)
Austenitic and austenitic-ferritic steels	A ≥ 35 % at room temperature	KV ≥ 100 J at room temperature and R_m ≤ 800 MPa at room temperature
	If A ≥ 45 % at room temperature	No Charpy impact test requirement on ISO V test specimen
Martensitic steels	A ≥ 14 %, at room temperature	KV ≥ 40 J at 0 °C and $R_{p0.2}$ / R_m ≤ 0,85 at room temperature
Bolting steels	A ≥ 12 % at room temperature	KV ≥ 40 J à 0 °C(1) and reduction in area ≥ 0,45 if 12 % ≤ A < 14 % at room temperature
(1) or, for bolting austenitic steels, KV ≥ 50 J at room temperature		
Acceptance values for $N2_{ESPN}$ Nuclear Pressure Equipment		
Ferritic steels	A ≥ 14 % at room temperature	KV ≥ 27 J at 0 °C
Austenitic and austenitic-ferritic steels	A ≥ 25 % at room temperature	KV ≥ 60 J at 20°C
	IF A ≥ 45 % at room temperature	No Charpy impact test requirement on ISO V test specimen
Bolting steels	A ≥ 12 % at room temperature	KV ≥ 40 J at 0 °C (1) and reduction in area ≥ 0,45 if 12 % ≤ A < 14 % at room temperature
(1) or, for bolting austenitic steels, KV ≥ 50 J at room temperature		
Acceptance values for $N3_{ESPN}$ Nuclear Pressure Equipment		
Ferritic steels	A ≥ 14 % at room temperature	KV ≥ 27 J at the lowest operating temperature or at 20 °C

Tab. 10 - Acceptance values for steels of ESPN

Annex 1 “RCC-MRx peculiarities”

A1.1 RCC-MRx radiation damage

When subject to neutron irradiation, the material behavior is modified. Involved phenomena are very complex; thus let’s identify here the main effects which have been considered in the establishment of the design rules.
The effect of irradiation on metallic material can be summed up as follows:

- Atoms displacement, induced by neutrons with a sufficient energy level. It is a dominating effect for steels and is measured with the number of displacements per atom (dpa). These displacements lead to disturbance and reconstruction of the regular atomic ordering in the crystal lattice. These processes are accompanied by the formation of characteristic lattice defects which affect both the microstructure and the macroscopic structurally sensitive properties of the irradiated material. The consequences may be a decrease of ductility and a hardening of the material, a swelling or irradiation creep;
- Changes in the chemical composition by stopping of the bombarding particles (called ion implantation) or capture of particles in the atomic nucleus with consequent transmutation;
- Excitation of electrons and ionization of atoms (which does not produce permanent damage in metals).

The design rules of the codes are established to prevent from mechanical damages: excessive deformation, plastic instability, fatigue, progressive deformation, creep, and fast fracture. Generally, the rules are based on a comparison between the estimation of the consequences of a given load in the structure (stresses, strains, cracking force etc..) and the capability of the structure material to resist to this effect (in link with the mechanical properties of the material, yield stress, ultimate stress, toughness etc..).
To establish rules preventing from these damages for the RCC-MRx code, only the consequences with an impact on the mechanical behavior of the components are considered.
The effect of irradiation is integrated in these design rules through a material effect and also through the estimation of the load effects (10).
From a macroscopic point of view, the irradiation leads to an increase of the yield strength and of the tensile strength (see fig. A1.1). In the same time, uniform and rupture elongations are decreased.

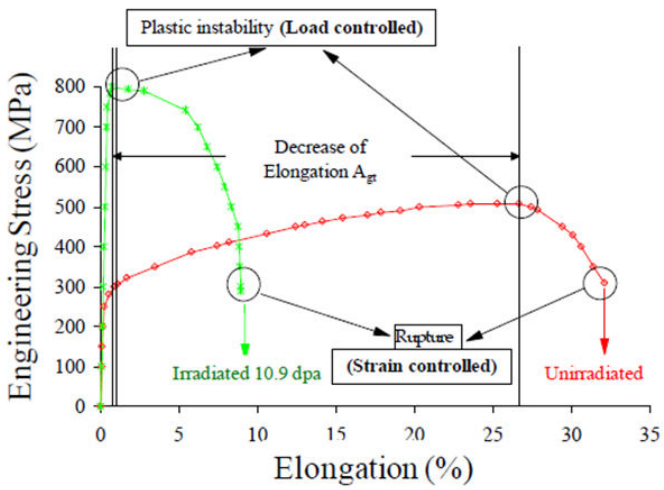


Fig A1.1 - Evolution of a conventional tensile stress-strain curve with irradiation (AISI 316L(N) steel).

These changes in the material behavior challenge the usual rules preventing mechanical damages because the prevention uses the principle of stress relaxation.

Hence, it results in 2 issues to be addressed:
- Knowledge of the mechanical behavior of the material when irradiated;
- The rules used to prevent mechanical damage of the structures.

These multiple considerations led to an approach in three steps for the definition of the rules to prevent irradiation damage:
- First, mechanical characteristics depending on relevant irradiation parameters have to be collected;
- Then the rules themselves have to be defined, considering the consequences of the loss of ductility on the existing classical rules;
- This implies the definition of the border lines for the application domain of the irradiated material prevention rules.

The drivers for the use of the rules are the following:

- Prevention of the mechanical damages of the structure;
- Use as far as possible of proven approaches and methodologies for the establishment of the rules;
- Easiness of use of the rules by designers.

In some specific cases, depending on the functions of the mechanical components some additional considerations regarding the effects of irradiation are to be done on a case by case basis especially for some components ensuring specific safety or mechanical functions requiring set-up or removal of assemblies, mechanical motions,… for which geometrical deformations are to be considered.

The details of the selected approach and rules are detailed hereafter.

A1.1.1 Rules overview

A1.1.1.1 Material properties

Data shall be given in function of parameters considered as driving the material mechanical behavior. Three materials families are concerned in the RCC-MRx code: stainless steels, aluminum alloy and zirconium alloy.

For stainless steels it is considered that material mechanical behavior is driven by dpa.
For aluminium alloys, it is considered that material mechanical behavior is driven by Si production in the alloy.
For zirconium alloys the material mechanical behavior is considered driven by irradiation flux in fast neutrons.

To feed the code, a huge effort in the collection and analysis of available experimental irradiation data has been done by the CEA. An experimental program to complete this data base is still on-going. The mechanical characteristics are available in appendix A3 of the code. There are two types of characteristics: the border lines and the properties needed to apply the design rules.

A1.1.1.2 Border lines

Two border lines are defined in the code in relation with irradiation:
- Negligible irradiation curve: below this curve, the design of the component is made without including irradiation effects;
- Maximum allowable irradiation: above this curve, the rules given by the code are not validated anymore.

To define these curves, the effects of irradiation on the mechanical properties have been analyzed. The borders have been selected on the basis of the following considerations:
- Negligible irradiation is based on a variation of ductility criterion;
- Maximal irradiation is based depending on the nature of the material either on the residual ductility or maximal swelling criteria.

The selected borders lines can be sum up in the following table:

Material designation	Negligible irradiation	Maximum allowable irradiation
A3.1S: « 316L(N) »	↘ Ductility	↗ Swelling
A3.3S: « 316L»	↘ Ductility	↗ Swelling
A3.7S: « 316L work hardening»	↘ Ductility	↗ Swelling
A3.4S: « 304L »	↘ Ductility	Not supplied
A3.1A: 5754-O (solution annealed)	↘ Ductility	↘Ductility
A3.2A: 6061-T6 (structural Hardening)	↘ Ductility	↘Ductility
A3.1Z: Zircaloy 2	↘Ductility	↘Ductility
A3.2Z: Zircaloy 4	↘Ductility	↘Ductility

Tab. A1.1 - Effects of irradiation for structural materials.

The selected borders are related to the applicability of the design rules and may have to be completed on a case by case basis according to a specific analysis covering:
- Deformation of the structure;
- Others considerations issued from the safety analysis and operating conditions of the component.

Fig. A1.2 shows the negligible, significant and maximum allowable irradiation borders curves for Cr-Ni-Mo stainless steels material family.
The criterion for the negligible irradiation curve is the loss of ductility (percentage of the minimum value of A% (unirradiated) – A is the percentage total elongation (elastic plus plastic) at fracture).

The criterion for the maximal irradiation curve is the variation of ΔV/V or ΔL/L due to swelling (where ΔV/V, ΔL/L are the variation of volume or linear dimension due to swelling).

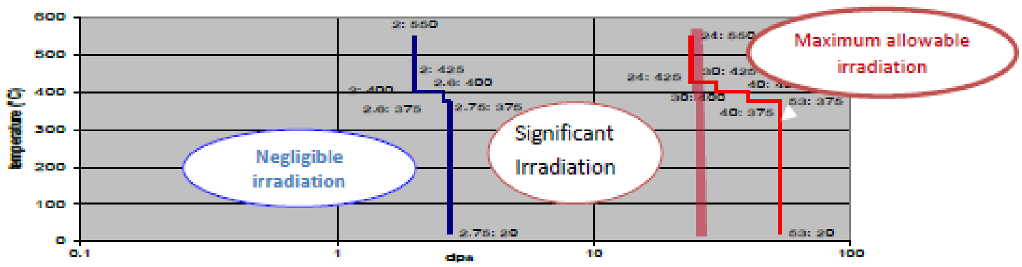


Fig A1.2 - Border line for CR-NI-Mo stainless steels.

A1.1.1.3 Design rules

Mechanical codes prevent from the usual damages: Excessive deformation, Plastic instability, Elastic and elastic-plastic instability, Progressive deformation, Fatigue, Creep, Fast fracture.

Design codes propose different possible methods:
- Direct verification: experimental analysis, elastic-plastic analysis;
- Elastic analysis: detailed elastic analysis, simplified elastic analysis (use of flexibility and stress indices for standard components).

The selected approach for the irradiated component rules establishment is based on the following approach:

- Additional rules for irradiated structures;
- When the ductility decrease, the idea is to complete the non-irradiated set of rules preventing the excessive deformation and plastic instability damages by a total stress and strain limitation criterion based on the irradiated material residual ductility;
- Thanks to the well-known elastic follow-up method (11) used by several nuclear design and construction codes for mechanical components, the use of an elastic analysis allowing to properly represent the actual stresses obtained through an elastoplastic behavior was selected.

This approach allows the use of the elastic analysis in order to assess the elasto-plastic stresses and strain.

Only the detailed elastic analysis will be treated here. As said before, the way to implement irradiation effect in the RCC-MRx code consists in a definition for the already existing rules of an "irradiation effect" through pertinent parameters.
In detail, it leads to the following sets of rules in the case of the detailed elastic analysis:

Rules to be met without irradiation effect	**Additional rules to integrate the irradiation effect**
Excessive deformation, plastic instability $\overline{P_L + P_b} \leq 1.5 \cdot S_m$ $\overline{P_L} \leq 1.5 \cdot S_m$ $\overline{P_m} \leq S_m$	Excessive deformation, plastic instability $\overline{P_m + Q_m} \leq S^A_{em}$ $\overline{P_L + P_b + Q + F} \leq S^A_{et}$
Fast fracture *$J(a,C) \leq J_{IC}$*	Fast fracture *$J(a,C) \leq J_{IC}$ (irradiated)*
Progressive deformation *P and ΔQ to compare to kSm*	Progressive deformation *Analyse non irradiated material*
Fatigue *Usage factor V = specified Ncycles / allowable Ncycles < 1*	Fatigue *Fatigue curve without irradiation: Δε increases*
Creep *Creep factor U or W ≈ application time / allowable time < 1*	Creep *Creep factor U or W ≈ application time / allowable time < 0,1*

Tab. A1.2 – Summary of design rule in RCC-MRx.

Annex 2 “ESP/ESPN French Legislation”

A.2.1 Pressure Equipment 97/23/EC (PED) and French Decree 99-1046 (ESP)

The Pressure Equipment Directive (acronym – PED) was adopted by the European Parliament and the European Council in May 1997 (4). It entered in force in all European Union from 29 May 2002. The directive provides an adequate legislative framework at the European level for equipment subject to a pressure hazard.

The French Decree No 99-1046 dated 13th December 1999 (amended by further Decrees) and Order dated 21st December 1999 concerning classification and conformity assessment (acronym ESP will be used) put the Pressure Equipment Directive in force in France (7).

The Directive and French Decree apply to the design, manufacture and conformity assessment of pressure equipment and assemblies with a maximum allowable pressure greater than 0.5 bar over atmospheric pressure (1.5 bars absolute).

These regulations introduce a categorization (Category I–IV, Category IV being the highest) of the pressure equipment, depending on the hazard due to pressure, volume of the vessel or diameter of the pipe, type of fluid and temperature. There is an additional category which is Sound Engineering Practice (SEP). For each category the so-called modules for conformity assessment in accordance with the Essential Safety Requirements are established. For equipment in Category II–IV the conformity assessment has to be performed by a Notified Body.
Some equipment operating under a pressure greater than 0.5 bar can be excluded from the scope of directive.

The ESP and PED formulate the Essential Safety Requirements (ESR) (see Annex 1 of ESP), which includes technical and legal conditions which have to be satisfied. These requirements are related to the design, manufacture, materials and other specific conditions. The manufacturer of equipment is under an obligation to analyze the hazards and must then design and construct it taking account of this analysis. The selection of C&S is the responsibility of the manufacturer; he shall demonstrate that the selected C&S provides conformity with ESR. The use of European harmonized standards in the design and manufacture of a product will give the presumption of conformity with those ESRs listed in Annex ZA of the particular harmonized standard.
After completion of the conformity assessment the manufacturer shall declare conformity and issue a CE mark. Pressure equipment’s are subject to the provisions applicable to operation and re-qualification, as required. The specific rules for the implementation of such requirements are described in the special order concerning the operation of pressure equipment (7).

A.2.2 French order concerning nuclear pressure equipment (acronym-ESPN)

This French law (5) defines nuclear pressure equipment as equipment that meets the following conditions:
– Is pressure equipment as defined by ESP;
– Is used in a Basic Nuclear Installation;
– Directly ensures containment of radioactive substances, and
– In case of failure leads to release of activity above 370 MBq.

ESPN has practically extended the application of the methodology foreseen by ESP and PED (ESR, conformity modules, etc.) to nuclear pressure equipment in France. ESPN has double classification

of the equipment:
– Pressure hazard based on ESP rules, Category I–IV, and Category 0 (equivalent to SEP);
– Nuclear level – N1, N2 and N3.

ESPN includes some additional requirement on ESR depending on the nuclear level of the equipment.

As far as C&S are concerned, the ESPN does not define specific requirements for the selection of the codes, but requires that the conformity with ESR is demonstrated.
In accordance with ESPN requirement, the operator of a nuclear facility shall provide the description of operational conditions, and the manufacturer of the equipment (who is responsible for the design, fabrication and conformity with regulation) shall select an applicable code which is used as a tool for demonstrating conformity with Essential Safety Requirements.

The ESPN also defines rules for maintenance and monitoring, periodic inspections, installation and operation and periodic requalification of nuclear pressure equipment. A manufacturer of nuclear equipment shall contract an Agreed (by the French regulator) Notified Body (ANB) and after completion of the conformity assessment shall declare conformity.

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