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Standardization of Eurofer material, a first step toward industrialization

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The diversity and the innovative characteristic included in the fusion technology are in opposition with a codification status, as code and standards are based on the recognized industrial feedback. By definition, no code exists for a real innovative system.

The extension of the scope of a code or a standard to innovative systems such as fusion reactors leads to revisit the background of the code to define the requirements to introduce a new process or a new material.

The developed methodology has been applied for the introduction of the X10CrWVTa9-1 steel (Eurofer), which is today in the Probationary Phase Rules of RCC-MRx. It was the first time that a "new" material was introduced into the code, new in the sense of non-existing in any current standardization. This process, still in progress, highlights the need to have a minimum of information on the expectation of the code regarding the material data.

This paper describes the different steps of the introduction of the Eurofer in the RCC-MRx code as well as the tools developed to facilitate the process.

Keywords: standardization, Eurofer, Fusion, RCC-MRx

1. Introduction: overview of the RCC-MRx code

The RCC-MRx [1] design and construction code constitutes a single document that covers in a consistent manner the design and construction of mechanical components for high temperature reactors, research reactors and fusion reactors.

This RCC-MRx code was first issued in 2012 from the merging of two codes:

- the RCC-MR code, devoted to high temperature reactors and ITER Vacuum Vessel,
- the RCC-MX code, dedicated to research reactors and related devices.

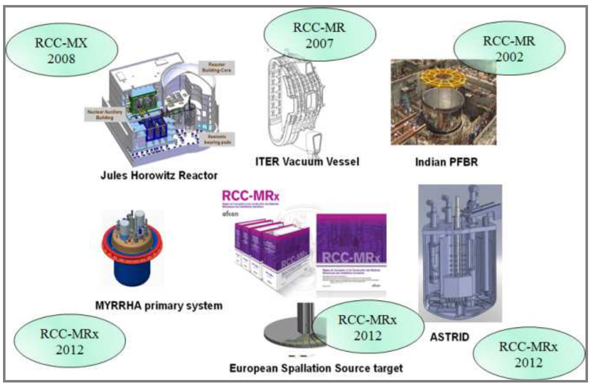

Fig. 1. Illustration of code references

The design and construction rules were adapted to cover the mechanical resistance of structures that, depending on the situation, can operate in significant thermal creep conditions and/or in significant irradiated conditions.

Today, RCC-MRx is used as reference code by project listed in fig. 1 and a process has been engaged to adapt the code to GEN IV reactors, to fusion reactors or to innovative systems needs, through for instance European collaboration as CEN 64 Workshop. The CEN Workshop 64 (CEN, CWA 64 [2]) has the objective to give the possibility to all participants to express their specific requirements for the long term modifications of the Codes, including identification of pre-normative research where necessary. In this frame, the potential extension of the scope of the code to other kind of reactors such as lead bismuth reactors is considered.

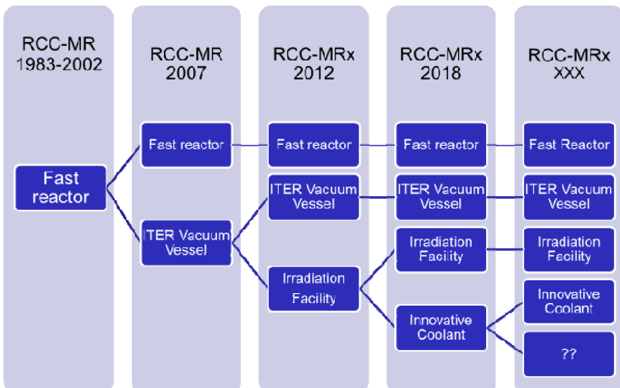

Fig. 2. Code evolution

It appears also through the users feedback and through the workshop that there is a particular

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expectation on how to proceed with the introduction of new materials or a new process.

This need is specific to innovative reactor and has led, in the last years, to one of the main evolutions of the code.

2. Code evolution process: case of the introduction of a new material

Initially dedicated to Sodium Fast breeder Reactors (SFR), the code included well-known steels with a large feed-back in reactors.

With the development of new concepts, a broader choice of materials than the steels used in Pressurized Water Reactors and Sodium Fast Reactors, such as reduced activation alloy steels (as Eurofer), could meet the requirements for the design and construction of research reactors [3].

To facilitate the process of introduction of innovations in the code, the following tools have been developed:

- creation of a dedicated part of the code to collect the results of such works as research and development or pre-normative developments, which not always have sufficient feedback to be included in the code: Probationary Phase Rules,
- to establish rules, there is also a need to understand how to proceed, especially for a new material or a new process: Introduction in the code of the concept of material file and development of a specific guideline to fulfil the material characteristics.

2.1. RPP

A Probationary Phase Rule (RPP) is a document that defines a rule for a technical field with insufficient industrial feedback to be included directly into the RCC-MRx Code as a mandatory rule. Nevertheless, the Code allows the use of a Probationary Phase Rule in addition to regular rules or, in specific cases, in replacement of general or specific rules from the various RCC-MRx code volumes under the user responsibility. The more a RPP is applied, the more feedback is obtained to enable the status of the rule to be changed from Probationary to a regular rule of the Code. A rule, which is identified as probationary, has an innovative nature compared with the rules set out in the RCC-MRx Code. The status of each RPP is re-examined within every new edition of the Code.

In RCC-MRx 2018, there are 15 RPPs that are available (see table. 1.), including RPP4 dealing with X10CrWVTa9-1 steel (Eurofer).

Table 1. List of RPP included in RCC-MRx 2018 edition.

RPP	Purpose	Status
RPP1-2012-RA5000	Establishment and use of a quality management system	Intro : 2012
RPP2-2012-9%Cr	Properties of steels from A3.18AS – cyclic behaviour and creep	Intro : 2012
RPP3-2012-RM 243-2	Extension of application of RM 243-2 to thick plates	Intro : 2012
RPP4-2012-Eurofer	Introduction of steel X10CrWVTa9-1	Intro : 2012 Modif: 2015 and 2018
RPP5-2012-Housing 6061-T6	Complement to Appendices A3.GEN and A3.2A to be considered using S-RPS RM 522-7	Intro : 2012 Modif: 2018
RPP6-2012 US inspection of aluminium welds	Introduction of measures for US inspection of welds on aluminium alloys	Intro : 2012 Added in the code: 2018
RPP7-2012-RB 32101 Locating defects	Definition of a general procedure for locating defects	Intro : 2012
RPP8-2013-2018-SMC2 method	Extension of the method of SMC2 to type S damages	Intro : 2012 Modif: 2018
RPP9-2013-800H alloy	Introduction of bars and tubes RPS in alloy 800H and the associated appendix A3	Intro : 2012
RPP10-2015-A3.2A.69 Swelling of 6061-T6	Modification of chapter A3.2A.69 dealing with swelling of 6061-T6 alloy	Intro : 2015
RPP11-2018-18MND5	Introduction of two G-RPS for the procurement of 18MND5 alloy and of the associated properties group A3.12AS.	Intro: 2018
RPP12-2018-A3.7SA NiCr19Fe19Nb5 Mo3 Alloy	Introduction of the NiCr19Fe19Nb5Mo3 alloy, so-called Inconel 718®	Intro: 2018
RPP13-2018-RMC6134	Introduction of requirements regarding the reference tube to be used for eddy current examination of steam generator tubes procured following RM 414-1	Intro: 2018
RPP14-2018-RDG2320	Introduction of guidelines for the use of the Code in innovative coolant environment	Intro: 2018
RPP15-2018-OAD	Introduction of hard anodizing surface treatment for aluminum alloys	Intro: 2018

2.2. Material File

The possibility to define a material not already codified has been present in the code since the 2012 edition, with the possibility to establish a material file (see fig. 3.).

The table of contents of the Material File shall be:

1. **Introduction**
   - Presentation of the grades
   - Codes and standards dealing with these parts or products
   - Reference Procurement Specifications in **Tome 2**
   - Industrial application and experience
2. **Physical properties**
3. **Base metal and welded joints mechanical properties for design and analysis**
   - Justification of the applicability of the Design Rules (**RB 3000**) for the specified usage conditions
   - Basic mechanical properties
   - Mechanical properties when creep is significant (if necessary)
   - Mechanical properties when irradiation is significant (if necessary)
   - Guaranty of the consistency between the properties of the final part laid-on the plant and the material properties used to design the component.
4. **Manufacturing**
   - Industrial experience
   - Metallurgy
5. **Fabrication**
   - Industrial experience
   - Forming operation ability
6. **Welding**
   - Weldability (**RS 1300**)
   - Industrial experience for the welding procedure qualification
   - Industrial experience for the repair welding procedure qualification
7. **Controllability**
8. **In service behaviour**
   - Thermal ageing, corrosion, erosion-corrosion, irradiation, …
9. **Conclusion**

Fig. 3. extract of RCC-MRx, chapter RB 2000.

Such a material file has first been established for the stainless steels in the code as detailed in Dubiez et al. (2011) [4] and also for the Eurofer in support to its introduction. However, the application of this concept of material file revealed that it is very useful to have complementary guidelines to fulfill the different parts of the material file. Under the umbrella of AFCEN, a first study was engaged on the part 3 of the material file (base metal properties for design and analysis) in a view to develop a guideline in support.

2.3. Guideline in support to codification

The aim of the guideline (established by Chosson et al. and published by AFCEN 2016 [5]) is to present the procedure to be followed for acquiring and gathering the data which describe the physical and mechanical behaviour of the material, necessary to apply the component design rules available in the RCC-MRx code. Therefore, this guideline details a method for establishing the data required in part 3 of the "Material file” (experimental results and design curves). The purpose of the guideline is to help the user to establish his material file, with a clarification of the content expected by the code organization. For the moment, the guideline is limited to base metal material, candidate to an introduction in the RCC-MRx and for a material which is totally new (not codified anywhere). The different characteristics needed for design are identified in the code.

The establishment of these properties requires a dedicated experimental program and the guideline gives general indications and good practices to perform this program in line with the background of the data already included in the code. Thus a reference to existing standards is made whenever it is possible but the door is still open to alternative practices, to be justified, taking into account the innovative aspect of the material.

The tests to be performed for the eight families (physical properties, border lines, fatigue behavior, behavior after irradiation, …) are indicated in the AFCEN guideline with the following structure:

- Determined characteristics,
- Test program conditions,
- Test performance conditions,
- Documentation.

To facilitate the use of the guideline, tables are also given in the end and provide for each property: the test type, the relevant standards, the number of tests to be considered, the temperature range and some additional comments or requirements from RCC-MRx committee.

3. Example of Eurofer Steel

Eurofer martensitic-ferritic steel is a candidate for components such as blanket modules for fusion reactors. Eurofer 97 was developed by the European Union and has been selected for the following benefits [6]:

- Low activation: elements with high levels of activation (Mo, Nb, Ni ,Cu and N) have been replaced or suppressed by elements with low levels of activation (W, Va and Ta).
- Improved resistance to neutron irradiation: negligible swelling up to 80 dpa, limited creep due to irradiation, He/H not produced.
- Improved compatibility with Pb/Li/ceramic environments.
- Improved thermomechanical properties at high temperatures.

However, in 2010, Eurofer was not yet included in any design Code.

3.1. Initial features: first codification

In the period 2011–2013, detailed design documents were prepared for Eurofer steel and submitted to AFCEN for Eurofer codification in the RCC-MRx. These documents have been partially approved since Eurofer has entered in a probationary status, in Tome 6 (RPP) of RCC-MRx.

The first files written for Eurofer code qualification were materials procurement files. In fact, during the code qualification, a minimum number of industrial heats (3–5) must be characterised to cover the effect of heat-to heat variations. Materials procurement files submitted for Eurofer steel covered plates, tubes and bars. All the base metal files were backed up with support documents that include results of inspections, examinations, macro and microstructural examinations, hardness, etc. for each product. However, only the plate products were approved and introduced in RCC-MRx 2012 edition (new RPS – Reference Procurement Specification - in Tome 2 of the code, RM 243-3) because the two other RPS were too generic.

The second set of files written for RCC-MRx was the modification request to create appendix A3.19AS in appendix A3 of the code (properties groups for materials). In a first step, only A3.19AS file was proposed (without origins of provided data), the RCC-MRx sub-committee needed complement information to be able to introduce something in the code. It was then asked to fulfil the request with an associated material file that justifies the mechanical data proposed for Eurofer. The Eurofer material file was organised, as requested in the RCC-MRx (RB 2000), in 5 sections:

- Physical properties.
- Borderlines.
- Basic mechanical data.
- Mechanical properties when creep is significant.
- Mechanical properties when irradiation is significant.

Physical properties required for conventional design have been proposed for Eurofer steels. They include: coefficients of thermal expansion (average and instantaneous), modulus of elasticity, Poisson's ratio, density, specific heat, thermal conductivity and thermal diffusivity. For the special case of fusion, magnetic and electrical properties have also been evaluated but they are not yet in the scope of RCC-MRx code.

Borderlines define the conditions under which analyses (concerning creep and irradiation) are required or not. For instance, thermal creep analysis is not required if the creep deformation does not exceed 0.05% (negligible creep) under a stress equal to 1.5 Sm at the service temperature. Evaluation of negligible creep requires long duration creep tests at low stresses, such kind of test are still insufficient for Eurofer. For the time being, based on the available results, one can reasonably assume that thermal creep can be ignored at temperatures below 375°C.

Basic mechanical data deals with time independent properties such as tensile, impact, fatigue and fracture. Tensile strength data were used to derive design stress intensity values Sm and S. Tensile ductility and toughness values were used to ensure that Eurofer has adequate resistance to brittle fracture. Fatigue results, mostly from continuous low cycle fatigue testing but also some high cycle and thermal fatigue results, were used to derive fatigue design curves, applying transposition factors of 2 on strain and 20 on number of cycles to failure. All the data requested by RCC-MRx were provided and justified for Eurofer and then introduced in 2012 edition of the code. An update of some of these data was done in 2014 and implemented in 2015 edition of the code (basic data for Fracture Mechanics were also added in this 2015 edition).

Mechanical properties when creep is significant deals with time dependent properties such as creep and creep-fatigue. In 2012 edition, these data were not introduced in RCC-MRx because the material file was not sufficiently fulfilled. The material file was updated in 2014 and then in RCC-MRx 2015 the following characteristics were provided:

- Allowable stresses St,
- Creep rupture stress Sr,
- Creep strain rules,
- Creep-Fatigue interaction diagram.

Mechanical properties when irradiation is significant deals with irradiation effects on time independent and time dependent properties. In 2012 and 2014 Eurofer Material File, the data provided were considered as insufficiently justified to be included in RCC-MRx code (too few available tests). However, considering the status of A3.19AS (in RPP part of the code, with a probationary status) AFCEN has reconsidered this part of the Material File in order to complete the appendix A3.19AS. In RCC-MRx 2018, the following characteristics were provided:

- Negligible irradiation curve and maximum irradiation curve,
- Yield strength ($R_{p0.2}$) and tensile strength (R_m) after irradiation,
- Allowable stresses S_{em} and S_{et} after irradiation,
- Ductility characteristics before and after irradiation.

The following figure summarize introduction of Eurofer in the different editions of RCC-MRx code between 2012 and 2018.

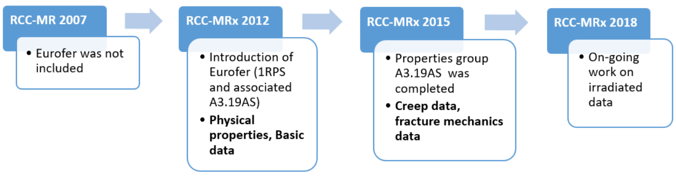

Fig. 4. Introduction of Eurofer in RCC-MRx editions

3.2. Complementary investigations and mechanical testing

Following the recommendations from the AFCEN guideline to introduce a new material in the RCC-MRx code, an analysis of the missing data has been performed for Eurofer 97. This analysis pointed out some lack of experimental results to be completed in order to extract Eurofer from RPP rules. The main needs for base metal are listed below, without any priority order:

- Tensile tests after additional heat treatment called SSHT (Simulated Stress-relieving Heat Treatment). This heat treatment is used to evaluate the effect of temperature history that could face base metal during fabrication process (mainly Post Welding Heat Treatment, PWHT). Tensile tests are required to check that the mechanical properties of base metal are not affected by SSHT.

- Cyclic tests at intermediate temperature (300-350°C). These tests will complete the database obtained at elevated temperature (400-550°C). A focus is expected on the investigation of cyclic softening of Eurofer. Non-symmetrical cyclic tests at low strain amplitude (cycling between 0 and $\Delta\varepsilon_t$) are required in order to evaluate K_s factor used in RCC-MRx creep-fatigue interaction methodology.

- Tensile tests after irradiation and irradiation creep tests. The effect of irradiation on tensile mechanical properties of Eurofer has already been studied [7]. However complementary results are foreseen particularly to evaluate more precisely the loss of ductility due to irradiation. The RCC-MRx does not contain any irradiation creep law at the moment, but thermal blanket modules for fusion reactor might experience high temperature and high irradiation damage. Irradiation creep is assumed to be non-damaging but induced stress relaxation can help to reduce stresses acting at high temperature.

- Mechanical properties for fast fracture mechanics. Experimental data allowing application of the RCC-MRx rules to prevent fast fracture in the ductile regime are missing for Eurofer. Crack extension resistance curves (J-R curves) are given in Probationary Phase Rule today (see Fig. 5.) but more data are expected for a scattering analysis. In addition, J-R curves at elevated temperature after irradiation will be necessary for thermal blanket module application.

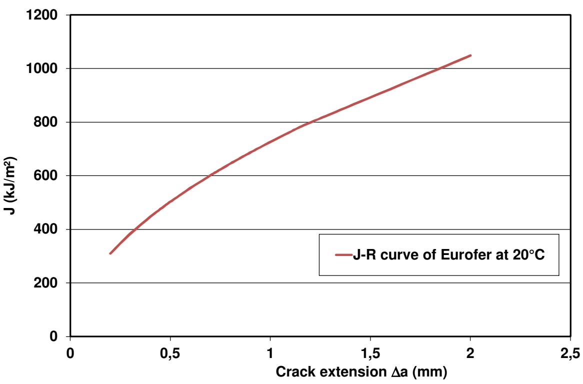

Fig. 5. J-R curve for Eurofer at 20°C in RCC-MRx Probationary Phase Rule

Additional specific R&D investigations are required either to validate or to adapt the RCC-MRx design rules to the Eurofer behaviour:

- Tension-torsion ratchetting tests. From experience on 9Cr steel [8], it is expected that efficiency diagrams available in the code will not cover ratchetting behavior of Eurofer (see Fig. 6., from [9]). Therefore, ratchetting tests at RT and elevated temperature are required to develop a specific efficiency diagram for Eurofer.

- Tensile tests after cyclic loading. Cyclic softening of Eurofer is a key issue for design rules to prevent structures from excessive deformation and plastic instability after cyclic loading. R&D investigations based on tensile tests after cyclic softening are planned to evaluate the consistency of RCC-MRx rules for Eurofer.

- Tensile and bending tests after irradiation. RCC-MRx code includes specific rules to prevent from immediate plastic flow localization and immediate fracture due to ductility exhaustion after irradiation. These rules rely on the allowable stresses S_{em} and S_{et} calculated from tensile tests performed after irradiation. Validation of S_{em} and S_{et} rules for Eurofer can be achieved through specific tensile and bending tests on notched specimen.

Among the recommendations of the guideline, experimental results obtained from various heats (at least three) are required. The investigations presented above will complete the material database with more procurements, product forms and manufacturing experience. This will increase our knowledge and confidence on Eurofer, necessary before introducing this material definitely in the code.

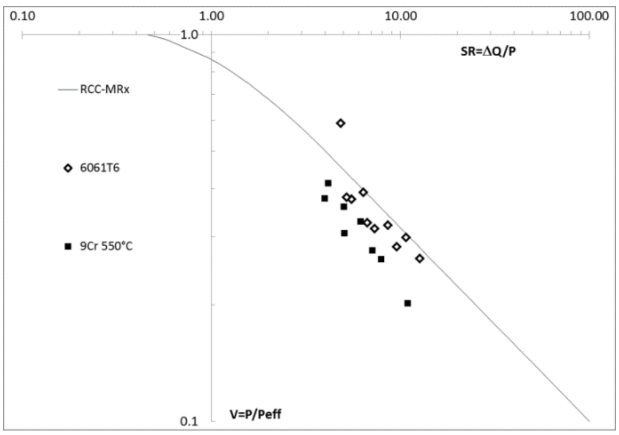

Fig. 6. RCC-MRx efficiency diagram for austenitic stainless steels compared to experimental effective primary stresses of tests performed on 6061-T6 aluminium alloy and Mod 9Cr-1Mo steel, from [9].

4. Conclusion: future developments

Tools have been developed and implemented in the frame of the RCC-MRx code to facilitate the introduction in the code of new process or new materials. As a result of this new philosophy, materials design properties and Requirement Procurement Specification of Eurofer have been added in the RPP part of RCC-MRx since 2012 edition.

However, the process is still ongoing, and developments of rules towards full codification of Eurofer will be completed in next editions of RCC-MRx Code.

Furthermore, AFCEN RCC-MRx subcommittee is still working on the improvement of support supplied to the users of the code.

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