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How to adapt a nuclear code to Advanced Modular Reactors, RCC-MRx example

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Abstract

The RCC-MRx is one of the seven AFCEN codes in the collection of design and construction rules for mechanical components of nuclear power plants. It was initially developed for Sodium Reactors (SFR), Research Reactors (RR) and Fusion Reactors (FR-ITER).

The 2022 edition of RCC-MRx code provides design and construction rules for mechanical components subjected to significant creep and/or significant irradiation, an extensive range of materials including Aluminium and Zirconium alloys (meeting requirements for neutron transparent materials of research or irradiation reactors), and a new volume for core internals among other updates.

There is a broad range of new reactor technology currently under development across many countries. In Europe, most AMR projects are still in the design phase and some projects will have to go through an industrialization stage requiring the commissioning of a demonstrator (First of a Kind). These projects cover all the reactor types included in the GEN IV family: fast neutron reactors with sodium coolant, fast neutron reactors with lead coolant, fast neutron reactors with gas coolant, very high temperature reactors, supercritical water reactors and molten salt reactors. Associated to these projects, there is thus a need of extension of the scope and rules of the RCC-MRx to be a possible reference.

The object of this work is to present the latest code improvements of the upcoming RCC-MRx 2025 edition to answer this need, possible notably thanks to a narrow collaboration with reactor projects using the code, and also international workshop such as CEN WS 64 supported by CEN (European Committee for Standardization).

I. Introduction

Facing the climate changes and risks on the supply of oil and gas, nuclear energy is reconsidered as a solution. This evolution is accompanied by the emergence of new projects. Among those, a place is given to innovation, especially regarding the small reactors, and numerous projects are qualified of Advanced Modular Reactors. A way to ensure the feasibility and industrialization of such projects is to rely on standardization and it leads to question the existing codes and standards regarding the emerging needs. In the following parts, we will show the case of RCC-MRx Code that is challenged today by new projects, the encountered difficulties and solutions to adapt the Code to their needs.

II. Nuclear codes general definition

A nuclear code can be define as a set of rules for the mechanical design and construction of nuclear components. The rules are based on industrial experience, technological improvements

and practices to meet regulatory requirements. Nuclear codes are documents developed by experts representing all nuclear stakeholders. Nuclear codes evolve with incorporating advancements in industry and lessons-learned from the state-of-the-art.

Since innovation is by definition something new, something yet to be implemented, innovation is not initially covered by codes and standards. However, to ensure that the codes continue to be relevant to the industries that use them, nuclear codes (especially RCC-MRx) adapt to innovation. The following are some examples.

III. Code adaptations to innovative systems: RCC-MRx example

a. RCC-MRx code background

The scope of application of the RCC-MRx design and construction rules is limited to mechanical components considered important in terms of nuclear safety and operability, mechanical components playing a role in guiding and/or securing and their corresponding supports, and devices such as pumps, valves, pipes, bellows, box structures, heat exchangers, irradiation devices, etc. The RCC-MRx Code was initially developed for Sodium-cooled Fast neutron Reactors (RCC-MR, first edition 1985) and the first major adaptation was the extension of scope leading to RCC-MRx.

b. First kind of adaptation: scope extension

In France, in the early eighties, AFCEN **[1]** developed the RCC-MR Code for fast breeder reactors using Phenix and Superphenix feedback. The first extension of that Code was a specific appendix dedicated to the ITER Vacuum Vessel **[2]** in 2007: the related material and fabrication process were already in the Code. Because of that, the Code adaptation limited to cover this specific component, the vacuum vessel (VV), by creating a link between the Code as it was and the VV. The result was a dedicated RCC-MR appendix.

The situation was different concerning RCC-MR Code adaptation to the experimental Jules Horowitz Reactor (JHR **[3]**). The need was cover the main parts of the reactor with the Code. This constituted an extensive need: design taking into account irradiation, specific materials (such as aluminium or zirconium alloys for transparency to neutrons), different components inside the reactor (small components, commercial components). A dedicate appendix was not enough to adapt the Code to this extensive need. A dedicated set of rules to JHR were developed by CEA **[4]**, the RCC-MX Code. Based on the evidence that most of technical tools were used by both projects, the solution was to merge RCC-MR with RCC-MX, leading to the very first edition RCC-MRx 2012 **[5]**. Since then, the unified Code keeps on the evolution process.

As illustrated in **Figure 1**, RCC-MRx code covers today all the steps from the design and material procurements, to fabrication and delivery of the components.

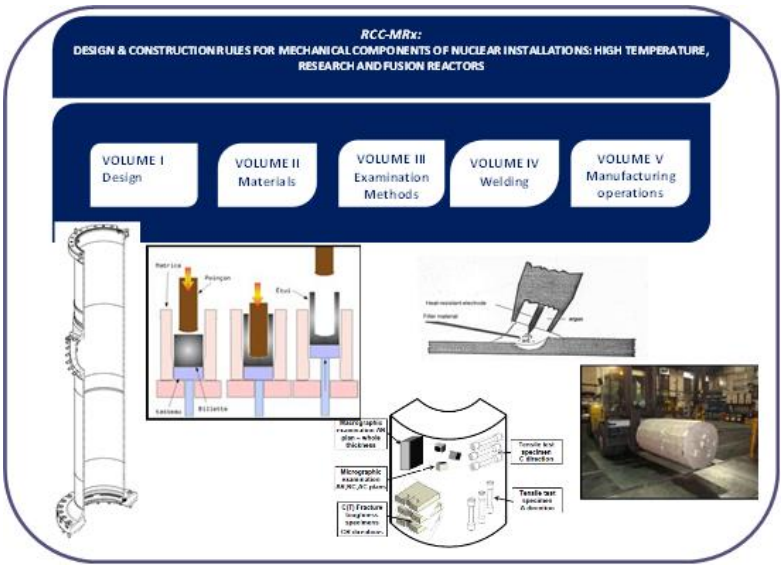

Figure 1: technical domains covered by RCC-MRx

IV. Tools to ease Code adaptations

As RCC-MRx is a code for advanced, experimental and fusion reactors, it faces innovative concepts. It was crucial to answer to the paradox "how to standardise innovation" in order to build a place where pre-normative work can be handled, and to share with newcomers a step-by-step methodology to facilitate the transition between research and standards.

a. The Section IV Probationary Phase Rules (RPP)

It appears that the earlier the standardization is integrated in the design process, the easier to transfer a concept to an industrial component. Based on this principle, a careful consideration is taken on how a concept could be designed within a standardization frame with feedback yet to be provided. This consideration resulted on the creation of a dedicated part of the code for research & development results or pre-normative developments, with expected feedback to be included in the code. This section is periodically reviewed to verify whether new elements are available for RPP justifications. If it is not the case, the probationary status of a rule remains unchanged. RCC-MRx contains now twenty-three rules in probationary phase (RPP) covering a broad scope of needs:

- Introduction of new materials or processes using the existing rules
- Introduction of new rules
- Extension of an existing rule to a wider use

Table 1 List of RPP included in RCC-MRx 2025

Title	Purpose
RPP1-2012-RA5000 [Introduced in 2012, Modified in 2022]	Quality management system in association of RCC-MRx
RPP2-2012-9%Cr [Introduced in 2012]	Properties of chrome alloy steels from Annex A3.18AS (X10CrMoVNb9-1 alloy products and parts) – cyclic behaviour and creep

Title	Purpose
RPP3-2012-RM 243-2 thick plates [Introduced in 2012]	Appl. of RM 243-2 to fabrication of X10CrMoVNb9-1 alloy plates with thickness over 150 mm up to 250 mm
RPP4-2012-Eurofer Steel X10CrWVTa9-1 [Introduced 2012, Modified 2018]	Introduction of Eurofer-97 ® Additional irradiation data included in RCC-MRx 2018 edition
RPP5-2012- Casing 6061-T6 A3.2A casing 6061-T6 [Introduced 2012, Modified 2018]	Type 6061 T652 Al-Si-Mg alloy forged blanks for the core casing New material properties before and after irradiation.
RPP6-2012 US inspection Aluminium welds [Introduced 2012, suppressed]	Introduction of measures for US inspection of welds on aluminium alloys **Rule incorporated in the 2018 Code.**
RPP7-2012-A16 Locating defects [Introduced in 2012]	Definition of a general procedure for locating defects. General procedure to specify the position of the section or defect in relation to the part as a whole
RPP8-2013-SMC2 method Use of the SMC2 method [Introduced 2012, Modified 2018]	Extension Seismic Moments Classification to type S damages. Complementary SMC2 seismic moments classifications.
RPP9-2013-800H [Introduced 2012]	Introduction of bars and tubes RPS in alloy 800H (nickel-chromium-iron alloy X8NiCrAlTi32-21 type) and the associated appendix A3
RPP10-2015-A3.2A.69 Swelling of 6061-T6 alloy [Introduced 2012]	Modification of chapter A3.2A.69 dealing with swelling law (after irradiation) of Aluminium 6061-T6
RPP11-2018-18MND5 18MND5 steel [Introduced in 2018, Modified in 2022]	Introduction of two G-RPS for the procurement of 18MND5 alloy steel forgings and plates, and of the associated properties group A3.12AS
RPP12-2018- A3.7SA [Introduced in 2018, Modified in 2022]	Introduction of Inconel 718 ®
RPP13-2018- RMC6134 [Introduced in 2018, Modified in 2022]	Introduction of requirements regarding the reference tube to be used for Eddy current examination of steam generator tubes procured following RM 414-1
RPP14-2018-RDG2320 Innovative coolants guidelines [Introduced in 2018, Modified in 2022 and 2025]	Introduction of guidelines for the use of the Code in innovative coolant environment
RPP15-2018-OAD Al-alloys hard anodizing [Introduced in 2018, Modified in 2022]	Introduction of hard anodizing surface treatment for Aluminium alloys
RPP16-2022-5SA.48 [Introduced in 2022]	Introduction an efficiency diagram and associated negligible creep limits for alloy X5NiCrTiAl33-21 annealed at 980°C
RPP17-2022-FFC [Introduced in 2022]	Compression during the holding time for creep-fatigue criteria
RPP18-2022-304L(N) [Introduced in 2022]	Introduction of 304L(N) stainless steel (X2CrNi19-10 controlled Nitrogen content steel) for parts in negligible creep conditions
RPP19-2022-RB3262 [Introduced in 2022]	Introduction of an alternative method to prevent from creep-fatigue damage for cyclic softening steels
RPP20-2022-SPT [Introduced in 2022]	Introduction of Small Punch Tests as a complementary tool to material characterization, for procurement or in-service behaviour
RPP21-2022-Vol.E [Introduced in 2022]	Introduction of a Subpart dedicated to metallic containments
PP22-2022-RB3643 [Introduced in 2022]	Possibility of elbows with flanges or rigid elements at their ends
RPP23-2022-CuCrZr [Introduced in 2022]	Introduction of Copper alloys CuCrZr
RPP24-2022-HJB [Introduced in 2022]	Introduction of general conditions for the use of HJB standards as an alternative to the EN and EN/ISO standards of the Code
RPP25-2022-TP [Introduced in 2022, suppressed]	Introduction of the possibility of using water-soluble polymer solutions for the quenching of certain steels. **Rule incorporated in the 2022 Code.**

Special mention to the RPP14 concerning *innovative coolant environment* that is object of continuous development in recent years: a number of AMR will use innovative coolants (Lead-Bismuth Eutectic, Lead, or supercritical water). RPP14 provides recommendations on the interaction of those kind of coolants with the structural material. Further details in the following paragraph concerning CW64 Phase II.

b. Guide to introduce a new material in the Code

Published by AFCEN **[1]**, this guideline presents the procedure to acquire the physical and mechanical material behaviour data to apply the RCC-MRx Code. Specifically the §3 of the "Material file" (experimental results and design curves). The establishment of these properties requires a dedicated tests campaign. This guideline gives general indications and good practices to perform this tests campaign in line with the data already included in the Code.

A3.X.2: Physical properties						
§	**Properties**	**Test type**	**Relevant standards**	**Number of tests**	**Temperature range**	**Comments or RCC-MRx requirements**
.21	Coefficients of thermal expansion	Absolute dilatometry	ASTM E228	3 per T	T_{min} to T_{max}+50°C Recommended: $\Delta T \leq 50°C$	• Recommended method: absolute dilatometry. • The mean and instantaneous values are required relative to 20°C.
.22	Young's modulus	Ultrasonic propagation	ASTM E111 ASTM E1875 ASTM E1876	1 per T	T_{min} to T_{max} Recommended: $\Delta T \leq 50°C$	• Method based on ultrasonic wave propagation.
.23	Poisson's ratio				20°C	• Method based on ultrasonic wave propagation.
.24	Density	Immersion in a solvent	N/A	1 per T	T_{min} to T_{max} Recommended: $\Delta T \leq 50°C$	• Test by immersion in water.
.25	Specific heat capacity	DSC calorimetry	N/A	3 per T	T_{min} to T_{max} Recommended: $\Delta T \leq 50°C$	• DSC calorimetry (thermal capacity).
	Thermal conductivity	Hot wire method	ISO 8894			• To be deduced from the thermal capacity and diffusivity measurements. • Or hot wire method.
	Thermal diffusivity	Flash method	ASTM E1461 ASTM E2585			• Flash method.

Table 2 Guide for introducing a new material in the RCC-MRx – extract.

Initially limited only to base metal materials, candidates to introduction in RCC-MRx Code, the coming edition of the guideline covers welded joints too. The guideline now introduces the requirements for obtaining the data necessary to be included in the RCC-MRx, to describe the behaviour of welded joints and to enable their design with the Code. The new version of this guideline will be available afterwards the Code.

V. Collaboration as a background of Code adaptations

Beyond tools, another fundamental aspect to bring innovation in standardisation is the collaborative work between the potential users and codes development organisation, as an example, two European collaboration initiatives have been settle.

a. CEN workshop WS 64

A first initiative was the set up in 2011 of the CEN Workshop for "Design and construction codes for mechanical equipment of innovative nuclear installations (CEN/WS 64)" proposed by the European Sustainable Nuclear Industrial Initiative (ESNII) and AFCEN. This Workshop on proposition of AFCEN **[1]**, in which participate a wide range of organizations among nuclear development stakeholders, aimed at investigating the potential of an existing code **[6]**: the RCC-MRx.

The CEN workshop 64 Phase 1, from 2011 to 2013, focused on the RCC-MRx Code only. The purpose was to allow the workshop participants to acquire complete knowledge of the RCC-MRx Code and to propose code modifications to meet the needs of ESNII projects **[7]**. After this first phase, this workshop continued to work through three other phases: phase II 2014-2018 **[8]**, phase III 2019-2022 **[9]** and, at present, CEN/WS64 Phase IV. Through phase IV, the European community brings together any nuclear stakeholders, willing to learn how to customize the Code to meet their specific needs. The workshop is organised in four specialized technical groups, so-called Prospective Groups (PG). *PG2 mechanics Gen-IV* is in charge of elaborating recommendation proposals for RCC-MRx. PG2 focuses on innovative reactors such as SMR and MSR reactors. Among the identified topics for this phase is the qualification of innovative cooling liquids such as lead or molten salt. Liquid lead procedures are assessed from test data and intended to be integrated in the Code. Pre-normative research proposals for molten salt qualification are also expected **[10]**.

First example of work performed throughout the workshop: innovative coolant. This subject, treated during phase II of the CEN Workshop 064 but also in phase IV, first led to the creation of RPP 14 in RCC-MRx 2018 edition. This RPP14 is a guideline for using the Code in an innovative coolant environment. A number of new reactors under development are going to use innovative coolants like LBE (Lead-Bismuth Eutectic), Lead, or supercritical water. Since return of experience of this kind of reactor's environment is inexistent, this RPP14 provides recommendations on the interaction of innovative coolant with the structural material to ensure structural integrity under operating conditions. European projects (such as GEMMA **[11]** and INNUMAT **[12]**) show that the main problem with innovative heat transfer fluids is the corrosion resistance of the materials in those environments. The reliability and durability of metallic materials is major concern. In the coming RCC-MRx 2025 edition, RPP14 is suppressed and transferred in Section II of the code in a dedicated chapter REC 4000 "*complementary requirements for domain extension*" and it is enriched with a guide for carrying out corrosion tests using liquid lead and static or dynamic LBE to demonstrate material integrity in those environments (new appendix 2 of the code, "*recommendations for the conduct of corrosion tests in liquid lead and LBE*").

A second example, treated during the Phase 3: the use of the small punch test in RCC-MRx 2022, in RPP 20. Small Punch testing for in-service inspection are now included in appendix A20, they are used for estimation material properties and are especially useful in material health monitoring. But SPT can be used for material properties screening, a new chapter "*other material*

selection parameters" has been created in RB 2000 part of the code. It enables to introduce the materials comparisons based on screening tests and especially based on small punch test techniques according to EN 10371 (although standard specimen tests are preferable).

b. HARMONISE

In the frame of the Euratom Research and Training Programme, HARMONISE is an EU-funded project studying the harmonisation in licensing of future nuclear power technologies in Europe **[13]**. One of the axes of this project is conducting research and cooperation activities towards standardising nuclear safety regulation in the EU. The main objective of the project is to identify gaps and potential improvements on codes and standards for mechanical components and materials. The identification and assessment of improvements will be placed on a proposal of a roadmap for optimization and harmonisation of codes and standards.

VI. Next steps

The RCC-MRx Code has been selected as the design reference for a number of AMR. Nuclear start-ups are aware of the importance of being an active player in codification and some of them had reached the RCC-MRx sub-committee, such as calogena **[14]**, newcleo **[15]**, nuward **[16]**, hexana **[17]** and naarea **[18][18]**.

A number of Code improvements are currently in progress. For instance, within the frame of the CEN/WS64, new needs are already identified concerning materials such as SiC/SiC ceramics having promising features for high temperature, corrosion and irradiation resistance. The workshop is assessing the Code design rules associated to those kind of materials. Components manufactured by additive manufacturing constitute another topic under assessment for a potential Code evolution: those kind of components can reduce costs and improve performance but need to be qualified. A validation approach has been developed and validated within the framework of the European NUCOBAM **[19]** project for LPBF (Laser Powder Bed) process and components made of 316L powder.

As for every new edition, the Code has been object of a number of modifications since its last edition **[5]**. The next figure illustrates the evolution of the scope covered by RCC-MRx since the first edition.

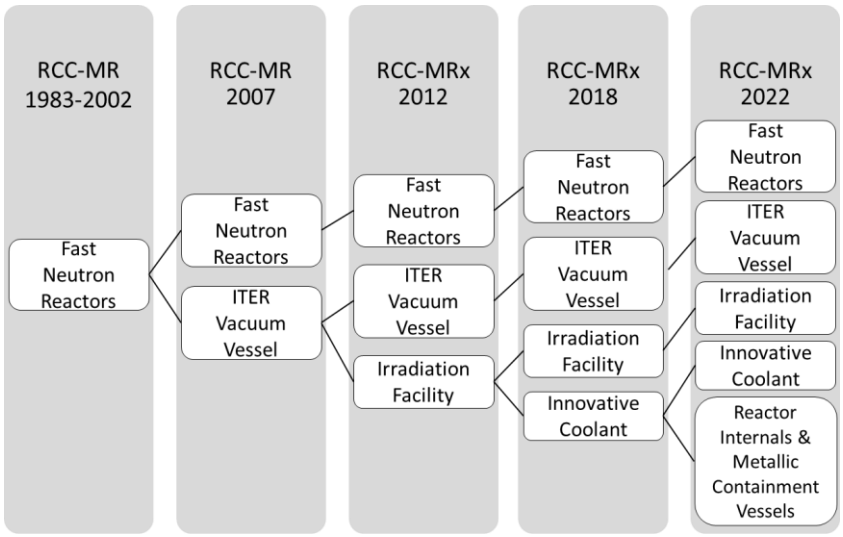

Figure 2 Code evolution over its editions

Conclusions

This paper presents a general overview of Code adaptations to design Advanced Modular Reactors (AMR) and other innovative installations. The Code can currently be used (provided demonstration of the applicability of the rules) for designing mechanical components of nuclear installations such as the Gen-IV reactors **[20]**.

For AMR, we consider there is no need to create new codes from scratch, but to adapt existing Codes like RCC-MRx. However, this adaptation implies considerable inputs from AMR projects themselves to answer their needs. A direct participation of experts from those projects into the evolution of Codes is one of the best solutions.

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