Design and Manufacturing Considerations for HCCP TBM-Shield Structures Based on RCC-MRx

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1. Introduction

1.1 Background

The Test blanket module (TBM) shield is one component of a TBM-set. A TBM-set typically consists of a TBM-box and a TBM-shield, and the TBM will be installed in ITER to generate the tritium by breeding and to transport the tritium [1, 2]. The TBM-shield structures in nuclear and high-temperature environments are essential for radiation protection, mechanical stability, and thermal resistance [3]. Prolonged exposure to radiation can lead to material degradation, including embrittlement, creep, and fatigue, which may compromise structural integrity over time.

To address these challenges, RCC-MRx provides comprehensive design, fabrication, and qualification guidelines for nuclear, high-temperature, and radiation environments [4]. Compliance with PED (Pressure Equipment Directive) [5] and ESPN (Équipements Sous Pression Nucléaires) [6] regulations ensures these structures meet European safety standards, establishing a classification-based approach to design, and manufacturing requirements. Understanding these classifications is essential for ensuring long-term operational reliability and structural performance in high-radiation environments.

1.2 Objectives

This study examines the design and manufacturing considerations for shield structures under RCC-MRx, PED, and ESPN classifications. It aims to ensure structural reliability, regulatory compliance, and long-term durability by analyzing material selection, fabrication standards, and testing requirements in high-radiation environments.

2. Overview of RCC-MRx and Classification

2.1 Overview of RCC-MRx

The RCC-MRx code, developed by AFCEN, provides a comprehensive framework for the design, fabrication, and qualification of mechanical and structural components in nuclear, high-temperature, and radiation environments. It outlines requirements for material selection, structural integrity, welding, non-destructive testing (NDT), and quality assurance, ensuring long-term reliability and safety.

RCC-MRx is widely applied in nuclear reactors, fusion energy systems, and research facilities, where mechanical stability under extreme conditions is critical. The code integrates with PED and ESPN regulations, aligning pressure equipment and nuclear safety standards to ensure full compliance with European regulatory requirements.

2.2 Classification of RCC-MRx

RCC-MRx classifies components into three categories based on safety significance and operational conditions. $N1_{Rx}$ applies to primary reactor circuits and critical safety structures, requiring extensive fatigue and creep analysis, strict quality assurance, and regulatory certification. $N2_{Rx}$ applies to radiation shielding and secondary systems, necessitating moderate safety measures and comprehensive structural analysis. $N3_{Rx}$ covers non-safety-critical components, requiring basic compliance with RCC-MRx but reduced inspection and verification standards. Detailed classification are shown in Table. I. These classifications align with ESPN and PED categories, ensuring regulatory compliance and optimized safety performance in nuclear applications.

Table I: Classification of RCC-MRx

Criteria	$N1_{Rx}$	$N2_{Rx}$	$N3_{Rx}$
Design standards	Primary reactor circuits	Radiation shielding structures	General structures
Fatigue and creep analysis	Mandatory	Require in some cases	Optional
Radiation Effects	Critical factor	Considered in certain cases	Non-considered
Welding and procedures	Certified procedures and qualification require	Compliance with RCC-MRx standards	Compliance with PED
Non-destructive testing (NDT)	100% inspection require	RT, UT, PT require	Basic inspection requirements
Quality assurance	Mandatory certification by ASN and third-party verification	Approval by certified bodies required	Internal quality management possible

3. Design and Manufacturing Consideration for RCC-MRx

3.1 Structural Analysis and Design Considerations

Shield structures under RCC-MRx must withstand mechanical loads, thermal stress, radiation exposure, and long-term material degradation. N_{1Rx} components require advanced fatigue and creep analysis, utilizing detailed numerical simulations and material testing to ensure structural integrity under extreme conditions. $N2_{Rx}$ components need comprehensive thermal and mechanical stress analysis to maintain shielding effectiveness in radiation environments. $N3_{Rx}$ components undergo basic stress assessments with minimal fatigue and thermal analysis due to lower safety significance. Finite Element Analysis (FEA) and compliance with PED and ESPN safety standards are essential to ensure stability and regulatory adherence.

3.2 Fabrication and Testing Requirements

The fabrication and testing of shield structures under RCC-MRx must comply with strict material selection, welding procedures, and quality assurance protocols. $N1_{Rx}$ components require radiation-resistant materials, overall non-destructive testing (RT, UT, PT), and ASN certification [7]. N2Rx components follow similar standards but with slightly relaxed inspection criteria. $N3_{Rx}$ components require basic material verification and pressure testing with lower regulatory oversight.

4. Consideration of PED/ESPN

The Pressure Equipment Directive (PED) and Équipements Sous Pression Nucléaires (ESPN) establish regulatory frameworks for pressure equipment safety and compliance in Europe. PED applies to general pressure equipment and classifies them into Categories 0 to IV based on pressure, volume, and fluid hazard levels. ESPN, specific to France, applies to nuclear pressure equipment and classifies components into N1, N2, and N3 based on their safety impact and radiation exposure risk.

PED ensures harmonized safety standards across EU member states, while ESPN introduces additional nuclear-specific safety measures. ESPN regulations integrate with RCC-MRx, the French nuclear construction code, ensuring compliance with nuclear pressure equipment design and manufacturing standards.

4.1 Overview of PED and ESPN

The PED regulates the design, manufacturing, and certification of pressure equipment in Europe, categorizing components into Categories 0 to IV. The classification follows:

- Category 0: Low-risk equipment exempt from conformity assessment.
- Category I-II: Moderate risk, subject to manufacturer’s self-assessment and partial third-party evaluation.
- Category III-IV: High-risk, requiring full third-party assessment, certification, and continuous monitoring.

The ESPN applies to nuclear pressure equipment in France, classifying components as:

- $N1_{ESPN}$: High-risk components requiring rigorous testing, material verification, and ASN (Autorité de Sûreté Nucléaire) certification.
- $N2_{ESPN}$: Medium-risk components subject to detailed verification and non-destructive testing (NDT).
- $N3_{ESPN}$: Low-risk components with simplified compliance measures and selective testing requirements.

4.2 Integration of PED/ESPN with RCC-MRx

The integration of PED and ESPN regulations with RCC-MRx ensures compliance, structural integrity, and long-term reliability in nuclear applications. The classification of components determines design verification, testing, and quality control requirements.

- High-risk components (PED Category III–IV, ESPN N1) require comprehensive material testing, fatigue analysis, and full non-destructive testing (NDT). These components must comply with RCC-MRx provisions on fracture mechanics, fatigue life assessment, and corrosion resistance.
- Medium-risk components (PED Category II, ESPN N2) generally allow selective non-destructive testing (NDT), meaning only critical welds and joints undergo full inspection. However, for components exposed to high radiation, elevated temperatures, or high-pressure conditions, a 100% weld inspection may be required.
- Low-risk components (PED Category I, ESPN N3) allow simplified stress analysis, optional fatigue evaluation, and selective NDT inspections (RT/UT), ensuring cost-effective compliance while maintaining safety standards.

It is important to note that the risk classification of a component is influenced not only by its ESPN rating but also by its PED category. Even if a component is classified as ESPN N2, it may still fall into the high-risk category if it meets PED Category IV criteria, due to the stringent safety requirements associated with high-pressure and high-temperature applications.

5. Application of Shield Structures

5.1 Design and Manufacturing Considerations

HCCP TBM-Shield structures classified under ESPN N2/RCC-MRx N2 require detailed thermal and mechanical stress analysis, fatigue and creep evaluations, and full-scale non-destructive testing (NDT) to ensure radiation shielding effectiveness and structural integrity [8]. In contrast, ESPN N3/RCC-MRx N3 allows for simplified stress analysis, optional fatigue evaluation, and selective NDT inspections (RT/UT). These classifications also permit the use of standard industrial materials, reducing manufacturing complexity while maintaining regulatory compliance and cost efficiency in nuclear applications.

5.2 Key in ESPN and RCC-MRx Classifications

The classification of shield structures under ESPN and RCC-MRx significantly impacts design, fabrication, testing, and regulatory approval. ESPN N2/RCC-MRx N2 requires comprehensive stress analysis, full fatigue and creep evaluation, and 100% non-destructive testing (NDT), ensuring radiation shielding and long-term durability. ESPN N3/RCC-MRx N3 allows simplified stress analysis, optional fatigue evaluation, and selective NDT, focusing more on structural stability than radiation shielding. Comparison table of applied code is presented in Table II.

Proper classification ensures optimal safety, regulatory compliance, and cost-effectiveness, balancing performance requirements with manufacturing constraints in nuclear applications.

Table II: Classification of code application for TBM-shield

Category	RCC-MRx N2 / ESPN N2	RCC-MRx N3 / ESPN N3
Analysis	Comprehensive fatigue & creep assessment	Basic stress analysis
NDT	100% RT, UT, PT	Selective RT, UT
	Radiation-resistant alloys	Standard industrial materials
Regulatory oversight	ANS certification required	Internal quality control

6. Summary and Further Work

This study examines the design and manufacturing considerations for TBM-shield structures under RCC-MRx, PED, and ESPN classifications, ensuring compliance with nuclear safety and mechanical integrity requirements. The classification of shield structures under the applied code class significantly impacts design, testing, certification, and quality assurance. Selecting an appropriate classification ensures regulatory compliance, cost-effectiveness, and long-term operational reliability. Future studies should focus on fatigue life assessment, shielding performance validation, and material optimization to enhance nuclear shield safety and efficiency.

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