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Review

Qualification Pathways for Fusion Structural Materials

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Abstract

Qualification is the evidence-based process through which confidence is established that a component will perform its intended function, in its intended environment, for its intended lifetime, with the required reliability. It is an owner-led activity that defines the type, quantity and quality of data required for codification and for the industrial deployment of components and their structural materials. This paper presents a structured qualification framework and applies it to a fusion machine breeder blanket structure as a representative component. It demonstrates that qualification, rather than material properties alone, dictates the use of fusion structural materials and the deployment of such materials under ASME BPV and AFCEN RCC codes. Current limitations in addressing irradiation synergy, liquid metal corrosion, and joint integrity expose gaps that these codes cannot yet prescribe. Two contrasting structural blanket material case studies: metallic-based ferritic-martensitic steel Eurofer97 and non-metallic-based silicon carbide fibre-reinforced composites (SiC_f/SiC) are used to illustrate the differing evidence requirements for each system type. Industrial scale-up considerations, including alloy specifications, manufacturing readiness, inspection reliability, and supply-chain maturity, are evaluated alongside the need for internationally harmonised datasets and design methodologies. Fusion programmes can use a phased qualification strategy in which early, time-limited operation under controlled conditions builds the evidence needed for codification and scale-up, with the required pre-operation qualification level depending on risk, component criticality and failure consequences, and with the pace of qualification ultimately setting how quickly industry can supply components for commercial fusion. Codification remains essential for commercial deployment because construction codes express codified material behaviour through allowable stresses and permitted fabrication routes, enabling designers to use advanced materials without disclosing proprietary data. In jurisdictions where ASME BPV compliance is mandatory, codification determines whether a material may enter pressure boundary service and must therefore form part of the fusion machine owner's long-term strategy for deployment.

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1. Introduction

Nuclear fusion offers a potential route to sustainable low carbon energy by fusing light hydrogen isotopes at very high temperatures [1]. In deuterium-tritium (D-T) systems,

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the reaction produces a high energy neutron that defines both the power output and the environmental conditions experienced by structural components [2,3]. Because tritium is scarce, fusion machines rely on in-situ breeding where lithium within the breeder blanket absorbs a neutron and transmutes to tritium [4,5]. These neutron-driven reactions define the irradiation spectrum, temperature, chemical exposure and thermal loading that materials must withstand [6,7].

Although fusion concepts differ in detail, all fusion devices expose structural materials to combinations of intense neutron irradiation, steep thermal gradients, high heat fluxes, strong electromagnetic fields and chemically reactive breeder materials [8–10]. These coupled conditions are absent in existing nuclear technologies [11]. Because no fusion power plant has yet operated, the behaviour of structural materials under fusion-relevant environments remains only partially understood [10]. Only a limited set of candidate materials currently appear capable of meeting the expected demands, and their performance must be demonstrated through a systematic qualification process [10,12] before, during, and after operation.

The breeder blanket component in all D-T fusion power plant designs illustrates the nature of the structural environment. It must breed tritium, extract heat, contain activated materials and protect the vacuum vessel while subjected to high radiation doses, elevated temperatures, coolant corrosion and repeated thermal and mechanical cycling [6,7]. Reliable performance under these combined demands is therefore essential to commercial plant operation [6,13].

It is important to emphasise that degradation in fusion materials is normal and expected. Mechanisms such as thermal/radiation embrittlement, radiation-induced swelling, creep, corrosion and cyclic softening are not failures in themselves [11,14]. All structural materials degrade in service; the engineering challenge is to determine whether this behaviour is sufficiently well understood that behaviour is predictable and acceptable for the intended function and lifetime. The purpose of qualification is to provide a structured basis for establishing confidence in component performance.

Qualification establishes confidence that a component will fulfil its intended function with the required reliability within its defined environment and lifetime. Although distinct from regulatory compliance, qualification underpins any subsequent safety arguments or code-based assessments. Regulation becomes relevant only when a component carries an explicit safety claim or when national law mandates the use of specific engineering design codes for certain types of components.

Where a component carries a safety claim or falls under national legislation, regulators typically require evidence that recognised engineering practice has been followed, that environmental conditions have been characterised, and that design decisions are supported by traceable evidence. These expectations arise from general safety principles rather than from material or design code requirements. The role of qualification is therefore foundational: it provides the technical basis upon which regulatory arguments, safety cases and compliance assessments must be built whenever a component contributes to the protection of the public, workers or the environment.

Qualification follows a graded approach to ensure that evidence requirements remain proportional to function, environment, and consequence of failure. More critical components require more extensive testing, detailed characterisation and increased analytical justification. Less critical components still require systematic approaches, but these may be simplified.

Across all grades, qualification typically includes:

- Definition of the component's function, the reliability with which it must be provided, and the expected performance envelope.
- Characterisation of environmental conditions, including irradiation, temperature, corrosion, electromagnetic loading and mechanical stress.

- Verification through representative testing, modelling and exposure.
- Documentation of a traceable evidence chain to support design decisions.

For structural or pressure-retaining components, qualification draws on international standards (published by ISO, BSI, ASTM and CEN, etc.) to ensure consistency in material property measurement and testing practice.

Where components operate above 0.5 bar(g) internal or external pressure, they are typically treated as pressure vessels in accordance with US State Laws [15–17], the UK Pressure Safety Systems Regulations, and European Pressure Systems Directive (not an exhaustive list). Consensus-based design codes such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code or EN 13445 are generally used to ensure that pressure-retaining components are designed and manufactured to perform safely. However, compliance with these codes is only possible once the materials possess sufficient qualification data to permit codification (where a material is accepted in the code for use). Fusion programmes therefore face a central challenge: promising "fusion grade" structural materials (such as Eurofer97 [12] and silicon carbide composites (SiC_f/SiC) [9]) do not yet have the data required for inclusion in these established design codes.

In the United States, State law's mandate that all unfired pressure vessels must be designed, constructed and certified in accordance with the ASME BPV Code. This requirement applies irrespective of whether the component is classified as safety-related. As a result, any fusion component in the US that functions as a pressure boundary must comply with the ASME BPV Code and the material has been sufficiently qualified to permit codification. Codification is therefore not only the basis for engineering confidence but also the prerequisite for meeting mandatory national pressure system legislation.

Conventional steels such as 316 and Grade 91 have long been used in neutron environments and are fully codified based on extensive fission experience [11], but do not provide the reduced activation and radiation tolerance needed for fusion [18]. Fusion programmes therefore require new materials including Eurofer97, oxide dispersion strengthened steels, vanadium alloys and SiC_f/SiC. These materials exhibit desirable properties but lack the breadth and depth of testing needed for qualification [12,19,20].

The combination of limited operational experience, stringent performance requirements and the novelty of proposed structural materials means that qualification is the primary mechanism through which confidence in fusion components must be established.

This paper examines how qualification frameworks can be applied to fusion structural materials, identifies key gaps that currently prevent codification, and uses case studies of a metallic structural material (Eurofer97) and non-metallic structural material (SiC_f/SiC) to illustrate contrasting qualification pathways. The intention is to provide a clear basis for developing the evidence, methodologies and standards required to support the safe and reliable deployment of fusion power plants.

2. A Framework for Qualification of Fusion Materials

Qualification is an evidence-driven process that reaches beyond design code requirements to determine how a material or component behaves in its environment. It begins with alloy design and material development, proceeds through laboratory testing, manufacturing trials, demonstration of quality control in material supply and reproducibility for scale-up, and continues into documentation, operation, monitoring and surveillance throughout plant life. Qualification establishes how a material or component behaves in its actual environment and ensures that this behaviour is understood, predictable and acceptable for the intended function and lifetime. Because design codes cannot anticipate all fusion-specific environmental effects, which vary between designs, qualification provides the structured process through which designers determine which degradation mechanisms are significant to their unique design, where evidence must be focused, and how uncertainty can be reduced to an acceptable level relative to failure consequences. The depth of qualification is therefore graded and proportionate: high-importance components demand extensive evidence and representative testing, whereas lower-importance items may be justified with simpler methods. Ultimately, the owner determines what level of qualification is appropriate, because only the owner possesses full knowledge of the component's functional role, performance targets and risk appetite. Components are assessed by function, consequence of failure, importance to plant performance and environmental severity. The outcome is a level of substantiation matched to how critical the system must perform over its intended lifetime within its environment. More critical components demand more evidence, more representative testing and tighter analytical justification. Less critical components can use simpler approaches that remain rigorous and traceable.

Across all grades, a robust programme includes six elements: definition of function and performance envelope, the reliability with which it must be provided, characterisation of environmental conditions, verification through testing and analysis in representative conditions, a documented and traceable evidence chain and a plan for in-service inspection and surveillance. International standards from ISO, BSI, ASTM and CEN provide the test and measurement methods that make this evidence consistent and repeatable.

Where a component claims a safety function, national regulators may require evidence that recognised engineering practice has been followed and that the qualification is adequate for the claimed function. Frameworks such as IAEA TECDOC-1851 [21] and SSG-30 [22] provide graded approaches to determine the safety significance, which in turn sets expectations for the depth of analysis and qualification.

Components operating above 0.5 bar (g) are generally treated as pressure vessels and therefore fall under established pressure systems codes such as ASME BPV and EN 13445. In the United States, all states require ASME BPV compliance for unfired pressure vessels. For fusion-relevant materials that are not yet codified, owners cannot waive pressure system code obligations; instead, they must demonstrate an equivalent level of engineering rigour through structured qualification programmes, conservative analytical approaches and traceable substantiation until full codification becomes possible.

Early phases can use small-specimen testing (as per the small-specimen testing standards in ASTM (such as E8 [23]) or ISO for example) as best as one can in representative environments to generate trend data efficiently. Where justified, extrapolation from fission datasets can be used for bounding cases, provided differences in spectrum, temperature and loading are accounted for. As designs mature, campaigns add long-duration creep, creep–fatigue interaction under irradiation, weldment performance and environmental compatibility studies.

Fusion environments introduce conditions that lie outside the scope of many existing engineering rules, and several candidate materials have not yet accumulated the datasets required for inclusion in established design codes. Until this evidence base matures, designers must use graded qualification programmes aligned with recognised standards, and codes will continue to evolve as new data emerge during prototype and power plant operation. The environmental data requirements outlined here are intended to support future incorporation into ASME BPV Section III Division 4 [24,25]. At present, Division 4 does not mandate specific environmental degradation datasets (e.g., irradiation synergy, liquid metal corrosion); however, these are strongly recommended as part of owner-led qualification programmes where these degradation mechanisms are present for the component under operation. As Division 4 evolves, such datasets may transition from recommended evidence to codified requirements, depending on the maturity and international consistency of fusion-relevant material files [26].

A qualification plan should specify what is monitored in service, how often, and with what acceptance criteria, so that the assumptions made at design are validated throughout life. In-service inspection and repair of nuclear facility components could use the framework outlined in ASME BPV Section XI [27], and access for inspection should be considered at design stage. By adopting a cyclic, risk-informed framework grounded in functional performance, designers can ensure that materials and components meet the stringent safety and reliability requirements necessary for the successful deployment of fusion power plants.

It is important to distinguish design methodologies from empirical evidence. "Design by Rule" (DBR) and "Design by Analysis" (DBA) are formal, codified methodologies that provide prescriptive or analytical justification of component performance. By contrast, "design-by-experiment" is not a codified methodology; rather, it reflects the use of accumulated operational and experimental evidence to inform or calibrate DBR/DBA approaches. It supplements, but does not replace, the structured design methods required for code compliance.

Importantly, qualification does not need to be fully complete before a fusion facility begins operation. Fusion programmes could adopt a phased qualification strategy in which early operation proceeds under controlled conditions while further evidence is generated. The extent of qualification required before first operation depends on the owner's risk appetite, the functional role of the component and the consequences of failure. Owners determine what level of evidence is "sufficient for purpose", because only they possess full knowledge of the component's operational envelope, performance expectations and acceptable margins. This proportional approach allows operation to begin, but permitted only for a limited time, while still building the datasets necessary for long-term codification and scale-up.

This framework establishes the principles and evidence requirements that underpin qualification across all fusion components. However, qualification alone is not sufficient: once adequate evidence exists, it must be translated into structured, enforceable design rules. The next section therefore examines the role of pressure codes and standards, particularly ASME BPV and AFCEN RCC-MRx [28], in converting qualified material behaviour into codified requirements for fusion structural components.

3. The Role of Pressure Codes and Standards in Fusion Structural Material Qualification

Pressure-retaining component design codes provide the structured rules and quality expectations needed to ensure safe and reliable construction of engineered systems. They define minimum requirements for materials, fabrication, inspection and performance, forming a common technical language between designers, manufacturers, regulators and operators. Codes do not replace engineering judgement, nor do they eliminate the need for qualification; instead, they rely on the qualification process to establish the material properties, environmental behaviour and performance limits upon which their rules are based [27].

Although codification depends on qualified evidence, it does not require disclosure of proprietary datasets. Pressure codes such as ASME BPV and AFCEN RCC-MRx [28] do not publish raw mechanical or environmental data. Instead, they communicate validated behaviour through allowable stresses, permitted fabrication routes and defined material specifications. This structure allows companies to retain intellectual property protection, including patented or commercially sensitive alloys, while still demonstrating that a material is suitable for pressure boundary use. In practice, many industrial alloys enter codes through these published allowables stresses, whereas the underlying developmental and environmental datasets (such as irradiation datasets) remain confidential.

For fusion materials, this distinction is particularly important. Environmental performance data generated during qualification, such as irradiation synergy, corrosion response and joining integrity, may remain proprietary to the owner. These datasets support the engineering justification but are not required to appear in the published code. Codification therefore provides a mechanism for industry to deploy advanced or commercially sensitive materials without revealing the detailed evidence base that underpins their qualification.

Codes, standards and regulations each serve distinct roles.

- Codes (e.g., ASME BPV, EN 13445, RCC-MRx) prescribe design, material allowables, fabrication, inspection, and quality program rules.
- Standards (e.g., ISO, BSI, ASTM, CEN) define testing methods and material specifications.
- Regulations define legal requirements, which may mandate the use of specific codes depending on safety classification and jurisdiction.

ASME BPV Section III Division 4 provides construction rules for fusion machine components and represents a significant step toward codifying fusion-specific structural requirements. The aim here is to define fusion-specific structural requirements using a dedicated and standalone framework.

Division 4 adapts design principles of Section III component code to fusion by defining rules for the materials, design, fabrication, testing, and inspection of fusion components that operate in nuclear-relevant environments. Each Division within Section III operates independently, and Division 4 does not inherit the fission-specific rules found in Divisions 1, 2, 3, or 5. This point is often misunderstood: because Division 4 sits within Section III, many assume that fusion machines are automatically bound by fission rules, which is not the case. Section III is structured as parallel Divisions, each addressing a different technology.

Fusion is placed within Section III because it pressure-retaining (or structural integrity related) components exhibit the same nuclear degradation mechanisms, such as high temperature creep, irradiation-assisted deformation, swelling and embrittlement, that Section III components are subject too. From a structural integrity perspective, the origin of the neutron is immaterial; the material response is governed by the neutron flux, spectrum, and resulting damage mechanisms rather than whether the neutron is produced by fission or fusion. What is technically relevant is that the associated degradation phenomena fall within the nuclear integrity domain for which Section III was specifically developed.

By contrast, Section VIII is not intended for components subjected to neutron irradiation driven degradation mechanisms, transmutation gas production, nuclear heating, or long-term creep-fatigue degradation, and high degree of quality assurance. Its rules assume metallurgical stability and environments dominated by thermal and mechanical loads. Fusion components that operate in high neutron fluence, cryogenic-but-high-field, or other fusion-unique conditions therefore lie beyond the scope of Section VIII, even if they are nominally pressure-retaining structures.

For this reason, Division 4 sits within Section III, not because fusion must follow fission practice, but because fusion pressure systems share the similar nuclear degradation phenomena that Section III is designed to analyse. Division 4 applies only those nuclear principles that are technically justified and proportionate for fusion, while introducing new evidence-based rules where fusion environments differ. Importantly, Division 4 is not a blanket code for all fusion-facility components; it applies only to those structures exposed to fusion-relevant nuclear environments, such as high neutron fluence, irradiation-assisted deformation, high degree of quality assurance, or combined nuclear–thermal–mechanical loading. The placement of Division 4 within Section III therefore reflects the physics and materials science of fusion pressure systems, not any hierarchical or historical link to fission engineering rules.

Division 4 (established in 2023) is intentionally evolutionary: it is updated every two years to incorporate new evidence as fusion materials mature. As a consensus code, it advances through verifiable and objective engineering evidence and broad industry participation through ASME committees and working groups. Design codes such as the ASME BPV Code provide structured rules for yielding, creep, fatigue, incremental deformation, and fast fracture, but they do not prescribe design-specific allowances for environmental degradation (e.g., irradiation, liquid metal corrosion, helium embrittlement). Those effects depend on architecture, materials, and local conditions; responsibility for understanding and justifying them rests with the owner through qualification, which then supplements code rules to enable proportionate, context-specific design decisions.

AFCEN RCC-MRx offers an alternative European pressure system code for high-neutron-flux and high-temperature service (including ITER components). Its probationary rules, for example for Eurofer97, allow limited, controlled deployment while full material files are developed. Both codes ultimately depend on comprehensive, validated material data.

Where components claim a safety function, national regulators may require evidence that recognised engineering practice has been followed using graded safety classification frameworks (e.g., IAEA TECDOC-1851 [21] and IAEA SSG-30 [22]). Where no safety claim is made, owners may still assign quality classes for asset protection and assurance for the availability of components during lifetime. Qualification evidence forms the technical basis for safety cases and regulatory arguments whenever public, worker, or environmental protection is at stake.

The term "nuclear grade" is often used informally but does not refer to a distinct material property. Instead, it reflects compliance with a rigorous framework of rules and quality assurance measures defined in recognised codes and standards. For example, in ASME Section III, components are assigned Classes 1, 2, 3, A, or B by safety significance and role; these classes govern permitted materials, specifications, manufacturing controls, and QA/inspection expectations proportionate to consequence of failure, and can be mapped to safety classifications as needed.

Harmonised, volunteer consensus-based codes and standards should be viewed as enablers of innovation rather than constraints. They provide common rules, shared evidence expectations and a practical template for developing qualification programmes—even before formal codification is achieved. In practice, qualification generates the technical evidence, codification embeds that evidence into design rules, and industrial scale-up relies on reproducible processes and documented quality programmes.

For fusion materials such as Eurofer97 and SiC_f/SiC composites, the pace of qualification ultimately sets the pace of codification (i.e., the rate-limiting step) and therefore how quickly industry can supply components for commercial fusion systems.

4. Case Study Component: Breeder Blanket Structure

The breeder blanket is one of the most demanding structural components in a fusion power plant. It must generate tritium, remove high-grade heat, provide a pressure boundary for coolant systems, manage large thermal and electromagnetic loads, and contain activated materials. These functions make reliability and predictable performance essential for plant safety, availability, and commercial operation. Qualification therefore becomes central to determining how the blanket can be designed, justified, and ultimately deployed.

In a commercial fusion machine, the breeder blanket can be regarded as a mission-critical component whose failure would result in unacceptable loss of availability, severe operational disruption, or, depending on plant design, the potential release of radioactive inventory [5,13,29,30]. Its safety classification depends on the owner's claimed functions and the regulatory framework of the host nation. If the blanket carries an explicit safety function, then national regulators may require evidence that recognised engineering practice has been followed, including a robust and structured qualification programme. If it is not safety-related, quality and reliability requirements are instead defined by owner-driven performance, availability, and asset-protection considerations.

Under either route, qualification remains the governing process. It determines the depth of evidence required to demonstrate that the blanket will perform its intended function in its intended environment, and for its intended lifetime. The owner defines what constitutes "sufficient evidence", because only the owner understands the full operational envelope, risk appetite and acceptable performance margins for the plant.

The blanket environment imposes a uniquely challenging set of conditions [2,4,6,31]:

- Pressure-retaining due to coolants (liquid metal, molten salts, water or gases),
- High neutron fluence (tens to >100 dpa over the design life),
- Steep temperature gradients,
- Volumetric nuclear heating,
- Cyclic thermal and mechanical loads,
- Corrosion and mass-transfer effects from lead lithium (Pb-Li) or liquid lithium coolants (Li) (if used),
- Tritium embrittlement,
- Large electromagnetic forces during plasma disruptions,
- Irradiation-induced degradation of structural alloys and joints.

Each factor introduces potential degradation mechanisms, but these only become failure modes if they exceed the allowable performance envelope. Qualification is therefore the process that identifies which mechanisms matter, what evidence is required to understand them, and how margins can be established and demonstrated.

Because very few fusion facilities have operated at representative blanket conditions, full datasets are not yet available. Engineering programmes typically adopt a phased qualification strategy, where early experimental facilities, prototype campaigns and limited-scope demonstrators generate initial evidence, and further data are accumulated during operation. Qualification does not need to be fully complete before a breeder blanket enters service, provided that operation begins under controlled conditions with appropriate monitoring and conservative margins. This accelerates deployment while ensuring that evidence continues to mature.

In practice, qualification of a breeder blanket structure requires:

- Definition of the required functions and the performance envelope under normal, transient and off-normal conditions.
- Environmental characterisation including irradiation levels, temperature distributions, coolant chemistry, electromagnetic loads and mechanical duty cycles.
- Verification through testing and analysis using specimens, mock-ups, joints and prototype segments under representative or bounding conditions.
- A traceable evidence chain, recording how data were generated, how uncertainties were treated and how margins were justified.
- In-service monitoring and surveillance, especially for irradiation, weld performance, corrosion and tritium-related embrittlement phenomena.

The breeder blanket therefore illustrates the broader principle at the heart of this paper: qualification governs codification, not the reverse. Until the evidence base for the material is sufficiently complete, designers must use graded qualification methods aligned with recognised standards, and codes will expand as new evidence emerges. Reliable breeder blankets require not only well-characterised materials, but also scalable manufacturing processes, inspectable welds, reproducible thermal performance, validated joining procedures, and well-designed surveillance programmes. The extent to which these elements are in place ultimately determines schedule, manufacturability, risk, and the commercial viability of future fusion power plants.

5. Fusion Structural Materials and Industrial Scale-Up

Qualification frameworks define the evidence base needed to establish material behaviour, but practical deployment requires that candidate fusion structural materials can be manufactured, joined, inspected and supplied at an industrial scale. This section provides an assessment of the leading fusion metallic and non-metallic structural materials for fusion breeder blankets, namelyEurofer97 and SiC_f/SiC, respectively, focusing on their technical maturity and readiness for industrialisation.

Industrial scale-up represents a critical bottleneck for codification, between promising laboratory results and deployable fusion components. It encompasses the growth of manufacturing capability, supply-chain (large volumes on a tonnage scale with predictable quality), robustness, weldability, in-service inspection routes, and quality assurance standards that must remain dependable across plant lifetimes.

This section assesses the readiness of key fusion structural material systems, focusing on a metallic system (Eurofer97) and non-metallic system (SiC_f/SiC), identifying the qualification gaps that currently constrain their route to codification for use in breeder blankets and other mission-critical fusion components.

5.1. Case Study 1: Metallic-Based Alloy, Eurofer97

Reduced Activation Ferritic/Martensitic (RAFM) steels are favoured for fusion blanket structural materials because their compositions minimise long-lived radioisotopes, supporting waste minimisation and facilitating disposal [32–38]. Eurofer97 exemplifies this approach, with low nickel (Ni) and niobium (Nb) content to significantly limit the formation of high-activity isotopes such as Nb-91, Nb-93m, and Nb-94 [36,37,39]. The global qualification effort spans Europe's Eurofer 97 [12,40–42], the USA-Japan collaboration on F82H RAFM steel, which has been selected for ITER test blanket modules and J-DEMO breeder concepts [4,6,40,43–45], and National variants such as Chinese Low Activation Material (CLAM), and South Korean ARAA (advanced reduced activation alloy).

Despite compositional variations, RAFM steels exhibit broadly similar mechanical behaviour and manufacturing limitations, and none are currently approved as a pressure-boundary material under RCC-MRx or ASME BPV Section III (nuclear pressure systems) or VIII (pressure systems), thus necessitating formal qualification [12,46–49]. The limitation is not fundamental safety but the incompleteness and inconsistency of the property data under fusion-relevant environmental conditions that would make it "qualified" to support codified design allowable stresses and joining rules. Eurofer97 will be used as the RAFM candidate in this study.

Eurofer97 (specification X10CrWVTa9-1, with 9% chromium (Cr) and 1% tungsten (W)) is presently included under the RCC-MRx 2012 edition, under RPP Probationary Phase Rule RRP4 [46]. RPP4 introduces the use of Eurofer97 for fusion applications, specifically providing a reference procurement specification for plates only, (1–50 mm thick) and detailing mechanical properties.

The procurement specification (RM 243-3) mandates strict control of chemical composition, such as chromium between 8.5 and 9.5% (in wt.%), tungsten between 1.0% and 1.2%, and minimal impurities. The manufacturing programme must record all heat treatment cycles, and plates should be delivered in a normalised condition (940–980 °C), quenched, and tempered at 740–760 °C. The microstructure is required to be homogeneous tempered martensite with delta ferrite limited to $\leq 3\%$ and hardness between 200 and 240 HV30.

Mechanical testing requirements include tensile, impact (Charpy V-notch), and bend tests at both room and elevated temperatures, including after simulated stress-relieving heat treatment. RCC-MRx supplements these requirements with formulas and tables for physical properties such as thermal expansion, Young's modulus, and Poisson's ratio, alongside irradiation damage limits, creep and fatigue rules, and fracture mechanics parameters. Non-destructive examinations such as ultrasonic testing, surface and volumetric inspections, and strict defect criteria are also specified. Comprehensive documentation must accompany each batch, including full test reports, chemical analyses, micrographs, mechanical results, and dimensional checks.

Mechanically, Eurofer97 performs comparably to other 9Cr-based steels in the unirradiated state, although conventional alloys such as Grade 91 exhibit superior high-temperature creep resistance due to stabilising carbides and nitrides resulting from Nb, Mo, N, and V additions [12,46,50–52]. Under neutron irradiation (300–450 °C), Eurofer97 exhibits comparatively lower embrittlement rate than Grade 91 due to its optimised composition, which reduces radiation-induced segregation and precipitation associated with Mn, Ni, Si, P, and Cu impurities [53].

Eurofer97 data currently extends to approximately 2% total strain, with targeted ranges of 0.8–1.2% for DEMO-relevant low-cycle fatigue (LCF) conditions [46,49]. These values provide a preliminary basis for dimensioning components but remain insufficient for full compliance with code provisions on cyclic loading, particularly under irradiation. Gaganidze et al. studies indicate that specimen geometry significantly influences LCF life, underscoring the need for standardised testing protocols aligned with code assumptions [12].

Both ASME and RCC-MRx mandate long-term (minimum 30,000 h) creep rupture data to establish allowable stresses ($S_t(T,t)$), defined as the lesser of: (i) two-thirds of the minimum fracture-inducing stress, (ii) 80% of the stress causing tertiary creep, or (iii) the stress producing 1% total strain. Eurofer97 meets the minimum requirement of 30,000 h stipulated for new materials. However, uncertainties persist as the operational window for Eurofer97 narrows significantly above 550 °C due to thermal ageing and reduced creep strength relative to traditional 9-Cr steels, limiting its applicability for helium-cooled blanket concepts targeting operational temperatures of 600–650 °C [2,46,54–60]. Furthermore, synergistic creep–irradiation data remain scarce, preventing the development of robust creep–fatigue interaction rules required by both codes.

In terms of fatigue, Eurofer97's performance is dominated by cyclic softening under prolonged operation, necessitating more conservative allowable stresses [2,12,46,61,62]. Current LCF data for unirradiated and irradiated states (up to 72 dpa from R&D in the literature) suggest minimal irradiation impact within DEMO strain ranges, yet extended cycle testing remains incomplete. This gap constrains the ability to validate fatigue life predictions under fusion-relevant duty cycles.

Fracture toughness and Ductile-to-Brittle-Transition-Temperature (DBTT) behaviour are critical for structural integrity assessments. Eurofer97 demonstrates a DBTT shift of approximately 200 °C at neutron doses above 30 dpa, accompanied by reductions in upper shelf energy similarly to F82H [40,51,53]. While this performance surpasses traditional 9-Cr steels, it remains a challenges for water-cooled blanket concepts operating in the lower-temperature window of 300–350 °C, where low-temperature hardening embrittlement (LTHE) is most severe [2,49,61,63].

Joining remains a major qualification barrier. Both ASME BPV and RCC-MRx codes impose stringent requirements for weld procedure qualification and post-weld heat treatment (PWHT) of 9-Cr steels. Eurofer97 weldments require tightly controlled PWHT in the 750–780 °C range, yet the behaviour of heat-affected zones under irradiation remains poorly characterised. In a study by Forest et al. (2020) on Narrow-Gap Tungsten Inert Gas (NG-TIG) Welding, NDE and destructive testing revealed porosity and oxide inclusions whose dimensions were in accordance with RCC-MRx code acceptance criteria [64]. However, the modified martensitic microstructures in these regions may exhibit heightened susceptibility to creep rupture and helium-induced cracking, necessitating additional substantiation beyond code prescriptions [7,65–68]. Filler materials must also be defined for Eurofer97 welding procedures (NG-TIG, Electron Beam (EB) and metal inert gas/laser hybrid), either for nominal and/or repairing methods. Current understanding is that a plausible candidate filler with comparable chemistry and behaviour is the F/M steel T91 [51,64,69,70].

Environmental compatibility introduces qualification barriers. ASME BPV Code and RCC-MRx do not incorporate or provide any guidance on allowances for transmutation-induced helium or hydrogen generation, which is known to significantly influence Eurofer97's mechanical response [65,71,72]. Helium concentrations exceeding 500 (atomic parts per million (appm) lead to severe ductility loss, while vacancy clustering promotes swelling and fracture at doses above 20 dpa [61,65,66,73–76]. Corrosion in Pb-Li environments, hydrogen isotope permeation and tritium retention also require experimental evidence, where the synergistic effects of irradiation, corrosion and thermal cycling are not yet well-enough understood to support design allowables. These phenomena fall outside the scope of current code-based stress limits, reinforcing the need for fusion-specific qualification frameworks [2].

To progress to full qualification as a pressure-retaining structural material, the material file must include justification of applicability, evidence of industrial experience in manufacturing, fabrication, and welding (in line with RS 1300), ease of monitoring, and in-service behaviour under thermal ageing, corrosion, and irradiation conditions. Additional data requirements include further measurements of thermal expansion coefficients, mechanical tests to validate ultrasonic Young's modulus data, negligible creep curves through testing at breeder blanket relevant off-normal temperature ranges of 425–475 °C, and fracture toughness parameters (K_{IC} and J_{IC}) supported by generated data and justification of the chosen approach. These requirements extend beyond procurement to include an evidence-based justification of applicability and robustness across fusion duty cycles.

A summary of the qualification gap analysis for Eurofer97 can be viewed in Table 1. Eurofer97 satisfies the baseline requirement for unirradiated creep and fatigue behaviour under RCC-MRx, but lacks sufficient irradiation-enhanced creep data, weld performance assessments (with irradiation), fracture toughness and environmental compatibility datasets required to achieve full code qualification [2]. The absence of synergistic creep–fatigue irradiation datasets and long-term thermal cycling data (>10,000 h) remains a critical barrier [2]. Future compliance strategies must combine conservative design margins, advanced modelling, and phased prototypic testing to bridge these gaps [69].

Table 1. Qualification gap analysis for Eurofer97 against ASME BPV and RCC-MRx.

Category	Required by ASME BPV/RCC-MRx	Eurofer97 Status	Eurofer97 Gaps
Stress–Strain Behaviour	Full stress–strain curves; allowable strain ranges; elastic–plastic and creep regimes	Data up to ~2% strain; LCF tested (unirradiated & irradiated)	Long-term thermal cycling; synergistic irradiation + thermal creep
Creep Strength	Minimum creep rupture stress for design life or ≥30,000 h; creep–fatigue rules	Data up to 30,000 h; meets RCC-MRx minimum	Extended creep; irradiation creep
Fatigue Behaviour	LCF/HCF curves; cyclic softening	LCF data exists; cyclic softening observed	Long-term fatigue; weld fatigue; irradiation synergy
Impact Toughness/DBTT	DBTT and upper shelf energy; irradiation embrittlement	DBTT shift ~+200 °C under irradiation, R&D data.	Full DBTT mapping; weld toughness
Fracture Toughness	Bulk and weld metal properties across service range	Limited weld data: HIP joints tested	High-dose weld toughness; PWHT influence

Table 1. *Cont.*

Category	Required by ASME BPV/RCC-MRx	Eurofer97 Status	Eurofer97 Gaps
Irradiation Effects	Mechanical property degradation under neutron spectrum; He/H effects	R&D Data up to ~78 dpa; hardening saturates ~10 dpa	Synergistic He/H effects; swelling at 20–50 dpa
Joining/Weld Integrity	Qualification of weldments; PWHT compatibility	PWHT narrow window; limited weld irradiation data	Database for weld irradiation; helium cracking
Environmental Resistance	Corrosion, erosion, liquid metal embrittlement	Limited Li/PbLi R&D corrosion data	Full corrosion database; tritium retention
Design Allowables	S_m, S_{mt}, S_t(T,t); time-dependent failure modes	Partial compliance unirradiated; σ_{UTS}/σ_{YS} ratio met	Applicability under irradiation uncertain
Database & Handbook	Complete property handbook for code use	Handbook in development; international collaborations	Fusion-specific irradiation database; standardised protocols

5.2. Case Study 2: Non-Metallic SiC_f/SiC Composites

Non-metallic structural material SiC_f/SiC composites provide an alternative structural material with promising characteristics for high-temperature fusion machines, offering high temperature capability (800 °C), low activation and good corrosion resistance in many environments [9,77–80]. Historically, monolithic SiC was dismissed for use in nuclear systems due to its inherently brittle nature and unpredictable failure behaviour under load. However, the development of SiC_f/SiC fibre-reinforced composites in the 1980s marked a breakthrough, enabling improved toughness and reliability [9]. Advances in commercial SiC fibres production have enabled these composites to be evaluated in fission systems, such as accident-tolerant fuel cladding, and positioned them as leading candidates for high-efficiency helium-cooled blankets operating at temperatures up to 1000–1200 °C.

SiC_f/SiC offers several advantages for fusion design: namely its low activation behaviour, meaning that upon irradiation, SiC_f/SiC produces minimal long-lived isotopes (particularly Nb, Ni, Fe, Mn, Mo based) compared to metallic systems containing Fe, Ni and Mn. Its low activation profile supports waste minimisation and disposal strategies, with predicted activity levels well below thresholds for surface disposal 100 years post-end-of-life. This positions SiC_f/SiC as a strong candidate for meeting stringent radiological safety requirements in DEMO and beyond.

Mechanically, SiC_f/SiC demonstrates excellent high-temperature thermo-mechanical stability and negligible swelling under neutron irradiation, with property changes saturating at low fluence (~2 dpa). However, SiC_f/SiC's brittle nature and anisotropic behaviour introduce unique challenges for structural reliability under complex loading conditions. Unlike ferritic steels, SiC_f/SiC does not exhibit ductile failure modes, necessitating probabilistic design approaches and robust joining technologies to ensure compliance with ALARA objectives. SiC_f/SiC also exhibits a high elastic modulus and low strain-to-failure, typically below 0.5%, which contrasts sharply with metallic systems. This behaviour necessitates design strategies that avoid localised stress concentrations and incorporate statistical reliability models. Current data from the literature and R&D support dimensional stability under irradiation, but comprehensive strain–life curves for cyclic loading remain incomplete.

Creep resistance, however, is a key advantage of SiC_f/SiC at elevated temperatures, with negligible deformation observed up to 1200 °C in unirradiated conditions. However, the primary gap lies in the synergistic effects of irradiation and thermal creep, which are poorly characterised. Code qualification under ASME BPV or RCC-MRx principles would require long-term creep rupture datasets exceeding 30,000 h and demonstration of compliance with allowable stress criteria adapted for ceramics which are not yet available.

Neutron irradiation also introduces helium and hydrogen via transmutation, promoting microcrack formation and degradation in fracture toughness [65]. While SiC_f/SiC exhibits lower swelling than steels, its brittle nature amplifies the impact of irradiation-induced defects. While the current data indicates property saturation beyond approximately 10 dpa, the behaviour at doses relevant for DEMO (20–50 dpa) is still uncertain.

Joining SiC_f/SiC remains a major qualification barrier because thermal expansion mismatch and irradiation degrade joint integrity. Techniques such as diffusion bonding and glass–ceramic interlayers show promise, but require validation under thermal gradients, cyclic mechanical loading and neutron doses up to 20–50 dpa. Post-joining heat treatments must also be validated for dimensional stability and crack resistance and remain a limiting factor.

Environmental behaviour must also be addressed. SiC suffers severe corrosion in PbLi environments and exhibits sensitivity to thermal shock. Mitigation strategies including protective coatings and modified matrix chemistries are under investigation but not yet mature.

At present, SiC_f/SiC lacks the comprehensive property handbook required for codification. Qualification will demand a material file that includes justification of applicability, evidence of industrial-scale manufacturing, and in-service behaviour under irradiation, corrosion, and thermal cycling. Additional data requirements include mechanical property validation under fusion-relevant conditions (700–1300 °C), irradiation creep and fatigue data at doses up to 20–50 dpa, environmental compatibility with lithium and lead-lithium coolants, and joining integrity under cyclic thermal and mechanical stresses [81–86]. Procurement specifications for SiC must address fibre architecture, matrix densification, and porosity control (likely <10%), alongside strict documentation of processing routes such as CVI or slurry infiltration. Joining methods (diffusion bonding and glass–ceramic interlayers) must be qualified for irradiation tolerance and thermal mismatch mitigation.

A summary of the qualification gap analysis for SiC can be viewed in Table 2. SiC satisfies key functional requirements and offers superior high-temperature performance, yet full qualification requires irradiation creep and fatigue datasets, environmental testing in lithium and lead-lithium systems under dynamic conditions, standardised joining protocols, and in-service inspection strategies [81,82]. Development of probabilistic design frameworks for brittle materials is also essential to enable future code qualification. Future compliance strategies must integrate advanced modelling, large-scale irradiation campaigns, and phased prototypic testing to establish a credible route to qualification for SiC in fusion environments.

Table 2. Qualification gap analysis for SiC against ASME BPV and RCC-MRx.

Category	Required by ASME BPV/RCC-MRx	SiC Status	SiC Gaps
Stress–Strain Behaviour	Full stress–strain curves; allowable strain ranges; elastic–plastic and creep regimes	Limited tensile data: brittle ceramic behaviour dominates	No standardised stress–strain curves; fracture mechanics under irradiation
Creep Strength	Minimum creep rupture stress for design life or ≥30,000 h; creep–fatigue rules	Very limited creep data: SiC joints degrade under stress	Long-term creep–fatigue under fusion conditions
Fatigue Behaviour	LCF/HCF curves; cyclic softening	Poor fatigue resistance: brittle fracture dominates	Fatigue data under thermal cycling and irradiation

Table 2. *Cont.*

Category	Required by ASME BPV/RCC-MRx	SiC Status	SiC Gaps
Impact Toughness/DBTT	DBTT and upper shelf energy; irradiation embrittlement	Extremely brittle; no ductile regime	Irradiation-induced microcracking; fracture toughness data
Fracture Toughness	Bulk and weld metal properties across service range	Low fracture toughness; joints critical	Joint integrity under irradiation and thermal gradients
Irradiation Effects	Mechanical property degradation under neutron spectrum; He/H effects	Minimal irradiation database; severe embrittlement	Full irradiation performance database; joining behaviour
Joining/Weld Integrity	Qualification of weldments; PWHT compatibility	Joining extremely challenging; brittle interfaces	Reliable joining technology; irradiation-tested joints
Environmental Resistance	Corrosion, erosion, liquid metal embrittlement	Severe corrosion in Li/PbLi; thermal shock issues	Corrosion mitigation strategies; coatings
Design Allowables	S_m, S_{mt}, $S_t(T,t)$; time-dependent failure modes	No code-based allowables; brittle failure mode	Development of design allowables for ceramics
Database & Handbook	Complete property handbook for code use	No comprehensive handbook; scattered data	Full material property handbook for fusion conditions

These brittle characteristics mirror the longstanding challenges faced by ASME BPV Code in codifying graphite for high-temperature gas-cooled fission reactors. Traditional ASME design philosophy aims to achieve extremely low failure probabilities by relying on ductile metallic behaviour, well-defined margins, and deterministic design rules. Brittle, anisotropic systems such as SiC and graphite cannot practically meet this philosophy: some degree of statistical variation and non-zero failure probability is inherent to the material system. Consequently, structural justification must incorporate probabilistic approaches to demonstrate that the expected frequency and consequence of failure remain tolerable. The qualification challenge for SiC in fusion therefore resembles the graphite challenge in fission, not in material composition, but in the need to combine material testing, statistical characterisation and probabilistic assessment to meet ALARA-consistent safety objectives.

6. Discussion: Industrial Scale-Up Challenges and Future Prospects

The case studies demonstrate that qualification, rather than nominal material properties, ultimately governs the pace at which structural materials progress toward codification and deployment. Before breeder blankets and other mission-critical fusion components can be manufactured reproducibly, inspected reliably and deployed at scale, a common set of cross-cutting challenges must be addressed across all candidate materials.

First, adequate design margins must be established to ensure separation between operating conditions and failure limits. Larger margins may simplify the analytical justification and reduce the sensitivity of design decisions to dataset uncertainty; however, they do not eliminate the need for rigorous substantiation. Whether the design margins are wide or narrow, they must be supported by qualified evidence generated under conditions representative of the component's actual service environment.

A second requirement is a comprehensive understanding of materials behaviour under the combined effects specific to fusion machines. Structural materials for breeder blankets must withstand high neutron fluence, elevated temperatures, volumetric nuclear heating, liquid metal corrosion, tritium permeation, and irradiation-induced microstructural changes or fracture behaviour. These interactions are only partially captured in existing engineering codes and will likely not be covered as they are unique to the design of the specific plant. Addressing these gaps demands sustained irradiation testing campaigns, coordinated international research efforts, and the maturation of databases for RAFM steels, SiC_f/SiC composites and other candidate alloys.

A third requirement concerns the associated manufacturing and inspection ecosystem. Fusion blanket modules, in-vessel structures and pressure boundaries rely on fabrication techniques such as hot isostatic pressing (HIP), additive manufacturing (AM), narrow-gap welding and diffusion bonding. Qualification demands reproducibility across heats, batches and suppliers, alongside validated inspection routes that remain effective post-irradiation. Inspection reliability after neutron exposure is a notable challenge, especially for weldments and bonded joints. Designing for inspectability during operation, replacement and decommissioning is therefore a key part of the qualification argument.

A central principle is that qualification is fundamentally 'owner-led'. Although qualification is often described as such, this should be understood in a specific sense. The code determines the type and depth of evidence required to justify performance, such as allowable stresses, weld qualification, creep–fatigue rules, or fracture limits. However, only the owner or machine designer can define the functional role of a component, the reliability with which that function must be delivered, and the environmental envelope it will experience. These selections establish the target performance that must be substantiated, and therefore indirectly determine the scope of the qualification programme. In this way, qualification is both code-governed and designer-driven: the code prescribes how evidence must be generated and justified, while the designer defines what must be justified.

The owner defines what constitutes "sufficient for purpose" evidence informed by knowledge of the component function, performance targets, operational envelope and acceptable margins. This drives the grading of evidence, the representativeness of tests and the degree of conservatism required. In practice, this owner-led stance shapes the material development programme: alloy selection; the required test types, quantity and quality of testing; the definition of relevant environmental exposures; the surveillance strategy; acceptable failure probabilities; in-service inspection; and the manufacturing and inspection requirements needed to deliver confidence in performance over life.

Qualification is best understood as a risk-informed decision framework rather than a compliance checklist. A key boundary condition exists across most jurisdictions: pressure-retaining components must comply with recognised pressure system regulations. The difference lies not in whether a code is required, but in which codes are acceptable. For example, in the US, unfired pressure vessels must comply with the ASME BPV Code by law, whereas in the UK and many European states, compliance may be demonstrated using any suitably justified pressure vessel code. In all cases, codification remains essential for pressure-boundary components as fusion progresses toward commercial operation. For fusion machines, this means codification is not optional for pressure-retaining systems and should be integrated into the owner's strategic plan from the outset to build market credibility and demonstrate engineering evidence.

These broader requirements are reflected in the staged roadmap for ASME BPV Section III Division 4 code [26], which continues to incorporate rules for fusion-specific environments as supporting data become available, spanning general code definition, design methodologies, analytical techniques and materials/manufacturing data. In practice, the qualification pace of Eurofer97, SiC_f/SiC, and related materials will determine how quickly new design rules, inspection standards and allowable stresses can be added to the code.

In parallel, international harmonisation remains essential. In the context of emerging fusion design codes, harmonisation therefore encompasses two pillars: (i) material data requirements, what evidence is considered sufficient, relevant, and representative; and

(ii) design methodologies, including how analytical, empirical, and rule-based approaches (Design-by-Rule/Design-by-Analysis) are applied consistently across fusion programmes. Alignment in test methods, terminology and acceptance criteria reduces duplication, improves database compatibility, and supports mutual recognition of evidence; this is critical for early commercial deployment that will depend on global supply chains.

Ultimately, qualification is a risk-informed, evidence-driven framework that enables safe and reliable operation under demanding fusion conditions. It requires a balance between representative testing, conservative analytical modelling and in-service surveillance to monitor degradation mechanisms during operation. This approach applies equally to higher-readiness materials such as Eurofer97 and to lower-readiness systems such as $\mathrm{SiC_f/SiC}$, ensuring that the extent of evidence is proportionate to the consequences of failure and aligned with the owner's performance expectations and risk appetite.

As fusion programmes transition from experimental facilities to industrial prototypes and early power plants, the qualification challenges identified in this paper will shape not only codification timelines but also alloy development, manufacturing strategy, quality assurance frameworks and supply-chain development. Embedding qualification early in design accelerates codification, reduces uncertainty, and supports commercial deployment.

7. Conclusions

The qualification of fusion structural materials demands approaches that extend beyond existing design codes. Fusion environments introduce combined irradiation, thermal, mechanical and chemical effects that are not yet addressed comprehensively within ASME BPV or RCC-MRx frameworks. Qualification therefore provides the essential evidence base for understanding material behaviour, establishing performance limits and supporting the eventual development of codified design rules.

Eurofer97 demonstrates that even high-readiness materials require substantial irradiated creep–fatigue, weld performance and environmental compatibility data before codification can proceed. $\mathrm{SiC_f/SiC}$ composites illustrate the contrasting challenge: a promising high-temperature material system with limited datasets, immature joining technologies and no established probabilistic design framework. In both cases, qualification, not intrinsic material capability, determines the pace at which these materials can be deployed in mission-critical components such as breeder blankets.

Because qualification is fundamentally an owner-led activity, the depth of evidence must be proportionate to the component's functional role, consequence of failure and the owner's risk appetite. For pressure-retaining components, codification will be required as fusion facilities move towards commercial deployment, particularly in jurisdictions such as the United States where ASME BPV compliance is mandatory. Integrating codification into long-term qualification strategies is therefore essential.

By embedding robust, graded qualification programmes early in design, fusion developers can reduce uncertainty, guide material development, accelerate codification and build confidence among regulators, investors and supply-chain partners. Qualification is thus the rate-limiting step, and the enabling pathway, towards reliable, industrial-scale fusion power systems.

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