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Technology readiness assessment of materials for DEMO in-vessel applications

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ABSTRACT

A dedicated procedure was developed to categorize the technology readiness of materials for specific DEMO in-vessel fusion reactor applications. This methodology was employed to assess the technological maturity of materials under development within the EUROfusion materials work package (WPMAT). This covers materials intended for structural, high heat flux, optical and dielectric applications in the European DEMO fusion reactor (breeder materials and barrier coatings are not covered here). The baseline materials have been assigned DEMO Material Technology Readiness Levels (MTRLs) of 4 (EUROFER97), 3 (conventional tungsten) and 4 (Copper-Chromium-Zirconium). In addition, a further 28 candidate materials (and groups of materials) were also assessed. These were generally assigned DEMO MTRLs in the range of 2-3. This process has highlighted the wide range of materials under development within WPMAT. However, it has also brought into focus the many challenges facing DEMO materials development. While the lack of technologically ready materials is clearly a source of risk to DEMO, the introduction of a biennial review of technology readiness within WPMAT is intended to facilitate more effective planning and targeted materials development, in line with the strategic plans of EUROfusion. This paper highlights the methodologies for fusion specific material technology readiness levels, their application for EU-DEMO and the effectiveness of these in strategic materials development.

1. Introduction

Construction of a European demonstration fusion power plant (DEMO) will require development and qualification of a range of high performance materials for critical applications, including structural, armour, diagnostic and control functions (see Fig. 1). Within the reactor vessel itself materials will be faced with extreme operational conditions: high heat flux, neutron irradiation, plasma erosion, mechanical stress, thermal cycling etc [1–3]. Furthermore, in order to demonstrate fusion as a viable commercial energy source, DEMO will need to operate with reasonable reliability, and this will require acceptable component (and material) lifetimes, although less stringent than what will be required in a commercial fusion power plant. Development of these materials is a major undertaking that carries significant risk in terms of the time and resources required to meet the technical challenges of DEMO [4]. Therefore, in order to address these issues and mitigate such risks, the Work Package MATerials (WPMAT) of EUROfusion has implemented a Materials Management Framework (MMF) to monitor progress, inform stakeholders and guide – in the future – strategic decision making. The central feature of the MMF is the use of DEMO Material Technology Readiness Levels (MTRLs) to assess the technological maturity of materials under development within WPMAT. This covers most materials intended for structural, high heat flux, optical and dielectric applications within the reactor vessel.

This paper details the methodology developed for assessing technology readiness within WPMAT and summarises the output of this exercise in the form of MTRLs. While this approach provides

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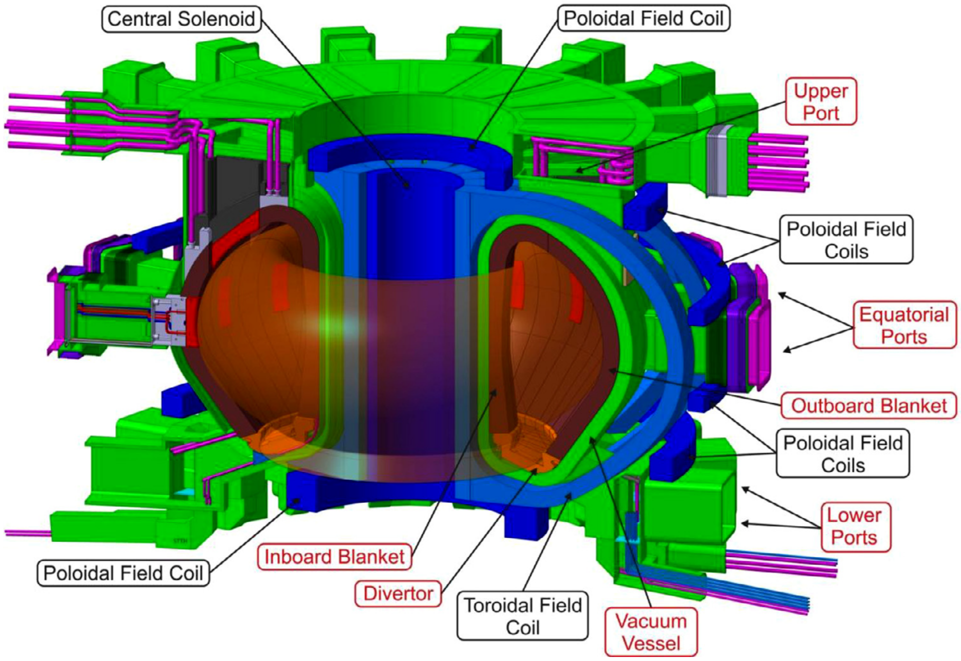

Fig. 1. Conceptual design of the EUROfusion DEMO reactor. WPMAT covers in-vessel materials for structural and high heat flux applications (utilised in the divertor and breeder blanket), in addition to functional materials for heating, diagnostic and control systems (residing in vessel ports/ducts).

a snapshot in time, it does not confer information on the rate of past or future (expected) progress towards qualification of a material. It is for this reason that the MMF also incorporates summary reports for each material, providing the necessary context in which to view each MTRL. These provide a more holistic assessment of each material by highlighting the associated risks and benefits of each option. Key points covered by these reports are summarised as part of the discussion in Section 4. The current readiness levels are based on the Horizon 2020 definitions [5], having been more narrowly defined for the relevant area (fusion materials) [6], and informed by ISO 16290:2013 [7]. The process of evaluating technology readiness within WPMAT is itself a work in progress and under continuous review as system requirements become clearer. Going forward, there is the intention to proceed with periodic reviews of the MTRLs on a biennial basis to monitor progress and assist with strategic planning of materials development.

2. Material technology readiness levels (MTRLs)

Within EUROfusion WPMAT, DEMO MTRLs were devised as a modification to the industrially accepted concept of Technology Readiness Levels (TRLs). The latter were originally conceived by NASA as a way to classify the maturity of developmental technologies on a numerical scale from 1 (basic research) through to 9 (fully operational) [8]. This approach was intended to help address the inherent risks faced by large research and development projects (which can manifest as delays, excessive costs or complete failure) [9]. TRLs were used to help manage internal technology transfer from fundamental research through to mission critical application. In addition, they were also utilised in strategic planning [10]. The determination of TRLs is usually undertaken as part of a Technology Readiness Assessment (TRA). This process begins with the identification of Critical Technology Elements (CTEs), which are then evaluated for their technological maturity [11–13]. This system has since been widely adopted throughout industry [10]. In the context of DEMO, the materials from which in-vessel components will be manufactured represent multiple CTEs, each of which can be assigned an individual TRL classification. To provide clarity within EUROfusion, the term Material Technology Readiness Level (MTRL) was introduced to emphasise the exact nature of these particular CTEs with respect to DEMO.

Table 1 illustrates the definitions of the nine-level Horizon 2020 (H2020) TRL scale [5]. However, in order for these definitions to be of use to the fusion community and external stakeholders, some further clarification is required, as indicated alongside the Horizon 2020 definitions, and covered in further detail below. It is important to note that TRLs are technology and application specific [7,10]. For example, tungsten is at TRL 9 when used in light bulb filaments and anti-armour munitions, but currently TRL 3 for use in the divertor of a *demonstration fusion power plant* (itself at a very low TRL). However, it should be noted that tungsten effectively sits at TRL 9 for use in the divertor of the Joint European Torus (JET), an *experimental fusion reactor* operating at low fusion power, low duty cycle and short pulse, i.e. low radiation damage conditions [14]. The key point is that how a final system is defined (and what constitutes 'proven operation') will fundamentally affect the detailed definitions of a TRL scale, since this defines the end point (TRL 9) from which the scale itself is derived. Thus, there must be common agreement and understanding of each technology readiness level for them to be of any use.

The example of tungsten light bulb filaments also serves to illustrate a second point. Technology Readiness, as originally defined by NASA, should not be confused with commercial/market readiness. Incandescent light bulbs were indeed commercially viable before their subsequent decline, but it is possible for a given technology to be rendered obsolete before it even reaches TRL 9 if development is too slow [10]. Under the H2020 definitions, a degree of market competitiveness is incorporated (see Table 1) [5,10]. However, this aspect is less applicable in the case of DEMO given its function as a demonstration power plant. A fundamental difference between DEMO and subsequent commercial fusion power plants (FPPs) is cost. While the unit price of electricity produced by an FPP will be influenced by the performance and reliability of mate-

Table 1
Technology readiness level (TRL) [5] and Material Technology Readiness Level (MTRL) Definitions.

TRL	Description (Horizon 2020)	MTRL Interpretation
1	Basic Principles observed	• Prior research exists
2	Technology concept formulated	• Application identified • Concept (solution) formulated
3	Experimental proof of concept	• Lab scale production demonstrated • Bulk material properties assessed
4	Technology validated in laboratory	• Consistent lab scale production achieved • Evaluation of fabrication processes (e.g. joining)
5	Technology validated in relevant environment[a]	• Consistent industrial scale production achieved • Bulk material properties assessed in fission/MTR irradiated state
6	Technology demonstrated in relevant environment[a]	• Evaluation of fabricated structures (e.g. joints) under fission/MTR irradiation • Modelling to extrapolate from fission/MTR irradiation data to fusion neutron conditions • Testing in non-neutron Component Test Facilities (CTF)
7	System prototype demonstration in operational environment	• Properties assessed via FNS testing (e.g. IFMIF) • MTRL 6 modelling validated through FNS data • Prototype components tested in integrated fusion environment
8	System complete and qualified	• Material accepted in relevant design codes • Material incorporated into final DEMO designs • Industrial supply chain in place
9	Actual system proven in operational environment[b]	• Material and component functionality proven through sustained operation in DEMO

[a] Industrially relevant environment in the case of key enabling technologies
[b] Competitive manufacturing in the case of key enabling technologies or in space

rials within it, this may not be sufficiently represented in a technology readiness scale *for DEMO*. In other fields, this lack of commercial assessment has prompted the development of additional measures, as in the case of Australia's Commercial Readiness Index (CRI) for Renewable Energy Sectors [15], or a proposed TRL 10 [16]. In the current DEMO MTRL scale, elements of commercial readiness are addressed with respect to scalability of production and the establishment of supply chains, since these will be critical to DEMO construction and operation. However, requirements for a FPP will be different and the TRL level of a given material when considered for FPP application will likely be different (lower). Cost of DEMO will of course be a factor in the decision-making process, but it is important to note that (M)TRLs are just one aspect of this, and down-selection is likely to take a more holistic approach, encompassing many different factors. Price of electricity on the other hand will be among the leading factors for successful development of fusion power and require additional material developments. This is already implicitly acknowledged in WPMAT, with the development of Risk Mitigation Materials (see Section 3) which indeed sit at different TRLs than the baseline DEMO materials.

The widespread use of TRLs led to the introduction of ISO standard 16290:2013, providing greater consistency in the classification and interpretation of each level [7]. However, in light of their application dependence, it is still necessary to customise the TRL scale for individual areas of interest, in this case (in-vessel) fusion materials. The underlying principle of a technology readiness scale is that of testing under conditions which are progressively more representative of the final operational environment. Technology readiness is therefore a qualitative measure of the risk that a technology poses if implemented at a given point in time (the point at which a TRL is determined). Less mature technologies represent a greater risk if selected for use, since there is a greater likelihood of encountering problems that would otherwise have been identified through subsequent testing [10]. In the case of materials for in-vessel fusion components, the objective is to ensure safe, reliable performance for the intended application. This will necessarily involve a significant amount of testing, beginning at a fundamental level and progressing to more integrated (component) testing under increasingly demanding conditions highlighting the strong interrelation between TRLs of systems and materials in particular at intermediate levels.

Given the range of applications within the vacuum vessel, the exact properties of interest, and their relative importance will vary between materials. Materials investigated under WPMAT are categorised as structural, high heat flux, optical and dielectric. Structural applications are those that need to carry mechanical loads and stresses or provide mechanical support to other (sub-) components e.g. stiffening plates in the breeder blanket [17]. Many of these applications in the breeding blanket, first wall and divertor base structure are required to handle pressurised coolants, and thus pressure vessel requirements such as hermeticity, heat transfer and behaviour under accident scenarios are also highly relevant. The high heat flux sub-project is dedicated to the material development and characterization of improved and novel plasma facing and heat sink materials as well as joints and interlayers between these, mainly for divertor applications but also to a minor extent for applications at the first wall blanket [18]. Optical and dielectric materials find their application in heating, diagnostic and control equipment (breeder materials as well as barrier coatings have been outside the scope of WPMAT within Horizon 2020 and are therefore not covered herein). What follows is therefore specification of the (Horizon 2020) TRL definitions in the context of materials for in-vessel DEMO components (MTRLs) [5–8]. It is important to note that while this is a Material Technology Readiness scale, it extends well beyond the existing remit of WPMAT itself, since final qualification and use is dependent on more integrated development that will encompass other work packages dealing with systems design for in-vessel components and interested parties (e.g. funding bodies, standards organisations, industrial partners).

2.1. MTRL 1: basic principles observed

All TRL scales begin with fundamental research in which basic principles are observed and reported. In many cases, no clear application is evident, but the discoveries and data are recorded for future use. In the context of fusion materials (MTRLs), examples of such research could include the discovery of tungsten in 1781, general advancements in ferrous metallurgy or the discovery/determination of dielectric properties in untested materials.

2.2. MTRL 2: technology concept formulated

MTRL 2 represents the point at which an application is identified and a potential solution (technology concept) is formulated. In the context of baseline materials, the proposal to use conventional tungsten as a divertor material could be considered the technology concept. For more advanced options, concepts may be based on the established principles that underpin the superior performance of composites e.g. tungsten fibre reinforced tungsten. It is important to bear in mind that there is no gradation in complexity of the concept as it progresses up the TRL (or MTRL) scale [7]. Conventional (baseline) tungsten will still be conventional tungsten if it reaches MTRL 9, even as it is integrated into more complex systems/components. However, two different concepts for the same application can vary in complexity at the same readiness level. As explained in ISO 16290:2013, performance requirements of the intended application are likely to be general and only broadly defined at this stage [7]. In the case of fusion, this is particularly true, as at the time of writing, DEMO itself is still in the pre-conceptual design phase and there remain a lot of unknowns about the exact conditions in-service. Otherwise, this level is characterised by analytical assessments and theoretical work to establish concept viability.

2.3. MTRL 3: experimental proof of concept

MTRL 3 establishes the practical feasibility of the concept. Although the term ‘laboratory’ is not introduced in the Horizon 2020 scale until TRL 4 (see Table 1), the use of the word ‘experimental’ at TRL 3 signifies that laboratory scale work has begun [5]. Thus, in the MTRL interpretation of level 3, production of the material must have been demonstrated on a laboratory scale. In addition, relevant bulk material properties should be assessed in the unirradiated state. The term ‘bulk’ is used to distinguish between semi-finished products (e.g. plate) and more complex structures, where fabrication techniques might alter final properties (e.g. welded joints, machined parts). The specific properties of interest and their relative importance will vary by application. In the case of structural materials, mechanical properties are of primary importance [19], whereas for heat sink applications, thermo-physical properties (e.g. thermal conductivity, heat capacity) are also key parameters [18,19].

In the case of materials for heating, control and diagnostics, it may be optical or dielectric properties that are of interest [20]. However, it is usually a balance of properties rather than a single property that dictates a material’s suitability for a given application. For example, although classified as a high heat flux material, the baseline heat sink material, CuCrZr also performs a structural function within the divertor by supporting the plasma facing target, handling pressurised coolant and tolerating thermally induced stresses (under pulsed [i.e. cyclic] operation) [4,18]. Although performance requirements are still only broadly defined at this stage [7], the critical material properties of interest should be assessed under relevant temperatures and conditions where known/estimated i.e. expected operating temperature(s)/cycles in DEMO based on current designs.

2.4. MTRL 4: technology validated in laboratory

At MTRL 4, the repeatability of the laboratory production process is confirmed through further testing, followed by a shift towards more integrated development. Whereas MTRL 3 focussed on bulk material properties, level 4 requires testing and evaluation of potential fabrication techniques e.g. welding processes. This is relevant not only for mechanical properties in structural applications, but also thermo-physical properties in functional and high heat flux materials. For example, various optical and RF windows will likely be subject to vacuum conditions on one or both sides. This is highly significant, since heat removal will then be determined in large part by conduction through physical connections with supporting structures (e.g. flanges) [20]. In addition, the unique environment within a fusion reactor also requires a more holistic assessment of material performance than assessment of basic properties will provide. This is particularly true of plasma facing materials subjected to extremely high heat flux and plasma erosion. In order to quantify material performance in this respect it is therefore necessary to conduct standardised high heat flux testing [21].

With a view towards future engineering design and licensing requirements, the applicability of existing design rules, norms and quality assurance measures shall be evaluated. Adaption, modification or new development is quite likely e.g. for novel materials such as composites or due to new regimes of application. Mock-up component tests and/or complex multi-damage experiments are needed to support conceptual design and provide data for development and validation of design criteria (or input to code frameworks). At this stage, these would typically be low fidelity prototypes intended to assess the suitability of fabrication processes and confirm basic principles of operation [7]. In order to be effective and meaningful this requires complementary development of materials (constitutive) models, along with accompanying analysis and proper evaluation and categorisation of data to help establish design related material properties. Data need to be analysed, assessed and stored in various forms: (i) in a Material Property database, (ii) a Material Property Handbook (MPH) and (iii) in dedicated Material Annexes to the respective selected (newly developed and/or existing) design code frameworks. Other key areas that require special attention include the absorption/retention/permeation of tritium. The relative importance of this will vary by application but can be studied initially with non-active simulants (e.g. H, D) before verifying with tritium.

2.5. MTRL 5: technology validated in relevant environment

In light of the volume and scope of testing required from MTRL 5 onwards, it is necessary by this point to demonstrate repeatable industrial scale production. This minimises the risk that scalability poses to the significant investment now required to test under increasingly complex, integrated conditions. A major source of this cost/complexity is the introduction of testing under a 'relevant environment'. This is a subset of the 'operational environment', that consists of the critical conditions that will limit system performance [7]. This will vary significantly between fields, and requires clarification in the case of fusion in-vessel components. The most significant risk facing materials development for fusion is the uncertainty surrounding the effects of high neutron-fluence irradiation. As an approximation, the 'relevant environment' for in-vessel fusion applications has been taken to be fission neutron irradiation combined with other relevant modes of loading and potential failure [22]. The effect on bulk material properties of exposure to these conditions must be assessed and compared with anticipated design conditions (performance requirements).

Fission Material Test Reactors (MTRs) can provide much useful information and correctly mimic displacement damage. However, an inherent critical limitation (important for high neutron-fluence and near plasma locations), are production rates of Helium and Hydrogen in structural materials that are one or two orders of magnitude lower than under a first wall fusion spectrum [23]. Attempts to address this shortcoming include the use of chemically and isotopically doped materials to simulate the co-generation of He and H, although these and other surrogate methods also have their own limitations [24,25]. For plasma facing materials like tungsten, the H and He production rates are two orders of magnitude lower than in steels and studies on the interaction between H and He at the plasma facing surface with significantly higher concentrations do not indicate that there will be issues with regard to H and He transmutation in tungsten. In contrast, tungsten faces the issue of re-transmutation due to thermal neutrons, which is overestimated in fission irradiation as is the associated material degradation. For both applications, these remain key risks to further development until a Fusion Neutron Spectrum (FNS) test facility becomes available (see MTRL 7) [25,26]. If the evaluation of existing design rules has highlighted gaps and inconsistencies (see MTRL 4), testing campaigns should now inform the development of new rules, and vice versa. These will be validated through the testing programmes that span MTRLs 5-7, and subject to revision where appropriate. Ultimately, it is these rules that will dictate the relative importance of specific material properties/characteristics for individual applications/designs e.g. whether erosion or structural integrity considerations will be the life limiting factor for the divertor [27].

2.6. MTRL 6: technology demonstrated in relevant environment

As with the distinction between levels 3 and 4, MTRL 6 represents an increase in the level of integration over MTRL 5. Whereas the preceding level assessed 'bulk' material properties under fission/MTR irradiation (the 'relevant environment'), MTRL 6 extends this assessment to cover fabricated parts e.g. joints. However, as explained earlier, the neutron spectrum of a fission MTR is not prototypical of a fusion reactor. This 'gap' represents a fundamental challenge in materials development for DEMO. To address this risk, extensive use of multi-scale modelling will be needed to extrapolate from surrogate irradiation data to actual fusion neutron conditions [4,19]. This will need to combine nanoscale irradiation effects models with engineering scale finite element modelling to accurately predict material and component performance [28]. Such models must be developed as a prerequisite for MTRL 6, before being validated at MTRL 7 with the use of an FNS test facility e.g. International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source (IFMIF-DONES). As mentioned earlier, performance requirements are only broadly defined at lower readiness levels. This is due to the design dependence of such requirements and the uncertainty this engenders at lower levels. However, by MTRL 6, designs should be sufficiently advanced that key performance requirements are known with a high degree of confidence. This is a prerequisite for MTRL 6, since component testing in non-neutron facilities should be sufficiently advanced to verify system functionality in an unirradiated environment.

2.7. MTRL 7: system prototype demonstration in operational environment

In a conventional technology readiness scale, TRL 7 represents demonstration in an operational environment [5–7,11,13]. Here MTRL 7 would rely on the use of a combined effects test facility to simulate an operational environment. However, while some planned facilities may be able to simulate certain specific conditions at a fusion relevant level (e.g. IFMIF-DONES [29]) or all of them at a lower duty cycle than DEMO (e.g. ITER), there are currently no plans for a facility that fully reflects the conditions and duty cycle of EU DEMO [23]. It is therefore anticipated that qualification will be based upon the use of high fluence neutron facilities (DONES-IFMIF) to irradiate small scale specimens in conjunction with component testing in non-neutron facilities and ITER. This will likely utilise FNS test facilities to identify where fission irradiation data is valid and provide fusion specific data where fission/MTR studies are inadequate/unrepresentative [26,30]. FNS data will also be key in validating models extrapolated from surrogate (fission) irradiation data [4,19,31].

Various studies have been carried out investigating the feasibility of using intermediate facilities based on the spherical tokamak concept as a risk mitigation step between ITER and DEMO [32–35]. Such facilities would act as component (integrated material) test facilities and could fulfil the MTRL 7 role. However, given the time and costs involved, it is expected that this step will be omitted in favour of the approach outlined above (and see Section 2.8). If operational environment testing is not employed, MTRL 7 cannot, in principle, be achieved. This approach adds significant risk given the lack of in-situ testing [6] and actually implies building DEMO with (some) materials at MTRL 6. This represents a cost-benefit trade-off that TRLs are ideally suited to illustrate. As mentioned earlier (see Section 2), TRLs are a qualitative measure of the risk that a technology represents if implemented at a given point in time/development. The decision to build DEMO with (some) materials at MTRL 6 rather than MTRL 8 entails substantial risk, but if successful, represents a faster route to demonstrating grid scale electricity generation from fusion. Qualification is a matter for stakeholders (regulators, funding bodies etc) and will be based on what all concerned parties agree is acceptable [25].

However, DEMO should be able to act as a Component Test Facility (CTF) for subsequent (commercial) Fusion Power Plants (FPP), thereby accelerating further development and minimising risk to future projects, but is not expected to benefit from a commensurate facility itself [23]. Since one of the key distinctions between a demonstration FPP and a commercial FPP is cost, a technology readiness scale may be ill-equipped to fully capture the risks. While there may be many significant technical differences between the two, these will ultimately be motivated by market concerns e.g. increasing plant availability through extending component lifetimes and reducing maintenance downtime. This will likely lead to a revision of material performance requirements, and a consequent regression in the readiness of materials on the MTRL scale. However, in this instance DEMO may be able to provide the operational environment to test materials/components against these enhanced requirements, thus facilitating the realisation of MTRL 7 for materials intended for a commercial FPP.

It should be noted that optical and dielectric materials will not be subjected to the same conditions as plasma facing and structural materials inside the vacuum vessel [20]. Given their sensitivity to irradiation, erosion and deposition, it is expected that careful design will be employed to shield components incorporating such materials (through specially shaped ducts, fins etc.) [20]. This should permit characterisation with a fission spectrum alone [20,25,31].

2.8. MTRL 8: system complete and qualified(8)

Upon completion of MTRL 8, a material is fully qualified and approved for its intended use in DEMO. This includes regulatory approval along with verification of system functionality from a design perspective. The details of regulatory approval are unknown today. If (as in the case of ITER [36]) the vacuum vessel is defined as the primary safety barrier, the approval of in-vessel materials/components is simplified since their function will not be safety critical, but strict criteria will still need to be met for reasons of 'investment protection' [25]. Qualification of in-vessel materials will be highly dependent on the expected performance of DEMO by key stakeholders (e.g. funding bodies) and their attitude to risk. To demonstrate fusion as a viable grid scale energy source, DEMO will need to operate with reasonable reliability, and thus require acceptable component (and material) lifetimes. Guided by precedent in other fields (e.g. fission and aerospace), the development of DEMO Design Criteria for in-vessel components (DDC-IC) over MTRLs 5-7 (see Section 2.5) will therefore require significant collaboration between standards organisations and funding bodies to decide what exactly constitutes 'qualification' [25]. By MTRL 8, a material must therefore be incorporated into a code framework agreed upon by all interested parties at a senior level. Final component/system design verification shall be based on an integrated application of design criteria, methodologies and material appendices of the selected code(s). Full scale industrial production should also be established and a supply chain capable of meeting the needs of DEMO must be in place.

However, as explained in Section 2.7 (MTRL 7), it is not expected at this point that operational environment testing will be employed during qualification of materials for EU DEMO [23]. This precludes the realisation of MTRL 7, and although qualification may be achieved via other means, it would be misleading to state MTRL 8 has been reached if MTRL 7 is not completed beforehand. However, if MTRL 9 is subsequently achieved (see below), this would supersede MTRL 7.

2.9. MTRL 9: actual system proven in operational environment

MTRL 9 is achieved once the material performance has been proven through actual system use in DEMO itself. A material forms an element within a component/system, such as the breeding blanket, divertor etc. The system must perform as expected without material failure under predefined operating conditions. Since DEMO is currently pre-conceptual, the operating conditions are not yet clearly defined. However, it is anticipated that a phased approach will be taken with DEMO operation [23,25]. Initially it will operate with conservative design margins and a 'starter' blanket having a nominal damage limit of 20 dpa (in the first wall steel). This would then be replaced with a second set of blankets, incorporating an optimised design and (if available) more advanced materials, to meet a higher damage limit of 50 dpa [4,23,30]. Such a strategy is also expected to aid in the optimisation of divertor design [4,27]. Furthermore, drawing on experience in the fission industry, it is likely (and from a qualification and risk mitigation point of view recommended), that surveillance specimens will be deployed in DEMO to monitor material degradation. Combined with complementary testing in FNS test facilities, this should facilitate reformulation of the initial safety case and reduce undue conservatism [25]. Such an approach should ultimately yield a comprehensive material database to inform the design and operation of future power plants.

3. Technology readiness assessment (TRA)

The accurate determination of MTRLs is not always straightforward as technology readiness can be a difficult concept to quantify. Therefore, to minimise subjectivity in the assessment process, a generic questionnaire was used to evaluate each material against the definitions described in Section 2. This was undertaken in consultation with material developers, group leaders for the respective sub-topics and project leaders. In addition, a review of the available literature (both internal and external) was carried out to substantiate the classifications, utilising published sources wherever possible. However, in some cases where work has not yet been published, only internal EUROfusion reports are available (for information on the content of these, please contact the author).

As mentioned earlier, the materials under development within WPMAT are subdivided into a number of categories: structural, high heat flux, optical and dielectric. These general categories are reflected in the organisation of EUROfusion WPMAT, with the optical and dielectric applications combined under the heading 'Functional Materials' (FM). The Reduced Activation Ferritic Martensitic (RAFM) steel EUROFER97 is considered the baseline structural material on account of its maturity [31], serving as a general purpose material for all breeder blanket options [30]. Similarly, for plasma facing armour and divertor heat sink applications, the current baseline materials are conventional tungsten and CuCrZr, respectively [18,37]. However, there still exist significant risks associated with the properties of baseline materials, and therefore the strategy of WPMAT has been to develop 'Risk Mitigation Materials' (RMM) in parallel with the baseline materials, in order to target the specific shortcomings of each baseline option [31]. Regular review of these RMMs is intended to ensure the most promising candidates are taken forward and benchmarked against the relevant baseline.

Within WPMAT, the Advanced Steels (AS) subproject oversees the development of structural RMMs. The intention of AS is to extend the operating temperature window and provide enhanced neutron irradiation resistance beyond that of EUROFER97. In the case of plasma facing and divertor heat sink applications, the High Heat Flux Materials (HHFM) subproject seeks to address key concerns with conventional tungsten and CuCrZr. As with the structural materials, expanding the operating temperature window and improving neutron irradiation resistance are key aims [28]. In addition, plasma erosion and tritium retention are also expected to be critical [38,39], with the former being life limiting. The Functional Materials (FM) subproject covers a diverse range of materials and applications in heating, diagnostic and control systems (details below), and as such there is currently no baseline material for this group. In the following sections the TRA is grouped along the lines of their function and the existing WPMAT substructure: Baseline, AS, HHFM and FM. The specific criteria that each group is evaluated against will be application dependent, leading to significant divergence as materials ascend the MTRL scale. For example, the exact details of what constitutes an operational environment in terms of temperature, heat flux, stress, particle fluxes etc. will vary significantly between applications. For this reason, it is necessary to subdivide MTRL criteria to provide a meaningful assessment, particularly at higher readiness levels. In order to account for this in the MTRL questionnaire, an N/A option is incorporated for use where questions are not relevant to the given application. However, the criteria become progressively more system and design dependent at higher readiness levels, so cannot yet be precisely defined at these higher levels, and may be revised in light of system requirements.

4. Results and discussion

It is important to note that MTRLs, like TRLs, are a snapshot in time, and provide no direct information on past progress or future development. Thus, when comparing readiness levels, it should be remembered that although more mature technologies/materials do represent a lower risk, it is not guaranteed that they will reach level 9 first [40]. This is why it is critical to view MTRLs in the context of other material specific information when considering their prospects. There can be certain 'show-stopper' issues which have the potential to render leading candidates unsuitable despite much initial promise. For example tungsten represents the best available choice for plasma facing armour, thanks to its sputtering resistance, high melting point and low tritium retention [31]. However, at the current stage of development, there is still uncertainty over the effect of neutron irradiation on plasma erosion and a lack of data on tritium retention in the irradiated state, both of which could severely hinder its use [31]. There are also matters related to industrialisation that impose additional risks. At MTRL 5 (see Section 2.5), the scalability of supply must be demonstrated to minimise further risk to development. This represents a major step, and if unsurmountable will render further development pointless. Although formal go/no-go points have not been defined in the MTRL scale, the strategy within WPMAT, as explained in Section 3, involves development of risk mitigation materials (RMMs) at a low readiness level, accompanied by screening programmes to allow rigorous down-selection. The EUROfusion roadmap includes specific gate reviews at the end of the pre-conceptual (2020) and conceptual (2027) design phase as well as an intermediate gate review in 2024, all aiming for the down-selection of designs, which should also aid in down-selection of materials [23].

Fig. 2 illustrates the current MTRL of materials under development within WPMAT. The solid bars indicate the current MTRL of each material. However, given the scope of each readiness level, there can be a loss of granularity, as the assigned MTRLs omit intra-level progress. Therefore, the dashed and shaded bars have been added to illustrate intra-level progress of over and under 50%, respectively. It can be seen that most of the RMMs, optical and dielectric materials sit at a relatively low level (MTRL 2-3), while the baseline materials are more mature, typically sitting at around MTRL 3-4, and showing considerable progress towards MTRL 5 (see Section 4.1). Nevertheless, this would suggest there is still quite some way to go before even the baseline materials will be ready to go into service. However, Fig. 2 also illustrates the wide range of materials currently under investigation, providing a degree of redundancy, as well as potentially superior alternatives to the baseline materials. When interpreting these values it is important to note that the scale is not linear. In general, the time, funding and resources required to move up a level all increase, often significantly, each time a technology element (material) progresses further up the scale [8,10,13]. However, this phenomenon is difficult to quantify accurately, and is likely to vary between different applications and materials [7]. As mentioned earlier, MTRLs cannot provide a complete picture on their own. They are a snapshot in time, and provide little information on previous progress or the likelihood of future success [40]. The following subsections therefore provide some context and background to the underlying justification for the current MTRL values.

4.1. Baseline materials

As Fig. 2 illustrates, the RAFM steel EUROFER97 is currently the most well developed material for structural applications in DEMO (MTRL 4). This relies partly on the legacy of steels in nuclear environments [41], but also the extensive research that has gone into understanding the metallurgy of EUROFER97. It has been well characterised, is the material of choice for the European ITER Test Blanket Module and incorporated into all current blanket and divertor cassette concepts within EUROfusion [30][38]. It is also the first material for which a DEMO Material Property Handbook (MPH) was compiled [42], and benefits from specialized industrial partners involved in development and large scale production. Investigation of welding procedures and fabrication of mock-ups has also been carried out [43–48]. The extension of activity up to Level 5 in Fig. 2 is based on the scale of production (multiple industrial heats) [42,46] and the inclusion of EUROFER97 in recent irradiation campaigns to acquire design relevant data [28,49], complementing a very significant irradiation programme carried out over 2001-2006 [50,51].

For application as plasma facing material, conventionally produced tungsten remains the current baseline material and sits at MTRL 3, although has made significant progress towards MTRL 4. This material has been utilised in component mock-ups for high heat flux testing and is included in at least seven DEMO divertor target concepts [52]. Compilation of an initial MPH has recently been completed [28,53]. However, despite being a commercially available material, these efforts have highlighted an issue with batch-to-batch variability [28,54]. This is currently a barrier to progression to MTRL 4. There is however significant activity up to Level 5, encompassing development of joining techniques (Level 4) [52,55] and irradiation campaigns (Level 5) [28,49].

The baseline material for heat sink applications (CuCrZr) currently sits at MTRL 3, and like tungsten, has also made significant progress towards MTRL 4. CuCrZr is an industrially available material, already set for use as the heat-sink material in the ITER blanket and divertor, and therefore presents less risk from a scalability/supply chain perspective. Experience with this, and similar grades, spans more than two decades. This includes irradiation campaigns (particularly in the US and Russia) and provides a sound basis for anticipating potential 'irradiation life' [56,57]. It has also been incorporated in at least four of the current design concepts for DEMO divertor targets [18,52]. Furthermore, as in the case of baseline tungsten, compilation of a draft MPH has recently been completed [58]. However, there is still a lack of suitable failure criteria for inclusion in design codes, and further irradiation campaigns will be needed in the development of these [18]. Fortunately, some are under way already [28] and investigation of fabrication techniques has made progress [52]. In summary, all baseline materials have been well characterised in the unirradiated condition, covering a wide temperature window and providing a densely populated matrix of properties for the database and MPH. Naturally this statement does not hold for the RMMs of HHFM and AS. They are still under development and thus databases are currently sparsely populated.

4.2. High heat flux materials

As can be seen in Fig. 2, there is a wide range of materials under development within the HHFM category for use as plasma facing or heat sink material. Consequently, various options have been grouped until down selection of specific compositions/process routes is made. The rationale behind each HHFM varies. In the case of self-passivating W-Cr-Y alloys, these were developed to address safety concerns over the formation of volatile radioactive tungsten oxide in the event of air/water ingress. They are expected to be utilised as a plasma facing armour material on the first wall. While they have indeed shown a significant improvement in oxidation resistance, production is currently only on a laboratory scale and the material suffers from reduced duc-

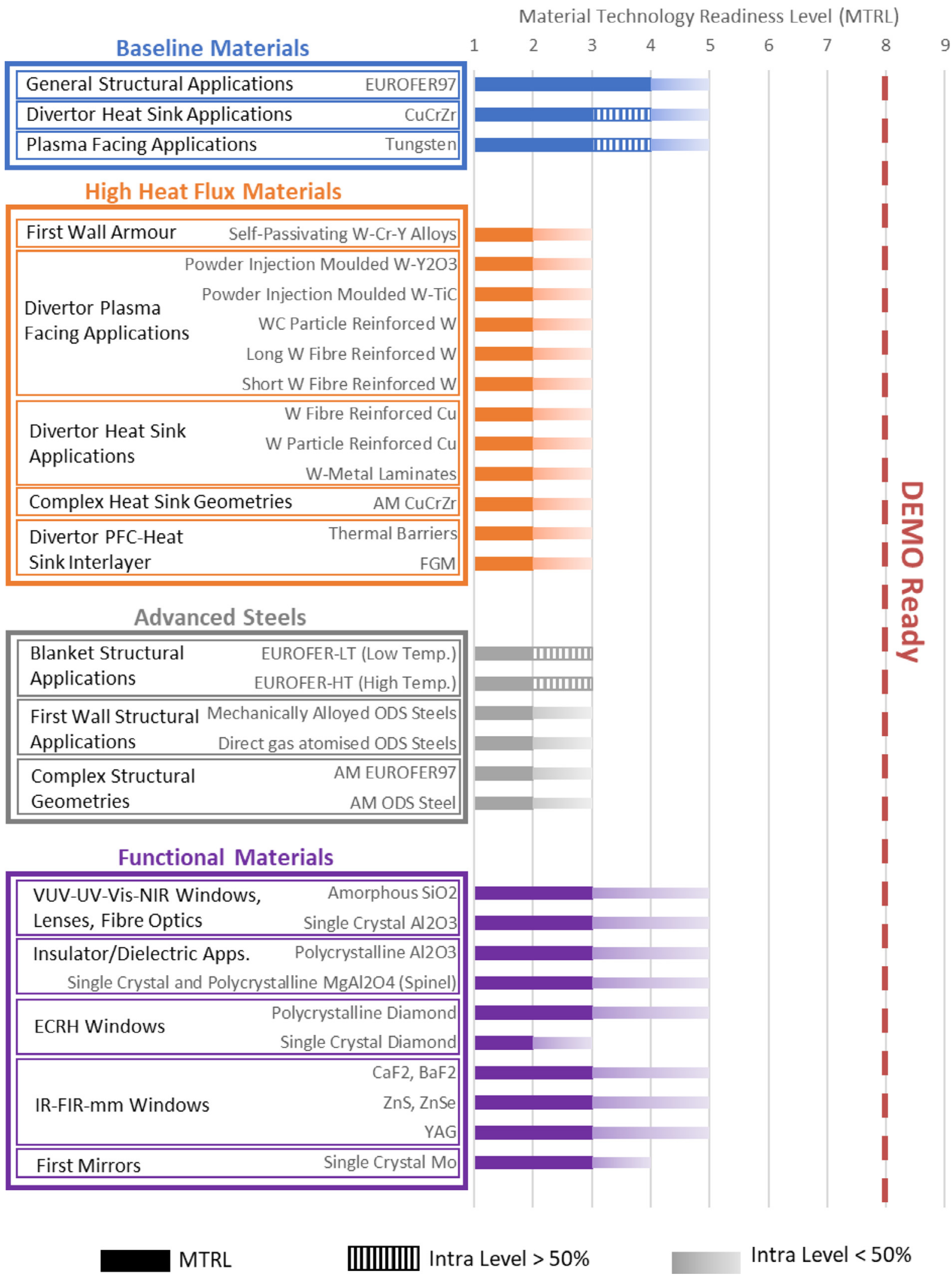

Fig. 2. 2020 MTRL Classifications of WPMAT materials for in-vessel applications. Solid colour illustrates current MTRL, dashed lines indicate intra-level progress over 50% and shaded lines indicate intra-level progress below 50%.

tility relative to other plasma facing materials [28,59]. However, joining techniques are currently under investigation [60] and they have also demonstrated comparable high heat flux behaviour [28]. In spite of this progress, self-passivating tungsten alloys, like the HHFM RMMs in general, lack a comprehensive material property database, and are therefore categorised as MTRL 2, despite the significant promise shown so far.

The operating window for tungsten is currently constrained by neutron embrittlement at low temperatures and concerns over recrystallisation at high temperature. Under certain scenarios, recrystallisation may prove unavoidable, but may be tolerable depending upon the final design [61]. Attempts to expand this window currently focus on alloying or particle/fibre reinforcement. This includes the use of Tungsten-Yttria (W-Y_2O_3), produced via Powder Injection Moulding (PIM), W-TiC also produced via PIM, WC particle reinforced W produced via Spark Plasma Sintering (SPS), long W fibre reinforced W (manufactured through Chemical Vapour Deposition [CVD]) and short W fibre reinforced W (manufactured via SPS) [28]. These sit at various stages of development, but in many cases have shown improvements in mechanical performance over baseline tungsten. However, most are currently only produced on a laboratory scale, although PIM is proven as a mass fabrication, near-net shape technology [62] capable of facilitating two component joining [63]. Of these materials, the PIM W-Y_2O_3, PIM W-TiC, WC particle reinforced W, and both long and short fibre W fibre reinforced W have all been included in recent irradiation campaigns for screening purposes [28,49]. High heat flux testing of the tungsten fibre and particle reinforced composites is also underway [28]. However, as mentioned above, the scarcity of data currently precludes an MTRL 3 classification. This will be addressed after careful down selection, in accordance with the broader WPMAT strategy.

The main objective of the development of advanced CuCrZr materials is an improvement in high-temperature strength of this precipitation hardened material. Of the heat sink candidates, tungsten particle and fibre reinforcement has successfully improved the mechanical properties of Cu based alloys [64]. The fibre reinforced composite has been developed in collaboration with industry and performed well under high heat flux testing [52]. Another approach found to improve ductility is the use of laminates [65]. These have been included in the recent irradiation campaigns for screening, along with the particle and fibre reinforced CuCrZr composites [28,49]. Furthermore, there have also been early studies into the feasibility of Additively Manufactured (AM) CuCrZr components, in order to achieve complex geometries and minimise joints. These have demonstrated the feasibility of the process, but are still at an early stage of development.

With regard to divertor design, another area of concern for the HHFM subproject (and Divertor Work Package), is the interface between plasma facing target and heat sink, due to the mismatch in thermal expansion [66]. Functionally graded materials (FGMs) and specially designed thermal breaks (to spread the heat load more evenly) have been developed as potential solutions [18,66]. Although these and the advanced heat sink materials have all shown promise, the data currently available does not yet approach that of the baseline materials. For this reason, they are presently limited to MTRL 2, pending down selection and further development, in line with the existing WPMAT strategy.

4.3. Advanced steels

Within WPMAT, the Advanced Steels (AS) subproject oversees the development of structural RMMs. There is currently a wide range of alloy compositions and process routes under consideration. These can be grouped into sub-categories according to their respective scope or fabrication process: EUROFER-LT (low temperature), EUROFER-HT (high temperature) [28,67], Additively Manufactured (AM) EUROFER, mechanically alloyed ODS steel (MA ODS), direct gas atomised ODS steel [28] and AM ODS steel. EUROFER-LT and HT aim to expand the EUROFER97 window in the low and high temperature direction, respectively, optimizing their properties for water-cooled or helium-cooled blanket options. Thus far, there has been greater success in extending the upper limit as compared to the lower temperature boundary [28]. However, from a technology readiness perspective, both options benefit from their similarity to conventional EUROFER97, the most mature structural material available. Although property handbooks do not yet exist for these variants, it may be possible to fast-track their qualification in the wake of conventional EUROFER97 development. Upscaling production should not present as much of an issue as some of the more novel materials below, as EUROFER-LT and HT will be produced via conventional industrial practises, rather than powder metallurgy routes. However, even for conventional EUROFER97, qualification is still some way off, so does not circumvent the need for extensive irradiation campaigns and qualification of joints, development of Non-Destructive Testing (NDT), component testing etc. They both therefore sit at MTRL 2, but have made significant progress towards MTRL 3. Their inclusion in the most recent irradiation campaigns [28,49] should also aid in screening and down selection.

ODS steels offer the potential to provide enhanced neutron resistance in particular with regard to He-embrittlement and higher temperature operation relative to EUROFER97, potentially allowing them to complement conventional EUROFER97 in certain high neutron flux applications (i.e. first wall of a He-cooled blanket) [68]. The conventional method of production is mechanical alloying (MA) and has been demonstrated on a semi-industrial scale (on the order of 30 kg) [28]. Fusion welding processes (e.g. laser, electron beam, arc) are unsuitable for ODS steels, as these techniques disturb the distribution of nanoscale oxide particles that are responsible for the enhanced mechanical properties. Diffusion bonding (e.g. HIP) is the preferred joining technique for ODS steel, and is envisaged for its use in first wall applications. However, although MA ODS steel remains a promising high temperature structural material, it resides at MTRL 2 based on its current level of characterisation. Cost and industrial scale fabrication are also typical issues for ODS steels. Attempts to address this include the use of gas atomisation to produce the powder feedstock. However, although this is eminently scalable, the microstructural features and the correlated mechanical performance of ODS steel produced via this route are currently inferior to conventional MA ODS steel [28]. Consequently, gas atomised ODS steel has been classified as MTRL 2. In both cases of AM structural steel (EUROFER and ODS), the properties have been found to be yet inferior to the conventional variants [69,70], and characterised to a lesser extent; thus these materials also sit at MTRL 2.

4.4. Functional materials (optical and dielectric applications)

The functional materials cover a wide range of applications in heating, diagnostic and control equipment e.g. windows, mirrors, electrical feeds, antennas, optics etc. (breeder and coating materials are not covered within WPMAT). Depending on the application, the requirements can vary significantly. Often the primary concern is not a mechanical property, but an optical or dielectric one (however, structural integrity is still important in applications such as windows, particularly under accident scenarios [71]). Understanding the effect of irradiation on such functional properties is critical to their successful use. Consequently, irradiation campaigns for many of these materials have already been carried out. Although IFMIF will not be available for some time, the difference between a fusion neutron spectrum and a fission neutron spectrum is expected to be less significant for many functional materials due to careful shielding at their operational location [25]. In addition, most functional materials are already commercially available, minimising supply chain issues. However, a particular issue with irradiation testing of many functional materials is the need for in-situ testing due to changes in behaviour between exposure and post-irradiation examination (PIE) [20].

Amorphous SiO_2 is expected to be utilised in optical applications (e.g. windows, lenses) for its good Vacuum Ultraviolet (VUV), UV, Visible and Near Infrared (NIR) transmission properties [20]. As a widely available material, supply is unlikely to be a problem, and since it has been well characterised in the unirradiated state, it sits at MTRL 3. As mentioned above, post irradiation characterisation has been carried out, but more integrated testing will be needed to advance further. Currently, there are two primary grades under investigation, produced by TYDEX and Crystaltechno. Among all the studied materials, these silica grades have been found the most resistant to neutron irradiation [72]. Recent EUROfusion irradiation campaigns have also confirmed the superior neutron irradiation resistance of these grades up to 0.4 dpa for transmission in the visible range [73].

Single crystal Al_2O_3 (MTRL 3) is also employed in optical transmission windows, in addition to finding use in dielectric applications [20]. For these uses, it possesses good UV transmission and a very low loss tangent although it does exhibit anisotropy. In addition, suppliers can provide very high purity material, unlike polycrystalline Al_2O_3, where contamination can be a problem (the latter is used as an insulator, rather than in optical applications [20]). Both reside at MTRL 3, pending clear definition of diagnostic tools to be used in DEMO and consequently further integrated testing. Although Al_2O_3 is the primary candidate for dielectric applications in areas such as Heating and Current Drive (H&CD), single crystal and polycrystalline $MgAl_2O_4$ (Spinel) are also under investigation for certain applications (MTRL 3).

Polycrystalline chemical vapour deposition (CVD) diamond is utilised in gyrotron windows, although single crystal diamond is a very recent development (MTRL 2) and could have a direct application in the future. Both variants are the only remaining candidates for this application. However, diamond has been shown to exhibit a dramatic drop in thermal conductivity under irradiation due to phonon scattering. This has implications for DEMO given the power transmission requirements, and will require careful design to minimise exposure. While some initial tests of windows incorporating these materials exist (i.e. including brazing), including some under neutron irradiation (for ITER), this field will need to be developed at higher fluences in future. Although amorphous SiO_2 is currently the favoured candidate for Vis-NIR windows, for the IR-FIR-millimetre range a selection of other materials are under investigation [20]. These include CaF_2, BaF_2, ZnS, ZnSe and Yttrium Aluminium Garnet (YAG). While they all currently sit at MTRL 3, irradiation campaigns and PIE are ongoing. This process has been hampered to an extent due to safety concerns with the fluorides, and activation issues with other materials [74].

In order to reduce the exposure of functional materials to irradiation and particle fluxes, mirrors will be employed in doglegged ducts to prevent direct line of sight between the plasma and sensitive components. The neutron, gamma and Charge Exchange Atom (CXA) particle fluxes at the First Mirror (FM) positions are expected to be an order of magnitude less than those at the FW [20]. Nevertheless, exposure at the FM locations will still be significant, and therefore single or polycrystalline Mo mirrors are currently favoured for their ability to withstand the expected neutron and particle fluxes [20]. For activation reasons, studies have largely focussed on ion irradiation as a surrogate for neutron irradiation. Although this does provide greater testing flexibility, the displacement damage is not prototypical of a fusion neutron spectrum, and penetration of the ions is very low [25]. The material itself sits at MTRL 3, with further progression dependent on the outcome of more integrated testing.

5. Conclusion

A technology readiness assessment has been carried out on materials under development within the EUROfusion Materials Work Package (WPMAT) for the EU-DEMOnstration reactor. The baseline materials have been assigned Material Technology Readiness Levels (MTRLs) of 4 (EUROFER97), 3 (conventional tungsten) and 3 (CuCrZr). In addition, a further 28 candidate materials (and groups of materials) were also assessed. This includes Risk Mitigation Materials that are intended to address specific shortcomings of the baseline materials. These were generally assigned MTRLs in the range of 2-3. This process has highlighted the wide range of materials currently under development within WPMAT in anticipation of stringent down selection. However, it has also brought into focus the many challenges facing DEMO materials development. Much of this concerns critical areas such as in-depth irradiation campaigns, transferability from testing to DEMO operational conditions, scalability of production, development of joining techniques etc. This leaves some way to go before any materials will be ready for use in DEMO. However, the MTRL system has been employed to highlight the key requirements towards utilisation of materials in DEMO, is helping to set the required research and development for each candidate and should be in future an integral part of the TRL assessment of the respective DEMO in-vessel systems.

Key steps that have been taken to address critical areas include the initiation of multiple irradiation campaigns, advanced high heat flux testing of mock-up components as well as the ongoing development of physics based material multi-scale models as a stringent requirement for proceeding towards MTRL 7. Nevertheless, as has been made clear throughout the assessment process, progression up just one MTRL is a significant undertaking, yet still ambiguous in terms of the time and resources required. This represents a significant source of risk, and while the lack of technologically ready materials is clearly a concern for DEMO, the introduction of a biennial review of technology readiness within WPMAT is intended to facilitate more effective planning and targeted materials development, in line with the strategic plans of EUROfusion. The technology readiness assessment procedure itself is still a work in progress, and the requirements at the higher levels will be subject to change as DEMO moves toward the next stage of development, i.e. the development and final selection of the conceptual design. However, it is clear that significant investment will be needed to address the challenges that lie ahead.

6. Data availability

This work was not directly reliant on raw/processed numerical data. In some instances, reference is made to internal EUROfusion reports. For information on their content, please contact the author.

Declaration of Competing Interest

None

CRediT authorship contribution statement

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References

[1] I.T. Chapman, A.W. Morris, UKAEA capabilities to address the challenges on the path to delivering fusion power, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 377 (2141) (2019).
[2] E. Surrey, Engineering challenges for accelerated fusion demonstrators, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 377 (2141) (2019).
[3] D. Stork, S.J. Zinkle, Introduction to the special issue on the technical status of materials for a fusion reactor, IOP 57 (2017).
[4] D. Stork, et al., Developing structural, high-heat flux and plasma facing materials for a near-term DEMO fusion power plant: the EU assessment, J. Nucl. Mater. 455 (2014) 277–291.
[5] “Annex G - TRL Scale,” *Horizon 2020 - work programme 2014-2015*. [Online]. available: http://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf. [Accessed: 05-Jun-2020].
[6] M.S. Tillack, et al., Technology readiness applied to materials for fusion applications, 15th International Conference on Fusion Reactor Materials, 2011.
[7] “International Standard ISO 16290 2013 Space systems. Definition of the technology readiness levels (TRLs) and their criteria of assessment,” 2013.
[8] J.C. Mankins, Technology readiness levels: a white paper, NASA (1995) [Online]. Available https://www.researchgate.net/publication/247705707_Technology_Readiness_Level_-_A_White_Paper. [Accessed: 05-Jun-2020].
[9] US Government Accountability Office, “Department of energy: major construction projects need a consistent approach for assessing technologyy readiness to help avoid cost increases and delays,” *GAO-07-336 report* to the *subcommittee on energy and water development, and related agencies, committee on appropriations, house of representatives*, 2007. [Online]. Available: https://www.gao.gov/assets/260/258104.pdf. [Accessed: 05-Jun-2020].
[10] M. Héder, From NASA to EU: the evolution of the TRL scale in public sector innovation, Innov. J. 22 (2) (2017) 1–23.
[11] US Department of Defence, “Technology readiness assessment deskbook,” 2009. [Online]. Available: https://apps.dtic.mil/dtic/tr/fulltext/u2/a524200.pdf. [Accessed: 05-Jun-2020].
[12] US Department of Energy, “Technology Readiness Assessment Guide,” 2015. [Online]. Available: https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1/@@images/file. [Accessed: 05-Jun-2020].
[13] US Government Accountability Office, “Technology readiness assessment guide,” 2020. [Online]. Available: https://www.gao.gov/assets/710/704769.pdf. [Accessed: 05-Jun-2020].
[14] A. Widdowson, et al., Overview of the JET ITER-like wall divertor, Nucl. Mater. Energy 12 (2017) 499–505.
[15] Australian Renewable Energy Agency, “Commercial readiness index for renewable energy sectors,” 2014. [Online]. Available: https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf. [Accessed: 26-Jan-2021].
[16] J. Straub, In search of technology readiness level (TRL) 10, Aerosp. Sci. Technol. 46 (2015) 312–320.
[17] A. Del Nevo, et al., WCLL breeding blanket design and integration for DEMO 2015: status and perspectives, Fusion Eng. Des. 124 (2017) 682–686.
[18] J.H. You, et al., European DEMO divertor target: Operational requirements and material-design interface, Nucl. Mater. Energy 9 (2016) 171–176.
[19] D. Stork, et al., Materials R&D for a timely DEMO: Key findings and recommendations of the EU roadmap materials assessment group, Fusion Eng. Des. 89 (7–8) (2014) 1586–1594.
[20] S.M. González De Vicente, E.R. Hodgson, T. Shikama, Functional materials for tokamak in-vessel systems - status and developments, Nucl. Fusion 57 (9) (2017).
[21] F. Schoofs, M. Gorley, A route to standardised high heat flux testing: an example for tungsten, Fusion Eng. Des. 139 (2019) 132–136.
[22] S.J. Zinkle, A. Möslang, Evaluation of irradiation facility options for fusion materials research and development, Fusion Eng. Des. 88 (6–8) (2013) 472–482.
[23] EUROfusion, “European research roadmap to the realisation of fusion energy,” 2018. [Online]. Available: https://www.euro-fusion.org/fileadmin/user_upload/EUROfusion/Documents/2018_Research_roadmap_long_version_01.pdf. [Accessed: 05-Jun-2020].
[24] S.M. González De Vicente, J.L. Boutard, S.J. Zinkle, H. Tanigawa, Materials testing facilities and programmes for fission and ion implantation damage, Nucl. Fusion 57 (9) (2017).
[25] D. Stork, et al., Towards a programme of testing and qualification for structural and plasma-facing materials in ‘fusion neutron’ environments, Nucl. Fusion 57 (9) (2017).
[26] H. Tanigawa, et al., Development of benchmark reduced activation ferritic/martensitic steels for fusion energy applications, Nucl. Fusion 57 (9) (2017).
[27] G. Federici, W. Biel, M.R. Gilbert, R. Kemp, N. Taylor, R. Wenninger, European DEMO design strategy and consequences for materials, Nucl. Fusion 57 (9) (2017).
[28] G. Pintsuk, et al., European materials development: Results and perspective, Fusion Eng. Des. 146 (2019) 1300–1307.
[29] A. Ibarra, et al., The IFMIF-DONES project: Preliminary engineering design, Nucl. Fusion 58 (10) (2018).
[30] G. Federici, L. Boccaccini, F. Cismondi, M. Gasparotto, Y. Poitevin, I. Ricapito, An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort, Fusion Eng. Des. 141 (2019) 30–42.
[31] D. Stork, et al., Assessment of the EU R&D programme on DEMO structural and high-heat flux materials, EUROfusion (2012).
[32] M.A. Abdou, et al., Results of an international study on a high-volume plasma-based neutron source for fusion blanket development, Fusion Technol 29 (1) (1996) 1–57.
[33] Y.K.M. Peng, et al., A component test facility based on the spherical tokamak, Plasma Phys. Control. Fusion 47 (2005).
[34] G.M. Voss, et al., Conceptual design of a component test facility based on the spherical tokamak, Fusion Eng. Des. 83 (2008) 1648–1653.
[35] M.A. Abdou, A volumetric neutron source for fusion nuclear technology testing and development, Fusion Eng. Des. 27 (1995) 111–153.
[36] N. Taylor, S. Ciattaglia, P. Cortes, M. Iseli, S. Rosanvallon, L. Topilski, ITER safety and licensing update, Fusion Eng. Des. 87 (2012) 476–481.
[37] F. Crescenzi, H. Greuner, S. Roccella, E. Visca, J.H. You, ITER-like divertor target for DEMO: design study and fabrication test, Fusion Eng. Des. 124 (2017) 432–436.
[38] J.H. You, et al., Conceptual design studies for the European DEMO divertor: rationale and first results, Fusion Eng. Des. 109–111 (2016) 1598–1603.
[39] E. Bernard, et al., Tritium retention in W plasma-facing materials: Impact of the material structure and helium irradiation, Nucl. Mater. Energy 19 (2018) 403–410 August2019.
[40] Nuclear Decommissioning Authority, “Guide to technology readiness levels for the NDA estate and its supply chain,” 2014. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/457514/Guide-to-Technology-Readiness-Levels-for-the-NDA-Estate-and-its-Supply-Chain.pdf. [Accessed: 05-Jun-2020].
[41] G.R. Odette, T. Yamamoto, T.J. Williams, R.K. Nanstad, C.A. English, On the history and status of reactor pressure vessel steel ductile to brittle transition temperature shift prediction models, J. Nucl. Mater. 526 (2019) 151863.
[42] E. Gaganidze, F. Gillemot, I. Szenthe, M. Gorley, M. Rieth, E. Diegele, Development of EUROFER97 database and material property handbook, Fusion Eng. Des. 135 (2018) 9–14.
[43] L. Forest, et al., The European ITER test blanket modules: fabrication R&D progress for HCLL and HCPB, Fusion Eng. Des. 136 (2018) 1408–1416.
[44] J.H. You, T. Höschen, G. Pintsuk, Damage and fatigue crack growth of Eurofer steel first wall mock-up under cyclic heat flux loads. Part 1: Electron beam irradiation tests, Fusion Eng. Des. 89 (4) (2014) 284–288.
[45] J.H. You, Damage and fatigue crack growth of Eurofer steel first wall mock-up under cyclic heat flux loads. Part 2: Finite element analysis of damage evolution, Fusion Eng. Des. 89 (4) (2014) 294–301.
[46] Q. Huang, et al., Recent progress of R&D activities on reduced activation ferritic/martensitic steels, J. Nucl. Mater. 442 (1-3) (2013) 2–8 SUPPL.1.
[47] P. Aubert, F. Tavassoli, M. Rieth, E. Diegele, Y. Poitevin, Review of candidate welding processes of RAFM steels for ITER test blanket modules and DEMO, J. Nucl. Mater. 417 (1–3) (2011) 43–50.
[48] A. von der Weth, J. Aktaa, Mockups of blanket cooling plates manufactured in different diffusion welding setups, J. Nucl. Mater. 386–388 (2009) 437–440.
[49] M. Rieth, “Internal EUROfusion report MAT-6-T002-D001: coordination activities and technical summary and conclusions of the 2018 IRRAD activities,” 2018.
[50] C. Peterson, et al., Mechanical properties of reduced activation ferritic/martensitic steels after European reactor irradiations, 21st IAEA Fusion Energy Conference, 2006.
[51] E. Diegele, “EUROfusion WPMAT RO (retired): personal communication.” 2020.
[52] J.H. You, et al., European divertor target concepts for DEMO: design rationales and high heat flux performance, Nucl. Mater. Energy 16 (2018) 1–11.
[53] M. Gorley, The EUROfusion materials property handbook for DEMO in-vessel components - status and the challenge to improve confidence level for engineering data, Fusion Eng. Des. (2020).
[54] M. Wirtz, et al., Material properties and their influence on the behaviour of tungsten as plasma facing material, Inst. Phys. 57 (2017).
[55] M. Rieth, et al., Recent progress in research on tungsten materials for nuclear fusion applications in Europe, J. Nucl. Mater. 432 (1–3) (2013) 482–500.

[56] M. Li, M.A. Sokolov, S.J. Zinkle, Tensile and fracture toughness properties of neutron-irradiated CuCrZr, J. Nucl. Mater. 393 (1) (2009) 36–46.
[57] S.A. Fabritsiev, A.S. Pokrovsky, D.J. Edwards, S.J. Zinkle, A.F. Rowcliffe, Effect of high-dose neutron irradiation on the mechanical properties and structure of copper alloys and Cu/SS joints for ITER applications, J. Nucl. Mater. 283–287 (2000) 523–527.
[58] K. Zhang, E. Gaganidze, M. Gorley, Development of the material property handbook and database of CuCrZr, Fusion Eng. Des. 144 (2019) 148–153.
[59] A. Calvo, et al., Self-passivating W-Cr-Y alloys: characterization and testing, Fusion Eng. Des. 124 (2017) 1118–1121.
[60] J. de Prado, M. Sánchez, A. Calvo, C. García-Rosales, A. Ureña, Development of self passivating W-Eurofer brazed joints, Fusion Eng. Des. 146 (2019) 1810–1813.
[61] M. Fursdon, J.H. You, M. Li, Towards reliable design-by-analysis for divertor plasma facing components – guidelines for inelastic assessment (part 1: Unirradiated), Fusion Eng. Des. 147 (2019).
[62] S. Antusch, et al., Mechanical and microstructural investigations of tungsten and doped tungsten materials produced via powder injection molding, Nucl. Mater. Energy 3–4 (2015) 22–31.
[63] S. Antusch, L. Commin, M. Mueller, V. Piotter, T. Weingaertner, Two component tungsten powder injection molding - an effective mass production process, J. Nucl. Mater. 447 (1–3) (2014) 314–317.
[64] A.V. Muller, et al., Melt infiltrated tungsten–copper composites as advanced heat sink materials for plasma facing components of future nuclear fusion devices, Fusion Eng. Des. 124 (2017) 455–459.
[65] J. Reiser, et al., Ductilisation of tungsten (W): Tungsten laminated composites, Int. J. Refract. Met. Hard Mater. 69 (2017) 66–109.
[66] C. Linsmeier, M. Rieth, J. Aktaa, T. Chikada, Development of advanced high heat flux and plasma-facing materials, Nucl. Fusion 57 (9) (2017).
[67] J. Hoffmann, M. Rieth, M. Klimenkov, S. Baumgärtner, Improvement of EUROFER's mechanical properties by optimized chemical compositions and thermo-mechanical treatments, Nucl. Mater. Energy 16 (2018) 88–94.
[68] S.J. Zinkle, et al., Development of next generation tempered and ODS reduced activation ferritic/martensitic steels for fusion energy applications, Nucl. Fusion 57 (9) (2017).
[69] C. Koehly, H. Neuberger, L. Bühler, Fabrication of thin-walled fusion blanket components like flow channel inserts by selective laser melting, Fusion Eng. Des. 143 (March) (2019) 171–179.
[70] J. Henry, "EUROfusion WPMAT Report on the coordination activities and technical summary and conclusion of the 2019 AS activities," 2020.
[71] N. Taylor, et al., Materials-related issues in the safety and licensing of nuclear fusion facilities, Nucl. Fusion 57 (9) (2017).
[72] I.I. Orlovskiy, K.Y. Vukolov, E.N. Andreenko, T.R. Mukhammedzyanov, Neutron irradiation of modern KU-1 and KS-4V fused silica, J. Nucl. Mater. 442 (1-3) (2013) S508–S510 SUPPL.1.
[73] D. Cruz, "EUROfusion WPMAT report on optical characterisation (VUV to IR) of neutron irradiated samples," 2020.
[74] R. Villa, "EUROfusion WPMAT report: samples selection and procurement for testing pre-irradiation dielectric properties (testing of dielectric properties of 3 types of Self-doped alumina samples)," 2015.