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The EUROfusion materials property handbook for DEMO in-vessel components—Status and the challenge to improve confidence level for engineering data

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ABSTRACT

The development of a specific materials database and handbook, for engineering design of in-vessel components of EU-DEMO, is an essential requirement for assessing the structural integrity by design. For baseline in-vessel materials, including EURFOER97, CuCrZr, Tungsten as well as dielectric and optical materials, this development has been ongoing for several years within the Engineering Data and Design Integration sub-project of the EUROfusion Materials Work Package. Currently the database is insufficient to ensure reliable engineering design and safety or hazard analysis and mostly does not yet exist in established nuclear codes.

In this paper the current status of EU-DEMO database and handbook for key in-vessel materials is provided. This comprises practical steps taken to obtain the raw data, screening procedures and data storage, to ensure quality and provenance. We discuss how this procedure has been utilized to produce materials handbook chapter on EUROFER97 and the critical challenges in data accumulation for CuCrZr and Tungsten, planned mitigations and the implications this has on structural design. Finally, key elements and methodology of our strategy to develop the materials database and handbook for the in-vessel materials are outlined, including concepts to accommodate sparse irradiated materials data and links to EU-DEMO engineering design criteria.

1. Introduction

The development of DEMOnstration reactors, that prove the scientific and technical viability of fusion reactors, is of paramount importance to realizing commercially viable fusion power for humanity. Within EUROfusion's Power Plant Physics and Technology programme [1] the design of EU-DEMO ranks as one of the world's leading DEMOnstration reactor design endeavors [2]. Within the EUROfusion roadmap to the realization of EU-DEMO [3], one of the most critical parts is the successful engineering of the in-vessel components, chiefly the Breeder Blanket and Divertor components, though the diagnostic and heating system ports should not be forgotten [4–7]. To enable the successful design of these components, principally through a design by analysis process [8], understanding the materials properties within the operational environment is critical.

The determination of in-vessel components materials performance, prior to operation, requires statistically relevant and high-quality materials test data over the operation design window for the components. The organization, collection, collation, quality checking and dissemination of structural, armor, heat sink and optical/dielectric in-vessel materials test data is underway within EUROfusion's Power Plant Physics and Technology programme, in the Engineering Design and Data Integration sub-project of the Materials work package. This is being realised through development of a specific materials database and handbook for these in-vessel materials.

The materials database is a storage medium containing relevant materials test data that had sufficient provenance and quality to be incorporated. The materials property handbook is a summary document, based upon statistically determined and quality checked data from the materials database.

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The EU-DEMO in-vessel components materials property handbook will be the document used by EU-DEMO designers to determine the materials allowables input to the design code/criteria used for engineering design (such as the DEMO Design Criteria [9]). The materials handbook will be required to ensure acceptable design and to justify the structural integrity of the EU-DEMO reactors. The materials property handbook is a critical document required, to different degrees of completeness, within the conceptual design, engineering design, construction and operational phases of the EU-DEMO project. Data base and MPH shall as well serve as basis for future material appendices in DEMO Design Criteria (DDC) or code frameworks.

This paper represents the first dedicated overview of the materials database and handbook development within EUROfusion. We will review the work on the development of the EU-DEMO in-vessel materials property handbook and databases to date; looking at the requirements of the database and handbook. Examine the current status and plans for the materials handbook and database for the key structural (EUROFER97), armor (Tungsten), heat sink (CuCrZr) and optical and dielectric materials considered for the EU-DEMO in-vessel components. This paper represents the first open reviews of the EUROfusion database and handbook developments on Tungsten and Optical and Dielectric Materials. Finally, we summarize the current status and strategy within EUROfusion to obtain the required materials properties to enable the engineering design of EU-DEMO in-vessel components; highlighting the proposed approaches to cover fusion specific properties within EU-DEMO project timeframes and progressively improve confidence in the engineering design.

2. The database

The EU-DEMO in-vessel components materials database is the storage medium which houses all the required materials properties tests data. The data from this database is screened, summarized and collated to form the materials properties handbooks.

Since 2014 the EUROfusion consortium has been developing a materials database for the in-vessel materials. Prior to this date (despite some efforts [10,11]) there was not a dedicated EUROfusion materials database, with previous material test data scattered across different EU-research laboratories and within the open literature.

From the outset of the Engineering Data and Design Integration subproject it was recognized that the long-term goal of the database was to hold materials data of sufficient quality and provenance that it could be used to justify the structural integrity of nuclear components. To support this, the key starting point of the work was development of database schema and templates. The schema and data templates were developed based on previous nuclear materials databases used for fission codes, designed to ensure sufficient quality and provenance of the data to allow design. The schema ensured that all the critically required test data, test parameters and supporting metadata, such as material manufacturer, batch, testing standards applied etc. were captured.

The inherent value of materials data is high, and EUROfusion developed secure online storage process behind secure servers that would enable data access to key collaborators, without open access to any proprietary or sensitive data.

To support pre-conceptual and conceptual design phases of EU-DEMO, it was a necessity to provide as much data as possible on the proposed materials in a ready timeframe. Resultantly significant efforts were placed in collating all available data from existing databases and from open literature. All data obtained underwent a screening procedure to ensure that it had sufficient quality and provenance. This was realized through translation of the open data onto the developed templates. Data with insufficient provenance or quality, as required by the database structures, was rejected. All accepted data was stored in the EU-DEMO in-vessel components materials database, which now provides a single readily extendable source for EUROfusion data (Table 1).

Table 1
Number of data inclusions (materials property data points) by year from EUROfusion for specific materials: EUROFER97, Tungsten, CuCrZr and Optical and Dielectric materials.

Material	#, 2016	#, 2017	#, 2018
EUROFER97	> 1000	> 2500	> 3000
Tungsten	0	> 500	> 2500
CuCrZr	0	0	> 1000
Optical and Dielectric	> 2100	> 6900	> 7400

3. The handbook

The EU-DEMO in-vessel components Materials Property Handbook is the collated and screened materials property data from the materials database. This is summarized to give clear and concise materials properties that can be used to determine materials allowables for design code/criteria analysis [9].

The properties within the materials property handbook are included to enable the design and cover the full operational regime anticipated. Though not exhaustive, as an example, the list of properties currently considered in the baseline Tungsten materials property handbook include: General information, Chemical composition, fabrication, microstructure, Mechanical properties (Stress strain curves, Yield strength, Ultimate tensile strength, Elongation, Weibull parameter, Young's modulus, Poisson ratio, Swelling, Fatigue, Creep, Charpy impact properties, Fracture toughness), Thermophysical properties (Thermal expansion coefficient, Density, Thermal conductivity, Heat capacity, Electrical resistivity, Emissivity, Vapour pressure), Brittle-ductile transition, hardness & recrystallization, Oxidation and corrosion, Fusion-specific properties (High heat flux properties, Neutron transmutation, Plasma-material interaction, Erosion & redeposition, Hydrogen implantation and retention).

Prior to being utilized within the materials property handbook all data within the database undergoes a screening procedure, this process ensured all data included within the EU-DEMO in-vessel components Materials Property Handbook is of sufficient quality to support nuclear component design. This screening procedure was developed to follow the same processes and quality checks as utilized in nuclear fission industry. The full details of this procedure are beyond the scope of this paper, but include critical checks for the provenance and compliance of the materials (manufacture, heat/product form, heat treatment, etc.), testing (e.g. performance to standards), test sample details (orientation, location and method of extraction and production) and ageing condition (for thermal and irradiation aged samples). All this data must be sufficiently available to ensure the provenance of the tests data before inclusion into the handbook.

The materials properties handbook is structured to provide concisely the materials properties required to determine the design limits of the materials. Presently the EU-DEMO in-vessel components Materials Property Handbook is divided into different chapters, where each chapter represents a different material. Each chapter is divided into different sections for the key properties, such as yield strength. For each section the data is summarized and typically provided in a basic table and graphical format. For most properties an averaged and minimal value are provided along with a simplified equation for their calculation within the limits of the data range provided (see Fig. 1). This follows typical conventions for materials handbooks for engineering design and construction projects.

This structure enables designers to readily obtain the key materials properties required to determine the materials allowables to be used within design rules to determine design limits.

The materials database and handbook structures as described here have been applied to key EU-DEMO in-vessel component materials. The current status and plans for the database and handbook chapters for these materials are overviewed in the proceeding section.

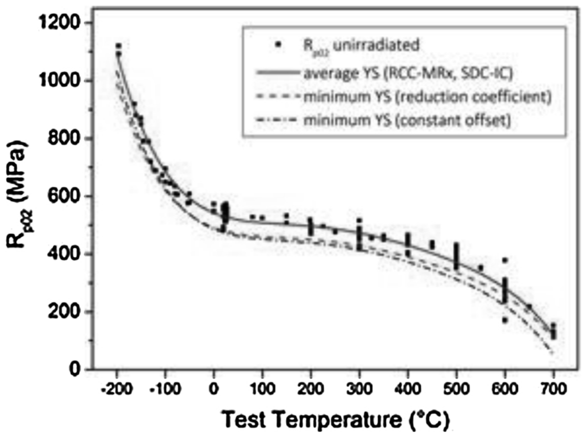

Fig. 1. Graphical representation of EUROFER97 yield strength showing different international accepted methodologies for calculating average and minimum curves, reproduced from [12].

4. Status of the database and handbook for EU-DEMO in-vessel components materials

4.1. EUROFER97

EUROFER97 is a reduced activation ferritic martensitic steel. It is the primary structural material considered for the European ITER Test Blanket Modules [13], the EU-DEMO breeding blankets [4] and the EU-DEMO Divertor cassette [5]. As the main proposed structural material, EUROFER97 plays a paramount part in the structural integrity assessments of the in-vessel components. This is a critical material that must have sufficient quality data to allow for component design.

EUROFER97 is a specialist steel in regards its allowable compositional range, however its manufacture can utilize existing steel knowledge and infrastructure, thus there are limited issues anticipated with mass production of consistent and reproducible EUROFER97 steel. There have been several batches of this materials produced on an industrial (10 s Tons) scale. This has allowed a standard materials manufacturing specification to be developed for EUROFER97.

Within a wider context EUROFER97 is undergoing a codification process within the RCC-MRx nuclear code, to meet the requirements of the ITER Test Blanket Modules [14–17]. There remains work required before this material can be moved from the probationary section of the RCC-MRx code to a fully codified material. This work was advanced under F4E (Fusion 4 Energy) and EUROfusion to support codification of EUROFER97 for the ITER Test Blanket Modules [4].

Presently, EUROFER97 represents the most advanced material in regards development of EU-DEMO in-vessel components materials database and handbook. A dedicated review paper was recently published specifically on this [12]. The present status and development plans are briefly summarized below.

The operational design window for the EU-DEMO in-vessel components go far beyond those of the ITER Test Blanket Modules [4,5,13]. There is significant missing data on the materials performance of EUROFER97 to cover EU-DEMO requirements. Some of the key failure mechanisms for the in-vessel components are anticipated after irradiation ageing and there is insufficient data to date on the neutron irradiation effects on EUROFER97, especially at higher doses, with correct fluence or under fusion neutron spectrum. Where available, neutron irradiated aged data is included within the EU-DEMO handbook chapter on EUROFER97. There is limited data on the interaction of EUROFER97 with proposed coolants and breeder materials, despite multi-material interfaces causing modifying effects on the steel. The welding and product forms are not confirmed for EU-DEMO and the existing handbook chapter only focuses on as manufactured plate and rod materials.

Work is ongoing within EUROfusion to address these issues with long term planning to address all areas and immediate developments on design limiting factors including: i) obtaining materials test data required for the ITER Test Blanket Modules, ii) fission materials test reactor irradiation testing to DEMO relevant levels (up to 20dpa). These represent the key developments to the EUROFER97 database and handbook with the Materials work package of EUROfusion [4,18].

As the EU-DEMO in-vessel components develop, and down select product forms, joining methods and interface materials, significant “technological” materials testing around these areas will be required to ensure the structural stability of the material and structural integrity of the EU-DEMO design. Thus, despite being the most advance in-vessel component material, there remains significant work required for the EUROFER97 handbook chapter.

4.2. Tungsten

Owing to the combination of high H/He plasma ions, high heat flux, high energy neutrons and energetic ions that escape from the plasma, the Divertor and Breeding Blanket components within EU-DEMO require a dedicated “armor” on their plasma exposed surfaces. Due to a range of favorable properties [19] Tungsten is the main armor material considered for the first wall of the breeding blankets [4] and plasma facing targets for the divertor [5]. While this is a primarily functional role the armor needs to retain sufficient bondage to the underlying materials, retain sufficient thermal and mechanical properties and maintain fusion specific interfacing performance (such as plasma erosion and high heat flux stability), to maintain its function. This stipulates the need for reliable and high-quality materials to be utilized, necessitating a materials property handbook chapter to support the engineering designs that utilize this armor material [9].

There is a critical issue that the fusion community needs to rapidly address to have a reliable and reproducible armor material we can use for design. Presently, to the knowledge of the authors, there is no reproducible supplier of high-quality tungsten. This is a significant statement considering tungsten’s proposed use in fusion for decades [20,21]. The result of this is that the materials performance of all tungsten presently produced from key manufacturers can’t be included into any materials property handbook or used for design, as the properties vary significantly from: different suppliers, different product forms and even batch to batch of the same product from the same supplier [18]. An example of this variation can be seen in Fig. 2, when considering just elongation to failure. Recrystallized tungsten shows a clear variation compared to its stress relieved state. The orientation of testing of tungsten bar has a significant effect. Clear difference is also evident between stress relieved tungsten rod and tungsten bar.

A long-term effort is required here and is underway in EUROfusion, linking with colleagues from Japan via the Broader Approach [22]; to work with manufacturers and develop a reproducible and high-quality tungsten with consistent materials performance from batch to batch of manufacture. While this effort is underway it will be several years until this material is being reliably produced and we hold sufficient materials data (including irradiation performance) to incorporate this into a materials property handbook chapter. This is a key focus for the materials work package in EUROfusion.

Owing to the timeframes of EUROfusion design, an interim materials property handbook chapter has been produced to provide designers with a consistent set of preliminary armor material performance data. This has been developed from data sourced on a variety of different Tungsten product forms and different manufacturers, with varying properties accordingly. Depending on the availability, the types of the tungsten products used for allowable calculations was unambiguously indicated throughout the interim tungsten materials property handbook chapter to highlight property variation from different products and allow the designers to select consistent sets of data.

This interim handbook chapter was developed from the screened

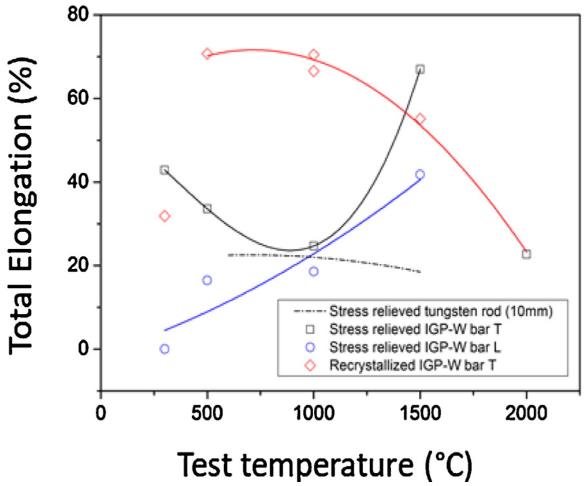

Fig. 2. Total elongation to failure vs test temperature for a range of different tungsten product forms and crystallographic states. Including Stress relieved tungsten rod (dashed black line), Recrystallized IGP-W bar tested in the transverse direction (diamonds and red line). Stress relieved IGP-W bar tested in the transverse direction (squares, solid black line). Stress relieved IGP-W bar tested in longitudinal direction (circles, blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

materials tungsten database, which was based from open literature and EUROfusion laboratory databases. There was insufficient materials data within the developed database to provide full design required materials performance, and presently designers must persist with limited understanding of the full range of anticipated performance; with irradiated tungsten materials data being particularly sparse.

Important progress has been made in the development of the structure of the armor materials handbook chapter on Tungsten. This chapter differed from EUROFER97 with inclusion of additional materials performance sections critical to armor, such as: Tritium retention, oxidation, hardness, plasma erosion and high heat flux performance [23]. These sections were included based on detailed discussions with all designers with interfaces with the armor material to capture all the required performance data.

The inclusion of plasma interaction specific properties highlighted potential difficulties, including a lack of consistent and accepted standards for how to: record, review and summarize the materials performance. As an example, there was no consistent method of recording or indicating acceptable high heat flux performance, negating any method of including the sporadic available data within the armor handbook chapter. To accommodate these issues the materials work package developed standards that would capture all of the key information relating to high heat flux testing and from this developed a new EU-DEMO standard for this data to be included in the handbook; the details of this example work can be found at [24].

There are thus three ongoing developments within EUROfusion surrounding armor materials handbook chapter. First, the co-development with manufacturers, via Broader Approach, of a reliable and reproducible high-quality tungsten which can form the baseline armor material to be considered for EU-DEMO. Second, the development of an interim handbook chapter based on (screened and reviewed) open data on various tungsten forms to allow designers consistent data for preliminary designs. Third, development of the handbook chapter for armor materials to include all required materials performance areas, including plasma interactions specific performance and the subsequent development of standard methods for exposing this data.

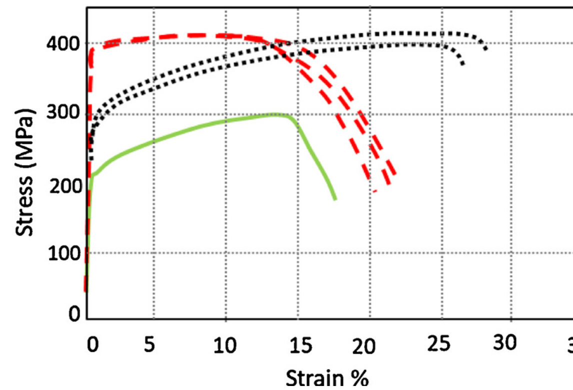

Fig. 3. Room temperature tensile tests of ITER grade CuCrZr after different heat treatments. All data and further details of the heat treatments are found in [25]. The different heat treatments are: Solution annealed and aged data in black (dotted line), Solution Annealed and Cold Worked (Dashed line) and Solution annealed aged and Hot Isostatically pressed and slow cooled in green (solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

4.3. Copper chrome zirconium

Copper Chrome Zirconium (CuCrZr) is considered the baseline “heat sink” material for plasma facing targets of the EU-DEMO divertor. Within present EU-DEMO divertor designs the primary use of CuCrZr is as the water-cooled pipe connected to the tungsten armor to remove the heat from the target assembly [5].

While CuCrZr is a readily available industrial material with consistent and reproducible manufacturing processes, its materials performance is strongly affected by heat treatments [25], as shown in Fig. 3. Within EU-DEMO there remains an open question on the materials properties that are needed for design, or specifically the material condition that should be used to best represent the performance in operation. The different manufacturing procedures for the proposed divertor target assemblies themselves can result in different heat treatments for the CuCrZr that changes its materials properties from the as supplied material condition [26]. It is also recognized that under the operational conditions proposed for the target [5] there will be significant variation in CuCrZr materials properties due primarily to irradiation and thermal effects.

It is likely that the final CuCrZr material condition to be included may need to wait for a down-selection of the target manufacturing technique, to ensure the CuCrZr material condition represents that of the “as manufactured” target assembly condition, with subsequent thermal and irradiation aged effects acting upon this “correct” material condition for start of life of the component. Nevertheless, fundamental properties for most likely failure mechnisms are is urgently needed in a broad range of likely conditions.

Owing to the timelines of EU-DEMO and to support pre-conceptual and conceptual designs, an interim materials handbook chapter on CuCrZr has been produced within the materials work package of EUROfusion. The CuCrZr handbook chapter is based on screened and summarized open literature data that was collated into our database and inclusive of a range of different heat treatment conditions, on ITER grade comical composition CuCrZr [27], to provide the EU-DEMO designs with a set of self-consistent materials property data that can be used. Further details of the interim CuCrZr handbook development and included data can be found in the recent paper [25].

There are several ongoing efforts within EUROfusion related to the heat sink materials handbook. First, the development of an interim handbook chapter based on screened and reviewed data from open literature. Second development of testing campaign requirements to ensure the ready development of a baseline materials handbook, once the material condition for the heat sink material for the divertor of the

EU-DEMO design are determined. This campaign will include thermally and irradiation aged data to incorporate operational changes in the heat sink material.

4.4. Optical and dielectric materials

Within the in-vessel components themselves there will be a range of functional materials associated with diagnostic and heating and current drive activities [28]. These include a wide range of optical and dielectric materials.

The final materials that will be utilized for the various diagnostic and heating and current drive ports is still undetermined with a range of materials under consideration. In many cases these materials may represent safety critical systems, either as they form the only barrier from the plasma to beyond the vacuum vessel (such as port windows in Neutral Beam systems) [29,30], or as their performance may effect plasma control (such as mirrors used for Thompson scattering measurement systems), which itself may hold a safety role in an operational EU-DEMO reactor. It was thus considered important to hold high quality and regulator reviewable properties for these materials.

Within EUROfusion the key initial task was determining the structure required for handbook chapters on these optical and dielectric materials, as the necessary materials performance metrics very significantly from structural materials. Working closely with design teams and the materials teams researching these optical and dielectric materials, database collection processes were started, including development of templates to standardize and provide consistent data for specialized properties, such as optical transmittance. This database formed the basis of interim materials property handbook chapters on optical and dielectric materials that have been produced and released to the EU-DEMO design teams.

The interim materials property handbook chapters on optical and dielectric materials presently cover a wide range of potential materials. Materials data was acquired through dedicated screening and storage of open data, through direct contact with manufacturers and collation of internal EUROfusion research into the materials. The sparse data on the effects of the operational conditions (e.g. gamma irradiation damage) have been actively sought and included, an example of the effects of gamma irradiation can be seen in Fig. 4. The properties included are still limited yet provide the designers with a consistent set of data and collates all the available data into a single location. This represents a critical project orientated step to ensure there is no “loss” of data or repeating of tests. It also holds a key role in supporting future development of these materials by highlighting where data is missing.

The continued development of the materials database and handbook chapters for optical and dielectric materials remains a key work within EUROfusion. This is realized via interactions with materials research and designer teams. Once materials are down selected by the design teams dedicated materials testing campaigns can be developed using the interim handbooks as a starting point for planning and developments.

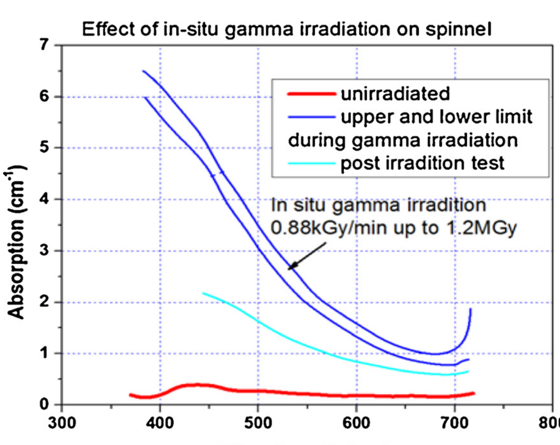

Fig. 4. Absorption vs wavelength of a spinnel material without irradiation (red), post irradiation (teal) and during irradiation (blue). Clearly showing the significant differences of in-situ vs post irradiation performance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

5. Challenges in data collection for EU-DEMO in-vessel components materials

There have been many papers that highlighted the challenges associated with gathering materials properties data for fusion, [9,18,31–35]. Given the significance of these challenges on the development of the EU-DEMO in-vessel components materials database and handbook some, but certainly not all, of the key challenges are highlighted below. Importantly, the presently proposed strategy for EUROfusion to address these challenges are also overviewed.

5.1. Dealing with fusion spectrum irradiation

Neutron irradiation flux is significant in EU-DEMO in-vessel components (see Fig. 5) and has many significant effects on the properties of materials and irradiation aged materials properties must be considered in the materials property handbooks to enable design of EU-DEMO [36].

The synergistic/in-pile effects of mechanical loads, neutron energy, fluence and temperature during neutron irradiation dramatically change the materials properties differently to independent or sequential effects [37,38]. To provide accurate results, tested materials should be subject to the correct neutron fluence, at the correct temperature while subjected to all other interfaces and loads. Without a working fusion reactor, with sufficient space to enable validation testing of new materials and components, gathering materials data that simulates all of these conditions is completely impractical.

The current proposed approach with EUROfusion is to gather sufficient data to allow, engineering sound and scientifically validated, approximations of the materials performance, supplemented with sufficient safety factors to enable a conservative and structurally safe design. This is a common approach within engineering structures, but it still requires significant data to support the scientific cases for approximations of the full environmental operating conditions. EUROfusion is approaching this in several ways, including:

Fission neutron irradiation tests to determine the effects of neutron damage to relevant dpa (displacement per atom) levels [36]. Fission irradiations will need to cover sufficient temperature ranges to

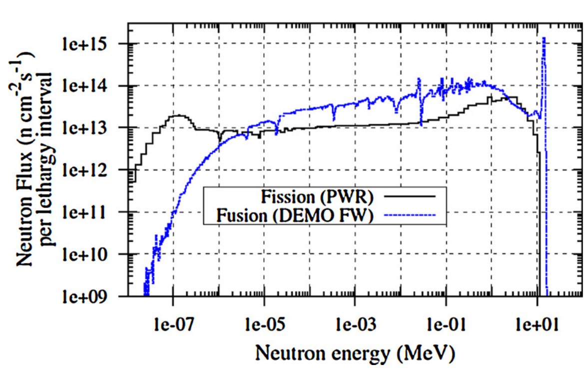

Fig. 5. Comparison of the neutron-energy spectra in fission and fusion reactors. For fission, the average neutron spectrum in the fuel assembly of a pressurized water reactor (PWR) is shown, while the equatorial first wall (DEMO-FW) armor spectrum for the EU-DEMO is representative of fusion. Reprinted from [44], Copyright 2012, with permission from IAEA.

highlight the strongly synergistic effects of temperature on the materials properties under neutron irradiation. It is also critical that relevant fluence level irradiation facilities are utilized to better match fusion irradiation effects. Where no microstructural changes are anticipated in the intermediary conditions, the "worst case scenarios" with highest dpa levels at maximum and minimum operational temperatures can be utilized to reduced initial testing volumes. Selective "in-pile" fission neutron irradiation testing will be used to elucidate synergistic loading effects under neutron irradiation.

Gathering of fusion spectrum neutron irradiation testing. This is considered a critical step to ensure there is negligible, variations in fission vs fusions spectrum effects, that we can't predict, at the dpa levels anticipated for the first blanket and divertors in EU-DEMO [3]. A sparse data set should be possible from one or two tests within EU-DEMO timeframes via IFMIF or DONES systems [39].

The total volume of materials that can practically be neutron irradiated in fission materials test reactors or within in IFMIF/DONES systems is very limited [40]. Thus, we must build up a scientifically valid justification based on sparse and incomplete data sets, while also qualifying and utilizing small specimen test techniques to maximize data gathered [40].

Improving management of incomplete and sparse data sets will be archived by ensuring the engineering tests data is supported by mechanistic modeling of the fundamental effects on materials, as is being considered in the IREMEV sub-project of EUROfusion's materials work package [18] and by incorporating probabilistic statistics and Bayesian logic into our data processing as proposed within the EU-Japan Broader Approach [22,45]

Thus EUROfusion has a multifaceted approach to deal with the irradiation damaging effects including: urgent and critically important work to obtain the substantial fission spectrum irradiation test data from high use of the limited (relevant fluence level) fission materials test reactors, development of predictive modeling to anticipate irradiation damage effects and variations in fission and fusion spectrum on material properties, carefully planning and utilizing the initial fusion spectrum materials test facilities (such as IFMIF/DONES) and incorporation of Bayesian logic into our statistical treatment of the materials test data to minimize uncertainty and ensure that the materials property handbook are always conservative but can be readily improved as new data becomes available.

5.2. *Dealing with complex nature of in-vessel components*

While it is beyond the scope of this paper to provide details of the in-vessel component design (readers are directed to [4–7]), there are some key factors, that we highlight here for the first time, that make the provision of accurate materials properties challenging, as highlighted below.

Owing to the significant and localized heat output from the plasma radiation on the in-vessel components, there are dramatic thermal and neutron fluence gradients within the components. Thus, the in-vessel materials properties must cover a significant range and combination of temperatures and neutron fluences.

Present in-vessel components designs propose a vast array of weld types and multi-materials interfaces, including interaction with coolants and breeder materials. All of these different welds, joints and multi-material interfaces affect the materials properties. Future codification of the materials may require specific joint and multi-material interfaces to be tested and validated to enable engineering designs to incorporate for these distinct areas.

The novel nature of the fusion in-vessel components necessitates the development of new design rules [9,31]. New design rules may require validating with engineering materials test data; these new design rules may necessitate new or advanced materials properties to be acquired, as an example true stress true strain data [41] is a potentially important property to accommodate design beyond yield, yet this will required additional test data, often utilizing specialist facilities to ensure accurate collection.

Although the host country is not determined the EU-DEMO plant will likely be a nuclear licensed facility and in-vessel components will fall within regulations of pressurized equipment and of nuclear code compliance [42]. Code compliance generally has a strict legal definition and may impose stringent requirements on the amount and relevance of the materials data collected.

The costs, size, complexity and lack of relevant testing theaters for full scale mock-ups of these in-vessel components, also imposes a design by analysis process, rather than a design by experiment process [43], for the EU-DEMO in-vessel components. Thus, sufficient materials tests data is required to support engineering design by analysis process in advance of component construction and operation.

Generally, the complexity, novelty of the materials and integrity requirements of the in-vessel components imposes a significant materials testing "volume" and often very specialized materials testing campaigns to gather the relevant data. Obtaining the full spectrum of test data is not presently available or readily achievable.

The vast test data needs are being accommodated pragmatically within EUROfusion by focusing testing on the key failure modes anticipated for design and or design limiting materials performance factors first. This is designed to enable confidence in engineering design in preliminary stages. This pragmatic approach is supported with integrated views of the needs of DEMO, realized via strong interactions with component designers, safety specialist etc. Long term planning to cover DEMO design limiting areas, such as verification tests for inelastic design rules and irradiation modification effects are targeted. Joining, corrosion and interface effects that are not design limiting are being considered only after a down-selection of concepts for the in-vessel components, this and many other efforts are minimizing the testing required to enable focused work that ensures viable materials allowables are provided for the EU-DEMO designers in a timely manner.

6. Conclusions

Within the EUROfusion programme there has been and remains dedicated work on the development of a database and handbook for the in-vessel components: structural, armor, heat sink, optical and dielectric materials. Significant work has been placed into the development of the required infrastructure around the database and handbook. Within the EUROfusion programme there has been developed: dedicated data templates, data storage mechanisms, data collection procedures, data screening procedures, standardization of data for key fusion specific materials properties (such as high heat flux performance).

None of the key materials discussed have sufficient data to cover the anticipated EU-DEMO operational conditions. Owing to the challenges of the EU-DEMO in-vessel components operational and environmental conditions there is a vast gap in the available materials test data. To accommodate the timeline and project practicalities of the EU-DEMO programme a pragmatic approach was developed. Initially data was gathered, screened and disseminated in a standardize manner from open literature and available existing databases to provide designers with as much early data as possible. Where key failure mechanisms from the design are identified, target testing is progressed to readily obtain these results. Tests on joints and materials interfaces, where possible, are postponed till down selection of components to minimize testing requirements. To accommodate fusion neutron spectrum irradiation effects and mitigate the effects of potentially sparse data, analogous fission irradiation testing, predictive modeling and Bayesian logic is applied to support the determination of materials allowables to be utilized in design.

Materials Handbook chapters or interim chapters have been developed for the key structural (EUROFER97), armor (tungsten), heat sink (CuCrZr) and optical and dielectric materials for the in-vessel components of EU-DEMO.

EUROFER97, is a reproducible, industrially manufacturable material with sufficient data to be included in RCC-MRx nuclear code. There remains very significant data gaps to cover the operational conditions for EU-DEMO, but plans are developed to gather much of this data needed for the conceptual design.

Tungsten manufacturability has shown significant materials property variation with no acceptable supply, thus there presently exists no “baseline” tungsten within EUROfusion. Significant work is required to obtain a reproducibly manufacturable tungsten of sufficient quality to form the baseline materials for EU-DEMO. Work is ongoing, with the Broader Approach, to develop this material. An interim handbook based on varying tungsten types has been produced to provide consistent data for preliminary engineering design. A large testing campaign will be implemented once a baseline material is available.

CuCrZr is a readily available industrial material. However, its properties are affected by the manufacturing conditions for the Divertor target assembly. Thus, the final materials condition to form the baseline testing, and upon which subsequent aged (thermal and irradiation) data should be gathered, is uncertain until a final manufacturing rout is determined. An interim handbook chapter has been produced covering ITER grade chemical composition CuCrZr with a range of thermo-mechanical processed conditions to provide the EU-DEMO team with consistent data to support preliminary design.

Optical and dielectric materials are critical to the diagnostics and heating and current drive ports. Significant work has been performed to develop templates and an interim handbook chapter that incorporates the required materials properties for these components. Given uncertainty on the final materials that will be utilized this interim handbook chapter contains a range of materials of interest to designers to provide them with self-consistent data, upon which to further develop. Given the potential safety criticality of these materials and components it is important to hold high quality, high provenance and statistically significant data on these materials.

The developed materials databases, containing the raw tests data of sufficient quality, feeds into the materials property handbooks. The handbooks are utilized to derive materials allowables that enable the design by analysis process for the realization of EU-DEMO design. Overall there has been significant work on the development of the materials database and handbooks. These form the basis of the preliminary design of the EU-DEMO in-vessel components. Staged completion of the handbook for the design phases of EU-DEMO requires vast testing campaigns supported by modeling, implemented in a timely manner. This work forms a critical part of the realization of the EU-DEMO project and our fusion powered future. Yet significant work remains within a very short timeframe to realise the materials allowables for the operating conditions of EU-DEMO.

CRediT authorship contribution statement

Michael Gorley: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Visualization, Supervision, Project administration, Funding acquisition, Writing - review & editing. **Eberhard Diegele:** Conceptualization, Methodology, Investigation, Data curation, Supervision, Project administration, Funding acquisition, Writing - review & editing. **Ermile Gaganidze:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing. **Ferenc Gillemot:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing. **Gerald Pintsuk:** Conceptualization, Validation, Investigation, Data curation, Supervision, Project administration, Funding acquisition, Writing - review & editing. **Frank Schoofs:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing. **Ildiko Szenthe:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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