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DEMO structural materials qualification and development

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ABSTRACT

This work addresses an overview of the recent progress, associated risks and development plans of structural materials for in-vessel components (IVCs) in DEMO plants. Reduced Activation Ferritic Martensitic Steels form the primary structural materials for most DEMOs IVCs and will be the focus of the paper.

An overview of EU- and J-DEMO programs RAFM steels developments is presented. We highlight the present status in their development for use in DEMO plants, with a focus on the structural materials' operational, and project-oriented, requirements. The development of materials property handbooks from high-quality data is illustrated. A process to validate these steels for operation in DEMO IVCs is summarised, revealing the pragmatic procedures ongoing, and limitations of this approach due to the synergistic operational effects on IVC materials; the use of in-situ or surveillance monitoring is outlined as a method to accommodate this limitation in synergistic effects and allow confidence in future DEMO operations.

The development of advanced modifications to F82H and EUROFER are highlighted, with minor modifications leading to improved low and high-temperature operational design space being open for DEMO reactors.

1. Introduction

Within the fusion community, we have a vast array of challenges to address toward the realisation of demonstration fusion reactors (DEMOs) that provide the scientific and technical basis for commercial fusion power plants of the future. This paper overviews the current status, cutting edge advancements and development steps for one of these key challenges, the development and qualification of the Structural Materials for the In-Vessel Components.

Within this paper, we will only cover the Breeding Blanket [1] and Divertor [2] as these represent the largest in-vessel components, and we will focus on the R&D programs for the Japanese and European Union DEMO reactors (J-DEMO and EU-DEMO) [3–5].

1.1. Operational requirements

A multitude of papers exist regarding the range of challenges of the structural materials for DEMO in-vessel components [6–10], for simplicity, we present here a non-exhaustive list of the key requirements of the structural materials for the DEMO breeder blankets:

- Compatibility with heating and current drive components.
- Compatibility with vacuum conditions.
- Tolerance to significant thermal gradients.
- Acceptable total mass.
- Erosion tolerance if plasma surface exposed.
- An operational temperature that matches required primary coolant temperatures.
- Coolant compatibility: water, liquid metals, etc.
- Breeder and multiplier material compatibility.
- Joinability to dissimilar materials, weldability.
- Compatibility with remote handling (rigidity, decay heat/irradiation on shutdown).
- Meeting lifetime performance requirements – fatigue, creep, corrosion, etc.
- Designable to required codes and standards.
- Manufacturable to acceptable tolerances.
- Compatibility with diagnostics components.

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- Resilience to fusion spectrum neutron damage.
- Meeting lifetime activation requirements.
- Compatibility with high magnetic fields.
- Acceptable tritium retention, permeation and diffusion.
- Tolerance to disruptions, runaway electrons, etc.
- Tolerant to gas production (He and H transmutation products).

While all of these requirements must be met, and must be met synergistically, the effects of fusion neutron irradiation and related transmutations are unprecedented elsewhere and represent the most complicated challenge to address [11].

1.2. "Project" requirements

Beyond the operational requirements for the structural materials for DEMO IVCs, there are also a host of more project-orient challenges that need to be addressed, a similar non-exhaustive list of these project oriented challenges include:

- Mass production.
- Quality assurance.
- Cost (R&D/qualification, raw material, final products).
- Reactor licensing.
- Waste limitations.
- Lifetime monitoring and inspection.

Finally, it is also critical for the fusion community to recognise that we must realise DEMO reactors and the subsequent commercial fusion reactors fleets, at a sufficiently fast timeline, to contribute to the current climate challenge recognised within the R&D funding around the globe [12–14]. This timeliness is perhaps most important remits surrounding the fusion community, it imposes a significant challenge to the development and qualification of structural materials and is recognised by the set timeframes for a range of DEMO reactors around the world.

Notable for this paper, Table 1, shows the timelines for the EU- and J-DEMO concepts of operation within 2050s. Although no certain timeframes have been set this 2050s operation will "likely" imply site selection and construction in 2040s, Engineering design phases and validation of components within 2030s, which means the conclusion of the conceptual design phases and selection and verification of the structural materials within 2020s.

1.3. Paper overview

This combination of unprecedented operational requirements of the structural materials, coupled with the project-oriented challenges (most notably the timeline for the realisation of DEMOs) provides our fusion community with a complex challenge in materials selection, development and qualification.

Based on many years of research and sound principles, most notably the availability of high quality (and quality assurance) production, manufacturing and inspection [19], the selected Structural Materials for EU- and J-DEMO IVCs are Reduced Activation Ferritic / Martensitic (RAFM) Steels [20,21].

This paper will overview RAFM steels, focusing on F82H and EUROFER (the Japanese and EU reference RAFM steels respectively). In section 2, we overview the current status of these materials. In section 3, we propose a procedure for the validation of these steels for use within a DEMO IVC environment, giving a spotlight on the use of Bayesian analysis and in-situ/surveillance monitoring techniques. In section 4, we overview the cutting edge development of novel variants of these steels. In section 5, we draw conclusions for the role of these steels' qualification and development within our fusion community.

Table 1
Provides approximate time frames for the operation of various proposed fusion reactors that aim to address the scientific and technological challenges of fusion power as a pre-cursor to commercial fusion power plants (DEMOs and their equivalents) [15–18].

Approximate timeline for net power-producing fusion power plants	
EU – DEMO (EU)	2050s
JA-DEMO (Japan)	2050s
K-DEMO (Korea)	2050s
CFETR -> DEMO (China)	2030s-2040s
US-DEMO (US)	2050s
Private endeavours (SPARC, ST-F1, DaVinci)	2020s-2040s

2. Status of DEMO IVC structural materials

Reduced Activation Ferritic/Martensitic Steels have been proposed for use in fusion for over 35 years [48,22], have been the subject of a substantial number of scientific reviews [21] and form the proposed structural materials options for the ITER TBMs [23] and EU- and J-DEMO IVCs [20,21].

Due to the substantial volume of scientific literature on these steels, we will not overview their development in this paper, readers are referred to the references above. We provide here new summaries of the status of F82H and EUROFER materials in 2020, where significant efforts have been realised in the development of the associated databases and materials property handbooks for these materials and are reported here first.

Both F82H and EUROFER97 have defined processing and manufacturing route, including chemistry and impurity tolerances. Significant efforts have been placed in gathering data on these steels in recent years. The leading databases for F82H and EUROFER now consist of >3100 and >3500 pedigree data points respectively; each data point has undergone significant screening to ensure it of sufficient pedigree for use (examples of this screening can be seen in [20]). These databases of high pedigree data have been collated into materials property handbooks that can be used to confidently support engineering design.

It is important, in regards the long term validation of these materials, to highlight the timeframe and "costs" associated with some of these tests; notable examples are the creep and ageing tests performed on F82H, see Fig. 1a) and b), where creep tests have lasted over 23 years and ageing data have been performed at over 100,000 h.

F82H and EUROFER are proposed for operational use within ITER TBMs [23] and are undergoing substantial testing and validation efforts now to allow the use, including codification in RCC-MRx for EUROFER [26] and Nuclear Particular Material Appraisal for F82H [27,28].

These data to date are primarily (but not exclusively) related to non-irradiated and base metal (excluding corrosion, joining, multi-material interfaces) conditions. The performance limits of the materials after representative operational conditions, including irradiation, corrosion, creep-fatigue, etc., must be addressed to validate the engineering performance of these steels, yet obtaining this data represents a significant challenge towards qualification [footnote[1]].

Thus the 2020 status of these RAFM steels is: substantial volumes of high pedigree data are collated, Materials Property Handbooks for F82H and EUROFER97 are available, preparations for the inclusion of these materials in codes needed for ITER TBM operations are ongoing, yet there is still relatively limited data on irradiated or synergistic operational effects.

[1] Within the context of this paper "qualification" is a generic term representing the documentation and quality assurance steps needed for the DEMO projects to consider the materials acceptable for use. Those will depend (also) on regulation requirements for IVC. For example, at the time of writing, it is not known, if this requires acceptance within a nuclear code or not. Due to the complexity of this subject will not be discussed further within this paper.

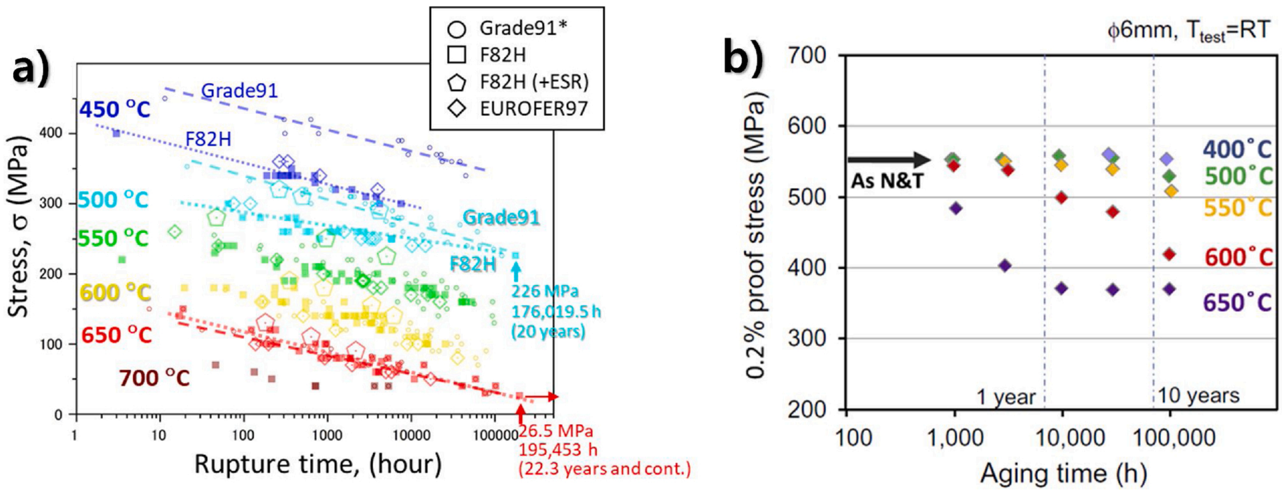

Fig. 1. a) creep life for various RAFM and Grade 91 steels at various temperatures, b) yield strength vs aging time for F82H RAFM steel at various ageing temperatures [21,24,25].

3. Processes to gain validated operationally representative performance data of RAFM steels for DEMO IVC environments

Of the significant developments required to validate the use of RAFM steels for DEMO IVC environments noted in the introduction, understanding the effects of fusion spectrum irradiation on the materials is paramount and processes to address this are reviewed here.

3.1. Effects of irradiation damage

It is well established that neutron irradiation has substantial effects on the performance of materials, notably hardening and embrittlement [11] as illustrated in Fig. 2 below.

It can be seen in Fig. 2 with the variation in Ductile to Brittle Transition Temperature (DBTT) of the curve, irradiated at 250−340 °C, and the rectangle, irradiated at 400−450 °C, that temperature has a substantial synergistic effect on the performance alteration of the RAFM steels.

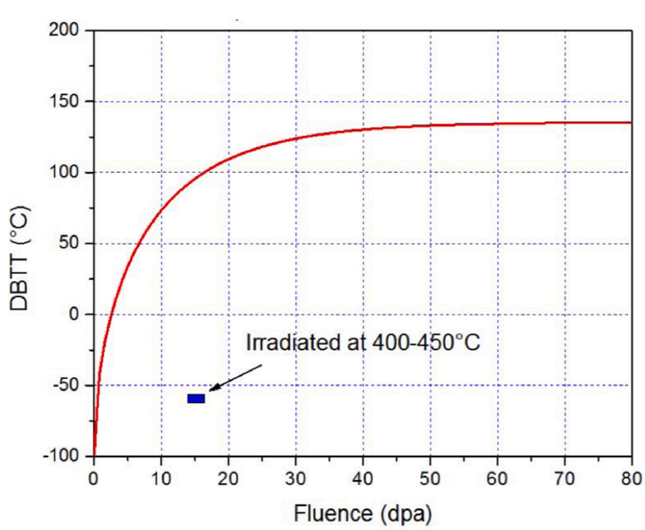

Fig. 2. show the change in Ductile to Brittle Transition Temperature (DBTT) of EUROFER97 as a function of the fission neutron irradiation fluence (dpa) obtained on KLST specimens irradiated at 250-340 °C. The blue point (rectangle) represents KLST specimens after fission neutron irradiation but irradiated at 400-450 °C [20]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

To support this paper we inform readers that in addition to temperature, it is well understood that changes (due to changes in displacement cascades and transmutation rates) in the spectrum of irradiation will change the properties of the materials. It is also recognised that the synergistic effects of stresses, materials form (e.g. initial microstructural state), corrosion and erosion with irradiation will alter materials performance and must be accounted for in engineering design [46].

3.2. Proposed process to evaluate and validate RAFM steels for DEMO IVCs

We present here a simplified summary of the 2020 pragmatic process proposed within J- and EU-DEMO programmes to address this challenge:

1 Develop a comprehensive understanding of the materials in its unirradiated state.
2 Develop a fundamental understanding of irradiation effects via modelling and experimental validation for this material.
3 Develop a database on materials properties after fission neutron irradiation.
4 Combine: Bayesian statistics, fundamental modelling, unirradiated and fission spectrum irradiated data, to predict fusion environment property changes.
5 Validate predictions using fusion spectrum neutrons (e.g. IFMIF-DONES or A-FNS [29,30]).

This process relies on modelling, including fundamental predictive modelling [31] and statistical modelling (most notably Bayesian [32]), to predict the performance of the materials beyond the available experimental data (which inherently can't cover the full operational ranges and conditions).

Bayesian data analysis is a method of data assessment which, instead of producing a single fitted value, produces a distribution of the probabilities of values. This is proposed as it has several potential advantages over more traditional methods of curve-fitting: The output is directly usable with probabilistic design approaches; it provides better results for small datasets, and it highlights the uncertainty of the fitted parameters to be directly measured. These are especially useful for determining which tests would maximise confidence or likelihoods associated with each new test data (maximising the engineering value from each test samples in limited irradiation testing) with these predictions able to support probabilistic based designs and provide high confidence with high uncertainty data [10].

It is recognised that due to the limitation of proposed fusion neutron spectrum materials irradiation facilities [29,30] this process, only validates scientific prediction with respect to combined temperature and spectrum effects. This is exacerbated by the shrinking availability of suitable neutron irradiation facilities of any type, including fission test reactors [46]. Although the experimental assessment and predictions of some synergistic effects are within the fusion community planning (EU and Japan specifically), there is limited practical ability to cover all combinations of operational effects, including but not limited to the synergistic effects of irradiation & temperature & stresses & corrosion & erosion & unpredictable duty cycles, etc.

3.3. *Proposed adoption of in-situ and surveillance monitoring of DEMO IVC materials*

The wider question of importance to the operation of DEMO reactors relates to "how to accommodate real-life performance degradation". At present, this is unknown in the community and must be addressed. It is proposed here that a combination of in-situ and surveillance monitoring may address this question.

A theoretical combination of techniques hypothesised by the authors may include:

1 Embedded and irradiation resistant sensors, such as strain gauges or neutron detectors, with fibre optic or alternative feeds through IVCs to evaluate components and provide real-time data that can be monitored against predicted models. These systems would be targeted to be located close to the front end of IVCs where degradation and changes would be the most significant and unpredictable. However, this would also mean that these sensors would experience high neutron damage far beyond yet acceptable levels and would require a whole new set of materials and components R&D.
2 Rapid removal capsules filled with test samples, akin to those in fission industry (see Fig. 3), set within blanket or divertor cassette bodies, with pipework system, robotic removal and vacuum ports built into components. This can provide periodic higher fidelity validation if early detections from embedded sensors stop operating or show anomalous results compared to prediction. Hereby it has to be taken into account that these capsules have to be actively cooled, requiring a separate cooling system in order to comply with the requirement of rapid removal. This is a question of available space and due to the loss of space, e.g. in the breeding blanket, it will also have an effect on the tritium breeding ratio.
3 Full removal (and replacement) and destructive testing of single IVC sections (e.g. blanket module, divertor cassette) via remote handling systems DEMO reactors are obliged to have. These single sections would need ready sectioning and destructive testing via on-site hot cells. This could provide high-quality data to re-validate and update the engineering design codes and allow continued operation of remaining components (or justify full replacement of all IVC). While this seems as the most likely option, the drawback here would be the required shut-down period of the reactor.

This "monitoring in-depth" approach would yield significant data to support scientific advancements as well as operational justification, likely leading to operational codes for the reactors (such as R5 in UK fission, which has seen extensive life extension of the AGR fleet [47]).

This area needs additional research and is only hypothesised at this point, though it represents a potentially leading methodology to gather this data and allow operation. There is precedence for this approach to the operation of nuclear reactors in the fission industry, see Fig. 3 for an example surveillance cell and in-situ pipe monitoring technique [33,34]. However, there are critical differences in the application of these techniques into fusion reactors compared to fission, some notable challenges for fusion include: the complex geometries of the IVCs, likely limited accessibility within the IVCs, limited spatial availability within IVCs owing to other demands (such as maintaining a high tritium breeding ratio), impracticality of gaining accelerated damage on IVCs (as they are

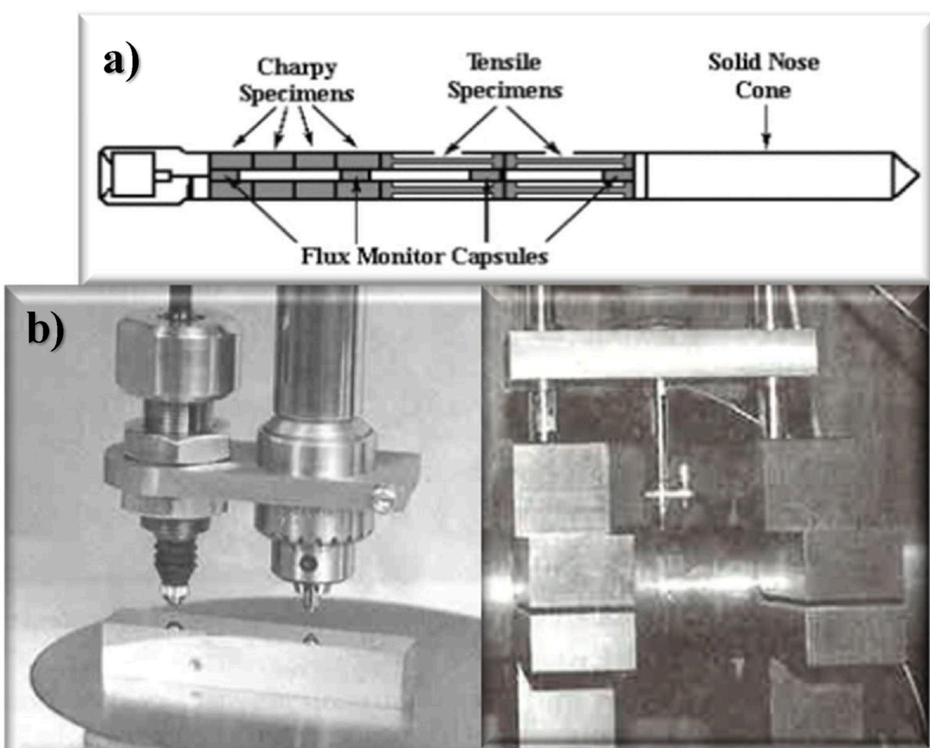

Fig. 3. a) example of surveillance cell use in fission reactors, b) left, example of hardness profile testing technique and right, example of the same testing technique used in-situ on a pipe [33,34].

already as close to the neutron source (plasma) as practical for operations), significantly increased irradiation effects (notably gammas) affecting embedded instruments, need to utilise remote handling tools for in-situ analysis due to high shutdown dose after operations, etc. These and many other areas must be considered in designing in-situ and surveillance monitoring for fusion reactors.

Of the challenges to be addressed in the development of these techniques, the requirement to develop and test and validate these diagnostic sensors and or sample holders within relevant environments is paramount. There are no current facilities that can simulate the environmental conditions anticipated within IVCs, and the planned facilities such as IFMIF-DONES or F-ANS [29,30] have limited availability to be used for validation of these techniques. Thus, a methodology for approval and validation of the in-situ monitoring and surveillance techniques themselves must be developed.

This monitoring process holds a key to an accelerated understanding of the operational performance of our IVCs. The use of these on DEMOs will not only support operational scenarios and lifetime extensions for DEMO but will accelerate scientific understanding we need for the design and operation of our future commercial fusion reactors.

4. Development of advanced RAFM steels

In parallel to the validation and planning steps for the utilisation of F82H and EUROFER97, there are ongoing developments to modify these steels and improve performance. The overarching strategic vision here is to retain the basic structure and advantages of the RAFM steels (existing database, industrial production, manufacturing, inspection and quality assurance procedures) while improving the operational performance. To achieve this overarching vision, subtle modifications are made to EUROFER97 and F82H, such that the performance can be improved in targeted areas while retaining the base performances.

Within EUROfusion, two approaches have been adopted, the reduction in the Ductile to Brittle Transition Temperature (DBTT) targeting the use of EUROER97 within water-cooled designs [35], and increased high-temperature strength, notably creep, targeting He gas-cooled designs [36].

Similar efforts look to modify F82H to enhance performance within the water-cooled designs of the J-DEMO IVCs.

The details of these works are, or will, be reported elsewhere [37–45], we highlight here the methodology and preliminary results to illustrate the significant improvements that are now known to be open to RAFM steel through minor modifications.

4.1. Advanced EUROFER

To accommodate the unacceptably high DBTT (above room temperature) after irradiation at <~300 °C [20], modifications to EUROFER97 were made aimed at reducing the initial DBTT. Efforts focused on the thermodynamical processing of the EUROFER97, an example of this is seen in Fig. 4, where modified thermodynamical processes have shifted the unirradiated DBTT to ~100 °C lower than conventionally processed EUROFER97.

To accommodate the loss of strength at >~550 °C modifications were made to EUROFER97 via changes in chemistry and alterations to thermodynamical processing. A range of alloys have been developed and the initial results are shown in Fig. 5 to illustrate the substantial improvements in creep performance that can be realised via subtle modifications.

4.2. Advanced F82H

To support enhanced operational performance, modifications are being made to F82H with subtle changes in chemistry and thermodynamical processing, including:

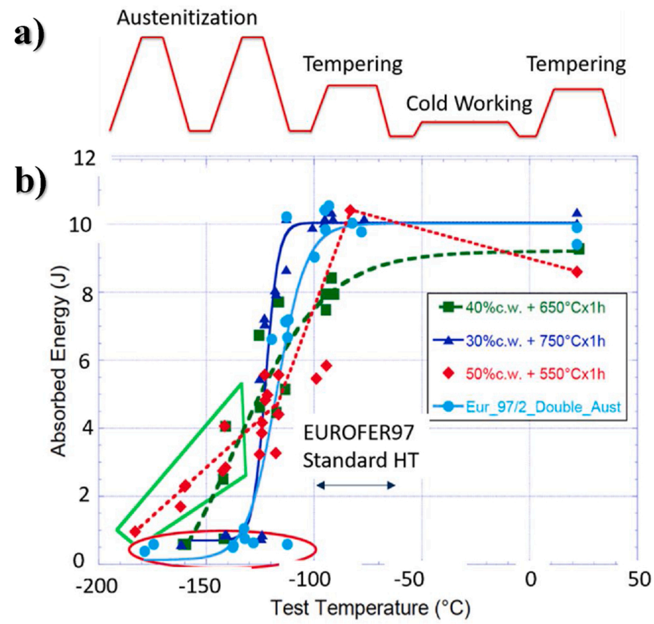

Fig. 4. a) example of a new thermodynamical processing procedure for EUROFER, b) absorbed energy vs test temperatures for new variations of EUROFER that underwent new thermo-dynamical processing conditions showing reduced transition temperatures compared to that of conventional/standard EUROFER97 [37–39].

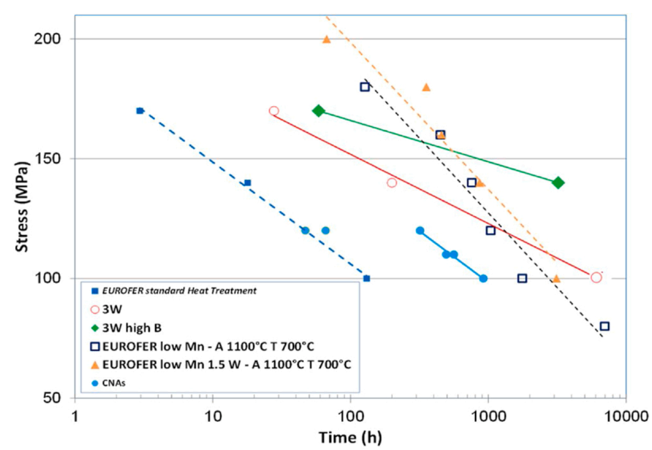

Fig. 5. variation in stress rupture times for various "modified" EUROFER steels, with conventional/standard EUROFER97 included for reference [40,41].

- Limiting [Ti] (<0.01 wt%) could prevent toughness loss [44].
- Increasing target [Ta] from 0.04 to 0.10 wt% makes the impact of deviation of heat-treatment condition insignificant, and it was demonstrated as an effective way to reduce irradiation-induced embrittlement [42–44].
- Increasing [N] to 0.01 wt% with an appropriate heat treatment condition could improve creep strength [44].
- Inducing re-melting process (ESR) was proved to be effective in removing harmful Ta-rich inclusions and improve mechanical properties [45].

These changes significantly improve the operational performances in creep and DBTT as illustrated in Fig. 6a) and b), where we see increased creep lifetimes and reduced DBTT.

These modifications in F82H and EUROFER need to be further tested and verified following irradiation damage. The overarching strategic vision of making only minor modification, however, allows these

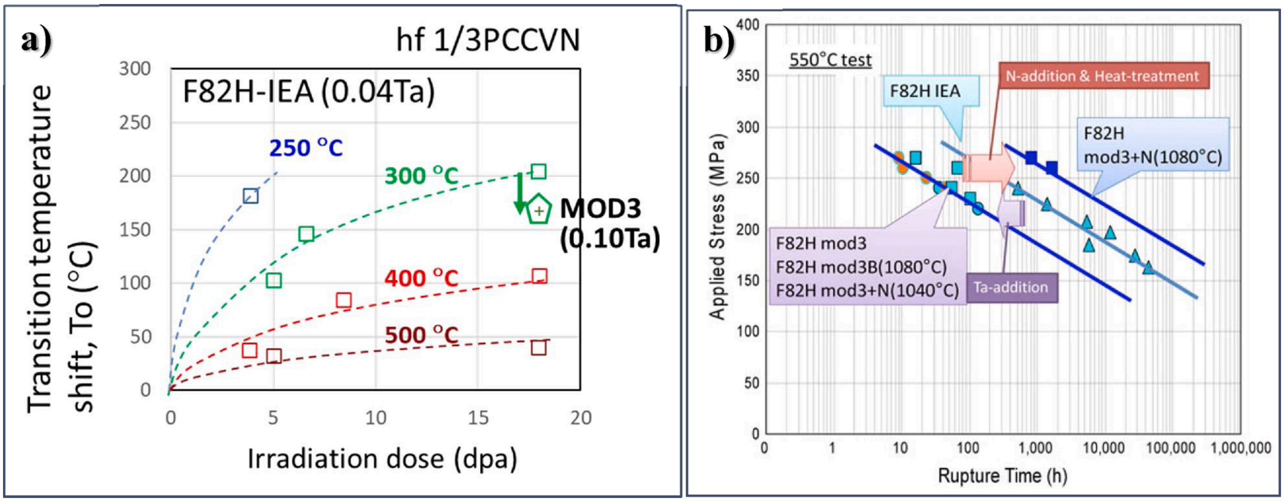

Fig. 6. a) transition temperature shifts vs irradiation dose (dpa) for H82H-IEA and example of shift due to modifications MOD3, with increased Ta content. B) creep strength of various F82H alloys following modifications to conventional/standard F82H IEA grade [42–45].

developments to be made in parallel to the design process and validation of the “conventional” EUROFER and F82H. These modified variants of F82H and EUROFER can be readily adopted later in the design phases of DEMO once the enhanced operational performances of the advanced RAFM steels are verified.

5. Conclusions

DEMO IVCs require structural materials that can retain their structural integrity and rigidity during operations, to enable the functional performance of the components, often facilitated by accompanying materials (breeders, multipliers, armour, coolants, etc.). Understanding the performance of these structural materials is paramount to the successful design and operation of the DEMO IVCs.

The DEMO IVC structural materials must operate under unprecedented environmental conditions and must be developed to meet the needs of the DEMO projects, including the timelines of the EU- and J-DEMO programmes targeting operation in 2050s.

To accommodate all of these challenges, reduced activation ferritic/martensitic steels have been selected as the candidate materials for the EU- and J-DEMO IVCs (blankets and divertors), owing to their potentially acceptable operational performance and the high-quality industrial production, manufacture and inspection available to RAFM steels.

There has been great progress in recent years to develop materials property handbooks, built upon high pedigree data, on F82H and EUROFER97. This progress should be celebrated for the success it represents, however it is recognised there is substantially more work required to validate the materials operational performance, most notably the need to understand fusion spectrum irradiation damage and the synergistic effects this has with other operational conditions (notably temperature and stresses).

A process is proposed for the validation of RAFM steels for DEMO IVCs that includes: 1. Develop a comprehensive understanding of the materials in its unirradiated state. 2. Develop a fundamental understanding of irradiation effects via modelling and experimental validation for this material. 3. Develop a database on materials properties after fission neutron irradiation. 4. Combine: Bayesian statistics, fundamental modelling, unirradiated and fission spectrum irradiated data, to predict fusion environment property changes. 5. Validate predictions using fusion spectrum neutrons.

It is noted that the end goal of this plan is to have predictive models, supported by statistical models to provide confidence integrals, on the operational performance of these structural materials (including fusion spectrum irradiation), however, there will be highly limited data on the synergistic effects of fusion spectrum irradiation and temperature with other stresses, corrosion, multi-materials interfaces etc. To accommodate this in-situ / surveillance monitoring approach to DEMO reactor operation were proposed as a potential avenue.

Finally, we highlighted developments of advanced/modified F82H and EUROFER97 RAFM steels. These advanced steels are premised around minor modifications to the conventional steels that target specific performance improvements. We highlighted the improvements in DBTT and creep strength that has been achieved through minor changes in thermodynamical processing and chemistry. While additional works are required to verify these enhancements are retained after irradiation and have no detrimental effects, they illustrate the improvements that can be made to these RAFM steels.

RAFM steels represent the primary candidate for EU and J-DEMO IVC structural materials and the leading options for the timely realisation of the designs. There remain significant uncertainties on their operational performance, notably on the waste legacy and synergistic effects of fusion spectrum irradiation, temperature and stresses. However, there is a development plan for these RAFM steels to allow their operation and ongoing advancements to improve their operational design window. With the overarching positions highlighted in this paper, for the rapid realisation of EU- and J-DEMO concepts, continued support and substantial developments in RAMF steels are needed.

Declaration of Competing Interest

The authors report no declarations of interest.

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