DEMO Structural Materials Qualification and Development

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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 focus on the structural materials' operational, and project orientated, 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.

Keywords: Structural Integrity, RAFM steels, DEMO, Engineering Design, In-vessel Components, F82H, EUROFER

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.
- 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.
- 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 orientate challenges that need to be addressed, a similar non-exhaustive list of these project orientated challenges include:

- Mass production.
- Quality assurance.
- Cost (R&D/qualification, raw material, final products).
- Reactor licencing.
- 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, in order 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.

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 (SPARK, ST-F1, DaVinci)	2020s-2040s

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].

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 orientated challenges (most notably the timeline for 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 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.

2. Status of DEMO IVC structural materials

Reduced Activation Ferritic / Martensitic Steels have been proposed for use in fusion for well over 20 years [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 references above. We provide here new summarises 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.

2.1 Data and handbooks for F82H and EUORFER97

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 consists 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 Figures 1 a) and b), where creep tests have lasted over 23 years and ageing data have been performed at over 100,000hrs.

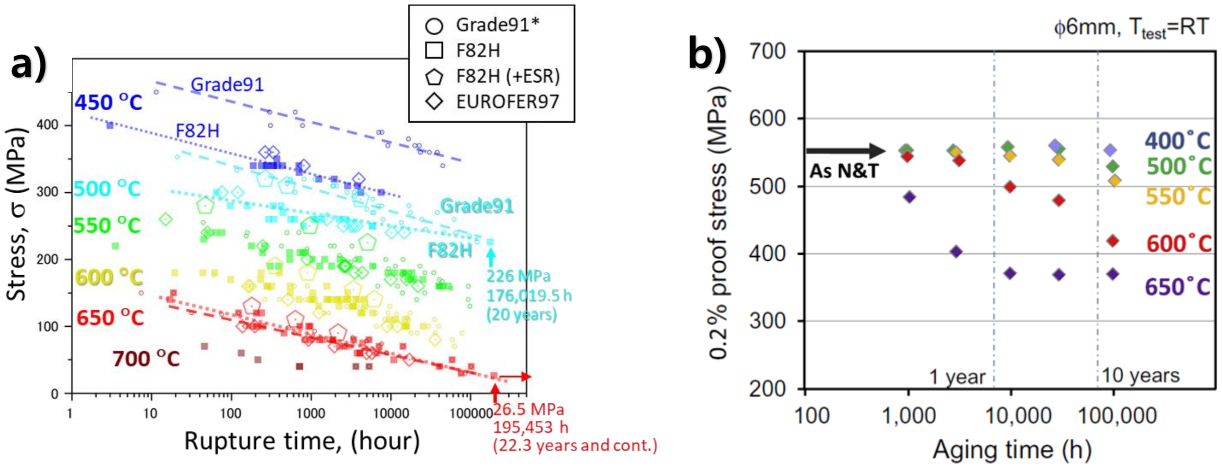


Figure 1 a) creep life for various RAFM and Grade 91 steels at various temperatures, b) yield strength vs aging time for F82H RAFM steel at various ageing temperatures [21, 24, 25].

F82H and EUROFER are proposed for operational use within ITER TBMs [23] and are undergoing substantial testing and validation efforts now to allow 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]].

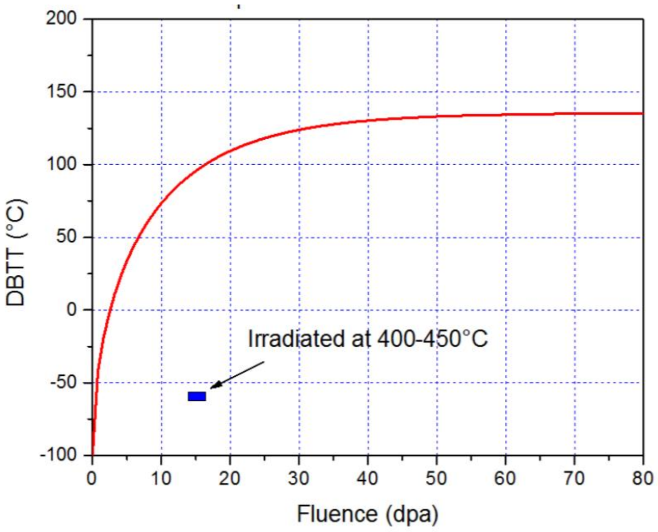
Thus the 2020 status of these RAFM steels is: Substantial volumes of high pedigree data is collated, Materials Property Handbooks for F82H and EUROFER97 are available, preparations for inclusion of these materials in codes needed for ITER TBM operations are ongoing, yet there is still relatively limited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

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 figure 1. below.



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[1] Within the context of this paper "qualification" it 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.

Figure 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].

It can be seen in Figure 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.

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 materials properties. 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.

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 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). The application of statistical modelling should target confidence or likelihoods associated with these predictions to support probabilistic based designs [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. Although the experimental assessment and predictions of some synergistic effects is 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 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 (potentially including removal and replacement of components) represents the leading methodology to gather this data and allow operation. There is precedence for this approach to operation of nuclear reactors in the fission industry, see Figure 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 already as close to the neutron source (plasma) as practical for operations), significantly increased irradiation effects (notably gammas) effecting 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.

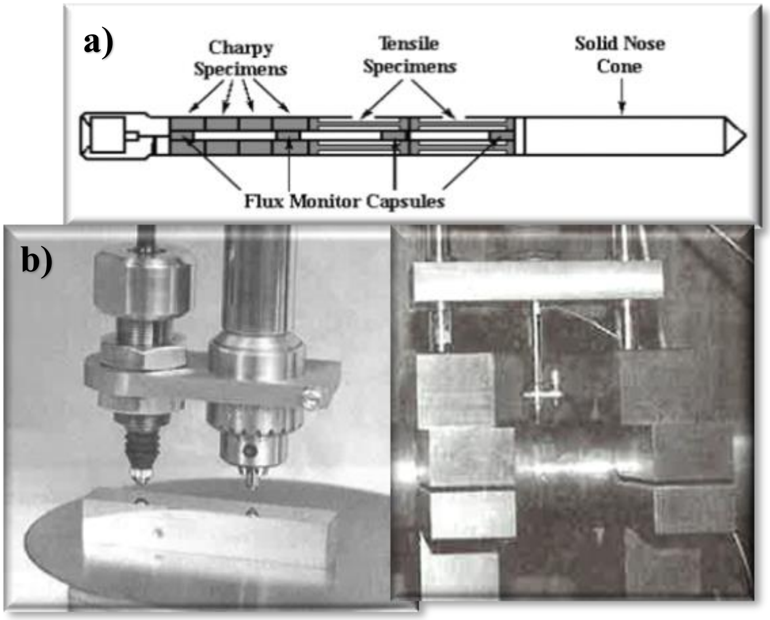

Figure 3 a) example of surveillance cell use in fission reactors, b) left, example of hardness profile testing technique and right, example of the same testing technique use in-situ on a pipe [33, 34].

Of the challenges to be addressed in 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 techniques themselves must be developed.

However, this monitoring process hold a key to accelerated understanding of 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 data base, industrial production, manufacturing, inspection and quality assurance procedures) while improving the operational performance. To achieved 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 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 Figure 4, where a modified thermodynamical processes have shifted the unirradiated DBTT to ~100°C lower then conventionally processed EUROFER97.

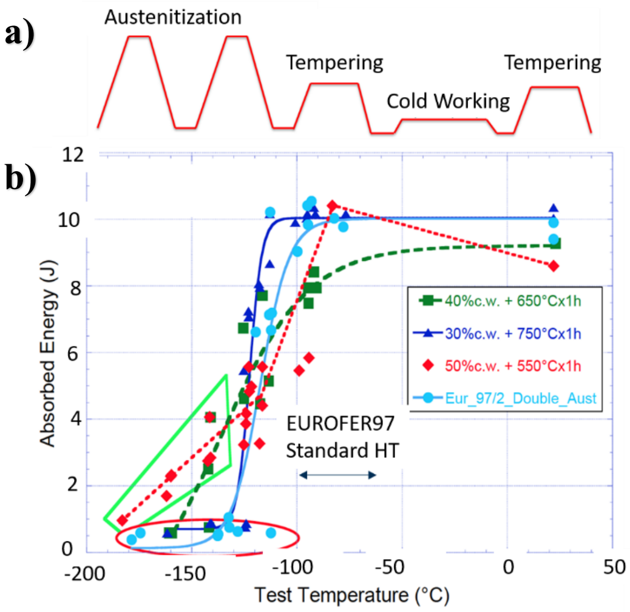

Figure 4 a) example of new thermodynamical processing procedure for EUROFER, b) absorbed energy vs test temperatures for new variations of EUROFER that underwent new thermo-dynamical processing conditions showing reduced transition temperatures compared to that of conventional/standard EUROFER97 [37-39].

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 Figure 5 to illustrate the substantial improvements in creep performance that can be realised via subtle modifications.

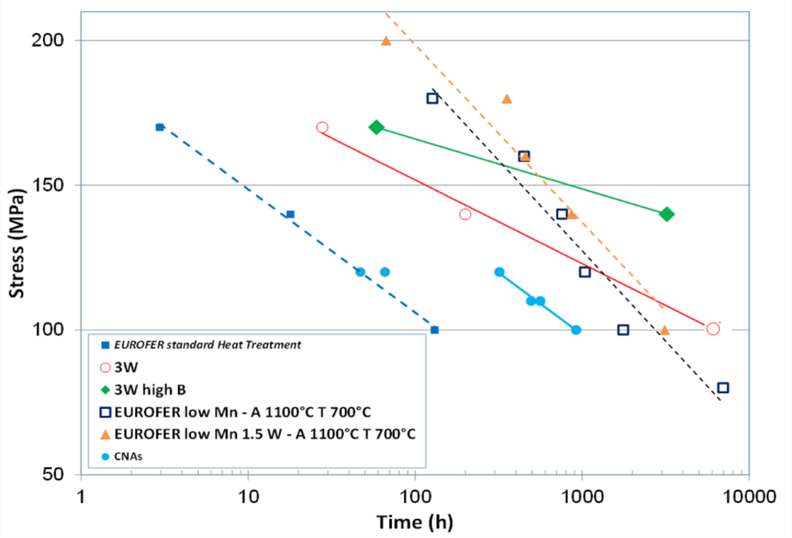

Figure 5 variation in stress rupture times for various "modified" EUROFER steels, with conventional/standard EUROFER97 included for reference [40-41].

4.2 Advanced F82H

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

- 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, 43, 44].
- Increasing [N] to 0.01wt% 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 Figure 6 a) and b), where we see increase creep lifetimes and reduced DBTT.

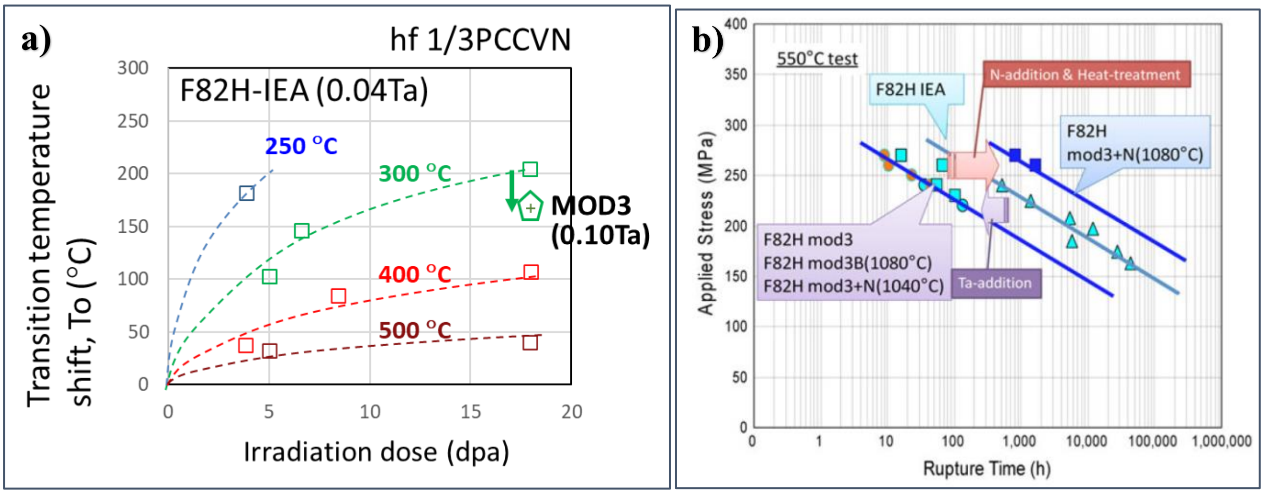

Figure 6 a) transition temperature shifts vs irradiation dose (dpa) for H82H-IEA and example of shift due to modifications MOD3, with increased Ta content. B) creep strength of various F82H alloys following modifications to conventional/standard F82H IEA grade [42-45].

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 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 diverors), owing to there 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, build 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 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 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.

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