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Abstract— **Fusion demonstration (DEMO) concepts are facing challenges in safety and licensing in part due to uncertainties with in-vessel components validation, which relate directly to the materials and design criteria used for assessments. These challenges come from the designed operation under unprecedented environmental conditions and reliance on the performance of complex in-vessel components over time spans of years. These critical components, including the divertor and breeding blanket, will rely on complex structures and multi-material interface that also utilize novel (in regards to nuclear environments) materials. Along with the high operational temperature and fusion spectrum irradiation effects the use of complex components provides key differences in the structural integrity and required design criteria for existing nuclear systems and the DEMO concepts. Overall addressing the challenges in the structural integrity case for fusion requires a new approach to the materials engineering and design interface and design criteria. The current pathways towards development of new DEMO specific design criteria are reviewed, with a focus on current issues and new approaches that are being adopted. Finally thoughts on potential internationalization of new fusion specific design criteria are postulated.**

Index Terms— **DEMO, Design Criteria, Fusion reactors, Materials Engineering, Structural Integrity**

I. Introduction

THE fusion community and fusion research is steadily progressing towards the realization of the ITER reactor [1] but at the same time there are many designs for reactors to proceed on from ITER including Engineering test reactors such as FNFS [2] (US) and CFETR [3] (China) and concepts that will combine the engineering testing along with tritium breeding (self-sufficiency) and providing net electricity to the grid, these concepts are typically called DEMOs [4] [5] [6]. The move towards DEMO reactors bring significant changes when compared to existing experimental reactors such as JET, EAST, LHD [7], [8] [9] and ITER [1] with areas such as increased tritium inventory, high availability & efficient power extraction. These factors necessitates that the in-vessel components and materials must operate for extended lifetimes and within extreme operational environments including high temperatures, significant temperature gradients and irradiation damaging effects. High reliability also necessitates more reliable components designs and critically DEMO devices will almost certainly be nuclear licensed rectors, which impose strict criteria on the structural integrity and safety case for operation.

Within most DEMO concepts the key in-vessel components of the Breeding Blanket and Divertor [10] [11] are not considered part of the primary containment barrier for the nuclear inventory [12] [13] and although this reduces (but will not exclude) regulator safety considerations, the cost and integrity of the in-vessel components to successful operation of DEMO requires a high confidence on the validity of the design and integrity of the in-vessel components [14]. A key aspect to the success of the in-vessel components and key to acceptability by investors and plant licensing will be the materials engineering and design interface. One of the most important aspects to this interface will be the structural design criteria.

Design criteria can be defined as body of rules offering a framework for design validation, supported by relevant material specifications and properties that may be found within the broader body of a code or in isolation [14]. Design criteria cover key aspect of engineering analysis, performed to allow analysis of in-service stress distributions and temperature for component designs. They are designed around rigorously assessed and conservative equations that form metrics to assess potential failure modes, which are compared against permissible values for the relevant structural materials, derived from materials property handbook or validated databases. This collection of allowable and metrics, which structural integrity of designs are assessed, form the structural design criteria.

Design criteria represent a key interface between design and materials engineering, where the allowables are derived

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directly from materials engineering understanding and databases containing knowledge over the operational range and conditions anticipated in the component lifetime and the metrics are defined by acceptable limits to avoid the anticipated failure modes.

Design criteria have been used for decades and across nearly all industries associated with structural integrity, from aerospace, automotive, civil construction to the nuclear industry [15] [16] [17] [18] [19]. The use of design criteria has been a key aspect in the success of the design by analysis approach where the structural integrity of components and design can be validated and accepted primarily on design basis alone, limiting the need for full scale destructive testing. However the unprecedented operational environment anticipated for fusion in-vessel components, such as breeder blankets and divertor, renders all existing design criteria (or codes[1]) inadequate for fusion as they don't account for i) the lack of a comprehensive library of data on the novel materials anticipated to be used, ii) complex 3D geometries and multi-materials interfaces, iii) effects of 14MeV neutron irradiation on the degradation of materials and the associated failure modes due to this.

The effects of the novel fusion environment on structure design criteria was very apparent in the design and development of the ITER reactor in-vessel components, where a new specific design criteria was developed to accommodate some of the issues, known as the ITER SDC-IC [21]. The developments made in the ITER SDC-IC represents very good progress in this area, however due to differences in materials, lifetimes, environmental effects and component designs between ITER and DEMO or commercial fusion reactors the ITER SDC-IC, nor any other existing design criteria or code, will be suitable to assess the structural integrity of the in-vessel components for DEMO or future fusion reactors. The development of new design criteria thus represents a key step in the success of commercialising fusion power.

This paper focuses on elaboration of key shortfalls in applying existing design criteria/codes to DEMO in-vessel components, highlights some new approaches under investigation for developing fusion design criteria and finally summaries with considerations on future international pathways for design criteria within the fusion community.

II. Issues with Existing Design Criteria

There are many concerns and consideration with the use of existing design criteria and codes for fusion that have been elaborated in many reviews [14] [22] [23] [24] [25] [26] [27] here we focus on a summary overview of three key areas including: limitations of fusion materials data, use of deterministic approaches and dominance of elastic analysis methods.

A. Limitation of fusion materials data

Within the context of existing design criteria there is generally a requirement to have sufficient materials data to provide materials allowables that cover the operational temperature and stress conditions over all environmentally modifying factors. To use highly reliable design criteria, as would be preferred for DEMO in-vessel components as they form part of a nuclear licensed site, sufficient provenance and statistical analysis of the materials data would be required. Acceptable levels of materials data to form allowables vary but in typical nuclear codes (such as RCC-MRx and ASME [28] [29] [30]) at least three industrial heats of the material in question should be tested using test specimen that meet acceptable standards, such as ASTM [30] [31], covering all product forms to be used, such as rolled plate or forged rods, tested from the minimum temperature of operation anticipated up to the maximum operational temperature in sufficiently small intervals (typically ~25°C), for all damage types (e.g. cyclic, creep, monatomic loading etc.), with enough repeat tests to get a statistical understanding of the data curves, and repeated to cover all non-negligible modification effects.

In the context of fusion in-vessel components we are typically using novel materials such as Reduced Activation Ferritic Martensitic steels [32] and tungsten or tungsten alloys [33] where there is limited data of the quality required for materials allowable definitions readily available. It would require a significant, but technically non-challenging, volume of standard materials fabrication and testing to establish the materials allowables needed for fusion in-vessel components, if we could ignore the effects of irradiation damage. However to provide materials allowable for the design of in-vessel components the effects of fusion spectrum irradiation has to be considered as this has a significant, non-negligible, modification effect on the materials properties. Resultantly all the testing recommended above, would in an ideal case, be repeated to cover all the difference irradiation conditions anticipated over the lifetime of the in-vessel components.

At present there does not exist any dedicated facilities for the testing of materials under fusion spectrum irradiation and envisioned facilities such as IFMIF [34] will not provide sufficient volumes of irradiated materials to cover a fraction of the required testing in an ideal case. This leaves the fusion community with the challenge of design and operation of DEMOs with, at best, sparse fusion irradiation relevant materials data.

This represents an almost unprecedented challenge and significant technical risk for future reactors, requiring a deviation from existing approaches to the input of materials

[1] A code is a set of rules and recommended practices to assist in the demonstration of regulatory acceptance. Nuclear codes typically include design criteria analysis as well as details on materials procurement, fabrication and inspection. Codes are typically owned by a Standards Development Organisation and often are required to be applied/followed by law for construction, e.g. use of parts of the ASME code for construction of nuclear reactors in USA *[20]*.

allowables into design criteria as the raw materials test data will not be available.

B. Deterministic analysis

Key existing nuclear design codes and design criteria (e.g. ASME, RCC-MRx, SDC-IC, etc.) follow a deterministic approach. The current deterministic or quasi-deterministic approaches rely on a combination of minimum values of materials properties and engineering metrics based on bounding data. As an example in SDC-IC the statistic treatment of the materials values requires the calculated allowable does not exceed 97.5% of the sample set with a 95% confidence level [21], thus the allowable to be used represents a single bounded value based on accepted (but not interrogated) minimum property values, with little to no consideration on the nature of the scatted in the materials data.

This approach looks to provide a simple pass/fail to designs based on bounding data intended to ensure negligible failure probability. Despite the high utilization of this deterministic or quasi-deterministic approach in many industries the use of bounding data creates a lack of transparency of the available margins and allocation across operating conditions, materials and loads, preventing a full interrogation of the level of conservatism in a given design. Overall this does not allow for movement of the acceptability of failure due to probabilistic analysis of data and probability of concurrent events, which provides high levels of conservative on designs and becomes overly demanding when the input data is sparse due to required data confidence levels.

A deterministic, or quasi-deterministic, approach to design may be inappropriate for the experimental design of non-safety critical in-vessel components, as the pass/fail nature of the analysis based on bounding data does not account for the statistical nature of concurrent events and does not provide the designers with knowledge of failure sources or flexibility in design.
This area needs to be re-evaluated in the context of the experimental components anticipated in future fusion rectors to determine appropriateness on a case by case assessment. The community should not simply accept the use of deterministic analysis due to its legacy of use.

C. Dominant of elastic analysis procedures

Most of the most relevant existing design criteria/codes including ASME, RCC-MRx and SDC-IC have a preference or requirement to perform elastic analysis to asses designs [21] [28] [29]. Elastic analysis approaches are often inappropriate for complex 3D (often thermal secondary stress dominated) components, such as those anticipated for in-vessel components of DEMO reactors. The inappropriateness of elastic analysis for 3D components comes from the need to use stress linearization and application of plasticity correction factors. Elastic analysis has been favored in older design criteria as although it was often recognized as not representative it requires significantly less computing power than an inelastic analysis, which was a key concern in the past but diminishing in the modern era with vast increases in computing capabilities. Elastic analysis is a typically conservative approach that does not take full credit for the global capacity of components or the material used, yet due to its wide adoption has been established in the mindset of designers and regulatory bodies within the nuclear industry.

Overall Elastic analysis procedures may be in-appropriate and overly conservative for many fusion in-vessel components. Moving away from purely elastic analysis will require a change in mindset of designers and regulators however to ensure alignment with modern (and generally improved) approaches to design criteria, this change away from purely elastic analysis may be a requirement.

III. New approaches to fusion design criteria

There has been recognition for some time that the existing design criteria/codes are in-appropriate for future fusion environments and efforts to improve on existing works and develop new approaches are ongoing within the community [14] [22] [23] [24] [25] [26] [27] [35]. A full summary of all activities is beyond the scope or aim of this paper, instead key and interesting adaptations are highlighted below to give examples of require/potential developments.

A. Multi-scale materials modelling as input data for design criteria

The need for modeling inputs to provide approximations of materials allowable in design criteria, as substitution for unobtainable real materials testing data, look set to become a difficult and challenging reality for the fusion community. This premise is based on a series of credible assumptions, i) regulators, designers and investors will want to have fusion spectrum irradiated data as inputs to the material allowable used in design criteria to evaluate the designs of in-vessel components, ii) there will be insufficient volumes of materials test data and properties under fusion irradiated conditions to provide all the required materials allowables to perform full design analysis under the operational conditions (likely as even with an IFMIF device and acceptability of small scale test technique the total volume of materials properties achievable is still limited [34]), iii) having prediction of materials properties based on fundamental modeling will be accepted (with appropriate conservatism applied) in the absence of reliable test data.

With these assumptions there is a clear need to start evaluating the extrapolation of fundamental modelling of fusion irradiation effect on materials from the micro- and meso-scale [39] to the continuum levels and provide simulated material allowable inputs to finite element based analysis. This approach will rely on modeling efforts being driven by the needs of the design criteria focusing on the most damaging or critically missing materials allowables as precedence. Appropriate conservatism and approximation will need to be utilized to ensure acceptability but this approach can provide key guidance on design limits/lifetimes that can be readily updated and improved as understanding develops. This approach could help establish in-situ surveillance testing requirements that could then validate if the modelling predictions are correct at early stages, in advance of any potential failures, and enable operation of future reactors beyond current knowledge base on real materials responses.

B. Probabilistic analysis

Probabilistic is the term given to data that has uncertainty associated to it. In engineering design, most elements are probabilistic, but with varying degrees of uncertainty. For example, when dealing with load conditions, gravity is probabilistic but with an extremely low level of variability, and the Electro Magnetic loads resulting from disruptions within fusion are also probabilistic, however with a much larger level of variability. In current structural integrity assessments a deterministic approach is adopted where bounding data values are used for probabilistic data, thus providing a large level of inbuilt conservatism.
The probabilistic approaches to engineering design look to address key shortfalls in deterministic analysis and provide engineers with an opportunity to make a risk informed decision to design solutions. A number of different probabilistic design assessment options are available, ranging from partial probabilistic to fully probabilistic. The most established being the Partial Factors approach [36]. This approach has been extensively and successfully used in the Civil Engineering industry for a number of years, and as such now exists in the associated Codes and Standards. This technique has also now made its way into the appendix of EN13445 (Unfired Pressure Vessels) [37]. More advanced fully probabilistic techniques are also gaining traction in the design criteria community with ASME developing a System Based Code that utilizes probabilistic techniques [38].

DEMO in-vessel components will need to be designed using data that have high levels of uncertainty (e.g. loads on disruptions and use of novel and brittle materials). Combined with demanding reliability requirements the design methods could benefit from a risk informed assessment that utilizes probabilistic techniques that can take account of the better statistical treatments of combined data, better approaches to risk assessments and more informed decisions based on reduction or removal of bounding data.

Work is ongoing to evaluate the use of partial factors to make statistically analysis of the risk involved with EU-DEMO component designs and better inform the designers and support fusion design developments. Efforts here are counter to conventional approaches in fission industry but must be evaluated for the non-safety critical and experimental in-vessel components if fusion is to better inform the designs and keep pace with costs saving advances in other industries.

C. Developing/adopting inelastic analysis procedures

To move away from the often inappropriate and conservative elastic analysis, that is required or recommended in many existing nuclear design criteria/codes; dedicated work is on-going to develop new inelastic/elasto-plastic damage assessment rules. The approach is generally to utilize existing inelastic rules where applicable in other design criteria/codes, adapt existing rules or where no adequate rules can be identified or develop new rules with supporting validation testing.

Inelastic/elasto-plastic approaches are often more complex to implement and can require additional materials allowables input data compared to purely elastic analysis, thus care must be taken when reviewing the use of inelastic/elasto-plastic analysis for fusion to ensure that the new procedures don’t require determinately extra materials data or complexities in analysis that can lead to under or over conservatism in designs. However most other advances design driven industries, including aero-space, automotive and civil construction use design criteria dominated by inelastic/elasto-plastic analysis as it has been proved to better represent real outputs and can be readily applied to complex geometries with reduced uncertainty or correction factors.

Inelastic/elasto-plastic analysis represents an important area for fusion design criteria developments that can be readily evaluated by looking at other industries. Sufficient validation testing and evaluations need to be taken to ensure acceptability of the use of inelastic/elasto-plastic analysis but it represents a key area where fusion design criteria can reduced overly conservative analysis and increase design space which can provide much required freedom to designers to develop improved in-vessel component designs.

IV. Summary

The move toward DMEO reactor designs imposes significant changes and challenges on the structure integrity case, in particular for in-vessel components due to the unprecedented environmental challenges, far beyond ITER or any existing system. This requires a new approach to the materials engineering and design interface and in particular requires the development of new design criteria specifically developed for these environmental conditions.

Reviews of the most relevant existing design criteria/codes for fusion indicates key shortfalls that may hamper DEMO in-vessel component designs, including: limitations on DEMO relevant materials data, limitations imposed by use of deterministic analysis and dominance of elastic analysis procedures potentially providing inappropriate and overly conservative analysis.

A review of some developments towards DEMO specific design criteria highlights key progress/approaches that may support the design of DEMO reactors, including: i) adaptation to inelastic analysis by evaluating existing inelastic analysis approaches in other industries, to enable more representative and less conservative designs, ii) evaluation and adaptations to a probabilistic approach to analysis, to capture advances from outside fusion community and to provide designers and engineers more freedom and better risk informed design basis, iii) multi-scale materials modelling to provide simulated input materials allowables to be used in DEMO design criteria assessments, required to mitigate the anticipated sever lack of fusion relevant materials test data.

Overall this paper looks to draw attention to the existing deficiencies in current design criteria/codes and highlight the efforts ongoing to try and solve these issues. It needs to be recognized that on most “roadmaps” to fusion power a DEMO reactors needs to be developed and the design and construction of the DEMO reactor can’t be easily realized without supportive DEMO specific design criteria. Thus on the timeframes for the development of fusion the development of Design Criteria must proceed the final DEMO designs. To realize fusion electricity on the grids in the 2050s (as in the EU roadmap to fusion electricity [4]), work must accelerate within the development of new design criteria to ensure this is available for the DEMO designs.

On an international perspective the design criteria represent a key aspect for the structural integrity case for nuclear licensed sites. In the fusion community the presented requirement to develop new fusion specific design criteria can represent a golden opportunity to look towards development or adoption of internationally accepted design criteria of fusion reactors. Such efforts have started at the Standards Development Organization (SDO) ASME [38] and could be up taken by IAEA or other SDOs however if not supported by the community they will not succeed and we risk independent development of many similar design criteria. Ultimately national variances in design criteria, structural integrity and safety cases would hinder the acceptance of singular commercial fusion reactor designs amongst different sovereign nations. The fission industry adopted nationally independent structural integrity cases during its early stage developments which has caused significant difficulties and added costs in exportation of reactor designs between nations and efforts are ongoing to develop join international codes to mitigate these issues [41]. The fusion community has an opportunity to work internationally to develop new design criteria necessary for the realization of fusion power [40]; this would be a key step in developing internationally accepted fusion reactor designs that could be exported without substantial modification and reassessments that could prove invaluable towards the future uptake of fusion power plants across the globe.

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