UKAEA-CCFE-CP(19)10

M. Kalsey, M. Gorley, P. Smith, D. Samuel

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This paper has been submitted to
2nd International Conference on Nuclear Power Plants: Structures, Risk and Decommissioning (NUPP),
Croydon, UK, 11-12 June 2018

DEVELOPING DEMO DESIGN CRITERIA

M. Kalsey & **M. Gorley**, *UKAEA, UK*
P. Smith & **D. Samuel**, *Wood, UK*

ABSTRACT

There is currently a European collaboration that is working towards developing a Demonstration Fusion Reactor (European DEMO). This project is currently defining the high level plant architecture of a DEMO reactor, whilst developing conceptual design solutions for technically challenging systems. One such area of development is the design of Plasma Facing Components (PFCs). The PFC's are subject to severe load conditions and need to operate in a highly irradiated environment. The unique environment in which these PFC's operate give rise to many through life material degradation unknowns. Collectively this provides a challenge when assessing the structural integrity (SI) of PFCs.

The traditional design codes, commonly used in the Nuclear industry, have been found to be inappropriate to validate the design of DEMO PFC's. Through-life material data for many of the materials used in PFC designs do not exist, and dedicated rules are required to cover the DEMO specific failure modes. Additionally, traditional codes are experience based and have been developed for standard equipment. These codes utilise a deterministic approach to structural design; where experience based safety factors are applied to the design in order to ensure a certain likelihood of failure. If these codes are used for DEMO PFCs, it would not be possible to appreciate the level of risk the design has.

To cover the shortfall in traditional design codes, the DEMO project is developing a set of design criteria specifically for DEMO PFCs. This is referred to as the DDC (DEMO design criteria). This paper highlights the challenges faced when assessing the SI of PFCs. And provides an overview of the developments of both a deterministic DDC that only includes non-linear based design rules. And a DDC that uses a probabilistically calibrated Partial Safety Factor (PSF) approach to assess the SI of DEMO PFCs.

NOMENCLATURE

β	Reliability or safety index
D	Diameter
DDC	Demo Design Criteria
FE	Finite Element
FORM	First Order Reliability Method
I	The total number of variables in the failure function
κ	Polynomial equation coefficient
P	Pressure
P_f	Probability of failure
PFC	Plasma Facing Component
PSF	Partial Safety Factor
R	Resistance
S	Load Effect
SORM	Second Order Reliability Method
T	Temperature
X	A variable in the failure function

1. INTRODUCTION

The international Fusion community (35 nations) is currently developing a new experimental Fusion reactor called ITER. This reactor is a key experimental step between today's fusion research machines and tomorrow's fusion power plants. ITER is currently under construction in France and is expected to be fully operational before 2030.

To realise the benefits from the ITER experiment, the European fusion community has also started developing a conceptual design of a demonstration fusion reactor (EU DEMO). This DEMO reactor is expected to follow in ITER's footsteps, as such, in the European Roadmap [1], it is envisaged that DEMO will demonstrate the feasibility of Fusion by 2050.

This co-ordinated research and development programme includes both European fusion laboratories and industry. The EU DEMO should deliver significant net electrical power to the grid (~100s MWe) for prolonged periods and demonstrate a suitable target availability (~30%).

The development of a DEMO reactor gives rise to significant engineering challenges beyond what has been seen in the existing experimental reactors and what is expected to be seen in ITER. DEMO is required to deal with an increased tritium inventory, provide high availability & efficient power extraction. These requirements translate into needing Plasma Facing Components (PFC's) that must operate in extreme operational environments including high temperatures, significant temperature gradients and irradiation damaging effects. This translates into needing to develop reliable PFC's with very limited operational design data, thus providing a structural integrity assessment challenge.

In the nuclear power plant industry, codes and standards (C&S) provide a means to demonstrate design structural integrity against regulatory requirements.

Historically, nuclear C&S's have originated from and hence served the fission industry. In contrast, the needs of the fusion industry have been secondary with only a limited amount of fusion specific guidance provided. With the increasing momentum from the fusion industry, in particular the initiation of the design and development of DEMO and it's unique needs in ensuring its structural integrity is maintained have been recognized. In response to this, the EUROfusion Consortium has initiated a project to develop a Fusion specific DEMO design criteria (DDC) primarily for PFC's. This paper highlights the challenges faced when assessing the SI of PFCs. And provides an overview of the developments of both a deterministic and a semi-probabilistic DDC.

2. EU DEMO PFC'S

The DEMO reactor shall be a magnetic confinement fusion power plant, often referred to as a Tokamak. At the core of a tokamak is a doughnut shaped vacuum vessel. Inside the vacuum vessel high temperatures and purity are required to achieve the fusion of two hydrogen isotopes, deuterium and tritium, to form products of helium and a neutron with substantial net energy released (~17.5MeV). This high temperature reaction creates a plasma which is confined inside the vacuum vessel by powerful magnetic fields. The purity inside this vacuum vessel is achieved with substantial supporting pumping infrastructure.

The DEMO vacuum vessel is the primary boundary to the radioactive particles within the plasma. This vacuum vessel is protected from the high temperatures and plasma erosion by two critical PFC's.

- Blanket: this component lines the majority of the vacuum vessel. It receives energetic neutrons from the plasma and needs to transfer this kinetic energy into heat that will in turn be converted into electricity via conventional power generation technology. This blanket is also required to breed tritium, thus providing a degree of sustainability in the Fusion reaction process.
- Divertor: this component is located at the bottom of the vacuum vessel. In addition to providing protection to the vacuum vessel, this component provides particle and heat exhaust for the charged plasma particles.

Both PFC components are required to exhaust high power densities though pressurised fluids. These components must maintain their structural integrity while operating in the demanding fusion environment for prolonged periods of time.

3. FUSION CODES AND STANDARDS

C&S provide a consistent means to demonstrate conformance with the required level of structural integrity and hence safety of nuclear power plant. How C&S's are applied varies from country to country. This variation is generally driven by the nations regulatory requirements. In the USA the nuclear regulator defines which Code an Nuclear Facility Owner should conform to. In contrast, in the UK, the Nuclear Regulator places the responsibility on the Owner-Operator to demonstrate compliance with the essential IAEA safety requirements.

Currently regulators are reluctant to provide a clear indication of the required C&S that need to be used for DEMO. This is mainly due to the infancy of the project. In addition, as a site has not yet been identified, it is not clear as to which regulator would need to be engaged.

An indication of the likely licensing regime for DEMO can be gained by using ITER as an example. The French regulator classes ITER as an Installation Nucleaire de Base (INB) and as such it treats ITER in the same way as every other

Nuclear facility in France. It would have been the preference of the French regulator that ITER had used a single Code such as AFCEN RCC-MRx for all of the SSC's. However, there was no single design code available that covers all of the needs of ITER. As a result, ITER used a multi-code strategy [2] to satisfy the unique technical requirements and the differing experience of the participating nations. This multi-code strategy was also supplemented by fusion specific design criteria wherever additional design rules were required. The safety critical areas such as the vacuum vessel was designed to the AFCEN RCC-MRx, with supplementary criteria and a dedicated Fusion specific appendix. Beyond the primary containment boundary, numerous ASME-oriented codes were applied to facilitate familiarity for the international partners and contributors.

For ITER PFC's (referred to as In-Vessel components), a number of unique features restricted the application of existing Codes. These features included complex 3D structures and irradiation effects. For these components a unique and specific design criteria was developed, Structural Design Criteria for In-Vessel components.

Currently DEMO is following in a similar direction as ITER. As such it has initiated the development of the specific Design Criteria for it's PFC's, this is referred to as the DEMO Design Criteria (DDC).

4. DETERMINISTIC DDC

In order to develop a European DEMO, key engineering challenges must be resolved including the development of viable plasma facing component designs. These components have conflicting design constraints and requirements that must be mutually satisfied. In particular, they are required to maintain structural integrity while operating within unique and harsh fusion environment. Currently, existing Nuclear Codes do not meet the needs of the DEMO Fusion community in number of key areas:

- Insufficient coverage of damage mechanisms in end of life conditions.
- Restrictive design space, making it challenging to develop a design solution.
- Insufficient irradiated material data.
- Insufficient coverage of modifying effects.
- Design rules have not been developed for complex 3D structures and modern FEA.

As such it has been recognized that a bespoke approach to design verification will be required, drawing on industry precedence and best practice.

The target for the DDC is to develop a new set of design criteria to enable the design of DEMO plasma facing components (Blanket and Divertor) including unprecedented environmental conditions, going beyond any existing framework.

The development of this DDC initiated in 2014. Following a period of establishment and strategic development it was determined that two separate DDC's were going to be developed on a staggered timeline.

- The first DDC is deterministic, where existing design rules are evolved and developed to reduce the number of pre-mentioned shortfalls. This is summarised in this section.
- The second DDC is intended to utilise more advanced design assessment techniques. This currently takes the form of Partial Factor assessment often found within the Civil Engineering industry. Details of this work can be found in Section 5.

The development of a Deterministic DDC is intended to address the key shortfalls of existing Deterministic Codes. As such it is being developed in the following areas.

4.1 DEVELOPING NON-LINEAR DESIGN RULES

The majority of existing relevant Nuclear Codes & Criteria including ASME, RCC-MRx and SDC-IC have a strong bias towards using an elastic deterministic design assessment procedure [3] [4] [5]. Although, a non-linear assessment route is also available, this is often seen as secondary and difficult to use. Currently within the Fusion industry there is a strong preference to follow the elastic route. However elastic analysis approaches are often inappropriate for complex 3D components, such as the Plasma-Facing components of DEMO reactors. The main reason for this is because the elastic techniques have been developed for pressure vessels. Part of the elastic analysis technique requires through wall stress linearization. The linearization technique is often open to judgement, and when applied to complex 3D structures there is a risk of incorrect application being performed.

In addition, when dealing with highly stressed components that go beyond the elastic behaviour range, an elastic analysis can not accurately predict stresses. In such circumstances, correction factors need to be applied to the results to adjust stress predictions to more accurate levels. This would not be required in a non-linear analysis.

Historically Elastic analysis (rather than non-linear) was preferred as a non-linear analysis would require large amounts of expensive computing power. However, this is no longer the case, modern computers are now capable of handling inelastic analysis with more reasonable run times.

Based on the shortfalls in the elastic analysis route (for PFC's) and the increased availability of appropriate computing power, a decision has been made to only include the non-linear route in the Deterministic DDC. Moving away from purely elastic analysis will require a change in mindset of designers to become open to using inelastic techniques. As part of changing the mindset of the designers, it is important that the DDC provides complete inelastic design rules for damage mechanisms that are easy to apply in a structural integrity assessment.

4.2 ACCOUNTING FOR IRRADIATION EFFECTS

To create effective criteria for fusion reactors, representative irradiation effects is a key facet for high dose PFC's. The end of life condition of PFC's could only be predicted if relevant irradiated physical and design allowable material data is available. Substantial unirradiated and irradiated materials testing campaign across available fission devices is necessary to populate the DEMO material database.

Currently the high cost and restricted availability of irradiated test facilities is proving to be a hurdle in populating the DEMO irradiated material database. In order to overcome this challenge, 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 [6] to the continuum levels and provide simulated material allowable inputs to finite element based analysis. As well as providing a means to populate the irradiated material database, this technique could support the development of new design rules for irradiation induced damage mechanisms such as irradiation induced swelling, hardening and embrittlement.

This approach could also 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.

4.3 DEVELOP EXISTING DESIGN RULES

4.3 (a) Brittle Fracture

Existing brittle fracture design rules protect against non-ductile damage mechanisms. However they provide very limited design space for operation at temperatures below the ductile-to-brittle transition temperature (DBTT) [7]. The development of brittle fracture design rules to cover specific fusion structural materials is an important area, particularly for materials that will be required to operate for significant periods of time near or below DBTT. Current investigations have shown that the inclusion of size effect on brittle failure and utilizing probabilistic approaches [8] could help in extending the design space towards lower operational temperatures.

4.3 (b) Fatigue

Fracture mechanics based assessment techniques (e.g. R6 [9], ASME BPVC Section XI [10], API579 [11]) provide more accurate estimation of in-service performance than the simplistic design rules typically found within structural design criteria. The application of these techniques during the design phase, could provide a useful reduction in conservatism in fatigue assessment. This is particularly important for DEMO in-vessel components where feasible design solutions are not readily available, and any increase in design space would be beneficial. Work has been progressing in this area and a number of crack initiation prediction techniques have been proposed. In addition, fatigue behaviour related to multi-axial stress conditions and residual stress is being investigated with the view of accounting for these effects in the DDC.

4.3 (c) Ratcheting

With high cyclic thermal stress within DEMO PFC's, ratcheting is often a design limiting damage mechanism. The design rules associated with this damage mechanism are being developed to allow for the application of non-linear analysis techniques that account for both cyclic softening and hardening material behaviours. This should provide an opportunity to more accurately predict ratcheting behaviour, and hence allow the designers to be in a better position to make an informed judgment on to how to proceed with the design of a PFC.

5. PARTIAL FACTOR DDC

As previously discussed, traditional design codes, commonly used in the nuclear industry, have been found to be inappropriate to validate the design of DEMO PFC's. These codes are experience based and have been developed for standard equipment. Traditional codes utilise a deterministic approach to structural design; where experience based safety factors are applied to the design in order to ensure a certain likelihood of failure. If these codes are used for DEMO PFCs, it would not be possible to appreciate the level of risk the design has.

The solution to this is to incorporate structural reliability methods to account for the uncertain nature of loads, resistance and other variables. And it is recommended that structural reliability is integrated in the form of Partial Safety Factors (PSFs).

5.1 STRUCTURAL RELIABILITY ASSESSMENT TECHNIQUES

A mechanical or structural component fails when the applied load exceeds the resistance of the component. Structural reliability methods use the probability density functions of both the resistance and load to obtain probability of failure (P_f) through the load-resistance interference. In short, one needs to know the load curves and the resistance curves and keep them widely separated to achieve high reliability by avoiding load-resistance interference.

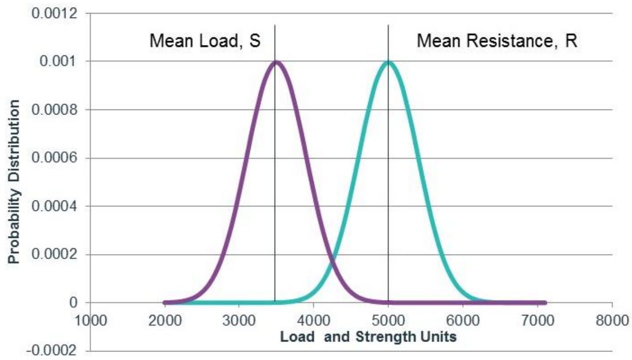

Figure 1: Example Load and Resistance Probability Density Graph

The probabilistic approach is fundamentally the same as the deterministic approach except that the load and resistance are assumed to be probabilistic. Depending on the failure mode being considered, the variables influencing the load and resistance are defined. To account for the variability, partial safety factors are applied to load and resistance to achieve target probability of failure.

There are three levels of structural reliability methods depending on the types of approximations made and the ways in which reliability is calculated [12].

(1) Level-III is an 'exact' probabilistic analysis for whole structural systems in which all design variables are expressed in terms of their full probability distribution functions. It is conceptually straightforward but in practice difficult to formulate and solve as it requires multi-dimensional numerical integration or the use of Monte Carlo techniques. To design a safety related structure or a component with probability of failure less than 10^{-6} it will require tens of millions of numerical simulations. Therefore, Level-III methods cannot be directly used for design.

(2) Level-II methods are used to perform safety checks only at the selected points on the failure boundary (as defined by the appropriate limit state i.e. for a particular failure mode) rather than as a

continuous process, as at Level-III. Level-II methods use means and standard deviations of load and resistance distributions for components and structural assemblies in terms of a reliability or safety index β which corresponds to a notional probability of failure or level or reliability for each failure mode or limit state during the life of the structure. Appropriate PSFs may then be derived for particular design situations. Level-II methods provide the basis for calculating rational PSFs for use in Level-I design codes.

(3) Level-I provides a workable design method in which appropriate safety margins are provided usually on a structural element basis by specifying a number of partial safety factors related to some predefined characteristic values of the basic variables. In the resistance model these values will usually correspond with the 'nominal' values specified in design such as minimum yield, etc. No explicit reliability calculations are undertaken and the levels of risk in different structures are essentially unknown. Design methods involving a number of PSFs are likely to be of much greater practical value than Level-III and II methods.

The approach followed in the Partial Factor DDC is to use the Level-II methods to derive rational PSFs for use in Level-I codes.

5.2 PARTIAL SAFETY FACTOR CALIBRATION

A process for calibrating PSFs has been laid out in the Partial Factor DDC. It is noted in the DDC that the Designer shall calibrate PSFs at the concept design stage that can be used at the detailed design stage. However, prior to PSF calibration, the Designer must be provided with a minimum of the following information:

- Component safety classification;
- Target Reliability;
- Component function;
- Loading specification;
- Material data;
- Statistical information.

The importance of this data is highlighted in the subsections 5.2 (a) to 5.2 (e) below in which the procedure for calibrating a PSF is explained.

A summary of the procedure for calibrating a PSF is as follows:-

- Identify the failure mode and related failure function
- Identify parameters and their ranges and probabilistic distributions
- Use structural reliability methods like FORM/SORM to obtain P_f
- Formulate the failure equation involving load and resistance terms along with PSFs
- Calibrate PSFs to achieve target P_f and codify the equation.

5.2 (a) Identify the Failure Mode

The PSFs differ depending on the failure mode being assessed. For example, the factors calibrated for a Plastic Collapse assessment will not necessarily be the same as those for a Fatigue assessment.

Once the failure mode has been identified it is necessary to determine the failure function. Some failure functions can be found in engineering handbooks, they may be predefined in design codes or can be derived from first principles. However in case of complex geometries and load actions, such closed form failure functions may not be available. Finite Element (FE) analysis allows us to compute solutions for these complex problems.

In order to determine the failure function for a complex FE problem, an approximation of the true failure function must be made.

An example procedure for approximating the closed form failure function is to perform a 2nd order response surface analysis and fit an equation to the surface. The response surface allows the user to understand the sensitivities of the output parameters (results) with respect to the input parameters.

The response surface is obtained by evaluating the load effect for different combinations of the variables. A polynomial is then fitted to the results to form the failure function.

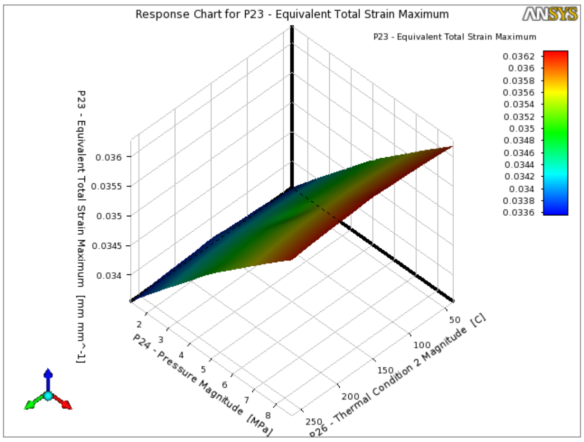

Figure 2: Example Response Surface Graph

The coefficients of the polynomial used for the response surface shall be optimised to fit an equation to the response surface curve. It is recommended to use a 2nd order polynomial without the mixed terms [13]. Eqn (1) is used to solve for the polynomial coefficients.

$$[Y]^T[Y](\kappa) = [Y]^T(S) \tag{1}$$

Where:

- The matrix [Y] contains values of the input data and the input data squared;
- (S) is a vector containing the deterministic solution for each evaluation point;
- (κ) is the vector of the polynomial coefficients.

The failure surface of the component shall be described by two main parts: R, the ‘resistance’ of the component, and S, the ‘load’ term of the component. The failure function shall be described by Z;

$$Z = R - S \tag{2}$$

The resistance depends on the failure mode. If excessive deformation is the reason for failure then R may be the yield or a limit on strain.

The load effect (S) shall represented by the following formula;

$$S = \kappa_0 + \sum_{n=1}^{I} \kappa_n Y_n \tag{3}$$

Where;

$$Y_n = X_i, \qquad n = 1, 2, \dots, I; \ \ i = 1,2, \dots, I$$

$$Y_n = (X_i)^2, \ \ n = I + 1, I + 2, \dots, 2I; \ \ i = 1,2, \dots, I$$

I is the total number of random variables in the failure function and X is a variable in the failure function.

For illustration, the load effect, S, considering three example parameters: Diameter (D), Temperature (T), and Pressure (P) would be the following:

$$S = \kappa_0 + \kappa_1 D + \kappa_2 T + \kappa_3 P + \kappa_4 D^2 + \kappa_5 T^2 + \kappa_6 P^2 \tag{4}$$

The load effect (S) is subsequently used in the calibration of PSFs.

5.2 (b) Identify Parameters and their Ranges and Probabilistic Distributions

It is necessary in PSF calibration to define the part of the code for which the PSFs are to apply, in terms of the range of design parameters and parameter combinations permitted. Parameters can be in the form of a load type, geometrical value or material property.

In addition to this the statistical variation of each parameter must be understood. The fundamental difference between probabilistic and deterministic structural analyses is that the design variables are considered to be random quantities [12].

The statistical data required for each variable, is the mean value, standard deviation, and the distribution type (e.g. normal, log-normal, extreme).

5.2 (c) Use Structural Reliability Methods like FORM/SORM to obtain the Probability of Failure

FORM/SORM methods are used to calculate the reliability of a structure, and hence the probability of failure (P_f), using a formulation based on the mean value, standard deviation, and the distribution type of the design variables.

These methods calculate the 'design point'. This is essentially the value of each variable at the most probably point of failure, effectively the worst combination of variables. From this the P_f can be approximated.

5.2 (d) Formulate the failure equation involving load and resistance terms along with PSFs

There is the potential to calculate a PSF for each design variable. However this can be too many for practical use, and it is sometimes necessary to calculate a reduced set of factors. For example, a failure equation that contains three PSFs can be written as is eqn (5).

$$(PSF)_{Load} \times Load\ Effects \leq \frac{(Strength)}{(PSF)_{Material} \times (PSF)_{Geometry}} \tag{5}$$

5.2 (e) Calibrate PSFs to achieve target P_f and codify the equation.

The final stage is to make the reliability analysis suitable for a design code, which involves calibrating PSFs applicable to a range of designs, e.g. a range of pipe diameters, internal pressures etc. This can be done by calculating PSFs using the 13 step procedure in CIRIA report 63 [12].

It is detailed in the Partial Factor DDC that the Designer shall identify all of the different parameters that shall be considered in the probabilistic calculation. Subsequently the Designer shall define a design envelope, within which the final detailed design of the component shall be located.

Using the 13 step procedure the Designer shall calibrate PSFs to use, such that all the possible combinations of design within the design envelope give at least the target reliability as specified by the Owner.

5.3 LINK BETWEEN COMPONENT SAFETY CLASSIFICATIONS AND PARTIAL SAFETY FACTOR

It is of importance in the partial factor DDC to be able to calibrate the factors according to a required reliability of a component. It is discussed in 6.3 that the designer must be provided with a target reliability index (β) which corresponds to a notional probability of failure or level or reliability for each failure mode. The PSFs are then calibrated in alignment with the selected β value.

The relationship between the reliability index (β) and probability of failure (P_f) is shown below.

Table 1: Relation between β and P_f

Pf	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1.28	2.32	3.09	3.72	4.27	4.75	5.20

The target reliability targets depends on consequences of failure and the costs of improving. Therefore it is clearly linked to the Safety Importance Classification (SIC). It will also be determined by the Limit State and the Load Case Classification (Normal Operation, Fault etc.).

The HSE ONR TAG 003 [14] provides a link between System Class and Probabilistic Targets.

Table 2: Link between System Class and Probability of Failure on Demand

System Class	Probability of failure on demand
Class 1	$10^{-3} \leq P_f \leq 10^{-5}$
Class 2	$10^{-2} \leq P_f \leq 10^{-3}$
Class 3	$10^{-1} \leq P_f \leq 10^{-2}$

Therefore, the reliability values relate to probability of failure, which in turn relates to safety classification of the component.

Thus it is shown that the probabilistically calibrated PSFs are traceable to the level of risk in the design.

Furthermore the advantage of this method is that all failure modes can have a specified probability of failure. It is likely that this is not the case for deterministic design codes where the proposed factors are determined based on experience.

6. CONCLUSIONS

It has been recognized that there is a requirement for fusion specific design criteria to provide guidance for the unique design challenges seen within a DEMO fusion reactor. In response to this, EUROFusion has started developing a design criteria for it's PFC's, this is known as the DDC.

To develop an engineering design solution for a PFC is technically challenging due to extreme and unique environment the PFC's are expected to operate reliably in. As such, the DDC must be able to predict end of life performance of components, whilst removing any unnecessary conservatism hence increasing the design space for PFC's.

The development of two versions of the DDC has been initiated. The first version, is a deterministic DDC, it is intended to develop / evolve existing design rules to suit the needs of a DEMO PFC designer. This lower risk route is expected to be delivered in a time for the conceptual design phase of the DEMO project. Key decisions have been made to ensure that the direction of the DDC is fundamentally different from what is currently available, and hence providing a new route to assess the structural integrity of PFC's. The main unique feature of the Deterministic DDC is the focus on developing non-linear design rules. This shall remove the need to perform linearization and to use correction factors. However, in order to make the non-linear only route useable, a number of developments need to be made to ensure that a designer can easily and unambiguously apply the non-linear design rules. In addition other design rule specific developments are being made to Brittle Fracture, Fatigue and Ratcheting, all of which are believed to increase the available design space of PFC's.

The DDC is also heavily reliant on having a fully populated material database. This is particularly challenging when dealing with irradiated material properties, particularly as the Fusion specific environment is not readily available to be able to irradiate samples before performing materials testing programme. In order to accelerate the irradiated material data population, more advanced techniques such as micro and meso-scale testing techniques are being explored. These techniques could also support the development of new design rules.

The second version of the DDC is a Partial Factors version. The Partial Factors DDC is still in the very early stages of development. Currently a procedure for probabilistically calibrating PSFs has been identified and demonstrated through a worked example. Yet further research is required in order to work through the uncertainties in the proposed procedure and solidify the overall method by understanding the most appropriate and effective techniques available.

The clear advantage of this method is the replacement of 'empirical' rules by science-based models which provide clear demonstration of the level of risk the design has.

The foundations and strategy of DDC development have been established. The DEMO project is now in a good position to develop the DDC and in future provide its PFC designers with a design criteria that will not only provide them with a means to assess the structural integrity of their designs, but should also increase the available design space.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053 and from the RCUK Energy Programme [grant number EP/P012450/1]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
The authors would like to thank the work of the Engineering Data and Design Integration group of EUROfusion who supported this work.

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