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Design Issues and Implications for Structural Integrity of Fusion Power Plant Components

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Abstract

The criteria and implications for successful design, licensing and power plant operation are assessed, and imposed constraints and limitations are examined. The design of a reliable fusion power plant is dependent on the availability of licensed nuclear materials and the structural–thermal loading conditions during normal and abnormal events. Various conditions in a tokamak lead to structural damage and possible failure. Taking into consideration all the possible structural failure mechanisms, the most likely are combinations of fatigue and creep. Issues encountered in the fusion environment are the significant amount of irradiation creep, the large ratio of helium production to displacement damage, and the degradation of fatigue strength and ductility, effects which are even encountered at low temperatures. Design codes distinguish between failure criteria under steady and transient loads, and lay down rules for failure prediction under combined creep–fatigue conditions. Currently, there are no established fusion specific licensing processes or component design codes. Any limits imposed on designs or performance are taken from existing design codes developed by the fission industry. There is a need to initiate the process of defining and developing tools for the design and licensing of fusion components and facilities to ensure nuclear safety.

1. Introduction

The design of a reliable fusion power plant is dependent on the availability of tested and approved nuclear materials and on the structural–thermal loading conditions during normal operation and during possible plasma disruptions. The various loading conditions encountered during the operation of a tokamak lead to structural damage and possible failure by such mechanisms as yielding, thermal creep rupture, fatigue due to thermal cycling, crack growth–propagation and radiation induced swelling and creep. Difficulties potentially encountered in fusion environments are the significant amount of irradiation creep, the large ratio of helium production to displacement damage, and the degradation of fatigue strength and ductility, effects which are even encountered at low temperatures. Component design, and accurate prediction of lifetime, requires established material databases, design curves (rules), specification for fabrication and testing, inspection methods, and rules and constraints for design, and in–service conditions. This paper discusses the criteria and imposed constraints and limitations that arise from fatigue and creep phenomena relevant to the structural design and lifetime of fusion power plant components operating under steady or load varying conditions, and assesses the implications for successful design, power plant operation and licensing.

2.0 Fatigue and Creep

Fatigue theory is well known and established [1], with typical strain to number of cycles to failure expression as:

$$\varepsilon_a = \underbrace{\frac{\sigma'_f}{E}(2N_f)^b}_{elastic} + \underbrace{\varepsilon'_f(2N_f)^c}_{plastic} \tag{1}$$

with b the fatigue strength exponent, σ'_f the fatigue strength coefficient, c the fatigue ductility exponent and ε'_f the fatigue ductility coefficient.

In systems and loading conditions relevant to fusion power plants, it is anticipated that stresses will more frequently assume values beyond the yield stress with plastic strain yielding. Thermal fatigue, as opposed to mechanical, is usually observed during operation of fusion experimental machines and expected in fusion power plants. Experimental evidence suggest that low cycle fatigue tests with thermally cycled constrained specimens do not correlate under all conditions or material type with mechanical fatigue.

In an irradiation environment, neutron fluxes lead to structural damage, and changes of material properties that affect fatigue behaviour [2]. Irradiation affects primarily the plastic behaviour of the material (true strain fracture ε'_f) rather than the elastic.

Creep, the deformation of material with time under an applied stress, can be due to thermal and irradiation effects. Thermal creep under multi-axial variable stress is treated with the concept of a mechanical equation of state where the strain rate is a function of the stress and temperature at the present time and independent of the previous history.

Irradiation creep has been extensively studied by the fission industry for various types of materials used in fission power plants, but data and experience gathered over the years refers largely to the class 316 austenitic stainless steels, and lately to ferritic–martensitic stainless steels and vanadium alloys. The focus of much of experimental work has been the study of micro-structural evolution in materials, and the beginning and growth of void swelling [3,4,5,6,7]. The majority of these experiments, and data gathered, are from fission reactors. There are no data that are fusion specific, although some attempts have been made to simulate the fusion environment and then draw conclusions about material behaviour [8,9]. Theoretical and semi-empirical data and work suggest that material ductility (true fracture strain) in a fusion neutron spectrum would be a function of several variables [3,4,10,11,12], and a typical expression is

$$\varepsilon_C = \left[B_o D + C_o S_V\left(D - D^*, T\right)\right]\sigma \tag{2}$$

with B_o the zero damage rate creep compliance, C_o the swelling-enhanced creep coefficient, and $S\left(D - D^*, T\right)$ the material swelling. Data show that for swelling there is an incubation time D^* beyond which there is exponential growth. More experimental data and analysis of the micro-structural behaviour of candidate materials are needed in order to characterise behaviour in a fusion environment. In fission systems the damage rate is typically in the range $1–10\text{x}10^{-7}$ dpa/s, and in fusion systems is 3 to 4 times as much and in the range $3–30\text{x}10^{-7}$ dpa/s. The production rate of transmutant helium in fission systems is in the range $3\text{x}10^{-8}$ to $3\text{x}10^{-7}$ appm/s, but in fusion environments is expected to be 30 to 40 times as much and typically in the range of $1–10\text{x}10^{-6}$ appm/s.

3.0 In-service or Lifetime estimation

Lifetime estimation is possible when stress-strain history with loading events and frequency of occurrence is coupled with design curves with materials properties. A typical guide chart is shown in figure 1. Possible events that may be included in a typical in-service/ lifetime analysis are shown schematically in figure 2.

Design curves for failure due to creep, for both thermal and irradiation components, can be constructed based on normalised stress-to-rupture curves (Larson-Miller) [1,13] and irradiation creep strain data, if available. Theory groups together time and temperature using a normalising parameter $P = T(c + \log_{10} t)$, with *c* a material dependent constant. Experimental data for martensitic steels [14] give a value for *c*=20. In general an equivalent to the Larson-Miller curve for irradiation creep is required, but due to lack of such data or theory, the strain limits imposed in fission design codes could be used as a guide. Proposed models assume that stress activates the growth of a fraction of grain boundary bubbles which contain helium in excess of a critical number, where bubble cavity density exceeds normal values, thus leading to embrittlement. The resulting expression for fracture strain (ductility) ε_f and/or stress-to-rupture versus time is

$$\varepsilon_f = \frac{I\sqrt{B(D,T)}}{\sigma\sqrt{R}} \quad or \quad S_r = \left[\frac{I}{\sqrt{R}}\frac{\sqrt{B}}{(B_o D + C_o S_V)}\right]^{1/2} \tag{3}$$

with the constant for austenitic steels I~1500 MPa$^{-3/2}$dpa$^{-1/2}$, when data from fission spectra and measurements are used, and *R* is the helium to dpa ratio. Presently there is no comparable formulation for martensitic steels or other alloys. The stress–time design curve limit due to irradiation creep strain is deduced from the assumption that component failure will occur at an effective stress level which will produce 1% strain averaged across any cross section of the component, based on fission rules. Using this model a typical design curve is shown in figure 3. In general, these models show that high stress and low helium environments, as in fission, are less sensitive to helium embrittlement than low stress and high helium, as in fusion environments.

In-service/Lifetime estimation is possible when the results from thermal and structural analysis for in-vessel components are used to obtain the variation of the cumulative creep $D_c = \Sigma(t / t_r)$ and fatigue damage $D_f = \Sigma(n / N_f)$ with time. Under irradiation and time varying loading conditions fatigue and creep must be superimposed using a combined rule. Theory suggests a linear summation rule typically used in fission design codes [1]:

$$D = \underbrace{\sum_{all\ events}\left(\delta t / t_r\right)}_{D_{creep}} + \underbrace{\sum_{all\ events}\left(n / N_f\right)}_{D_{fatigue}} \le w \tag{4}$$

with δt the time and n the number of cycles spent at a given stress level, D the total damage, t_r the time to reach the design strain or component to fail at a given stress level and N_f the number of cycles to failure at a given stress level. The theoretical value of the constant is *w*=1, but experimental fission data suggest lower values. Fusion operating environments are needed to determine the range of the constant *w*.

Combination of creep-fatigue rule based on possible events shown in figure 2, results in estimation of lifetime. An example from [15] with lifetime estimates is shown in figure 4. The zero–fatigue lifetime (i.e. creep cumulative damage only) is 2.52 years, but using the hypothetical event scenario in figure 2, gives the range 1.3–1.45 years. As the operational temperature increases, the structure becomes more susceptible to fatigue; even a small number of large duration events is capable of reducing lifetime significantly; that kind of behaviour is observed as a function of the number and time duration of the various events.

Lifetime improvement is possible if the time to failure at the full power–on stress level can be extended. This can be achieved through geometrical shape optimization, minimizing the stress level at the critical points of the component, and by optimization of material compositions, based on data from high-fluence fusion neutron sources.

3.0 Component Design

Component design requires an established material database, material properties (design curves), specifications for fabrication, testing and inspection methods, and constraints for design and in–service conditions. Some of the issues involved are:

(a) Classification of components according to their functionality, physical position in the machine and safety importance
(b) Classification of loading conditions, which is dependent on the frequency of occurrence of the load or event
(c) Choice of elastic or inelastic analysis. When creep and thermal cycling effects are significant inelastic analysis may be required to provide a good assessment
(d) For non-ductile failure and if creep effects are not negligible a fracture analysis must also be performed

An important factor for successful design of a component is knowledge of thermo-physical and structural material properties. Other data needed for performing thermal-structural analysis are related to the estimation of in-service lifetime and possible failure due to the creep and fatigue mechanisms. The classification of components and loads plays an important role in the rules to be used to guard against component failure.

4.0 Discussion - Implications for Structural Integrity and Lifetime

In general the issues that will impact the design and licensing process of future power plants, the effects of irradiation on the fatigue properties, and the estimation of lifetime and failure from such mechanisms, were dealt with and were presented in detail in previous studies, [15,16,17,18,19].

Design Code relevance and applicability: The accurate prediction of in-service/lifetime and prevention of component failure is usually based on well defined procedures and requires the use of well established design curves for the structural material. The existing design codes [20,21,22] cover component operation at low and elevated temperatures, and guard against creep-fatigue effects at high temperatures and against time independent failure modes at low temperatures, but they do not directly address irradiation effects. Issues in the design codes are the non-existence of rules for low temperature creep-fatigue damage and the treatment of irradiation creep at low and high temperatures. **Design codes do not cover** a range of operating and loading conditions which are important for fusion machines, and are of frequent occurrence during the expected life of the in-vessel components. These conditions include: non–ductile fracture (brittle, all materials), with brittle fracture not addressed by existing codes, irradiation damage and effect on material properties, irradiation creep induced stress-to-rupture with failure even at low temperatures (there are no relevant design curves), thermal instead of mechanical fatigue and relevant design curves, combined creep–fatigue failure rules, loss of ductility, fatigue, and fracture strength reduction and hardening or softening behaviour due to irradiation, and complex geometries, other than pressure vessel type.

The implication is that the existing rules and constraints constitute a non conservative upper limit in terms of design criteria when applied to fusion power plants or experimental machines, and should therefore be treated as such by the designer.

Material damage and design curves - creep and fatigue: The parameters governing the material behaviour under irradiation are the damage rate and the ratio of helium production to damage, with both parameters being dependent on the local neutron spectrum, i.e. they are design and physical position dependent.

The behaviour of materials under the neutron spectra expected in fusion environments is currently treated using data from fission facilities, and by examining this experimental data to determine the micro-structural mechanisms that govern the damage rate and the production of helium in the material. The relevant creep models and theory have been used to predict swelling and creep under irradiation in a fusion environment, calibrated to fit experimental data from fission facilities and then scaled accordingly to anticipated fusion conditions. Until the necessary experimental measurements are conducted to obtain relevant data for the proposed materials to be used in the construction of vessel and in-vessel components, the stress to number of cycles to failure and stress to rupture and ductility design curves developed can be used as a guide in the design of components.

Design by analysis: Non–linear elastic-plastic analysis is computationally more complex, since it requires knowledge of the stress–strain and hardening/softening behaviour of the material as well as of the creep law, but does not require application of any correction factors, and can be directly used with design curves to determine component failure and predict lifetime. The alternative is to perform an elastic analysis, to determine the stress and strain history in the component. This approach involves relatively straightforward calculations although several material parameters must also be known. The difficulty with this approach is the complexity in applying the design code requirements and in considering all the necessary correction factors which account for stress and strain concentrations, stress relaxation, enhanced strains due to irradiation creep and various effects during the hold and dwell times. Also, the correction factors are applicable to specific geometrical shapes and do not in general apply to the more complex structures and components found in a fusion machine.

Therefore, the non-linear time-dependent analysis is more fundamental, since it involves application of first principles in performing the structural analysis. Modern finite element codes have the capability to perform such analysis, with the difficulty lying in obtaining the proper material data and constitutive laws to be used for the calculations.

The concept of the safety factor was introduced in order to allow the designer to accommodate:

a) material property uncertainty,
b) load and stress calculation inaccuracy,
c) severity of operating conditions,
d) quality of maintenance.

Guidelines have been proposed [23], that account for the uncertainties in material behaviour and properties and conditions of environment, load and stress. The average value of the safety factor suggested for normal components is SF~2 on the stress and strain. The proposed safety factor for untried materials used under "average" conditions (i.e. there is some uncertainty in the environment and loading conditions) is SF~3-4.

In–Vessel Components under Load: Several conclusions and implications can be drawn on the behaviour of in-vessel components, based on the analysis and results obtained in several previous reports on in-vessel components [15,16,18,19].

The accumulation of creep damage seems to saturate to a maximum value and the damage beyond that point in time is entirely due to fatigue damage accumulation. This behaviour results from relaxation of stress intensity with time and the specific shape of the stress to rupture design curves.

Both fatigue and creep mechanisms are important for component damage; the contribution of creep damage depends on such conditions as the initial value of stress and the ratio of hold (power–on) to dwell (power–off) time. Irradiation creep result in an increase of the residual stress at zero thermal load and relaxation of full power load stress.

The behaviour of strain with time is somewhat different. The strain range in components, between the power-on and power-off conditions, seems to be constant, with the time history curves moving to larger values of strain but in the process preserving their shape.

Creep damage is accumulating faster at the beginning of operation of the machine but as the stress relaxes with time the operation moves further and further away from the ductility limit. Although there is no contribution to the accumulation of creep damage during the power–off periods, care should be taken so that the combination of higher residual stresses and increased strains does not exceed the ductility limit. In general results are considered optimistic since design curves (creep-fatigue and stress to rupture) are based on fission data and non-conservative safety factors respectively.

5.0 Conclusions

It is important to properly classify fusion components and correctly identify loading conditions. The choice of a specific route of design by analysis will dictate the degree of effort in deliberations with design code committees and licensing bodies. It must also be pointed out that the analysis and assessment presented in this study does not address other issues, such as plasma-surface interaction constraints, plant efficiency, waste management and component activity.

As a general conclusion, the materials, properties, design curves, and all relevant design codes must be brought in-line with fusion neutron spectra and operating environment for successful design, construction and operation of fusion power plants.

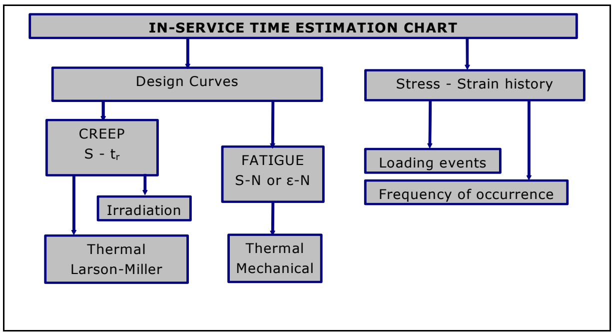

Fig. 1: Typical in-service/lifetime chart

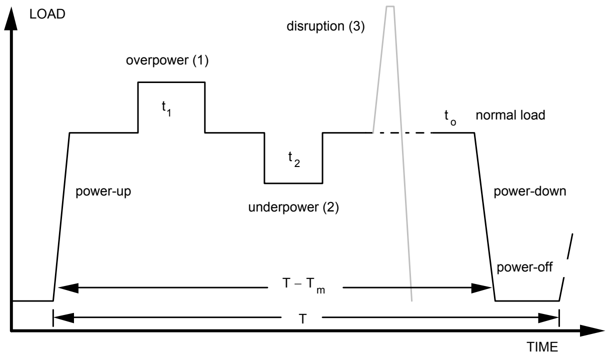

Fig. 2: A schematic of the loading histogram for in-vessel components event history.

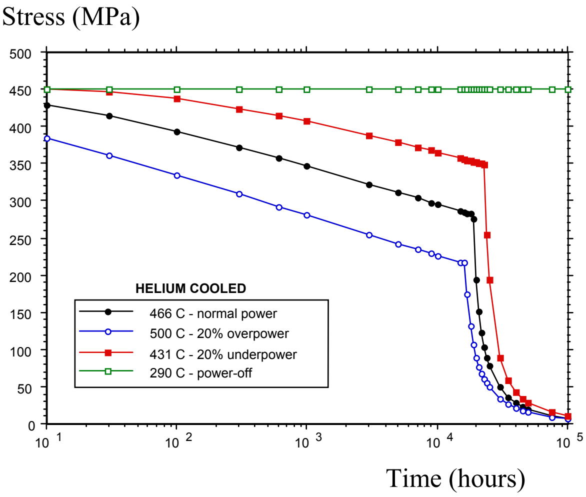

Fig. 3: Stress to failure variation with time, temperature and damage rate for various events

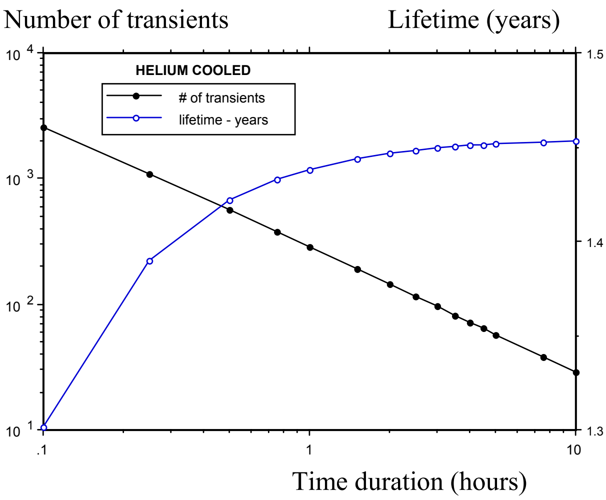

Fig. 4: The variation of the number of allowed power transients with their time duration, and lifetime.

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