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

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## This talk will:

- Present a brief review of the existing design framework.
- Identify the necessary material data and other parameters needed for component estimation of in-service time.
- Discuss the design code rules and constraints – fusion specific processes that codes cover and do not cover – relevance of existing framework and rules.
- Discuss issues and implications for fusion irradiation conditions.

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# BACKGROUND INFORMATION

- At the moment there are no fusion-specific licensing processes or component design codes.
- Any limits imposed on designs or any performance criteria are “informal”,

  i.e. are only used within the fusion community and are not yet substantiated to the level expected for use in the course of a regulatory/licensing process for a commercial power plant.
- Licensing is closely linked to Design Codes and QA Systems. These assure that a good safety case will be submitted to the regulatory body.
- The design codes provide the procedures, rules and constraints (materials properties and design curves) in order to ensure nuclear safety.

## Component design, in general, requires:

- An established material database
- Design curves - rules and constraints for design and in–service conditions.
- Specifications for fabrication, testing and inspection methods.

## Modelling and Simulation for fusion components comprise:

- Thermal and fluid dynamics (steady and time dependent) – linked to thermal stresses and strains, and relevant in safety analysis.
- Structural (linear, non-linear and time dependent) – study of component performance under loading.

## DESIGN CODES COVER

- All necessary conditions for components that are exposed to less than 1dpa dose (…..but fission spectra).
- Rules for linear and non-linear elastic or inelastic analysis.

## DESIGN CODES DO NOT COVER

- Non–ductile fracture (brittle).
- Irradiation creep leading to failure at low and high temperatures, and properties - design curves.
- Thermal instead of mechanical fatigue, and properties and design curves.
- Combined creep–fatigue failure rules at low temperatures.
- Loss-of-ductility, fatigue and fracture strength reduction due to irradiation.
- …..but leave the opportunity to the Owner to specify irradiated components and materials constraints and rules to cope with the in–service conditions.

# IS A FUSION SPECIFIC DESIGN CODE NEEDED?

- Yes, a design code will be needed, for power plants.
- In the long term a fusion specific design code will emerge, based on information gathered over the years from:

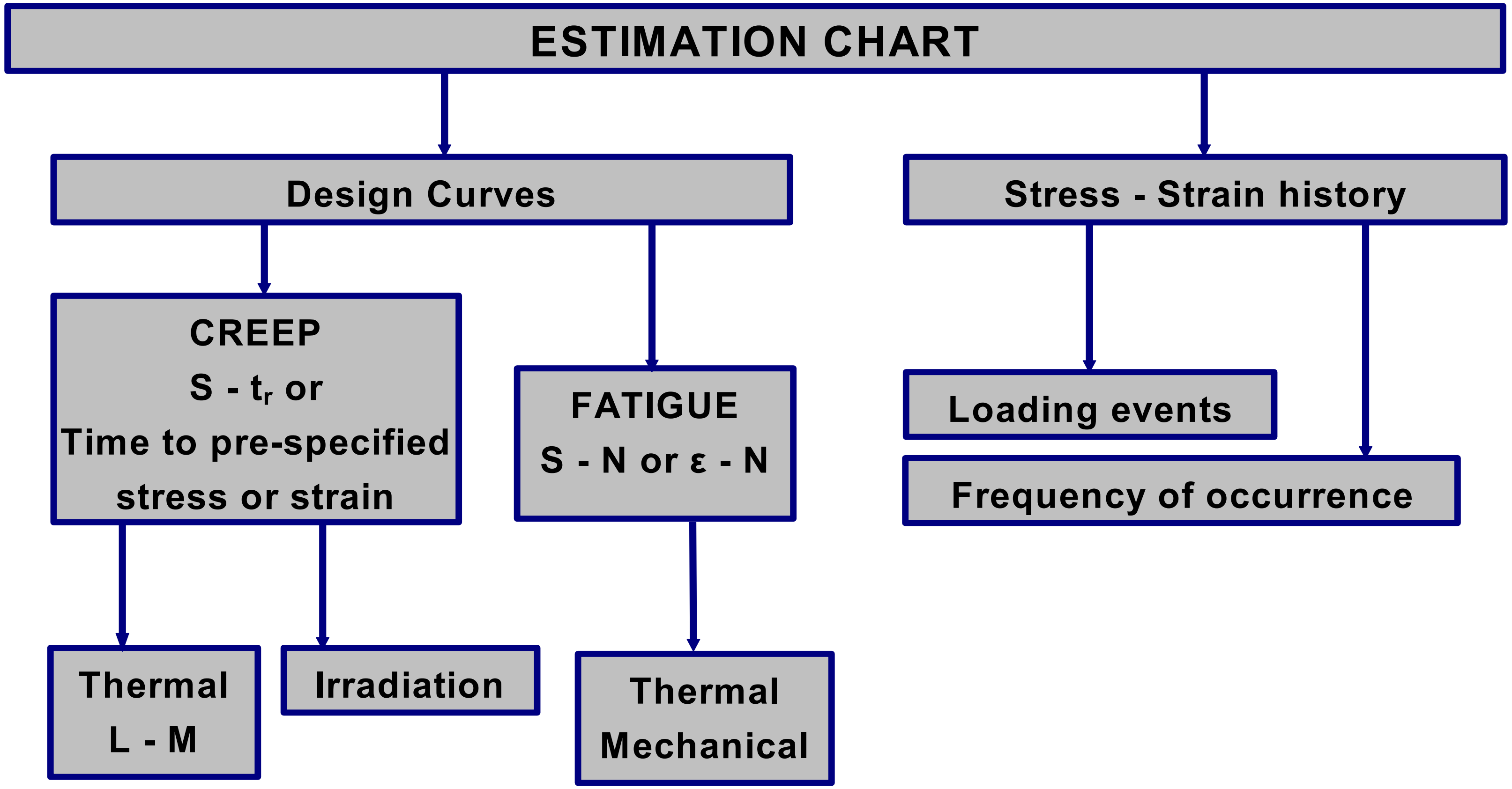
  Experimental machines such as ITER.

  IFMIF Facility.

  DEMO and prototypes.

- It should allow implementation of future advances in computer aided design (CAD) and finite element analysis (FEA, CFD).

# IN – SERVICE TIME / LIFETIME

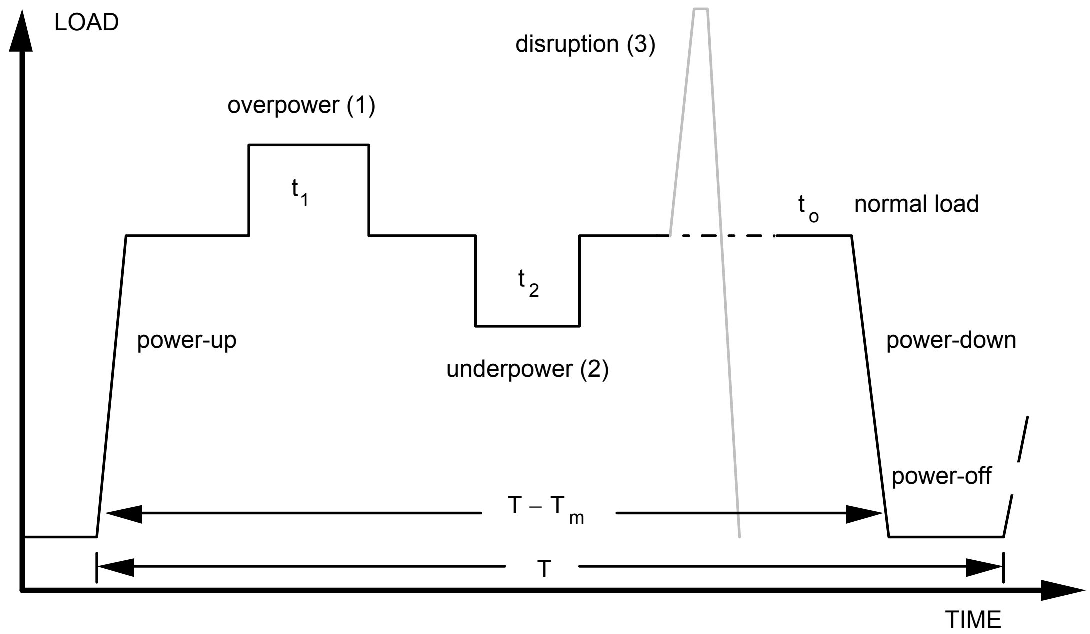



**To calculate we need: load histories and material properties design curves**

# LOADING EVENTS – HISTORIES

- During power plant life various in-service loading events inflict damage to the structure.
- It is important to the designer to identify the main loading events and their operational limits. It is also necessary, in order to apply countermeasures.
- In-vessel component lifetime will dictate maintenance schedules and plant availability.
- Scheduled (i.e. routine) maintenance is desirable,anticipating all possible abnornal events.
- Unscheduled/unplanned events are not desirable.

# LIFETIME/IN-SERVICE TYPICAL FUSION LOADING EVENTS




Possible events important in lifetime analysis, are:

0→ normal load power on periods, duration $t_0$

1→ overpower transients, at a level of +x%, duration $t_1$

2→ underpower transients, at a level of -y%, duration $t_2$

3→ disruptions, duration $t_3$ (hours)

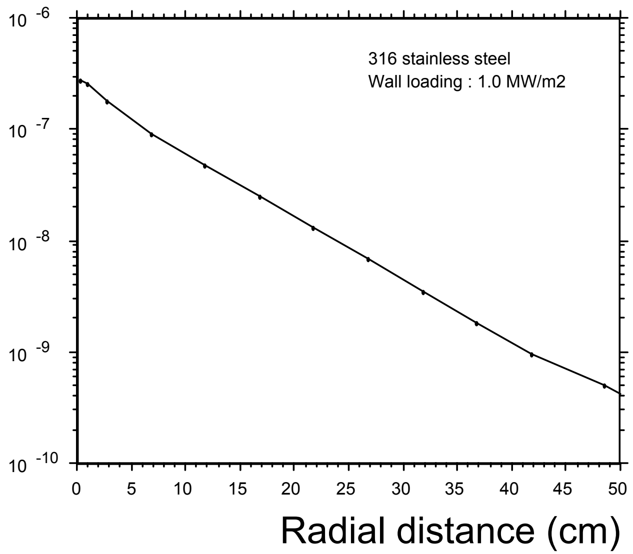
4→ power–off or scheduled maintenance, duration $T_m$

- In-service/Lifetime estimation is possible when thermal and structural analyses for in-vessel components are used to obtain the cumulative creep and fatigue damage with time.

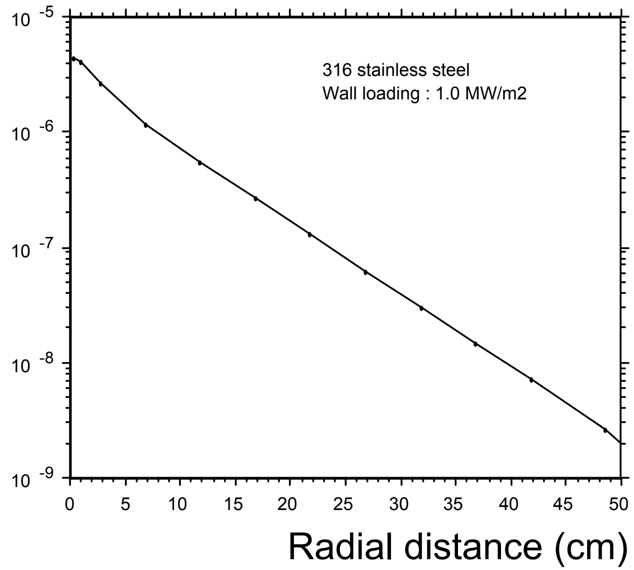
# MATERIAL PROPERTIES – DESIGN CURVES

## Typical irradiation parameters

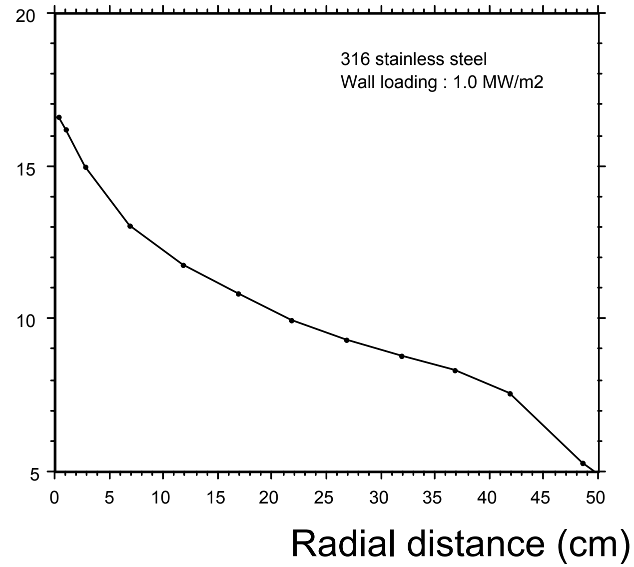
Damage rate $G_{dpa}$(dpa/s–MW/m2)




Helium production rate $G_{He}$(appm/s)




$G_{He}/G_{dpa}$ (He appm/dpa)




- Rates are obtained from neutronics MCNP (or other) and FISPACT (or other) calculations using local spectra.
- Rates are scalable but ratio will be approximately the same.

# FATIGUE AND IRRADIATION

- Prediction is based on strain (or stress intensity) range versus number of cycles to failure ($\Delta\varepsilon$ or S – N), if available.
- Thermal fatigue is usually observed and is expected to contribute.
- The strain comprises the plastic and elastic portions
- Experimental evidence suggests that irradiation affects primarily the plastic rather than elastic behaviour.
- The database should be revisited to bring out critical dependencies of constants and coefficients to irradiation controlling parameters

  …for example the He/dpa ratio, swelling….
- The effect of 'hold' and 'dwell' times should be included and examined.
- **Irradiation effects for fusion conditions are yet to be determined.**

# CREEP AND IRRADIATION

- Creep can be either thermal or irradiation.
- Thermal creep properties are well established for a variety of materials.
- Irradiation creep strain is postulated in terms of the dose D (dpa), temperature T (C) and the local effective stress $\sigma$ (MPa):
- Theoretical and semi-empirical analyses and data, suggest that material ductility in fission spectra is a function of several variables:

$$\varepsilon_f = \text{function}\{ D, T, \sigma, (He/dpa) \}$$

- Presently there is no comparable formulation for fusion steels or other fusion materials.
- **Appropriate strain limits under fusion neutron spectrum irradiation conditions, are yet to be determined.**

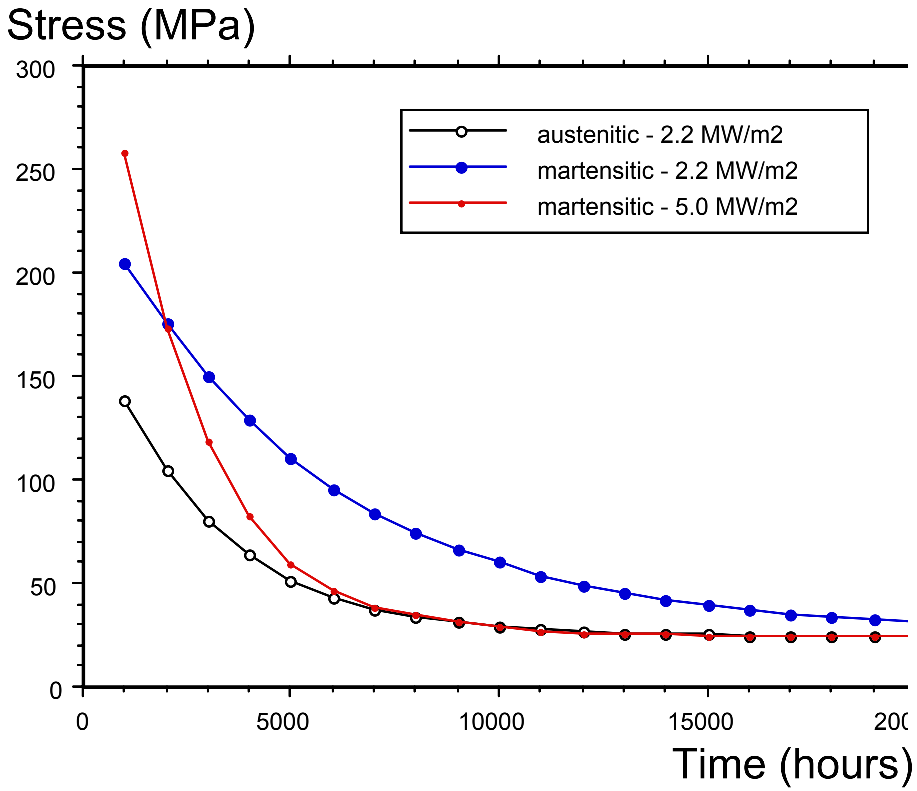
# Design curves, may be constructed by combining irradiation and thermal creep

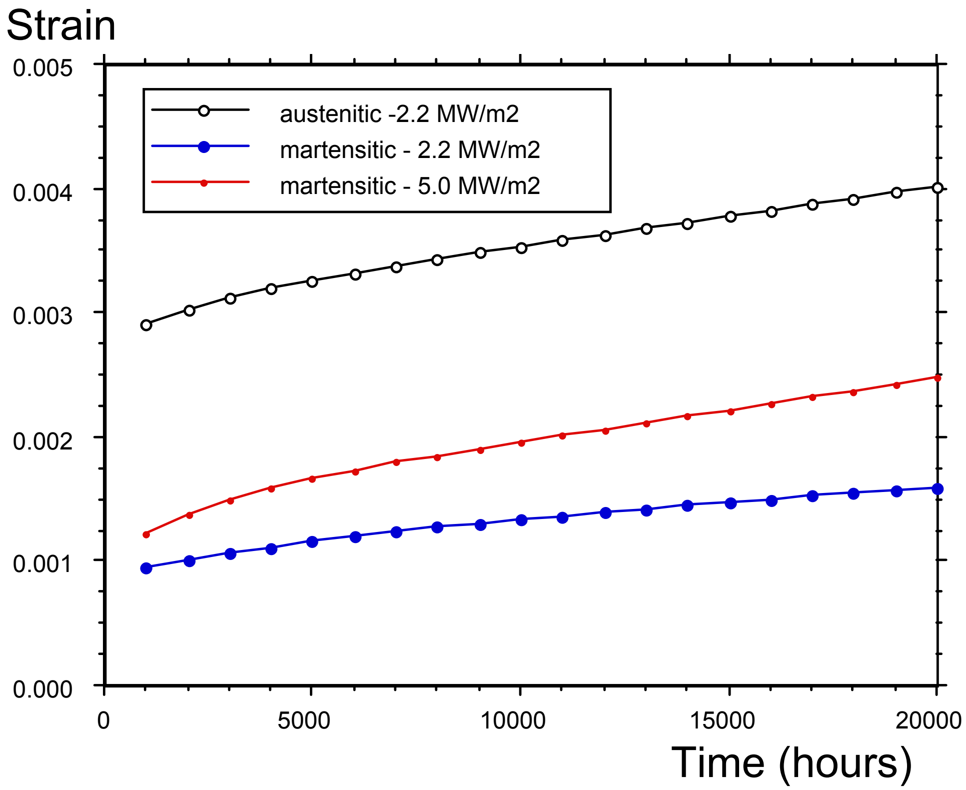
- BUT is the superposition linear?……or is there non-linear synergy ?

- The strain limit, appropriate for a fusion plant in-vessel environment, is yet to be defined.
- Existing fission design codes give limit values of 1% averaged across a section of the component, or 5% if localised.
- In general, these limits are due to observation and calculation, and are in direct correspondence to the ductility limit of the material.
- **Therefore, the material ductility under fusion neutron spectrum irradiation conditions is required.**

# STRESS RELAXATION DUE TO CREEP

- Typical variation of stress and strain demonstrating stress relaxation and strain enhancement due to creep.



## The implications of the observed stress relaxation under irradiation are:

- the structure has deformed to accommodate the stress, thus experiencing a much higher strain
- failure could occur either during possible power transients or during power down periods, due to stress reversal
- i.e. the structure at full power load and at this “relaxed” stress state might not be able to accommodate any further load fluctuations.
- The results show that stress relaxation is a function of the wall loading, and is accelerated, i.e. it takes the stress less time to relax, as the wall loading increases.
- BUT…….more analysis and experimental evidence is required to confirm behaviour for operation beyond the complete relaxation state in a fusion relevant environment.
- The difficulty defending these results lies in the uncertainty arising from the limited database and experience of the material properties in fusion environments.

# CONCLUSIONS

- In-vessel component lifetime will dictate maintenance schedules and plant availability, and thus plant economics. This is dictated by the combined creep-fatigue behaviour.
- For material properties the philosophy adopted is to use existing data and through rigorous examination establish the theoretical basis for scaling to fusion conditions.
- The use of fission data is a good starting point, but the fundamental dependencies on critical parameters must be used for scaling to fusion values, until we have data from fusion specific spectra.
- Design curves for irradiated components can only be established after the operating conditions are fixed and remain the same in time (for example in fission the design geometry and neutron spectrum is established).

## For irradiation conditions the desired actions involve determination of:

1. **Dose, He/dpa ratio and swelling** dependency of basic thermo-physical and structural material properties.

2. Any **anisotropy effects** on material properties.

3. The **creep constitutive equation, and fatigue** behaviour in a strongly stress relaxing environment (faster relaxation with increasing neutron rates or wall loading).

4. The **stress-strain data for the material**, including the fracture strain (ductility limit) variation with stress and helium to damage ratio.

## Other issues not covered here:

5. Dpa calculations for alloys are based on response functions of the individual elements weighted according to composition.

   Is the linearity rule correct for the alloy?

6. Safety factors – we adopt the same as in fission. They are a result of long years of operation and working experience in the fission environment.

7. Ceramic and other 'brittle' materials that are in abundance in fusion machines.

8. Plasma surface interaction – erosion behaviour, plasma abnormal operation.

9. Coolant corrosion and activation issues.