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Design Standard Issues for ITER In-Vessel Components*

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1. Introduction

Safety–class components of fission reactors in the United States are normally designed according to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessels Code, Section III, and additional rules are detailed in Code Case N47 for elevated temperature applications. For a component to be stamped with an N Code Symbol, the ASME Code imposes strict guidelines for design analysis, allowable materials and material properties, acceptable weldment and fabrication methods, quality assurance, in–service inspection, etc. Nuclear facilities in other countries are legally required to satisfy their own sets of structural design criteria, such as RCC–MR in France, MITI Notification No. 501 in Japan, and PNEAG–7–002–86 in the Russian Federation. Although there are differences in details, all of these design criteria are very similar. Their primary goal is to minimize the risk of damage to public health and property outside the plant perimeter. Although they do not require probabilistic risk analysis, safety is ensured primarily by limiting the options for structural materials to very ductile annealed materials and by imposing conservative safety factors on material properties.

Because they are internal reactor structures, the in–vessel components of the ITER need not be ASME–Code–stamped. However, because of a significant inventory of tritium and the expense (both in terms of replacement cost and lost time) of replacing the blankets, the in–vessel components must be designed with a high degree of reliability that is derived from standards that are comparable to the ASME Code, Section III. But the design environment for in–vessel components of the ITER differs significantly from that of the out–of–core safety–class components of fission reactors in several respects: (1) the high heat flux on the first wall and divertor are without parallel in the fission reactor; (2) the first wall is subjected to moderate doses of high–energy neutrons with the accompanying problems of material embrittlement and irradiation–induced creep that are generally not problems for fission reactor out–of–core components; and (3) the frequent occurrence of plasma disruptions, which are unique to tokamak fusion reactors. These three unique features of the plasma–

facing components of the ITER create difficult stress and fracture problems that were not considered in the development of fission reactor design codes. To address these additional concerns, new design criteria will be needed for ITER in-vessel components.

2. Purpose of Design Criteria

The primary purpose of any set of design rules is to ensure that proper safety margins are maintained with respect to mechanical damage that might occur in the structural materials due to imposed loadings. Such potential damage in the in–vessel components of the ITER includes:

- Excessive deformation due to time–independent plasticity,
- time–independent plastic instability,
- time–independent elastic and elastic–plastic buckling,
- excessive deformation due to fluence–dependent irradiation–induced creep,
- fluence–dependent irradiation–induced creep buckling,
- cycle– and fluence–dependent ratcheting,
- fatigue crack initiation and propagation (including influences of environment and fluence),
- brittle fracture under static and dynamic loadings (including influence of fluence),
- liquid metal corrosion,
- irradiation–assisted stress corrosion cracking, and
- fluence–dependent hardening and loss of ductility and strain–hardening capability.

It is anticipated that ITER in–vessel components will operate at temperatures and fluences where effects of thermal creep and irradiation–induced swelling will be negligible.

3. Design Loadings and Service Conditions

The design loadings on the in-vessel components of the ITER consist of:

(a) Coolant pressure,

(b) weight of components, including static and dynamic heads of liquid,

(c) electromagnetic and thermal loads during plasma disruptions,

(d) surface and volumetric heat fluxes,

(e) earthquake loads, and

(f) reaction of supports

Normal operating condition for an ITER component is defined as loadings to which the component may be subjected in the performance of its specified function, including incidents of moderate frequency that the component must withstand without damage that require repair. Such loadings include start-up, shut-down, plasma on-off burn cycles, plasma disruptions, and control malfunction. In addition, ITER components may be subjected to upset loading conditions (e.g., earthquakes) which will require a system shutdown for inspection or repair of possible damage. In general, the safety factors for normal operating conditions are higher than those for upset conditions.

4. Design by Analysis

4.1 Ductile Materials (Section III, ASME Code)

The design rules of all existing design criteria are rooted in the limit-analysis principles of the theory of plasticity, which is applicable to ductile materials. This allows deformation-controlled stresses (e.g., thermal stress), called secondary stresses, to be treated differently (lower safety factor) from load-controlled stresses (i.e., stresses required to satisfy equilibrium with applied mechanical loading), called primary stresses. The reason is that unlike primary stresses, secondary stresses are limited by plastic yielding. For the same reason, local stresses (peak stresses) due to stress concentrations are also treated differently. Generally, the safety margins provided in Section III of the ASME Code are dependent on the depth of analysis conducted during design. The safety margins are highest if elastic analysis is used, somewhat relaxed if simplified elastic-plastic analysis is used, and even more relaxed if detailed elastic–plastic analysis is used.

4.1.1 Single Application of Loading In the ASME Code, the design rules for the prevention of large plastic strains and plastic instability due to a single application of loading are based entirely on limiting the maximum primary membrane stress (P_L) and the maximum primary membrane plus bending stress (P_L+P_B) to a multiple of S_m, which is defined as the lesser of the two stresses determined by applying factors of safety of 1.5 (1.1 for austenitic stainless steels) on the yield strength and 3 on the ultimate strength, as follows:

$$P_L \le S_m \tag{1a}$$

and

$$P_L + P_B \le K\, S_m \tag{1b}$$

where K is a plastic bending shape factor (defined as the ratio between the stress at the extreme fiber of an elastic beam subjected to the fully plastic moment and the yield strength) which is equal to 1.5 for solid rectangular sections.

Secondary and peak stresses, which can be relaxed by plasticity, are generally not included in the above limits. Satisfaction of the above primary stress limits is waived if plastic analysis or tests can show that the specified load does not exceed two–thirds of the plastic collapse load (or a lower bound) or test collapse load.

4.1.2 Multiple Applications of Loading Multiple applications of loadings can lead to failure by either plastic ratcheting or fatigue. Limits on cyclic secondary stresses and peak stresses are provided in order to guard against failures due to ratcheting and fatigue, respectively.

The objective of a ratcheting analysis in the ASME code is to ensure shakedown or, for highly strain–hardening materials, to limit the maximum accumulated local plastic strain at any point to 5%. If the elastic analysis route is selected, shakedown (except possibly in localized regions) is ensured by limiting the maximum range of primary (P_L +P_B) and secondary stress (Q) to $3S_m$, i.e.,

$$P_L + P_B + Q \le 3S_m \tag{2}$$

A check on ratcheting due to steady primary and cyclic secondary stresses is also required by using a Bree diagram. If inequality (2) is violated, then either a simplified or detailed finite–element elastic–plastic analysis is required to ensure that ratcheting will not occur

For conducting fatigue analysis, all three types of stresses – primary, secondary and peak– are considered. The maximum alternating stress amplitude S_a is computed by either elastic analysis (with the Tresca criterion) or elastic–plastic analysis (by multiplying the maximum principal strain range by Young's modulus). The allowable cycles N_d is obtained from a design fatigue curve that includes factors of safety. The ASME Code, Section III does not require a fatigue crack growth analysis for design. Such analysis is required in connection with in–service inspection, according to procedures given in Section XI.

The ASME Code, Section III provides rules to guard against buckling due to external pressure and axial compressive loading on axisymmetric shell structures. Also, it requires a check on nonductile fracture of vessels and provides some guidelines for conducting the analysis for ferrous materials based on the linear elastic fracture mechanics methodology given in nonmandatory Appendix G.

4.2 Special Considerations for ITER

Three aspects of ITER design will require special consideration and possibly a new set of design rules. They are irradiation effects on material behavior, plasma burn cycles and disruptions, and the use of coating, tiles, and/or composite structure in the first wall.

4.2.1 Irradiation Effects. ASME Code rules were written for materials that remain ductile throughout life. Although the code requires that effects of irradiation, if present, be considered, it does not provide guidance on how to include irradiation effects into the design rules. Conventional structural materials such as austenitic stainless steels and ferritic steels show large loss of ductility and increase in ductile–brittle transition temperature at moderate fluences. Uniform elongation of type 316 stainless steel can drop to <1% at relatively low fluences. Some of the more unconventional materials such as vanadium–based alloys show better ductility and swelling characteristics than the conventional alloys and are also being considered for application to the ITER blanket and divertor. Design rules for the ITER must address situations in which the structural material will display one or more of the following three types of material behavior at various stages of life:

Ductile behavior (ε_u>5%): During the initial stages of the ITER, the material will be ductile and the ASME code rules would be applicable. However, with accumulating fluence the material will lose ductility. The 5% limit on uniform elongation is an estimate of ductility, above which the ASME code rules are applicable, and must be confirmed for ITER structural material and geometry. If the material retains the minimum ductility throughout life, the ASME code rules with some modifications can be used for the design of ITER in-vessel components. Modification will be needed for the Bree diagrams, which were developed for axisymmetric structures under a constant axisymmetric primary stress and cyclic axisymmetric secondary stress, which are not relevant for ITER geometry and do not cover all possible loading modes of the ITER. The first wall of the ITER blanket will be subjected to a steady primary stress due to coolant pressure and cyclic thermal stress due to plasma burn cycles, as well as cyclic primary stress due to electromagnetic loading during plasma disruptions. In addition to membrane stresses, significant bending stresses will also be developed in the first wall. Ratcheting of the first wall will be further aggravated by the presence of irradiation-induced creep. Constitutive equations for irradiation-induced creep and new ratcheting rules or modifications of existing code rules will be needed for the first wall of the ITER blanket.

Semi-brittle behavior (1%<ε_u<5%): For a material embrittled to this extent, the ductile stress limits are not enough; additional rules to guard against brittle fracture are needed. Particularly, the plastic bending shape factor K (see Eq. 1b) for bending stresses will have to be reduced to take into account the embrittlement of extreme fibers. Avoidance of brittle fracture must also be ensured by flaw-tolerance analysis. Life prediction methods for fatigue of a material with decreasing ductility through life due to irradiation effects must be developed. Effects such as interaction between fatigue and ratcheting, which are normally not a problem for ductile materials, have to be considered and new design rules developed. Development of these rules will, of course, be predicated upon availability of material test data.

Brittle behavior (ε_u<1%): A different approach to design rules must be adopted for this highly embrittled material for which the distinction between primary, secondary, and peak stresses with different safety factors for design cannot be justified. Further, variability of material properties and the presence of local small notches (both physical and metallurgical), which are less of a concern for the more ductile materials, can have a significant influence on failure of brittle materials. Design rules based on fracture mechanics principles may be better suited for these materials, and statistical treatment of material properties may become necessary.

4.2.2 Plasma Burn Cycle. The plasma in the ITER will operate in a pulsed mode. During plasma burn, plasma-facing components such as the blanket first wall and divertor will be subjected to surface heat fluxes that can have high peak values (≈1 MW/m^2 for the first wall). In addition, the blanket and shield will be subjected to nuclear heating. In its entire design life, the blanket and first wall will be subjected to ≈10^5 plasma on-off cycles. The large cyclic thermal stresses are unique in the energy industry and can potentially lead to ratcheting or fatigue failure of the first wall.

4.2.3 Plasma Disruptions. During its entire design life, the ITER will experience more than 1000 plasma disruptions, which require special consideration because they are also without precedence in the energy industry. Thermal stresses created in a thin surface layer of the coating, tiles, or cladding by the rapid melt-freeze cycle during disruptions may lead to early initiation of cracks that, in the case of bonded coating or tiles, may propagate into the base metal. Plasma disruptions will also cause impulsive loading on the vacuum vessel, blanket, and divertor because of electromagnetic effects. The dynamic stresses imposed on the first wall while it is still highly stressed by the surface heat flux existing prior to the plasma disruption, may lead to fast brittle fracture of the first wall, particularly when it is embrittled by irradiation. Also, effects on ratcheting of the first wall need investigation. The dynamic stresses created in the strongback, which is the primary load carrier for the ITER blanket, will need careful analysis for both fracture and buckling.

4.2.4 Coating, Tiles, Cladding, or Laminated Structure. Plasma-facing surfaces of the divertor and the blanket first wall will be either coated or covered with tiles or cladding made of a low-Z material (e.g., Be) that will protect the substrate structural material from the harsh environment of the plasma during the burn cycles and during plasma disruptions. Significant portions of the coating, cladding, or tiles in the divertor, as well as the first wall, may be eroded during plasma disruptions; this will require that they be amenable to repair by remote maintenance (e.g., by plasma spraying) after a number (≈100) of disruptions. The possibility of cracking of a thin surface layer due to melt-freeze cycle during disruptions has already been discussed. Potential delamination of bonded coating or tiles during plasma burn cycles and disruptions is also a concern.

In some designs, a laminated structure of copper alloy and stainless steel is being considered for application to the first wall. Defining the membrane and bending stress intensities for such a configuration will need some clarification. Currently, none of the design codes offer any guidance or design rules for preventing delamination. Because of the presence of an elastic stress singularity at the interface, a simple criterion based on maximum principal or effective stress will not suffice. New design rules are needed.

4.3 Fission Reactor Core Components

Some guidelines for ITER design criteria may be obtained from design standards developed in the United States for application to fission reactor components. These rules were specifically concerned with embrittlement of austenitic stainless steel structures and were modeled after the ASME Code Section III, Code Case N47. Some of the rules were based on testing on irradiated specimens and components made of austenitic stainless steels; others were set conservatively on the basis of analyses.

In these standards, it was recognized that for $\varepsilon_u \geq 5\%$ (5% uniform elongation corresponds to $S_y/S_u \sim 0.6$, where S_y and S_u are the irradiated yield and ultimate tensile strengths, respectively), austenitic stainless steels have sufficient work-hardening capability so that the usual primary membrane stress limit (S_m) of $0.9S_y$ provides sufficient structural integrity. For $\varepsilon_u < 5\%$, the work-hardening capability of austenitic stainless steels is reduced significantly and the primary membrane stress allowable was set at $0.55S_u$.

4.3.1 Primary Membrane Plus Bending Stress Limits. It was recognized that embrittlement of the extreme fibers poses a potential cracking problem for bending; therefore, to be conservative, the allowable primary membrane plus bending stress limit (Eq. 1b) was replaced by:

$$P_L + P_B \leq K_t\, S_m \text{ for } \varepsilon_u \geq 5\% \qquad 2(a)$$

where

$K_t = 1 + (K-1)[1-P_L/S_m]$

and K is the plastic bending shape factor,

$P_L + P_B \leq S_m$ for $\varepsilon_u < 5\%$ 2(b)

4.3.2 Primary Plus Secondary Stress Limits. A modified Bree diagram was proposed for preventing ratcheting and ensuring shakedown as long as the uniform elongation is ≥1%, which corresponds to the elastic strain at ≈1.6 times the yield stress of the irradiated material. If the shakedown criterion is violated, then either a simplified or a detailed elastic–plastic analysis must be carried out to demonstrate that the maximum ratcheting strain was within allowable strain limits.

For $\varepsilon_u < 1\%$, the potential for cracking by secondary stresses was assumed equivalent to that for primary stresses and a limit was set as follows:

$P_L + P_B + Q < 0.6\ S_u$ for $\varepsilon_u < 1\%$ (3)

which typically limits the accumulated plastic strain to <<0.1%.

4.3.3 Maximum Principal Tensile Stress Limit. When a material has sufficient ductility, elastic stress concentrations are relieved by plastic flow and no limit on maximum principal tensile stress is needed. However, under irradiation a material can become notch–sensitive, i.e., its ductility is reduced in the presence of a notch. For large triaxiality factors TF (defined as the ratio between the hydrostatic stress and the von Mises stress), ultimate tensile strength can also be reduced (notch–weakening) significantly. To discourage the use of notches in highly irradiated areas, the following limit on the maximum principal tensile stress was proposed:

No limit on S_{max} when %RA/TF > 10% 4(a)

$S_{max} < S_u$ when %RA/TF ≤ 10% 4(b)

where %RA is the percent reduction of area of a smooth specimen. To be conservative, no credit can be taken for stress states for which TF<1, i.e., TF should be set equal to 1 in such cases.

4.3.4 Strain Limits. The various stress limits discussed above are all based on linear elastic analyses, which are permitted provided the combined linear swelling plus irradiation–induced creep strain at the end of design life is ≤0.05%. If this strain limit is violated, then elastic–irradiation–induced–creep–swelling analysis is required. The allowable stress limits for elastic analysis are still applicable in this case, except that the value of the plastic bending shape factor K is set equal to 1. If any of the stress limits are not met, then a full inelastic analysis is required and strain limits are imposed as discussed below.

Components subjected to plastic strain may fail by tensile plastic instability or local ductile rupture. In the first case, uniform (membrane) plastic strains reach a critical value and then increase unstably without increase in applied load, e.g., necking. In localized rupture, maximum principal plastic strains exceed fracture ductility, causing material to crack locally. Because both uniform elongation and fracture ductility (measured by true strain at rupture) decrease with increasing fluence, the rules are written in incremental summation forms.

Membrane Strain Fraction Rule: The rule for preventing failure by tensile instability is

$$\Sigma(\Delta\varepsilon_m/\varepsilon_L) < 0.3 \qquad 5(a)$$

where $\Delta\varepsilon_m$ is the largest principal membrane plastic true strain increment in a given period of time and ε_L is the plastic tensile instability strain limit at thickness–averaged temperature, strain rate, and fluence. It was recommended that ε_L be estimated by $\varepsilon_u/2$.

Plastic Strain Fraction Rule: To prevent local ductile rupture, the local maximum principal plastic strain (including strain concentration) at any point in the structure is limited by

$$\Sigma[\Delta\varepsilon_t/(\varepsilon_f/TF)] < 0.3 \qquad 5(b)$$

where $\Delta\varepsilon_t$ is the maximum principal true plastic strain increment; ε_f is minimum true strain at fracture, i.e., $\varepsilon_f = \ln[100/(100\text{–}\%RA)]$, evaluated at the temperature, strain rate, and fluence for the point under consideration; and TF is the triaxiality factor.

Irradiation–Induced Creep and Swelling: There were no ductility–based design limits put on irradiation–induced creep and swelling strains. These strains were required to be considered for satisfying functional adequacy of the structure and also for any influence they have on the stress distribution in a component.

4.3.5 <u>Protection against Brittle Fracture</u>.

Fracture toughness of austenitic stainless steels decreases significantly with increasing fluence. Thus, a flaw that is subcritical at the beginning of life may become critical as the material loses toughness with time. To guard against brittle fracture, a procedure was suggested by postulating an initial flaw of a size at least as large as one that might go undetected by the NDE procedure for the component under consideration, and by assuming it to be oriented perpendicular to the direction of maximum principal tensile stress. Growth of the flaw must be tracked with the cyclic loading associated with normal and anticipated faulted events. The updated crack size was required to satisfy the following limits:

$$K_I < K_c/2 \qquad 6(a)$$

for elastic analysis, where K_I is the elastically calculated mode I stress intensity factor, and K_c is the minimum plane strain fracture toughness (unless a higher value can be supported by test data) at a given temperature, fluence, and loading rate. A similar criterion was given for inelastic analysis:

$$J_I < 2/3J_c \qquad 6(b)$$

where J_I is the mode I J integral, and J_c is the inelastic fracture toughness at a given temperature, fluence, and loading rate.

5. Conclusions

Unique requirements that must be addressed by a structural design code for the ITER have been summarized. Existing codes such as ASME Section III or the French RCC–MR were developed primarily for fission reactor out–of–core components and are not directly applicable to the ITER. They may be used either as a guide for developing a design code for the ITER or as interim standards. However, new rules will be needed for handling the irradiation–induced embrittlement problems faced by the ITER blanket components. Design standards developed in the past for the design of fission reactor core components in the United States can be used as guides in this area.

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