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Structural design criteria for ITER

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ABSTRACT

Design criteria for ITER have been developed within the scope of an international working group, providing design rules in order to address the special features of fusion.

The ISDC (Iter Structural Design Criteria) proposes a comprehensive set of Design rules "by analysis", founded on the European Fast Reactor design and construction code RCC-MR, chosen as a sound basis to integrate the best features of the nuclear design practices used in the world by other parties (USA, Russia Federation and Japan). ISDC take into account un-irradiated and irradiated conditions for which the effect of embrittlement, swelling, and creep are considered.

NOTATIONS

Φ	Neutron flux (E > 0.1 MeV)	ε_u	Uniform elongation
Φt	Fluence (E > 0.1 MeV)	ε_r	Total elongation
θ	Temperature	r	elastic follow-up factor
E	Young's modulus	ε_{tr}	true ductility
S_y	Conventional yield stress	S_{tu}	true rupture stress
S_u	Conventional rupture stress		

Subscript i is for irradiated characteristics.

1. INTRODUCTION

The ITER (International Thermonuclear Experimental Reactor) is being developed within the framework of an international co-operation involving United State (US), Japan (JA), Russian federation (RF), European community associated with Canada (EC).

As the project enters its engineering design phase (1993-1997), the need for a structural design guidances arises.

ITER design environment differs significantly from those of fission Nuclear Power Plant in several respects, such as high heat fluxes (on the first wall and the divertor plate), high energy neutrons irradiation inducing phenomena of embrittlement, swelling and irradiation creep, and plasma disruptions generating high magnetic dynamic loads.

The geometry of the vacuum vessels, first walls divertors and other main components in fusion plants is also to be considered.

Therefore, the San Diego ITER joint central team (JCT) has initiated a task which objectives were formulating, documenting and justifying Structural Design Criteria for ITER.

A document has been edited (ISDC: Iter Structural Design Criteria) which issues the general design rules for ITER. A joint justification document presents the background of the different rules and arguing about the choices made.

The task on Structural Design Criteria is now going on to complete some specific sections of ISDC, to conduct trial analysis for analytical and theoretical tests and to plan experimental validation tests.

Irradiation may induce substantial evolution in the mechanical behaviour of steels, these evolutions being favourable or unfavourable, depending on the phenomena considered and on the type of mechanical damage.

The effects of irradiation and their influence on the mechanical behaviour are listed in this paper. The mechanisms involved are very complex but for macroscopic behaviour, three main phenomena have to be considered: irradiation-induced creep, irradiation-induced swelling and changes in material properties.

Consequent specific damages are then to be assessed in the design analysis. Moreover, the treatment of non-specific damages must include irradiation influence.

The present version of ISDC will be presented and main technical issued will be discussed.

2. THE ITER MACHINE

ITER is a tokamak fusion experimental reactor, which intends to demonstrate the potentiality of ignition (self supporting of a fusion reaction). Ignition supposes a thermal power of 1500 MW during an impulsion of 1000s.

The project also aims to demonstrate the safe behaviour of fusion reactors.

Many experimental reactors, using tokamak principle, have preceded ITER: *Tore Supra* (CEA/Cad, 1988), *TFTR* (US), *JT-60* (JA), *JET* (EC; 1978-1999). All of them have proved satisfactory operation conditions, both on the mechanical and on the fusion related points of view, but ITER dimensions are to be much more important than JET, that has still produced a thermonuclear power of 2 MW (e.g. 250 millions degrees during 2s).

The construction is planned to take place between 1998 and 2005 and the exploitation phase will follow for a period of twenty years (e.g. up to 2225).

ITER will also constitute an experimental base for the demonstrative project that will be the last step before the industrial phase for fusion power, in the frame of the *DEMO* project.

3. ISDC : ITER STRUCTURAL DESIGN CRITERIA

Design criteria for ITER have been developed within the scope of an international working group, providing design rules in order to address the special features of fusion reactors.

The code has been based on an existing code to the extent that it was possible to do so. The general approach has been to select a single code as a basis, to modify the code as necessary to meet the needs of the designers and to seek comments from the different home teams. A consensus has been made by the experts representative of the different countries to take RCC-MR, the European Design Code for LMFBR, as a sound basis to develop ITER Design rules "by analysis". This choice has been determined by the fact that RCC-MR is the most recently developed published code that was applicable to fast reactors, wich need larger application domain of design methods than pressurised reactors components

ISDC have been developed in such a way so that it is acceptable to all four parties. Then, the criteria have been derived from RCC-MR, by addition of rules or modification of the current rules. To take the most of the international co-operation, these changes have encompassed the best features of the nuclear Codes used by the other parties:

- Case N47-29 for US
- Miti notification N501 (Monju Guide) for JA
- PNEAG-7-002-86 for RF

RCC-MR, like the other nuclear Codes, doesn't take into account irradiation effects. But analysis rules for irradiated material are proposed in the frame of ISDC, accounting for the effect of embrittlement, swelling, and creep.

The task on Structural Design Criteria has been performed in parallel with a task on Material Properties Handbook (MPH) which aims to develop fundamental engineering properties of materials to be used in thermal, stress and electromagnetic analysis. Both the tasks are developed in close cooperation in order to obtain a self supporting document including both the rules and the limits to be applied.

At their final stage, the criteria will include the following topics:

- Scope and applicability of the rules
- General design rules
- Design by experiment
- Technical appendices including material properties
- Construction, qualification and inspection.

4. IRRADIATION EFFECTS

Irradiation effects are due to a succession of atomic displacements following collisions between fast neutrons and the nuclei of the crossed material.

The neutrons flux causes modifications in the crystal network, such as transmutations, ion implants, atom displacements or lattice defects. It enhances the precipitation of impurities and phase modifications, inducing detrimental effects on material properties.

Induced crystal defects (isolated pairs, loops, cavities) may give rise to different phenomena such as:

- swelling due to ion implant (for $\theta < 200°C$)
- swelling due to lattice defects (void growth)
- hardening due to loops
- precipitation directed by the loop: irradiation creep
- inter granular embrittlement
- sensitivity to corrosion

Inter granular embrittlement is due to Helium bubble precipitation at grain boundaries, but the temperature at which it appears is high (500°C) and this phenomenon has not to be considered for ITER.

The sensitivity to corrosion is due to a change in the chemical distribution near grain boundaries. We will not deal much with the corrosion aspect as, even if it is now known to be an important factor for the appearance of degradation, the phenomenon is not adequately understood.

4.1 Irradiation measure

Irradiation effects depend on the temperature, the energy of the neutrons, the neutron flux and on its integral with time (fluence).

Usual units of measure of fluence is:

n/cm^2 (E > 0.1 MeV)
or n/cm^2 (E > 1 MeV)

Fluence is often related to the number of atomic displacement: *dpa*. The correlation between fluence and the number of *dpa* depends of the neutron spectrum.

4.2 Irradiation- induced creep

Irradiation creep is due to directed precipitation of dislocation loops under irradiation. This phenomenon can be superimposed on classical creep phenomenon, increasing it.

For stainless steels, irradiation creep rate can be considered to be proportional to the applied stress (Walters, 1977); it depends also on flux and on swelling.

As thermal creep, irradiation-induced creep, due to atom displacements, leads to strains which shall be bounded. These strains are considered as "non damaging" because, as creep rate is directly proportionnal to the stress, instability necking is reduced and no creep rupture tests have never been achieved. But this strain, as with other inelastic strains, must be considered for exessive deformation, fatigue and ratchetting assessment.

On the other hand, irradiation creep relaxes residual or strain control stresses.

4.3 Irradiation- induced swelling

Irradiation can cause large structural distortions, due to swelling in isotropic materials or growth in anisotropic materials. Swelling is due to the aggregation of lattice defects.

It is generally admitted that swelling is proportional to fluence, and is also dependent on temperature, for temperature and fluence greater than thresholds values.

Addition of impurities (such as titanium) or work-hardening limit swelling. For example, at 500°C, volumetric swelling of 316 steel, for a fluence of 70 dpa, is equal to 8%, if annealed, 2%, if 20% work-hardened, and less than 0.5% for 316 ti 20% work-hardened (Gauthron, 1986].

Swelling reduces also the Young's modulus.

This phenomenon is irreversible and may lead to high stresses. Such stresses are strain controlled and relaxation effects of irradiation-induced creep give benefits to be considered in the calculation of the constrained swelling stresses.

Abo-el-ata (1978) showed that due to irradiation induced relaxation, swelling stress rapidly reaches a maximum value, considering simplified, but realistic, swelling and creep laws. Abo-el-ata noted that temperature dependence of this stress varies with the material but the variation is generally low.

4.4 Irradiation- induced changes in material properties

Large changes in material properties can be induced by atomic displacements due to irradiation, and enhanced by irradiation creep. Irradiation-induced changes in material properties are mainly correlated to irradiation embrittlement (transgranular).

Significant irradiation induces hardening and loss of ductility, strain-hardening capability, and fracture toughness. These phenomena can occur at a relatively low fluence (5 or 10 dpa).

4.4.1 Tensile characteristics

Irradiation influence on tensile properties is similar to a cold-working effect. Indeed, hardening is due to irradiation defect precipitating in loops, whose nature is very similar to the one of dislocations that are present in cold-worked materials.

A large increase in the yield stress can be seen and, on a smaller scale, in the rupture stress, and a great reduction of the ductility. For cold-worked materials, the increase in stress is lower than for annealed materials.

Typical irradiated and non irradiated tensile curves are shown in figure 1.

Real ductility is generally unknown as striction measurement is very difficult on irradiated sampling. Available values are uniform elongation and rupture elongation.

For cold-worked 316 SS, uniform elongation is very low (less than or equal to 1% for 350°C).

Rupture elongations are larger (up to 7%).

Even if striction has been observed to be very limited, values of true ductility are expected to be less unfavourable than the elongation values.

These phenomena depend on fluence but reach maximum (or minimum) values for fluence of approximately 4 10^{22} n/cm^2 (E >0.1 MeV) (e.g. 20 dpa) for annealed stainless steels, and 2 10^{22} n/cm^2 (E >0.1 MeV) (e.g. 15 dpa) for cold-worked ones (cf. figure 2 for typical evolution laws for a cold-worked 316 stainless steel).

The Young's modulus is not much influenced by irradiation, as long as the swelling is limited.

4.4.2 Fatigue characteristics

Due to enhanced yield and rupture stresses and the reduction of ductility, fatigue life of irradiated components is reduced for low cycle fatigue but increased for low strain ranges (Murty, 1982) (cf. figure 3).

Consider Manson's equation for fatigue life (Manson, 1953),

$$\Delta\varepsilon_t = 3.5\left(\frac{S_u}{E}\right)N^{-0.12} + \varepsilon_{tr}{}^{0.6}\,N^{-0.6}$$

It can be seen that fatigue life reduction, for oligocyclic fatigue, is equal to the ratio between irradiated and unirradiated ductility.

Irradiation has little effect on the defect propagation rate in fatigue.

4.4.3 Toughness characteristics

Cracking strength J_0 (i.e. energy necessary to initiate a existing defect) and tearing modulus T (i.e. hindering propagation of the crack once initiated) decrease significantly under irradiation (Huang, 1988):

at θ = 400°C, for a cold-worked 316SS,

	Φt = 0	*Φt = 50 dpa*
J_0	60 kJm^{-2}	30 kJm^{-2}
T	150	15

5. IRRADIATION RELATED DAMAGES

In this paragraph, we are going to deal with the irradiation damages, e.g., the mechanical consequences of the above described effects of irradiation on materials properties.

We will firstly deal with the rules that must be modified in their content (but not in their formal presentation) to account for irradiation; and we will secondly expose the irradiation-induced damages that are not considered at all in usual design codes as RCCM, RCC-MR or ASME Codes.

Irradiated structures have two opposite singular properties. As cold-worked material, they have a good resistance to load because of their high yield stress. But they can be very dangerous as the domain between the end of elasticity and rupture is severely limited.

Taking irradiation into account in the design stage gives way to modify allowable stresses for classical damages and also allows specific failure risks to be considered.

5.1 Classical damages

The main element to be pointed out when irradiation structures are considered is the time effect, even in the domain where thermal creep is negligible. As a consequence, allowable limits depend on time,both for monotic and cyclic loads.

Concerning cyclic load, irradiation effect affect the strain limit. For progressive deformation limitation, the strain limit shall take account for the ductility exhaution. Also, the ratchet strain limit shall be a small fraction of the true ductility if this one is sufficiently low.

Fatigue analysis of irradiated materials shall take into account two effects of irradiation. The first one is the modification of the fatigue curves under irradiation. As the procurement of such curves is quite difficult, not much material characteristics are available and most analysis are going to be done using the unirradiated fatigue curves. Correction factor must so be proposed.The second one is the possible change in the inelastic strain range value. Therefore, the strain range determination procedure, based on the elastically calculated strain range, shall consider potential elastic follow-up due to irradiation. Indeed, as fluence varies in a given component, material characteristics may vary much from one point of the structure to another inducing strain concentration in the weaker parts.

5.2 Specific damages

Loss of ductility and low hardening moduli are the major factors that induce additional damages. They lead to limit inelastic strains, even for high hypothetical loadings.

When examining, the potential failure mode due to loss of ductility, it can be seen that usual design rules for unirradiated structures do not prevent against this type of failure in two cases:

- under primary stresses, for level D criteria(high hypothetical loadings), the global strain is limited by the uniform elongation but local strain may reach greater values,
- under secondary (or total) stresses, the strains are usually limited only for their cyclic effect under in-service loading: they may be much higher than the elastic limit, even for level A criteria, due to an elastic follow-up effect.

Safety margins must be taken to prevent against the failure by loss of ductility. In this case, the total strain has to be evaluated and should be limited to a fraction of the true ductility. Its implies that secondary loads have to be limited non only for cyclic effects but also to prevent rupture during the first quarter of a cycle (cf. figure 4).

In order to compute the total strain, it must be noted that due to elastic follow-up effect, secondary stresses are not always kinematically determined. (Roche,1985) proposes a method to account for this effect using an elastic follow-up factor r.

Another point has to be considered concerning strain limits. For irradiated stainless steel, onset of necking occurs very early for fluences greater than 5 dpa. At the design stage, primary stresses are limited to a fraction of the ultimate tensile stress (Su). If, during the life of the component, the strain exceeds the value of ε_u, then the actual ultimate tensile stress may become lower than Su. Therefore,stress limit shall consider both the usual stress limits (Sy and Su) but also the limit in ductility. This implies that the long term behaviour is not always the more severe and that sensitive materials are those for which the strain hardening is limited, such as cold-worked stainless steel.

Loss of toughness is not usually considered at the design stage, but in the particular case of a material of very low toughness, fast fracture of undetected defects has to be prevented.

Irradiation creep shall be considered as interfering with progressive deformation. Moreover, long term excessive deformation due to irradiation creep is a potential damage.

In conditions where thermal creep is negligible, relaxation of stresses due to irradiation shall be examined. As the irradiation creep rate is lower than the one for thermal creep, it should be taken into account the fact that the relaxation time is longer but that the reduction in the extreme fibber bending stress and the effect of the creep redistribution on local primary stresses are not so great as in the case of thermal creep.

When the thermal creep is significant, the creep laws have to be determined in irradiation conditions as irradiation decreases the creep rate but also decreases the lifetime during creep (Dupouy, 1977).

Irradiation assisted stress corrosion cracking (IASCC) should be taken into account as irradiation has an effect on the intergranular stress corrosion cracking (IGSCC) resistance (Clarke, 1983). But the laboratory results are not sufficient at the present time to allow for the proposal of a criteria to prevent against IASCC.

6. ITER GENERAL DESIGN RULES

ITER general design rule for class 1 component (IRB 3000) have been derived from RCC-MR, taking into account irradiation damages as stated before, and considering, for the general design rules, a critical comparison of the corresponding rules from other public codes.

Not all the issues have yet been resolved and some validation tests and trial analyses are now been carried out in order to have more confidence on the proposed rules.

The present document encompasses the following sections:

SECTION I - FUSION REACTOR COMPONENTS
  SUBSECTION "A" GENERAL
    IRA 1100 General
    IRA 1110 Introduction
      IRA 1111 Features Unique to ITER
    IRA 1120 Organisation of this document
SUBSECTION "B" CLASS 1 COMPONENTS
  IRB 1000 GENERAL
    IRB 1100 INTRODUCTION
  IRB 3000 DESIGN RULES FOR CLASS 1 ITER COMPONENTS
    IRB 3100 GENERAL DESIGN RULES
    IRB 3200: GENERAL RULES FOR ANALYZING COMPONENT BEHAVIOUR

IRB 3210 General
IRB 3220 Analysis related terms
IRB 3230 Constitutive equations for materials used in the various analyses
IRB 3250 Rules for the prevention of M type damage
    IRB 3251 Immediate damage
    IRB 3252 creep-related damage
IRB 3260 Rules for the prevention of C type damage
IRB 3261 Negligible thermal and irradiation-induced creep
APPENDIX A1 Materials characteristics

6.1 Negligible or moderate Swelling and creep tests (IRB 3216)

These tests have been introduced in a paragraph introductory to the component analysis, in order to determine:

- the type of analysis to be conducted,
- the type of rules to be applied.

A pessimistic swelling strain can be deduced from the irradiation history. Swelling is said to be moderate if swelling, expressed as a change in volume per unit volume, does not exceed 6%. In that case, an elastic analysis considering low displacements hypothesis is valid. In the opposite case, a visco-plastic analysis is necessary.

Independently of this test, swelling may be or not be considered as negligible over a certain period of the life of the component. This is verified by the negligible swelling test of IRB 3250 (rules for monotonic loads). This test has not been included in IRB 3216, as swelling may be considered as negligible during the operating life of the component and can become significant only in faulted conditions.

If swelling is considered as negligible, swelling strain will not be explicitly limited but swelling induced stress will be added to other stresses.

For given flux and temperature, creep is considered as negligible during a time t, if the creep strain due to the application during the time t of a given stress does not exceed 0.05%. This stress has been taken as equal to 1.5 $Sm(\theta, \Phi t)$, which is the value limiting the primary membrane-plus-bending stress intensity in IRB 3250.

To integrate the creep damage over the all life, a usage fraction rule has been defined, considering that the life of the component may be divided in a limited number of intervals during which the temperature and the flux may be considered as constant.

6.2 Rules for monotonic loads (IRB 3250)

For stress limit, it is convenient to use, the lower stress limit within the life of the component, corresponding to the material characteristics in the unirradiated phase .

The local membrane stress is limited by S_e in order to insure the loading capability of the structure (reduction in uniform elongation):

$$S_e(\theta, \Phi t) = \frac{\alpha\, E\, \varepsilon_u + (r-1)\, \beta\, S_u}{r}$$

where r is an elastic follow-up factor and α, β accounts for the structure dependence of the uniform elongation ε_u and the conventional rupture stress S_u.

The total stress is limited in by S_d order to prevent against rupture by loss of ductility:

$$S_d(\theta, \Phi t) = \frac{E\,\varepsilon_{tr} + (r-1)\,S_{tu}}{3\,r}$$

where ε_{tr} is the minimum true ductility and S_{tu} is the minimum true rupture stress

For these equations, the total stress has to be determined, including the swelling induced stress. Considering the calculation described in paragraph 4.3, swelling is regarded as an additional load, with a value equal to this asymptotical stress, included irradiation creep relaxation.

6.3 Rules for cyclic loads

For progressive deformation, either of three methods, namely "efficiency diagram rule", "Bree diagram rule" and "3 Sm rule", are proposed. The method "efficiency diagram rule" is derived from RCC-MR (*RB 3261.1.1.4: efficiency diagram*). The method "Bree diagram rule" is derived from CASE N47-29 (*T1330: satisfaction of strain limits using simplified inelastic analysis*): *test B-1* for test 1 and *test B-3* for test 2. Test 1 insures that the structure behaves in the domain E, S1, S2 or P of the Bree diagram, corresponding to elasticity, shakedown or cyclic plasticity, without ratchetting.

The efficiency diagram rule and test 2 of the Bree diagram rule do not impose to ensure shakedown and allow for a limited progressive deformation.

For austenitic stainless steels, the imposed limitation on the effective primary stress means that, in the most unfavourable case, a membrane strain of 0.45% is allowable which is acceptable as long as the cumulated strain is negligible in regard to the material ductility, e.g. for material ductility up to 5%.

For strain limits, associated to cyclic loads in case of test 2 of the Bree diagram rule, it has been chosen to break down the total operating period into several intervals of time, during which temperature and flux change as little as possible. The strain limit is then replaced by an usage factor that linearly combined the unitary usage factor for each intervals of time. The strain limit is calculated for the worst temperature and fluence conditions in the interval and take into account the true ductility for the considered conditions.

For fatigue evaluation, fatigue curve correction factors are proposed.

In the oligocyclic fatigue region, the number of cycles to failure is proportional to the ductility. A correction factor $(fi)_j$ is then proposed, which is equal to the ratio between the minimum instantaneous ductility, function of temperature and independent of fluence (ε_{tr}), and the minimum instantaneous ductility function of temperature and fluence (ε_{tri}):

$$fi_j = \left(\frac{(\varepsilon_{tr})_j}{(\varepsilon_{tri})_j} \right)$$

High fatigue life of a material depends on its strength rather than on its ductility and the above correction factor $(fi)_j$ may be overly conservative in this region. So ISDC proposes as an alternative procedure to determine the fatigue life correction considering the other terms of the fatigue life equation. In order to take into account an endurance limit, and to have a few coefficient to determine, a fatigue life equation for the unirradiated "design curve" has been considered in the form of the equation proposed by (Langer,1971):

$$\Delta\varepsilon = A\,N^{-0.5} + B$$

As design fatigue curves in appendix A1 are not given in that form, the coefficients A and B are to be fitted on the curve.

The exponent of the equation (here -0.5) is assumed to be the same for the irradiated and unirradiated data. Then design allowable number of cycles (N_j) under irradiation, corresponding to a strain variation $\Delta\varepsilon$ is given by the following equation:,

$$\Delta\varepsilon = \Phi_e\, B + \Phi_p\left[A\left(N_j\right)^{-0.5}\right]$$

where, denoting the unirradiated values by the subscript u :

$\Phi_e = \left(S_u\right)_i / \left(S_u\right)_u$, $\Phi_p = \left(\varepsilon_{tr}\right)_i / \left(\varepsilon_{tr}\right)_u = (fi)_j$

Nevertheless, fatigue data on irradiated material will be ultimately needed to validate the fatigue design of ITER.

The value of the real strain range, for entering the design fatigue curves, is obtained from the elastically calculated one using a simplified elasto-plastic route, either by the RCC-MR procedure nor (as an alternative rule) by the procedure of ASME Code section III (NB 3228.5).

The first procedure is based on a two coefficients rule: K_ε account for the effect of extended cyclic plasticity and concentration region, K_v account for effect of triaxiality.

In the alternative one, the real strain range is obtained by multiplying the elastic strain range, excluding the part that is deformation controlled by the factor K_e. This procedure is derived from the works of Tagart and Langer.

7. CONCLUSION

A document including a set of criteria for the general design rules and an accompanying justification document is now available for the design team in charge of the ITER engineering project. The proposed methods could be useful to assess the design of irradiated structures like experimental irradiation devices or fission core structures.

Ensuing work is focused on the topics that have not been entirely treated in ISDC.

Thermal creep damage assessment, in irradiated and high temperature conditions, need a better knowing of the creep laws in these conditions.

Design by experiment is a priority matter as design by analysis would not be possible in the design of some specific structures of ITER. So are the rules dedicated to multi-layer components: in this case, special rules are to be defined as usual Design Codes do not provide rules for these structures.

Experimental work is needed in order to validate the proposed rules. As experiments on irradiated component are long, expensive and difficult to achieve, substitution material are now studied that will allow to treat the same problems but within less delays and with more instrumentation, for a better understanding.

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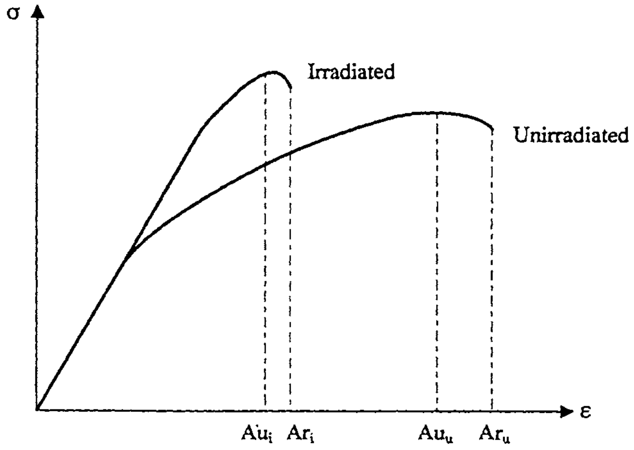
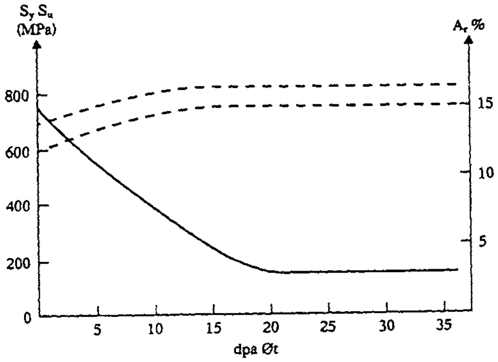


figure 1



1 dpa = 1.4 10^{21} n/cm^2 (E > 0.1 MeV)

figure 2

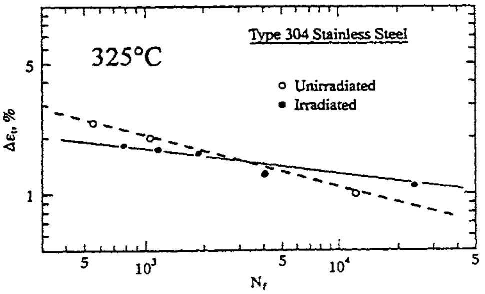


figure 3

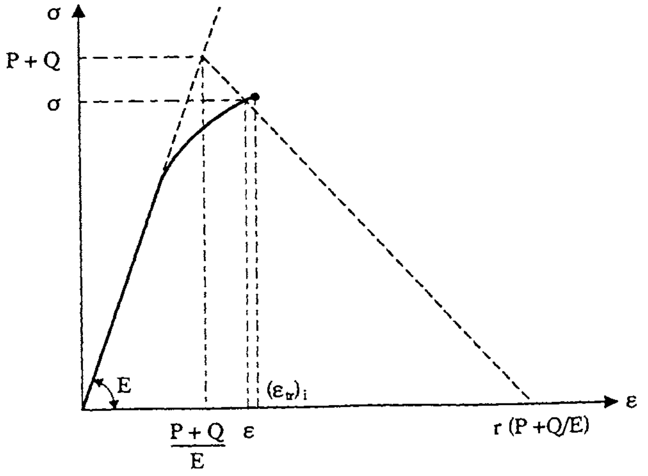


figure 4