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Preliminary Elevated-Temperature Core Structures Design Criteria

W. J. McAfee
T. W. Pickel

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Reactor Division

PRELIMINARY ELEVATED-TEMPERATURE CORE STRUCTURES DESIGN CRITERIA

W. J. McAfee
T. W. Pickel

MARCH 1976

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

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FOREWORD

This compilation of design rules for elevated-temperature reactor core structures was prepared as part of the High-Temperature Structural Design (HTSD) Program (189a OH048) at the Oak Ridge National Laboratory. The purpose of the program is to develop verified structural design methods and criteria for reactor system components and nonreplaceable core structures that operate at temperatures in the creep range. The program is sponsored by the Division of Reactor Development and Demonstration of the U.S. Energy Research and Development Administration (ERDA) (formerly U.S. Atomic Energy Commission).

A number of individuals contributed to the preparation of this report. W. K. Sartory provided assistance in data analysis where recommended design curves were developed. A. W. Dalcher, formerly of Atomics International; H. D. Garkisch of Westinghouse-ARD; and E. Y. W. Tsui, J. V. Marron, and A. T. Brown of General Electric Breeder Reactor Department supplied recommendations for design rules. W. J. O'Donnell provided valuable input to this effort through his review of and comments on the initial draft of this document. Finally, the authors wish to thank J. M. Corum and W. L. Greenstreet for the programmatic direction provided within the HTSD Program.

PRELIMINARY ELEVATED-TEMPERATURE CORE STRUCTURES DESIGN CRITERIA

W. J. McAfee
T. W. Pickel

ABSTRACT

Rules are recommended for use in the design of elevated-temperature core structures that are classified as being non-replaceable. These rules are presented in a format similar to ASME Code Case 1592 and RDT Standard F9-4 and are presently limited to design with annealed and irradiated types 304 and 316 stainless steel.

The design rules contained in the above criteria have been used as the basis for these recommendations. The concept of satisfaction of both stress and strain limits has been retained. The effects of irradiation have been included wherever possible through modification of the existing high-temperature design limits to reflect the manner in which material properties change with increasing fluence. Additional deformation and failure modes that may be significant for structural materials subject to neutron flux have been identified and preliminary scoping rules included.

Key words: Core structures, core structural design, high-temperature design, LMFBR Program, irradiation effects, ASME BPV Section III, ASME Code Case 1592, RDT Standard F9-4.

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1. INTRODUCTION

1.1 Background

The design of advanced reactor systems to operate at elevated temperatures requires the use of structural design and analysis methods that, in many cases, exceed the limits of the available technology. In recognition of this, national programs have been formulated to develop this needed technology. One such effort is the High-Temperature Structural Design (HTSD) Program at the Oak Ridge National Laboratory, which has as its objective the development of verified high-temperature structural design methods and criteria applicable to LMFBR components and core structures.

The work reported herein covers the task of developing preliminary structural design rules for core components.

In developing a suitable program plan for the HTSD Program, an identification of the state of the art is required to form a foundation from which needed research and development plans can grow. For the HTSD Program, interpretive reports by experts in the field have played an essential role in state-of-the-art assessments and formulation of research and development (R&D) plans. These interpretive reports provide for utilization of the knowledge and ideas of leaders in the fields of design, analysis, and materials behavior.

For the task of developing design rules for core structures, several companies with highly developed commercial reactor and Liquid-Metal Fast Breeder Reactor (LMFBR) programs were contacted to prepare interpretive reports. These reports were to include recommendations for design rules and the needed R&D to support these rules. The companies participating in this activity were Atomics International; General Electric, Breeder Reactor Department; and Westinghouse Advanced Reactors Division. The reports for recommended design rules from each of the above companies are listed as references 1, 2, and 3 respectively.

In addition, ORNL has maintained close contact with ASME and RRD groups working to develop elevated-temperature design criteria and analysis guidelines. The developments under the ORNL HTSD Program have been extensively utilized as they relate to unirradiated materials behavior. No experimental irradiation effects studies were performed as part of this effort, but use was made of as much data as could be found on the effects of neutron irradiation on the behavior of structural materials. An assessment of all the above information forms the basis for the recommended design rules contained herein.

1.2 Scope

The purpose of this document is to recommend design rules for reactor core structures, exclusive of fuel cladding, where the effects of irradiation and elevated temperatures on reactor structural materials, as well as time-dependent material behavior, must be taken into account. Irradiation

effects are considered not to be significant below a fluence of 10^{20} neutrons/cm^2 ($E > 0.1$ MeV). This fluence is thus taken as the lower limit at which these rules are to be applied. These rules are intended to apply to components designed to function for the lifetime of the plant, that is, permanent or nonreplaceable components. Since permanent structures are given primary consideration, a philosophy and, in many cases, design rules similar to those of the ASME Codes have been adopted. These rules do not apply directly to replaceable or consumable components, although the designer may at his option utilize these guidelines for such structures. Generally, however, replaceable components are designed for high end-of-life fluences and relatively short lifetimes and may require special design considerations or design methods. For such components, alternate design rules to those contained herein may more specifically reflect the necessary design needs and performance standards.

Section III of the ASME Boiler and Pressure Vessel Code[4] contains design criteria and limits applicable to nuclear components under service conditions where thermal creep and relaxation effects are negligible. Subsection NG of Section III contains design rules for core support structures but, like Section III, is limited to maximum temperatures of 800°F. Additionally, Subsection NG does not explicitly address fluence effects, so that the designer is left essentially to his own devices. Thus only time-independent failure modes of unirradiated materials are considered. Section III is supplemented by ASME Code Case 1592-1 (Ref. 5), RDT F9-4T (Ref. 6), and RDT F9-5T (Ref. 7) to provide design rules, allowable stress limits, and analysis guidelines under service conditions where the time dependency of materials properties and structural behavior is important.

In formulating these criteria, principal concerns have been the loss of material ductility due to irradiation and the alteration of structural response due to irradiation-induced creep and swelling. These are reflected in both the rules and the limits proposed.

The rules are presented in a format very similar to RDT Standard F9-4 and ASME Code Case 1592. This is, to some extent, a matter of convenience since the proposed rules are based on the design guidelines for elevated temperatures as set forth in the above Standard and Code Case. In addition, presentation of the core structures design rules in a form which is

already familiar to the designer should simplify implementation. An effort has been made, where possible, to establish design rules and limits that are continuous functions of accumulated neutron fluence. The purpose is to avoid situations where large step changes in design limits are encountered as the accumulated fluence increases. In addition, it has been the intent to recommend rules that are consistent with the rules of existing codes and standards[4-6] where the criteria contained herein interface with these codes and standards.

To provide the designer with a general overview of major rule or limit changes as compared to ASME Code Case 1592 and RDT Standard F9-4, Table 1.1 has been prepared. This table does not represent every detail of variance between the subject documents, but it does present, in a highly concise form, features that the designer should be aware of in applying these rules.

The general effects of irradiation are to increase tensile strength, decrease tensile ductility, decrease creep-rupture strength and ductility, decrease fatigue resistance, and decrease fracture toughness. In this document, irradiation is considered as degrading all mechanical properties, and allowable limits are decreased with respect to unirradiated material limits. (An exception is certain cases of elastic analyses where enhanced tensile strength may be used.) The proposed limits on stress are intended to insure adequate ductile material response and to consider the fluence dependency of both mechanical strength and ductility. Generally, the stress limits are viewed as preventing a short-term structural overload, whereas long-term behavior is limited more by deformation.

The strain limits proposed are based on postirradiation tensile and creep-rupture elongation data. It is recognized that postirradiation time-dependent data do not adequately represent in-reactor behavior, but, until in-reactor data are available in sufficient quantity to formulate design information, the limits on deformation contained herein are recommended. Stress rupture limits are also formulated on the basis of postirradiation data, and the same reasoning as for deformation limits applies. The fatigue limits have been based on a Universal Slopes type equation where loss in tensile ductility is used to predict the decrease in fatigue strength with increasing fluence. Any enhancement of fatigue strength

Table 1.1. Summary of Major Rule or Limit Changes as Compared to ASME Code Case 1592 and RDT Standard F9-4

I. Load-Controlled Stress Rules

A. Introduces S_{It}, a fluence- and time-dependent stress limit that is applicable to Normal plus Upset, Emergency, and Faulted Conditions.

B. Provides for use of S_m, based on postirradiation tensile properties, for special loading cases.

C. Requires evaluation of Life-Fraction where the properties of irradiated materials are considered.

II. Strain and Deformation Rules

A. General simplified methods (elastic) are not sufficient where irradiation-induced swelling strain plus irradiation creep are equal to or greater than 0.05%.

B. The strain categories of wall average, equivalent linear distribution, and peak are preserved, but the limits are fluence dependent.

C. Irradiation-induced creep and swelling strains are limited only through functional requirements.

D. In addition to the rules as contained in ASME Code Case 1592 for satisfaction of strain limits using elastic analysis, limits are also specified for the creep strain.

III. Fatigue and Creep Rules

A. Fluence-dependent limits are provided for assessing fatigue strength.

B. Rules are provided to modify creep limits with fluence.

C. Irradiation-induced swelling and creep strain are not considered in the damage evaluation.

IV. Rules for Brittle Materials

A. All materials for use in core structures shall be classified as being in the ductile or brittle state with respect to a particular application and operating environment.

B. Rules provided are intended primarily for scoping purposes. For more detailed consideration of fracture behavior, the designer is referred elsewhere.

C. A procedure for classifying materials as being in the ductile or brittle state is provided.

D. Rules provided are based on concepts of linear elastic fracture mechanics.

predicted by the Universal Slopes equation due to increases in tensile ultimate strength are not allowed. While all the limits as discussed above have been developed using postirradiation data, provisions are included that permit the designer to utilize in-reactor data as they become available.

An additional potential failure mode for which rules are included is that of brittle fracture. Brittle behavior of highly irradiated materials covered by this document has as yet to be adequately demonstrated. However, the large decrease in ductility with increasing fluence seems to imply the potential for brittle fracture. The rules included herein are intended primarily for scoping purposes and to provide limits that would indicate the need for more detailed fracture mechanics analysis.

It must be realized that some of the materials data required for the support of this document are not now available. The designer is thus required to provide data, make extrapolations, or restrict design, subject to the approval of the Owner, if the design rules of this document are to be satisfied. It must also be understood that this document is not intended to supplant the ASME Code or Code Cases; where there is a conflict, the latter will take precedence. Implementation of these design rules requires the design curves contained in ASME Code Case 1592 (Ref. 5). For materials data, the designer is referred to the Nuclear Systems Materials Handbook, Design Data.[8]

2. GENERAL REQUIREMENTS

2.1 Materials and Material Properties

The materials for use with the criteria of this document are presently limited to annealed and irradiated types 304 and 316 stainless steels. This restriction is dictated by the lack of data on the high-temperature time-independent and time-dependent behavior of irradiated materials. The inclusion of other materials for use with these criteria must be evaluated as data on high-temperature irradiation effects become available.

In addition to the materials properties information provided in this document, data and correlations from the following sources may be used without prior approval of the Owner: Section III, ASME Boiler and Pressure Vessel Code,[4] ASME-BPV Code Case 1592,[5] and Nuclear Systems Materials Handbook, Design Data.[8] Use of these data is subject to the corrections for irradiation effects as included in these criteria.

2.2 Modes of Failure

Modes of failure considered by the design rules of this document include

1. ductile rupture from short-term loadings,
2. creep rupture from long-term loadings,
3. creep-fatigue failure,
4. excess accumulation of inelastic strain, including strain ratchetting,
5. brittle fracture.

Also, brief guidelines are provided for the following additional failure modes.

1. loss of function due to excessive deformation,
2. buckling due to short-term loadings,
3. creep buckling promoted by changes in geometry due to creep deformation associated with long-term loadings,
4. buckling due to dimensional changes caused by neutron irradiation,

5. fracture by strain concentration due to irradiation-induced loss of material strain-hardening capability.

2.3 Core Component Classification

In establishing the design rules and limits contained in this document, the intent was to provide criteria which are continuous with increasing fluence. However, beyond the fluence levels shown in Chapter 5, the design rules are tentative. These rules, including the basis for establishing them, may change as a better understanding of irradiated material behavior is gained. It is the responsibility of the designer to take cognizance of this fact, to evaluate a component based on its end-of-life fluence and proposed operating history, and to provide for replacement where needed.

2.4 Analysis Methods

Inelastic analyses are sometimes required to demonstrate adherence to the criteria contained in this document. However, it is the intent to permit broad usage of elastic analyses, including cases of irradiation swelling and irradiation creep and swelling. For those cases requiring detailed inelastic analysis, guidelines for methods to be used without prior Owner approval are given in RDT Standard F9-5T.[7] These methods presently apply only to unirradiated materials; thus the designer is required to supply the methods for performing irradiation creep and swelling analyses. The materials properties information required to implement these methods should be obtained in accordance with Section 2.1.

2.5 Ductile-Brittle Material Behavior Classification

One effect of neutron irradiation on structural materials is a loss of ductility to the point where these materials may exhibit brittle tendencies due to flaw sensitivity. All materials for use in LMFBR core structures shall be classified as being in the ductile or brittle state with respect to a particular application and operating environment. This classification shall be based on all available materials properties data,

past experience, estimates of flaw characteristics, and critical-stress-intensity factors. In this document, brittle fracture is considered to be crack initiation and unstable crack propagation under applied loads where only small plastic strains are developed during fracture (see Sect. 3.1). A phenomenon similar in appearance is that of failure by localized strain concentration due to irradiation-induced loss of material strain-hardening capability. In such failures, unlike brittle failures, large highly localized plastic strains are accumulated. Design guidance to guard against this mode of failure is given in Chapter 7.

2.6 Neutron Spectrum Effects

The design guidelines used in these criteria are presented in terms of fast fluence, that is, time-integrated flux with energy greater than 0.1 MeV. Irradiation damage and the response characteristics of the material are dependent on the spectrum of the irradiating neutron flux. Thus, the designer must consider the effect of the neutron spectrum in assessing the rules and limits of these criteria. The methods used must be subject to Owner approval and be justified in the Stress Report.

3. DEFINITIONS

General terms used in this document are defined in this chapter. Primarily, it is the intent to present terms related to irradiation effects on a basis consistent with existing criteria. As such, there is some repetition of definitions included in ASME Section III and supporting Code Cases. Some terms needed for special applications are defined where used.

3.1 Controlled Quantities

In these design criteria, the stress and strain limits for design evaluation are related to the type of structural response under loading. The controlled quantities fall into two categories.

3.1.1 Load-Controlled Quantities

The limited quantities are mainly stress intensities which result from equilibrium with external loads during plant operation. Included in this category are primary general membrane, local membrane, and bending stresses; and secondary stresses with a large amount of elastic follow-up.

3.1.2 Deformation-Controlled Quantities

These quantities are strains, cyclic strain ranges, or deformations which result from load deflection and/or strain compatibility.

3.2 Damage and Failure Modes

3.2.1 Brittle Fracture

In this document, brittle fracture is defined as a failure by unstable crack propagation from an existing or developed defect at stress levels not exceeding a critical stress (see Chapter 8). Such failures are generally characterized by a sudden energy release and by low local elongations.

3.2.2 Creep Damage

Thermally activated creep damage is that part of the total material damage caused by time exposure to steady and transient stresses at elevated temperatures. This damage is expressed as a time ratio and is affected by the presence of a neutron flux. Relaxation damage is a special case of creep damage caused where the total strain, elastic plus inelastic, remains constant. The stress level is reduced during relaxation as the material undergoes creep strain.

3.2.3 Creep-Fatigue Interaction

The creep-fatigue interaction is the effect of combined thermal creep and fatigue on the total accumulated material damage at failure.

3.2.4 Fatigue Damage

Fatigue damage is that part of the total material damage caused by cyclic deformation which is independent of creep effects such as stress or strain hold times and frequency. This damage is expressed as a cycle ratio and is affected by the presence of a neutron flux.

3.3 Design Conditions

The specified design parameters for the Design Conditions loading category shall equal or exceed those of the most severe combination of assumed coincident pressure, temperature, and load forces specified under Normal Conditions (see Sect. 4.1) for the same zone of the component. These specified design parameters for Design Conditions shall be called Design Temperature, Design Pressure, and Design Mechanical Loads and shall be used in computations to show compliance with the requirements on Design Conditions in Subsection 6.2.1.

3.3.1 Design Temperature

The Design Temperature is equal to, or greater than, the maximum local average (through the wall or thickness) temperature that will exist in a given zone of the structure during Normal Operating Conditions.

3.3.2 Design Pressure

The Design Pressure is as defined in ASME Code Section III, Par. NB-3112.1.

3.3.3 Design Mechanical Loads

The Design Mechanical Loads are as defined in Section III, Par. NB-3112.3, with the addition that the actual mechanical loads shall specifically include those caused by irradiation-induced swelling.

3.4 Ductility and Ductility Limit

Ductility is a measure of the capability of a material to undergo inelastic deformation without failure. The permanent plastic and/or thermal creep strain at which failure occurs is the ductility limit. Presently, only plastic and thermal creep strain components are considered to contribute to ductile failure of a material (see Sect. 3.8).

3.5 Irradiation-Induced Deformation

3.5.1 Irradiation-Induced Creep

Irradiation-induced creep, or "irradiation creep," strain is a component of inelastic deformation caused by the application of stress to a structure in the presence of a neutron flux field and is in addition to thermally activated creep. All stress-dependent irradiation-induced dimensional changes, including volumetric changes, are considered to be a result of irradiation creep strain.

3.5.2 Irradiation-Induced Swelling

Irradiation-induced swelling, or "irradiation swelling," is an isotropic volume increase due to neutron radiation which, like thermal expansion, is converted to an equivalent normal strain. In this document, irradiation-induced swelling is assumed not to be a function of stress. This assumption may need to be revised dependent upon future data.

3.6 Minimum Design Limits

When definitions of design limits refer to "minimum" properties, the value of the property shall be defined statistically as follows.

(a) For a large amount of data, it is the value which is predicted with a 95% confidence level to be below 95% of all data points.

(b) For a limited amount of data, it is the value which is predicted to be below 97.5% of the available data points.

If a statistical analysis of material data is not appropriate, engineering judgment must be used to define minimum properties. In this case, approval of the Owner is required.

3.7 Ratchetting

Ratchetting is a progressive cyclic inelastic deformation. Total inelastic strain per cycle may vary from cycle to cycle in the most general situation. If the net inelastic strain from a given load cycle is constant for subsequent cycles, the ratchetting is said to be stable.

(a) Progressive incremental inelastic deformation can occur in a component that is subjected to cyclic variations of mechanical secondary stress, thermal secondary stress, or both in the presence of a primary stress.

(b) Where creep effects are significant, creep ratchetting can occur, even in the absence of plastic yielding. At least two mechanisms are involved in creep ratchetting. First, creep can alter the residual stresses and thus affect the time-independent behavior. Second, the time-dependent deformation can be enhanced because of the nonlinear interaction of primary and secondary stresses. This latter effect is referred to as enhanced creep.

3.8 Strain Classification

3.8.1 Ductility-Limited Strain

The ductility-limited strain is that strain or combination of strain components that contributes to ductile material failure. Only plastic

and thermal creep strains are considered to be ductility limited. Thus, primary emphasis is placed on limiting these strains to values below which material failure will not occur. Irradiation-induced creep and volumetric swelling strains presently are not considered to be ductility limited and are only limited by functional requirements.

3.8.2 Total Strain

The total strain at a given point includes strains due to mechanical and thermal loadings and to irradiation effects. It consists of elastic (including thermal expansion), plastic, thermal creep, and irradiation-induced creep and volumetric swelling. The total permanent strain is the total strain excluding the elastic component.

3.9 Stress Intensities

3.9.1 Stress Intensity

The stress intensity is defined as twice the maximum shear stress. In other words, the stress intensity at a given point is the difference between the algebraically largest principal stress and the algebraically smallest principal stress at that point. Tensile stresses are considered positive, and compressive stresses are considered negative.

3.9.2 Stress-Intensity Limits

The following stress-intensity limits are used throughout this document.

3.9.2.1 S_m – Time-Independent Stress Limit. At a given temperature, S_m is the lowest stress value among the time- and fluence-independent strength quantities which are defined in ASME Section III (Ref. 4) as criteria for determining S_m. Using these same bases, S_m has been extended to elevated temperatures (see ASME Code Case 1592).[5] Reference to S_m in this document implies use of values for the appropriate material and temperature as contained in Refs. 4 and 5.

3.9.2.2 S_t – Time-Dependent Stress Limit. At a given temperature, S_t is the time-dependent stress value for annealed material. The data considered in establishing these values are obtained from long-term,

constant-load, uniaxial tests. For each specific time t, the S_t values shall consider test results including (a) the stress required to obtain a total (elastic plus plastic plus creep) strain of 1%, (b) the stress to initiation of tertiary creep, and (c) the stress to rupture.

3.9.2.3 S_{mt} – Primary Membrane Stress Limit. The limit on primary general membrane stress intensity, S_{mt}, is to be used in calculations for the actual service life, the Design Conditions, and the Normal plus Upset operating conditions. The allowable values are given for the appropriate material in Ref. 5. The S_{mt} values are the lower of two stress-intensity values, S_m (time independent) and S_t (time dependent), and are based on properties of annealed material only.

3.9.2.4 S_{It} – Time- and Fluence-Dependent Stress Limit. At a given temperature and fluence, S_{It} is the time-, temperature-, and fluence-dependent stress value used in conjunction with S_{mt} to establish stress limits. In determining the values of S_{It}, consideration is to be given to the time-dependent deformation and rupture properties of irradiated materials. The method used to determine values of S_{It} is given in Subsection 6.1.1(b), and the necessary data are given in Ref. 8.

3.9.2.5 S_y – Minimum Uniaxial Yield Stress. The notation S_y is used for the minimum expected uniaxial 0.2% offset yield stress of an unirradiated material at a given temperature as determined at a strain rate of 0.005 min^{-1}.

3.9.2.6 S_{Iy} – Minimum Uniaxial Yield Stress of Irradiated Material. The notation S_{Iy} is used for the minimum expected uniaxial 0.2% offset yield stress at a given temperature and fluence and for a strain rate of 0.005 min^{-1}. Values of S_{Iy} are contained in Ref. 8.

3.9.2.7 S_{Iu} – Minimum Uniaxial Ultimate Stress of Irradiated Material. The minimum uniaxial ultimate stress for irradiated material is denoted by S_{Iu}. These values are determined from the maximum load measured in a conventional stress-strain test at a strain rate of 0.005 min^{-1} for the conditions of temperature and fluence of interest. Values of S_{Iu} are contained in Ref. 8.

3.10 Stress Symbols

The following symbols are used throughout this document to indicate computed stress quantities.

3.10.1 P_m, P_L – Average Primary Membrane Stress

The average primary membrane stress components (P_m, P_L) are as defined in ASME Code Section III, Par. NB-3213, and they include stresses due to thermal expansion and irradiation-induced swelling if these expansions lead to a net axial or shear force at a structural cross section.

3.10.2 P_b – Primary Bending Stress

The primary bending stress at a surface, P_b, is as defined in ASME Code Section III, Par. NB-3213, and it includes stresses due to elastic follow-up as defined in Subsection 3.10.3(a).

3.10.3 Q – Secondary Stress

Secondary stress Q is as defined in ASME Code Section III, Par. NB-3213, and it includes strain-controlled stress arising from the effects of thermal expansion or irradiation-induced swelling. Examples of the latter are:

(a) Bending stress in piping where loads cannot cause excessive creep deformation (e.g., buckling or dimpling) in a local region. However, if a condition of elastic follow-up exists, net bending stresses which cannot be reduced by small deformations shall be considered as primary bending stresses, P_b, in a portion of the system so affected.

(b) Bending stress due to linear thermal strain or irradiation-induced swelling strain, or due to the equivalent linear portion of the non-linear thermal or irradiation-induced swelling strain profile.

3.10.4 F – Peak Stress

Peak stress F is as defined in Par. NB-3213 of ASME Code Section III and includes stress due to irradiation-induced swelling.

3.10.5 P_e – Expansion Stress

It should be noted that expansion stress P_e, as defined in Par. NB-3213 of ASME Code Section III, is deleted for these design criteria. Stresses resulting from the constraint of "free end displacement" and the effects of anchor motion must be separated into the two categories of primary or secondary stress. These categories are defined above in Subsections 3.10.1, 3.10.2, and 3.10.3(a).

4. CLASSIFICATION OF OPERATING CONDITIONS

Each operational condition to which an LMFBR component will be subjected is to be classified in accordance with the categories defined in Par. NB-3113 of ASME Code Section III. These conditions will be described in the Design Specification in sufficient detail to provide a complete basis for design in accordance with these rules.

4.1 Normal Conditions

Normal Conditions include any condition in the course of system startup, operation in the power range, hot standby, and system shutdown, other than Upset, Emergency, or Faulted Conditions. These conditions are expected to occur at frequent or regular intervals in the course of power operation, refueling, maintenance, or maneuvering of the plant.

4.2 Upset Conditions

Upset Conditions are deviations from normal conditions anticipated to occur often enough that design should include a capability to withstand the conditions without operational impairment. Upset Conditions include transients which result from any single operator error or control malfunction, transients caused by a fault in a system component requiring its isolation from the system, and transients due to loss of load or power. Upset Conditions also include abnormal incidents not resulting in a forced outage and forced outages for which the corrective action does not include any repair of mechanical damage. The latter category includes the specified earthquake for which the system must remain operational or regain its operational status. The estimated duration of an Upset Condition shall be included in the Design Specification.

4.3 Emergency Conditions

Emergency Conditions are deviations from Normal Conditions which require shutdown for correction of the conditions or repair of damage in the system. The conditions have a low probability of occurrence but are

included to provide assurance that no gross loss of structural integrity will result as a concomitant effect of any damage developed in the system. The total number of postulated occurrences for such events shall not exceed 25. If more than 25 are expected, some types of events must be evaluated by the more stringent requirements of Upset Conditions.

4.4 Faulted Conditions

Faulted Conditions, those combinations of conditions associated with extremely low probability, are postulated events whose consequences are such that the integrity and operability of the nuclear energy system may be impaired to the extent that only considerations of public health and safety are involved. Such considerations require compliance with safety criteria that may be specified by jurisdictional authorities.

5. FLUENCE LIMITS

5.1 Unirradiated Fluence Limit

A fluence limit has been tentatively set below which the effects of neutron irradiation on material deformation and failure characteristics are not considered to be significant and these rules would not be applicable. This limit is expected to be revised as more data become available on the mechanical properties of materials subjected to a reactor core environment. Where deviations from these rules are employed, it is the responsibility of the designer to assure that the design is conservative either by furnishing supporting data or by making acceptable trend extrapolations or interpolations.

This lower fluence limit is presently set at 10^{20} neutrons/cm^2 ($E > 0.1$ MeV). It is to be used for all temperatures and materials covered by these criteria.

5.2 Fluence Limits for Strain-Limit Modification

The strain limits as presently employed by ASME Code Case 1592 are not acceptable for highly irradiated structures due to the inelastic behavior of irradiated material, particularly the reduction in ductility. Strain limits and their application to irradiated materials are discussed in detail in Chapter 7.

The fluences beyond which the effects of irradiation on ductility must be accounted for are listed in Table 5.1. In establishing these limits, consideration was given to short-time tensile and thermal creep strains and to their variation with fluence and temperature.

The designer should be cautioned that the limits presented in Table 5.1 are directly applicable to strain limits only. Beyond the fluence limit of Sect. 5.1, the designer must consider the effects of irradiation on all behavioral features of the material. For example, the rules of Chapter 6 require assessment of changes in thermal creep and rupture behavior based on data contained in Ref. 8.

Table 5.1. Fluence Limits for Strain Limit Modification

Material Type, Limited Strain	Fluence [Neutrons/cm^2 (E > 0.1 MeV)]	
	SA 304 Stainless Steel[a]	SA 316 Stainless Steel[a]
Strains averaged through the thickness, ϵ_{avg}	2.3×10^{21}	2.6×10^{21}
Strains at the surface due to an equivalent linear distribution of strain through the thickness, ϵ_{max}	1.1×10^{21}	1.3×10^{21}
Strains[b] at discontinuities, $K_p \epsilon_{max}$	6.0×10^{20}	1.0×10^{21}

[a]SA = solution annealed.

[b]K_p = plastic strain concentration factor.

As fluence limits applicable to other design and analysis requirements (in addition to strain limits) are developed, they will be included. In the interim, where fluences exceed those of Sect. 5.1, the designer should assess the effect of irradiation on all features of material behavior.

6. LOAD-CONTROLLED STRESSES: ALLOWABLE VALUES AND DESIGN RULES

The design rules set forth in this chapter are to protect against ductile rupture from the application of load-controlled stresses. Irradiation-enhanced yield and ultimate strengths have not been used in setting general limits for load-controlled stresses, since the peak loads normally may occur at any time during the operating life. To take advantage of the enhanced strength would require a complete knowledge of loads and flux as a function of life, and it would require consideration of the ductility loss and embrittlement suffered by irradiated materials. However, it is recognized that there are loading conditions that must only be considered at specified times in the life of the component and for which the material properties can be defined with reasonable confidence. Examples of these are refueling operations and end-of-life excursions. In cases where the load duration is short term (less than 10 hr), the designer may use strength properties representative of the condition of the material at the time of load application to assess the time-independent load-carrying capability of the component. The specific rules for this case are covered in Subsection 6.1.2.

The following design rules for load-controlled stresses are for temperatures greater than 800°F. For the materials covered by this document, the designer is to use the allowable stress-intensity limits set forth in ASME Code Case 1592. For temperatures below 800°F, the designer is to use the design rules and allowable limits of ASME Code Section III. It should be noted that use of ASME Code Section III rules and limits does not relieve the designer of the responsibility of demonstrating compliance with the limits of Chapters 7 and 8 contained herein.

6.1 Allowable Stress Values

6.1.1 Allowable Stress Values for General Use

The values of allowable stress-intensity limits to be used in the design of reactor core structures are based on the time-independent and time-dependent properties of annealed and irradiated material.

(a) The values of S_m, S_t, and S_{mt} for annealed material are presented in Refs. 4 and 5.

(b) The values of S_{It} are to be based on the minimum of the following postirradiation creep properties of irradiated material:

(i) Two-thirds of the minimum stress to cause rupture under constant loading conditions at temperature T and fluence Φ.

(ii) The minimum stress to produce a permanent ductility-limited strain of ϵ_t under constant stress conditions at time t and fluence Φ. The value of ϵ_t is presently to be taken as the irradiation-modified strain limit shown in Fig. 7.1a, Chapter 7.

The necessary tensile and creep properties for irradiated material are to be taken from Ref. 8. Where sufficient data are not available in Ref. 8 or from other sources to construct the S_{It} values using the bases above, these values may be obtained using the allowable ϵ_t values shown in Fig. 7.1a and the isochronous stress-strain curves of Ref. 5. The procedure is to determine ϵ_t corresponding to the maximum fluence Φ for the component and, using this value of ϵ_t, enter the isochronous stress-strain curve for the correct temperature and determine the allowable stress combination for ϵ_t and the time duration of loading.

If materials properties are taken from other sources or furnished by the designer, justification must be given in the Stress Report.

6.1.2 Allowable Stress Values for Special Time-Independent Loading Conditions

For load applications where (a) the load application will occur at a specific point in the component life such that the accumulated fluence can be predicted with reasonable confidence and (b) the conditions are such (low temperature or short load duration) that time-dependent deformation will be negligible, the designer may use an alternate value of allowable stress. The time-independent stress intensity is to be limited by two-thirds of the 0.2% offset yield stress or one-half the ultimate stress of the irradiated material; that is,

$$S_m < \begin{cases} 0.67S_{Iy} \\ 0.50S_{Iu} \end{cases} . \qquad (6.1)$$

These alternate limits must be satisfied in conjunction with the rules covering ductility loss and embrittlement in Chapters 7 and 8.

6.2 Design Rules for Load-Controlled Stress

The rules for design against failure from load-controlled stress, illustrated in the Hopper Diagram (Fig. 6.1), are explained in this section. Note that the stress-intensity limits do not insure compliance with the strain and/or deformation limits of Chapter 7 or the limits for flaw-sensitive materials in Chapter 8.

6.2.1 Design Conditions

The stress intensities for design conditions shall be elastically calculated and shall be limited as follows.

(a) The general primary membrane stress intensity is limited by

$$P_m \leq S_{mt} \ . \tag{6.2}$$

(b) The combined local primary membrane plus bending stress intensity is limited by

$$(P_L + P_b) \leq 1.5S_{mt} \ ; \tag{6.3}$$

S_{mt} is determined for the Design Temperature and the time corresponding to end of life for the component.

As in Section III of the ASME Boiler and Pressure Vessel Code, the summation indicated in the above equation does not represent the sum of two stress intensities. The stress components of P_L and P_b are summed, and the stress intensity is then determined for the resulting stress state; P_L and P_b may each contain six components.

6.2.2 Normal plus Upset Operating Conditions

The stress intensities for Normal plus Upset Conditions, which are to be elastically calculated, shall be limited as follows.

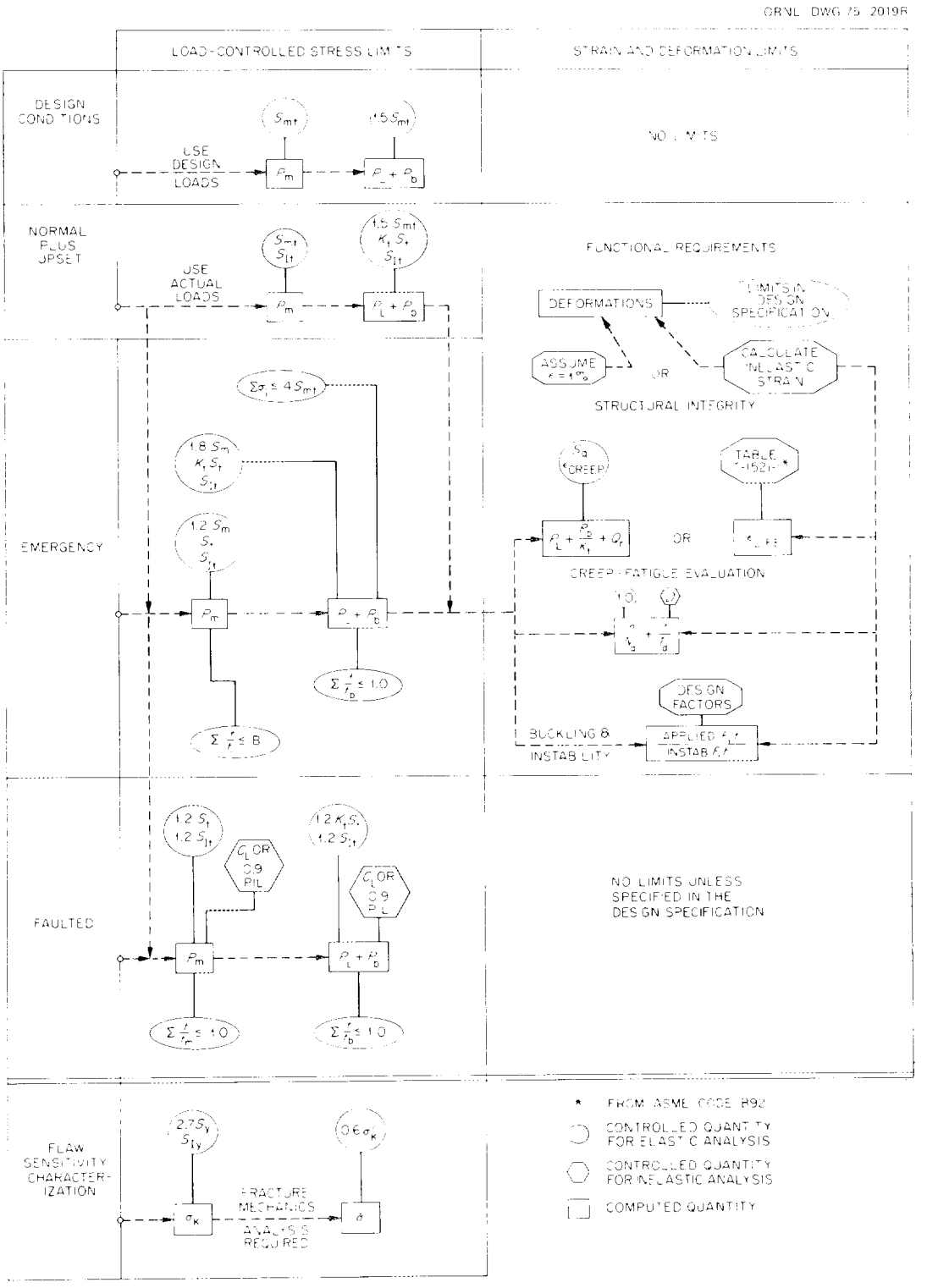


Fig. 6.1. Hopper diagram.

(a) The general primary membrane stress intensity for Normal plus Upset Operating Conditions shall be limited by the smaller of

$$P_m \leq \begin{cases} S_{mt} \\ S_{It} \end{cases} , \tag{6.4}$$

where S_{mt} is determined for the time t corresponding to the total duration of the loading at temperature T, and S_{It} is determined for the conditions at the end of the load cycle; i.e., accumulated fluence Φ, duration of loading t, and temperature T. When the time-dependent limit S_t or the time- and fluence-dependent limit S_{It} is controlling, the loading history may be divided into several load levels and into several temperature or fluence levels at any given load level.

(b) When t is less than the total specified life of the component, the cumulative effect of all the loadings shall be evaluated by Eq. (6.10) of Subsection 6.2.5.

(c) The combined local primary membrane plus bending stress intensities for Normal plus Upset Operating Conditions shall not exceed the smaller of $1.5S_m$, K_tS_t, or $1.0S_{It}$:

$$P_L + P_b \leq \begin{cases} 1.5S_m \\ K_tS_t \\ 1.0S_{It} \end{cases} , \tag{6.5}$$

or, equivalently,

$$(1/1.5)(P_L + P_b) \leq S_m ,$$

$$P_L + \frac{P_b}{1 + k_s} \leq S_t ,$$

where

$$K_t = 1 + k_s\left(1 - \frac{P_L}{S_t}\right), \tag{6.5a}$$

and

$$k_s = \alpha(K - 1) \ . \qquad (6.5b)$$

The factor K is the section factor for the cross section being considered. Values of K for various sections are given in Table A-9221(a)-1, ASME Code Section III. At this time, α shall be taken as 0.5.

In evaluating across-the-wall bending of shell-type structures, K = 1.5 (for rectangular sections) shall be used. Thus, for across-the-wall shell bending, $k_s = 0.25$ in Eq. (6.5a).

(d) In Eqs. (6.5), the time-dependent limit S_t is determined for the time t corresponding to the total duration of the combined stress intensity derived from P_L and P_b and the maximum temperature T during the entire service life of the component. The time- and fluence-dependent limit S_{It} is determined for the time t corresponding to the duration of the combined stress intensity P_L and P_b and for the end-of-life fluence Φ and maximum temperature T during the service life of the component. The values of S_{It} are constructed as described in Subsection 6.2.5.

(e) When t is less than the total specified service life of the component, the cumulative effect of all $P_L + P_b$ loadings shall be evaluated by Eq. (6.11) of Subsection 6.2.5. It is permissible, and often advantageous, to separate a loading history into several load levels and into several temperatures at any given load level. The fluence to be used is that corresponding to the end of life for the component unless the designer can justify separating the load history into discrete segments and using the accumulated fluence at the end of each segment of loading history to evaluate the limiting time. Such a procedure requires justification of the particular segmentation of the load history chosen.

6.2.3 Emergency Operating Conditions

The stress intensity for Emergency Operating Conditions is to be elastically calculated and shall be limited as follows.

(a) The general primary membrane stress intensity is limited by $1.2S_m$, $1.0S_t$, or $1.0S_{It}$:

$$P_m \leq \begin{cases} 1.2S_m \\ 1.0S_t \\ 1.0S_{It} \end{cases} . \qquad (6.6)$$

(b) The combined primary local membrane plus bending stress intensity is limited by the smaller of $1.8S_m$, K_tS_t, or $1.0S_{It}$:

$$(P_L + P_b) \leq \begin{cases} 1.8S_m \\ K_tS_t \\ 1.0S_{It} \end{cases} . \qquad (6.7)$$

where K_t is defined by Eq. (6.5a).

(c) Additionally, the use fraction sum shall be satisfied for increments of both general primary membrane stress and combined primary local membrane plus bending stress per the rules of Subsection 6.2.5.

6.2.4 Faulted Conditions

The stress intensity for Faulted Conditions shall be elastically calculated and shall be limited as follows.

(a) The general primary membrane stress intensity shall be limited by

$$P_m \leq \begin{cases} \text{limit for } P_m \text{ in Appendix F of} \\ \quad \text{ASME Code Section III} \\ 1.2S_t \\ 1.2S_{It} \end{cases} \qquad (6.8)$$

(b) The combined local primary membrane plus bending stress intensity shall be limited as follows.

$$(P_L + P_b) \leq \begin{cases} \text{limit for } (P_L + P_b) \text{ in Appendix F} \\ \text{of ASME Code Section III} \\ 1.2K_t S_t \\ 1.2S_{It} \end{cases} , \qquad (6.9)$$

where K_t is defined by Eq. (6.5a).

(c) In addition, the Life-Fraction rule of Subsection 6.2.5 shall be used as the limit for all loadings with the following modification. Use $P_{im}/1.2$ instead of P_{im} for membrane stress intensities and use $[(P_L + P_b)/(1.2K_t)]_i$ instead of $[(P_L + P_b)/K_t]_i$ for primary local membrane plus bending stress intensity to obtain the t_{im} or t_{ib} values from the S_t vs time curves or from S_{It} vs time data.

In the limits of Appendix F of ASME Code Section III where limit analysis or plastic instability calculations are made, unirradiated material properties are to be used. Note that the above stress limits and fraction rule do not insure compliance with the strain and deformation limits of Chapter 7.

6.2.5 Life-Fraction Evaluation

In addition to the stress limits for sustained loading, the possibility of rupture due to creep at various stress levels, temperatures, fluences, and durations of loading shall be guarded against by the Life-Fraction sum. The Life-Fraction sum associated with the primary stress for all increments of loading during Normal, Upset, and Emergency Operating Conditions shall satisfy the following requirements:

$$\sum_i \left(\frac{t_i}{t_{im}}\right) \leq B \text{ for primary membrane stresses,} \qquad (6.10)$$

and

$$\sum_i \left(\frac{t_i}{t_{ib}}\right) \leq 1.0 \text{ for local primary membrane plus primary bending stresses,} \qquad (6.11)$$

where

t_i = the total time duration at a specific stress-intensity level P_{im}, temperature T_i, and fluence Φ_i. Note that $\sum_i (t_i)$ is equal to the specified component design life.

t_{im}, t_{ib} = the allowable time at the stress P_{im} or $[(P_L + P_b)/K_t]$, temperature T_i, and fluence Φ_i. Where S_t limits the allowable stress, the value of t_{im} and t_{ib} can be determined from plots of S_t vs time and temperature given in Ref. 5. Where the S_{It} limit is controlling, t_{im} and t_{ib} are to be established using data contained in Ref. 8 and the basis for S_{It} values as given in Subsection 6.1.1(b).

B = Life-Fraction usage factor normally equal to 1.0; it may be less than 1.0, if so stated in the Design Specifications.

The method of determining t_{im} or t_{ib} to use in evaluating the Life-Fraction usage factor for the case where S_t is the limiting stress is shown schematically in Fig. 6.2 for two loading conditions at two different temperatures. For the case where S_{It} is limited by ϵ_t, the method for obtaining t_{im} or t_{ib} is shown in Fig. 6.3.

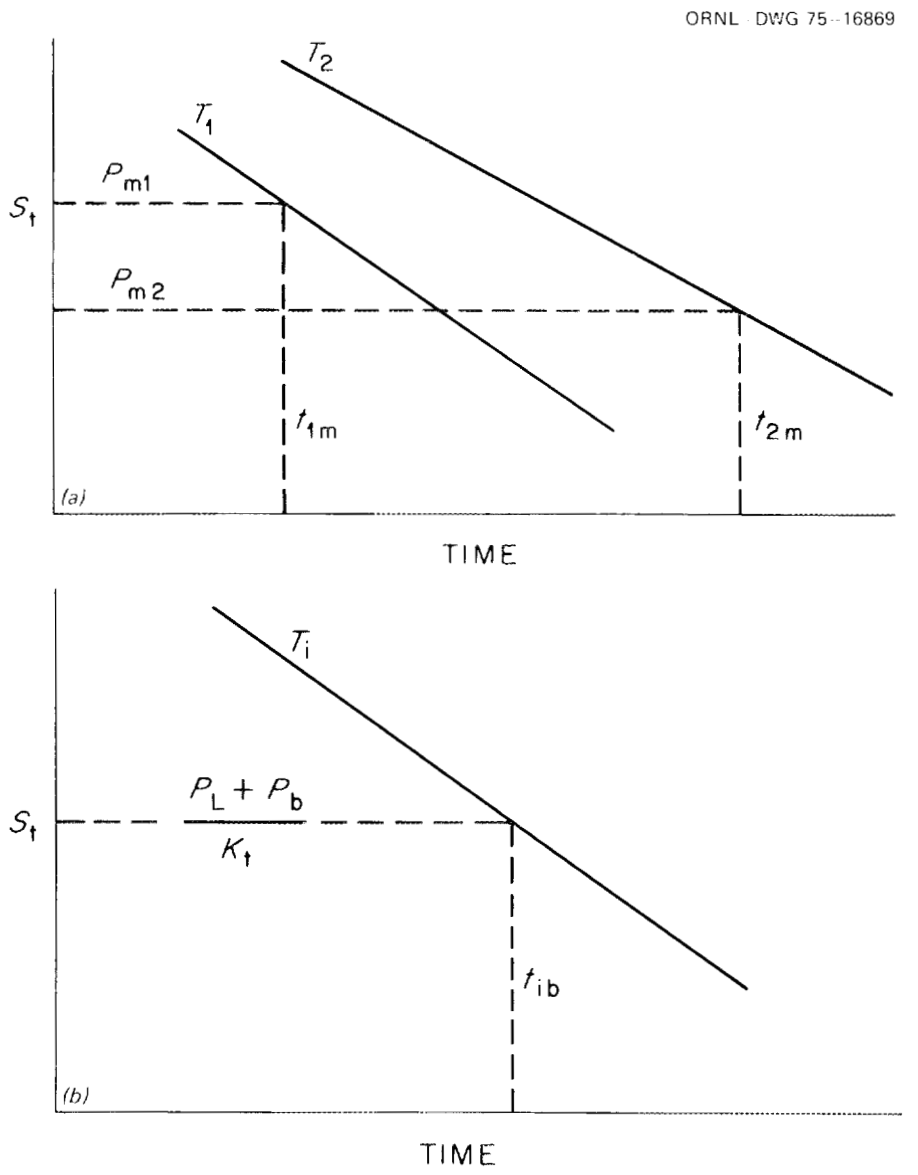


Fig. 6.2. Use fractions for (a) membrane and (b) membrane plus bending stresses.

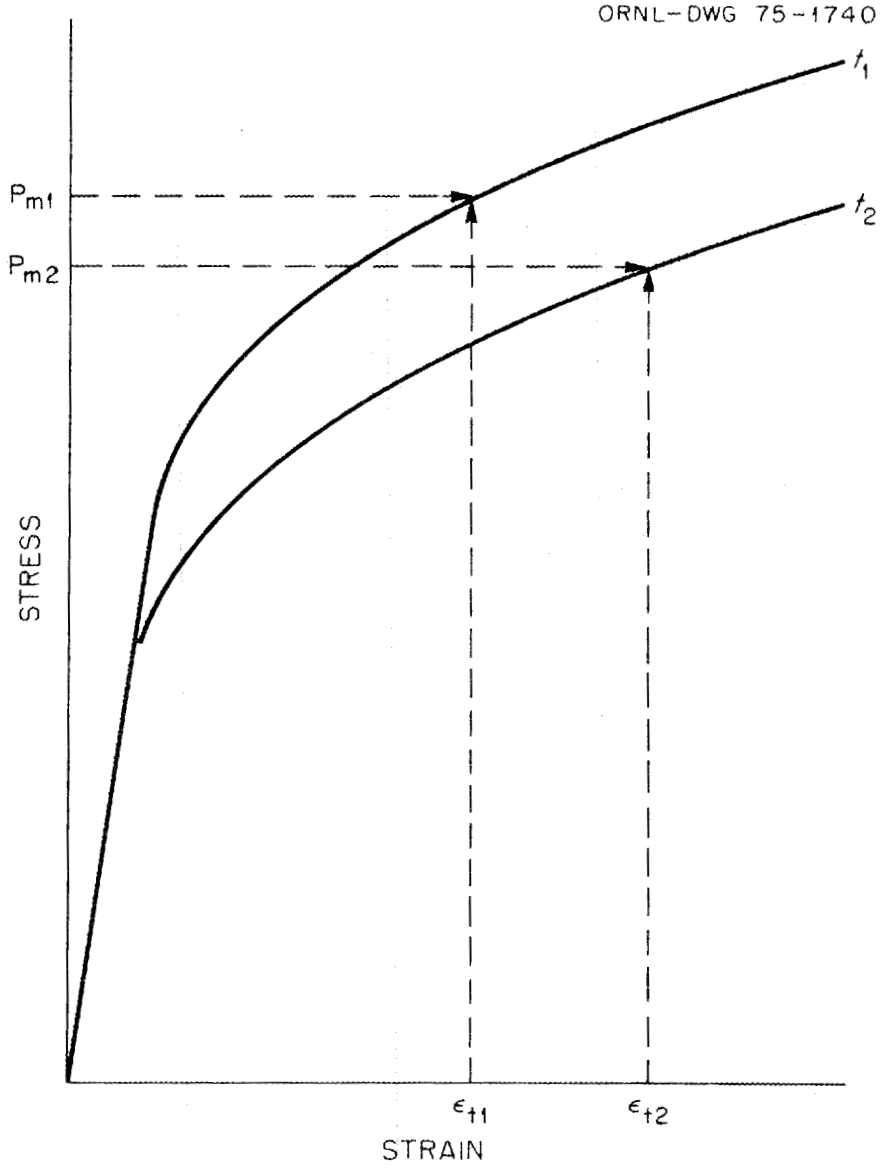


Fig. 6.3. Illustration of procedure for determining limiting time to be used in use-fraction equation for case where irradiated materials properties limit primary stresses.

7. STRAIN, DEFORMATION, AND FATIGUE LIMITS

For structures in and near the reactor core, rupture strains due to time-independent and time-dependent loadings are reduced by irradiation damage. In addition, one of the most deleterious effects of irradiation damage is associated with the loss of material strain-hardening capacity. This lack of strain hardening allows strains to accumulate along very narrow slip lines, thus leading to ductile fracture where the inelastic strains are concentrated in a highly localized region. This loss of ductility and strain-hardening capacity requires modification of strain limits as established for unirradiated materials. The strain limits presented in this chapter are designed primarily to guard against time-independent and time-dependent ductile rupture. However, the potential for localized strain concentration leading to failure should be recognized by the designer and structural points of strain concentration avoided wherever possible.

The strains and deformations resulting from the worst combination of Normal, Upset, and Emergency Conditions shall be evaluated by considering ratchetting, the interaction of creep and fatigue, and the possibility of buckling and structural instability. These potential failure modes are of significance to the design of elevated-temperature components and, in general, cannot be guarded against by placing limits on elastically calculated stress intensities. As a portion of the Stress Report, the manufacturer shall document the conditions considered, the final analysis procedures, the evaluation criteria, and the conclusions.

Pending development and verification of complete rules for the evaluation of these potential failure modes, the procedures and properties contained in the remainder of Chapter 7 shall be used. Alternate criteria may be applied by the designer, but the Owner's approval must be obtained and the alternate criteria included as a certified revision to the Design Specification.

Design against gross distortion and fatigue at temperatures where creep and swelling effects are significant generally requires an inelastic analysis to provide a quantitative assessment of deformations and strains. However, elastic and simplified inelastic methods of analysis

may, when justified, be used to establish conservative bounds for deformation and to reduce the number of locations in a structure requiring detailed inelastic analysis.

The rules for design against gross distortion and fatigue are illustrated in Fig. 6.1. The Design and Faulted Conditions are exempt from strain and deformation limits, as summarized below.

Design Conditions	Strain and deformation limits not applicable
Normal Upset Emergency	Apply the strain and deformation limits of Chapter 7
Faulted	Strain and deformation limits not applicable except as necessary to satisfy functional requirements

7.1 Deformation Limits for Functional Requirements

Deformation limits to insure proper component functioning shall be specified in the Design Specification for the component or shall be established by the Manufacturer for the proper performance of the component. Any such limits may restrict the design more severely than those specified for load-controlled stresses in Subsection 7.2.2. The limitations on stress intensity contained in these criteria are intended to restrict the accumulated inelastic ductility-limited strain (averaged across the wall thickness) to 1% or less. However, when elastic analysis is used, the occurrence of inelastic ductility-limited strains of this magnitude may not be apparent. If functional deformation requirements are specified, the designer shall insure that they are not violated by assuming that ductility-limited strains of 1% plus the most conservative estimate of neutron-induced swelling and irradiation creep occur within the structure in that distribution which leads to the worst possible deformation state consistent with the directions of loading. If this deformation state does not exceed the specified limits, all functional requirements shall be considered as demonstrated for the design. Otherwise the designer must provide justification, such as by performing inelastic analyses, for satisfaction of functional deformation limits.

7.2 Deformation and Strain Limits for Structural Integrity

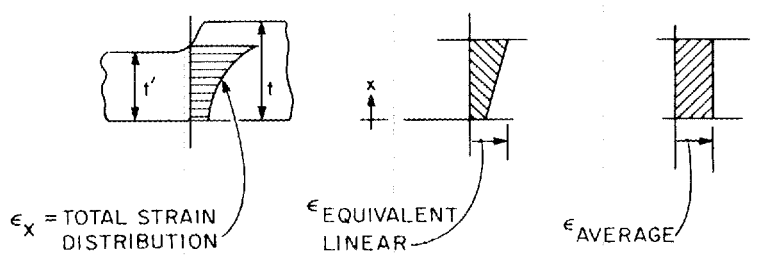
7.2.1 Strain Limits for Inelastic Analysis

The maximum accumulated ductility-limited strain shall not exceed the values listed in Table 7.1 and the supporting figures, Figs. 7.1 and 7.2. These limits apply to computed strains accumulated over the expected operating life of the element under consideration and computed for some steady-state period at the end of this time during which significant transients are not occurring. These limits apply to the maximum positive

Table 7.1. Strain Limits for Inelastic Analysis

	Type 304 Stainless Steel	Type 316 Stainless Steel	Welds
Strains averaged through the thickness, ϵ_{avg} Strains at the surface due to an equivalent linear[a] distribution of strain through the thickness, ϵ_{max}	Fig. 7.1a	Fig. 7.1b	One-half allowable for base metal
Strains[b] at discontinuities, $K_p \epsilon_{max}$	Fig. 7.2	Fig. 7.2	One-half allowable for base metal

[a]



Equivalent linear distribution is defined as

$$\epsilon_{\text{equivalent linear}} = \epsilon_{avg} + \frac{6}{t^2} \int_0^t \epsilon_x \left(X - \frac{t}{2}\right) dX ,$$

where

t = wall thickness (that of thickest section for a transition area),

ϵ_x = total principal strain at X,

ϵ_{avg} = average total strain through the wall,

X = distance into section from wall surface.

[b]The symbol K_p is strain concentration factor due to plastic and creep strain.

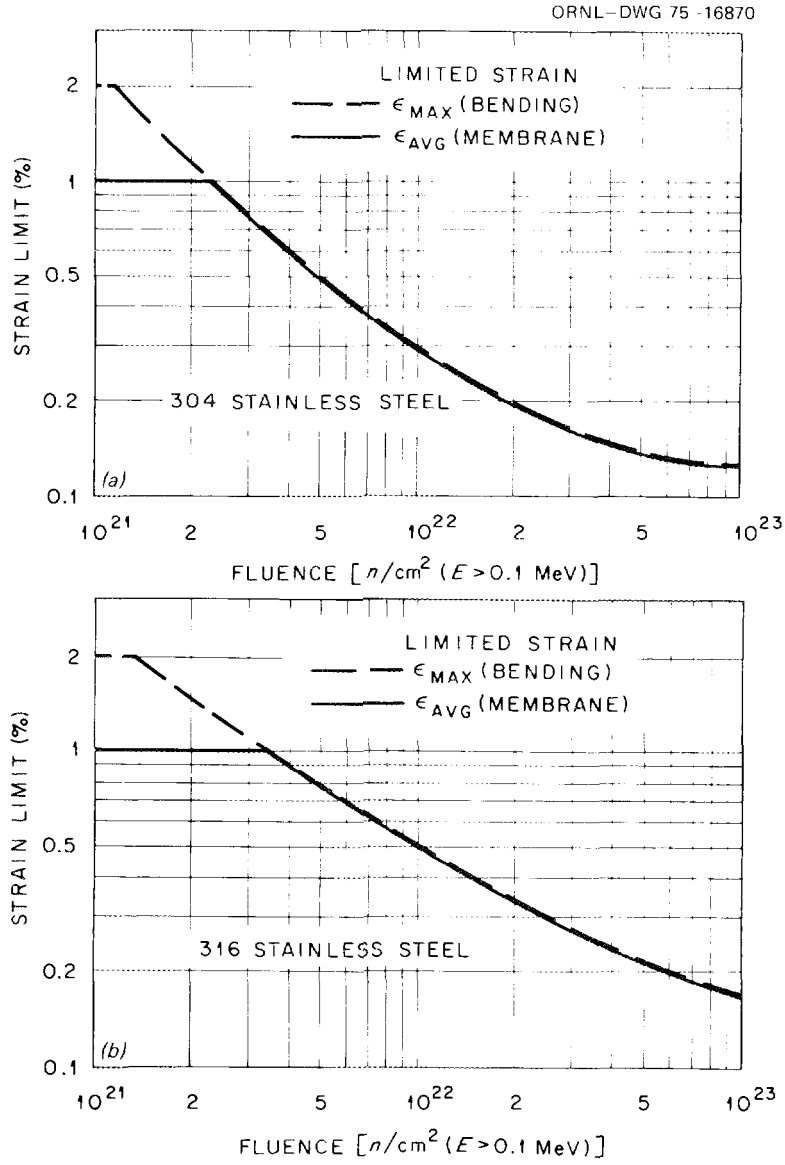


Fig. 7.1. Limits on average and bending strain for annealed and irradiated types 304 and 316 stainless steel.

value of the three principal inelastic strains. A positive strain is defined as one for which the length of the element in the direction of the strain is increased. The principal strains are computed for the strain components (ϵ_x, ϵ_y, ϵ_z, ϵ_{xy}, ϵ_{xz}, ϵ_{yz}). When the strain is computed at several locations through the thickness, the strains are first averaged and linearized on a component level and then combined to determine the

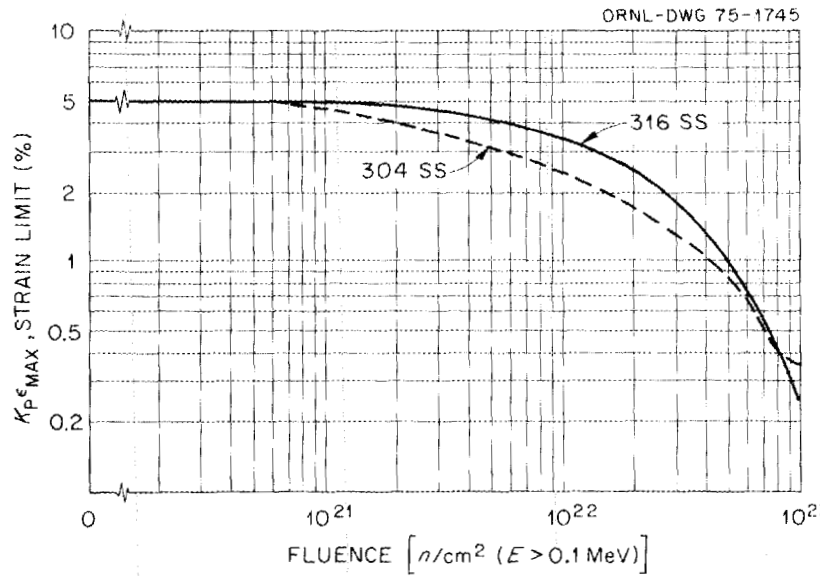


Fig. 7.2. Limit on strains at discontinuities for annealed and irradiated types 304 and 316 stainless steel.

principal strains for comparison to the limits on average and surface strain defined in Table 7.1. The limits on local strains are based on the computed strains at the point of interest. Where detailed inelastic analyses are required, the design allowables for unirradiated materials must be satisfied, but properties representative of the material condition for the period of load duration may be used provided justification is given.

In assessing the strain limits for welds, the properties of the base metal are to be used, but the accumulated strains are to be limited to one-half the allowable values for base metal as shown in Table 7.1. Where sufficient data on prototypic weld properties are available in Ref. 8, the designer may use these in lieu of base metal properties for evaluating deformation behavior. Alternate rules and limits may be used by the designer, but they must be justified in the Stress Report.

7.2.2 Satisfaction of Strain Limits Using Elastic or Simplified Inelastic Analysis

7.2.2.1 General Requirements. The following rules are to be applied for conditions where irradiation-induced swelling strain plus irradiation

creep are less than 0.05%. In assessing the above limit, irradiation creep strain shall be evaluated using elastically calculated stresses and including all operating transients. When these irradiation-induced strain components, either individually or collectively, exceed the above limit, significant relaxation of secondary stress may occur at both the high- and low-temperature ends of the cycle. For such a case, the following rules do not apply and inelastic analysis including consideration of irradiation creep and swelling will be required.

The deformation and strain limits of Subsection 7.2.1 shall be considered to have been satisfied, and an inelastic analysis is not required if the criteria of this section are satisfied. In using elastic or simplified inelastic analyses, the design allowables and material properties for unirradiated materials, as specified in Refs. 4 and 5, are to be used.

The guidelines of (a) through (c) below should be used in establishing the appropriate cycle to be evaluated in Paragraphs 7.2.2.2 and 7.2.2.3.

(a) An individual cycle, as defined in the Design Specification, cannot be divided into several subcycles to satisfy these requirements.

(b) At least one cycle must be defined which includes the maximum secondary stress range Q_R and the maximum value of $(P_L + P_b/K_t)$ which occurs during all Normal plus Upset operating conditions.

(c) Any number of cycles can be grouped together and evaluated according to the conditions of Paragraph 7.2.2.2 or 7.2.2.3, whichever is applicable. Note that Paragraph 7.2.2.3 provides for the separate inelastic evaluation of selected operating cycles.

(d) If all the cycles as defined above satisfy the conditions of Paragraph 7.2.2.2, the strain limits of Subsection 7.2.1 are satisfied. Paragraph 7.2.2.3 provides methods for determination of strains for compliance with the strain limits of Subsection 7.2.1. Under the provisions of item (c), no strain increments due to ratchetting or enhanced creep need to be included for those cycles or groups of cycles which satisfy the conditions of Paragraph 7.2.2.2.

(e) The time and temperature conditions used in selecting the isochronous curves shall always sum to the entire life regardless of the procedures used.

(f) The following definitions apply:

$$X = \left(P_L + \frac{P_b}{K_t}\right)_{max} \div S_y \ , \qquad (7.1)$$

where S_y is the average of the S_y values at the maximum and minimum wall-averaged temperatures during the operating conditions being evaluated, $(P_L + P_b/K_t)_{max}$ is the maximum value of the primary stress, adjusted for bending via K_t, during the operating conditions being evaluated, and

$$Y = \frac{(Q_R)_{max}}{S_y} \ , \qquad (7.2)$$

where $(Q_R)_{max}$ is the maximum range of the secondary stress during the operating conditions being considered and S_y is the average of the S_y values at the maximum and minimum wall-averaged temperatures during the period of time.

7.2.2.2 Limits for Elastic Analysis. When elastic analysis is used, freedom from ratchetting, excessive deformation, or both, and conformance with deformation requirements for structural integrity are considered to have been demonstrated if the following three conditions are satisfied. If these conditions are not satisfied, either a simplified or a detailed inelastic analysis and adherence to the strain limits of Subsection 7.2.1 are required.

(a) The stress-intensity range from primary-plus-secondary stresses shall not violate Eq. (7.3):

$$X + Y \leq \frac{S_a}{S_y} \ , \qquad (7.3)$$

where S_a is the lesser of the average of the S_y value for the highest and lowest wall-averaged metal temperature during the cycle or $1.25S_t$ taken at the highest temperature during the cycle and at 10^4 hr.

(b) The creep strain, as determined from the isochronous stress-strain curves at the maximum metal temperature in the cycle, the total time at temperature under load, and a stress intensity $(X + Y)\cdot S_a$, shall

be limited to the strain limits for inelastic behavior as listed in Table 7.1, Subsection 7.2.1.

(c) To prevent creep ratchetting, one of the extreme conditions which defines the secondary stress-intensity range Q_R must be such that negligible creep relaxation occurs at this point in the loading cycle. This requirement of negligible relaxation will be satisfied provided the temperature is below the value corresponding to the point where $S_m = S_t$ for $t = 10^5$ hr.

7.2.2.3 Strain Limits for Simplified Inelastic Analysis. The detailed inelastic analyses generally required to demonstrate that the maximum accumulated ductility-limited inelastic strains do not exceed the limits of Subsection 7.2.1 can be time consuming and expensive. Consequently, simplified rules and procedures which may, in certain situations, be used in lieu of a detailed inelastic analysis are presented in this section. When applicable, these rules and procedures are considered to provide sufficient evidence that the requirements of Subsection 7.2.1 have been met.

The rules and procedures in this section are all based on mathematically one-dimensional inelastic analyses of unirradiated thin-walled cylindrical vessels (straight pipes) under internal pressure with a cyclic temperature gradient through the wall. Their conservative applicability to straight pipes with axisymmetric thermal and mechanical secondary stresses has been verified through comparisons with the results of a series of detailed inelastic analyses. Also, they have similarly been shown to be applicable to straight beams, including thin-walled pipes, and to a nozzle-to-spherical-shell geometry.

The diagram shown in Fig. 7.3 represents the various stress regimes that determine the ratchetting behavior for the one-dimensional case on which these rules are based. The boundaries between the various regions are given in the figure. The factor K_t is defined by Eq. (6.5a), Subsection 6.2.2.

For the idealized material behavior considered in the development of Fig. 7.3, including perfect plasticity and no creep, ratchetting occurs in regions R_1 and R_2, shakedown occurs in regions S_1 and S_2, plastic cycling occurs in region P, and the behavior is always elastic in region E. Creep can cause ratchetting to occur in all six regions.

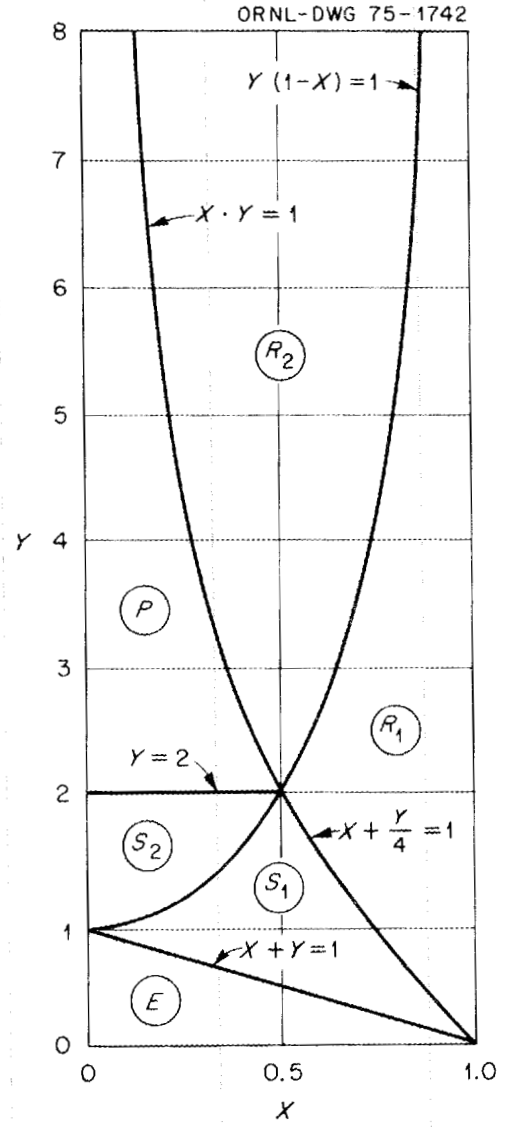


Fig. 7.3. Stress regimes and boundaries for use in ratchetting evaluations using elastic analysis.

On the basis of existing experience, the rules and procedures of this section can, in general, be applied to axisymmetric shells subjected to axisymmetric loadings in locations where there are no local structural discontinuities (as defined in Par. 3213.3 of Ref. 5). The elastically calculated maximum primary and maximum secondary stress intensity ranges for the one-dimensional case must be equal to those for the particular point being considered in the axisymmetric structure. When the rules and

procedures are applied to straight beams, including straight pipes subjected to net nonaxisymmetric bending, the maximum outer fiber bending stress must be treated as a primary stress in the one-dimensional evaluation. However, even in these applications, the methods should be used with reasonable caution; the designer must keep their bases and limitations in mind and exercise sound engineering judgment in their application.

It is expected that the rules and procedures in this section may conservatively apply to a broader class of structural situations, but the experience required for more general application is not currently available. Thus, the designer must justify, to the Owner's satisfaction, any application of this section to situations other than those specified above. In cases where the geometry or conditions do not vary significantly from the above, the designer may be able to rationalize the use of the rules on a sound engineering basis. Where the geometry or conditions do vary more significantly, the applicability can generally be demonstrated only by comparison with detailed inelastic analyses of similar situations. As such comparisons are documented and collected, it is anticipated that support will be established for the broader application of simplified rules and procedures.

(a) Simplified Method for Use Only Where Creep Is Insignificant. When the maximum metal temperature at the location being considered is always below the value corresponding to the point where $S_m = S_t$ for $t = 10^5$ hr, the deformation and strain limits for structural integrity of Subsection 7.2.1 are considered to have been satisfied, and a ratchetting analysis need not be performed if

$$X + \frac{1}{4} Y \leq \frac{S'_y}{S_y} , \qquad (7.4)$$

for

$$X \geq 0.5 \frac{S'_y}{S_y} ,$$

or

$$X \cdot Y \leq \frac{S_y'}{S_y} , \qquad (7.5)$$

for

$$X \leq 0.5 \frac{S_y'}{S_y} ,$$

where S_y' is the yield stress for the maximum operating metal temperature at the location being considered.

(b) Simplified Methods for Use Where Creep Is Significant. Any one of three different methods may be used to predict ratchetting strains, even when the maximum metal temperature at the location being considered is sometimes above the value corresponding to the point where $S_m = S_t$ for $t = 10^5$ hr: (i) the O'Donnell-Porowski method, (ii) a modified Bree complete relaxation method, and (iii) a mathematically one-dimensional detailed inelastic analysis based on the behavior of an infinitely long straight pipe.

In all three methods, any stresses with elastic follow-up (e.g., secondary stresses other than those caused by radial temperature variations) should, unless otherwise justified, be included as primary stresses for purposes of predicting ratchetting strains. Alternatively, the strains due to such stresses may be separately calculated and added to the predicted ratchetting strains, the sum being limited to the values of Subsection 7.2.1. If the latter is done, stresses with elastic follow-up should be treated as secondary stresses.

(i) O'Donnell-Porowski Method. This method is applicable provided that one of the extreme conditions which defines the secondary stress intensity range Q_R is such that negligible creep relaxation occurs at that point in the loading cycle. This requirement will be satisfied provided the temperature is below the value corresponding to the point where $S_m = S_t$ for $t = 10^5$ hr.

In this method, the elastically calculated primary and secondary stresses are used to determine an "effective creep stress," σ_C, which in

turn is used to determine a creep ratchetting strain that includes enhanced creep. The effective creep stress for any combination of loading is given in Fig. 7.4 in dimensionless form.

Since the use of minimum properties is required, the creep ratchetting is determined by multiplying σ_C by 1.25 and evaluating the creep strain associated with the $1.25\sigma_C$ stress held constant throughout the temperature-time history of the entire service life. The isochronous stress-strain curves of Ref. 5 or uniaxial creep laws and stress-strain representations from Ref. 8 should be used to obtain the ratchetting strain. The total service life may be subdivided into temperature-time blocks and the strain increment for each block evaluated separately. The times used shall sum to the total service life. The strain increments for each time-temperature block shall be added to obtain the total ratchetting strain, which shall not exceed the limits of Subsection 7.2.1.

The dimensionless expressions for the effective creep stress, $Z = \sigma_C/S_y$, in regimes S_1, S_2, and P of Fig. 7.4 are

$$Z = X \cdot Y \tag{7.6}$$

in regimes S_2 and P and

$$Z = (Y + 1) - 2\sqrt{(1 - X)Y} \tag{7.7}$$

in regime S_1. The equations defining the boundaries of the regimes (P, S_1, and S_2) are shown in Fig. 7.4.

Alternately, the total inelastic strains due to any number of selected operating cycles may be evaluated separately using an inelastic analysis. The sum of these strains, plus the strains due to elastic follow-up (evaluated as described above) plus the strains due to σ_C, must not exceed the limits of Subsection 7.2.1.

(ii) <u>Bree Complete Relaxation Method</u>. Deformation and strain limits for structural integrity are considered to have been satisfied, and a detailed inelastic ratchetting analysis need not be performed if the following four conditions are satisfied.

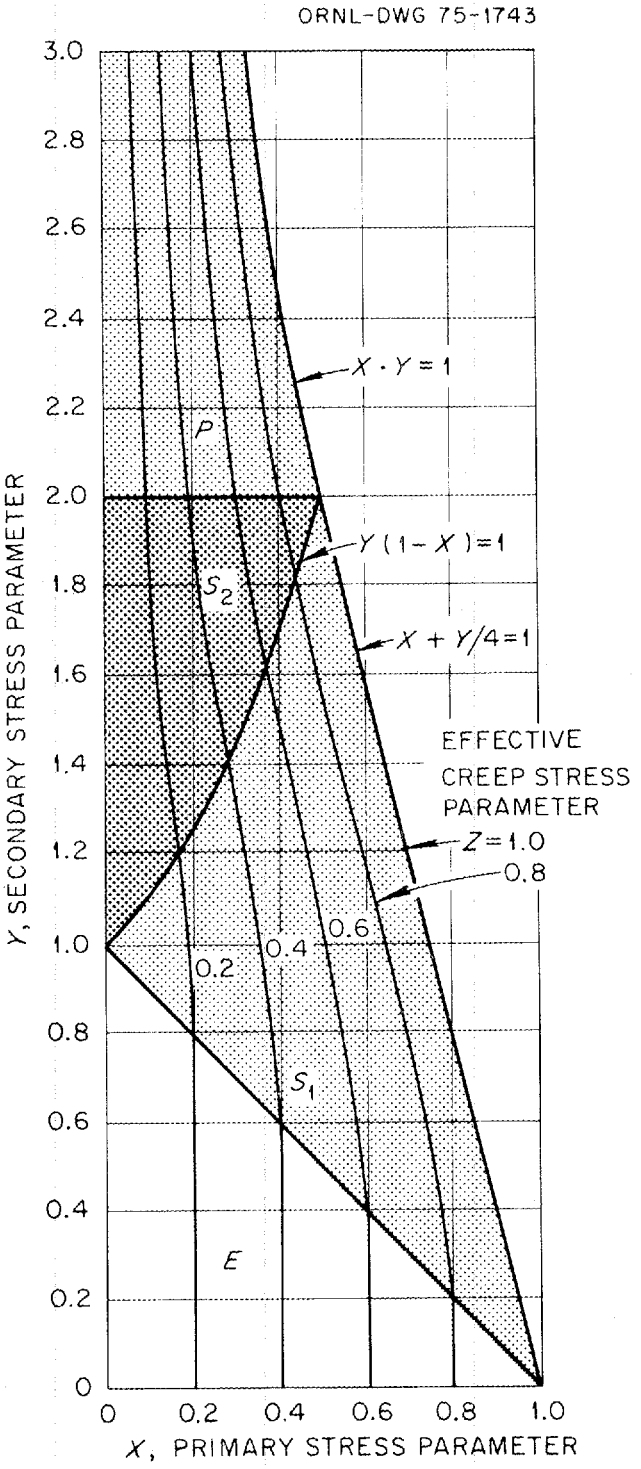


Fig. 7.4. Effective creep stress parameter for ratchetting and enhanced creep.

(1) The approximate inelastic strain averaged through the thickness, ϵ_{avg}, is less than the limit of Subsection 7.2.1 with

$$\epsilon_{avg} = \epsilon_c + \epsilon_r \ , \tag{7.8}$$

where ϵ_c = cumulative creep strain based on the primary stress $(P_L + P_b/K_t)$ and the appropriate isochronous stress-strain curves and ϵ_r = cumulative ratchet strain based on Bree's complete relaxation analysis. The values of ϵ_r are given by

$$\epsilon_r = \sum_i N_i (\Delta\epsilon_r)_i \ , \tag{7.9}$$

where N_i = number of type "i" cycles and $(\Delta\epsilon_r)_i$ = ratchet strain per cycle for type "i" cycles from Bree's complete relaxation equations.

The Bree complete relaxation equations are

$$(\Delta\epsilon_r)_i = \frac{S_m}{E} \left\{1 - x'' + y'' \left[1 - 2\left(\frac{1 - x''}{y''}\right)^{1/2}\right]\right\} \tag{7.10}$$

in region S_1 of Fig. 7.3,*

$$(\Delta\epsilon_r)_i = \frac{S_m}{E} \left\{1 - x'' + 2y'' \left[1 - 2\left(\frac{1 - x''}{y''}\right)^{1/2}\right]\right\} \tag{7.11}$$

in region R_1 of Fig. 7.3,

$$(\Delta\epsilon_r)_i = \frac{S_m}{E} \left[x'' (y'' - 1)\right] \tag{7.12}$$

in regions S_2 and P of Fig. 7.3, and

$$(\Delta\epsilon_r)_i = \frac{S_m}{E} \left[x'' (2y'' - 1) - 1\right] \tag{7.13}$$

---

*It is understood that X and Y in Fig. 7.3 are to be replaced by x'' and y'' when considering Eqs. (7.10) through (7.13).

in region R_2 of Fig. 7.3. In the above,

$$x'' = \left(P_L + \frac{P_b}{K_t}\right)/S_m ,$$

$$y'' = Q_R/S_m ,$$

and S_m corresponds to the maximum operating metal temperature at the location being considered.

(2) The maximum principal surface strain ϵ_{max} is less than the limit of Subsection 7.2.1, with

$$\epsilon_{max} = \epsilon_p + \epsilon_c + \epsilon_r , \tag{7.14}$$

where

$$\epsilon_p = \begin{cases} \frac{1}{E}\,(S_{max} - S_m) & \text{for } S_{max} > S_m , \\ 0 & \text{for } S_{max} \leq S_m , \end{cases}$$

with S_{max} = maximum stress intensity due to primary and secondary stresses, including discontinuity stresses.

(3) The ratio of secondary stress range to S_m is

$$y'' \leq 3 . \tag{7.15}$$

(4) To limit creep ratchetting, one of the extreme conditions which defines the secondary stress-intensity range Q_R must be such that negligible creep relaxation occurs at this point in the loading cycle. This requirement will be satisfied provided the temperature is below the value corresponding to the point where $S_m = S_t$ for $t = 10^5$ hr.

(c) <u>One-Dimensional Inelastic Analysis</u>. Both of the preceding methods are conservative approximations to detailed one-dimensional inelastic ratchetting analyses. In many cases they are extremely conservative, so that often it will be to the designer's advantage to perform a detailed one-dimensional ratchetting analysis.

It is acceptable to analyze each type of cycle for only a few cycles and estimate the total accumulated strain for that type of cycle by multiplying the strain accumulated in the last cycle by the remaining number of cycles of that type and adding that value to the accumulated strain for the cycles that were analyzed. The total accumulated ductility-limited strains, including any strains due to elastic follow-up, from all types of cycles that occur during the life of the component shall be calculated, and their sum must meet the limits of Subsection 7.2.1.

7.3 Creep-Fatigue Evaluation

7.3.1 General Requirements

7.3.1.1 Damage Equation. The combination of Normal, Upset, and Emergency Conditions shall be evaluated for accumulated creep and fatigue damage, including hold time, mean stress (or strain), strain rate, and fluence effects. For a design to be acceptable, the creep and fatigue damage shall satisfy the following relation:

$$\sum_{j=1}^{p} \left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q} \left(\frac{t}{T_d}\right)_k \leq D \ , \qquad (7.16)$$

where

D = total creep-fatigue damage (see Fig. T-1420-2 of Ref. 5).

n = number of applied cycles of loading conditions j.

N_d = number of design allowable cycles of loading conditions j from the fatigue curve corresponding to the maximum metal temperature during the cycle and adjusted to the end-of-life fluence for the component (see discussion below). If the designer so desires, the component-load history may be broken up into increments and the fatigue life evaluated based on the accumulated fluence at the end of that increment. However, exercising this option requires an analysis of the proposed loading history for the component with the cycles being in the correct sequence.

t = time duration of the load condition k.

T_d = allowable time at a given stress intensity (for elastic analysis) or at a given effective stress (for inelastic analysis) from load k; T_d values are obtained by entering the appropriate stress-to-rupture curves of Ref. 5 at a stress value equal to the calculated stress (from load k) divided by the factor k′, which is 0.9 for austenitic stainless steel. T_d is adjusted for the end-of-life fluence of the component.

When the accumulated fluence is below the values listed in Table 5.1, determine N_d from the appropriate figure in Ref. 5 (Fig. T-1420-1A, 1B, or Fig. T-1430-1A, 1B). The design fatigue curves of Fig. T-1420-1 were determined from completely reversed loading conditions at strain rates greater than, or equal to, those noted on the curves. The design fatigue curves of Fig. T-1430-1 include the effect of hold times and slow strain rates and are used for elastic analysis. When $N_d > 10^6$ cycles, the design fatigue curves may be extrapolated by use of a straight line tangent to the curve at 10^6 cycles on the existing log-log plots in Figs. T-1420-1 and T-1430-1 of Ref. 5. Alternately, where data are available in Ref. 8, the fatigue design curves may be extrapolated by first establishing the shape of the fatigue curves beyond 10^6 cycles and then performing the extrapolation based on this shape.

For components irradiated to higher fluences than those listed in Table 5.1, either of two methods may be used to develop fatigue design curves.

(a) Where sufficient data are available in Ref. 8 for the required temperature, strain rate, hold time, and fluence, fatigue design curves may be constructed by developing a best fit to the existing data (if not supplied in Ref. 8) and reducing this fit by factors of 2 on strain and 20 on cycles. These calculations must be documented in the Stress Report.

(b) Alternately, the designer may develop fatigue design curves using the following equation, which is based on the Universal Slopes method:

$$\epsilon_t = AN_d^a + \overline{R}_f BN_d^b , \qquad (7.17)$$

where the constants A, B, a, and b are the result of least-squares fits to the fatigue design curves for unirradiated material as presented in

Ref. 5. These constants are listed in Table 7.2. The factor $\bar{R}_f$ is a reduction factor that reflects the loss in ductility of irradiated material. Values of $\bar{\bar{R}}_f$ are determined from Fig. 7.5 for materials covered by these criteria.

The allowable time to rupture, T_d, at a given stress intensity or equivalent stress for materials irradiated to fluences less than those listed in Table 5.1 is to be taken from stress-to-rupture curves (Fig. I-14.6) of Ref. 5. For fluences equal to or greater than those listed in Table 5.1, either of the following methods may be used to determine minimum stress-to-rupture design values.

(a) The designer may use stress-to-rupture data contained in Ref. 8 for the stress, temperature, and fluence applicable to the component being analyzed. The allowable time to rupture is

$$(T_d)_{irrad} = \left(\frac{t_{Ri}}{t_{Ru}}\right) T_d \ , \qquad (7.18)$$

where

$(T_d)_{irrad}$ = the allowable minimum time to rupture for the irradiated material.

T_d = the allowable time to rupture for the unirradiated material at the same stress.

t_{Ri} = the average time to rupture of the irradiated material for the conditions of stress, temperature, and fluence being analyzed. These values are to be taken from the appropriate curves as presented in Ref. 8.

t_{Ru} = the average time to rupture of the unirradiated material for the conditions of stress, temperature, and fluence being analyzed. These values are to be taken from the appropriate curves as presented in Ref. 8.

(b) Alternately, time-to-rupture design values may be determined using Eq. (7.19):

$$(T_d)_{irrad} = \bar{\bar{R}}_C (T_d)_{unirrad} \ , \qquad (7.19)$$

Table 7.2. Constants Describing Strain-Cycle Fatigue Curves for Unirradiated Austenitic Stainless Steel

	Temperature (°F)	A	a	B	b
Curves for elastic analysis	800	0.010061	−0.13211	0.11830	−0.51859
	850	0.010926	−0.15697	0.09369	−0.64827
	900	0.008520	−0.15875	0.08925	−0.83441
	950	0.005728	−0.15043	0.12045	−1.10693
	1000–1200	0.003287	−0.12887	0.10770	−1.21541
Curve for $\dot{\epsilon} \geq 1 \times 10^{-3}$ in. in.$^{-1}$ sec^{-1}	100	0.008734	−0.11694	0.13213	−0.49671
	800	0.010899	−0.13767	0.12207	−0.53320
	900	0.013672	−0.16899	0.11601	−0.63033
	1000–1200	0.006105	−0.12629	0.09840	−0.58767
	1300	0.005275	−0.12341	0.06288	−0.58250

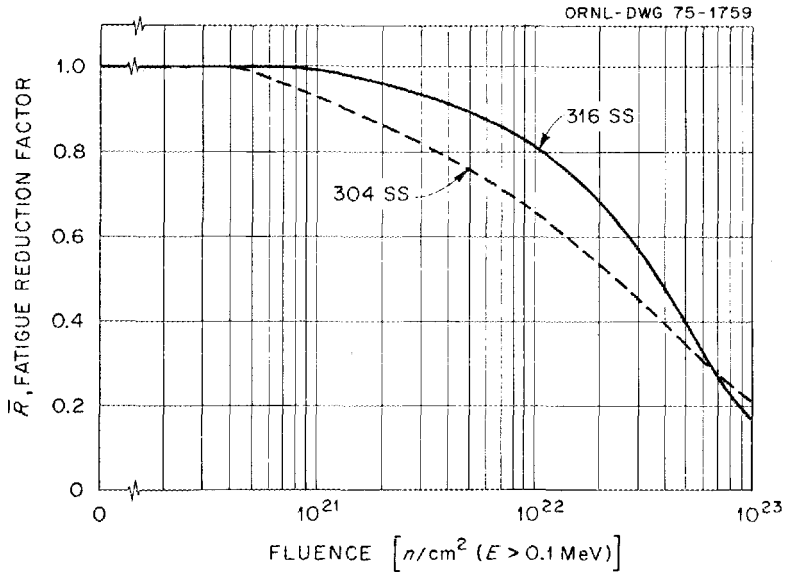


Fig. 7.5. Fatigue reduction factors for annealed and irradiated types 304 and 316 stainless steel.

where $\bar{R}_C$ is a creep life reduction factor. Values of $\bar{R}_C$ are determined from Fig. 7.6 for the type of material, temperature, and accumulated fluence. Other methods of considering the effects of irradiation on rupture life may be used if they are justified in the Stress Report and are acceptable to the Owner.

7.3.1.2 Exemption from Fatigue Analysis. The rules in ASME Code Section III [NB-3222.4(d)], Ref. 4, which permit exemption from fatigue analysis, do not apply to temperatures above the limits of Section III (800°F for austenitic stainless steels).

7.3.1.3 Equivalent Strain Range. An equivalent strain range is used to evaluate the fatigue damage sum for both elastic and inelastic analysis. When the Design Specification contains a histogram delineating a specific loading sequence, the strain range shall be calculated for the cycles described by the histogram. If the sequence of loading is not defined by the Design Specification, the method of combining cycles described in ASME Code Section III, NB-3222.4(e)(5), shall be applied. The equivalent strain range is computed as follows:

Step 1. Calculate all strain components for the strain history (ϵ_x, ϵ_y, ϵ_z, ϵ_{xy}, ϵ_{yx}, ϵ_{zx}, vs time) for the complete cycle. Strain concentration factors are added at this step.

Step 2. Select a point when conditions are at an extreme for the cycle, either maximum or minimum. Refer to this time point by a subscript i.

Step 3. Calculate the history of the change in strain components by subtracting the values at the time i from the corresponding components at each point in time during the cycle: $\Delta\epsilon_x = \epsilon_x - \epsilon_{xi}$, $\Delta\epsilon_y = \epsilon_y - \epsilon_{yi}$, etc.

Step 4. Calculate the equivalent strain range as for each point in time.

$$\Delta\epsilon_{equiv} = \frac{\sqrt{2}}{3}\left[(\Delta\epsilon_x - \Delta\epsilon_y)^2 + (\Delta\epsilon_y - \Delta\epsilon_z)^2 + (\Delta\epsilon_z - \Delta\epsilon_x)^2 + 6(\Delta\epsilon_{xy}{}^2 + \Delta\epsilon_{yz}{}^2 + \Delta\epsilon_{zx}{}^2)\right]^{1/2} . \quad (7.20)$$

Step 5. Use the maximum equivalent strain range calculated as the range of strain to enter the fatigue curves.

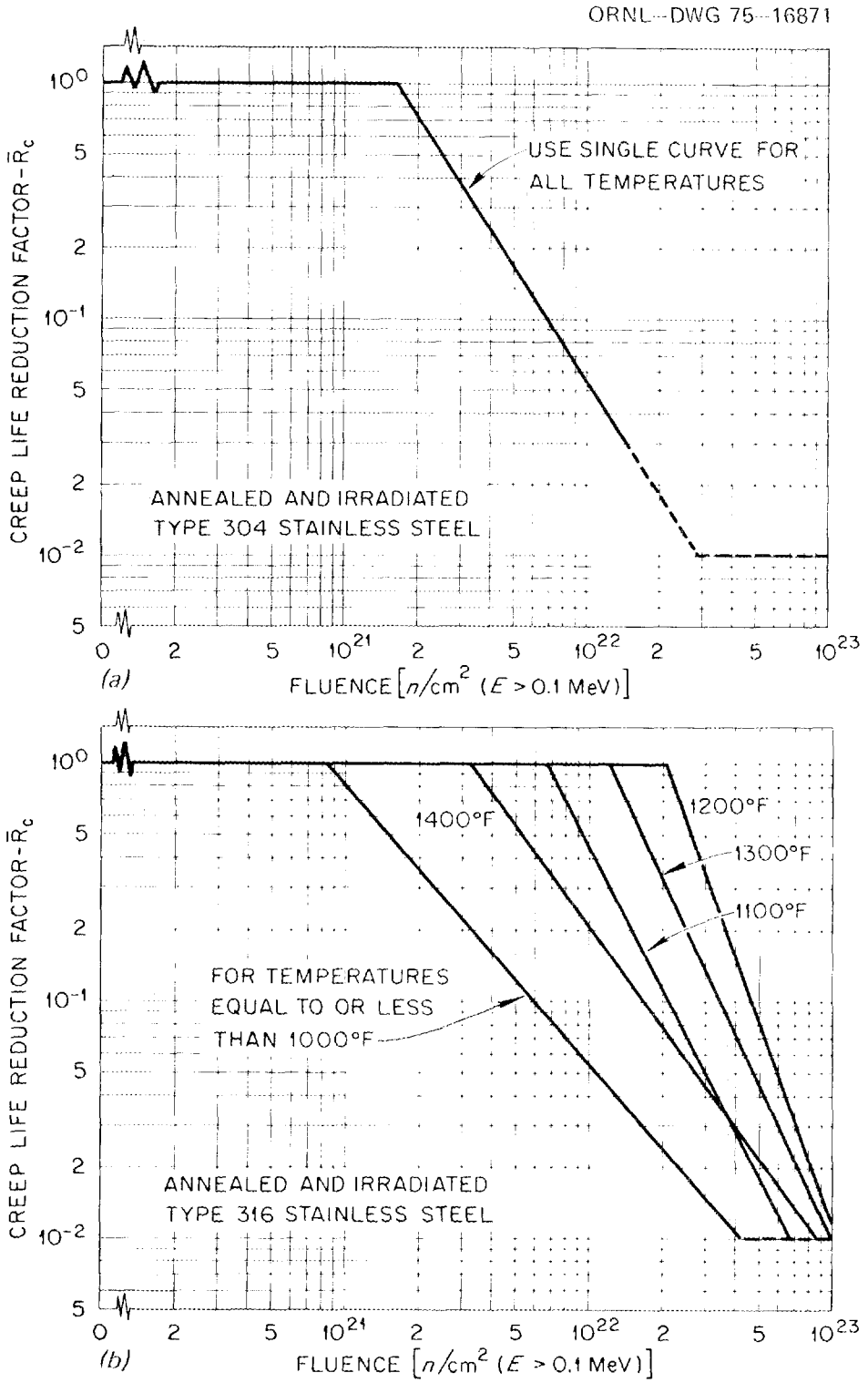


Fig. 7.6. Creep life reduction factors for annealed and irradiated types 304 and 316 stainless steel.

(a) The above procedure may be used regardless of whether principal strains change directions or not.

(b) An alternate to the above sequence, applicable only when principal strains do not rotate, is given in Paragraph 7.3.1.4.

7.3.1.4 Alternate Calculation Method – Equivalent Strain Range. An alternate calculational method for equivalent strain-range determination is as follows:

Step 1. Same as step 1 above.

Step 2. Determine the principal strains vs time for the cycle.

Step 3. At each time interval of step 2, determine the strain differences $\epsilon_1 - \epsilon_2$, $\epsilon_2 - \epsilon_3$, $\epsilon_3 - \epsilon_1$.

Step 4. Determine the history of the change in strain differences by subtracting the values at the time i from the corresponding values at each point in time during the cycle. Designate these strain difference changes as $\Delta(\epsilon_1 - \epsilon_2) = \epsilon_{12} - \epsilon_{12i}$, $\Delta(\epsilon_2 - \epsilon_3) = \epsilon_{23} - \epsilon_{23i}$, $\Delta(\epsilon_3 - \epsilon_1) = \epsilon_{31} - \epsilon_{31i}$.

Step 5. Compute the equivalent strain range as:

$$\Delta\epsilon_{equiv} = \frac{\sqrt{2}}{3}\left\{[\Delta(\epsilon_1 - \epsilon_2)^2] + [\Delta(\epsilon_2 - \epsilon_3)^2] + [\Delta(\epsilon_3 - \epsilon_1)^2]\right\}^{1/2} . \qquad (7.21)$$

Step 6. Use the maximum equivalent strain range calculated as the range of strain to enter the fatigue curves.

7.3.1.5 Irradiation-Induced Strain. Irradiation-induced swelling and creep strain components are presently not considered ductility limited and therefore do not need to be considered in the damage evaluation.

7.3.2 Limits Using Inelastic Analysis

When inelastic analysis is used to satisfy Eq. (7.16), the following rules apply.

(a) Creep-rupture damage may also be calculated by using the integral form:

$$\int_0^t \frac{dt}{T_d} .$$

(b) The fatigue damage sum shall be evaluated by using the equivalent strain range when entering the appropriate fatigue design curve of Ref. 5. The selection of fatigue and stress-rupture design curves for irradiated components follows the rules of Subsection 7.3.1.

(c) The total damage factor D shall not exceed the creep-fatigue damage envelope as presented in Ref. 5 (Fig. T-1420-2).

7.3.3 Limits Using Elastic Analysis

7.3.3.1 General Requirements. (a) The elastic analysis rules in this section may be used only when the elastic ratchetting rules of Subsection 7.2.2 have been satisfied.

(b) When elastic analysis is used to satisfy the requirements of Paragraph 7.3.1.1, the total fatigue and creep-rupture damage shall be summed linearly and the total damage factor D shall not exceed unity. The individual damage terms are to be evaluated in accordance with the following paragraphs.

7.3.3.2 Fatigue Damage Evaluation. (a) For the fatigue damage term, the strain range ϵ_t is used with the design fatigue curve to determine N_d. The appropriate design curve selected should correspond to the maximum metal temperature experienced during the cycle.

(b) When using elastic analysis for fatigue damage calculations, the computed maximum strain does not reflect the true strain accumulation due to plastic or creep flow. Therefore, the following method may be used to account for increased strain due to inelastic behavior in the region under consideration:

$$\epsilon_T = K_\epsilon \epsilon_e + K_\epsilon^2 \epsilon_p + K_T \epsilon_F , \qquad (7.22)$$

where

ϵ_T = the derived maximum strain for the loading condition which is to be used in entering the appropriate fatigue curve;

ϵ_e = the elastic strain in the region under consideration, exclusive of strain concentrations;

K_ϵ = the theoretical elastic strain concentration factor;

ϵ_p = the inelastic strain in the region under consideration, exclusive of strain concentrations and peak thermal strains;

ϵ_F = peak thermal strain associated with the peak thermal stress as defined in the ASME Code, Section III;

K_T = strain concentration factor applied to peak thermal strain component ϵ_F.

(c) The value of ϵ_p is determined by subtracting the elastic strain component ϵ_e from the calculated total ductility-limited strain. The total ductility-limited strain ϵ_n is the sum of the load-controlled and the deformation-controlled strains exclusive of strain concentration, peak thermal strain, and irradiation-induced creep strain, which is not considered ductility limited.

$$\epsilon_n = \epsilon_{\text{load controlled}} + \epsilon_{\text{strain controlled}} , \qquad (7.23)$$

where

$\epsilon_{\text{load controlled}}$ = the strain as determined from the appropriate isochronous stress-strain curve for the elastically calculated stress, the temperature, and the duration of one cycle of the transient being considered,

$\epsilon_{\text{strain controlled}}$ = the strain determined from the elastically calculated stress resulting from the strain-controlled deformation ($\sigma_{\text{strain controlled}}/E$).

(d) The equations of plasticity may be used to resolve inelastic strain components for the computed inelastic strain obtained either from the isochronous stress-strain curves or from other calculations of deformation-controlled loadings.

7.3.3.3 Creep Damage Evaluation. Creep damage from primary and secondary stresses resulting from sustained operating conditions between cycles shall be evaluated as follows.

The stress intensity S due to primary-plus-secondary stresses from load condition k shall be taken as the lesser of:

(a) The minimum specified yield strength of the material under evaluation.

(b) $(P_m + 0.5S_r)$, where S_r is the maximum range of primary-plus-secondary stress intensity.

(c) The value of T_d is obtained from the stress-to-rupture curves of Ref. 5, but the value of stress is divided by a factor k′, which is 0.9 for austenitic stainless steel. If the fluence exceeds the values listed in Table 5.1, the value of T_d is to be determined per Subsection 7.3.1.

7.4 Structural Instability and Buckling

This subsection is adapted directly from ASME Code Case 1592.[5] Since, as has been stated, this document requires use of the design curves contained in Ref. 5, the rules covering buckling and instability have been reproduced verbatim. Note that all references are to other paragraphs or figures within the Code Case. These rules were written to consider the effects of thermal creep; however, the deformations caused by irradiation creep and swelling shall also be considered.

T-1500 Buckling and Instability
T-1510 General Requirements

(a) The stability limits in NB-3133 of Section III pertain only to specific geometrical configurations under specific loading conditions. These Section III limits include the effects of initial geometrical imperfections permitted by fabrication tolerances. However, Section III limits do not consider the effects of creep due to long term loadings at elevated temperatures and the effects of the other loads or other geometries. The T-1500 rules provide additional limits which are applicable to general configurations and loading conditions that may cause buckling or instability due to time-independent as well as time-dependent creep behavior of the material. These additional limits are applicable to all specified Design and Operating conditions.

(b) For the limits specified in T-1520, distinction is made between load-controlled buckling and strain-controlled

buckling. Load-controlled buckling is characterized by continued application of an applied load in the post-buckling regime, leading to catastrophic failure...e.g. collapse of a tube under external pressure. Strain-controlled buckling is characterized by the immediate reduction of strain-induced load upon initiation of buckling, and by the self-limiting nature of the resulting deformations. Even though it is self-limiting, strain-controlled buckling must be avoided to guard against failure by fatigue, excessive strain, and interaction with load-controlled instability.

(c) For conditions under which strain-controlled and load-controlled buckling may interact, the Load Factors applicable to load-controlled buckling shall be used for the combination of load-controlled and strain-controlled loads to guard against buckling in the interactive mode.

(d) For conditions where significant elastic follow-up may occur, the Load Factors applicable to load-controlled buckling shall also be used for strain-controlled buckling.

(e) For load-controlled buckling the effects of geometrical imperfections and tolerances, whether initially present or induced by service, shall be considered in the calculation of the instability load.

(f) For purely strain-controlled buckling the effects of geometrical imperfections and tolerances, whether initially present or induced by service, need not be considered in the calculation of the instability strain. However, if significant geometrical imperfections are present initially, enhancement due to creep may cause excessive deformation or strain. These effects shall be considered in the application of deformation and strain limits of T-1260 and T-1300.

(g) The expected minimum stress-strain curve for the material at the specified temperatures shall be used. The expected minimum values may be obtained by normalizing the appropriate average hot tensile curve of Fig. T-1800 to the expected minimum yield strength given in Table I-14.5.

(h) The limits of both T-1521 and T-1522 shall be satisfied for the specified Design and Operating conditions.

T-1520 Buckling Limits
T-1521 Time-Independent Buckling

For load-controlled buckling, the Load Factor; and for strain-controlled buckling, the Strain Factor, shall equal or exceed the values given in Table T-1521-1 for the specified Design and Operating conditions to guard against time-independent (instantaneous) buckling.

TABLE T-1521-1 TIME-INDEPENDENT BUCKLING LIMITS

	Load Factor(1)	Strain Factor(1)(3)
Design Conditions	3.0(2)	1.67
Operating Conditions		
Normal	3.0	1.67
Upset	3.0	1.67
Emergency	2.5	1.4
Faulted	1.5	1.1
Testing(4)	2.25	1.67

(1) Load (Strain) Factor = [Load (strain) which would cause instant instability at the design (or actual operating) temperature.] ÷ [Design or expected load (strain).]

(2) Changes in configuration induced by service need not be considered in calculating the buckling load.

(3) For thermally-induced strain-controlled buckling, the Strain Factor is applied to loads induced by thermal strain. To determine the buckling strain, it may be necessary to artificially induce high strains concurrent with the use of realistic stiffness properties. The use of an "adjusted" thermal expansion coefficient is one technique for enhancing the applied strains without affecting the associated stiffness characteristics.

(4) These factors apply to hydrostatic, pneumatic, and leak tests. Other types of tests shall be classified according to 3113.7 of Code Case 1592.

T-1522 Time-Dependent Buckling

To protect against load-controlled time-dependent creep buckling, it shall be demonstrated that instability will not occur during the specified lifetime for a load history obtained by multiplying the specified Operating condition loads by the factors given in Table T-1522-1. A design factor is not required for purely strain-controlled buckling because strain-controlled loads are reduced concurrently with resistance of the structure to buckling when creep is significant.

TABLE T-1522-1 TIME-DEPENDENT LOAD-CONTROLLED BUCKLING FACTORS

Operating Conditions	
Normal	1.5
Upset	1.5
Emergency	1.5
Faulted	1.25

8. DESIGN RULES FOR BRITTLE MATERIALS

8.1 General

The design rules of this section are preliminary and are only intended for use in the design of irradiated components. A threshold fluence limit has not been set below which brittle fracture need not be considered. The data required to perform a fracture mechanics analysis are to be taken from Ref. 8; when these data are not contained in Ref. 8, it is the responsibility of the designer to furnish such data, trends, or extrapolations by which to assess these rules. Any such data, trends, or extrapolations furnished by the designer must be acceptable to the Owner and be justified in the Stress Report.

8.2 Definitions

This section provides definitions and nomenclature applicable to fracture mechanics and crack propagation analyses. Due to their specialized nature, they were not included in Chapter 3.

8.2.1 Flaw Size

Flaws can be introduced through fabrication, may be an inherent part of the design of a component, or may develop due to service. Reliable nondestructive testing (NDT) methods are able to detect flaws to some minimum size. Although a component may not contain flaws as large as this minimum detectable size, the designer is to assume that at least one flaw is initially present and is the minimum flaw size that can be detected by the NDT technique to be used on the component being analyzed. Crack growth due to sustained or cyclic loading shall be considered in obtaining the final flaw size to be analyzed.

(a) a_m – Minimum detectable flaw size, in.

(b) a – The depth of a surface flaw or the semiminor axis of an internal flaw, in.

(c) c – The half length or the semimajor axis of a surface or internal flaw, in.

8.2.2 K – Stress-Intensity Factor

The symbol K is commonly used to denote stress-intensity factor, ksi $\sqrt{\text{in.}}$

(a) K_I, K_{II}, K_{III}, etc. – The stress-intensity factor is associated with the mode of loading (I, II, or III) and the method of loading [e.g., static (K_{Ic}) or dynamic]. Note that the stress-intensity factors are not to be confused with section shape factors, stress intensities, or stress concentration factors.

(b) K_i – Initial Critical-Stress-Intensity Factor. The initial critical-stress-intensity factor is the value of fracture toughness for the material after exposure to maximum service fluence. Although K_i is used for illustrative purposes, the value of the critical-stress-intensity factor representative of the loading and environmental conditions being investigated should be used (e.g., K_{Ic} for plane-strain static loads and K_c for non-plane-strain conditions). Where fatigue loadings are being considered, the change in critical-stress-intensity factor with crack growth shall be taken into account.

8.2.3 Q – Flaw Shape Parameter

The symbol Q (dimensionless) is basically a geometry factor and relates the flaw orientation, type, and the flaw size in relation to the section size. In all cases it is assumed that the flaw is oriented perpendicular to the stress field.

8.2.4 σ_K – Critical Stress Intensity

The critical stress at which unstable crack propagation initiates is denoted by σ_K.

8.2.5 $\bar{\sigma}$ – Characteristic Stress

The characteristic stress $\bar{\sigma}$ is that value of stress that must be limited and is calculated from the fracture mechanics analysis. Details are given in Section 8.4. The characteristic stress is limited to 60% of the critical stress intensity; i.e.,

$$\bar{\sigma} \leq 0.6\sigma_K \ . \qquad (8.1)$$

8.3 Flaw-Sensitivity Characterization

Materials are to be classified as being in a ductile or brittle state according to the following procedure. In making this classification, the worst set of conditions to which the component will be subjected is to be used.

The potential for brittle fracture shall be considered, and a fracture mechanics analysis is required if, for a defined minimum flaw size a_m and a critical-stress-intensity factor K_i, the critical stress for unstable crack propagation σ_K, as defined by

$$\sigma_K = \frac{K_i}{Q\sqrt{\pi a_m}} , \tag{8.2}$$

is less than the minimum yield stress S_{Iy} at temperature for the irradiated material or 2.7 times the minimum yield stress S_y at temperature for the unirradiated material,

$$\sigma_K \leq \begin{cases} 2.7S_y \\ S_{Iy} \end{cases} . \tag{8.3}$$

For classification purposes, only two shape factors need be considered: (a) through-edge and part-through surface flaws, $Q = 1.1$, and (b) through-center and internal flaws, $Q = 1.0$. These Q factors should yield conservative results. The designer may use other shape factors applicable to the specific geometry in question if he so desires.

If the material is evaluated as flaw sensitive, the design rules of the following section apply.

8.4 Fracture Mechanics Analysis

The rules of this section, including the screening test of Eq. (8.2), are based on the concepts of linear elastic fracture mechanics. The use of these rules where the stresses exceed the yield stress does not account for plastic strain accumulation.

It has been shown that the locally elevated stress fields around a crack are related to a stress-intensity factor. Brittle fracture occurs

when the stress-intensity factor reaches a critical value. This critical-stress-intensity factor shall be experimentally determined for the particular operating environment and design life of the element under consideration.

The basic purpose of a fracture mechanics analysis is to determine a value of the critical stress at which unstable crack propagation initiates. To account for errors in modeling factors (see step 4 below), the allowable stress intensity (i.e., the characteristic stress) is restricted to 60% of this critical stress intensity [Eq. (8.1)]. This characteristic stress is determined by performing an elastic analysis of the component.

The following procedure is recommended for analysis of flaw-sensitive materials.

Step 1. On an elastic basis, determine the critical stress areas in the component. These areas are determined by reviewing (a) the gross elastic stress distribution throughout the structure and (b) the local environment. The gross elastic stress distribution is defined as the stress calculated, without the presence of a crack, from classical analytic models or finite-element techniques.

Step 2. Determine from Ref. 8 the minimum value of K_i (K_c, K_{Ic}, or applicable value) for the material being used as a function of operating environment. Where data are not available in Ref. 8, the designer is required to furnish experimental data or correlations. Justification of the method used is to be given in the Stress Report and must be approved by the Owner.

Step 3. The flaw types and sizes in the critical stress areas are to be determined. If no identifiable flaws are present originally, a conservative size crack is to be assumed to be present in the worst location and oriented in the worst direction. This assumed flaw size shall be at least as large as the minimum size flaw that is readily detectable by standard inspection techniques and shall include crack growth during operation.

Step 4. Select a fracture mechanics model that approximates, as closely as possible, the stress geometry situation being investigated.

(a) Real configurations subjected to linear elastic fracture mechanics can, in general, be represented by one of the following combinations of stress distribution and geometry.

(i) Uniform stress distribution in semi-infinite and infinite structures.

(ii) Uniform stress distribution in finite structures.

(iii) Nonuniform stress distribution in semi-infinite and infinite structures.

(iv) Nonuniform stress distribution in finite structure.

(b) Fracture mechanics models can generally be represented by Eq. (8.2) where Q factors account for geometry variations. For the specific case of (a)(i) above, Q factors are as given below and defined in Fig. 8.1.

(i) Through-edge flaws, $Q = 1.1$.

(ii) Through-center flaws, $Q = 1.0$.

(iii) Part-through surface flaws, $Q = 1.1/\sqrt{Q'}$.

(iv) Internal flaws, $Q = 1.0/\sqrt{Q'}$.

In (b)(iii) and (b)(iv) above,

$$Q' = \Phi^2 - (0.212)(\sigma/\sigma_{ys})^2 , \tag{8.4}$$

where σ_{ys} is the yield strength representative of the material conditions at the operating life being considered. The quantity Φ is the complete elliptic integral of the second kind,

$$\Phi = \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2\theta}\, d\theta , \tag{8.5}$$

where

$$k = \sqrt{1 - 4(a/2c)^2}$$

and a and c are as defined in Section 8.2. These terms are illustrated in Fig. 8.1.

For $0.05 \leq (a/2c) \leq 0.50$, an alternate empirical expression for Φ is

$$\Phi^2 = 1 + 4.593(a/2c)^{1.650} . \tag{8.6}$$

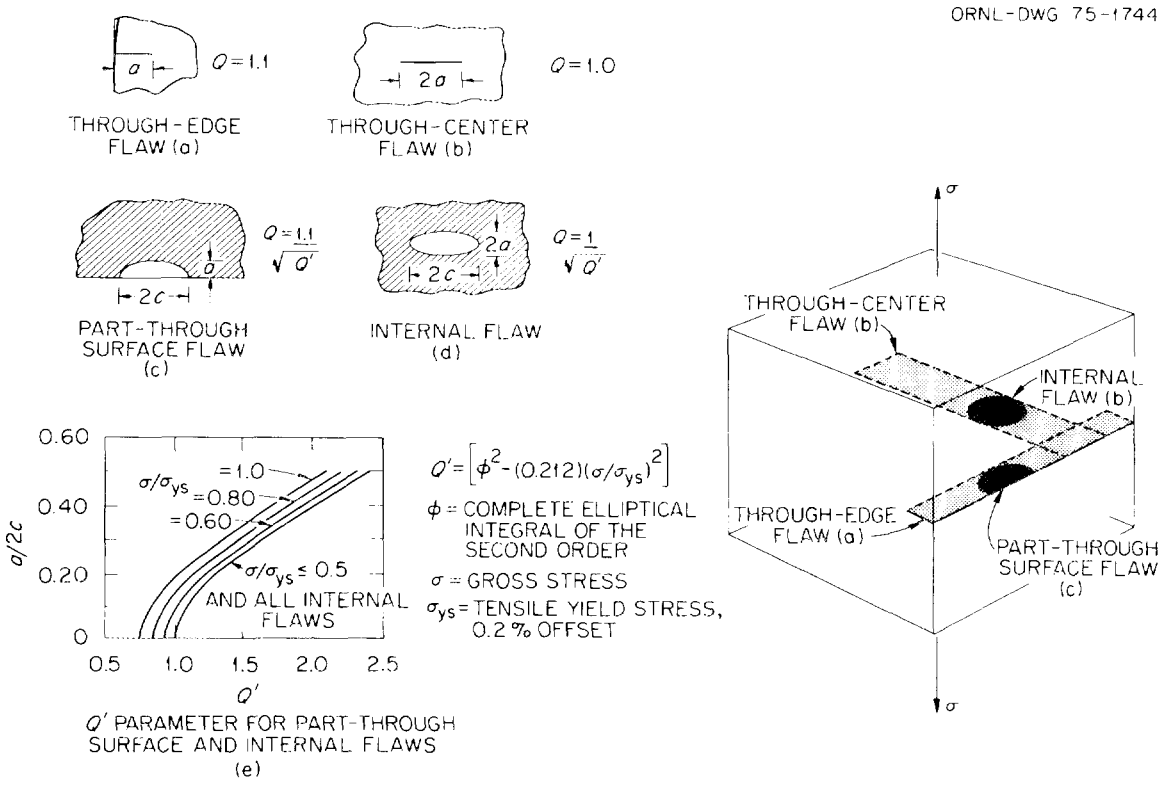


Fig. 8.1. Basic flaw types, corresponding geometry factors, and nomenclature.

Q factors applicable to (a)(2) where the crack propagation mechanism is influenced by the structure boundary can be found in the literature.

For nonuniform stress distributions, the stress-intensity factor may be calculated from models utilizing the finite-element technique or approximate methods. For semi-infinite and infinite structures, (a)(3) above, the Q factor may be taken to be 1.0 and the characteristic stress is approximated as defined in step 5 below. Additional information[9] for other common crack geometries and stress fields is given in Figs. 8.2 through 8.5.

Step 5. The characteristic stress associated with the fracture mechanics model shall be compared with the allowable stress-intensity limit. The characteristic stress is determined from the gross elastic stress distribution as follows.

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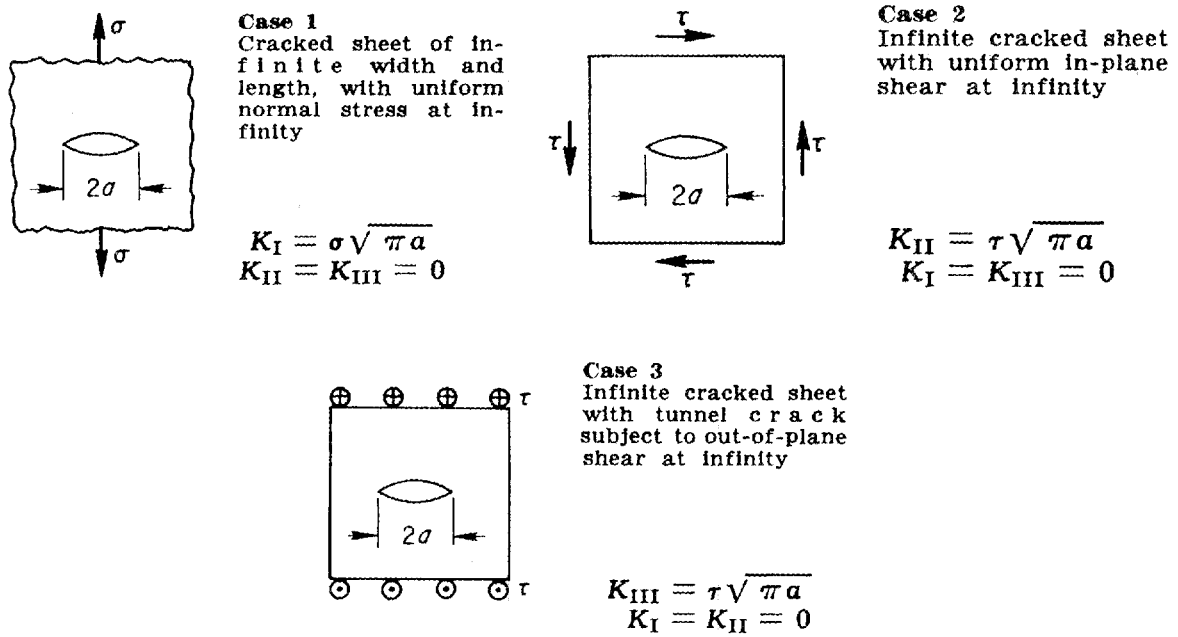

Fig. 8.2. Stress intensity factors for common configurations (Ref. 9).

(a) For uniform stress situations, steps 4(a)(i) and (ii), the characteristic stress is defined as the uniform stress.

(b) For nonuniform stress distributions in semi-infinite and infinite structures, step 4(a)(iii), use the following procedure.

(i) If the gross elastic stress increases in the direction of anticipated crack propagation, the characteristic stress shall be the value of the gross elastic stress at the midpoint of the critical section through the component at the location of the anticipated flaw.

(ii) If the gross elastic stress decreases in the direction of anticipated crack propagation, the characteristic stress shall be the gross elastic stress in the vicinity of the crack tip.

A comparison of stress shall be made, and the characteristic stress as determined above shall not exceed the allowable stress limit; i.e.,

$$\bar{\sigma} \leq 0.6\sigma'_K \ , \qquad (8.7)$$

where σ'_K is the critical stress intensity for the geometry being analyzed.

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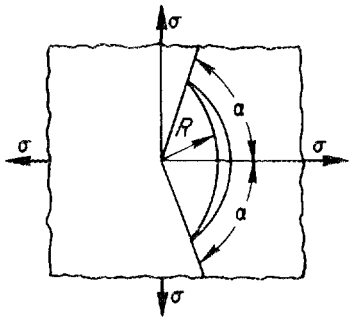

Case 4
Curved crack in equal biaxial stress field

$$K_I = \frac{\sigma(\pi R)^{1/2}}{\left(1 + \sin^2 \frac{\alpha}{2}\right)} \left(\frac{\sin\alpha(1 + \cos\alpha)}{2}\right)^{1/2}$$

$$K_{II} = \frac{\sigma(\pi R)^{1/2}}{\left(1 + \sin^2 \frac{\alpha}{2}\right)} \left(\frac{\sin\alpha(1 - \cos\alpha)}{2}\right)^{1/2}$$

Case 5
Cracks from hole in infinite sheet

$$K_I = \sigma\sqrt{L\pi}\, f\left(\frac{a}{r}\right)$$

$$K_{II} = 0$$

L/r	One Crack $f(L/r)$ Uniaxial Stress	One Crack $f(L/r)$ Biaxial Stress	Two Cracks $f(L/r)$ Uniaxial Stress	Two Cracks $f(L/r)$ Biaxial Stress
0	3.39	2.26	3.39	2.26
0.1	2.73	1.98	2.73	1.98
0.2	2.30	1.82	2.41	1.83
0.3	2.04	1.67	2.15	1.70
0.4	1.86	1.58	1.96	1.61
0.5	1.73	1.49	1.83	1.57
0.6	1.64	1.42	1.71	1.52
0.8	1.47	1.32	1.58	1.43
1.0	1.37	1.22	1.45	1.38
1.5	1.18	1.06	1.29	1.26
2.0	1.06	1.01	1.21	1.20
3.0	0.94	0.93	1.14	1.13
5.0	0.81	0.81	1.07	1.06
10.0	0.75	0.75	1.03	1.03
∞	0.707	0.707	1.00	1.00

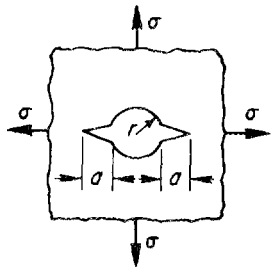

Fig. 8.3. Stress intensity factors for common configurations (Ref. 9).

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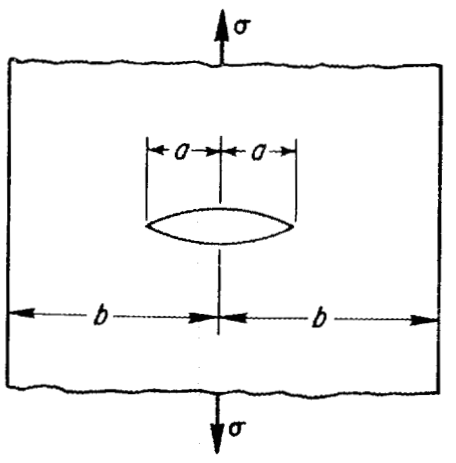
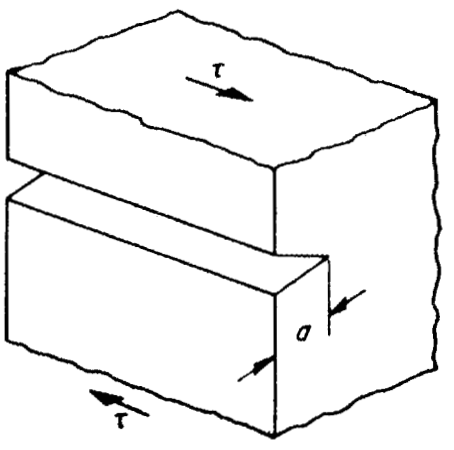
Case 6
Central crack in strip subject to tension (finite width)



$$K_I = \sigma\sqrt{\pi a}\, f(\lambda)$$
$$\lambda = a/b$$

λ	$f(\lambda)$
0.074	1.00
0.207	1.03
0.275	1.05
0.337	1.09
0.410	1.13
0.466	1.18
0.535	1.25
0.592	1.33

Case 7
Edge crack in a semi-infinite body subject to shear



$$K_I = K_{II} = 0$$
$$K_{III} = \tau\sqrt{\pi a}$$

Fig. 8.4. Stress intensity factors for common configurations (Ref. 9).

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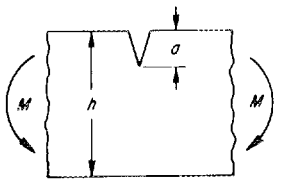


Case 8
Notched beam in bending

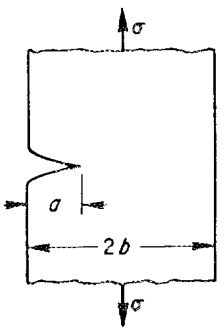
$$K_I = \frac{6M}{(h-a)^{3/2}} f(a/h)$$

$$K_{II} = K_{III} = 0$$

a/h	$f(a/h)$
0.05	0.36
0.1	0.49
*0.2	0.60
0.3	0.66
0.4	0.69
0.5	0.72
0.6	0.73
>0.6	0.73

Case 9
Single edge notch

$$K_I = \sigma\sqrt{\pi a}\, f(a/b)$$
$$K_{II} = K_{III} = 0$$



a/b	$f(a/b)$
0.1	1.15
0.2	1.20
0.3	1.29
0.4	1.37
0.5	1.51
0.6	1.68
0.7	1.89
0.8	2.14
0.9	2.46
1.0	2.86

Fig. 8.5. Stress intensity factors for common configurations (Ref. 9).

9. SPECIAL NOTES AND LIMITS

9.1 General

This section provides special notes and limits for several areas that must be considered by the designer. These are intended to supplement similar notes and limits included in the ASME Code.[4,5] The designer shall consider the rules in this section as they apply to the particular component being considered.

9.2 Multidimensional Stress Analysis

The material properties of these criteria are based on uniaxial tests. Inelastic analysis shall use appropriate multiaxial stress-strain relationships and associated flow rules. Acceptable techniques and methods for use in performing detailed inelastic analyses are given in Ref. 7. Alternate methods, on theoretically and experimentally sound bases, may be used by the manufacturer provided Owner approval is obtained prior to their use. Where the design rules of these criteria require performance of inelastic analyses considering irradiation effects, the designer shall supplement the methods of Ref. 7 to include irradiation creep and swelling and, where applicable, changes in plastic-thermal creep behavior. The materials properties information required to implement inelastic analysis methods is to be obtained in accordance with Section 2.1.

This document relates extensively to the properties and characteristics of unirradiated materials. However, to satisfy the limits given in Chapter 7, it is the intent of the criteria to allow the use of elastic-plastic and thermal creep properties that are fluence dependent. If this option is exercised, the Stress Report shall contain the material properties relationships along with justification, unless they are included in the data sources listed in Section 2.1.

For elastic analysis allowed by these criteria, unirradiated material properties shall be used. Also, the maximum shear stress theory shall be used to compare calculated stresses with design allowables.

9.3 Environmental Effects

9.3.1 Sodium Effects on Allowable Stress Limits

The designer shall consider the effect of high-temperature sodium on the allowable stress limits so that adequate margins of safety will be maintained at all times.

9.3.2 Corrosion Allowance

Provisions shall be made for thinning by corrosion of components or parts thereof during the design or specified life of the component by a suitable increase in or addition to the thickness of the base metal over that determined by the design formulas. Material added or included for this purpose need not be of the same thickness for all parts of the component if different rates of attack are expected for the various parts.

9.4 Welds

9.4.1 General

Because of the potential for limited ductility of weld metal at elevated temperatures and the potential for high strain concentrations (both metallurgical and geometric) in the heat-affected zones of weldments, the requirements in the following subsection shall be satisfied for the design and location of all pressure boundary and other primary structural welds subject to Normal Conditions at metal temperatures above those for which allowable stress values are given in Appendix I of the ASME Code Section III.

9.4.2 Material Properties

In calculating strain deformations in a weld region, the parent material properties shall be used up to the center line of the weld. Alternately, the use of material properties of prototypic welds may be used, provided (1) the method is acceptable to the Owner; (2) the materials properties are obtained from Ref. 8, or, where material properties are supplied by the designer, full justification is included in the Stress Report; and (3) the full weld geometry shall be analyzed as a unit (i.e.,

the deformation behavior of the base metal, weld metal, and heat-affected zone cannot be considered separately).

9.4.3 Strain Limits

Inelastic strains accumulated in the weld region shall not exceed one-half the strain values permitted for the parent material.

9.4.4 Weld Geometry

(a) All category A, B, C, and D welds in vessels and all equivalent pressure boundary welds in other components shall be full-penetration butt welds equivalent to those required for category "A" welds under the ASME Code Section III. All butt welds shall comply with the fitting and alignment requirements of NB-4230, the surface requirements of NB-4424 (as supplemented by RDT E 15-2) and NB-4425, and the reinforcement requirements of NB-4426 (as supplemented by RDT F 15-2), where the maximum reinforcement is measured from the adjacent surfaces of the two abutting members. (All paragraph numbers referred to are in the ASME Code Section III.)

(b) Observations of surface geometry can be visual, remote visual (i.e., using a borescope device or making a surface replica), ultrasonic (based on a weld mockup test in which the same weld procedures are used on the same nominal pipe diameter and wall thickness), or based on a radiographic technique that is suitable for inspection of internal surfaces.

(c) Non-full-penetration welds, where permitted, and attachment welds shall have general surface geometry free from weld irregularities and abrupt changes in contour. If the designer determines that contour control is required for the criteria of this document to be satisfied, the necessary dimensions and tolerances shall be indicated on the fabrication drawings.

9.4.5. Analysis of Geometry

The analysis for stresses, strains, and creep-fatigue interactions at welds shall use stress and strain concentration factors appropriate for the worst surface geometry, including drawdown and weld buildup, and shall be included in the Stress Report (see NB-3350 of ASME Code Section III, as supplemented by RDT E 15-2).

9.5 Bearing Loads

The rules of the ASME Code Section III shall apply with the restriction that the average shear stress shall be limited to $0.6S_{mt}$ for Normal plus Upset Operating Conditions.

9.6 Elastic Follow-Up

The computation of deformation-controlled stress ranges on an elastic basis fails to reflect the actual strain distribution in systems where only a small portion of the structure undergoes plastic strain and/or creep strain while the major portion of the system remains essentially elastic. In these cases, the parts with higher creep rate or higher stress will be subjected to inelastic strain concentrations because of the elastic follow-up of the rest of the structure. Such unbalance can be produced when flexible structural parts are in series with stiffer parts and the flexible sections are highly stressed. Examples are:

(a) Local reduction in size of a cross section or local use of a weaker material.

(b) In a piping system of uniform size, a configuration for which most of the system lies near a straight line drawn between anchors, stiffeners, flanges, or other stiff members, with only a very small portion that projects away from this line and absorbs most of the expansion strain.

If possible, the above conditions should be avoided in design.

10. REFERENCE DOCUMENTS

1. A. W. Dalcher, Structural Design Criteria for the FBR Reactor Core, TI-001-210-008, Atomics International, North American Rockwell (January 1971).

2. E. Y. W. Tsui, J. V. Marron, and A. T. Brown, Interim Stress Design Criteria for LMFBR Vessel and Core Structures, GEAP-13719, Breeder Reactor Department, General Electric Co. (May 1971).

3. H. D. Garkisch, Preliminary LMFBR Core Structural Design Criteria, WARD-3045T2C-5, Westinghouse Electric Corporation, Advanced Reactors Division (February 1973).

4. Rules for Construction of Nuclear Power Plant Components, ASME Boiler and Pressure Vessel Code, Section 3, The American Society of Mechanical Engineers, New York, 1974.

5. Interpretations of ASME Boiler and Pressure Vessel Code, "Case 1592-4, Class 1 Components in Elevated Temperature Service," The American Society of Mechanical Engineers, New York, June 30, 1975.

6. Requirements for Design of Nuclear System Components at Elevated Temperatures, RDT F9-4T, January 1974.

7. Guidelines and Procedures for Design of Nuclear System Components at Elevated Temperatures, RDT F9-5T, March 1974.

8. Nuclear Systems Materials Handbook, Design Data, TID-26666, Vol. 1.

9. C. C. Osgood, "A Basic Course in Fracture Mechanics – Lesson Number 3 – Applying Fracture Mechanics to Design," Machine Design 43(20), 102–6 (Aug. 19, 1971), American Society of Mechanical Engineers, New York.

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