ANL-6389
Metals, Ceramics,
and Materials
(TID-4500, 16th Ed.,
Amended)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

DESIGN CRITERIA FOR STEEL IN NUCLEAR REACTORS

by

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July 1961

Operated by The University of Chicago
under
Contract W-31-109-eng-38

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ABSTRACT

Criteria for stress analysis and structural design with steel for the critical components of nuclear plants are presented. An effort is made to integrate the effects on the strength of steel of the coexisting phenomena, such as mechanical and thermal loads, stress cycling and fatigue, creep and creep rupture, irradiation and loss of ductility.

Extensive use of the plastic region of steel is made for the accommodation of thermal stresses. The concept of cumulative damage in the plastic region is expounded for thermal fatigue and creep.

A short description is given of the five avenues followed by scientists all over the world for the development of a theory governing the strength of materials. A particularly promising approach is taken up that attempts to establish a "theory of fatigue" based on experiments.

I. NOTATION

ϵ_i	initial strain
ϵ_t	thermal strain
ϵ_y	yield strain
S_t	thermal stress (real or imaginary)
S_y	yield stress
S_i	initial stress
S_{max}	maximum thermal stress
S_{min}	minimum thermal stress
S_{mean}	mean component of thermal stress
S_{alt}	alternating component of thermal stress
S_f	fatigue limit of alternating stress
S_v	maximum safe alternating stress
S_s	maximum safe mean stress
S_u	ultimate strength

II. INTRODUCTION

The established criteria reflected by the methods and procedures employed in engineering design with structural steel are not sufficient in nuclear applications. Extensive implementation is needed to take into account severe environmental requirements and the behavior of steel past its yield point.

The need for the new design criteria does not extend to the conventional parts of nuclear plants. It only pertains to the components that are unique in these plants or to those ordinary components that are expected to satisfy unique requirements. Under this category would definitely fall equipment such as reactor vessels, reactor grids (support structures for fuel elements), fuel cladding, piping systems (primary and secondary, if any), heat exchangers, primary containment structures, superheaters, evaporators, and a host of other lesser components that could vary according to the type of the reactor or the overall plant.

An effort is being made through theoretical and experimental work to relax design criteria for the secondary containment vessels (spheres and cylinders) of nuclear plants. These vessels have to conform to strict requirements imposed by the ASME Code for Unfired Pressure Vessels Substantial relaxation of the ASME Code provisions for these large vessels - through better evaluation of the containment objectives and utilization of the plastic range of the material - could amount to considerable savings.

III. ORIGIN OF STRESSES IN NUCLEAR COMPONENTS

Primarily, stresses in nuclear components originate by the application of mechanical loads and by the restraint of thermal expansion or contraction. The first is a broad category including all types of loads and fluid pressures. Stresses can also result upon the elimination of external loads or reduction of temperature in a component, if such component had substantially advanced into its plastic range or had crept sufficiently.

Experience with critical components in steel for nuclear reactors has revealed that the heretofore satisfactory elastic theory is not adequate to provide criteria for design. At temperatures well above 650°F - reducing the yield point of steel and placing an upper limit on the mechanical loads that need be provided for - the elastic range of the material is easily transgressed. Efforts to remain within the elastic range of steel in some very critical and eventually inaccessible components result in such thick cross sections that serious doubts as to their metallurgical qualities arise. One should consider design criteria which do allow yielding in such cases.

At first glance, it may appear that economics is the motivating force fostering the utilization of the plastic range of steel in nuclear applications. Although this may be the case with the large vessels intended for secondary containment, it is not so with the multitude of structural components associated with the direct operation of the reactor. The critical nature and the inaccessibility of some of these components make it economically feasible and prudent to use more steel if this were to insure a safer performance. Employment of thicker sections, however, does not always guarantee safer performance and, in certain cases, such as piping systems, may increase thrusts and stresses at connections.

The developing philosophy for the stress analysis and structural design of these components is to differentiate between stresses as to their origin; to treat them independently; and to combine the results (not necessarily the stresses) judiciously.

IV. STRESSES DUE TO MECHANICAL LOADS

Stresses in nuclear components due to mechanical loads constitute the more conventional part of structural design. These stresses may result from gravity loads, such as those applied by the fuel elements on reactor grids; from pressures present in reactor vessels, heat exchangers, superheaters, and evaporators; from thrusts, torsion, and bending, such as those found in piping systems, tube bundles, and other combinations of these and other effects. In this situation, the critical stresses are kept considerably below the yield point of the material by the application of a suitable factor of safety correlating the working stress to the yield stress of the material. In dealing with stresses of thermal origin which may be superimposed on the above type, advantage should be taken of relief by plastic flow. It appears that correlation of the loads to be accommodated to the ultimate strength of the material(1,2) through the concept of load factors is more realistic. The factor of safety or load factor to be employed can be judiciously correlated with the importance of the component, its replaceability, and the other environmental and functional factors, such as irradiation, reversal of stress, fatigue, and creep.

The rather complicated geometric configurations of the structural components in nuclear installations inevitably result in areas of severe stress concentration. Although it is good structural design to avoid or to provide for discontinuities as much as possible, there should be no difficulty in relieving stress concentrations in a ductile steel by plastic flow at highly stressed points.(3) The ductility available in most structural steels will alleviate stress concentrations by plastic flow. An exception to this can be severely deformed punched holes.

It is recommended at this time that as a criterion for failure of steel in nuclear applications the shear-stress failure theory be used.[4] It gives conservative results for ductile steels and ultraconservative results for brittle metals, such as cast iron, subjected to stresses of opposite sign. Actually, the stresses herein described are stress intensities. They are obtained from each set of calculated principal stresses. The stress intensity to be provided for in the design is the largest algebraic difference between any two of the three principal stresses.

V. TEMPERATURE VARIATIONS AND THERMAL STRESSES

Most of the primary components in a nuclear power plant have to sustain temperature fluctuations and temperature gradients because of the nature of the heat-extracting process. If the expansion or contraction due to temperature changes of a component is totally or partially restrained, thermal stresses occur. By nature these stresses are different than those of mechanical origin. The thermal stress disappears when the restraint to expansion or contraction is removed. Also, if the restrained condition imposed involves strains greater than those at the yield point of the material, plastic flow will take place and relieve stress. Thus corresponding stresses in the ductile material will not advance materially above yield unless extensive strain hardening occurs. A ductile steel possessing a modulus of elasticity of 30×10^6 and a yield point of 30,000 psi can exhibit a total elastic elongation of 0.001 in. An additional plastic strain of 0.002 in. can accommodate total, imaginary elastic stresses up to 90,000 psi. Yet the 0.2% plastic strain is much less than one-tenth of the total plastic deformation that most ductile steels can exhibit.

This quality becomes exceedingly important in the treatment of thermal stresses. It permits their differentiation from those due to mechanical loads. Large thermal stresses, considerably above the yield point, should not necessarily be a cause for alarm. The physical characteristics of the material do not necessitate their algebraic superimposition on the mechanical stresses. The reversal of stress, however, that can be experienced because of thermal variations[5] should be investigated for fatigue failure in the plastic range.[6,7] A series of thermal stress conditions[5] are shown below:

The case of a ductile steel for which the thermal strain ϵ_t is greater than the yield strain ϵ_y is illustrated in Fig. 1. If the material had retained its elastic characteristics at $S_t > S_y$, the stress-time cycle (Fig. 1a) would have followed the path OABAB and the stress-strain cycle (Fig. 1b) would have been represented by the straight line OA. When the thermal stress reaches the yield point, the material yields to satisfy the restrained condition at no additional stress. Thus the actual stress-time cycle is represented by the path OA'A'B'A'B', and after the first half-cycle the stress-strain cycle by the line A'B' in Fig. 1b.

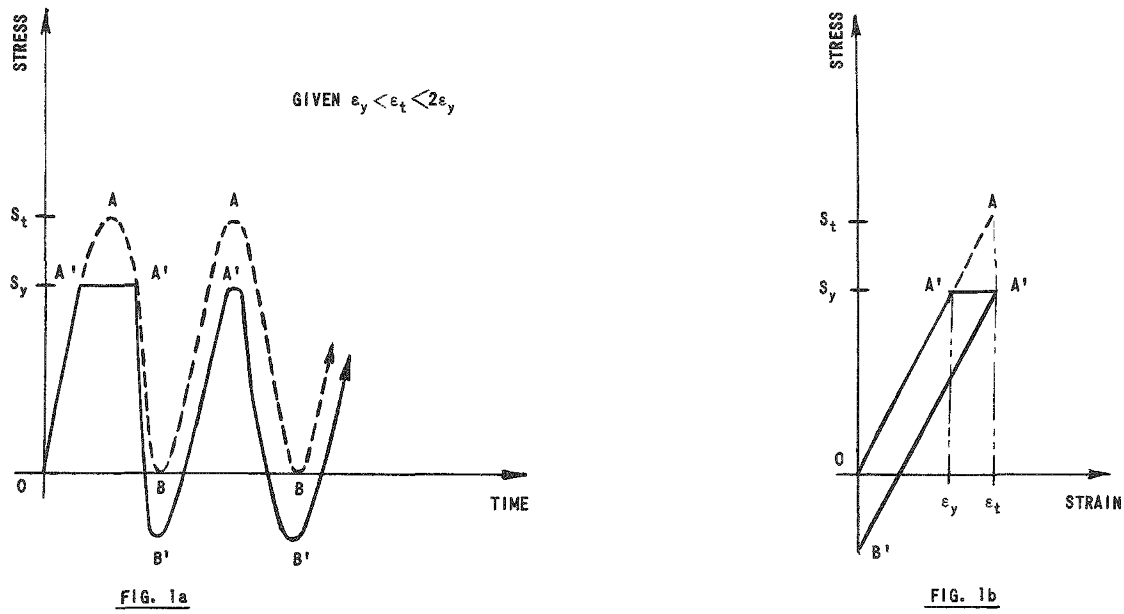

FIG. 1
STRESS, STRAIN, AND REVERSAL DIAGRAM FOR PURE CYCLICAL THERMAL STRESS (RELATIVELY SMALL PLASTIC STRAINS)

In the case of large thermal strains exceeding twice the yield strain of the ductile steel (see Fig. 2), the material would follow the path OAFAF if it could behave elastically for these large strains. Actually, the path it follows is OA'BCDEB in Fig. 2a. The stress-strain cycle after the first half-cycle, will be represented by the parallelogram EBCD in Fig. 2b.

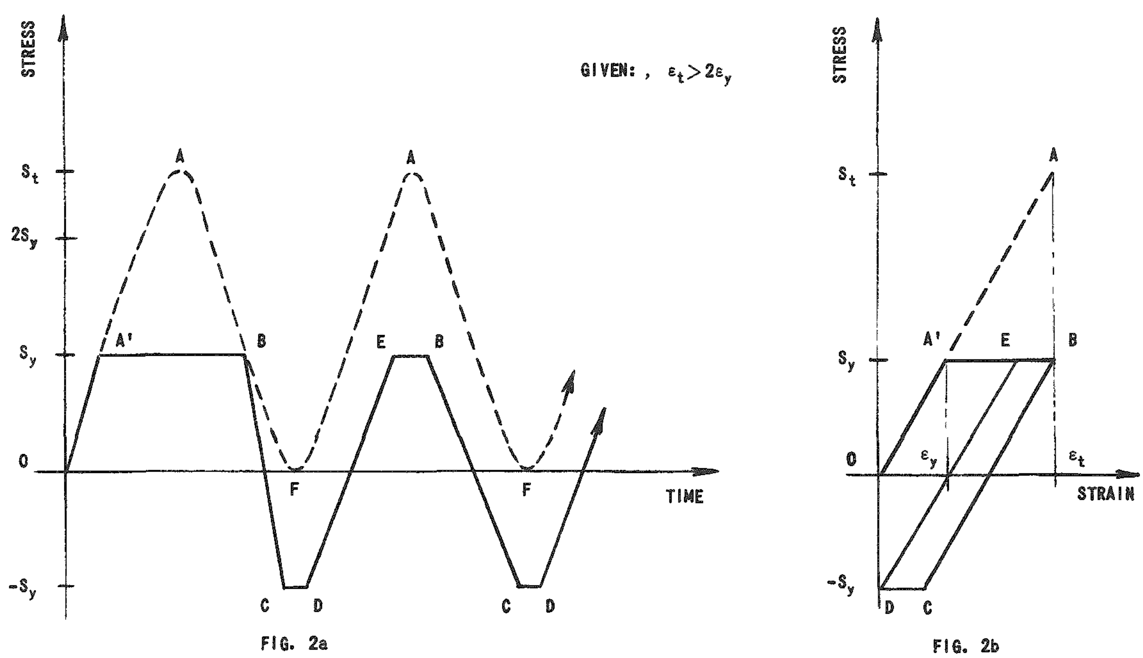

FIG. 2
STRESS, STRAIN, AND REVERSAL DIAGRAM FOR PURE CYCLICAL THERMAL STRESS (RELATIVELY LARGE PLASTIC STRAINS)

In the case of an initial stress in the member to which the thermal stress is superimposed, the cycle is as shown in Fig. 3. The initial stress S_i in the member is represented by ordinate OA in Fig. 3a. Upon superimposition of the thermal stress S_t, the steel, unable to attain elastically the combined stress corresponding to point B, yields along line B'B", and upon removal of the thermal stress it acquires a stress equal and opposite to the initial stress S_i. Subsequent reapplication of the same thermal stress will provide a stress condition moving up and down line A'B" of Fig. 3b. This condition is stress-wise quite similar to the one described in Fig. 1. It indicates the relative unimportance to the overall safety of the component of any initial static stresses, provided the material has sufficient ductility left to perform in this manner.

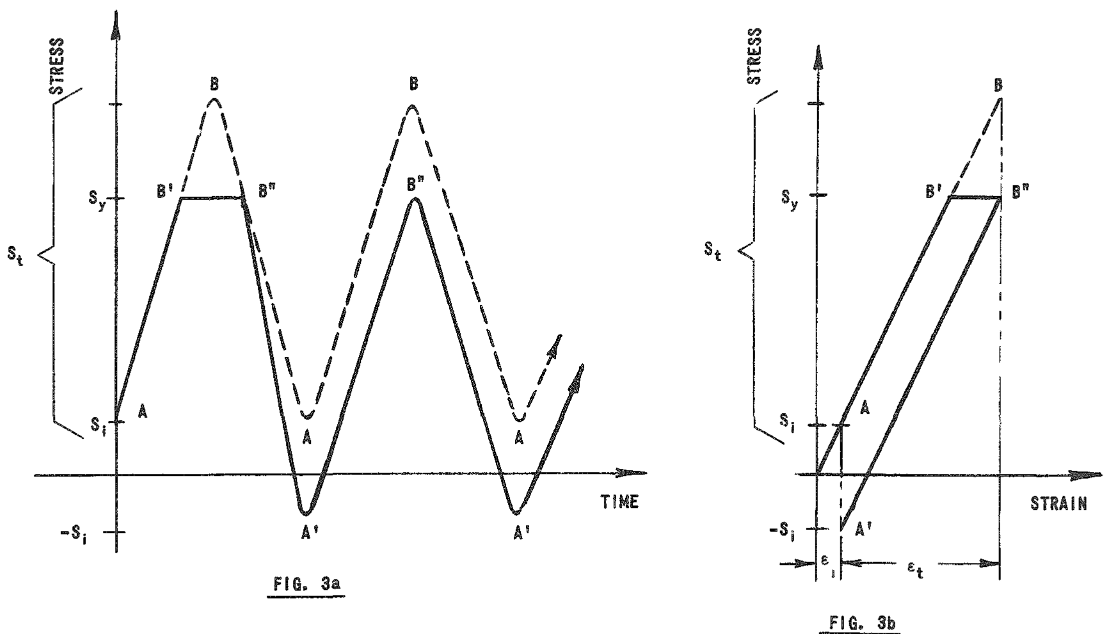

FIG. 3
STRESS, STRAIN, AND REVERSAL DIAGRAM FOR COMBINATION OF INITIAL STRESS AND CYCLICAL THERMAL STRESS

The above three figures oversimplify the behavior of ductile steel at yield point. Ordinarily, the stress-strain curve past the yield point is not horizontal but gradually ascends. In spite of this, the conclusions drawn are safe for the relatively small plastic strains under consideration.

VI. THERMAL STRESS CYCLING AND FATIGUE OF STEEL

Whenever fluctuation of stresses occurs in the elastic region of the material of a structural member, the design is for infinite life. Fluctuation of stress in the plastic region, however, brings in the concept of finite life for the component. The type of failure common to fatigue resulting from these fluctuations is cracking, although the possibility of failure due to extensive distortion also exists. This latter type of failure probably involves very large, repetitious, plastic strains.

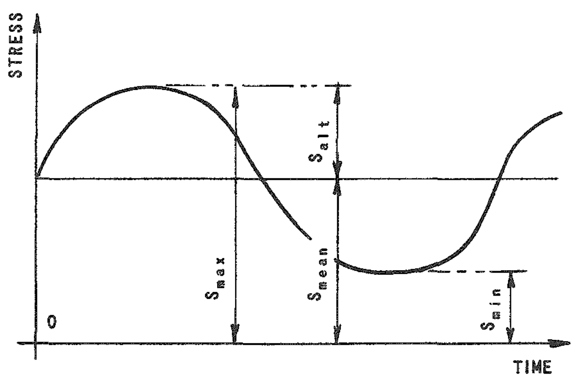

FIG. 4
GRAPHICAL REPRESENTATION OF CYCLIC THERMAL STRESS

If a fluctuating thermal stress condition(4) is graphically represented, as in Fig. 4, as varying between a maximum and a minimum stress level, it can be separated into an alternating and a mean component:

$$S_{mean} = \frac{S_{max} + S_{min}}{2}$$

$$S_{alt} = \frac{S_{max} - S_{min}}{2} \quad .$$

A plot of S_{mean} and S_{alt} comprising steady and transient thermal effects, respectively, in a reactor component can be used for predicting the fatigue characteristics of the component. Such a modified Goodman Diagram(8) is shown in Fig. 5. Combinations of mean and alternating stresses falling above and to the right of line AB are definitely unsafe.

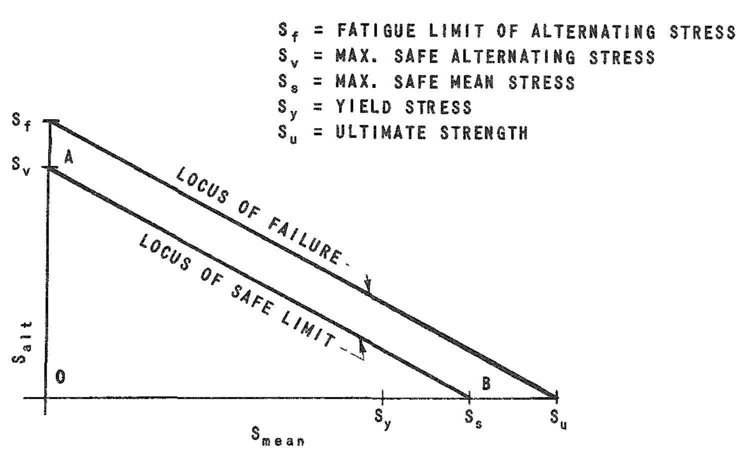

FIG. 5
MODIFIED GOODMAN DIAGRAM OF CYCLIC THERMAL STRESS

In a nuclear reactor component, a series of mean and alternating stress combinations can be expected during normal operation. This brings up the question of cumulative damage to the component.

If a set of conditions produce alternating stresses S_1, S_2, $S_3 \ldots S_n$, and S_1 is repeated t_1 times during the life of the component, S_2 t_2 times, and S_n t_n times, then the cumulative damage can be estimated in the following manner: From a diagram (see Fig. 6)[5] relating alternating stress to the total number of cycles for failure for the steel under consideration, the total number of cycles for failure at each stress is found. This number includes a large margin of safety. Let these be T_1, T_2, $T_3 \ldots T_n$ for stresses S_1, S_2, $S_3 \ldots S_n$, respectively. If $t_1 \geqq T_1$ or $t_2 \geqq T_2$ or $t_n \geqq T_n$, the design is obviously unsatisfactory and has to be modified. For satisfactory performance of the component, the condition[9]

$$\frac{t_1}{T_1} + \frac{t_2}{T_2} + \frac{t_3}{T_3} + \cdot \cdot \cdot + \frac{t_n}{T_n} < 0.8$$

must be met.

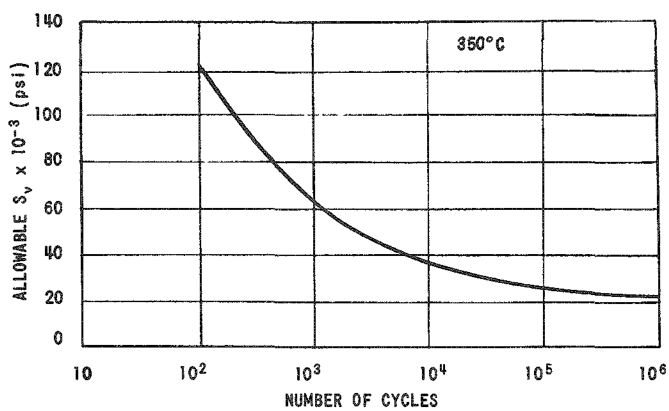

FIG. 6
ALLOWABLE VALUES OF S_v FOR TYPES 304, 347, A-201, A-212, AND A-302 STEELS

The values of T shown in Fig. 6 pertain only to alternating stresses. In the majority of cases in which a mean stress also exists, its effect on the alternating stress will have to be taken into account. For this purpose the modified Goodman diagram (see Fig. 7) is used. Assume that point N corresponds to a set of mean and alternating stresses. A straight line drawn through points S_S on the abscissa and N cuts the ordinate at point N'. The alternating stress including the effect of the mean stress for which the proper cycle number T is to be selected is not the one corresponding to N but the one determined from N'. Attention should be exercised to the fact that the mean stress shown on the abscissa (Fig. 7) includes the effect of the load stresses and the thermal stresses. These criteria, however, should not be used in the evaluation of the safety of load stresses.

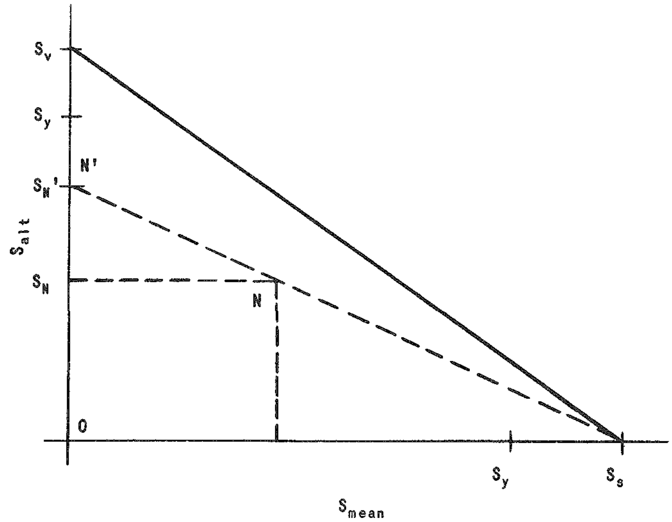

FIG. 7
MODIFIED GOODMAN DIAGRAM SHOWING EFFECT OF MEAN COMPONENT ON THE ALTERNATING COMPONENT OF STRESS

VII. CREEP AND CREEP RUPTURE

Creep is of primary importance in reactor components. A brief sequential description[10] of the phenomenon is given in Fig. 8. When a uniaxial creep specimen is subjected to a constant stress, it exhibits an initial elastic and plastic strain represented by the straight line AB. With no increase in stress, the specimen creeps during the passage of time at a swift but variable rate represented by the curved line BC. This interval is known as primary creep. At point C the creep rate becomes constant. The interval during which the creep strain rate remains constant is known as that of secondary creep. This interval of constant creep rate is the most sustained and useful in creep-stress calculations. As secondary creep progresses, the cross section of the specimen decreases because of the principle of constancy of volume, and at a certain point I the creep rate increases primarily because of the necking of the element. At point J creep rupture under "constant stress" occurs.

For purposes of illustration, it is assumed that at point D the stress is released. An elastic recovery DE will immediately take place. This will be followed by an extended creep recovery represented by EF. If it is further assumed that at point F a stress equal and opposite to the original stress is applied to the specimen, again an initial elastic and plastic deformation will be observed. The corresponding strain is FG. From point G on the same characteristics of the creep cycle are observed as the ones described for the first half-cycle.

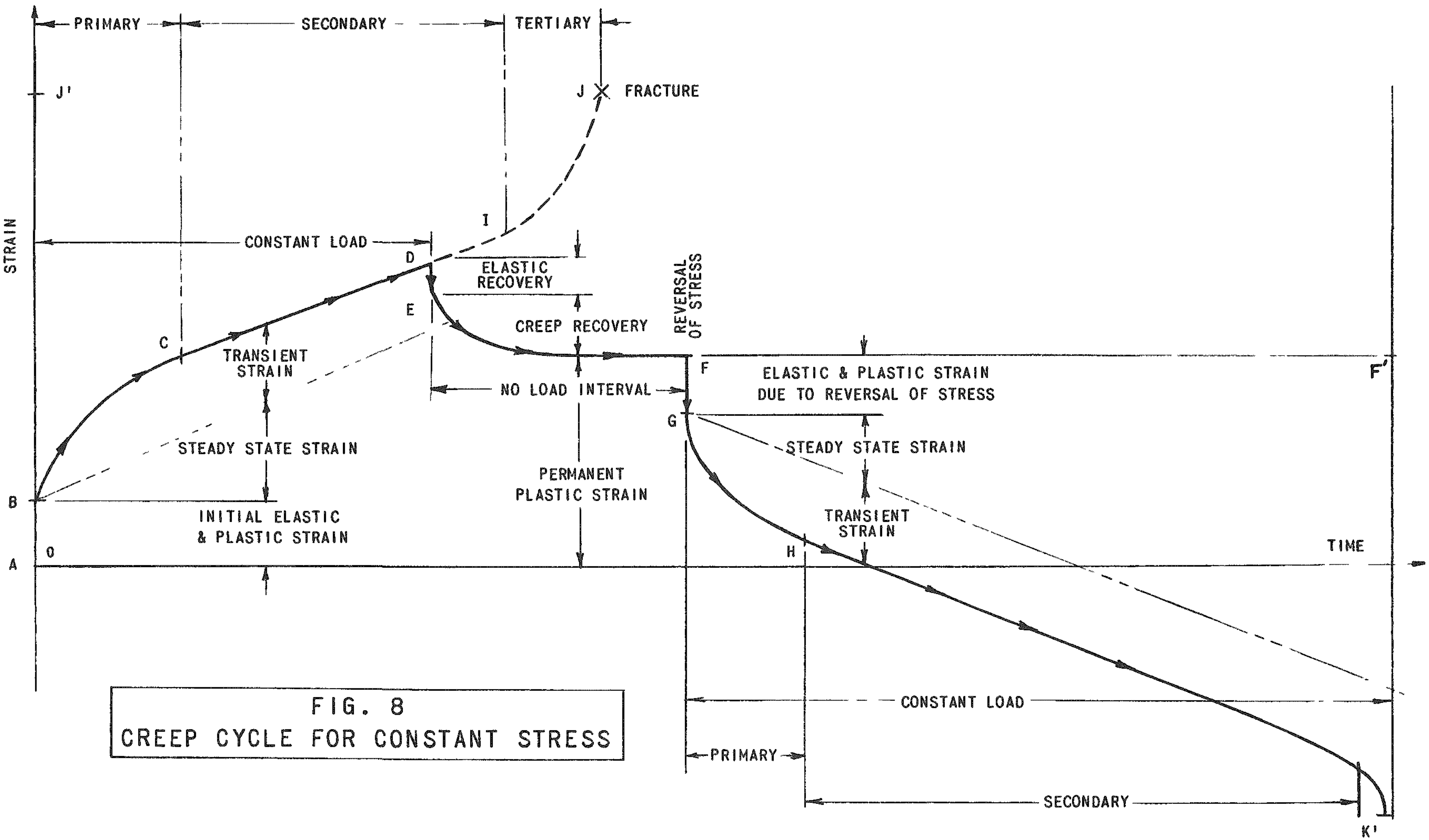

FIG. 8
CREEP CYCLE FOR CONSTANT STRESS

It is important to note that in the first half-cycle, creep rupture could occur at a strain equal to the ordinate AJ'. At the second half-cycle, failure occurs at K', corresponding to a strain ordinate F'K'. This brings out the important fact that in cases of reversal of stress, creep failure is independent of the original physical dimensions of the component. After the first half-cycle, the abscissa passing through origin A is of no direct consequence. In the preceding description if there had been no zero stress interval in the cycle and the reversal of stress were almost instantaneous, as it could be with transients in reactor vessels, piping systems, or heat exchangers, line EF would be eliminated, and the right half of the graph will move to the left and upward until points F and E coincide.

In stress analysis for creep, only approximate solutions are possible and justified, because of the inherent complexity of the phenomenon and the multitude of variables that can affect it (temperature, material composition, heat treatment, changes of stress, method of manufacture). When creep is large in comparison to the initial elastic and plastic strain of the component, the initial elastic-plastic strain and the transient creep strain can be neglected. Computations take into account only the significant stretch of steady-state creep. However, in cases in which the transient creep is substantial, a sizable error is introduced by ignoring it and basing calculations on steady-state creep alone. In the specific area of buckling, for which initial deformations are significant, steady-state creep solutions may overestimate strength and result in unsafe conclusions.

For varying stress conditions the steady-state creep solutions are not satisfactory. The history of the stress levels and intervals becomes important. The existing strain-hardening and time-hardening theories for creep behavior are not supported by sufficient experimentation to permit their reliable superimposition for the development of design criteria. Also, the approach incorporated in a steady-state creep analysis does not provide for the gradual creep recovery which is observed upon unloading or partial unloading of a component. Creep recovery has not been investigated sufficiently. Although its significance is not of great importance in design, understanding of this phase of creep behavior may contribute to the overall understanding of the mechanism of creep.

The foregoing discussion has assumed that a constant temperature exists. In components subject to temperature gradients or to temperature fluctuation due to transients, creep strains are materially affected. Of greater importance is the observed relief of thermal stresses by creep. When a condition of thermal stress is totally or partially alleviated by creep, on cooling, the thermal stresses produced will be of opposite sign to their initial value. This explains the tensile failure of brittle materials in components (particularly piping systems) designed to withstand compressive stresses. Also, a potential spot for creep failure is a weak section of a thermally restrained assembly. The weak section absorbs most of the deformation and becomes seriously overstrained.

The creep deformation under constant external loads will increase due to thermal strain cycling. Efforts were made(11) to correlate creep and thermal stresses. Recent developments(12) indicate that, in multiaxial stress conditions, although creep strain rate is affected by an invariant quantity, creep rupture depends rather on the maximum tensile stress.

To predict the life of a component subject to creep deformation under different temperature and stress conditions, a concept for cumulative damage(11) is used which is similar with the one employed in considerations of fatigue failure due to thermal stress reversal. This concept assumes that creep rupture occurs when the sum of the fractions (time at a given stress and temperature divided by rupture life at that stress and temperature) reaches unity. Additional experimentation is needed, however, to establish the limitations of this approach.

Although a proper understanding of the creep mechanism is necessary to ascertain the contribution of the phenomenon to the overall strength of the component, generally the presence of creep becomes desirable by relieving large thermal stresses. As for the mechanical loads in the component - those due to static loads and fluid pressures - they can be kept sufficiently low by proper structural design.

The properties of creep rupture,(12) on the other hand, should be investigated and ascertained for the specific steel that is to be employed in each critical component. This is necessary because of the long periods of time during which reactors operate at full temperature. Short-time tensile tests are not dependable since certain steels (such as precipitation-hardened stainless steel) are affected by sustained high temperatures.

VIII. RADIATION EFFECTS

Generally the effect of neutron irradiation on the structural qualities of steel is to increase the yield point and ultimate strength, to decrease the ductility of the material, and to raise the ductile-to-brittle transition temperature. Since nuclear components in steel are exposed to the variety of effects previously described, loss of ductility is the most important and undesirable contribution of irradiation. Ductility is indispensable in accommodating high thermal stresses in the plastic region of steel and in alleviating stress concentrations and initial locked-in stresses in the material. Any loss of ductility automatically amounts to an indeterminate reduction in the margin of safety of the component.

Data on the strength and ductility changes of steel subjected to irradiation are voluminous.[13,14] Such data are useful for qualitative exercise of judgment. There appears to be dissatisfaction,[15] however, with the lack of knowledge connected with the neutron flux and spectra employed in the material irradiation experiments.

Radiation damage to steel[13] is reduced with increasing environmental temperature during radiation. Some steels show no net radiation damage when radiation takes place at 415°C, in contrast to increasingly severe net damage at lower temperatures. In contrast to ferritic steels, it appears that austenitic steels retain a considerable amount of ductility under heavy neutron irradiation. Also, fine-grained steels and high-purity iron-carbon alloys stand better under irradiation than coarse-grained steels and alloys of lesser purity.

A major concern to industry is the observed increase in the ductile-brittle transition temperature of steels subjected to irradiation.[16] This aspect could amount to loss of flexibility in reactor systems, even to precluding room-temperature pressurization.

Until the effect of irradiation is quantitatively determined and its effect on coexisting phenomena, such as plastic flow, thermal fatigue, creep, and creep rupture, is ascertained, a general recommendation is to select (consistent with other requirements) steels having high ductility and low transition temperature, and which have exhibited ability to retain a major portion of this ductility after considerable irradiation.

IX. TRENDS IN DESIGN CRITERIA

The need for the development of adequate design criteria governing the strength of materials has resulted in a proliferation of theories and approaches. The many efforts of the investigators could come under five distinct areas:[17]

The dislocation theories deal with detailed mechanisms and can be applied to a large number of physical phenomena. These theories are very flexible and they have advanced to the stage of offering dependable quantitative solutions for simple cases. They are being explored by scientists all over the world.

The theories of absolute reaction rate postulate a unit flow which conforms to thermodynamic criteria. These theories, which depend on the interpretation given, can be used to predict creep.

The thermodynamic theories of fracture strength depend on the analogy that failure of a bond between atoms is equivalent to the melting process. These theories are inherently very broad and all embracing. As such, they cannot account for defects of crystal origin and for variations in microstructure.

The theories based on equations of state substitute strain, strain rate, stress, and temperature for the better known quantities of volume, temperature, and pressure. These theories make it potentially possible to predict the behavior of materials. Their drawback is their dependence on the history of the material, which is not always possible to ascertain for equipment components or structures.

The theories of great importance to engineering design are those based on empirical relationships and parameters. A functional relationship between strain, strain rate, time, stress, and temperature is defined by grouped parameters. These theories constitute the means by which the bulk of knowledge on the properties of the materials has been obtained. They are dependable for properties within the ranges investigated. Extrapolation outside these ranges is inadvisable and basically dangerous.

A comprehensive theory,[18] which appears promising, attempts to establish analytical equations - based on experiments - that relate fatigue in the material due to mean and alternating stresses of a cycle; five material characteristics; and the resulting number of cycles to failure. This seems to be a successful attempt to develop a concept of a unified approach to the fatigue of metals. Its advantage is that it is dependable, readily usable, and provides for planned tests to yield the five material characteristics in a most convenient and economical manner. It also sets up guide posts for future testing that will make test results meaningful.

The increased demands imposed on steel by the constantly improving nuclear reactors and industrial processes in general cannot wait for the development and verification of theories which start with the abstract and end with the practical. Rather, the reverse process is more likely. This is the reason why analytical relationships based on experimental results are most promising at this time.

X. ACKNOWLEDGMENT

The criteria described herewith were applied in the design of the components of the Experimental Breeder Reactor II, developed by Argonne National Laboratory and built at National Reactor Testing Station, Idaho Certain aspects pertaining to the thermal stress criteria were utilized by the Franklin Institute in the stress analysis of some components. Subsequent to the design of EBR-II, certain procedures and concepts utilized as stress-analysis criteria fragmentally appeared in the open literature, and they are cited here in the interest of brevity and the benefit of the reader.

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