HOLD-TIME EFFECTS IN HIGH-TEMPERATURE LOW-CYCLE FATIGUE

A LITERATURE SURVEY AND INTERPRETIVE REPORT

Prepared for

The Metal Properties Council

by E. Krempl and B. M. Wundt

STP 489

AMERICAN SOCIETY FOR TESTING AND MATERIALS

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FOREWORD

The Metal Properties Council Subcommittee on Fatigue sponsored preparation by B. M. Wundt of an extensive Bibliography on Low-Cycle Fatigue. Published by ASTM in 1968 as their Special Technical Publication No. 449, that survey listed over 800 references for the years 1957 through 1967.

Encouraged by a larger-than-anticipated demand for that Bibliography, the Subcommittee is now promoting the preparation and publication of surveys telling the general content of the literature pertaining to each of several major factors affecting low-cycle [high strain] fatigue behavior.

The present report surveys the influence of hold time on low-cycle fatigue failure at constant temperature. It covers most of the papers listed under Subject 3 of the 1968 Bibliography, together with some more-recent papers.

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THE METAL PROPERTIES COUNCIL
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HOLD-TIME EFFECTS IN HIGH-TEMPERATURE LOW-CYCLE FATIGUE A LITERATURE SURVEY AND INTERPRETIVE REPORT

E. Krempl[1] and B. M. Wundt[2]

ABSTRACT

A literature survey was made of the effect of hold time on the deformation and fracture behavior during low-cycle fatigue loading at elevated temperature. The need for such investigations is traced back to the operational conditions of power generation, chemical processing and flight propulsion plants.

Hold time is shown to have a significant influence on the cyclic strain hardening (softening) behavior and on cycles to failure. The effect depends on the nature of the surrounding atmosphere. Stress analysis and failure criteria have to be modified to account for these time dependent effects. The presently available design approaches are reviewed and recommendations for future research are given.

KEY WORDS: Fatigue (materials), high temperature tests, fractures (materials), life (durability), cyclic loads, stress cycle, plastic deformation, thermal stress, strains, crack propagation, damage, design, stress relaxation, creep properties, austenitic stainless steels, alloy steels, review, evaluation.

[1]Associate Professor, Mechanics Division, Rensselaer Polytechnic Institute, Troy, New York.

[2]Consultant, Schenectady, New York.

NOMENCLATURE

$\Delta\epsilon_{pr}$ = plastic strain due to stress relaxation [in/in]

$\Delta\epsilon_{p}$ = plastic strain range [in/in]

$\Delta\epsilon_{t}$ = total strain range [in/in]

ϵ_{max} = maximum strain [in/in]

ϵ_{min} = minimum strain [in/in]

$\Delta\epsilon_{c}$ = creep strain accumulated during hold time in stress control [in/in]

$\dot{\epsilon}_{s}$ = secondary creep rate [1/time]

$\Delta\sigma$ = stress range [psi]

σ_{r} = stress at the end of the hold time [psi]

$\Delta\sigma_{r}$ = total stress relaxed during hold time [psi]

σ_{max} = maximum tensile stress [psi]

σ_{min} = minimum tensile stress [psi]

σ_{u} = ultimate tensile strength [psi]

E = modulus of elasticity [psi]

N_{i} = number of cycles to crack initiation

N_{f} = number of cycles to failure

α, β = constant

C, C_1, C_2, A = constants with appropriate dimensions

k, k_1 = constant with appropriate dimensions

t_f = time to failure

t_H = hold time

ν = frequency of testing [cycles/unit time]

T = time for one cycle = $1/\nu$

D = tensile ductility = $ln \frac{100}{100\text{-}RA}$

RA = reduction in area [percent]

t_r = time to rupture failure in a creep test [h]

CONTENTS

Introduction

The problem of elevated temperature low-cycle fatigue deformation and fracture behavior is of great importance to the design of power plants, petroleum and chemical processing factories, and other machinery which operates at elevated temperature. Repeated cyclic plastic deformation caused by thermal stresses at discontinuities such as may occur during start-ups may cause early cracking with all the undesirable consequences. It is therefore of economic interest to study the material deformation and fracture behavior under simulated service conditions.

Although actual low-cycle fatigue fracture is caused by thermal stresses due to the changing temperature, the behavior of materials is customarily investigated at constant temperature under mechanical loading. As test temperature, the maximum operating temperature or even higher ones are selected. It is assumed that in such a way the limiting minimum life can be established.

The objective of any laboratory investigation on the deformation and fracture behavior of materials at loads where this behavior is strongly time dependent, is to establish a failure criterion and a knowledge of the stresses (strains) as they develop and finally lead to failure. Both inputs are needed in reliability analysis to calculate the actual stresses and determine whether these stresses are in the safe range. If time-dependent behavior is important, the actual service conditions must be closely simulated so that important influences are not excluded.

Previously, most of the evaluation of materials for low-cycle fatigue life has been done at uninterrupted cycling. Correlation with actual service experience using this data was not encouraging. Therefore, a closer simulation of the actual service condition was made by introducing hold times. These hold times were shown to have a cycle-reducing effect at elevated temperature when compared with uninterrupted cycling under the same conditions. Figure 1 illustrates what is meant by hold time. Generally, this term refers to a stop in the increase in stress (or strain), with a following constant stress (or strain) for a certain period of time. This time is referred to as hold time or dwell time. After the end of the hold time, cycling continues and the pattern will be repeated during each cycle as shown in Figure 1.

This type of laboratory cycle is considered an approximation of the operation of some machinery at elevated temperatures. Adjustment of the load of steam turbines according to the demand for electricity requires sometimes a change in the steam inlet temperature which in turn causes temperature transients in shells and rotors. In addition, other transients such as cold starts and hot starts occur during the lifetime of a turbine and other plants, [*48, 49*].[1]

Prior to 1964 the results of elevated temperature, strain controlled low-cycle fatigue tests without hold time were considered to be relevant for design [*5, 42*]. Later on it was pointed out [*17, 29*] that simple uninterrupted low-cycle fatigue is seldom limiting in design of pressure vessels operating at elevated temperatures.

[1] The italic numbers in brackets refer to the list of references at the end of this report.

Edmunds, [*17*] stated that for hot pressure vessels the influence of "repeated creep relaxation" is an important consideration. "The argument is relevant to a plant which is maintained on load at high temperatures for periods reckoned in hours or even days, and in particular it refers to small plastic zones in an essentially elastic system, such as found in the vicinity of the inlet belt of a steam turbine. Here the conditions of high secondary stresses, stress concentration, high temperatures, and large temperature gradients all occur together, so that it is highly likely that the worst position will suffer a combination of circumstances which includes plastic yielding in compression during warm-up period, strain cycling of an amplitude about equal to (or somewhat above) yield and creep relaxation of the peak stresses during the period when the plant is held on load". He then continues to show that strain-controlled tests with hold-time yield the proper material information for design.

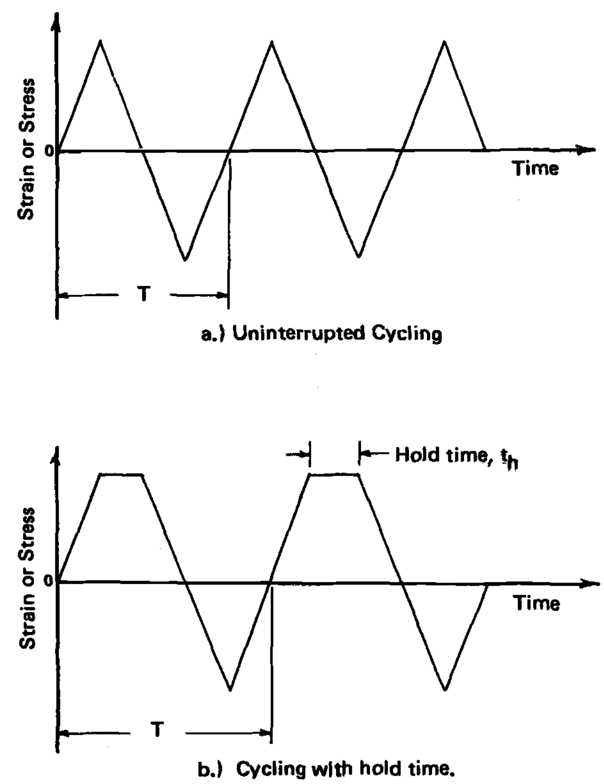


FIG. 1—*Schematic Diagrams Comparing Uninterrupted Cycling and Cycling with Hold Time.*

Timo and Sarney [*48*] and Timo [*49*] favor the use of data obtained in a laboratory-type cycle with hold-time, but point out that the actual conditions in components are not always represented by the strain-controlled laboratory data with hold-time in the tension part of the cycle. They differentiate between

1) "A *very severe* cycle (fast temperature change rate and large temperature change) which produces a

TABLE 1—*Typical Boiler/Turbine Operating Cycle History*
20 Year Basis

	Unit Age			
	0-7 Years	7-14 Years	14-20 Years	Total
Cold startup (Turbine less than 300 F)	25	30	45	100
Fast depressurization and hot restart within 3 hours	25	30	45	100
Weekend shutdowns (48 h)	20	190	490	500
Overnight shutdowns (8 h)	20	640	1340	2000
Major load changes (70% of rating)	300	900	1800	3000
Minor load changes (25% of rating)	2000	6000	12000	20000

After Hanzalek and Ipsen [26].

high strain range cycling (e.g., strain range several times the yield strain range)

2) A *moderately severe* cycle which produces an intermediate strain range (e.g., strain slightly greater than the yield strain range)
3) A *mild cycle* which produces only a small strain range (e.g., strain range much lower than the yield strain range)" (Timo [*49*])

Figure 2, after Timo [*49*], depicts schematically the stresses and strains induced by these cycles. It is pointed

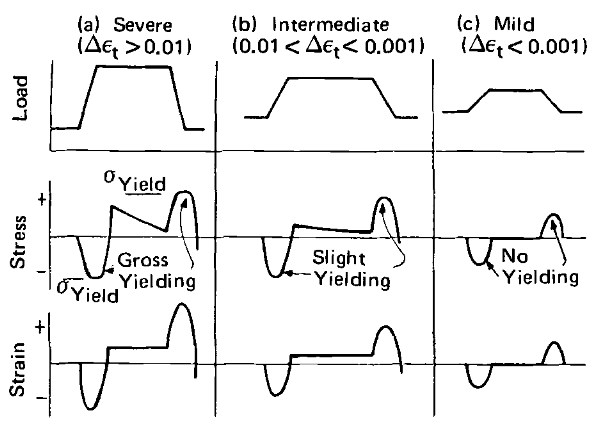


FIG. 2—*Typical Stress and Strain Cycles for Severe, Intermediate, and Mild Load Changes in Steam Turbine Rotors. From Timo, [49]*

out that for each of these cycles different design calculations are required which will be discussed later in this survey.

In all the references cited so far the use of strain-controlled data was favored. However, another school of thought proposes the use of load (stress) controlled data in design. Tilly [*47*] points out that rotor discs of aircraft gas turbines are "subjected to repetitions of tensile stress for hold-times up to several hours, together with peak stress for short times, giving rise to a combined creep and fatigue problem". Dawson [*13*] shows that "creep processes that occur during the steady running of the (steam) turbines are widely simulated by introducing constant-strain dwell periods, but there may be cases where a constant-stress dwell period would be a closer representation". One example is given for this case (Fig. 5 [*13*], not reproduced). It consists of a thin member attached to a rather thick channel which will restrain the thin member upon temperature changes.

So far nothing has been said about the number of hold-time events during the projected lifetime of power plants. While it is generally agreed that the events involving cyclic plastic deformation occur from 100 to less than 10,000 times during the lifetime of a power plant, specific numbers are rarely given in publications. One exception is a paper by Hanzalek and Ipsen, [*26*], from which Table 1 has been taken.

In the foregoing, the reasons for the interest in hold time during low-cycle fatigue were traced to the operation of power plants and gas turbines. The common features may be described as follows.

A start-up or load change may lead to thermal stresses of such magnitude that the elastic limit of the material is exceeded locally. A period at rated conditions follows. During this period, relaxation and/or creep can take place in the regions previously deformed plastically. After that period at rated conditions, the apparatus is shut down or the load is reduced and then the whole cycle (start-up, rated conditions, shut-down) repeats itself. It is in the nature of the operation of the machinery of interest that not more than about 10,000 cycles, in many cases less than 1000 cycles, are experienced in the projected lifetime of the equipment.

Since hold times are simulations of actual service cycles and since cycles-to-failure reductions were experienced with hold times under constant strain, the behavior under hold-time conditions can become limiting. It is therefore of considerable practical interest to study the behavior of actual materials under these conditions. The deformation and fracture behavior should be known. Both are, of course, necessary for appropriate fracture control plans. The first one is of interest for the determination of the time-dependent stresses or strains of actual structures, the second one for the formulation of fracture criteria.

SCOPE OF THIS LITERATURE SURVEY

In this survey the influence of hold time on the low-cycle fatigue failure at constant temperature will be discussed.

The influence of creep and fatigue interaction of which hold-time effects are a part was recently considered by Ellison [*19*]. In that study the high-cycle creep and fatigue interaction is emphasized.

Related but separate effects such as influence of frequency and rate of straining on fatigue failure will be reviewed in separate reports. However, it is felt that a short discussion of their inter-relation is useful here for the understanding of hold-time and frequency effects.

At room temperature at stress levels of engineering interest in structural materials, hold-time and frequency effects on fatigue life are believed to be insignificant. If such an influence exists it is so small that it is easily masked by the scatter of the results. If one were to introduce hold time at room temperature at stress levels of engineering interest, no significant cycle-reducing effect would be observed. Any creep or relaxation processes during the dwell time would be transient in nature and would shortly reach an asymptotic value [*36*]. It appears therefore that a necessary condition for the existence of the cycle-reducing hold-time effect is the occurrence of significant creep or relaxation during the hold-time.

At room temperature, empirical formulas were developed for the prediction of fatigue life from significant test variables. The Coffin-Manson Law is well known; e.g., [*8, 38*].

It turns out that these prediction techniques are unconservative at elevated temperature even for the case of continuous cycling. It is therefore necessary to consider time-dependent quantities (rate of strain, frequency, creep) in these formulas, [*6, 39, 44*].

A variation in the frequency of strain cycling from 10^{-3} to 1Hz causes an increase in fatigue life from 50 to 5000 cycles at a total strain range of $\Delta\epsilon_t = 0.009$ for L-605 alloy at 1180 F, (Fig. 3). This result shows one

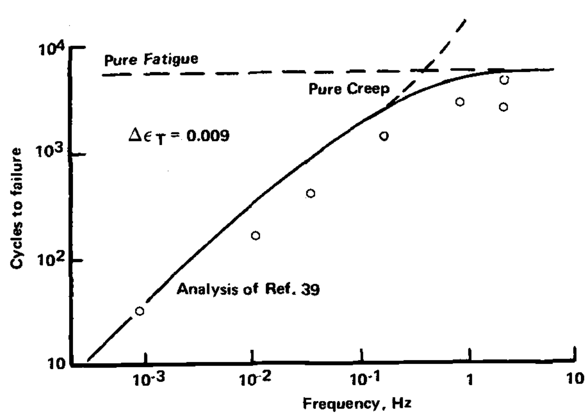


FIG. 3—*The Influence of Change of Cyclic Frequency on the High-Strain Fatigue Life of L605 Cobalt Base Alloy at 1180 F. Solid line represents predicted life at* $\Delta\epsilon_t = 0.009$, *Data of Manson et al., [39].*

general trend of the data: The lower the frequency (rate of straining) the fewer the cycles-to-fracture. The time-to-fracture may or may not be influenced. No such strong influence of frequency is present at room temperature. It is because of these elevated-temperature material properties that the room-temperature prediction methods have to be modified at elevated temperature.

Basically the introduction of hold time has the overall effect of reducing the frequency and therefore a reduction in cycles-to-failure should be expected. At the same time the total time-to-failure may increase. There are, however, definite periods of creep or relaxation during the hold-time which are not present in uninterrupted cycling tests. From this point of view, hold-time tests are a combination of cycling and of creep or relaxation tests. Therefore, a separate look at this problem is warranted.

In the following, the material behavior under conditions of hold time will be reviewed for a uniaxial state of stress. Methods of predicting the hold-time effect as well as design applications will be discussed.

THE UNIAXIAL DEFORMATION AND FRACTURE BEHAVIOR OF ENGINEERING MATERIALS.

Low-Cycle Fatigue with Hold Time

Basically, the hold time can be introduced at any point of the cycle. Its effect on the fatigue cycles will depend on the position, the length of the hold time, the material, and the temperature. In the majority of the tests, the hold time is introduced during the tensile part of the cycle. A few investigations use hold times in compression or at some other part of the cycle. In the following, if no mention is made of the location of the hold time, it has been introduced at the maximum tensile position of the cycle.

The various possibilities of conducting the hold-time test are listed below. It is possible to control either stress or displacement (strain) during the test. If the former is adopted, creep will occur during hold time; while relaxation is going to take place if strain is the controlled variable.

1. *Hold Time with Relaxation.* The test is under displacement control all the time and stress relaxation occurs during hold time, see Fig. 4.

   Since the displacement (strain) limits are fixed, the stresses and the plastic strain will vary from cycle to cycle, as will be shown later on. Also the shape of the relaxation curve will depend on the number of cycles. Therefore the amount of stress relaxation $\Delta\sigma_r$ per cycle depends on the number of cycles.

   The material is called cyclic strain hardening if the stress range $\Delta\sigma$ increases with cycles; it is called cyclic strain softening if the stress range is decreasing with cycles*. Compared to uninterrupted cycling, an increase in the plastic strain range is observed for hold-time tests. If it is assumed that unloading is elastic with elastic modulus E, the in-

*The increase or decrease in stress range may stop after a certain number of cycles, the material is then said to be in its cyclic steady state or shakedown condition. This shakedown condition may never be reached at elevated temperature.

crease in plastic strain range $\Delta\epsilon_{pr}$ due to relaxation can be calculated by

$$\Delta\epsilon_{pr} = \frac{\Delta\sigma_r}{E}. \quad (1)$$

Due to the nature of the control forced on the specimen (constant displacement) it will not increase its length beyond the displacement range permitted by

HOLD TIME WITH RELAXATION

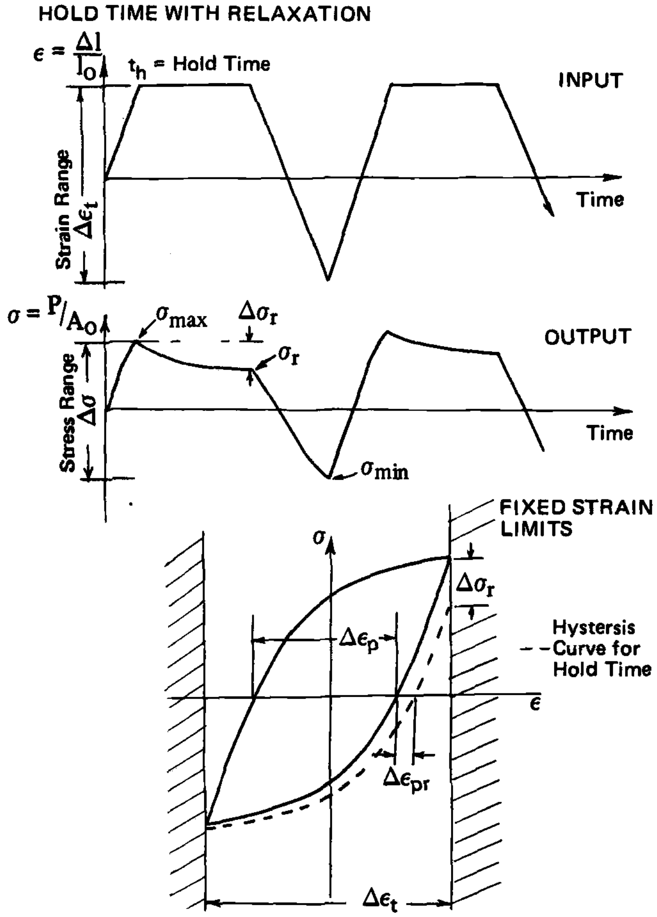


FIG. 4—*Schematic Diagram Showing Stress and Strain Variation during Hold Time with Relaxation Cycling (Strain Control)*

the control. The fatigue fracture will then propagate without any visible plastic deformation and reduction in area. Only the final rupture area will show some reduction in area.

2. *Hold Time with Creep.* The test is under load control all the time and creep will take place during hold time, see Fig. 5.

   In this case constant stress limits are forced on the specimen and during hold time the specimen is free to elongate, the specimen creeps by the amount $\Delta\epsilon_c$ during each hold time. The amount of creep strain $\Delta\epsilon_c$ per cycle will vary from cycle to cycle and will generally increase as the number of cycles increase. No definition of cyclic strain hardening or softening has been given in this case. The increase in total strain range and plastic strain range per cycle cannot be easily calculated in this case.

   Due to the nature of the control, the specimen will continuously elongate and finally fracture with a reduction in area and visible plastic deformation.

3. *Hold Time, Mixed.* Various possibilities exist of transfer of control from load to displacement at the start of the hold time; e.g., displacement control during cycling, load control during hold time and vice versa. The deformation and fracture behavior during this type of control is complicated and not yet well understood. The method of control will be explained when the individual paper is reviewed.

Hold Time with Relaxation.

One of the first investigations of the effect of hold time on fatigue life seems to have been conducted by Swindeman [*45*], on Inconel. Specifically, he investigated the influence of hold time (0.5 to 30 min) at 1500 F on the exponent and the constant in Coffin's equation

$$\Delta\epsilon_p N_f^a = C. \quad (2)$$

The exponent a increased with hold time from (0.79 to 0.89), and C decreased from 0.82 to 0.75. The reported

HOLD TIME WITH CREEP

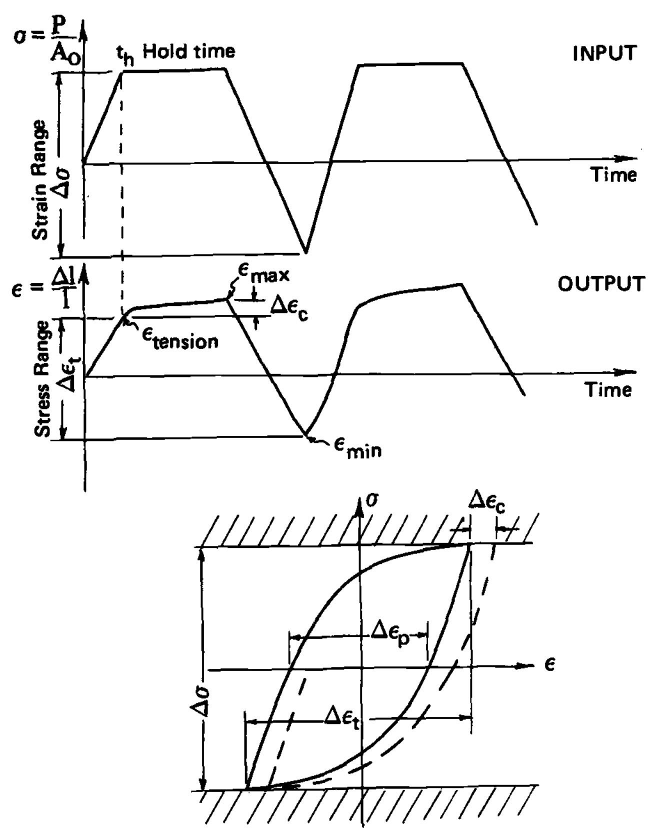


FIG. 5—*Schematic Diagram Showing Stress and Strain Variation during Hold Time with Creep Cycling (Load Control)*

hysteresis loops [Appendix, Fig. A4, not reproduced] indicate that the displacement was not kept constant as it should have been. Therefore, some complicated interactions between relaxation and partial increase in displacement existed which cloud some of the results.

In a paper presented at the First International Conference on Creep, C. D. Walker [*52*] conducted tests with a hold time at 510 C. Most of the tests were run with a hold time of an average of 12 hrs (8 h and 16 h, due to the 8 hour working day). A modified Scotch yoke testing machine used by Baldwin et al., [*1*] was employed to compare the behavior of four different steels: Cast 1% Mo, 1% Mo-1% Cr, 12% Cr - 0.5% Mo, and Type 316 SS with the addition of Co. The tests were such that the fatigue life did not exceed 300 cycles, with most of the tests lasting around 100 cycles. He concluded that the 1% Cr - 1% Mo was the best and Type 316 was the poorest material investigated. He also plotted the hold time versus number of cycles-to-failure as shown in Fig. 6. It can be seen that the increase in hold time reduces the fatigue cycles progressively without indication of an asymptotic limit. Also it should be noted that the total strain range is rather high (2% and 3.4%).

Edmunds and White, [*18*] used four-point bending to evaluate a 2-1/4 Cr - 1 Mo steel at ambient temperature and at 600 C. (The motivation for this investigation was that the usual high-strain fatigue formula [Eq. (2)] did not satisfactorily predict the occurrence of cracking in steam turbines.) The specimen had a rectangular cross section 1.75 in. by 0.2 in. and a stress biaxiality ratio of 0.4. The authors reason that the hold-time effect will be more pronounced at lower strains than at higher strains and the results confirm their reasoning. The ratio between cycles-to-failure with 300 min hold time and cycles-to-failure with no hold time was found to be 1/(4.2) at $\Delta\epsilon_t = 0.6\%$ and roughly 1/(2.2) at $\Delta\epsilon_t = 2\%$. The reduction of cycles-to-failure becomes more severe as the strain range decreases. At the same time, total testing time increases. This observation is very important for design and it will be seen that it is confirmed by other investigations. Creep-rupture and relaxation data obtained from separate investigations for the 2-1/4 Cr-Mo material are also given. The authors attempted to explore the effect of the position of the hold time in the cycle. Two specimens were tested and the 30 min hold time was introduced at approximately zero surface stress; practically no reduction in cycles-to-failure compared to continuous cycling was observed.

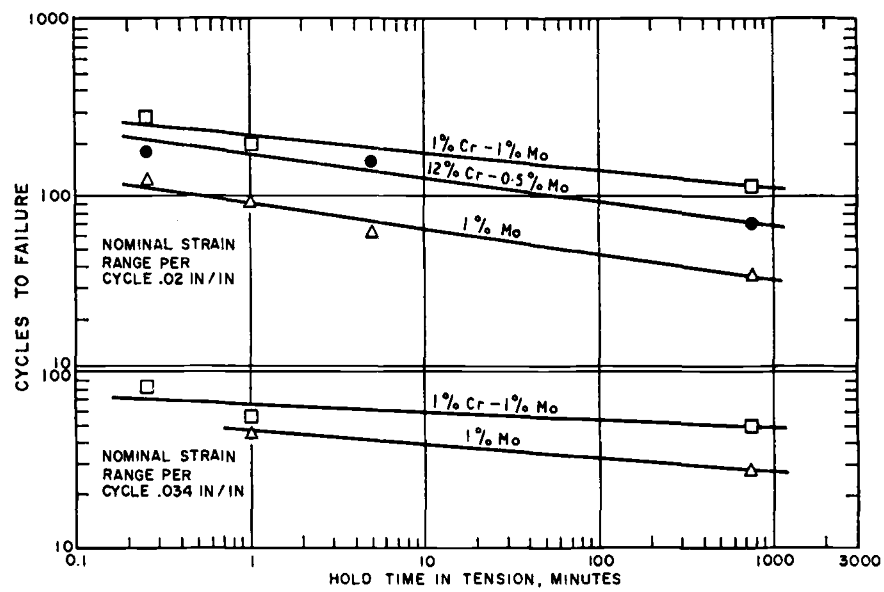
It was found that the environment had a considerable influence on the fatigue life. If argon was admitted to the furnace, the fatigue life improved considerably in continuous cycling. It is likely that the same effect will be observed in tests with hold time. Metallographic observations on only two specimens showed initial intergranular cracking with a transition to a transgranular mode as the cracks spread.

Coles and Skinner [*9*] report on the effect of hold periods and frequency on the low-cycle fatigue life. The authors point out that the Coffin relationship overestimates the endurance, and they propose to correlate the data by

$$\nu^k t_f = \text{const.} \tag{3}$$

For a given strain range and various test frequencies ν, the following extreme situations are distinguished by the authors:

1) *Pure fatigue.* It is said that fatigue is the controlling mechanism if the product $\nu \cdot t$ = const = N for every frequency ν. If this is the case k = 1.



Walker, [52].

FIG. 6—*The Influence of Hold Time on Cyclic Life of Some Steam Turbine Materials at 950 F.*

2) *Creep.* If creep processes are controlling then the time-to-failure is independent of the frequency ν. The product $\nu^k t$ has to be independent of ν and therefore a $k = 0$ is required.

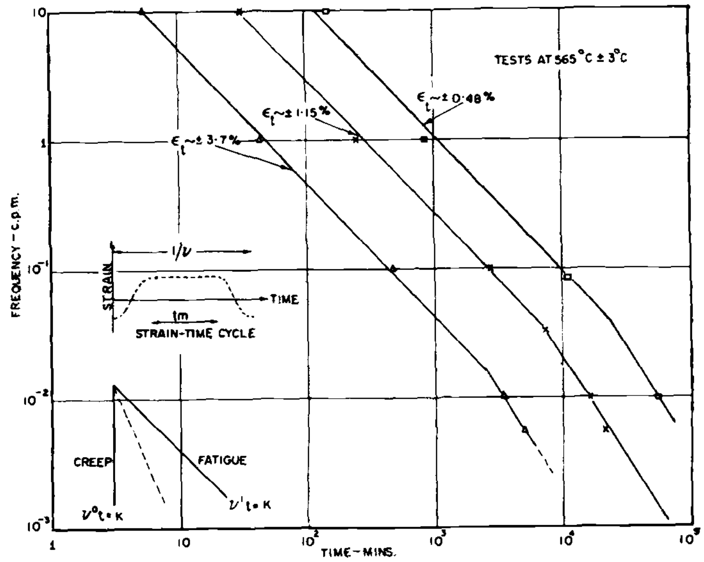
This method is used to analyze their tests on a Cr - Mo - V steel at 565 C. In their interpretation, hold time is considered to be frequency reducing and their analysis proceeds accordingly. They conclude that for lives below 11,000 minutes hold times contribute only in a "frequency effect" manner (at 2.3% $\Delta\epsilon_t$), and fatigue is controlling. Creep effects appear only at longer test durations. These creep effects are evidenced by a knee in the log ν - log t plot of Fig. 7. Another characteristic associated with the knee is the shift from transgranular to intergranular fracture. The former is associated with fatigue fracture, the latter with creep fracture. The knees are also shown for strain ranges $\Delta\epsilon_t$ = 0.96% and 7.4% in Fig. 7. No mention is made of the nature of the cracks at these strain ranges.

However, the knee is not very pronounced. The conclusions reached by Coles and Skinner are discussed by Barnes and Tilly, [*2*], who point out that the behavior of materials is more complex than Coles and Skinner tend to indicate in their interpretation. Barnes and Tilly quote their own work on the fatigue behavior of Nimonic 90 to show that a shift from transcrystalline to intercrystalline fracture at the knee is not necessarily due to creep damage. Their experience indicates that intercrystalline fracture can occur in pure fatigue tests with a decrease in applied frequency and/or increase in temperature and mean stress. Their interpretation is apparently than trans- and intercrystalline fracture can occur in creep and fatigue.

At a recent Conference on Thermal and High-Strain Fatigue in England in 1967, a number of papers investigated the influence of hold time on ferritic and austenitic steels for use in power plants. The tests were almost exclusively generated in a Forrest-Penfold type reversed bending machine, [*22*].

Coles et al [*11*] investigated the influences of strain range, frequency of strain cycling, length of dwell periods and of test temperature on the fatigue life of ferritic steels of the Cr - Mo - V and 2-1/4 Cr - 1 Mo variety up to 600 C. The majority of tests were run at 550 C.

To give an impression of the variety of materials investigated, Fig. 8 has been reproduced from the paper of Coles, et al. A rather uniform influence of hold time on cycles-to-failure is seen. The disadvantage of this type of plotting is that zero hold times cannot be accommodated. This property of the plot together with the fact that hold-time effect will increase with longer hold time caused those authors to introduce an exponential horizontal scale, Fig. 9. They state that this method of plotting has the disadvantage of a decrease in sensitivity as hold time increases. They discuss results obtained from extrapolation of the data. For the Cr - Mo - V material, an increase in hold time from 10 min. to 10^4 min. (1 week) would reduce the life from 300 to about 35



Coles and Skinner, [9].

FIG. 7 –*Relationship between Frequency and Time-to-Failure for Tests with Hold Time on a Cr-Mo-V Rotor Steel at 565 C.*

cycles ($\Delta\epsilon_t$ = 2%, 565 C, Material A-1). This number is indeed low in light of our Table 1 where a possibility is indicated of 100 cold starts with hold times of more than a week between the starts in the lifetime of a turbine. It is possible that a strain range of $\Delta\epsilon_t$ = 2% can be reached during a cold start. Coles, et al. then indicate that more long-time tests are required before the extrapolation can be used with confidence.

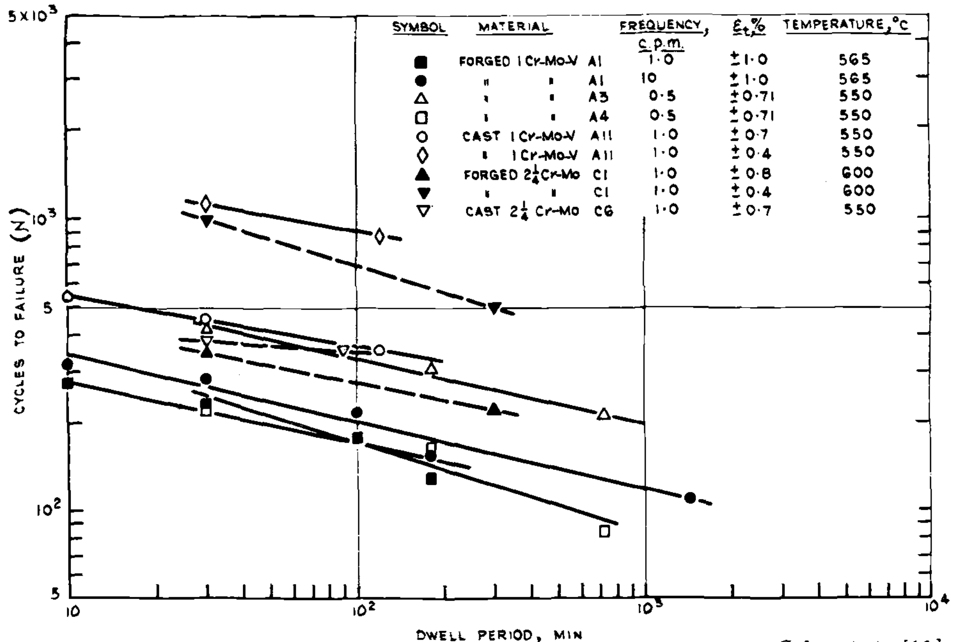
The combined influence of frequency and hold time on the cycles-to-failure is depicted in Fig. 10. Two factors are evident from this graph:

1) The effect of frequency and hold time on cycles-to-failure is much less pronounced at high strain ranges than at low strain ranges.
2) At long dwell periods, the effect of frequency is small.

The observation 1) conforms the findings by Edmunds and White, [*18*].

Some tests conducted in vacuum resulted in longer cycles-to-failure than in air (cycle increase by about a factor 2). The authors conclude that oxidation, which is present when the tests are run in air, contributes to the cause of cracking.

The lives so far reported refer to the failure of the tests specimen. An attempt was made to determine crack initiation in the specimens. Since no marked changes in bending moment or strain range were coincident with crack initiation, the only reliable technique was to interrupt the test at various stages, remove the oxide layer, and examine the surface by a 20x microscope. Crack initiation was then defined by the occurrence of cracks 0.015 in. long. The following ratios N_i (initiation): N_f (failure) were found at 550 C (cast Cr - Mo - V, 30 min dwell, 0.5 cpm) : N_i/N_f = 0.17 for $\Delta\epsilon_t$ = 1.44%, and N_i/N_f = 0.43 for $\Delta\epsilon_t$ = 0.52%.



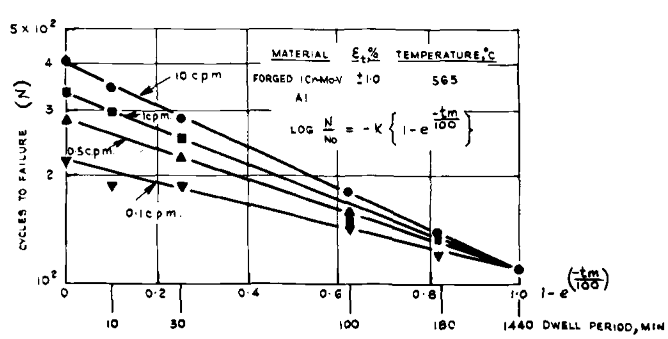
Coles, et at., [11].

FIG. 8—*Influence of Dwell Time on the Fatigue Life of Various Cr-Mo-V Steels at the Indicated Temperatures.*

Edmunds and White indicate that the data are typical; low ratios of N_i/N_f at high strain ranges, and high ratios at low strain ranges.

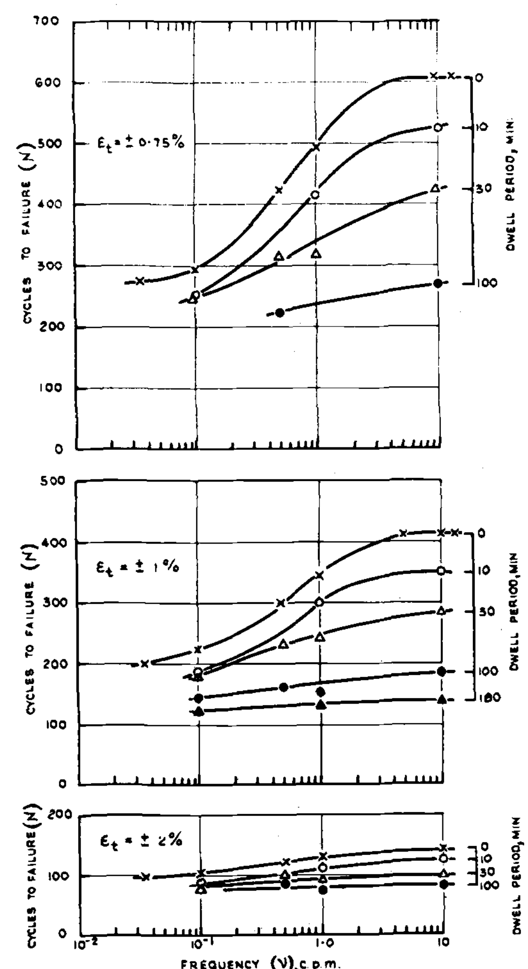
The writers concur with the conclusion that crack initiation should receive greater attention in the future.

Hill [27], investigated at 550 C two forged 1% Cr-Mo-V steels with significantly different creep-rupture properties. Whereas no difference was observed for continuous cycling, the introduction of dwell periods discriminated between the two steels. Figure 11 shows his results. The material B behaves in a brittle manner in creep-rupture and exhibits shorter cycles-to-failure in fatigue tests with hold time than does steel A. Therefore a definite correlation between the behavior in a creep-rupture test and in a fatigue test with relaxation is observed. (Material A and B are slightly different in their



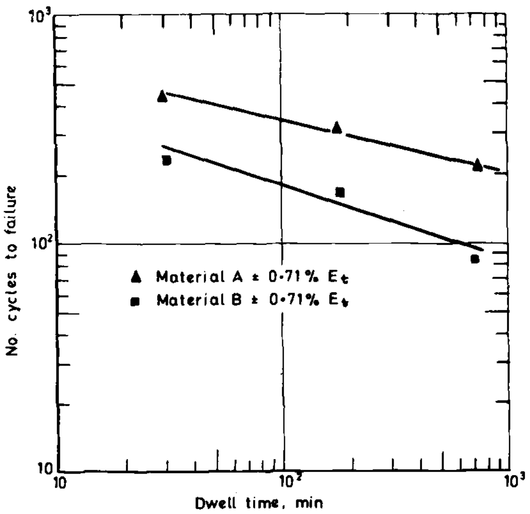
Coles, et al., [11].

FIG. 9—*Influence of Dwell Time. (Exponential scale is used on the abscissa).*

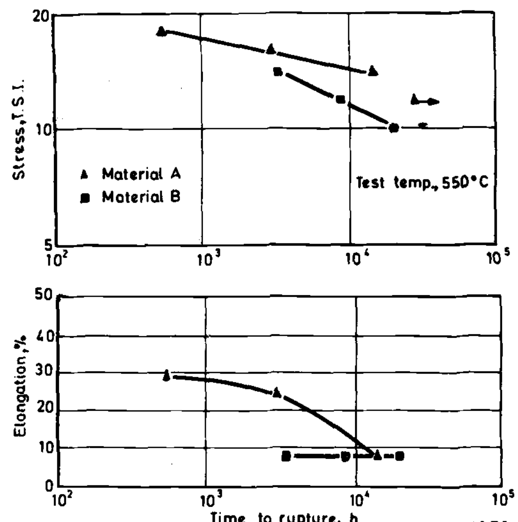


Coles, et al., [11].

FIG. 10—*Interaction of Frequency and Hold Time for Forged 1 Cr-Mo-V Steel at 565 C.*



Dwell time $(t)_D$ *vs. cycles to failure.*



Hill, [27].

FIG. 11 –*Influence of Dwell Time on Cycles-to-Failure for the Two Materials Characterized by the Creep Rupture Data Shown.*

chemistry and underwent a different heat treatment.)

The cracks propagated in a transgranular manner for continuous cycling. In dwell tests, intergranular-oxidation effects were found first, the cracks became increasingly transgranular as their depth increased, and finally ended up in an intergranular void-type growth. The fracture mode in creep-rupture tests of equal duration was mostly shear deformation and no evidence of intergranular fracture was observed. Only with test durations of 2000 h and longer was intergranular cracking found to take place.

In the writers' opinion, this difference in the cracking behavior is mostly due to the geometric constraints imposed on the specimens. Displacement control which limits the overall deformation is employed in the cycling tests, no limit is imposed on the length of the specimen in the creep test. Therefore, necking and shear deformation can occur in the latter but not in the former test. The elongation at fracture usually reduces with test duration in a creep test, so that the conditions of the two types of tests approach each other as the testing time increases.

Detailed informatin on the cracking behavior on the tension and compression side of the specimen (tension is the side of the bar that is held in tension during hold-time) is given and the influence of grain boundary sliding is discussed in detail.

Dawson et al., [*14*] investigated three types of austenitic steels (Type 316 SS, Esshete 1250, and A286) at 600 C. The influence of hold time on cycles-to-failure of Type 316 steel is shown in Fig. 12. The usual trend which is familiar by now is evident. However, one important point is emphasized by Fig. 12; the hold-time effect is more pronounced for push-pull tests than for bending tests, and the lines are steeper for the former than for the latter case.

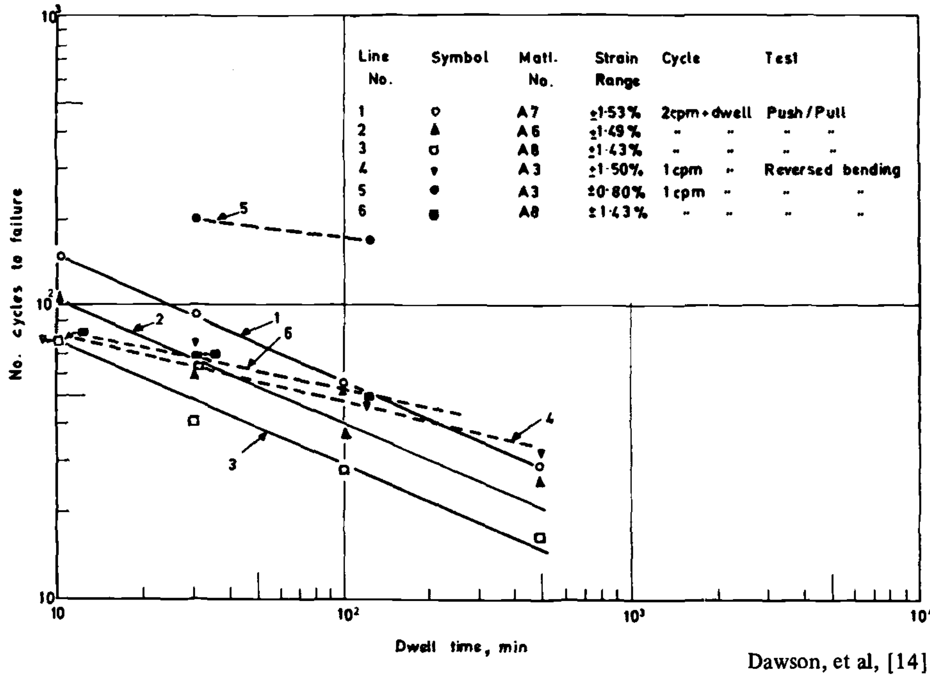
Dawson, et al. explain the difference in the results of bend and the push-pull tests by a different amount of elastic follow-up during the dwell period. The extensometer was attached to the shoulder of the specimen in the push-pull tests, thereby allowing an elastic follow-up during hold time. Although the explanation is plausible, the question remains what would have been the hold-time effect without follow-up. Since the cycle reduction was enhanced by the presumed reduced follow-up of the push-pull test, it is not unreasonable to assume that further reductions would have been experienced for zero elastic follow-up. The writers concur with the authors' suggestion that future dwell tests should use push-pull tests and *constant* strain during hold time.

For Type 316 SS. crack initiation was reported to have occured (0.030 in. long crack) at around 50 to 60 percent of the fatigue life. At high strain ranges, the N_i/N_f ratios became very small. 0.1 to 0.2, as shown in Fig. 16 (not reproduced) of their paper.

A comparison of the three steels on the basis of their performance in continuous cycling and tests with a dwell time of 30 min, shows that the relative ranking of the materials is different in the two types of tests. While the results scatter, thus making a conclusion difficult, it appears that the highest ranking steel in continuous cycling is A286, followed by Esshete 1250, and Type 316 SS. For a 30 min dwell period the order (highest rank first) is Type 316 SS, Esshete 1250, and A286 (for $N_f > 2000$, A286 is superior to 316 SS and Esshete 1250, very few points). The authors indicate a correlation with creep-rupture properties; for details see Figures 20 and 21 of Dawson et al. [*14*]. The intorduction of the 30 min dwell period reduced the life at $\Delta\epsilon_t = 1\%$ from 2000 cycles at no hold-time, to roughly 500 cycles.

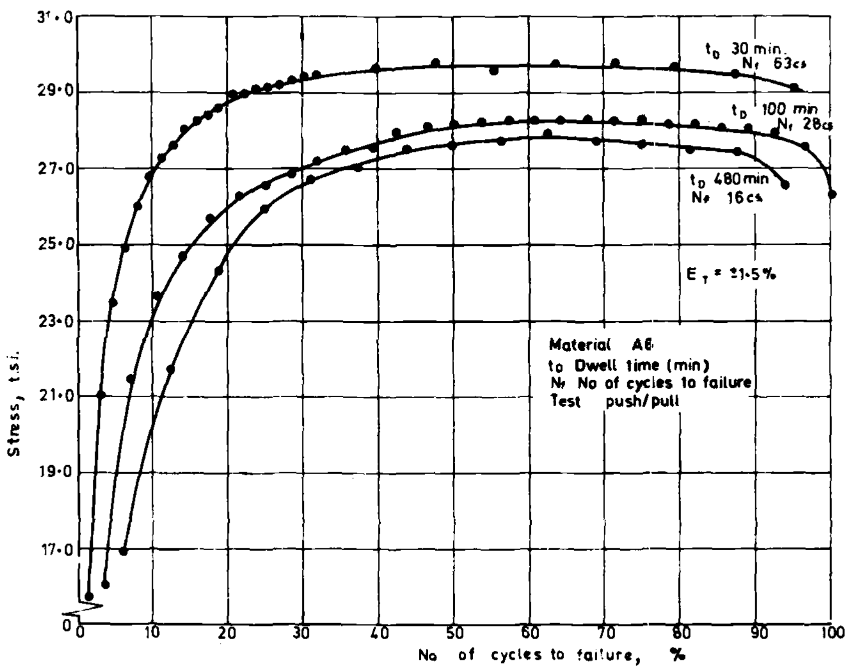
Cracking is reported to shift from a transcrystalline mode in continuous cycling to an intercrystalline mode upon the introduction of dwell times of 10 min or longer. Triple-point cracks were observed in push-pull tests and detailed discussion on the role of triple-point cracks in crack propagation is presented.

The use of push-pull tests permits the measurement of the output variable, the stress. The stress range changes considerably with cycles. An example is given in Fig. 13. The variation in the peak stress of Type 316 SS for a strain range $\Delta\epsilon_t = 3.0\%$ is shown for three different hold times. The introduction of hold-time can



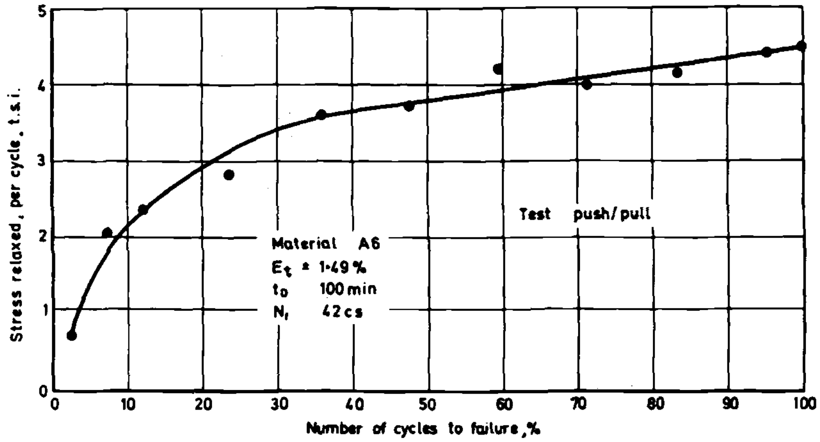
Dawson, et al, [14].

FIG. 12—*Effect of Dwell Time on Endurance for Type 316 Steel. (A comparison is made between the hold-time effect in push-pull and in bending at 600 C.)*



Dawson, et al, [14].

FIG. 13—*Variation in Peak Tensile Stress with Number of Cycles during Tests with a Dwell Time. Total strain range* $\Delta\epsilon_t = \pm 1.5\%$*, 600 C, Type 316 Stainless Steel.*

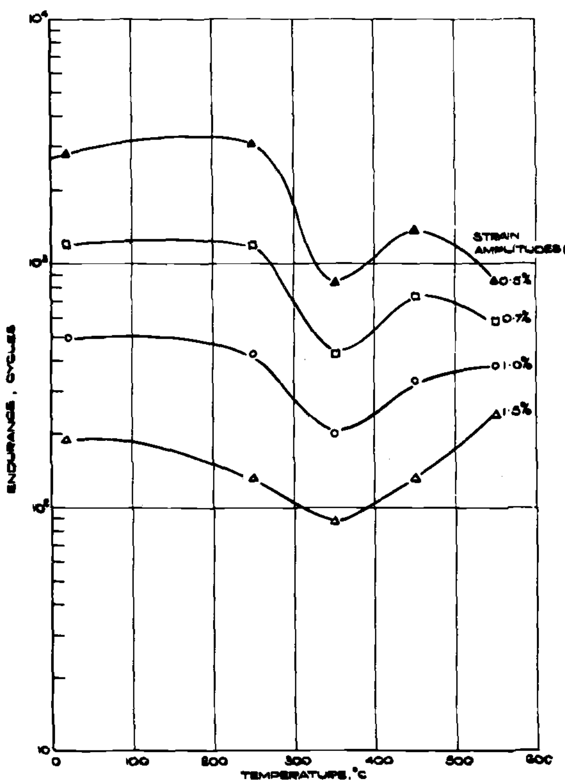


Dawson, et al. [14]

FIG. 14—*Variation in Total Relaxed Stress during a Test with Dwell Time.*

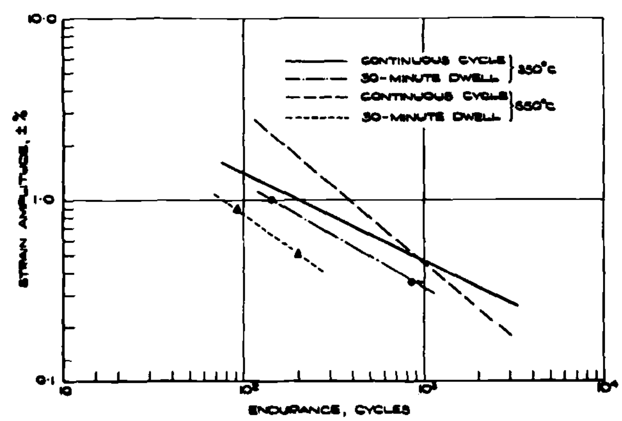
be seen to change the value of the resulting peak stress. The general pattern of the variation is similar for all hold times. Also the amount of stress relaxation per cycle (the difference between the stress at the beginning and at the end of the hold-time, $\Delta\sigma_r$ in Fig. 4) is changing as a function of cycles as shown in Fig. 14. In this case, $\Delta\sigma_r$ increases with the number of applied cycles.

Coles and Chitty, [*10*] set out to investigate the low-cycle fatigue strength of a C – Mo and a 2Cr-Mo-V steel as a function of temperature. The tensile properties of the C – Mo material show a trough in tensile ductibility at 350 C (strain aging) and therefore this material is of special interest. Consequently, the cycles-to-failure at a given strain range shows a minimum at this temperature and the life at 350 C is lower than that at 550 C, Fig. 15. The "natural order" is restored at both temperatures when a hold time is introduced (Fig. 16). The



Coles and Chitty, [10].

FIG. 15—*Influence of Temperature on the Cyclic Endurance of C-½Mo Steel at Various Strain Amplitudes.*



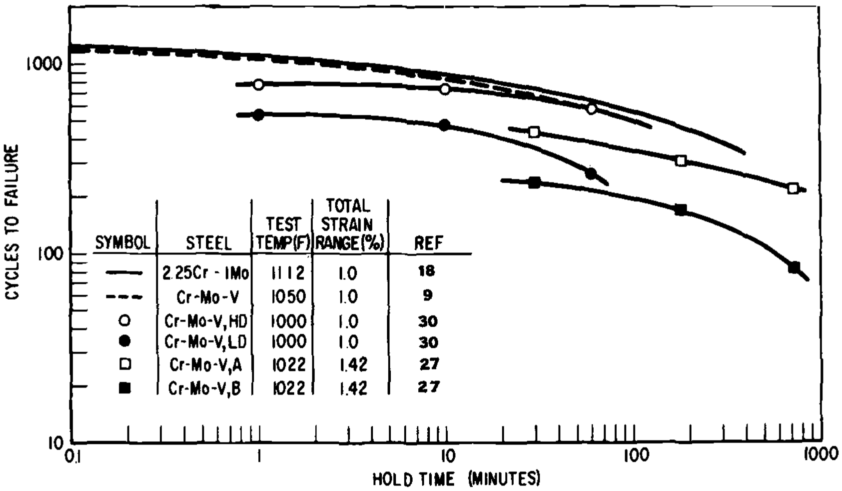
Coles and Chitty, [10].

FIG. 16—*Influence of Dwell Time on the Strain Cycling Resistance of C-½Mo Steel at 350 and 550 C.*

550 C hold time data exhibit clearly the minimum life in the hold-time tests.

Coles and Chitty conclude that for materials with a ductility trough such as the C – Mo steel, it may be necessary to simulate the actual thermal cycle to obtain realistic design data.

Krempl and Walker, [*30*] heat-treated a Cr – Mo – V



Krempl and Walker, [30].

FIG. 17—*Comparison of the Hold-Time Effect as Reported by Various Investigators.*

forging to obtain a high and a low creep-rupture ductility. Subsequent push-pull tests with accurate strain control, using hold-times of 1, 10 and 60 minutes at 1000 F for $\Delta\epsilon_t = 0.5\%$ and 1.0%, showed the following results.

The hold-time effect was higher for the condition of low than for the condition of high creep-rupture ductility. In each case the highest cycle reduction was observed at the low strain range of 0.5%. A comparison between the results of this investigation and results discussed previously, is given in Fig. 17. The data fall within a reasonable scatterband; however, the downward bend of the curves for the low-ductility (LD) material and Hill's data [*27*] are somewhat disturbing. An extrapolation to longer hold times is uncertain under these conditions.

It is reasoned that the hold-time effect is not sufficiently explained by the increase in plastic strain alone (compared to no-hold tests) but that the additional assumption of creep damage introduced during the hold period has to be made. Only then can the different effects of hold time on the low and the high ductility version of the material be qualitatively explained.

The fractures advanced by a combination of intergranular and transgranular cracks. They tended to shift from transgranular to intergranular as the hold time increased. The shift was more complete for the low-ductility material than for the high-ductility material.

The variation of the stress range during cycling was different for the two conditions of heat treatment. The high-ductility version of the material showed continuous strain softening ($\Delta\sigma_t$ decreases), whereas the relatively constant stress range was observed for the low-ductility version. After-test hardness measurements indicated a smaller hardness drop for the low-ductility material than for the high-ductility material. The amount of stress relaxation per cycle was also different for the two conditions of heat treatment. Thus a definite pattern of the variation of the dependent quantities was observed in all the tests for the two conditions of heat treatment.

In all previously discussed papers, introduction of hold time was at the maximum tensile strain of the cycle. Berling and Conway, [*3*] introduced the hold time at three different positions in the strain cycle, as illustrated in Fig. 18. A very accurate experimental

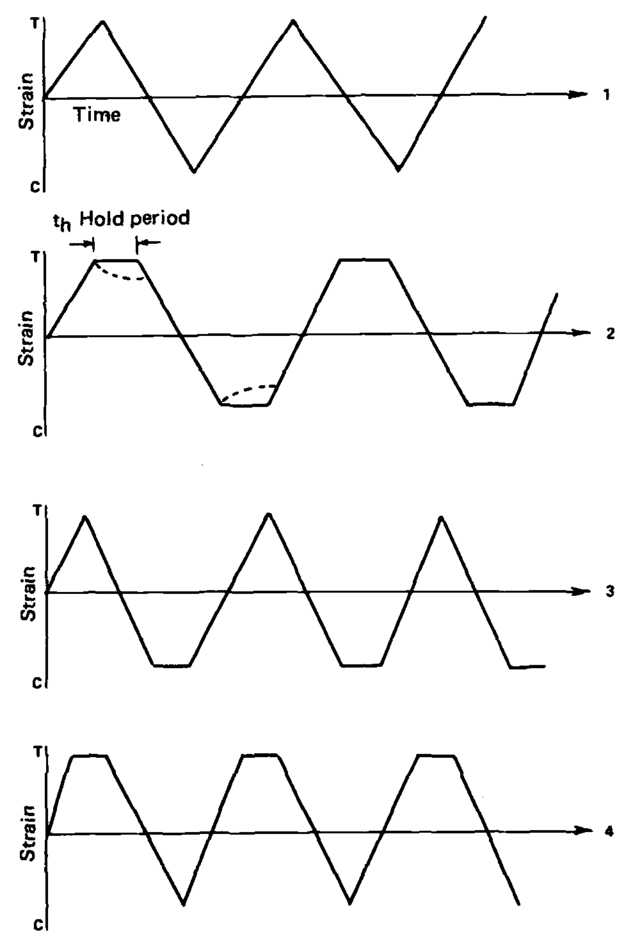


FIG. 18—*Various Waveforms Used by Berling and Conway, [3].*

set-up was used including servo-controlled testing equipment induction heating, diametral strain measurements, and a special strain computer to enable axial strain control. (Keeping the diametral strain constant is not equivalent to keeping the axial strain constant in hold-time tests.) Most of the testing was done with Type 304 and Type 316 SS at two strain rates, 4 x 10^{-5} and 4 x 10^{-3} sec^{-1}.

Berling and Conway conclude that only a hold in tension (waveform no. 4 in Fig. 18) shows a considerable cycle reduction. They are capable of measuring the total strain range accurately. A plot of log plastic strain range (presumably measured at $N_f/2$) vs. number of cycles is shown in Fig. 19. It can be seen that the plastic strain range does not correlate the data. For the same plastic strain range various N_f values are obtained depending on the hold time.

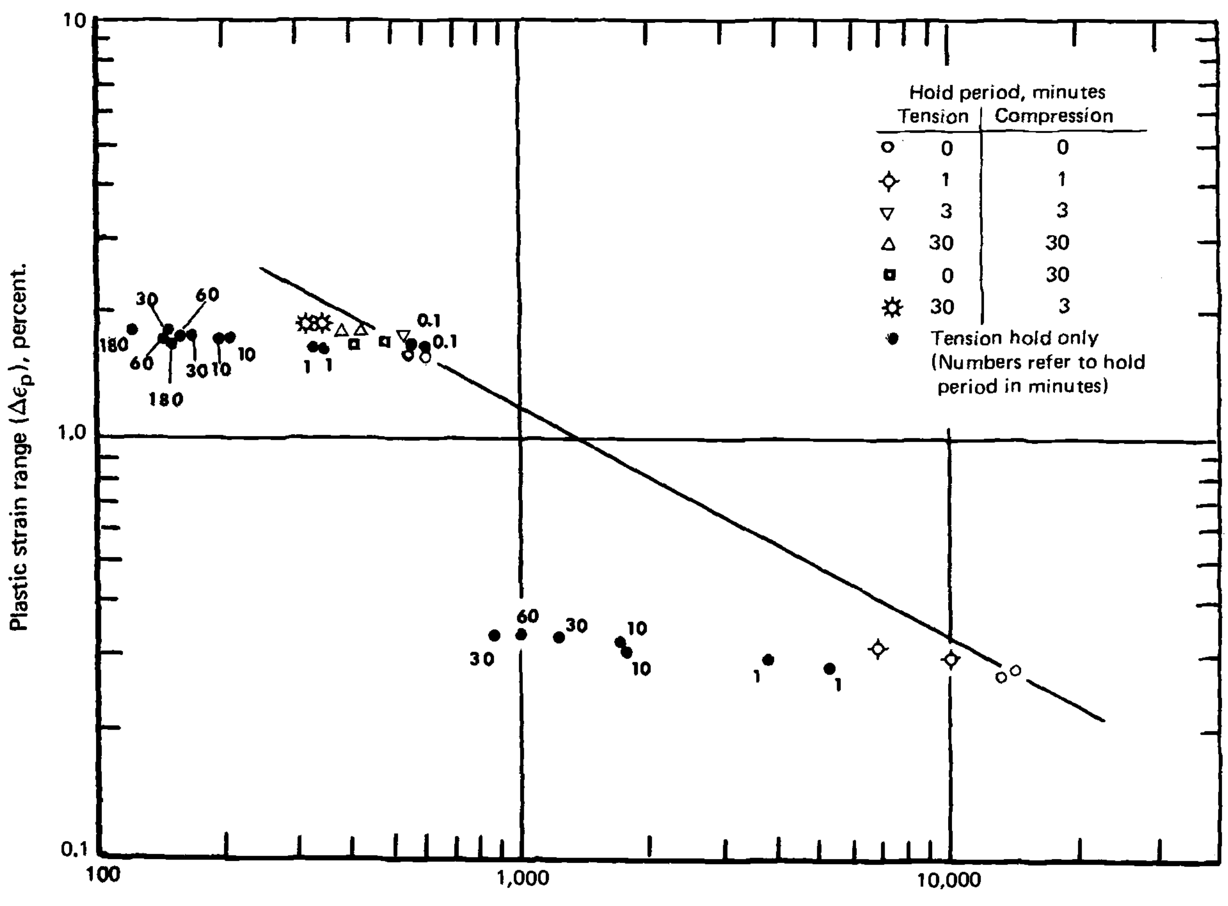
The tensile hold tests were shown to correlate with the creep-rupture curve of the same material. The stress of the cycling test used to correlate the result is the average of the relaxation stress ($\sigma_{max} - \Delta\sigma_r/2$) during the hold-time. If this stress (presumably taken at $N_f/2$) is plotted versus time to failure, it correlates well with the creep-rupture curve, Fig. 4 in Ref. 3.

It is known that the peak stress and the amount of stress relaxation during hold time vary with cycles, e.g., Figs. 13 and 14. Each cycle will therefore have a different average relaxation stress. It appears to the reviewers that the correlation with creep tests will depend on the cycle from which the value of the average relaxation stress was picked. This information, however, is not given in the paper.

Berling and Conway show a definite levelling-off in the cycles-to-failure reduction due to hold time beyond a 30 min hold time. Further confirmation with additional test results would be helpful. No further reduction in fatigue life is observed beyond this hold time, (Fig. 5 in [3], not reproduced.). It is important to note that none of the previous authors indicated such a saturation effect. Berling and Conway surmise that this might be due to their very accurate control which none of the previous authors were able to employ.

The fracture initiated and propagated transgranularly in all cases except in the specimens with a hold in tension only. These specimens showed intergranular initiation and propagation of the cracks.

In an additional analysis of the work discussed in the preceeding paragraph, Conway et al., [12], investigate



Berling and Conway, [3].

FIG. 19—*Effect of Hold Period and Strain-Wave Form on the Plastic Strain Fatigue Resistance of AISI 304 Stainless Steel Tested in Air at 1200 F and a Strain Rate of 4 x 10^{-3} sec^{-1}.*

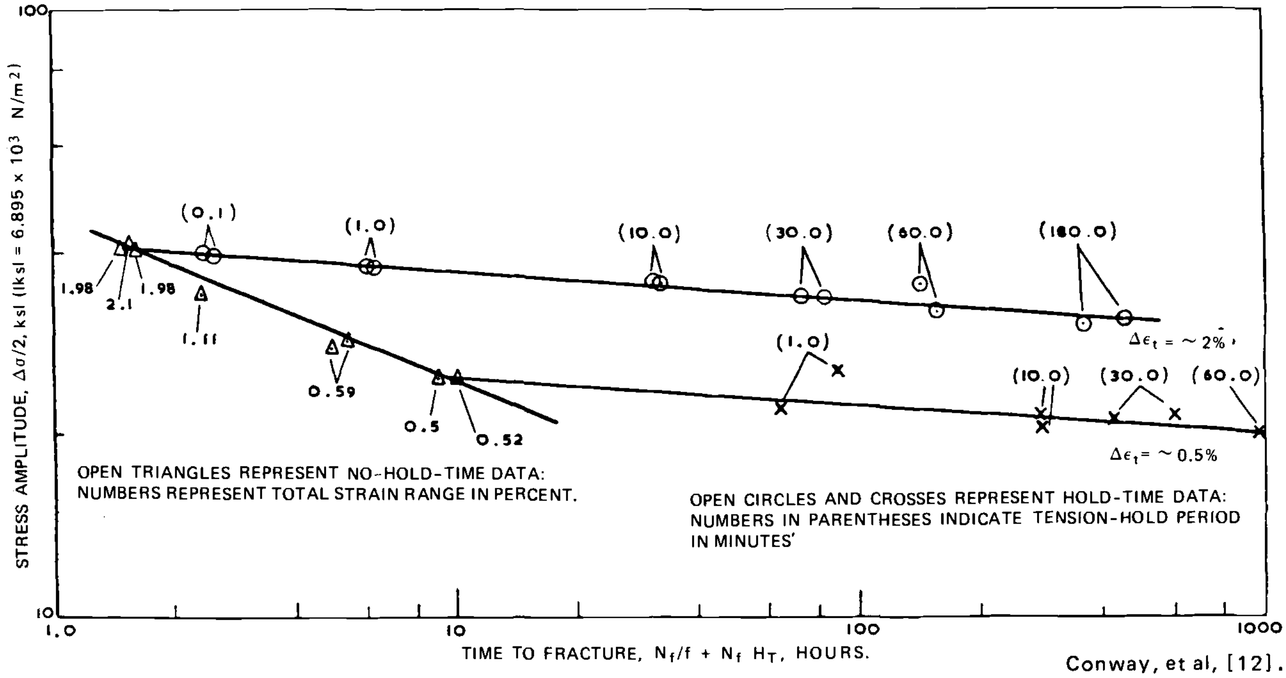


FIG. 20—*Stress Amplitude versus Time-to-Fracture Correlation of Hold-Time Data Involving Hold Periods in Tension Only for AISI 304 SS in Air at 650 C. Strain rate 4 x 10^{-3} sec^{-1}.*

the hold-time properties of AISI Type 304 and Type 316 stainless steel. Two methods of data correlation for hold-time tests are pursued. The first one is based on the stress amplitude at $N_f/2$ for tests with no hold time, and presumably on $\sigma_{max} - \Delta\sigma_r/2$ at $N_f/2$ for the hold time tests. Figure 20 shows the correlation obtained for AISI 304 SS at 650 C and 4 x 10^{-3} 1/sec strain rate. The curves for the hold-time tests branch off the no-hold-time results at the pertinent strain range and have the same slope. The authors indicate that this type of plotting does not permit the exact prediction of the hold-time effect, but rather the trend of the data.

Another type of correlation for the 650 C hold time for AISI 304 is based on the plot of log time-to-fracture vs. log time for one cycle, given in Fig. 21. One should recognize that a similar plot, using frequency instead of time for one cycle, was employed by Coles, [*9*] and was reproduced in Fig. 7. The data in Fig. 21 fall in one straight line for a given strain range. The slope of these lines, however, are different for the two strain ranges. The authors discuss the potential usefulness of this observation in eliminating the need for long time testing, provided that further results will confirm the findings of Fig. 21. Figures 19, 21, and 23 of Ref. [*35*] indicate the same type of correlation for ferritic and austenitic materials.

At one point in Ref. [*12*] the authors state the generally-known fact that hold times decrease the number of cycles-to-fracture and increase the total time-to-fracture. They conclude "If a design life is established based on no-hold-time data, a specimen or component tested with hold periods at peak strain could not, within this design life, be subjected to the number of cycles necessary to cause it to fracture."

While this conclusion is true for specimen testing where number of cycles and test time are directly connected, it may not be valid for design application. In this case total plant operation time and the total number of cyclic operations can be specified separately. Therefore the design has to be checked whether a limitation exists due to the cycles or due to the total operating time. For the former case, hold-time data are definitely necessary.

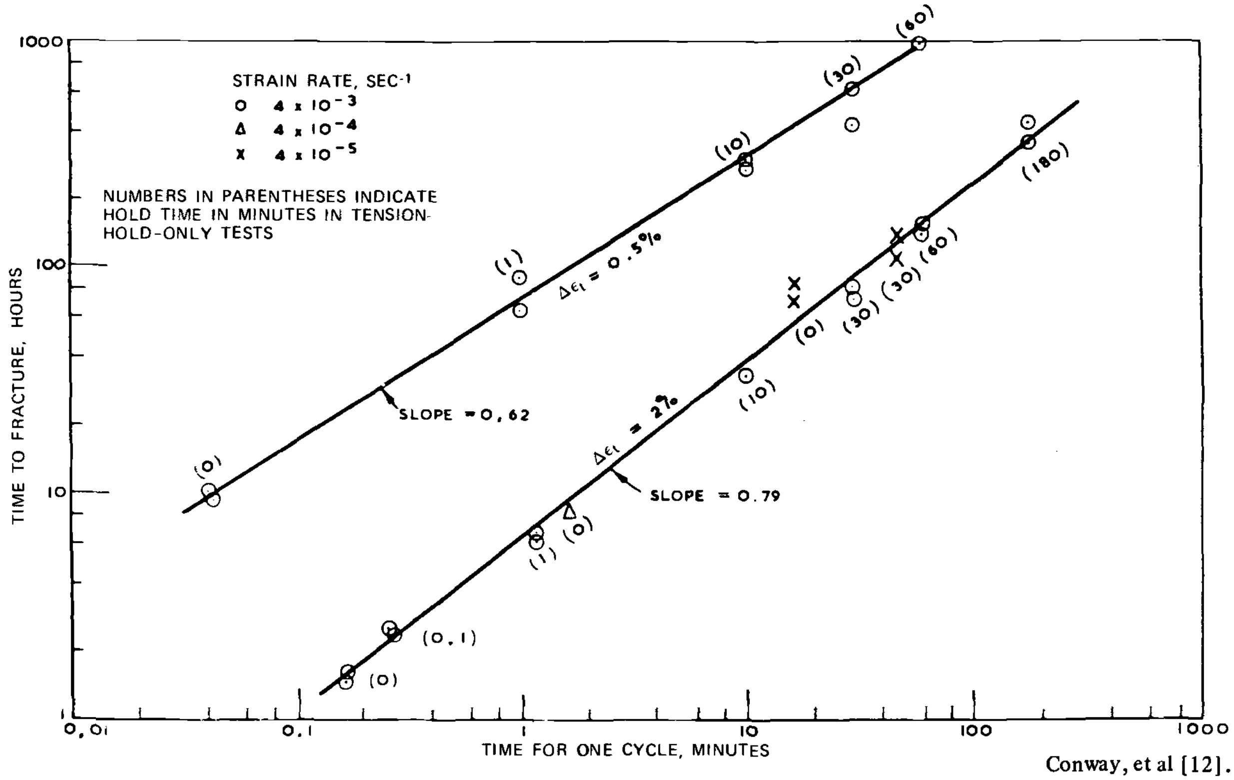
The effect of the introduction of a vacuum on the fatigue life with and without hold time for a ½ percent Molybdenum steel at 500 C was investigated in Ref. 55. Figure 22 gives a summary of the results. It is important to note that the introduction of a 30-min hold time reduced the cycles-to-failure in air and in vacuum by roughly the same ratio. The absolute value of the cycles-to-fracture was considerably higher for vacuum than for air. It is therefore evident that both the environment and mechanical damage will have an effect on the fatigue life at elevated temperature.

Hold Time with Creep

As explained earlier, the bar is under load control all the time and therefore a continuous elongation and a final necking down of the specimen is possible. Compared to hold time with relaxation, this subject has received little attention.

Tilly, [*47*] investigated the behavior of a nickel-chromium alloy and of a 11% chromium steel under completely-reversed load-controlled conditions at *room temperature.* The cycle-dependent creep was measured with a diametral extensometer. The cyclic frequency was 0.12 cpm and the investigation included cycles-to-failure from ½ (tensile test) to about 1000.

The cycles-to-failure depended on the direction of the first quarter cycle. If compression was applied first, the life was longer than when tension was applied first. The



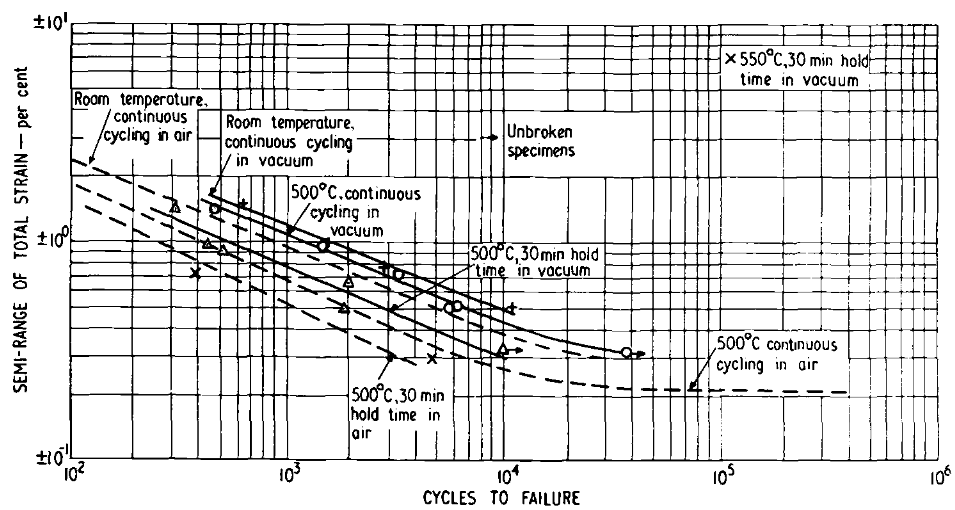
Conway, et al [12].

FIG. 21 – *Correlation of Low-Cycle Fatigue Data for 304 SS Tested in Air at 650 C for no Hold Time and for Hold Time in Tension Only.*

difference in the life diminished as cycles-to-failure increased.

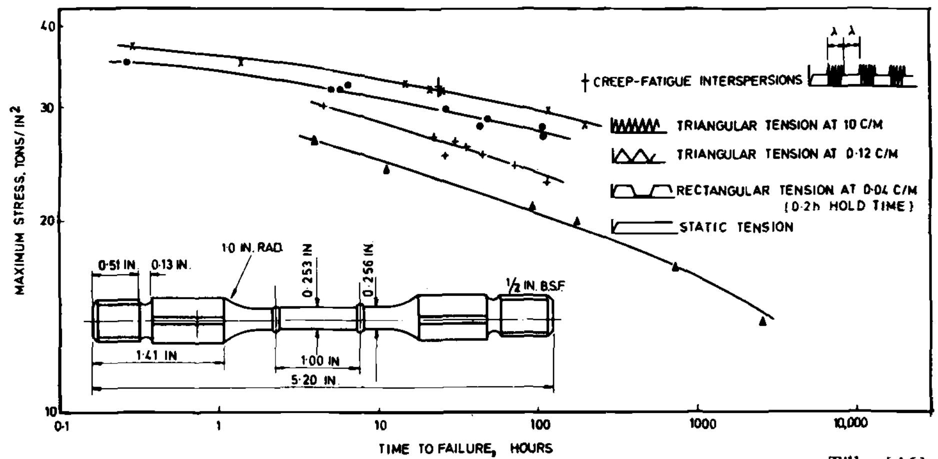
The resulting creep curves were analyzed and a curve fit was made using the method of Graham and Walles which is termed a rheological approach. (For a description of this approach, see Kennedy, [*28*].) The creep curves for the condition of tension and compression first were different, more strain was accumulated in the tension-first creep curves. In every case a permanent tensile strain developed.

It is the writers' opinion that the results are somewhat hard to interpret since only engineering stresses and not true stresses appear to be reported. At the end of the paper, it was shown that there is not an appreciable difference between the true tensile and compressive stress if they are compared on the basis of strain amplitude. However, the argument should have been based on the condition at the first quarter cycle where a substantial difference between the compressive and tensile true stress exists.



White, [55].

FIG. 22 – *The Effect of Hold Time and Temperature on the Fatigue Life of a ½ Percent Mo Steel in Air and in Vacuum.*



Tilly, [46].

FIG. 23–*Effect of Hold Period in Hold-Time Tests with Creep for 11% Chromium Steel at 600 C.*

The same 11% chromium steel was then investigated at 600 C for a variety of loading conditions under zero-to-tension loading. (See Tilly, [46]). Fig. 23 shows the results; the labeling is self-explanatory.

As the hold time is increased the time-to-fracture and the cycles-to-failure decrease. The creep-rupture test has the shortest life by each measure. The behavior of this material under stress control is therefore somewhat different than the trend of the data for hold time with relaxation.

The previously mentioned method by Graham and Walles was used again to curve-fit the strain vs. time curves. It was found that the test which accumulated the strain in the most rapid way showed also the shortest life.

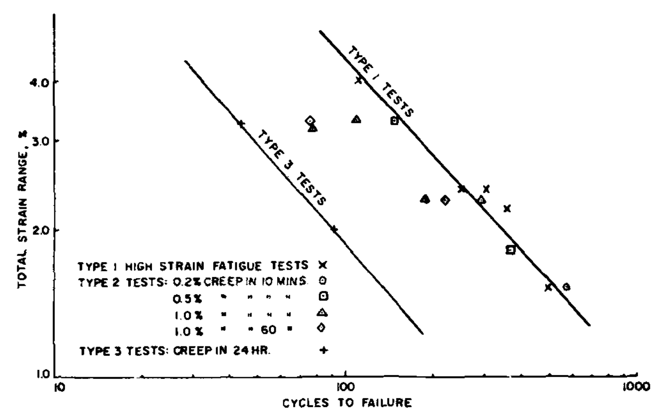
No results of metallurgical studies were reported.

Hold Time, Mixed

Wood, [57] investigated the behavior of an aluminum grain refined pressure vessel alloy steel at room temperature and 350 C. He conducted three types of tests. Type I tests were conventional strain-controlled tests at room temperature and 350 C. It appears from the diagrams that zero-to-tension strain control was used. In the Type II tests, a switch from strain control to stress control was employed at a predetermined tensile stress. The specimen was then allowed to creep 10 min or 1 h. After that period, the strain was rapidly reduced to zero strain and then the whole cycle was repeated. The Type III tests were characterized by a 24 h hold under stress control and rapid compression to zero strain. The maximum strain at the end of the 24 h hold was predetermined. The Type II and III tests were conducted at 350 C.

It is clear that the test conditions in the Type II and III tests were overspecified. It is not possible to predict accurately the creep strain at the end of the hold time. The material changes its creep characteristic due to the cyclic loading and therefore the strain reached after a specified time at a certain stress will vary from cycle to cycle. Because of that property, the authors find that the actual creep time was often slightly different from the nominal creep time required.

The influence of hold time on cycles-to-failure is depicted in Fig. 24. The Type III tests with creep



Wood, [57].

FIG. 24–*Effect of Creep on High-Strain Fatigue Behavior at 350 C for an Aluminum Grain Refined Pressure Vessel Steel.*

hold time introduce a considerable reduction in cycles-to-failure.

The author found that cyclic strain hardening was much more pronounced in the Type I tests at 350 C than in the room temperature tests. This was attributed to strain-aging of the material.

In explaining the hold-time effect, the author cites a paper by Feltner and Sinclair, [21]. These latter authors state that the fracture is fatigue controlled (dependent on cycles) when $T/T_m < 0.25$ (T = test temperature, T_m = melting temperature of the material, T is measured in deg. K). If $T/T_m > 0.50$ the fracture is time dependent; i.e., creep controlled. In Wood's tests at 350 C, $T/T_m = 0.35$; therefore a combined criterion of creep and fatigue fracture will have to be used. Wood sets out to develop a fractional damage concept which will be discussed later.

In an effort to separate time-dependent cracking from cycle-dependent cracking, low-cycle fatigue tests with hold time were conducted with Udimet 700 at 1400 F by Wells and Sullivan, [*54*]. Their hold time was under stress control, whereas the rest of the cycle was under strain control. They find that the introduction of hold time in compression is more damaging than in tension. This result is contrary to the findings of Berling and Conway, [*3*]. Wells and Sullivan indicate that crack initiation occurs adjacent to the grain-boundary precipitate.

PREDICTING CYCLE-REDUCING HOLD-TIME EFFECT

Before discussing the possibility of predicting the hold-time effect in low-cycle fatigue at elevated temperature, it is useful to consider briefly the evolution of low-cycle fatigue life prediction techniques.

The well-known Coffin-Manson Law predicts low-cycle fatigue life for completely-reversed, strain-controlled conditions at room temperature. This law is used in slightly different form by different investigators. However, the power law between cycles-to-failure and plastic or total strain range is well established. The engineering significance of this law lies in the fact that the fatigue life can be predicted with engineering accuracy from the properties measured in a tensile test.

Initial attempts to use this law at elevated temperature showed in many cases that the prediction was unconservative when compared with actual test results. It was then recognized that time-dependent effects which are not present at room temperature have to be considered in the prediction technique for elevated temperature.

The existing attempts to predict elevated-temperature, strain-controlled fatigue life under completely-reversed conditions could probably be classified into two groups. The first group tries to predict the hold-time effect using a frequency type approach. The second one attributes the hold-time effect to creep-fatigue interaction. Also, it should be kept in mind that most of the prediction methods are not specifically tailored to the hold-time problem. They are rather aimed at the elevated-temperature strain-fatigue problem of which frequency and hold-time effects are a part.

Frequency Approach

Coffin, [*6*] experiments with Type A-nickel at 550, 650 and 750 C at crosshead speeds of 0.2, 0.05, 0.005, and 0.0005 in/min. He then uses the previously-mentioned equation (3)

$$\nu^k t_f = C_1 \tag{3}$$

to plot the results at a given plastic strain range (Coles and Skinner, [*9*] used total strain range). Coffin finds that the exponent *k* is nearly independent of the plastic strain range, as seen in Fig. 25. (Nominal plastic strain range is used; actually the plastic strain range is an output variable and therefore changes with cycles in a given test.) From this diagram, C_1 can be determined for a given nominal plastic strain range. A cross plot of C_1 vs. nominal plastic strain range ($\Delta\epsilon_p$) reveals that the data can be represented by

$$C_1^\beta \Delta\epsilon_p = C_2. \tag{4}$$

The values of C_1, β, C_2 for A-nickel, Type 304 SS (from Berling and slot, [*4*]) and for Mo-V steel (from Forrest, [*23*]) are calculated and fall in a rather narrow range. (None of the investigators used hold time in their studies.) It is evident that $\nu \cdot t_f = N_f$. Using this relation, Coffin arrives at the formula

$$N_f = (C_2/\Delta\epsilon_p)^{1/\beta} \nu^{1-k} \tag{5}$$

Coffin then states that the necessary constants β, C_2, k can be determined from relatively short-time experiments to permit predictions of life when the actual life is extremely long. Finally he discusses the possibility of using Eq. (5) for the prediction of hold-time effects and writes "Equation (5) presumes that the frequency is defined in terms of a full cycle without regard to the wave shape. If this could be verified, the resulting simplification in experimentation and design could be of significant value. Thus, provided $\Delta\epsilon_p$ and ν remain constant, the life would be the same whether, for example, the straining is sinusoidal, or contains hold periods or other complications. Experimental attention needs to be given to this equation."

This approach is extended further in Ref. [7]. Starting with equation (5) which involves the plastic strain range, an assumption is made about the frequency dependence of the steady state stress range as a function of $\Delta\epsilon_p$. The equation

$$\Delta\sigma = A(\Delta\epsilon_p)^n \nu^{k_1} \tag{6}$$

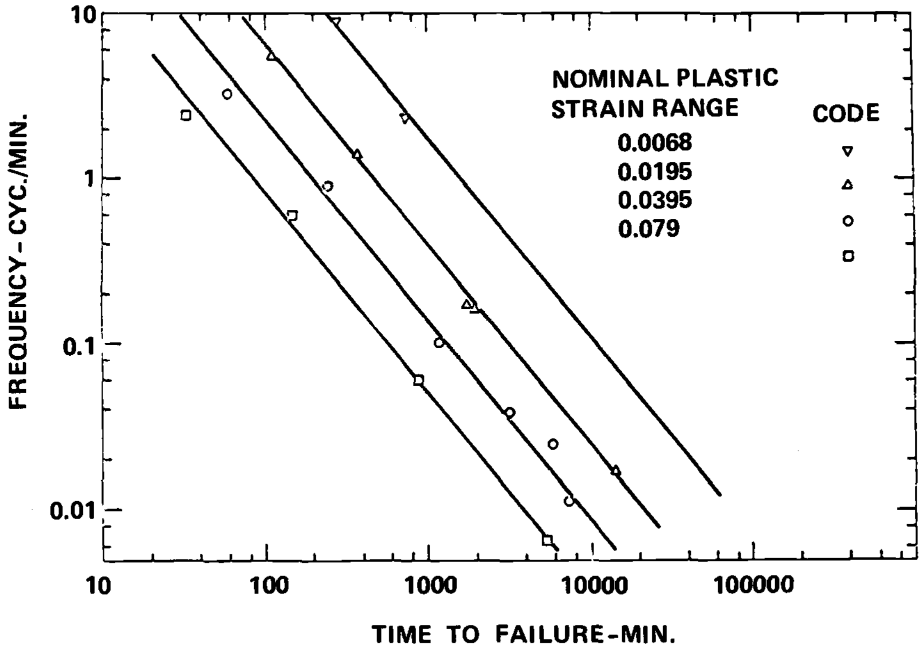
is stated. The elastic strain range is found to be $\Delta\sigma/E$. The total strain range $\Delta\epsilon_t$ is composed of the elastic and the plastic strain range. Hence, $\Delta\epsilon_p$ is eliminated and $\Delta\sigma/E$ obtained from (6) is combined with (5) to obtain

$$\Delta\epsilon = \frac{AC_2^n}{E} N_f^{-\beta n} \nu^{k_1+(1-k)\beta n} + C_2 N_f^{-\beta} \nu^{(1-k)\beta} \tag{7}$$

It is discussed how to obtain the six constants in (7) and it is shown that the proper choice of the constants will lead to Manson's universal slope equation (9) and to an equation proposed by Langer. To apply equation (7) to the prediction of cycles-to-failure for tests involving hold times, the frequency is determined to be

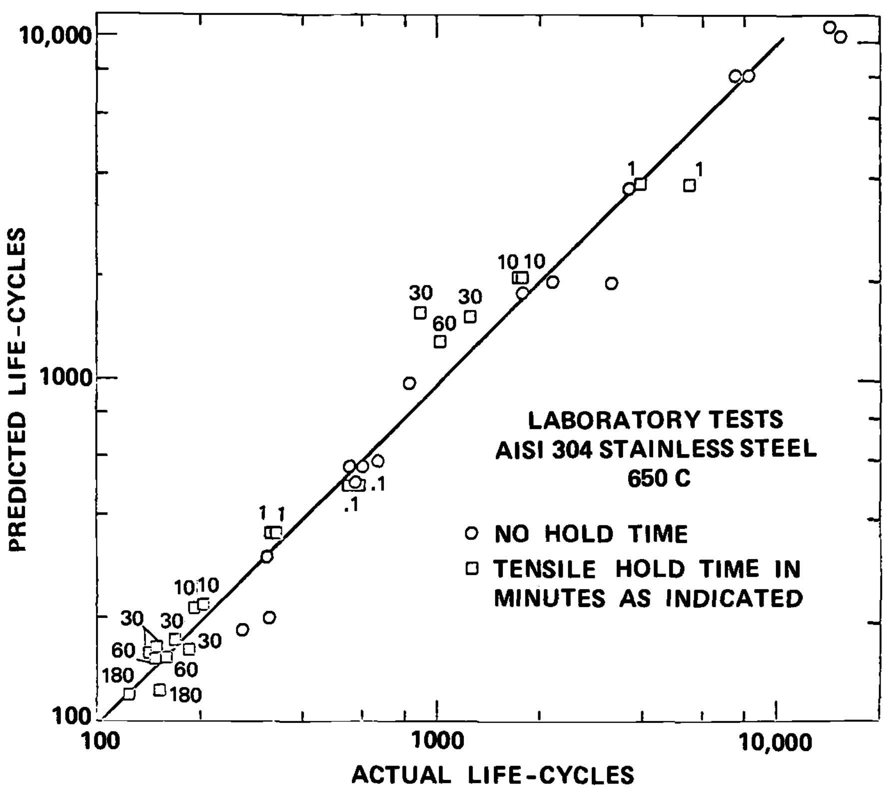
$$\nu = \frac{1}{T}. \tag{8}$$

Using this method the constants are determined for AISI 304 SS at 1200 F (650 C) from the data of Refs. [*4 and*



Coffin, [6].

FIG. 25—*Frequency Versus Time-to-Failure. "A" Nickel at 550 C; various nominal plastic strain ranges.*



Coffin, [7]

FIG. 26—*Comparison of Predicted Cycles-to-Failure [Eq. (7)] and Actually Observed Cycles-to-Failure for no Hold Time and for Hold Time in Tension Tests of AISI 304 SS at 1200 F (650 C).*

12]. A comparison between predicted and actually observed cycles-to-failure for these data is given in Fig. 26. A similar comparison is made for 1 Cr – Mo – V steel investigated in [*11*] and for some unpublished data on René 41.

The methods proposed by Coles and Skinner, [*9*], and Conway et al. [*12*] also consider hold-time effects to be of the frequency type. Their analysis was discussed previously. The idea expressed in Eq. (3) is due to Eckel, [*16*] who correlated fatigue tests on lead in this fashion.

Creep Fatigue Interaction Approach

Manson and Halford, [*38*], and Halford and Manson, [*25*] compare their elevated temperature prediction method with a great variety of experimental data.

To account for an indirect creep effect, they determine the cycles-to-failure directly from the universal slopes equation (the tensile properties are evaluated at the temperature of interest)

$$\Delta\epsilon_t = \frac{3.5\sigma_u}{E} N_f^{-0.12} + D^{0.6} N_f^{-0.60}. \qquad (9)$$

In most cases, adequate lower-bound, average and upper-bound lives have been found to be $N_f/10$, $N_f/5$, and N_f, respectively.

The possibility of a damaging direct creep effect is also considered. It is possible that the lower-bound of the previously mentioned estimate is not conservative. This may happen if the slope of the stress-rupture curve is steep, the temperature is high, and the frequency is low. Then the fatigue life is given by

$$N_f^* = \frac{N_f}{1 + (k/AF)\, N_f^{\frac{(m+.12)}{m}}} \qquad (10)$$

where

N_f = cycles-to-failure computed from Eq. (9),

k = factor expressing the fraction of a cycle at which the material is at the peak stress,

F = frequency

A and m = constants given by the representation of the creep-rupture curve by $\sigma_r = 1.75\,\sigma_u(t_r/A)^m$,

σ_r = stress of creep-rupture test,

t_r = time to creep rupture under stress σ_r.

A criterion is then given whether Eq. (9) or (10) is to be used in the form of a diagram of m vs. AF. The method represented by Eq. (10) is proposed on an interim basis.

About 75 different sets of data are examined and compared with the prediction. "The method provided lower-bound fatigue lives for about 85% of the data, upper-bound lives for approximately 95% of the data and nearly 80% of the data fell within a factor of three on either side of the estimated average lives."

The lives obtained from hold-time tests were mostly either below or at the lower-bound of the estimates. Krempl and Walker, [*30*] used the methods discussed above and found that the prediction method was not conservative for their hold-time tests.

A new prediction method was developed by the same authors, Manson et al., [*39*]. Basically, the new method, to be regarded as an interim method, proposes the substitution of a more relevant creep-rupture test than the ordinary creep-rupture test. The authors use a sort of cyclic creep-rupture test to determine creep-rupture life. In this test the stress is controlled between equal compressive and tensile values, and the stress is reversed whenever a predetermined strain value is reached. An example of this test is given in Fig. 27. (It should be noted that the changing material properties during cycling manifest themselves by a gradual reduction of the time spent at maximum stress.)

In the interpretation of this type of test, the question arises how to consider the effect of compressive stresses on creep damage. The authors assume that compressive damage is present in the strain cycling tests while it is not assumed to be present in the cyclic creep-rupture tests. Life fraction rules are used and creep and fatigue damage are weighed equally, added and equated to unity. With this method it was possible to account for the effect of frequency on fatigue life of Type 316 stainless steel at 1300 F and of the colbalt-base alloy L605 at temperatures from room temperature to 1360 F. An example of the severity of the frequency effect and the success of the prediction method for L605 alloy is given in Fig. 3. The authors conclude that they had reasonably good results with their method. At the same time they indicate that the linear damage rule may not hold for other types of stress patterns and indicate that more study is needed. It should be noted tha: the methods proposed are not specifically aimed at hold time.

Wood [*57*] developed a fractional damage concept to account for the hold-time effect. He calculates the fatigue damage by $\frac{N_c}{N_f}$ and the creep-rupture damage by $\frac{t_c}{t_f}$.

The symbols denote:

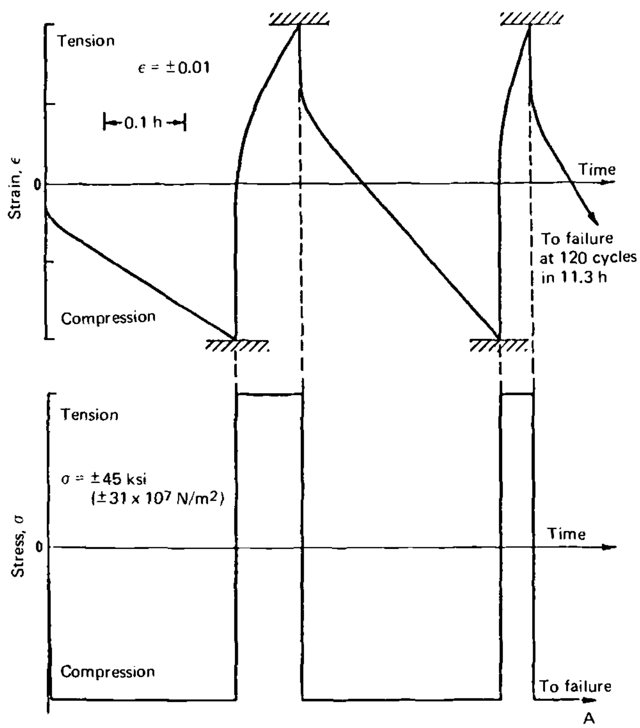
N_f = number of cycles-to-failure at a given strain range at *room* temperature

N_c = number of cycles-to-failure at the same strain range at 350 C

t_c = total time under creep conditions at a given stress level

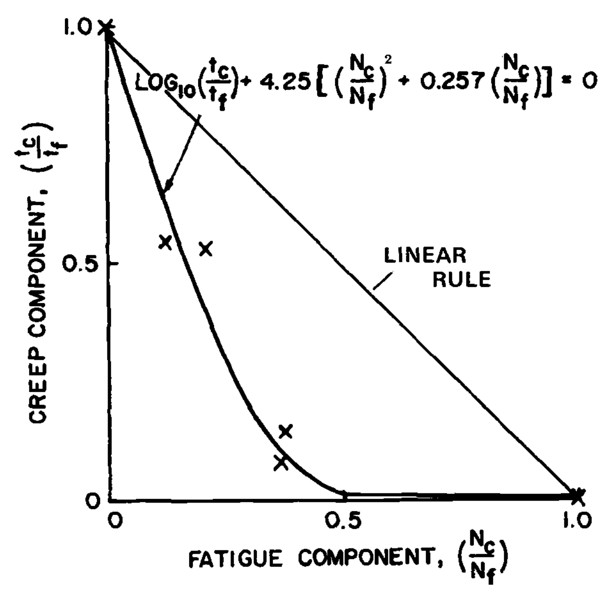
t_f = time-to-creep-rupture failure at a stress level relevant to the hold-time.

The computed values of $\frac{t_c}{t_f}$ and $\frac{N_c}{N_f}$ are plotted in Fig. 28.



Manson, et al., [39].

FIGURE 27–*Auxiliary Cyclic Creep-Rupture Test at 1300 F for Type 316 Stainless Steel. (Note higher creep resistance in compression, and cyclic increases in creep rates in both tension and compression. Results traced from strip or chart recordings.)*



After Wood, [57].

FIGURE 28–*Relationship between Creep Rupture and Fatigue Damage. (Note: A linear damage law would predict the straight line shown).*

The result is of interest due to the great deviation from the linear damage rule. This rule would predict the straight line connecting the points $\frac{N_c}{N_f} = 1$ and $\frac{t_c}{t_f} = 1$. It is therefore advisable to check the validity of the linear rule under combined creep and fatigue action before it can be applied with confidence.

Edmunds and White, [*18*] use three different methods in an attempt to predict the hold-time effect. The calculations were only made for one strain range, 0.3%. (The necessary relaxation data could apparently only be obtained at a strain amplitude of 0.15%).

Method A. The stress relaxation $\Delta\sigma_r$ during a cycle (see Fig. 4) is determined. This stress was converted to strain by division with Young's Modulus. The total relaxation strain was summed, and failure was said to occur when this strain was equal to the elongation in a creep-rupture test, which was taken to be 20%. Thus,

$$N_A = \frac{0.2}{\Delta\sigma_r/E} \; .$$

Method B. Exhaustion of time-to-rupture t_r is assumed to be the failure criterion. The relaxation curve was divided into a number of time increments Δt. The average stress was determined and the time-to-rupture t_r read from a creep-rupture curve. The cycles-to-failure were then determined by $N_B = \frac{1}{\Sigma \frac{\Delta t}{t_r}}$ where Σ indicates summation over the hold-time.

Method C. Secondary creep-rate fracture criterion. The relaxation curve was subdivided as before, for each stress the secondary creep-rate $\dot{e}_s$ during that interval Δt was determined from a separate diagram. Rupture was said to occur when

$$N_c = \frac{0.2}{\Sigma \dot{e}_s \Delta t} \; .$$

The elongation at creep rupture was again taken to be 20%.

The results of the three prediction techniques are reproduced in Table 2 for two hold-times, 30 min and 300 min. The column labeled relaxation cycle indicates the cycle at which the necessary information for methods A, B, C was taken from the respective relaxation curve. N_A, N_B, N_C indicate the number of cycles-to-failure calculated according to method A, B, and C, whereas N is the actually observed value. It can be seen that the result depends greatly on which relaxation cycle was used for prediction of the life. "The chief impediment in this interpretation is the *variation that occured from one relaxation curve to another.* No doubt some of this variation arose because neither load nor strain rate control was available on the creep relaxation machine, but even so it appears that some of the variation was a genuine reflection of material properties" (Edmunds, [*17*].) In evaluating the results reproduced in Table 2, Edmunds

TABLE 2—*Comparison between Predicted Lives (Methods A, B, C) and Observed Lives N.*

Hold time	Relaxation cycle	N_A	N_B	N_C	N
30 min	1	840	680	2000	4500
	10	810	1330	5390	
	20	750	1200	4670	
	30	630	1300	5100	
	40	590	1780	7790	
	50	580	1900	8790	
300 min	1	440	220	930	1500
	10	540	290	1650	
	20	490	290	1560	
	30	430	350	1950	
	40	420	470	2830	
	50	410	550	3630	

After Edmunds, [17].

concludes, "... it would be valuable if endurance tests with hold time were supplemented by a relatively small amount of creep data of the kind suggested". The auxiliary data are the creep-rupture curve and a plot of secondary creep rate versus stress obtained at the same temperature as the low-cycle fatigue test.

Esztergar and Ellis, [*20*] reviewed and evaluated the methods proposed in [*17*] and [*57*] using data reported in [*17, 30* and *57*]. Using the prediction methods A, B, and C proposed by Edmunds and White [*17*], poor correlation was found (their Fig. 17) which was attributed to the simplifying assumptions in the methods, such as neglect of cyclic softening and lack of accurate creep data. The authors note that the method proposed by Wood, [*57*] is directly applicable only for hold time with creep. Hold periods with relaxation have to be converted into equivalent hold periods with creep for which they evaluate four methods. They calculate damage fractions from the test data in [*17, 30* and *57*] for comparison with the linear creep-fatigue interaction rule

$$\frac{N_c}{N_f} + \frac{t_c}{t_r} = 1 \qquad (9)$$

The results are shown in Fig. 29. The improbably-high creep damage fractions are considered to be a result of unrealistic damage concepts in developing the equivalence methods. They conclude that the hold-time effect on cycles-to-failure cannot be predicted with certainty by any of the four methods considered and that the linear creep-fatigue interaction assumption is not reliable.

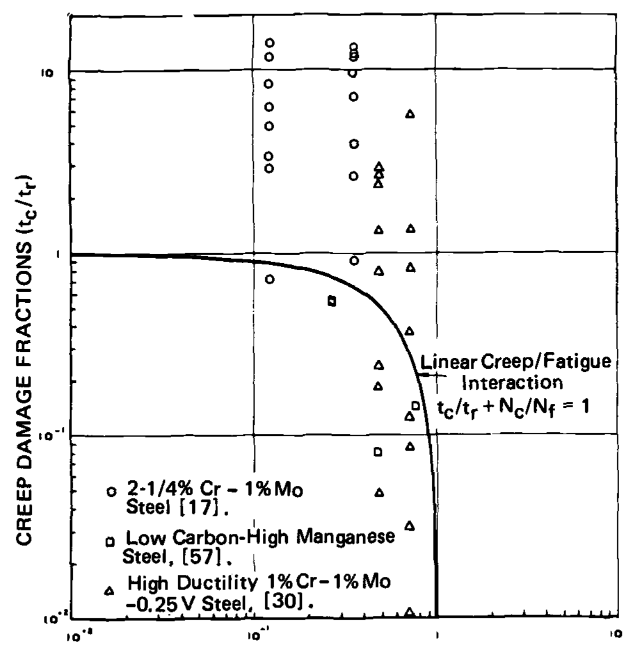
Marshall and Cook, [*40*], consider a slight modification of the linear interaction rule. They observe that the actual relaxation curve in hold-time tests with relaxation levels off after about 10 minutes, and that the stress level thereafter remains essentially constant ([*30*] and internal Central Electricity Generating Board Reports). The point in time after which the stress level remains essentially constant (to be observed from experimental data) is the onset of creep damage and from thereon the second term in equation (9) contributes to the overall damage. Good correlation is found for a limited set of data. The authors indicate that further evidence of good correlation for long hold-time data is necessary before the model can be considered fully proven.

CONSIDERATION OF HOLD-TIME EFFECT IN DESIGN

It is clear that only highly stressed components of a machine have to be designed against low-cycle fatigue with hold time. At the same time, these are the components which determine the overall reliability of the machine under consideration. It requires only this particular component to fail for an unscheduled outage to occur. The rest of the system may be completely in good operating condition. Therefore, a reliable design procedure for the design against low-cycle fatigue hold-time failure is necessary.

The ultimate objective of design is to assure reliable operation of the system and therefore a reliability analysis has to be performed. Ideally, this analysis consists of two parts:

1) Stress analysis. The magnitude of the stresses is calculated as a function of time and location under suitable boundary conditions which may in general vary in time.
2) A decision whether the stresses so calculated will ensure reliable operation. For this, a relevant fracture criterion is absolutely essential.



After Esztegar and Ellis, [20].

FIGURE 29—*Comparison of Calculated Damage Fractions with the Linear Creep/Fatigue Interaction Rule.*

Figure 30 shows a simplified schematic of the steps involved in reliability analysis for hold-time conditions. The stress analysis part is either performed by closed form solutions of simplified geometries or of approximate solutions for the actual geometries by finite element computer programs. These programs are extremely versatile in handling complex geometries and boundary conditions.

The relevancy for low-cycle fatigue with hold time of the stresses calculated by the classical method and by

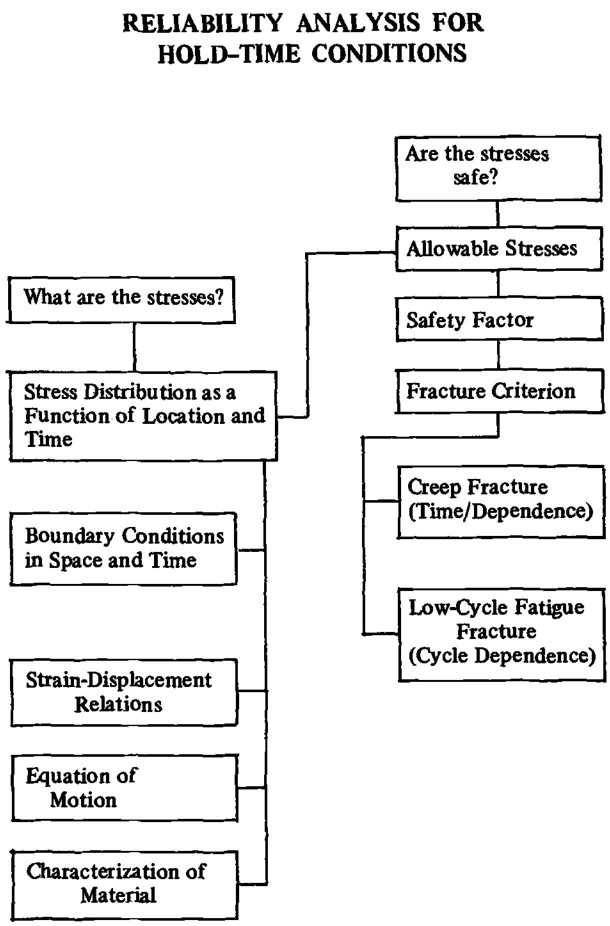


FIGURE 30–*Schematic Diagram Illustrating the Various Elements of Reliability Analysis for Hold-Time Conditions.*

the finite element computer method hinges on the characterization of the material used in these calculations. The previous survey has shown that for conditions of low-cycle fatigue with hold time structural materials show strain rate sensitivity, cyclic hardening or softening as well as creep and relaxation. If the stress analysis procedure used in design is tailored to the uniaxial case of the test specimen, it should be capable of reproducing the observed phenomena which are schematically represented in Fig. 31. It can be said that none of the material characterizations used in the papers to be discussed in this section can reproduce all of the observed behavior shown in 31. The approaches with respect to this aspect differ from author to author and will be discussed in the following.

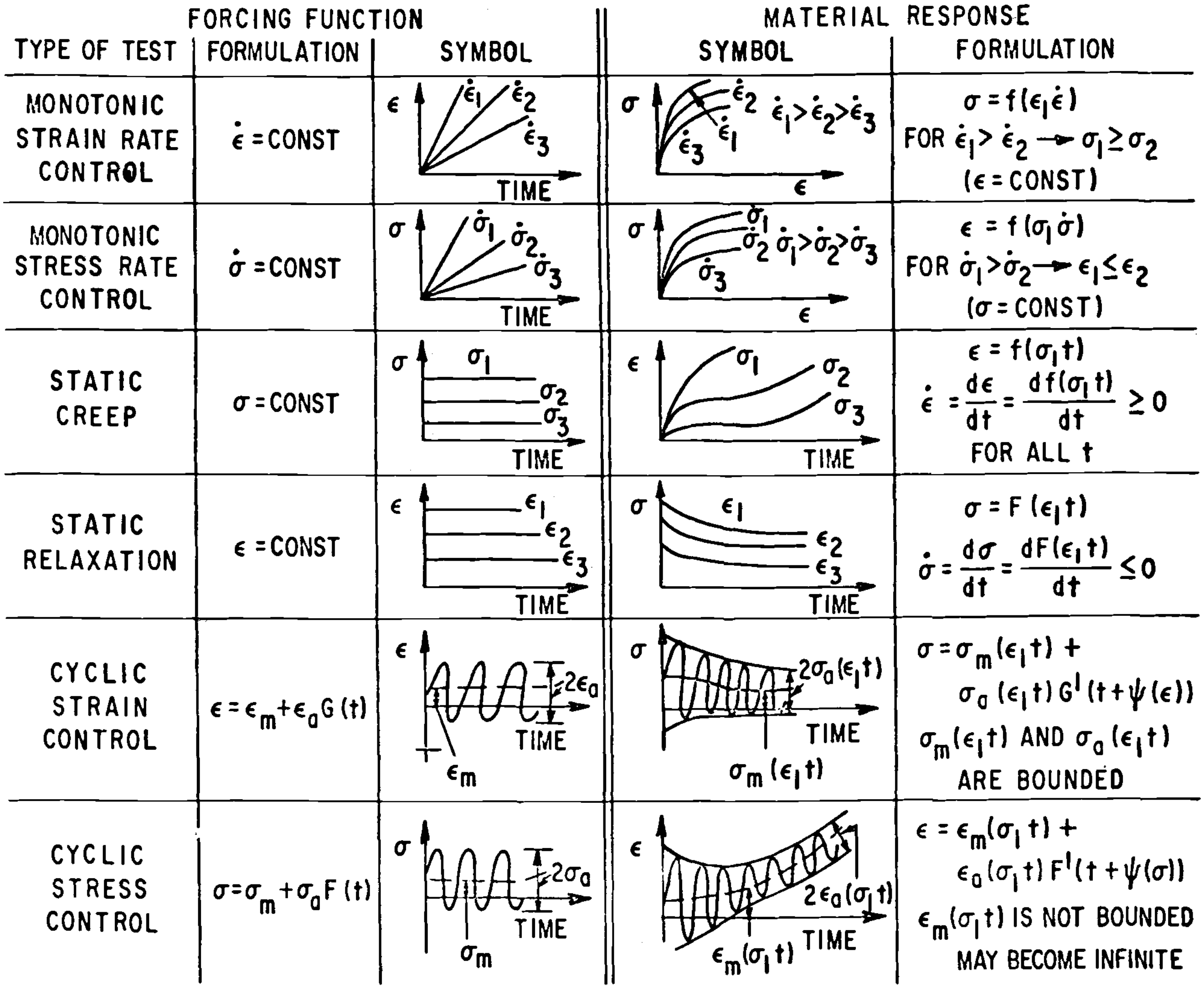
The design philosophies leading to the proper fracture criterion are also not uniformly established. One general difficulty is represented by the fact that elevated temperature low-cycle fatigue testing has been done under uniaxial state of stress whereas design problems are usually for multiaxial states of stress. To extract information from uniaxial tests, an effective stress has to be defined. No experimental support for the preference of any one of the effective stresses or strains was found for hold-time conditions. White, [*56*], quotes work by Pascoe and DeVilliers, [*41*], and Mackenzie et al., [*37*], which shows that the equivalent octahedral shear strain failed to correlate the results of room temperature low-cycle fatigue tests.

Since thermal fatigue cracking is mostly experienced in stress raisers, the treatment of discontinuities deserves special attention. This question will, however, be deemphasized since a separate review will be devoted to this subject.

The aim of a reliability analysis is to prevent cracking. However, circumstances arise where a crack is found in machinery and then decisions have to be made on the disposition of the problem. Therefore crack-propagation information is being generated on a limited scale, [*49, 50*].

Timo, [*49*], performs an elastic thermal stress analysis for idealized turbine components such as beams, slabs and cylinders and obtains a nominal strain range for a trapezoidal temperature cycle called a general cycle. An elastic stress concentration factor K_t is used to characterize the stress raisers present in the actual structure. An elastoplastic analysis yields the strain concentration factor for a given material, a given K_t and a given nominal strain range. The concentrated strain range is obtained by multiplying the nominal strain range by the strain concentration factor. The analysis therefore considers elastic and elastoplastic material behavior to estimate the maximum concentrated strain range. Creep and relaxation and strain hardening (softening) are not considered.

To obtain a fracture criterion for conditions relevant to power plant, it is necessary to consider the relation between the laboratory and the actual service cycle as explained in the Introduction, and to extend the hold-time data beyond $N_f > 10^4$. Available creep-rupture information is used for the latter purpose. The number of cycles-to-failure multiplied by an assumed hold time defines time failure which is interpreted as time-to-rupture for a creep test. Associated with this time-to-rupture is a creep-rupture strength. For zero hold time, the estimated fatigue strength is used. The corresponding total strain range is obtained by dividing the creep-rupture strength by the proper modulus of elasticity and multiplying by two. In this manner, several points are obtained through which the corresponding hold-time curves are extrapolated, see Fig. 32. For design purposes, Timo recommends simplified curves (not reproduced)



Krempl, [31].

FIGURE 31–*Schematic Diagram Showing the Behavior of Structural Materials under Monotonic, Static and Cyclic Loading. (A low-cycle fatigue test with hold time is a combination of the tests listed.)*

shown in Fig. 14 of [*49*] and Fig. 8 in [*50*]. Therefore, creep, relaxation and cyclic strain hardening are implicitly considered in the failure criterion.

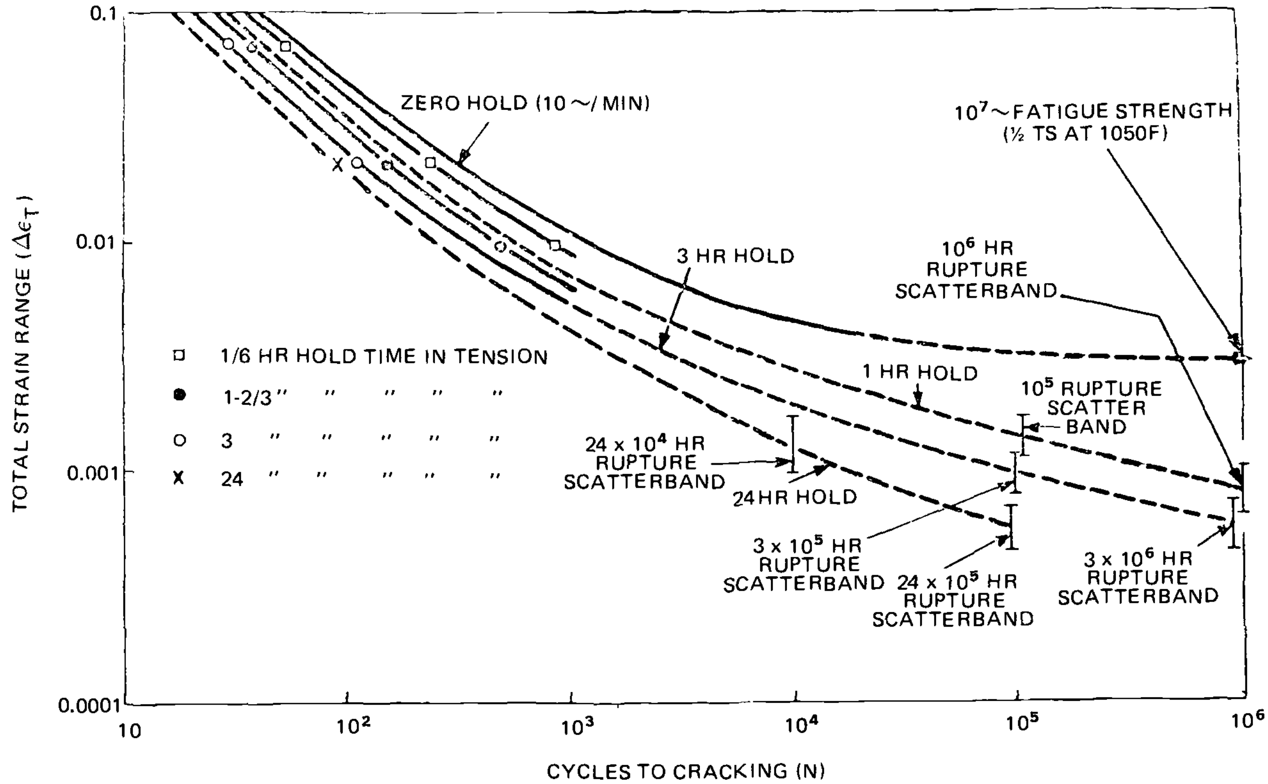
The number of cycles to cracking is then obtained by entering the concentrated strain range into the low-cycle fatigue curve. The method of life calculation is therefore based on the maximum strain range.

A statement is made about the approximations inherent in the analysis. Timo says: "However, because of the inherent variability in material properties, the uncertainty in determining thermal stresses accurately, the inumerable variations in actual service cycles, the effects of strain concentrations, etc., it is believed to be neither feasible nor necessary to attempt a more rigorous approach at the present time".

Dawson and Neill, [*15*] in their paper emphasize that thermal stress and thermal fatigue analysis are undergoing continuous development and that their paper represents the current state of development of one particular approach.

Dawson and Neill approach the problem by considering a two-dimensional axisymmetric problem for temperature and thermal strain distributions. The nominal strains are calculated on an elastic basis, using a computer program. Concentrated strain ranges are obtained by an elastoplastic analysis based on the cyclic stress-strain curve which gives the strain concentration factor. The biaxial state of stress in the actual component is recognized and the von Mises equivalent strain is used for comparison with the uniaxial failure data. These failure data are obtained by extrapolation of hold-time data to hold times relevant for design. A safety factor of two is built into the calculation method.

In this analysis, creep and relaxation effects are not considered for stress analysis but are contained in the failure criterion. Cyclic hardening is thought to be im-



After Timo, [49].

FIGURE 32–*Extrapolation of Low-Cycle Fatigue Hold-Time Data for Design Purposes using Creep-Rupture Data.*

portant since the cyclic stress-strain diagram is used. Also von Mises equivalent strain is adopted for the comparison of calculated strains with uniaxial failure criterion.

Wellinger et al., [*53*], consider thermal stress in the design of boiler drums. The maximum thermal stresses are calculated for the steady-state temperature distribution in the vicinity of holes (stress concentration approximated by $K_t = 2$) using elastic analysis. These thermal stresses are combined with the stresses derived from mechanical loading. Special consideration is given to the addition of mechanical and thermal stresses in the elastic-plastic state. A total strain range is calculated using experimentally determined correction factors. The life-to-cracking is obtained by entering this calculated strain range into a low-cycle fatigue curve which is obtained for uninterrupted cycling. The influence of mean strain is, however, considered.

In this analysis, creep and relaxation as well as cyclic strain hardening (softening) are not considered in the stress analysis and in the failure criterion. This appears to be feasible since the maximum temperature for which the analysis is intended is below 350 C. Below this temperature, time effects are generally considered to be unimportant, Lawton, [*34*]. A careful analysis of the hold-time data on C - ½Mo steel by Coles and Chitty, [*10*], however, indicated that a reduction in cycles is observed when a 30 min hold-time is introduced at 350 C.

Zlepko, [*59*], considers the operational reliability of boiler drums in large steam generators. He states that "a full understanding of low-cycle thermal fatigue is not feasible at present because of the difficulty of the analysis". Therefore, no stress analysis is pursued by the author and evaluation is based on the relative ranking of various Russian ferritic and austenitic materials in simulated service testing.

The first kind of test is a creep-rupture test with cyclic temperature excursions of varying magnitude. The results are given in Table 3 for the Russian Steel 12XIMΦ (equivalent to a 1 Cr ¼Mo V alloy steel). Even a small temperature excursion causes a considerable reduction in the time-to-fracture. (The percentage value following 565 C is not explained in the text.) The author states that the principal factor determining the percentage reduction in time-to-fracture is the total time at excess temperature, not the number of cycles of temperature variation. (The author does not give sufficient experimental data so that an independent check could have been made.)

However, this evidence is contradicted by service experience and therefore simulated service tests on tube bends were performed. The result was that both total time and cycles had an effect on the life-to-cracking.

The final results of the investigation were recommended safe maximum operating temperatures, e.g., 585 C for the 1 Cr - ¼Mo V steel.

It is clear that such an approach is only feasible for standard operating pressures (or for a given stress) and

TABLE 3–*Life Reduction due to Temperature Excursions in Creep Tests of a 1Cr 1/4 Mo V Steel*

Nos.	Duties	σ = 16 kg/mm² (157 MN/m²)	σ = 18 kg/mm² (176 MN/m²)	σ = 20 kg/mm² (196MN/m²)
		Percent reduction in time to rupture compared with t = 565 C.		
		Δt = 10°C		
1.	t = 565°(75%) + 575°C	17	22.2	15.5
2.	t = 565°(50%) + 575°C	22.7	42.2	16.4
3.	t = 565°(25%) + 575°C	39.2	—	47.7
	t = 575°C	—	53	65.8
		Δt = 25°C		
4.	t = 565°(75%) + 590°C	17.5	20.8	—
5.	t = 565°(50%) + 590°C	34.4	39.5	15.4
6.	t = 565°(25%) + 590°C	58.3	64.7	54.0
	t = 590	78	80	90.2
		Δt = 50°C		
8.	t = 565°(75%) + 615°C	—	20.6	23.8
9.	t = 565°(50%) + 615°C	44.5	45.3	—
10.	t = 565°(25%) + 615°C	71.5	72.5	71.4
	t = 615	94.3	96	97.6

From Zlepko, [59].

therefore is limited to relatively constant conditions, excluding transient thermal stresses.

Unksov et al. [*51*] investigate thermal stresses in turbine discs and boiler drums. For the turbine disc, elastic-thermoplastic analysis was performed with a digital computer. Their material was idealized as follows:

For a single load application isotropic hardening is assumed with the yield surface dependent on the instantaneous temperature and the strain history. Flow rules are also given. To make this type of plasticity theory amenable to cyclic application, two further assumptions about unloading, reloading and the shape of subsequent yield surfaces at each half cycle are introduced. For the actual calculation the material was assumed to be cyclically stable (no strain hardening in the writers' opinion) and the strains at the rim and the bore are calculated for the first five half cycles. Due to the assumption of cyclic stability, stable conditions were obtained after the second loading.

The strain range so calculated was used to determine cycles-to-failure from a failure criterion determined from Coffin's original thermal fatigue investigation, [*8*].

This investigation is unique in that it considers, at least in principle, cyclic strain hardening or softening which can be considerable, as illustrated in Fig. 13.

However, it does not include time-dependent deformation such as creep, or relaxation in the stress analysis or in the failure criteria.

The boiler drum is analyzed by a purely elastic thermal stress analysis based on experimentally determined temperature distributions. The creep and fatigue characteristics of the respective materials were determined in air and partly in high-temperature water. The effect of acid cleaning, oxygen content of the boiler water is also included. Direct life calculations of the components are not included.

Recently, Spera, [*43, 44*] considered the interaction of low-cycle fatigue and creep damage on the basis of a linear damage rule to calculate elevated temperature low-cycle fatigue life of components. His analysis, which is complete in the sense that both stress analysis and life calculation are done for certain representative geometries under expedient simplifying assumptions, does not consider hold time proper. It will therefore not be discussed here.

After reviewing the various design approaches to low-cycle fatigue with hold time, it is clear that a complete analysis has not yet been performed. Most authors consider elastic material behavior only, modified by elastic-plastic strain concentration factors. Strain hardening is infrequently factored into the analysis and creep and relaxation are altogether ignored. It is only in the failure criteria that these effects appear to be considered relevant. The area of reliability analysis for hold-time conditions offers therefore considerable room for improvement.

SUMMARY

A survey was made of the influence of hold time on the deformation and fracture behavior of structural materials at elevated temperature. The following conclusions can be supported by the results of research papers consulted in this survey.

An introduction of hold time will reduce the number of cycles-to-failure compared to uninterrupted cycling; the total time-to-failure, however, is increased.

For the stress-controlled mode, available data indicate that the conventional creep-rupture test exhibits a shorter life-time than repeated zero-to-tension load application in either triangular or rectangular waveform. The basis for this conclusion are plots of maximum stress versus time-to-rupture [Tilly, *46*], Fig. 23.

For hold time with relaxation (strain-controlled mode) the papers surveyed showed the following common trend if the hold time is introduced at the maximum tensile strain of the cycle. It is clear that the hold-time effect is dependent on temperature. All the values quoted were obtained near the maximum operating temperature of the respective materials.

1) The cycle-reducing hold-time effect is more pronounced at low-strain ranges than at high-strain ranges; i.e., the cycle reduction is higher at low-strain ranges than at high-strain ranges.
2) At a given strain range, cycle reduction increases with increasing hold time (Figs. 6, 8, 9, 11, 12). On a plot of log cycles-to-failure versus log hold time, straight lines are obtained. Sometimes a slight downward trend is observed (Fig. 17). Only one investigation reports a saturation effect; i.e., no further reduction of cycles-to-failure with increase of hold-time, [Berling and Conway, *3*.].
3) The hold-time effect is more pronounced in push-pull than in bending (Fig. 12). Different amounts of elastic follow-up of the testing machines used were considered to be responsible for the observed difference in the severity of the hold-time effect. It appears then that push-pull tests with accurate strain control will furnish the most reliable information.
4) The following should be considered a rough indicator of the cycle reducing hold-time effect for ferritic and austenitic power plant materials. For a given cycles-to-failure the introduction of a 3-h hold time amounts to a 50% reduction in the allowable strain amplitude (Timo, [*49*]).

   At about one percent total strain range, an increase of the hold time by a factor of 10 reduces the cycles-to-failure by 40% of the initial value. At higher strain ranges the reduction is less, at lower strain ranges the reduction is more than at one percent strain range. Presently, the magnitude of the cycle reducing hold-time effect at long hold-times ($> 10^4$min) is uncertain. A comparison of the hold-time effect on various ferritic materials is given in Fig. 33, [*35*].
5) The nature of the cracks tends to shift from transcrystalline to intercrystalline as the hold time increases. However, it does not appear to be possible to attribute intercrystalline cracking exclusively to creep effects and transcrystalline cracking to fatigue effects. Trans- and intercrystalline cracking can be found in pure fatigue as well as in pure creep tests [*2, 24*].
6) The effect of introducing hold time at other than the maximum tensile strain point of the cycle is relatively unexplored. Hold times at the maximum compressive position are reported to be either less severe [*3*] or more severe [*54*] than the ones introduced at the maximum tensile position of the cycle. Hold time introduced at zero surface stress showed no appreciable life-reducing effect [*18*].
7) If the tests are conducted in vacuum and in air, the cycles-to-failure are considerably higher in vacuum than in air. The atmosphere has therefore a deleterious effect on cycles-to-failure. The introduction of hold time led to about the same percentage reduction of the no-hold-time cycles-to-failure in air and in vacuum, [*55*].

Attempts are made to predict the cycle-reducing hold-time effect. The methods specifically aimed at the hold-time problem appear to be more successful than creep fatigue interaction methods. The modified linear damage rule yielded extremely poor correlations.

In design, not all the phenomena observed in hold-time tests are considered in the stress analysis part of the reliability analysis. Strain-rate effects, creep and relaxation were ignored in all the reviewed papers. Some considered cyclic strain hardening (softening) to a limited extent. Most stress analysis is done on an elastic basis modified by elastoplastic considerations.

No consensus was found what effective stress (strain) should be used in comparing the effect of multiaxial states of stress with the failure criteria established from uniaxial data.

The failure criteria are only established for uniaxial conditions and contain the effects of hold time and frequency as far as experimentally feasible. Extrapolation techniques are used for conditions not covered by the experiments, [*49, 15*].

Future Work

The following points should receive attention in future investigations:

1) Separation of the crack initiation from the crack propagation phase in conducting the experiments.
2) An accurate recording of all the dependent variables during the test duration. Dependent variables are those which are not forced on the specimen. These variables yield important information on the changes which occur in the materials due to the cyclic plastic straining. For a strain controlled test such variables are the stress range, the relaxation curve, the hysteresis loops. Examples of the desired information are given in Figs. 13 and 14.

3) Auxiliary information such as tensile stress-strain diagram and associated properties, creep strain curves and creep rupture curves is extremely desirable.
4) To perform stress analysis relevant for low-cycle fatigue with hold time, a material characterization has to be developed which can reproduce the behavior shown in Fig. 31. It can be shown that neither elasticity, plasticity nor viscoelasticity can reproduce all these properties. A new characterization of the behavior of structural materials at elevated temperature is needed and could be used in conjunction with the other inputs shown in Fig. 30 to obtain realistic stresses and strains in components as a function of time. Such a method would be able to account for strain rate sensitivity, creep, relaxation, cyclic hardening (softening) and would be most versatile in conjunction with a finite element computer program.
5) Low-cycle fatigue investigations involving multiaxial states of stress at elevated temperature are urgently needed. It is necessary to establish failure criteria for multiaxial states of stress for the condition of hold time. The customary approach of using effective stress or strain based on the maximum stress (strain) criterion, the von Mises criterion, and the maximum shear stress criterion needs confirmation.
6) Failure criteria for multiaxial states of stress are needed. Creep fatigue interaction has to be considered. A possible modification for the modified linear damage rule has to be developed, since it was shown to yield unsatisfactory correlation, [*20, 57*].
7) A rational reliability analysis has to be developed on the basis of a realistic stress analysis which considers time and cyclic effects. These realistic stresses should then be compared with a multiaxial relevant failure criterion. With such a method, maximum reliability of the highly stressed components could be achieved.
8) The influence of the surrounding atmosphere on crack initiation and cycles-to-failure needs careful investigation.

Point or Curve	Hold Time	Time for 1 Cycle	Temperature		Material	Type of Test	Investigators	Ref No.
	Minutes	Minutes	°F	°C				
——	0 & 60	1 & 61	1000		A2	Axial	Timo & Sarney	**48**
——	180 & 1440	181 & 1441						
○--○	0	1	1112	600	A3	Bend	Edmunds and White	**18**
●--●	30	31						
✦--✦	300	301						
○	0	0.11	1022	550	A4	Bend	Hill	**27**
●	30	32						
□	0	0.11	1022	550	A5			
■	30	32						
△	0	0.1	1022	550	A6	Bend	Coles, Hill Dawson, Watson	**10**
▲	30	32						
◇	0	0.5	950	510	A1	Axial*	Hengstenberg	
◆	30	78	650–950	343–510	A1	Axial	Bennett	
✦	360	360.5	950	510	A1	Axial	Hengstenberg	
✦	720	721	950	510	A7	Axial	Walker	**52**
◇	0	0.5	950	510	A8	Axial*	Hengstenberg Ceschini	
✦	360	360.5						

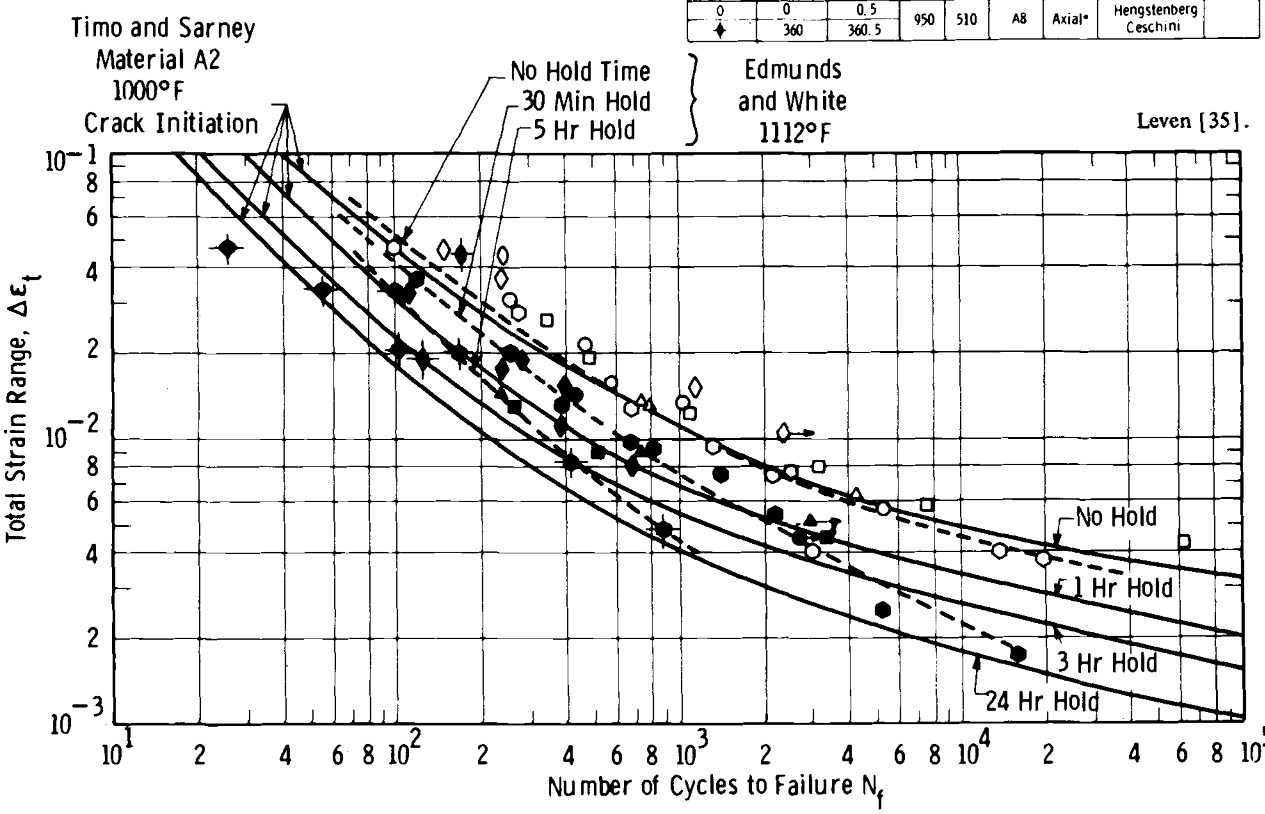


FIGURE 33–*Effect of Told Time at Maximum Tensile Strain on the Cycles-to-Failure of Cr-Mo-V Steels in the Temperature Range 950 - 1112 F.*

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