176
11/14/79

DR. 299

GA-A15320
UC-77

REVIEW OF FATIGUE CRITERIA DEVELOPMENT FOR HTGR CORE SUPPORTS

by
F. H. HO and R. E. VOLLMAN

MASTER

Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy

DATE PUBLISHED: OCTOBER 1979

GENERAL ATOMIC COMPANY

DISCLAIMER

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $5.25; Microfiche $3.00

GA-A15320
UC-77

REVIEW OF FATIGUE CRITERIA DEVELOPMENT FOR HTGR CORE SUPPORTS

by

F. H. HO and R. E. VOLLMAN

Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy

GENERAL ATOMIC PROJECT 6400
DATE PUBLISHED: OCTOBER 1979

GENERAL ATOMIC COMPANY

ABSTRACT

Fatigue criteria for HTGR core support graphite structure are presented. The criteria takes into consideration the brittle nature of the material, and emphasizes the probabilistic approach in the treatment of strength data. The stress analysis is still deterministic. The conventional cumulative damage approach is adopted here. A specified minimum S-N curve is defined as the curve with 99% probability of survival at a 95% confidence level to accommodate random variability of the material strength. A constant life diagram is constructed to reconcile the effect of mean stress. The linear damage rule is assumed to account for the effect of random cycles. An additional factor of safety of three on cycles is recommended. The uniaxial S-N curve is modified in the medium-to-high cycle range ($>2 \times 10^3$ cycles) for multiaxial fatigue effects. The strength of the weak axis is recommended for use in all the orientations to conservatively avoid the uncertainties of the orientations of cyclic stresses with respect to the material axes. The effects are also discussed of other factors which influence fatigue, such as temperature, irradiation, oxidation, stress concentration, etc. Finally, recommendations for future work in this field are listed.

CONTENTS

FIGURES

TABLE

1. INTRODUCTION

Graphite core support components in a high temperature gas-cooled reactor (HTGR) are often subjected to cyclic stresses caused by seismic events, flow induced vibrations, transient thermal responses, and other operational cycles. The potential for cyclic fatigue failure has long been identified for these components. Therefore, fatigue design criteria are necessary for operational life verification for these components.

The conventional ASME Boiler and Pressure Vessel Code approach for metallic fatigue design criteria is to obtain the design stress amplitude values from the best fit S-N (stress amplitude vs number of cycles) curves by applying a factor of two on stress or a factor of twenty on cycles, whichever is more conservative at each point (Ref. 1). These factors were intended to cover such effects as surface finish, environment, size effect and scatter of data, and thus it is not to be expected that a vessel will actually operate safely for twenty times its specified life. The appropriateness of the chosen safety factors for metallic fatigue has been demonstrated by tests. No crack initiation was detected at any stress level below the allowable stress, and no crack progressed through a vessel wall in less than three times the allowable number of cycles.

Graphite is, in general, brittle and flaw sensitive. It is therefore necessary to consider the subject of design criteria in conjunction with brittle material design practice since there are significant changes necessary from ASME fatigue criteria as typically developed for ductile materials. The principal reason for these changes is the need to recognize the probabilistic nature of material strength properties. This makes it necessary to at least consider whether all of the criteria should be treated on a probabilistic basis or combination of probabilistic and deterministic principles.

This report recommends a phenomenological fatigue criteria as evolved at General Atomic Company through many years experience in stress analysis and material property testing. It is intended to be used in Division 2, Section III of the ASME B. & P.V. Code, Subsection CE, Graphite Core Support Structure, Paragraph 3580, Fatigue Criteria. In the following the inherent assumptions and bases are discussed before the criteria are presented. Factors affecting the fatigue strength are discussed in detail. Future work in the field needed to improve the criteria are also recommended. As more test data are acquired, new material models are conceived, better quality assurance techniques are developed, and sophisticated computer codes are available, etc., it is expected that this approach will be changed and evolve into an even more rigorous criteria. Finally, PGX graphite fatigue data are presented in the Appendix to demonstrate the application of the criteria.

It is the responsibility of the individual engineer to analyze the structure and use the fatigue criteria correctly and assume responsibility for the results.

2. APPROACH

An accurate calculation of the number of stress-strain cycles needed to produce fatigue failure under given service conditions requires a knowledge of the laws governing crack initiation, subcritical crack growth rate and the size, location, orientation, sharpness and distribution of the initial flaws. Fracture mechanics would appear to be the most suitable for this application. However the present state-of-the-art for graphite materials is not sufficiently advanced to make this type of evaluation feasible for use in design stress analysis. However, research is in progress in this field, a practical procedure that has been used for many years is the cumulative damage approach, which utilizes the concept of design fatigue curves derived from fatigue test data produced with uniaxially loaded specimens. This approach, often referred to as the phenomenological approach, is the basis of the fatigue criteria in this report.

The probabilistic approach is potentially a more logical procedure than the deterministic approach, since it takes into consideration the probability distribution of the applied stress and the material strength variations. Both are statistical in nature. If the criteria are to be approached probabilistically, it is desirable to be able to specify the allowable failure probability of the structure, considering all of the various loads and load repetitions, and their probability of occurrence, the thermal effects, and the variable material and structural response characteristics under the spatial and time varying stresses from these conditions. In addition, the reliability of analytical technique to predict accurate results and test methods and of experimentally determined data should be included. All of these considerations are then combined into an overall probability of failure value.

Obviously, this is a very involved process and most probably it will never be completely attained in practice. The main reason is the huge amount of statistical data and computational effort that would be required. This becomes impractical, expecially since much of the data requires extensive material characterization as well as testing of full scale components. Probabilistic methods of defining loads cannot be determined until a large amount of information is available on the structure. For these reasons it is felt that a primarily deterministic approach to fatigue life evaluation is the most practical way to proceed.

In this report we continue with the practice of separating the stress prediction and strength considerations. The approach to be taken for graphite core support fatigue criteria is to emphasize probabilistic treatment of material test data for the specification of allowable stress-strain ranges, while the main part of stress analysis is deterministic. A factor of safety is applied to the number of fatigue cycles to ensure the necessary margin of safety on operational life of the components.

Cyclic fatigue tests performed are almost all uniaxial push-pull or rotating beam bending tests, while in practice, stress state are mostly multiaxial. Biaxial or triaxial cyclic tests are impractical and seldom performed. Multiaxial effects on fatigue properties should be considered in order to develop a rigorous criterion for graphite.

A strength theory has to be adopted to relate the various cases. The current general practice at GA employs the maximum stress theory. This theory is simple to use and has been found satisfactory when appropriately conservative factors of safety are applied. One reason for adopting this simplified approach is that there is no one strength theory currently accepted for graphite by the carbon industry as proven satisfactory for all conditions. One of the inconsistencies in the maximum stress theory is the factor of safety. The ideal situation is to apply a unique factor of safety for all stress states. This represents a uniform shrinking of the failure surface. The true minimum factor of safety in the maximum stress theory is often attained in the triaxial or biaxial tension case. If one uses this approach, the allowable stresses in all other stress states are penalized. Another difficulty with the theory arises when the principal axes of stress do not coincide with the material axes. The strength of the weak axis may be used for all orientations, provided the penalty can be tolerated in stronger directions. The penalty will be small for near isotropic graphites such as those used in core supports.

An alternative approach is to employ the effective stress concept. The effective stress may be defined utilizing the quadratic tensor strength theory proposed by Tsai and Wu (Ref. 2). This definition is not necessarily unique, but it is promising. It is premature to fully incorporate this approach into the fatigue criterion until some of its shortcomings can be resolved. We will discuss this subject and the maximum stress theory later in greater detail. The present fatigue criteria are to be based on the maximum stress theory until a better failure theory can be established.

3. FATIGUE CRITERIA - UNIAXIAL

Most of the fatigue criteria developed along the phenomenological approach have been derived from uniaxially stressed specimens either in uniform tension-compression or bending. Uniaxial testing has worked well for metals but has some limitations when applied to graphite. Possible effects such as biaxial softening of the stress-strain response and strain gradient effects need to be accounted for because they appear to be more pronounced in graphite than in metals. Specimen size effects are more pronounced in graphite because graphite contains many flaws. These and other effects will be discussed in more detail in what follows.

3.1. UNIAXIAL FATIGUE TEST DATA

Before presenting the fatigue criteria, we shall discuss briefly the results of the uniaxial fatigue tests reported in the literature. This is important in formulating the design criteria. A review of the literature on this subject has been carried out by Brocklehurst and can be found in Ref. 3. Most of the data acquired in the last decade were analyzed in terms of "homologous stress" σ_H and plotted as σ_H vs N curves, where N is the number of stress cycles. The homologous stress σ_H is defined as the ratio of applied stress in fatigue to the expected one-half cycle strength measured on nominally identical control specimens and determined in the same mode of testing. A different definition, used by Wilkins (Ref. 6) and designated as σ_h, employs the instantaneous fracture stress, σ_i, expected for each individual specimen in the population for normalization use. This definition is superior to the previous one, since it includes both the mean value and the dispersion (as manifested by the standard deviation) in the normalization process. By adopting this definition, the scatter of the fatigue data is reduced considerably. However, it is quite difficult to use in practical design application.

Leichter and Robinson (Ref. 4) analyzed their own data on graphite EP-1924 and combined it with other data from the literature. They found congruent similarity in the shape of σ_H-N curves for a range of different graphite grades. It was concluded that the use of σ_H gives a good correlation of fatigue strength for various types of graphite. We will show later that this conclusion is approximate to the first order, since the data have to be categorized according to the stress ratio R (= $\sigma_{min}/\sigma_{max}$). They also found little difference in the resulting curves whether the homologous stress was based on the strength of a mate specimen cut adjacent to the fatigue specimen or on the average strength of the sample population.

Table 1 summarizes fatigue strength data from a variety of published sources. The variation of σ_H is quite significant for a given N. The variation is reduced if the data are grouped according to R values. It can be seen that σ_H at R=-1 is approximately equal to 90% of σ_H at R=0. No systematic differences are found between the with grain (//) and the across grain ($\perp$) directions in the uniaxial data.

The biaxial data on the French graphite FHAN shows that the homologous stress ratios are consistently lower than uniaxial data. Unfortunately, no comparison of uniaxial and biaxial data was made in Ref. 12. Thus it cannot be determined whether graphite FHAN has lower fatigue strength than other graphites or if the reduction is solely attributed to biaxial effects. More biaxial data are needed to fully understand this essential ingredient of fatigue behavior in order to develop a sound fatigue criteria.

Fatigue strengths of POCO and RC4 graphite reported in Refs. 5 and 6 are not included in Table 1 because the authors used a different and modified definition of homologous stress. Fatigue data in or prior to the sixties were not analyzed in terms of σ_H, and they also are not incorporated in the table. These early publications are referred to in Refs. 3 and 4.

TABLE 1

FATIGUE STRENGTH σ_H WITH 50% SURVIVAL PROBABILITY

Graphite	R	Orientation	Life Cycles N 10^2	10^3	10^4	10^5	10^6	10^7	Type of Tests	Frequency (Hz)	No. of Specimens	Ref.
PGX	0	⊥	0.85	0.81	0.78	0.74			Push-Pull	7	38	7
	0	//	0.92	0.90	0.87	0.85				7	38	
	-1	⊥	0.83	0.77	0.71	0.66				7	49	
	-1	//	0.86	0.82	0.78	0.74				7	38	
ATJ	0	//	0.86	0.81	0.77	0.73			Push-Pull	3	38	8
	-1	//	0.78	0.70	0.63	0.57				3	71	
H451	0	//	0.85	0.80	0.75	0.70			Push-Pull	7	30	7
	0	⊥	0.90	0.86	0.83	0.80				7	35	
	-1	//	0.80	0.73	0.66	0.60				7	44	
	-1	⊥	0.86	0.82	0.78	0.75				7	35	
NA, NP	0		0.88	0.81					Push-Pull	0.0028 to	55	9
(IM1-24)	-1		0.84	0.75	0.64	0.55	0.50	0.49	and Bending	50	25	
EP-1924	-1		0.81	0.72	0.68	0.66	0.65		Rotating Beam	8 and 167	43	4
Pechiney	0				0.73	0.67	0.63	0.58	Bend and	Unknown	30*	10
	-1				0.75	0.70	0.65	0.59	Push Pull			
FHAN	0		0.78	0.69	0.64	0.62	0.60		Biaxial Tube	Unknown	17	11
Gilsocarbon	+0.5				0.82	0.75	0.70		Push-Pull	30	<15*	12
H-205-85	0.02 ∿ 0.344	//	0.88	0.83	0.78				Diametral Compression	0.583	15	26
HLM-85	0.04 ∿ 0.33	⊥	0.85	0.78	0.72				Diametral Compression	0.583	13	26

*Tests performed at σ_{mean} = constant.

The data presented by Oku, et al., (Ref. 27) are not included in Table 1 either, because it is not clear what R ratios were used in the tests and how the fatigue strength was normalized. Their data on compression-compression fatigue are the only tests performed so far in this range. Although it may not be usable directly in HTGR graphite component design, they definitely aid the understanding of the material behavior. The results of the tests generally fall into the same range of that in Table 1.

Examination of some typical S-N curves (plotted as S vs log N) for several graphite grades (Refs. 4, 7, 8, etc.) shows a generally flat shape to the curves. In the high cycle region ($>10^4$ cycles) the curve is nearly a straight line. When they are compared with a typical S-N curve for metals, it is found that the graphite curves have a similar shape to metal curves in the low-to-high cycle transition region and in the high cycle region. If the metal curve were shifted to the left by 10^3 to 10^4 cycles, both metal and graphite curves would look alike. This finding is quite significant. It enables us to apply knowledge obtained in metal fatigue to graphite. For example, the well-known equation for high cycle fatigue (Ref. 13)

$$\sigma_a = \lambda N^b$$

should be able to represent successfully the fatigue life of graphite material, where σ_a is stress amplitude, N is life cycle, and λ and b are constants. When this equation is applied to the fatigue curve of EP-1924 graphite (Ref. 4), we obtain

$$(\sigma_a)_H = 0.77\ N^{-0.013}$$

where the stress amplitude is in terms of the homologous stress σ_H. Good agreement between the data and the equation is achieved. Improvement in the knee region of low cycle fatigue ($<10^3$ cycles) can be made if the total strain range equation (Ref. 13) is used. It is also known in metal fatigue that a Goodman diagram provides a good description of the mean stress effect in the high cycle range. We expect this in graphite also.

3.2. SPECIFIED MINIMUM FATIGUE DESIGN CURVES (S-N CURVES)

Mechanical test data of graphite generally show a great variability. Statistical analysis of the fatigue test data is needed to generate S-N curves associated with a given probability of survival, M, and confidence level, L (abbreviated as M/L curve). The 99/95 curves are defined as the specified minimum fatigue design curves. This is consistent with the definition of specified minimum strength defined by the Core Support Working Group of the Joint ACI/ASME Code Committee to develop graphite design criteria. Although we have no preference for any particular statistical model, a normal distribution will be used if possible because it simplifies data manipulation. A different model, for example, Weibull distribution, may be used if it can be shown that it is significantly better in describing the fatigue life data.

Similar to the case of defining the static allowable stresses, we shall also base the fatigue design on the 99/95 minimum curves. This presents some problems in the applications. Two sample populations are said to have the same stress allowables, if they have the same specified minimum strength. Usually they will not have the same mean strength. Conversely, sample populations having the same mean strength may not have the same specified minimum strength. Inconsistency occurs if σ_H is used for correlation of the S-N curves between various graphite grades, since they may possess considerably different specified minimum strengths. Even if this is applied to one particular type of graphite, one has to assume the same variability for all logs in all batches. Because the specified minimum values are used in design, we should examine other possibilities for a correlation parameter, such as using the specified minimum strength, or σ_h, etc. to see if a consistent criterion can be established.

In design analysis fatigue data will be categorized according to orientation and stress ratios R. Ideally, the fatigue tests should be performed at the R ratio that would be experienced by the component in the reactor operating conditions. This can be done if the exact manner of loading is known, and there are only a few R ratios involved. However, in almost all structural applications stress in an element of a component will vary in intensity frequently in a random manner. Since it is not practical to conduct tests in which all possible sequences of stress levels are examined, methods have been developed for assessing the material damage accumulated by the number of cycles at each stress level. Before selecting a damage rule, a method is presented to obtain the fatigue allowable stresses at any arbitrary R ratio by interpolating or extrapolating from the known allowable values at the R ratios at which the fatigue tests have been performed.

3.3. CONSTANT LIFE FATIGUE DIAGRAM (GOODMAN DIAGRAM)

The constant life diagram has been used successfully to compensate for the effects of mean stress in metallic components. The concept will be applied here for graphite components too.

Suppose that several R ratios have been examined in the fatigue tests in addition to the uniaxial tests of controlled specimens (R=1). The two R ratios, 0 and -1, comprise the minimum requirements for fatigue consideration. The test data have also been analyzed statistically to obtain the specified minimum S-N curves. The construction of a constant life diagram is demonstrated in Fig. 1. The abscissa and the ordinate, denote the minimum stress and the maximum stress, respectively, in a repeating stress cycle. At a given number of cycles the specified minimum fatigue strengths are obtained from the specified minimum S-N curves for several R ratios. The values are then plotted in Fig. 1 along their respective R-axis. A curve can be drawn through the points which constitute the desired fatigue curve. This is repeated for different numbers of cycles. A set of fatigue design curves is thus obtained. Shapes of the curves show that the allowable σ_{max} is generally increasing with R ratios. The aforementioned relation, $(\sigma_{max})_{R=-1} = 0.9 \times (\sigma_{max})_{R=0}$ appears to be a good approximation.

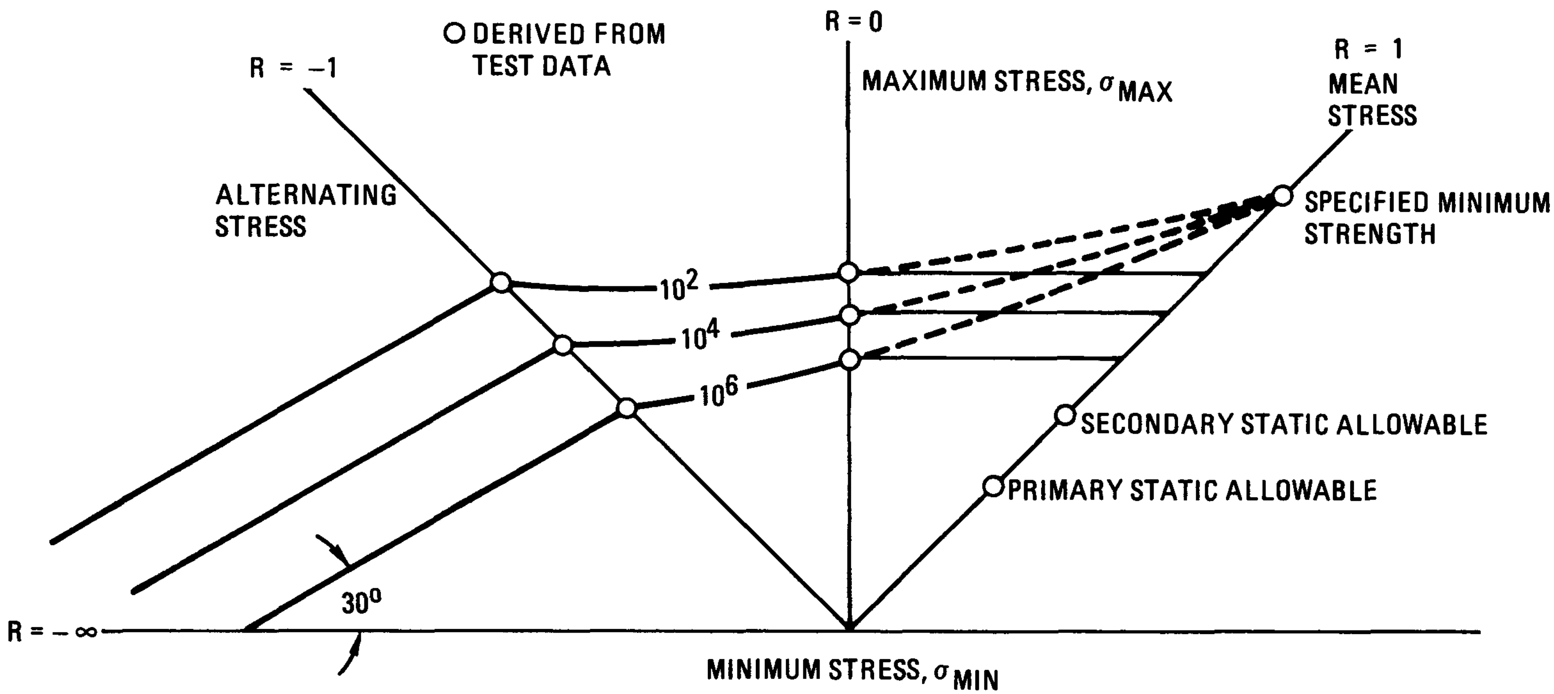

Fig. 1. Constant life fatigue diagram

However, there is some flexibility when curve-fitting the data points. We only know the general shape of these curves. Taking experience gained from fatigue curve construction for H451 graphite, where more R ratios have been examined in the fatigue test (Ref. 7), one can make some assumptions about shapes. Special care should be exerted in this maneuver. The curves between the R=1 and the R=0 axes will be modified for the reason stated below. In the constant life diagram the effect of mean stress is usually outweighed by the effect of the stress amplitude when R increases from 0 to 1. A higher allowable maximum stress is obtained when moving towards the R=1 axis.

All of the fatigue curves converge to a single point on the R=1 axis. This point will be near the minimum static strength. If sufficient data exist the actual design fatigue curves can be obtained between R=0 and R=1. Where data is sparse or unavailable the following temporary curves can be constructed.

Since we know that the allowable maximum stress increases in going from R=-1 to R=1 it would be conservative to extrapolate the data at R=0 horizontally over to the R=1 axis as shown in Fig. 1. This allows one to construct design curves from data obtained only at R=-1 and R=0 until data on all stress ratios of interest are available.

In general most cyclic stress states lie between R=-1 to R=1, and there is little interest in the region from R=-1 to R=-∞. However, because of its brittle behavior, in the design of graphite structures there is a concerted effort to design all load paths to be principally in compression. This places a greater emphasis on fatigue evaluation in this region of the Goodman Diagram as compared to metals. Bullock (Ref. 8) has performed some exploratory tests in this region on ATJ graphite. The results of these tests indicate that the allowable maximum stress decreases as the absolute value of the compressive mean stress increases; however, the allowable maximum stress amplitude increases. Based on this data set, a straight line approximation to the data can be constructed which lies conservatively below the actual curves. As shown in Fig. 1, these straight lines are drawn at an inclination of 30° with respect to the $R=-\infty$ axis. This approach can be used until statistically significant quantities of data are available to construct actual design curves.

Oku, et al., (Ref. 27) reported some tests results in which the maximum stress was compressive. These, together with some tension-tension fatigue data, were used to establish a tentative Goodman diagram for two Japanese types of graphite. The curves in Ref. 27 are consistent with the foregoing discussions.

3.4. CUMULATIVE DAMAGE RULE

The linear damage rule, known as Miner's rule, is generally used to assess the cumulative effect of various random stress cycles expected to be encountered in the life of a component. Theoretically, based on mean samples with no factor of safety, failure occurs when the cumulative damage factor, defined as the sum $\eta_1/N_1 + \eta_2/N_2 + \eta_3/N_3 + \ldots$ is equal to 1. N_1 represents the expected number of cycles which would produce failure at a stress level S_1. η_1 is the cycles expected to be experienced by the component at the same stress level. By assumption, η_1/N_1 is the fraction of the total material life. It is evident that this rule attributes no significance to the sequence of loadings, which may not be the case in reality. Other hypotheses for estimating cumulative damage have been proposed for metal fatigue (Ref. 14). Better accuracy could be obtained, however, only if the loading sequences were known in considerable detail at the time of analysis, and tests were performed accordingly. The rule could then be modified to sum to other than 1.0 depending on the sequence of loading. Before this could be accomplished, a series of tests would be needed to obtain the loading history effect on total damage fraction.

In the interim, the linear damage rule will be used for simplicity. If tests to be performed later show significant deviation from the linearity assumption, modifications will be made then. Normally a fatigue test program designed to substantiate the linear damage rule has block loading sequences like high-low, low-high or random sequences. An examination of the HTGR reactor operating conditions reveals that the occurrence of various cycles is not totally random and is also not totally ordered either, like those performed in the test. Except for the emergency cycles, all operating cycles, whether normal or upset conditions such as startup shutdown cycles, rapid or normal load increase/decrease cycles, step load increase/decrease cycles, reactor or turbine trip cycles, etc., are shuffled together into a more uniformly mixed event. In other words, a unit loading block can always be found. For example, an annual loading block consists of one yearly refueling and several other types of load cycles. Many of these repetitious load blocks span the life of the reactor. Attention should be paid to this ordered simulation of random events while designing a test program to verify any damage rule.

The following facts have been observed in metal fatigue (Ref. 14):

1. The linear damage rule overestimates the fatigue life in random loading and decreasing stress level (i.e., hi-lo) sequences,

2. The linear damage rule is conservative in the high cycle fatigue region and in the case of increasing stress level loading sequence,

3. The linear damage rule is reasonably accurate in the low cycle fatigue region.

The similarity of the S-N curves between graphite and metals suggests that the above facts regarding fatigue damage of metal may apply to graphite too.

In the linear summation expression, (S,N) is obtained from the mean S-N curves. The life can only be expected in a statistical sense. Since a very variability in graphite fatigue exists the mean value loses its meaning in design applications. In this case the specified minimum S-N curve is used. It is consistent to assume that when the linear sum is equal to one, a 99% survival probability with 95% confidence level is achieved. An additional safety factor may be desirable beyond this as discussed in the following section.

3.5. FACTOR OF SAFETY IN FATIGUE CYCLES

The fatigue test data are usually obtained under certain restrictive conditions. Scatter of the data is accommodated by using the specified minimum curves. The effect of the mean stress is considered through the constant life diagram. The linear damage rule takes care of the effect of random load sequences. Effects of other influential factors such as environment also need to be considered in the evaluation. These will be examined one by one later. In addition, a factor of safety is always required to provide a margin of safety to cover uncertain factors that may be overlooked at present or a change of loading history unforeseen at the time of analysis. It is recommended here that a factor of three on cycles be adopted. This is consistent with safety factors established for static loading where the same 99/95 criteria is used to establish minimum strength. This leads to a cumulative damage rule of:

$$\Sigma\ \eta_i/N_i \leq 1/3 \quad .$$

It is preferable, at this point in the fatigue criteria development, to incorporate the safety factor into the cumulative damage summation rather than the S-N diagram so that changes can be readily made as data and experience indicate use of a different safety factor on cycles.

4. FATIGUE CRITERIA - MULTIAXIAL

Most of the ambiquity in fatigue design arises from the presence of more than one fluctuating stress component, not necessarily in phase, and a lack of co-axiality of the principal stress and the material axes. This is probably the most difficult problem to handle at the present. A few publications have addressed the first part of the problem, only on in-phase biaxial tensile fatigue. The second part has never been dealt with. We will begin the subject by reviewing the small amount of available literature.

Wilkins and Reich (Ref. 5) examined the cyclic fatigue behavior of POCO (molded) graphite in proportional biaxial loading and 3-point bending. All specimens were fatigued on the R=0 axis with some samples proof-tested at the applied peak stress σ_A or some higher stress. They defined a ratio of σ_A/σ_i as the homologous applied fatigue stress σ_h, where σ_i is the instantaneous fracture stress expected in the same mode of loading for each individual specimen in the population. A general relationship between σ_h and fatigue life N was established for all modes of loading. The large scatter usually associated with fatigue data is reduced by the use of statistically inferred values of σ_i for normalization.

Uniaxial and in-phase biaxial tensile fatigue data are compared in terms of σ_h in Ref. 5. It reveals that both cases possess the same fatigue life for a given σ_h when N is less than approximately 5×10^3 cycles. Biaxial tensile fatigue show a gradually decreasing life when N is greater than 5×10^3 cycles. Wilkins and Reich have tested a total of more than 140 biaxial fatigue specimens. Close to half of the specimens went beyond 10^4 cycles, and 25% to 10^5 cycles or beyond. The conclusions should be quite accurate for the graphite tested.

Brocklehurst and Brown (Ref. 9) later explored the mechanical fatigue behavior of preproduction grades NA and NP2 of IM1-24 graphite. Of the 12 biaxial tests performed, only two had a life between 10^3 and 10^4 cycles, the remaining had a life of less than 10^3 cycles. They concluded that there are no significant differences in fatigue strength between uniaxial and biaxial tensile stressing modes when the corresponding expected mean static strengths are used to obtain the homologous stress σ_H. This definition of σ_H is less informative than the one used by Wilkins. However it is convenient to use. It turns out that the findings of the two reports actually concur with each other.

The French graphite FHAN was biaxially tested with 17 tubular specimens and the data were reported by Schill and Richard (Ref. 11). The general shape of the fatigue curves was confirmed. No comparison between uniaxial and biaxial data was made. The comparison of this data with other graphite data obtained from uniaxial specimens indicates a lower fatigue life in biaxial tension as shown in Table 1.

All researchers in the evaluation of multiaxial fatigue treated the case of uniform biaxial tension in phase, or radial loading without any shear components. Nevertheless, some general fundamental information is provided. Presently we rely on this to formulate the fatigue criteria until further experimental results are obtained.

Some intuitive approaches that can be used to estimate the fatigue life in a multiaxial stress state from uniaxial test data will now be discussed. Their difficulties and inconsistencies in applications are to be pointed out. A hopefully logical and conservative approach will be recommended for interim use until sufficient data is available.

Current approaches to multiaxial fatigue in metallic structures entail the equivalent stress or strain concept (Refs. 15 and 16). They all assume that the stress components vary in direct proportion to each other. It is implied that the stress components are either in phase or 180° out of phase.* An equivalent alternating stress or strain is calculated using an acceptable theory of strength. The equivalent mean stress is defined as the highest algebraic principal stress caused by all the mean loads. The equivalent stress amplitude and mean stress are applied to the uniaxial S-N curves or the constant life diagram. If there is no direct proportionality between the stress components, the phase angles are another important variables regarding which little experimental information is available. Since such information has not been available, it has been assumed that conservatism introduced by safety factors will suffice to compensate for neglecting the phase angles. Application of the above approach to graphite is not practical, as will be discussed below. The inherent differences in material properties between graphite and metals result in some difficulties which cannot be resolved easily.

A natural extension of the metal fatigue criteria to graphite is the adoption of the effective stress concept. The effective stress, σ_{eff}, or a similar parameter, may be used to correlate a multiaxial stress state with uniaxial fatigue data. The strength criteria proposed in Ref. 2 have been labeled as the present choice for graphite materials (Ref. 17). We may define

$$\sigma_{eff}^2 = F_{ij}\sigma_{ij} + F_{ijkl}\sigma_{ij}\sigma_{kl} \qquad i,j,k,l = 1,2,3$$

where F_{ij} and F_{ijkl} are strength tensors of second and fourth ranks. σ_{eff} can be considered as the counterpart of the homologous stress in the multiaxial stress state.

For constant static loads, the effective stress is considered as an unsigned absolute quantity. The restriction on sign can be removed. We are facing now a series of unclear choices. What sign shall be given to σ_{eff}? What is σ_{min} and σ_{max} in a cycle? Are they $(\sigma_{eff})_{min}$ and $(\sigma_{eff})_{max}$? What is σ_{mean}? Is $\sigma_{mean} = 1/2\ (\sigma_{eff})_{min} + 1/2\ (\sigma_{eff})_{max}$ or some other

*This means that we have a radial loading case.

relation? How is the constant life diagram to be used? With grain or across grain or what? Finally, if σ_{eff} is identified as σ_H (homologous stress), inconsistency exists when σ_{eff} is degenerated to the one dimensional case. Consider the uniaxial tensile case. The applied uniaxial homologous stress is $(\sigma_H)_u$. The effective stress σ_{eff} can be calculated if F_{ii} and F_{iiii} (no summation) for the i^{th} direction are known. It can be seen that $\sigma_{eff} \geq (\sigma_H)_u$, as long as F_{ii} is non-negative, which is the case for graphite grades considered so far (Ref. 18). There is also a possibility that all the stress components are oscillating in such a way σ_{eff} remains constant. All these cannot be resolved easily without further analytical and experimental work.

An alternative way to approach the multiaxial fatigue is to postulate the existence of failure surfaces for fatigue. For some given R ratios, a set of failure surfaces, eccentric to each other, can be established. Fig. 2 depicts schematically biaxial failure and fatigue surfaces. Although the approach has its own technical merit in application, there are a few fatal flaws in it too. There are six independent R ratios, one for each stress components. Determination of the instantaneous failure surface is already troublesome. Besides the technical difficulties of performing shear fatigue tests, it is not economically possible to obtain accurate fatigue failure surfaces. This method is impractical.

One apparent way to approach multiaxial fatigue is to modify the linear damage rule. It may be written as

$$\sum_i \left(\frac{n_i}{N_i}\right) = D\ (\sigma_{ij},\ R's)$$

where damage value D is a function of σ_{ij} and R's. The left hand side is evaluated using a particular stress component, perhaps the one having the maximum value. Then, D will account for the multiaxial effect. The main difficulty in this case is to define D. The degree of difficulty is no less than in the previous case.

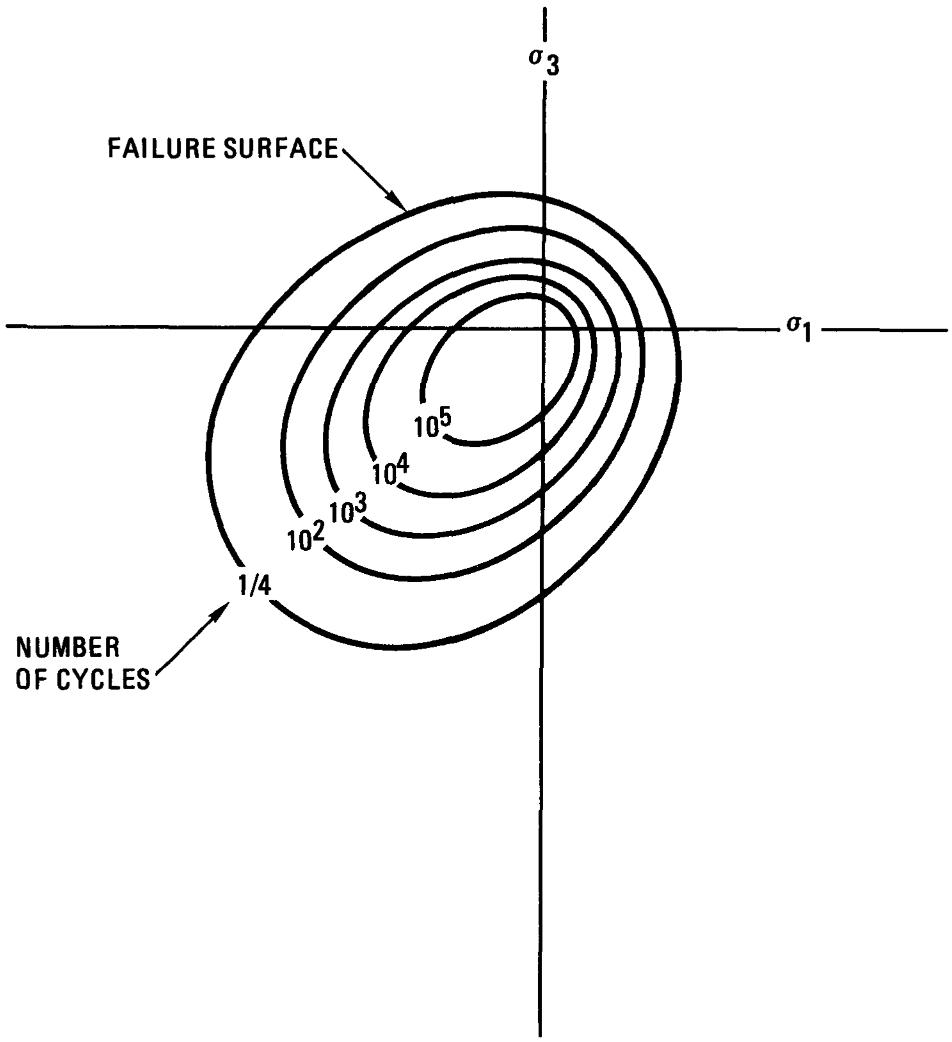

Fig. 2. Schematic biaxial fatigue failure surfaces in the principal stress space

The linearity assumption on the life fraction can be pushed further to apply separately for each stress component. For example, the cycle ratio, η_i/N_i, could be assumed to be equal to the sum of the cycle ratios for each stress component. To avoid the troublesome shear stress components, this can be done in the principal stress space. The non-coaxiality problem of the principal stress axes and the material axes are yet to be solved. The approach sounds simple and promising, but it needs further work and substantiation.

The non-coaxiality problem can be treated by using an empirical formula of Hankinson's developed for the timber industry (Ref. 19). The formula is

$$\alpha = (\cos^2\theta + \sin^2\theta/\alpha_s)^{-1}$$

where α is the strength ratio with respect to the weak material axis of a transversely isotropic material, and θ is the angle measured from the weak material axis. Here, α_s is the value of α in the strong axis. Although it lacks a sound theoretical background, the formula may have reference value.

Another approach is an extension of the concept of homologous stress. The fluctuating stress state at a critical point is normalized instantaneously with respect to the strength obtained from the same stressing mode. The mean stress and stress amplitude have to be defined. The non-coaxiality problem also needs to be solved.

Many details in all the above approaches have to be worked out and all the ambiguities have to be resolved before applications to design can take place. In spite of this, the following provisional procedure concerning multiaxial fatigue is proposed.

First, we shall construct the specified minimum fatigue design curves in the case of multiaxial fatigue based on the available information. The design S-N curves can be obtained using the biaxial fatigue test results from Ref. 5. A proposed design S-N curve is schematically shown in Fig. 3. The portion of the uniaxial curve with N less than, say, 2×10^3 cycles is assumed to be valid for any biaxial or triaxial stress states in the principal stress space. Beyond $\sim 2 \times 10^3$ cycles, some correction must be made for biaxial and triaxial effects. It is further assumed that the correction can be estimated from biaxial fatigue data in Ref. 5. In the biaxial case the curve is lowered from the uniaxial curve by an amount to accommodate the biaxial tension effect. It is labeled as biaxial in the figure. We assume that the effect of transverse tension is linearly additive, so a curve, labeled as triaxial, is constructed. It can be seen that the multiaxial effect is increasingly significant in the high cycle region. In HTGR applications, thermal stress cycles are less than 2×10^4 cycles. According to Ref. 5, the fatigue life at this level may be reduced by a factor as high as 2 due to biaxial tension effect.

Strictly speaking, the biaxial and triaxial curves descrived above are for the cases of equal tension. In practice, the principal stress components are not necessarily equal in magnitude, and they may even be opposite in sign. The following guidelines on the application of the design S-N curves to the above situation are recommended:

1. Use uniaxial curve when: only one principal stress component is tensile, including uniaxial T, biaxial T-C, and triaxial T-C-C quadrants,

2. Use biaxial curve when: any two principal stress components are tensile, including biaxial T-T and triaxial T-T-C quadrants,

3. Use triaxial curve when: stress components are in the triaxial T-T-T quadrant only,

where T = tension and C = compression.

The guidelines would reduce the allowable life significantly in the high cycle region when the transverse stress component is tensile, but

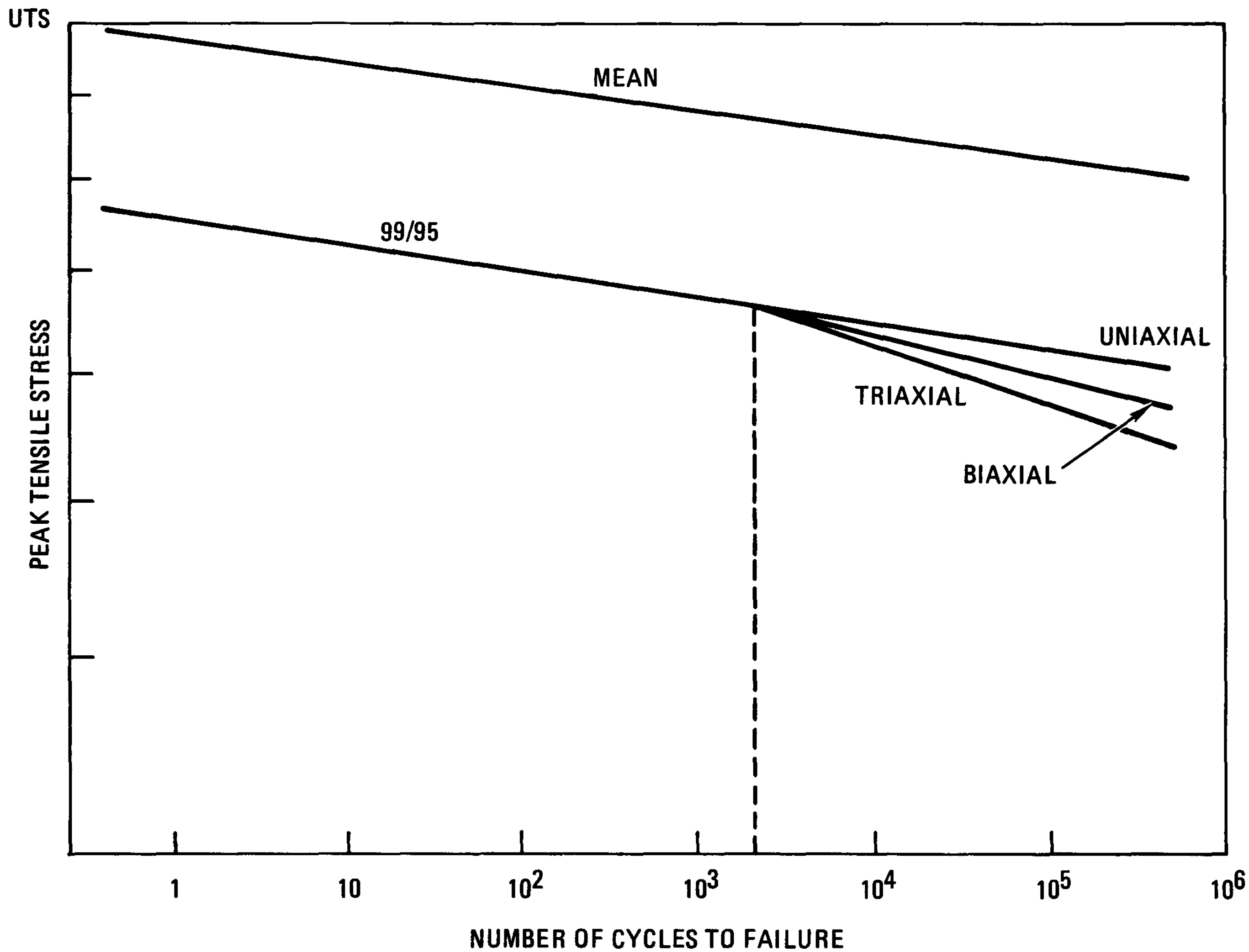

Fig. 3. Multiaxial fatigue design curves

small. Note that there is a discontinuity in the criterion as the small transverse component changes from compression to tension.

The principal stress components at any material point 0 in Fig. 4 vary cyclically both in magnitude and in orientation. At some instant in a cycle, one of the principal stresses reaches the maximum value, denoted by σ_{max}. All other principal stresses are less than or at most equal to σ_{max}. This maximum stress σ_{max} is usually tensile (positive), since cyclic stresses in HTGR component are induced by either thermal cycling or seismic loadings. Now we define a right rectangular pyramid whose vertex is at the material point of interest, whose axis is in the direction of σ_{max}, and whose lateral surfaces bisect the axis of pyramid and the appropriate remaining principal axes. Construction of the pyramid is demonstrated in Fig. 4. The minimum principal stress within this pyramid in a cycle is designated by σ_{min}. In most cases, σ_{max} and σ_{min} will not have the same orientation. We assume that σ_{min} occurs in the same orientation as that of σ_{max}. Properly designed S-N curves can be applied to obtain the specified minimum life if σ_{max} and σ_{min} are identified as the maximum stress and the minimum stress, respectively, in a stress cycle.

Failure of graphite is normally associated with the tensile mode. Tension is the most detrimental stress condition to the structure. This is the reason why the maximum principal stress is selected as the maximum cyclic stress for the fatigue evaluation. By doing so, all the transverse stress components are less than or at most equal to σ_{max}. The assumption of using σ_{min} as the minimum cyclic stress, occurring in the same orientation as σ_{max} is probably conservative. The process leads to a lower R value algebraically producing a lower specified minimum life from the constant life diagram.

The selection of σ_{max} as the maximum cyclic stress has an implication of theoretical importance. The cyclic frequency is fixed as that of σ_{max}. The transverse stress components may have, in general, different cyclic frequencies. In the HTGR graphite core support structure, the sources of

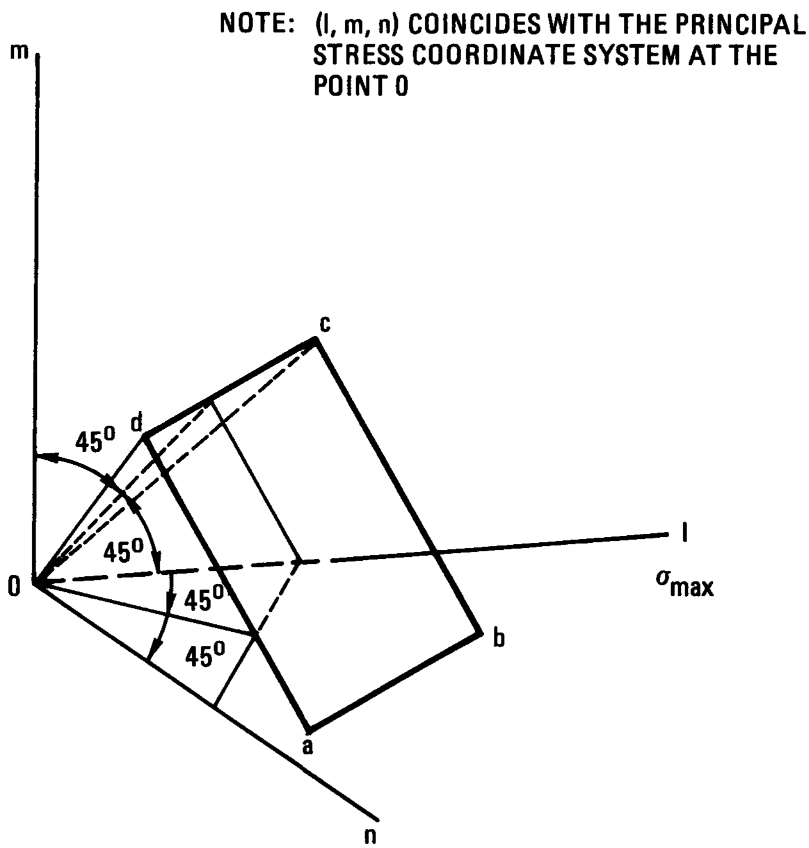

Fig. 4. Orientation of the right rectangular pyramid Oabcd at a material point 0

fluctuation are the slow varying thermal cycles and the fast varying, and short-duration seismic impacts. We can resolve the difference in cyclic frequency by considering them as two linearly independent events.

Finally we recommend the use of the fatigue strength of the weak axis for all orientations of the maximum cyclic stress when the principal stress axes are not coincident with the material axes. It is conservative to do so, in view of the lack of a proven logical way to interpret the strength in directions other than the weak and strong axes.

5. IMPORTANT INFLUENTIAL FACTORS ON FATIGUE LIFE

Effects of some important influential factors on fatigue life are discussed below. Most of the effects are not included in the criteria and further work will be required in most of these areas.

5.1. EFFECT OF TEMPERATURE

It is well known that the ultimate tensile strength of graphite increases with temperature and reaches a maximum at about 2500°C. Very limited fatigue tests have been performed on graphite at elevated temperatures. Green (Ref. 20) investigated fatigue properties of grade AUF graphite at ambient and 1950°C. The endurance limit obtained from reverse bending tests was found to increase from 2500 psi at room temperature to about 4400 psi at 1950°C. The increase of about 75% was larger than that indicated for the static strength of this material. He then concluded that the endurance limit increases with temperature. Later discussions on this subject by others, e.g. (Ref. 2), always referenced his conclusion. That conclusion, rigorously speaking, is premature and unsubstantiated. Two temperatures, room and 1950°C, were examined. A conclusion drawn from two points may be risky and misleading. Furthermore, part of the increase in the endurance limit may be due to outgassing of the test specimens. The quantitative effect of outgassing has to be determined before any conclusion about temperature can be drawn.

Gateau, et al. (Ref. 21) studied isotropic Gilsocarbon graphite in zero to tension fatigue tests at room and 800°C temperature. Tests were performed at three mean stress levels. No significant effect of temperature was found at room and 800°C, although the results have been complicated by oxidation of the specimen in the tests at 800°C. They tried to assess the oxidation effect by annealing additional specimens in the same condition except some in argon and some in vacuum. Subsequent fatigue tests at room temperature showed a higher strength for specimens annealed in vacuum. Both produced lower fatigue strength than specimens without annealing pre-treatment. Probably two factors were affecting the test results, namely, oxidation and outgassing. The proper quantitative explanation may be that oxidation reduced the fatigue strength by ∿200 psi, while outgassing increased it by about 100 psi. If the same correction factors are assumed to be applicable to the high temperature test data, the effect of temperature on fatigue strength is found still not very pronounced.

Until such time as some carefully designed experiments can be performed for the types of core support graphite in the temperature range of interest, we recommend the room temperature, RT, curve be used in design analysis for all HTGR temperature conditions.

5.2. EFFECT OF IRRADIATION

Brocklehurst and Brown (Ref. 9) reported a limited number of fatigue studies on pre-irradiated NA and NP2 type graphite specimens. Room temperature fatigue strengths for pre-irradiation specimens were found higher than the un-irradiated values. When expressed in terms of homologous stress σ_H, there are no significant differences in the values. No test has been performed on irradiated specimens at the irradiation temperatures. The fast neutron doses considered so far are 10^{19} and 2.5×10^{21} nvt (DEN) at 45°C and 900°C, respectively.

Price (Ref. 7) also investigated the effect of neutron irradiation on fatigue. A total of 42 H451 type graphite specimens were irradiated at 900 to 990°C with fast neutron fluence range from 3.0 to 8.5×10^{21} nvt (E > 0.18 Mev). Ten of the specimens were tensile-tested in the fatigue machine to establish the mean ultimate tensile strength. He found that neutron irradiation increases the homologous stress limits for fatigue endurance. If the unirradiated tensile strength is used as the basis for normalization, the fatigue stress limits are about doubled by irradiation.

In the HTGR applications, the top of the core support block has a 40 year fluence level less than 10^{16} nvt, and the inside surface of the PSR has about 6.5×10^{19} nvt at end of life. The doses decay exponentially away from the core and are considered low. We assume an invariant fatigue strength at these dose levels, thus the room temperature S-N curves can be used for all core support components.

5.3. EFFECT OF CORROSIVE ENVIRONMENT - OXIDATION

The effect of oxidation on the static strength and failure strain has been extensively examined for PGX graphite at GA. A structural analysis method has been developed to include the softening in stiffness in the oxidized zone. The effect on fatigue is still unknown. Presently it is assumed that the fatigue strengths in terms of σ_H are constant for the virgin as well as the oxidized specimens. The design S-N curve can be used in the oxidized zone if proper modification is made to the static strength to account for oxidation.

5.4. EFFECT OF STRESS CONCENTRATION

It is well known that the apparent stress concentration factor (SCF)* in graphite is always less than the theoretical elastic value, K_t. In fact, it never exceeds 2 for the materials tested in Refs. 9 and 22. This is apparently a combined manifestation of the nonlinear material and the statistical volume and grain size effects. These effects were overlooked in the previous analyses. When properly accounted for, the apparent SCF can be brought equal to or reasonably close to the theoretical SCF. This will be discussed in detail in a separate report later.

In metal, the fatigue SCF, K_f, is always less than the static or elastic SCF K_t. The generally acceptable practice involves making a correction for the notch sensitivity, q, of the material by $K_f = 1 + (K_t - 1)\,q$. A

---

*The word apparent is used because this is measured by observing a load at failure, not the actual stress.

completely homogeneous material would have a notch sensitivity of 1 for all notches. All actual materials are nonhomogeneous to some extent, so the value of q is then always less than 1. The same conclusion is probably true for graphite. No work is known to have been done on this subject.

We suggest that the theoretical elastic K_t be used in fatigue design at the present time until a more rigorous procedure for evaluating K_f can be developed.

5.5. EFFECT OF STRAIN RATE

No systematic study has been performed to quantify strain rate effects on fatigue life. The cyclic frequency range used in the fatigue tests shown in Table 1 is from 10 c/hr to 120 c/sec, almost five orders of magnitude difference. But no conclusion on the effect of cyclic rate can be drawn from existing data. In an HTGR environment, two types of cycles are involved. The slow-varying thermal cycles due to power demand have a period on the order of a day or a month. The short duration stress cycles due to seismic loads have a period of 10^{-2} to 10^{-4} sec. The range is well beyond the test range.

Due to the lack of useful information, we shall not consider the effect of strain rate in fatigue analysis. But it is expected that the grain structure of graphite will exhibit some effects in high frequency oscillation. Until data are available it is recommended that the effect of strain rate be omitted.

5.6. EFFECT OF SURFACE FINISH

Surface condition affects the fatigue life of metallic components. But graphite is a granular material, and the effect will not be significant so long as the surface roughness is near or less than the grain size of the material. In general machining practice, a ∠125 surface finish should not result in a reduction in fatigue strength. Surface roughness greater than ∠125 should be accounted for in fatigue evaluation.

5.7. SIZE EFFECT

For bending and torsional loading of metallic specimens, the endurance strength tends to decrease as size increases (Ref. 23). Reductions of 25 percent or more are possible. Size has shown negligible influence in uniaxial loading. In graphite the size effect is more pronounced. It includes two parts, the volume effect and the grain size effect. The larger the volume, the lower the strength. The smaller the grain size or the larger the least dimension of the specimen relative to the grain size, the higher the strength. The relation can be correctly predicted by a modified Weibull theory (Ref. 24).

In fatigue tests, usually one specimen size (normally small) is examined. These test data can be used for the design of different sized components if proper accommodation is made for the size effect. It is assumed here that the size effect in fatigue is identical to that in the static loading case. The modified Weibull theory can then be used to adjust the fatigue curves. This is an interim approach until actual fatigue data quantifying volume and grain size effects is obtained and evaluated.

5.8. EFFECT OF STRESS DISTRIBUTION

The Weibull theory of strength predicts not only the volume effect but also the effect of stress distribution. This effect should be considered in the analysis. It is possible that the highest stress point in a component will not be the critical point if the distribution is such that the stress gradient is high or that a very small volume of material is at the high stress. It could be that a lower stressed volume of material is critical because of the higher average stress over the volume. It seems logical that this principle applies to both static as well as cyclic stress states.

5.9. EFFECT OF MATERIAL VARIABILITY

Mechanical properties of graphite, including strength, show a dependence on the manufacturing process, the size and the shape of the material log, and the spatial location of a high stress point in a log, among other things. Variations from one log to another log and within a material log shall be examined systematically. Correlation and accommodation may be needed. Density appears to be an appropriate parameter for this purpose (Refs. 8 and 26).

5.10. EFFECT OF PROOF TESTING

Proof testing of the components improves the structural reliability. The lower end of the material strength distribution curve is truncated by the proof test. The allowable working stress becomes higher. However, the proof test cycles must be added to the design loading history for the cumulative damage evaluation to be complete.

In actual application mechanical loads may be reproduced in a proof test, but thermal loads are often difficult to simulate. It is economically infeasible to have many proof tests for numerous design conditions. It is almost impossible to find a single proof test which will produce the maximum stresses at all points in the components at the same time. Therefore several fictitious proof test load cases will be needed to simulate worst operating loads, and the order of loading must be considered. Unless that duplicated an actual service condition, it would not even be desirable since it would probably be a much more severe condition than any actual design condition. The effects of proof tests on strength criteria and design practice should be developed and optimized.

6. SUMMARY OF RECOMMENDATIONS

The following is a summary of the recommended graphite fatigue criteria based on this report.

1. Minimum fatigue strength curves should be used such that the probability is 99% that all of the data will be above the minimum curve at a confidence level of 95%.

2. Modified Goodman diagrams should be used to present minimum fatigue design curves. Approximate diagrams should be constructed as explained in Section 3.3 as an interim practice until sufficient data become available to construct more accurate curves.

3. As an interim measure, minimum fatigue strength curves can be constructed for graphites where no fatigue data exists but which do have sufficient static strength data by the use of the homologous stress fatigue curves as outlined in Section 3.1.

4. Miner's rule for cumulative damage summation should be used for non-uniform cyclic loading.

5. Currently, no rigorous multiaxial fatigue theory has been experimentally verified. Thus, the small amount of data available indicates that multiaxial effects can be accounted for by appropriate modification of the uniaxially-based fatigue design curves as explained in Section 4.

6. The effects of temperature can be ignored until sufficient data have been generated to quantify the effect. This is possible since most data show that fatigue strength increases with temperature.

7. The effects of irradiation can be neglected since available data show that fatigue strength increases with increasing neutron dose. However, experimental work in this area should continue to verify this extrapolation to other graphites.

8. The effects of oxidation on fatigue strength are unknown at this time but probably can be neglected since the oxidized layer becomes very compliant and probably does not affect the fatigue life of the remaining unaffected material. Thus, if the extent of oxidation can be accounted for in stress analysis, fatigue life can also be predicted. This hypothesis must be verified experimentally. The above statements do not apply to uniformly or near-uniformly oxidized graphite.

9. Use elastically determined values of stress concentration, K_t, to account for stress risers until experiments show otherwise.

10. Neglect strain rate effects on strength until such time as experiments indicate otherwise.

11. Size effects or grain size effects should be accounted for in the fatigue analysis. No cross section should be less than 10 times the maximum grain size for its smallest dimension after the effects of corrosion have been considered.

12. Proof testing cycles should be included as part of the operation history for fatigue evaluation as discussed in Section 5.10.

7. RECOMMENDATIONS ON FUTURE WORK

The previous discussion on the fatigue criteria leads to the following recommendations:

1. To fulfill the near term design needs for the specified minimum fatigue design curves, data in Ref. 5 should be re-analyzed in light of the present fatigue criteria. Assuming an equivalence of the homologous stress quantity for given stress ratio R in fatigue between various graphite grades, it is possible to obtain quantitative modification factors for multiaxial fatigue. This together with data in Refs. 7 and 8 will enable the generation of the desired design curves for the core support graphite materials.

2. A long term test program should be planned to establish the fundamental fatigue data base for core support graphite. Influential factors which are believed to be detrimental to fatigue life should be examined first, followed by those factors believed to be beneficial to life. Possibly, the coupling effect of some factors should also be investigated.

3. Continuous theoretical development in the field should be carried out. This includes constitutive relations, strength criteria, non-coaxiality of the material and the principal stress axes, and phase angle offsets, etc.

4. Refinement and development of design practices and stress analysis techniques incorporating the up-to-date results from items 2 and 3 above should be pursued and continued. The probabilistic approach on strength for practical application should also be

emphasized. Especially, the Wilkins' definition of the homologous stress and its merits should be thoroughly studied.

5. Alternative approaches to correlate the fatigue design curves with graphite logs having different strength distributions should be thoroughly explored. An appropriate reliability function should be defined in conjunction with the design criteria to replace the somewhat arbitrary factor of safety on cycles.

6. The fracture mechanics approach to fatigue (especially to account for oxidation effect) should be continuously worked on.

Partial contents of the recommendations 2, 3, 4 and 6 have already been discussed in detail in Ref. 25.

8. CONCLUSIONS

Tentative fatigue criteria for HTGR graphite core support structures have been presented in this report, and status of ongoing work to improve the criteria has been discussed. Although an endeavor has been made to make the criteria as self-consistent as possible, they are incomplete at this time. These criteria need to be constantly modified and updated as data shed more light on the material behavior and the design philosophy advances. In the interim, the fatigue criteria outlined in this report are recommended for use in graphite core support designs.

ACKNOWLEDGMENT

The authors would like to express their thanks to Messers S. J. Brown, R. J. Price and P. D. Smith for their review and critique of the report.

REFERENCES

1. "Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis in Section III and VIII," Division 2, The American Society of Mechanical Engineers, New York, 1969.
2. Tsai, S. W. and E. M. Wu, "A General Theory of Strength for Anisotropic Materials," J. Composite Materials, 5, 1971, p. 58.
3. Brocklehurst, J. E., "Fracture in Polycrystalline Graphite," Chemistry and Physics of Carbon, 13, p. 145, 1977.
4. Leichter, H. L. and E. Robinson, "Fatigue Behavior of a High Density Graphite and General Design Correlation," J. Am. Ceram. Soc., 53, 1970, p. 197.
5. Wilkins, B. J. S. and A. R. Reich, "The Dynamic Fatigue Behavior of POCO and RC4 Graphites and a General Fatigue Design Criterion," AECL-4216, 1972.
6. Wilkins, B. J. S., "Probability of Failure of Brittle Materials Subjected to Dynamic or Static Fatigue," J. Materials, 7, 1972, p. 251.
7. Price, R. J., "Cyclic Fatigue of Near Isotropic Graphite: Influence of Stress Cycle and Neutron Irradiation," GA-A14588, November 1977.
8. Bullock, R. E., "Fatigue Behavior of ATJ Graphite," J. Materials Science, 12, 1977, p. 1215.
9. Brocklehurst, J. E. and R. G. Brown, "Fatigue, Notch Sensitivity and Work of Fracture Studies on Isotropic Graphite," TRG Report 2513(S), 1974.
10. Smith, E., "Fatigue of Graphite in Relation to HTR Fuel Pin Integrity," DPTN 29, 1970.
11. Schill, R. and A. Richard, "Essais de Fatigue Bi-axiale sur Eprouvettes Tubulaires en Graphite," Report on test SECMRG 74/17, Dept. of Technology, France, 1974.
12. Gateau, M., et al., "Fatigue Testing of Isotropic Gilsocarbon Graphite," DP-Report-888, Dragon Project Report, June 1974.

13. Morrow, J. D., "Cyclic Pastic Strain Energy and Fatigue of Metals," ASTM STP 378, 1965, p. 45.

14. Dubuc, J., et al., "Unified Theory of Cumulative Damage in Metal Fatigue," WRC Bulletin 162, 1972.

15. Manson, S. S., "Thermal Stress and Low-Cycle Fatigue," McGraw Hill, 1966.

16. Wirsching, P. H. and J. E. Kempert, "Fatigue Failure in A Real World," Machine Design, 48, 19, Aug. 12, 1976, p. 86.

17. Tang, P. Y., "A Recommendation of a Triaxial Failure Theory Failure for Graphite," GA-A15333, 1979.

18. Chang, T. Y. and T. Weng, "A Strength Criterion for Graphite under Combined Stresses," presented at ASME Pressure Vessel and Piping Conference, San Francisco, 1975.

19. Merritt, F. S., editor, "Standard Handbook for Civil Engineers," McGraw-Hill, 1968.

20. Green, L., Jr., "The Behavior of Graphite Under Alternating Stress," J. Appl. Mech., 18, 1951, p. 345.

21. Gateau, M., et al., "Fatigue Testing of Isotropic Gilsocarbon Graphite," DP-Report-888, Dragon Project Report, June 1974.

22. Bazaj, D. K. and E. E. Cox, "Stress Concentration Factors and Notch Sensitivity of Graphite," Carbon, 7, 1969, p. 389.

23. Lipson, C., Juvinall, R. C., Handbook of Stress and Strength, McMillan Co., New York City, 1963.

24. Ho, F. H., "A Four Parameter Weibull Theory for the Strength of Granular Brittle Material," Proc. 14th Conf. on Carbon, 1979, p. 338.

25. Svalbonas, V., et al., "Evaluation of the Structural Integrity of High Temperature Gas-Cooled Reactor Core and Support Elements," Franklin Institute Report F-C4230, April 1976.

26. Kachur, V. and E. F. Vandergrift, "Low-Cycle Fatigue in Structural Graphite Under Localized Loading," WANL-TME-1764, March, 1968.

27. Oku, T., M. Eto and T. Arai, "Strength and Fatigue Properties of Near-Isotropic Graphite," presented at IAEA Specialists Meeting on Mechanical Behavior of Graphite for High Temperature Reactors, Gif sur Yvette, France, 11-13 June, 1979.

APPENDIX A

UNIAXIAL FATIGUE CURVES OF PGX GRAPHITE

Design fatigue diagrams for PGX graphite are presented in Figs. A-1 and A-2. The diagrams are generated from fatigue test data in Ref. A1. The fatigue tests were performed only at two R ratios, namely -1 and 0, where R is the ratio of the minimum stress to the maximum stress. Those together with the uniaxial tensile strength on the R=1 axis constitute the desired fatigue curves. The results shown in the aforementioned figures are the fatigue curves with 99% survival probability and 95% confidence level, or abbreviated as the 99/95 lower fatigue curves. The mean and the 99/95 lower tensile strengths of the companion specimens are also given in the figures.

Before using the curves in general fatigue design, it is necessary to ensure that the fatigue specimens were from the same population as the total PGX data bank. The fatigue specimens and their companion tensile specimens were taken from a specific sampling zone in a single log. The PGX data bank consists of the tensile strength data from Refs. A1 through A4. Size effect believed to be small is not considered in the following comparison.

The comparison is done by first constructing the cumulative distribution curves showing the survival probability vs the tensile strength. Figs. A-3 and A-4 are for the companion tensile strength and Figs. A-5 and A-6 are from the tensile data bank. Statistical information obtained from these figures are tabulated below.

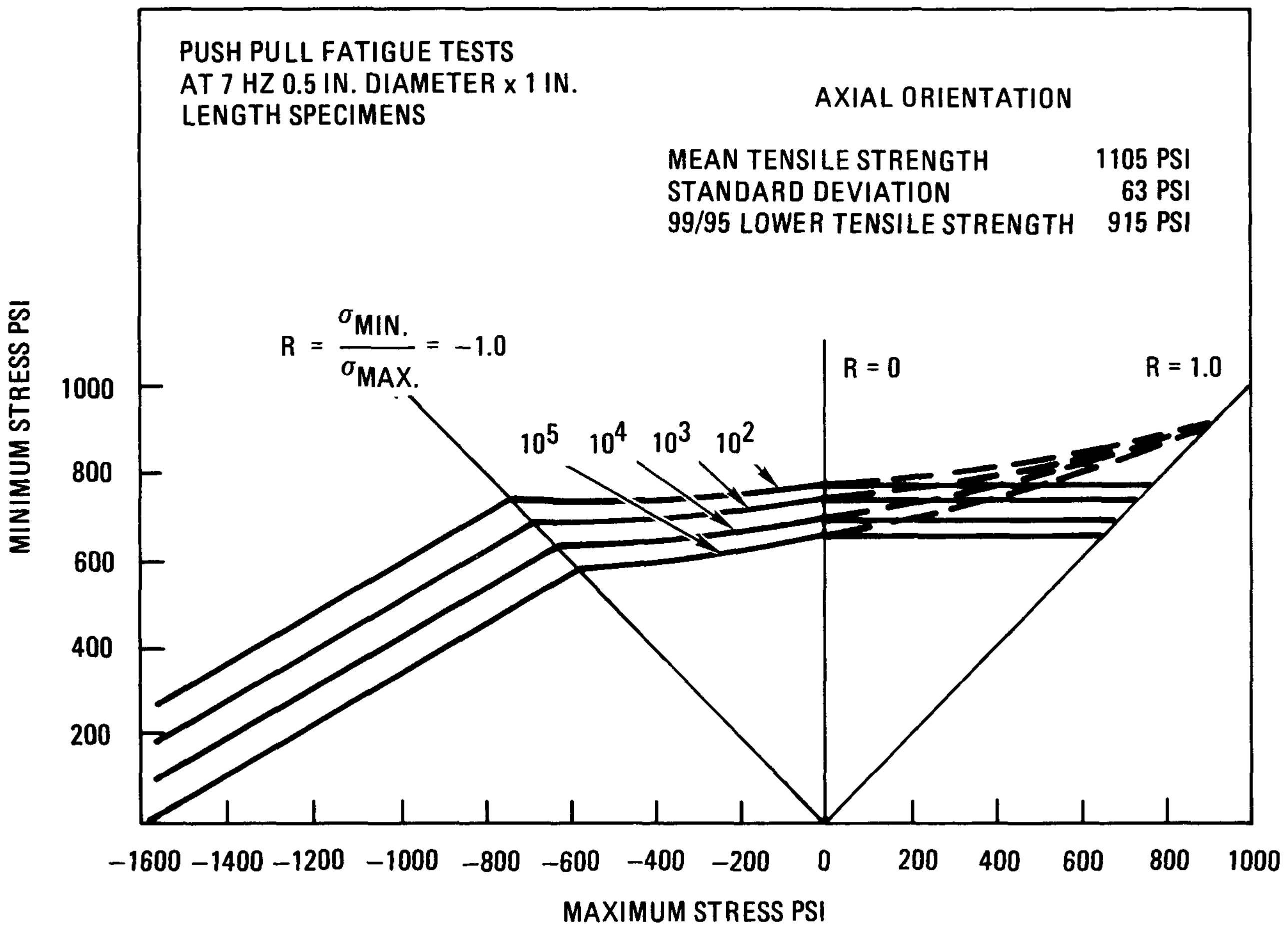

Fig. A-1. Design fatigue diagram for PGX graphite with 99% survival probability and 95% confidence level - axial orientation

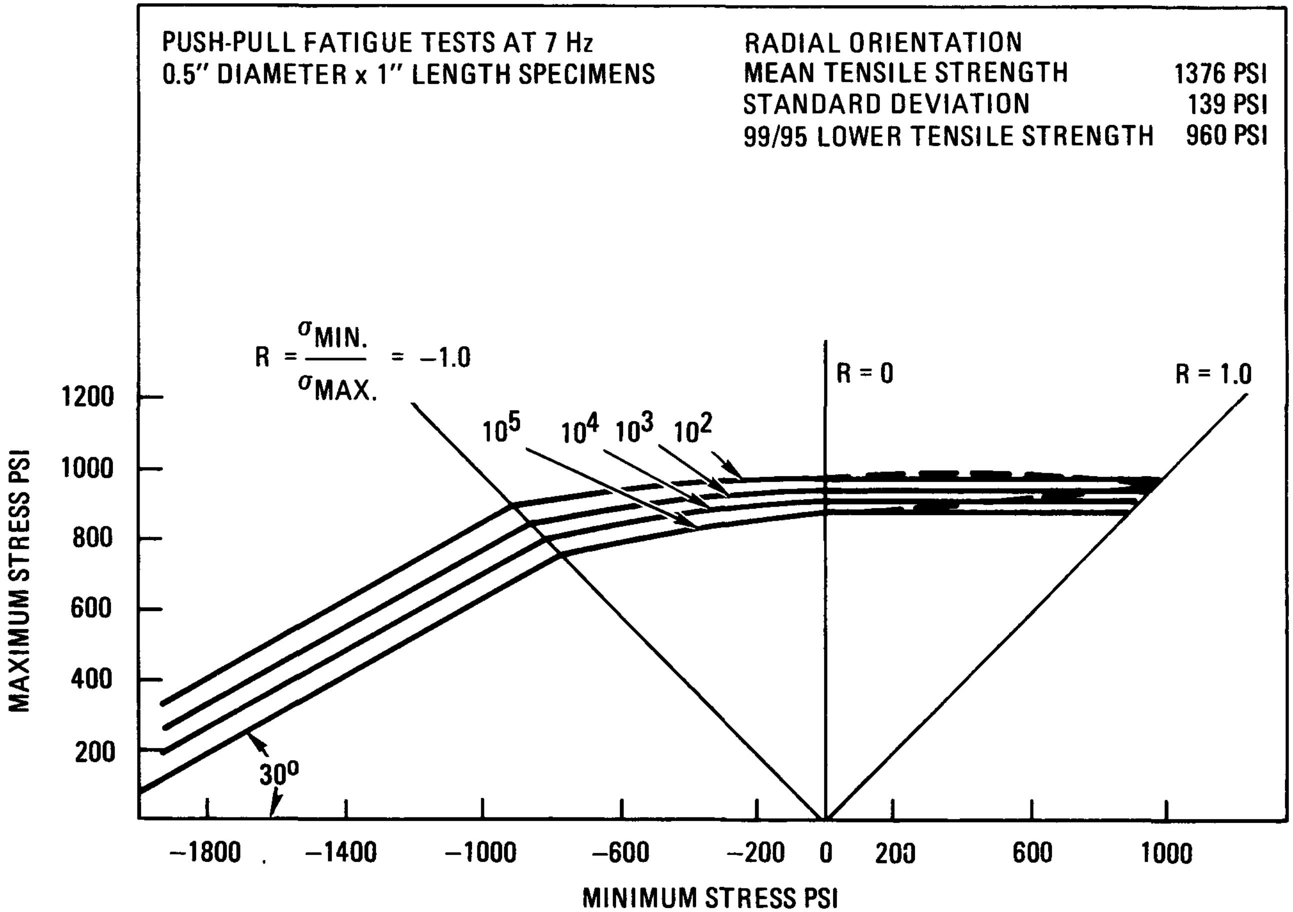

Fig. A-2. Design fatigue diagram for PGX graphite with 99% survival probability and 95% confidence level - radial orientation

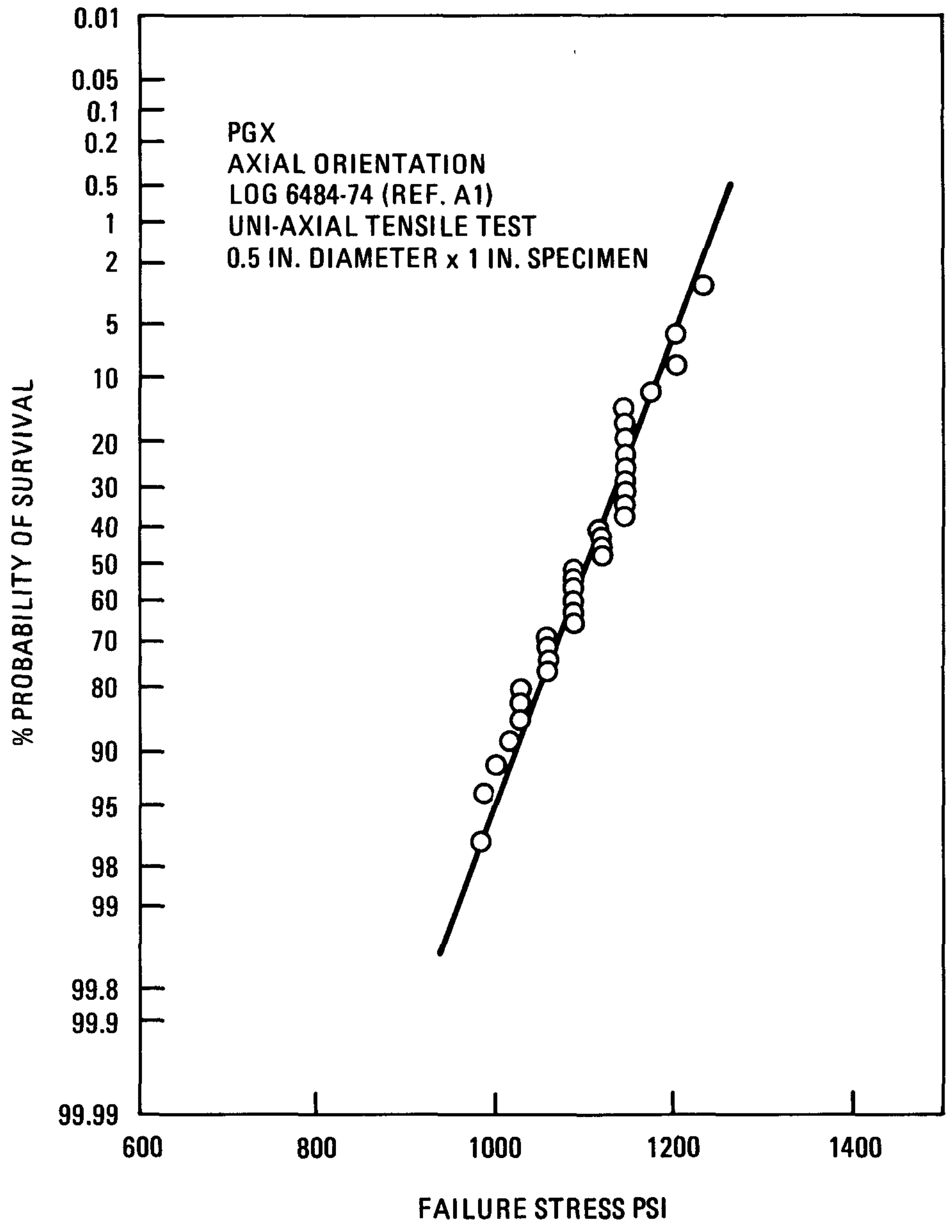

Fig. A-3. Cumulative distribution curve for companion tensile strength - axial orientation

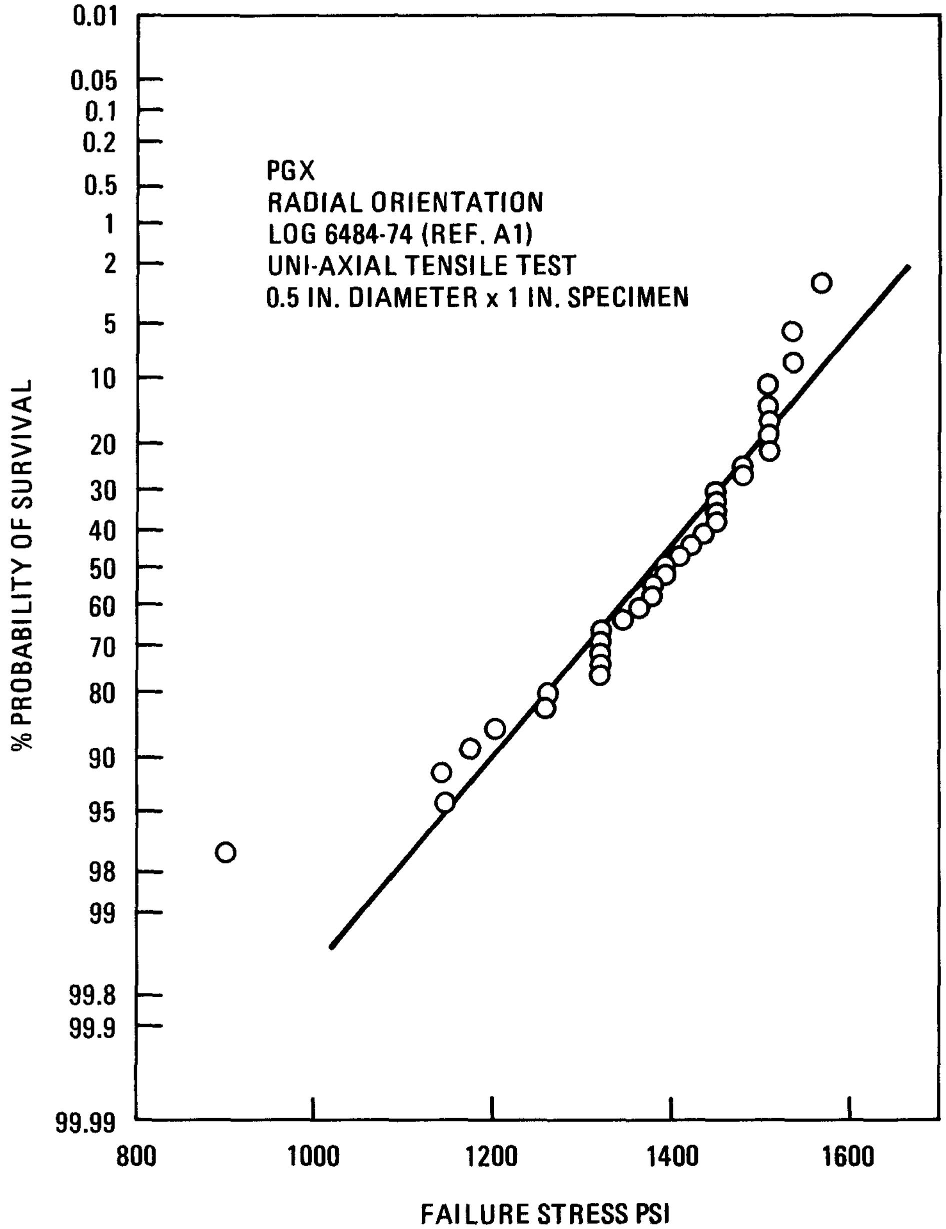

Fig. A-4. Cumulative distribution curve for companion tensile strength - radial orientation

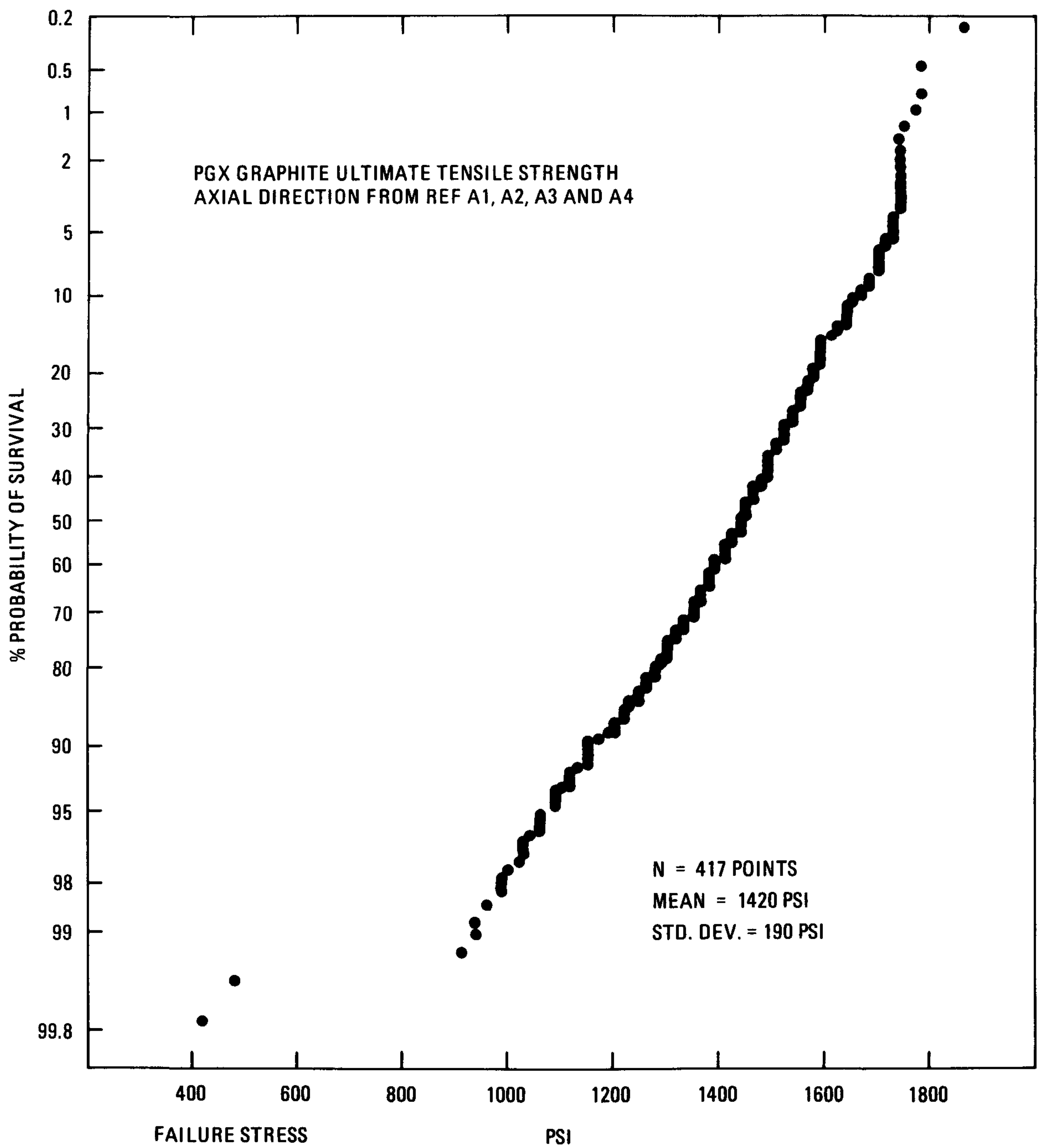

Fig. A-5. PGX graphite ultimate tensile strength axial direction from Refs. A1, A2, A3, and A4

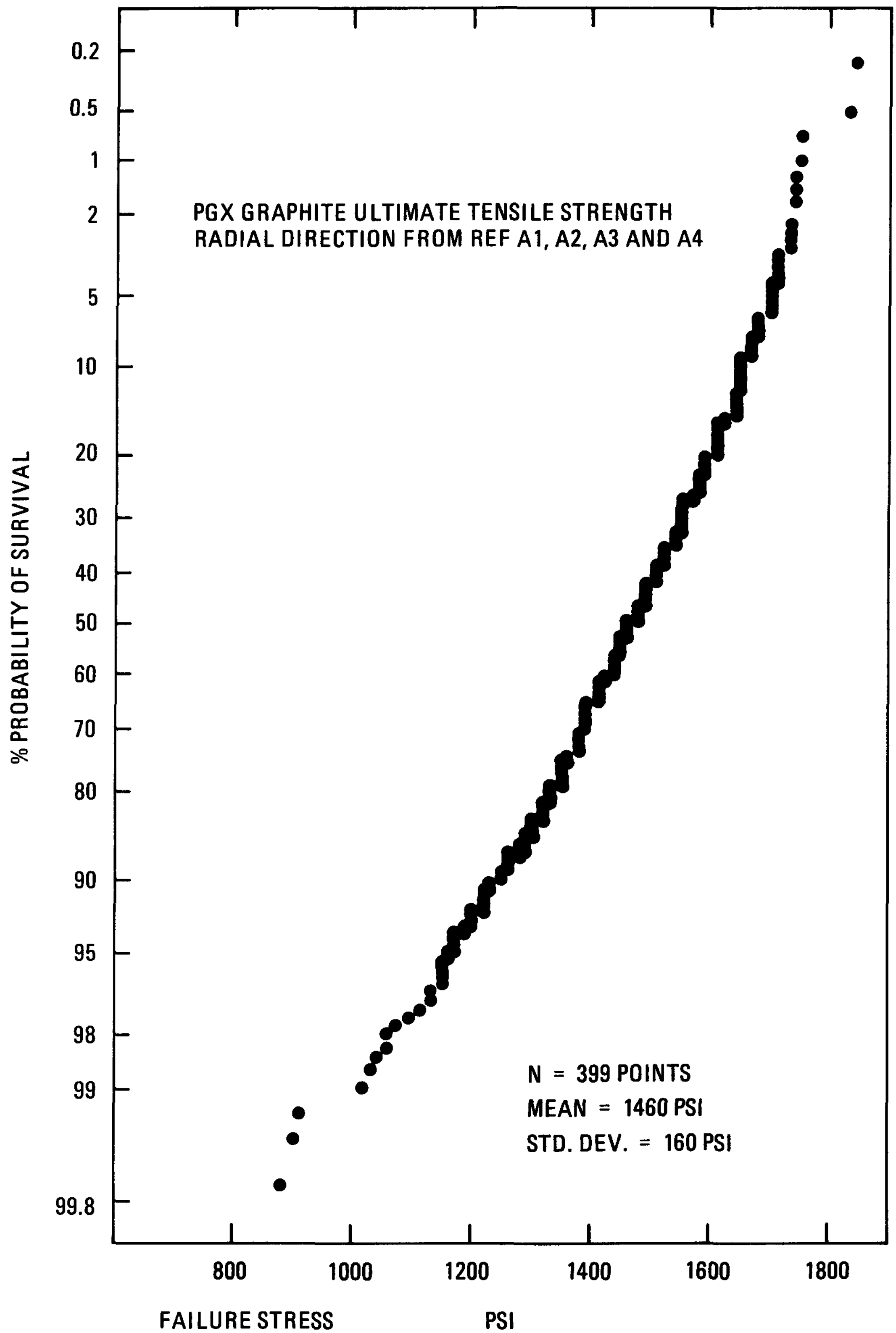

Fig. A-6. PGX graphite ultimate tensile strength radial direction from Refs. A1, A2, A3, and A4

Source	Orientation	Mean Strength (psi)	99/95 Lower Strength (psi)	Standard Deviation (psi)	Number of Specimens
Companion Test	Axial	1105	915	63	34
	Radial	1376	960	139	35
Data Bank	Axial	1420	954	190	417
	Radial	1460	1067	160	399

The mean strengths in both orientations are considerably different between the two sources, the data bank and the companion specimens. The 99/95 lower strengths can be considered reasonably close. When we superimpose Figs. 3 and 4 on Figs. 5 and 6, respectively, it is seen that the lower tails of the distributions of the two populations are quite near each other. The upper tails are significantly different from each other. The maximum deviation occurs almost at the very upper end of the tail. Using the Kolmogorov-Smirnov test for goodness of fit we reject the hypothesis that the companion test population is from the general data bank population at the 1% level. If only the lower tail is emphasized, acceptance can be made at the 1% level. This illustrates that the basis for a correlation parameter is important. The fatigue curves in Figs. A-1 and A-2 may have to be adjusted for design purposes, which certainly depends on the choice of the correlation parameter.

No biaxial or triaxial correction are attempted here, since no quantitative information is readily available.

REFERENCES

A1. R. J. Price, "Cyclic Fatigue of Near-Isotropic Graphite: Influence of Stress Cycle and Neutron Radiation," GA-A14588, November 1977.

A2. G. B. Engle and L. A. Beavan, "Properties of Unirradiated Graphites PGX, HLM, and 2020 for Support and Permanent Side Reflector LHTGR Components," GA-A14646, June 1978.

A3. G. B. Engle, "Properties of Unirradiated HTGR Core Support and Permanent Side Reflector Graphites: PGX, HLM, 2020, and H-440N," GA-A14328, May 1977.

A4. Memo and Data from H. Stuart Starrett, Southern Research Institute, to R. Vollman, General Atomic Co., dated September 29, 1978.