Equivalent Damage - A Critical Assessment

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ABSTRACT

The overall goal of achieving improved life cycle management of aircraft engine, gas turbine components is a major industry thrust. Low Cycle Fatigue (LCF) crack initiation prediction, an important element of life cycle management as traditionally applied, may be overly conservative in estimating total cyclic life capability. Consequently, there is increasing pressure to improve predictive methods both for crack initiation and for subsequent crack propagation. This increased emphasis is the result of significantly higher component replacement costs as a consequence of more complex designs coupled with advanced materials and processing techniques. Moreover, despite added strength, the increased performance demands placed on engine components to achieve higher engine thrust-to-weight ratios have resulted in decreased cyclic lives. It is apparent, therefore, that significant cost savings can be realized through improved accuracy in high temperature, LCF crack initiation prediction.

In practical applications, engine components generally undergo very complex cycles of multiaxial strain, temperature, and dwell time, all of which add uncertainty to the problem of life prediction. During the process of designing and analytically evaluating the lifetime of gas turbine engine components, it is necessary to simplify many of these complexities to make the problem tractable. Nevertheless, there remain several important questions which can be clarified through the study of life prediction models: among these are how to address the problems of multiaxial loading, cumulative damage, and mean stress effects, and how they influence fatigue crack initiation life.

Consequently, an 18-month study was undertaken to determine the utility of equivalent damage concepts for application to hot section components of aircraft engines. Specifically, the topics studied were mean stress, cumulative damage, and multiaxiality. Other factors inherently linked to this study were the basic formulation of damage parameters at elevated temperatures and the fact that hot section components experience severe temperature fluctuations throughout their service lifetime. Both of these latter considerations placed contraints on the level of confidence with which recommendations regarding

specific equivalent damage criteria could be made since most such criteria were developed for use at lower temperatures. Despite this, the study yielded useful results, both from the point of view of data consolidation techniques under isothermal conditions and in producing concepts that will be useful in future studies.

Through a literature review of the three areas of interest, the most promising techniques were extracted for further study. In the case of mean stress techniques, statistical evaluations of suggested approaches were made by comparing each technique to various isothermal data sets. Similiarly, a combined literature review and isothermal data analysis technique was used to determine the most appropriate cumulative damage approach. In the case of multiaxiality, this decision process rested solely on the basis of the literature review. Following the initial screening, both the mean stress techniques and the cumulative damage concepts were tested against data sets involving either time dependent aspects of damage and/or varying temperature. The following conclusions were suggested by this study:

1. The equivalent strain relationship is the best mean stress criteria for low homologous temperatures and aircraft gas turbine engine alloys if the appropriate isothermal data are available. The Leis technique appears to be the best predictive mean stress parameter when data are not available to determine the exponent in the equivalent strain technique.

2. Thermal mechanical fatigue (TMF) experiments are required to verify the mean stress criteria. However, an elevated temperature mean stress criterion should be more conservative than normal approaches when applied to the out-of-phase TMF cycles which are normally encountered in hot path components.

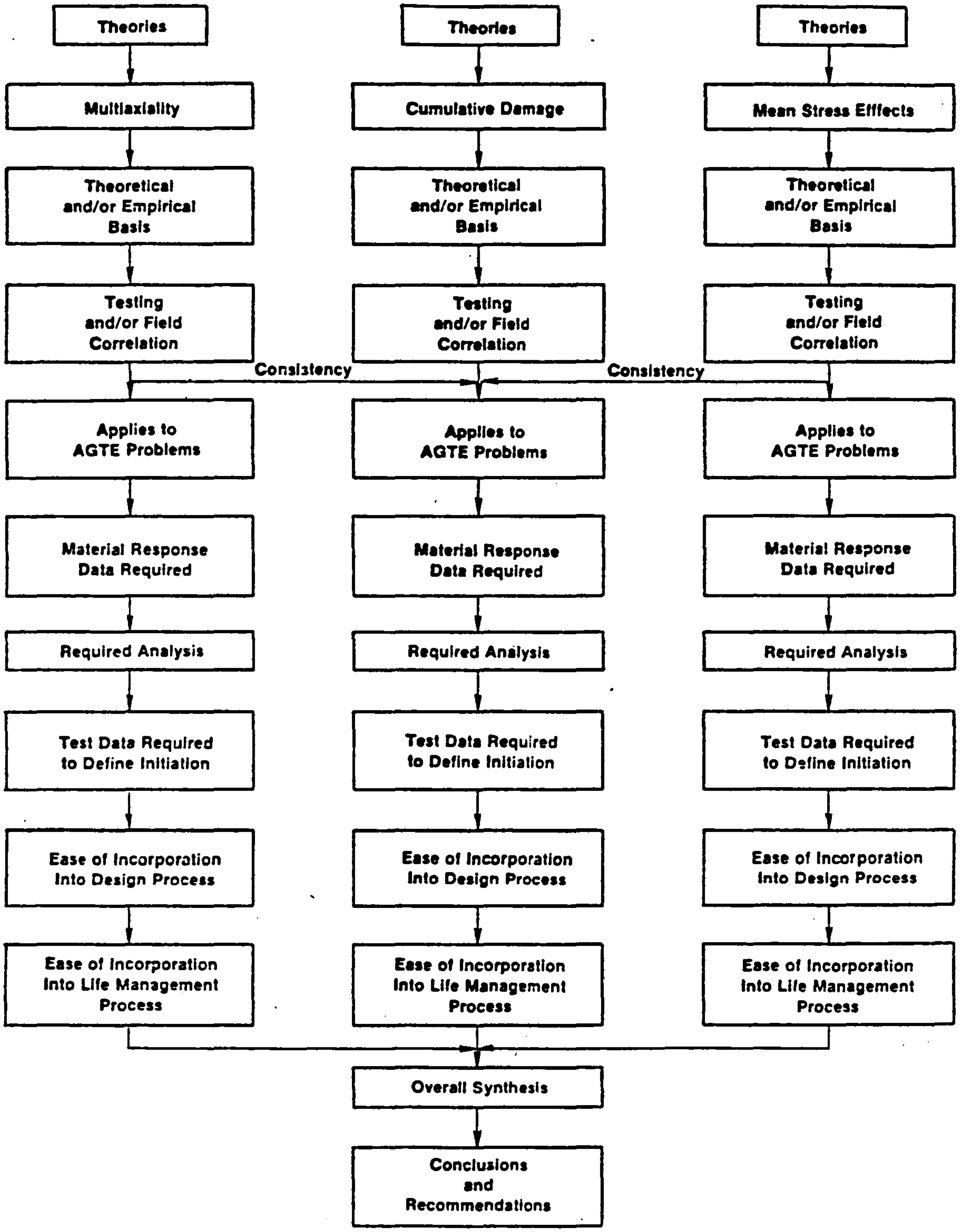
3. Isothermal mean stress criteria should be verified in the longer life (design) regime. Most experimental results are obtained in the shorter cycle life range where more inelastic strain is present. A specific series of experiments was described.

4. The double linear damage rule is the best isothermal cumulative damage technique currently available. However, the technique was not consistent (it was conservative) in predicting a series of two-step tests where a temperature change was introduced into the second block of loading.

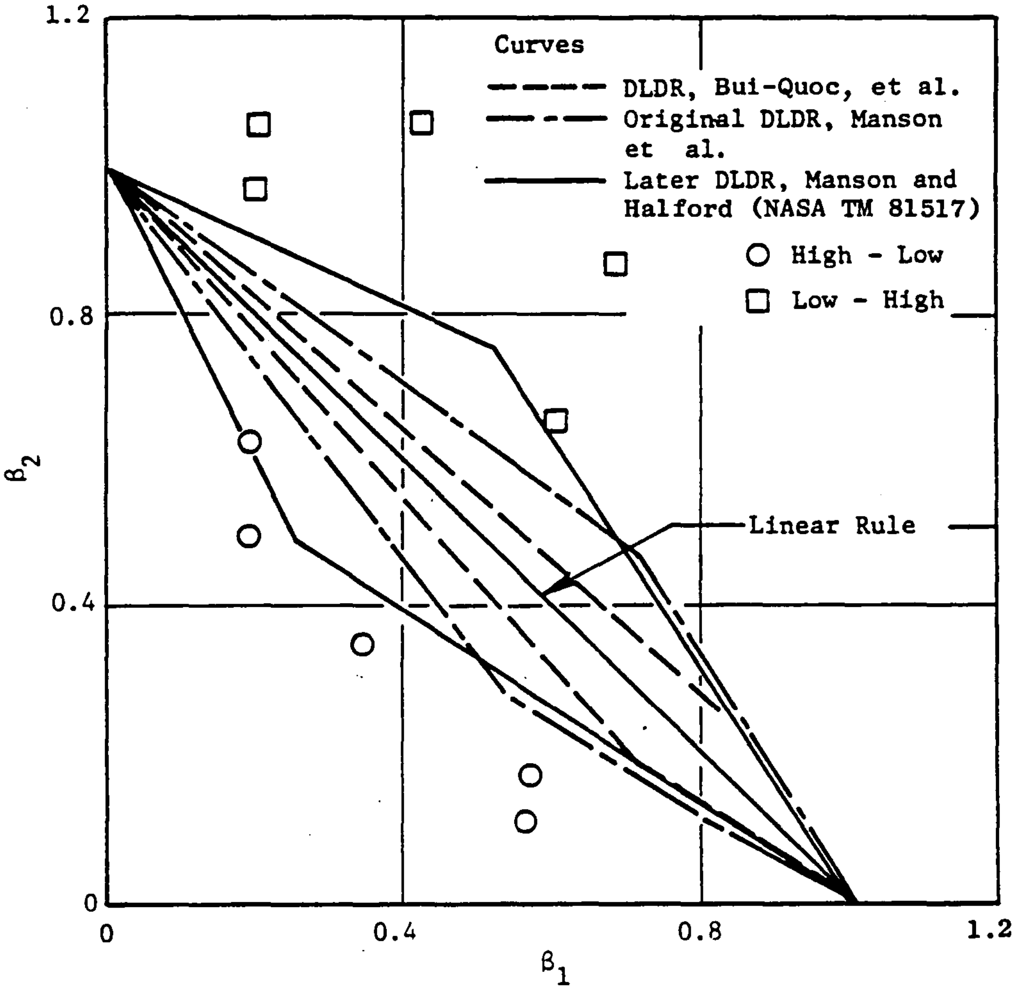
5. A test series was described for developing a consistent damage methodology. These tests used a so-called equal life technique to aid in the formulation of uniaxial equivalent damage criteria, and involved changing temperature during the experiments. Such a test series was viewed as a first step in developing a damage methodology for TMF.

6. A multiaxial equivalence criterion was developed based on a literature review. The criteria deemed important were the use of a triaxiality factor function and a consistent mean stress formulation.

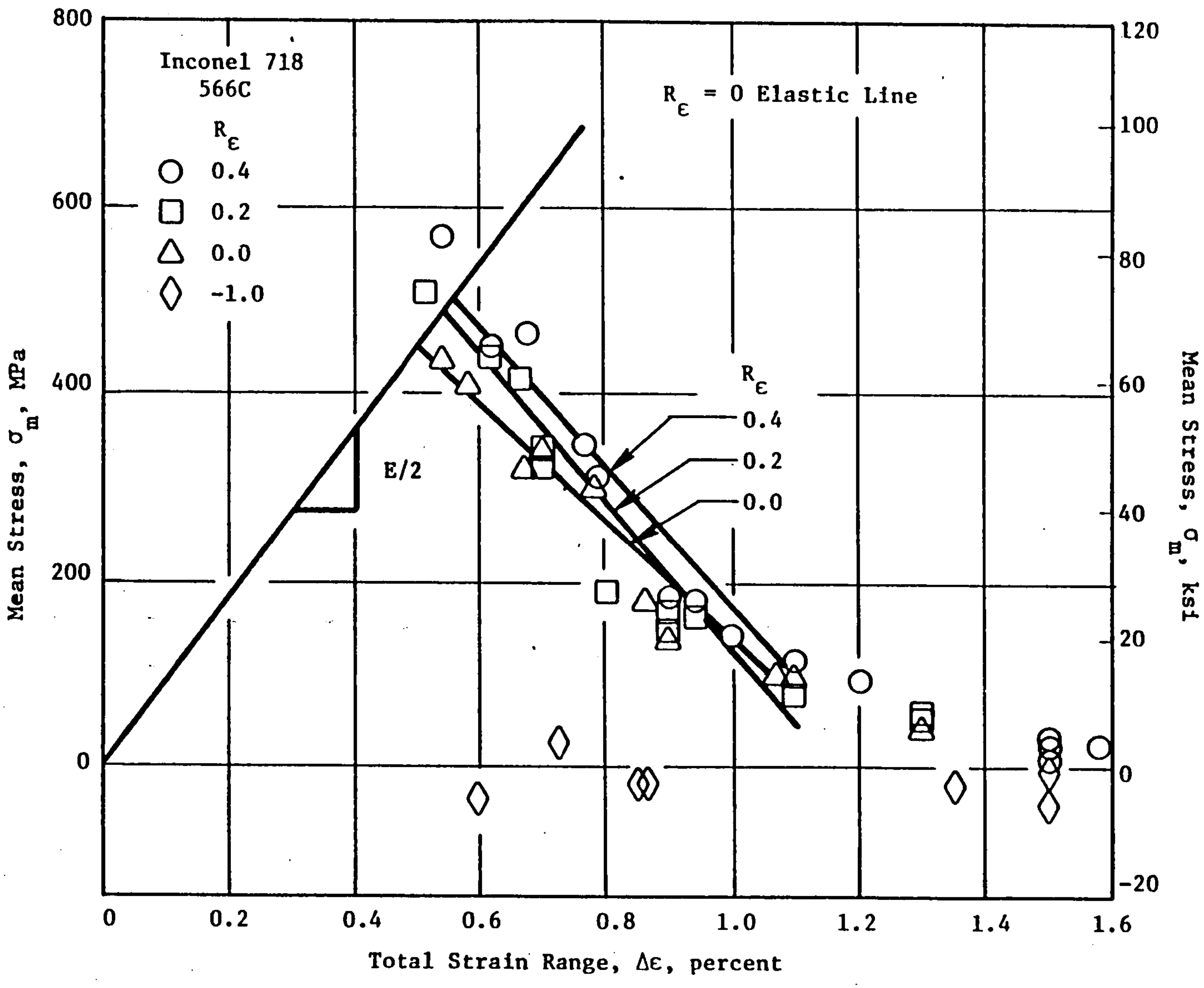
7. A need exists for multiaxial test data on aircraft engine industry alloys. These experiments should concentrate on positive biaxial stress ratios, and should study the effect of mean stress. In general, multiaxial relationships for elevated temperature applications will remain an open research area for quite a while. Current research should concentrate on lower temperature phenomena which would suggest criteria at elevated temperatures. Uniaxial damage considerations at elevated temperatures appear complicated enough for the present.



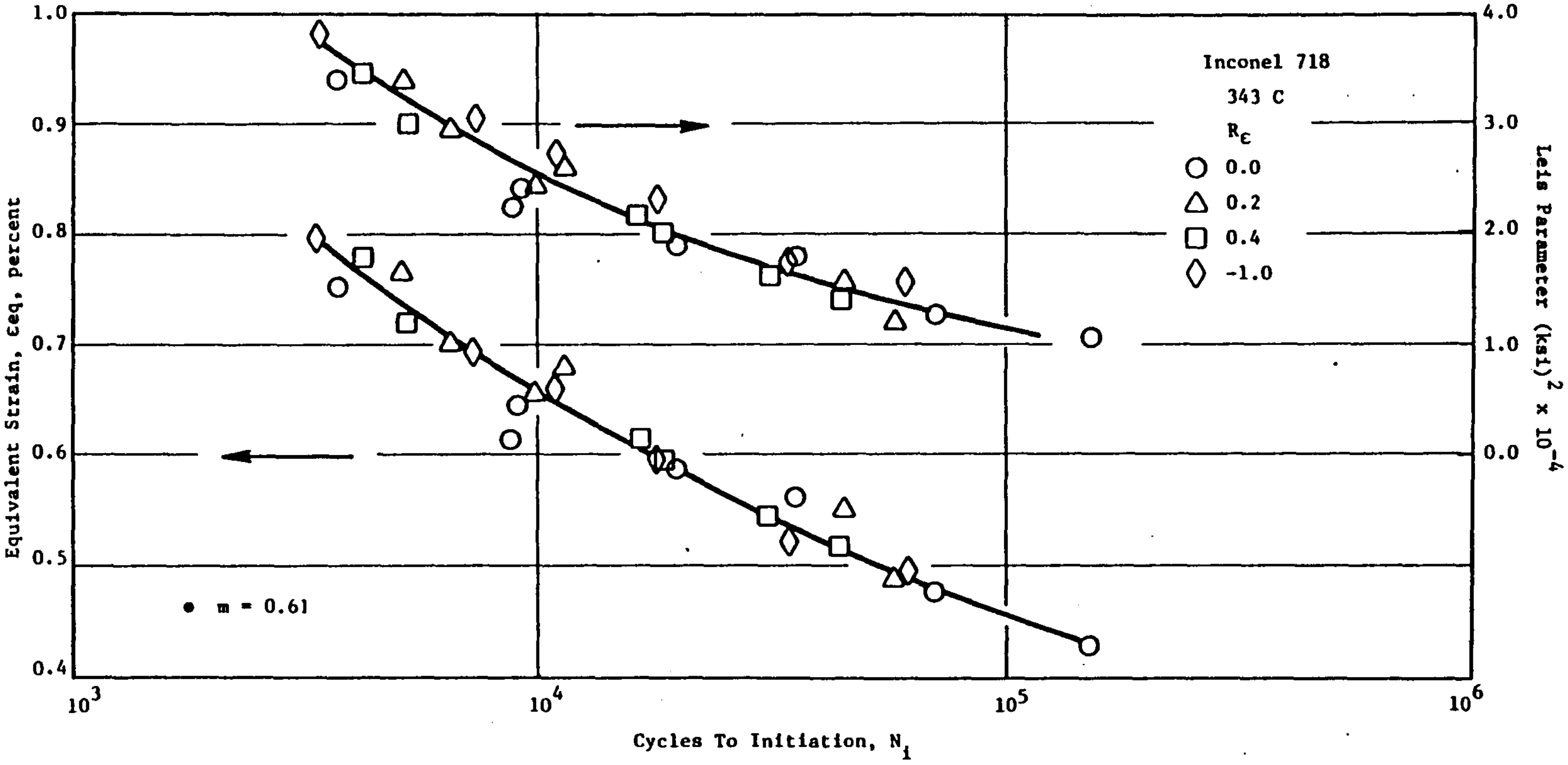
Criteria Diagram.



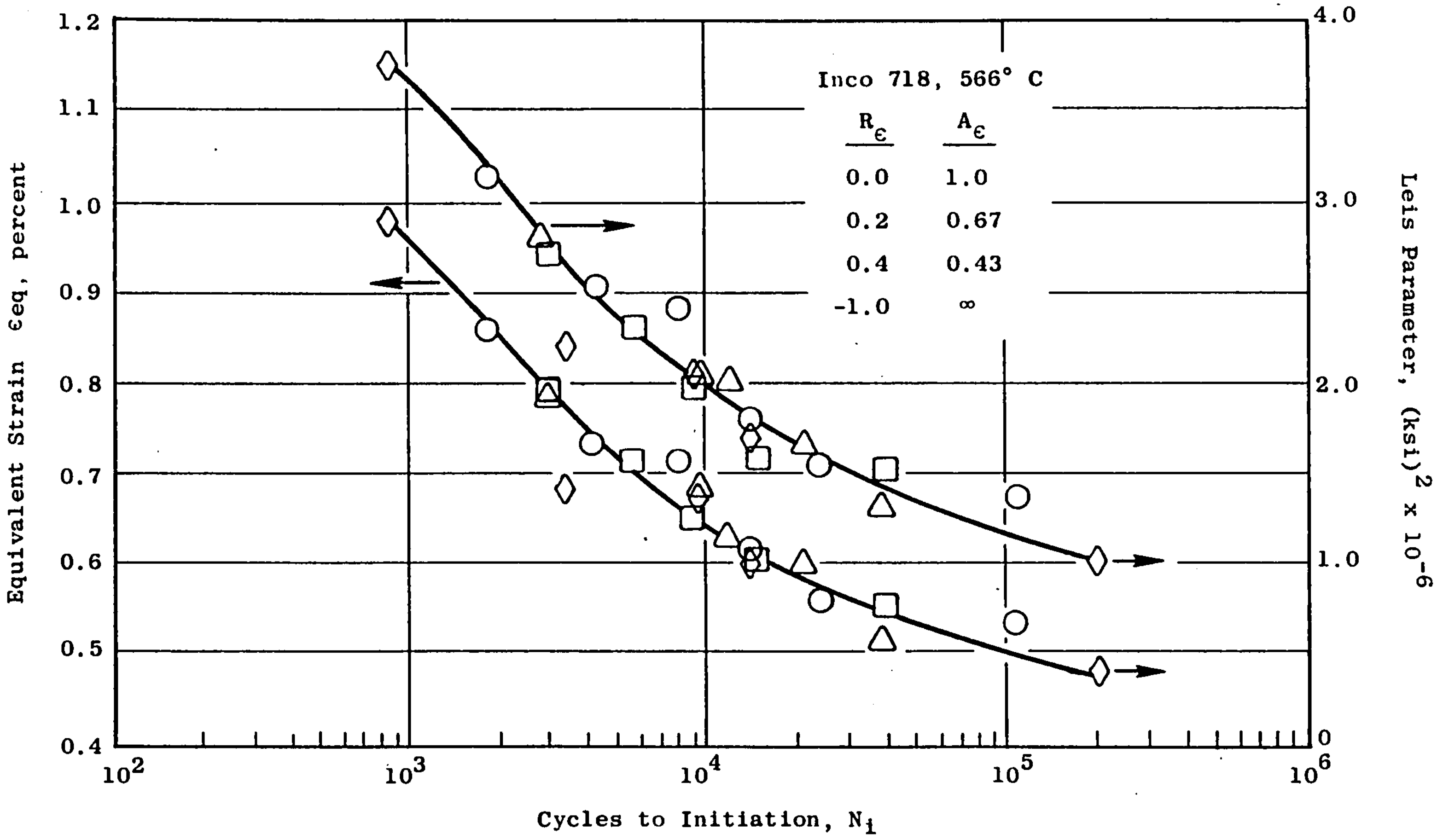
Sequence Test Results Versus Theories; Inconel 718 566° C Three DLDR Theories.



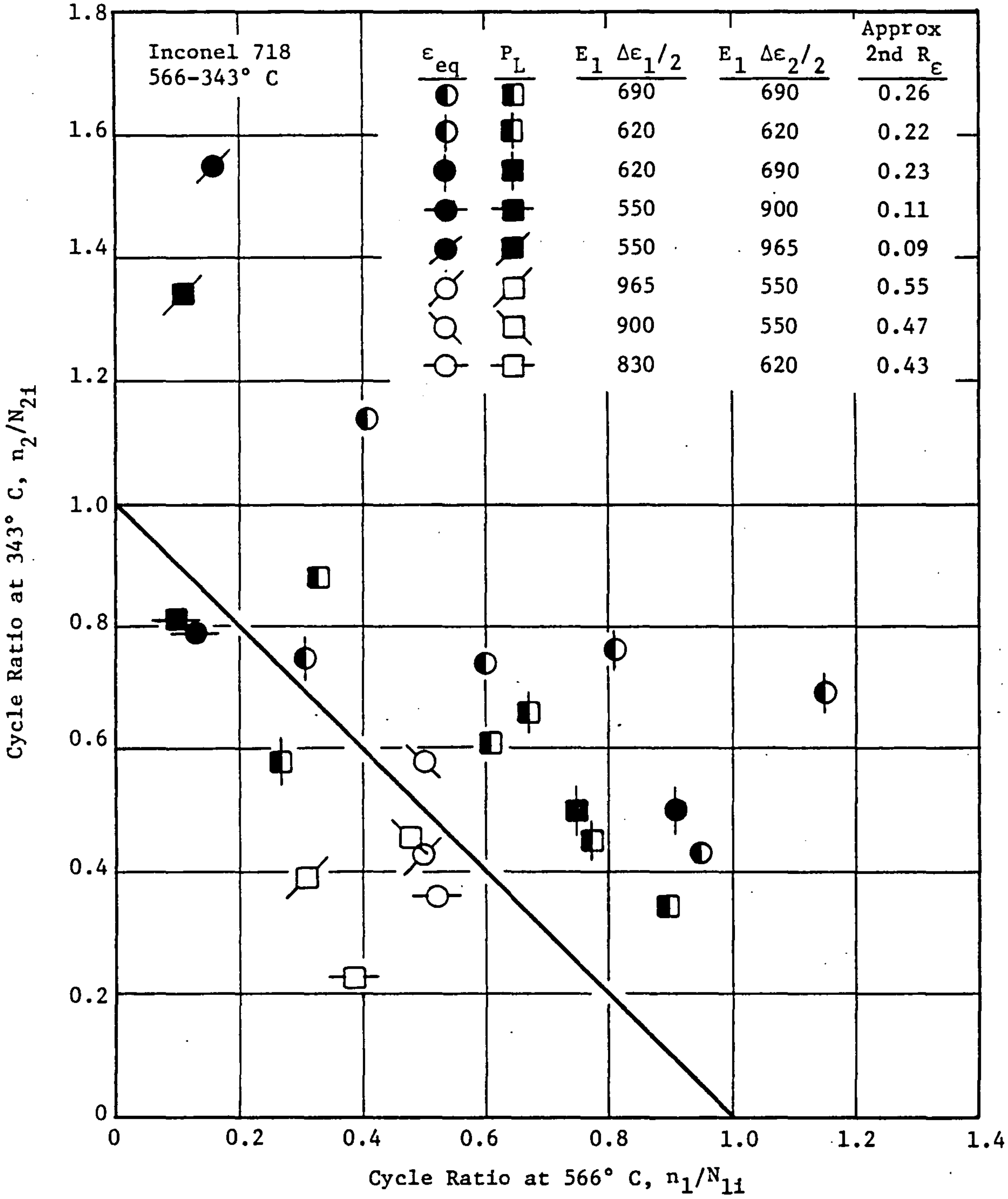
Mean Stress as a Function of Total Strain Range for Inconel 718 at 566° C, 20 CPM.



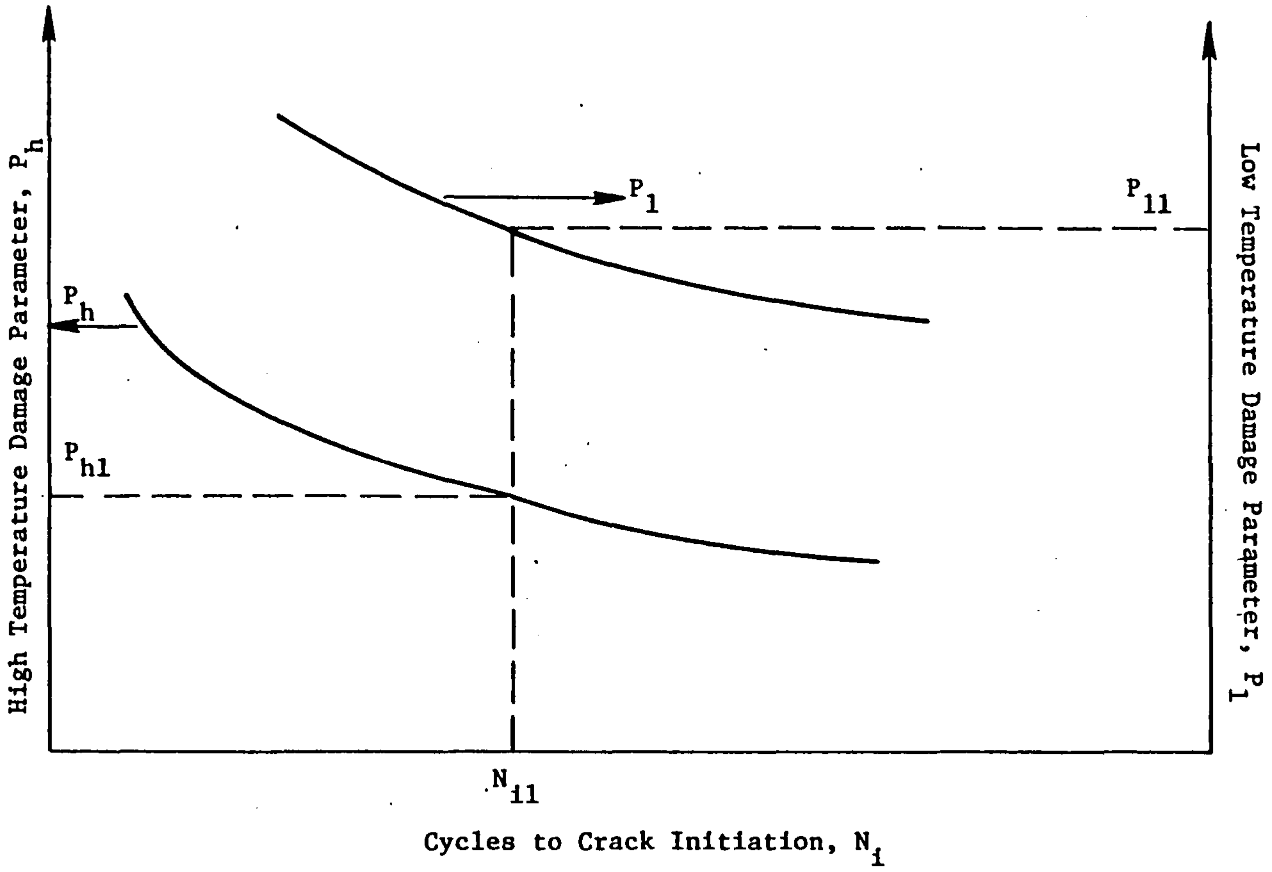
Baseline Data at 343° C Analyzed by the Equivalent Strain and Leis Parameter Methods.



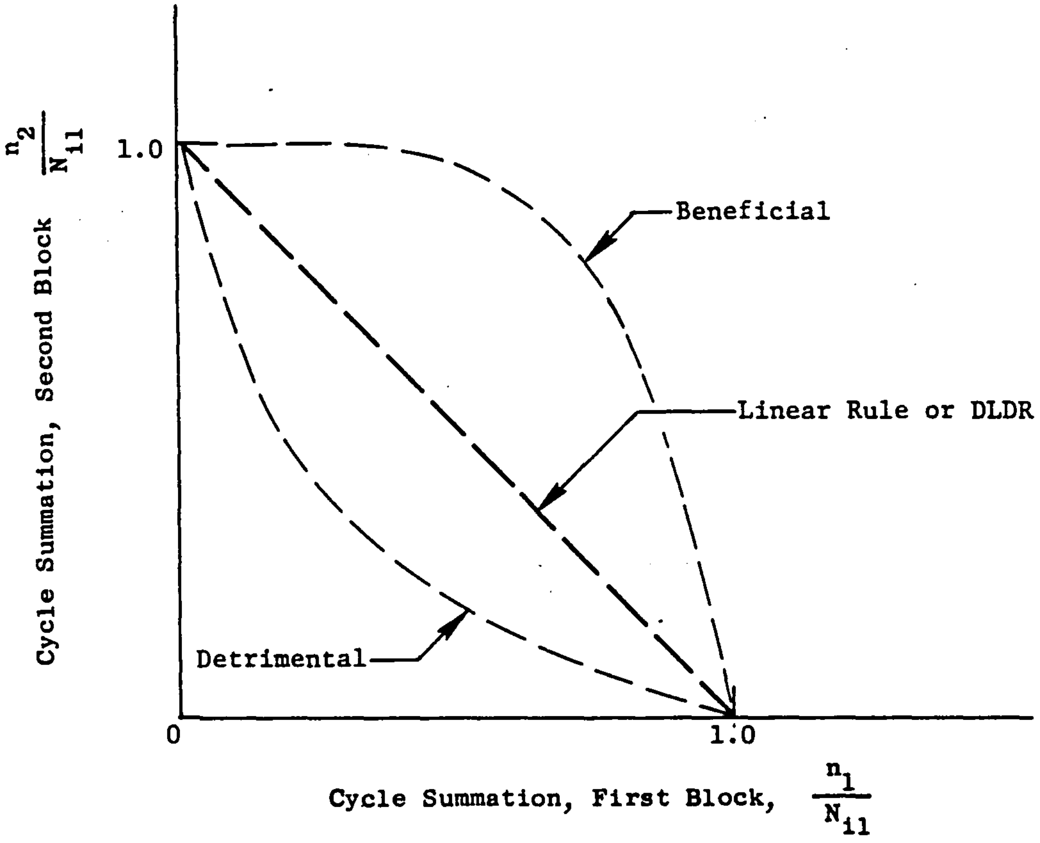
Baseline Data at 566° C Analyzed by the Equivalent Strain and Leis Parameter Methods.



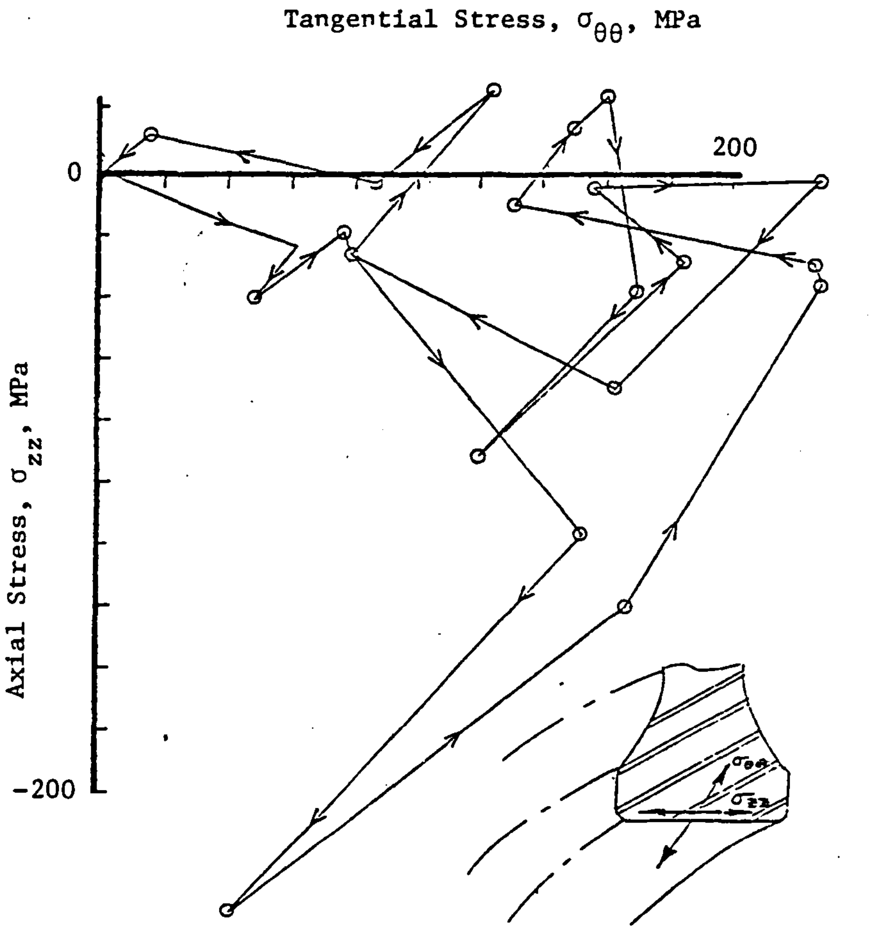
Results of Two-Step Load/Temperature Tests: R_ε Variable in Second Step.



Generalized Equal-Life Test.



Potential Results of Equal-Life Tests.



Example of the Complex States of Stress That Can Evolve During a Simulated Mission in a Disk Bore.

Suggested Multiaxial Formulation

$$\frac{\Delta \epsilon_e}{2} = \frac{\epsilon_f}{f_2(TF)} (2N_f)^{-\alpha} + \left(\frac{\sigma_f - k^* I_{\underset{\sim}{\sigma} m}}{E^*} \right) (2N_f)^{-\beta}$$

Where:

$$\Delta \epsilon_e = \sqrt{\frac{2}{3} \Delta e_{ij} \Delta e_{ij}}$$

$$e_{ij} = \epsilon_{ij} - \frac{1}{3} \epsilon_{kk} \delta_{ij}$$

$$TF = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}}$$

$$I_{\underset{\sim}{\sigma} m} = \sigma_{1m} + \sigma_{2m} + \sigma_{3m}$$

$$E^* = \frac{3E}{2(1+\mu)}$$

ϵ_f, α, σ_f, k^*, β are material parameters

N_f = Cycles to Failure