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LIFE PREDICTION MODELING BASED ON CYCLIC DAMAGE ACCUMULATION

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A high temperature, low cycle fatigue life prediction method has been developed by Pratt & Whitney under the sponsorship of the Lewis Research Center's Gas Turbine Engine Hot Section Technology Program (HOST) (Moreno et al, 1984). This method, Cyclic Damage Accumulation, has been developed for use in predicting the crack initiation lifetime of gas turbine engine materials, where initiation has been defined as a 0.030 in. surface length crack. A principal engineering feature of the CDA method is the minimum data base required for implementation. Model constants can be evaluated through a few simple specimen tests such as monotonic loading and rapid cycle fatigue. The method has been expanded to account for the effects on creep-fatigue life of complex loadings such as thermomechanical fatigue, hold periods, waveshapes, mean stresses, multiaxiality, cumulative damage, coatings, and environmental attack (Nelson et al, 1986). A significant database has been generated on the behavior of the cast nickel-base superalloy B1900+Hf, including hundreds of specimen tests under such loading conditions. This information is being used to refine and extend the CDA life prediction model, which is now nearing completion. The model is also being verified using additional specimen tests on wrought INCO 718, and the final version of the model is expected to be adaptable to most any high-temperature alloy. The model is currently available in the form of equations and related constants. A proposed contract addition will make the model available in the near future in the form of a computer code to potential users.
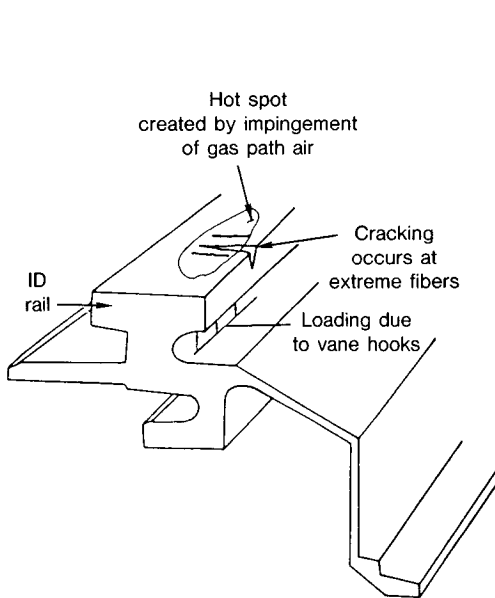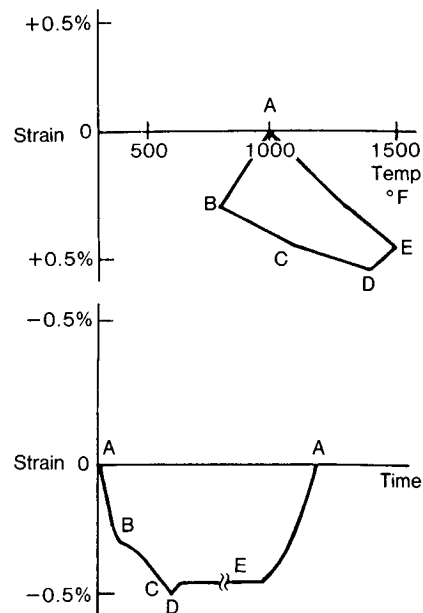
LIFE PREDICTION MODELING BASED ON CYCLIC DAMAGE ACCUMULATION (CDA)

Modern applications of high strength materials often involve high homologous temperatures (greater than 0.5) combined with complex time-varying stresses and strains. The figure shown here depicts typical strain and temperature histories for such a location and shows the resulting damage to the structure after application of a sufficient number of these cycles. Clearly, this situation gives rise to many difficulties when life predictions are required for such service conditions, since several different damage mechanisms (such as creep, fatigue, and oxidation) may be activated simultaneously. Many researchers have devoted large portions of their careers to the solution of such problems and have developed several useful techniques for high temperature life prediction in the presence of creep-fatigue-environment interactions (Halford, 1986; Cailletaud et al, 1983). In order to build on their work and to enhance hot section durability, the current effort was sponsored by the Lewis Research Center's Gas Turbine Engine Hot Section Technology Program (HOST). The intent of this work has been to examine fundamental approaches to high temperature crack initiation life prediction, identify modeling strategies, and develop a practical model which can produce accurate life predictions for a wide range of component relevant conditions (Moreno et al, 1984). Though originally developed for aerospace use, the work is relevant to most high temperature applications of current and future isotropic alloys.

THE EFFECTS OF COMPLEX STRAIN AND TEMPERATURE HISTORIES
MUST BE DETERMINED FOR ACCURATE LIFE PREDICTIONS


Outer vane support
TMF crack location

Critical location
strain-temp-time histories

EXECUTIVE OVERVIEW OF:

LIFE PREDICTION MODELING BASED ON CYCLIC DAMAGE ACCUMULATION (CDA)

The work under the HOST contract began with a base program during which existing life prediction approaches were examined in detail. Monotonic tests and continuously cycled strain controlled isothermal fatigue tests of cast B1900+Hf specimens were performed to provide baseline data for comparison. Desirable features from several of these methods were identified, and the result was a new approach for life prediction called Cyclic Damage Accumulation (CDA). This is being expanded during the option portion of the program to account for the effects of thermomechanical fatigue, multiaxiality, cumulative damage, environment, coatings, and mean stresses (Nelson et al, 1986). The B1900+Hf specimen database has been greatly expanded during this work to provide clear data regarding material behavior under such complex conditions. Finally, the CDA model is being refined and modified to account for the behavior of other types of high temperature engineering alloys, wrought INCO 718 being used as the alternate model material for this work. It should be noted that these databases will, when completed, comprise the results of approximately 350 specimen tests of B1900+Hf and 110 specimen tests of INCO 718. By themselves, they are therefore of great interest to any researcher in the field of high temperature life prediction. A proposed extension to the contract would also provide software of immediate value to those desiring to perform high temperature life predictions using the CDA method.

HOST ISOTROPIC CREEP-FATIGUE CONTRACT HAS PRODUCED EXTENSIVE DATABASES AND PRACTICAL LIFE MODEL

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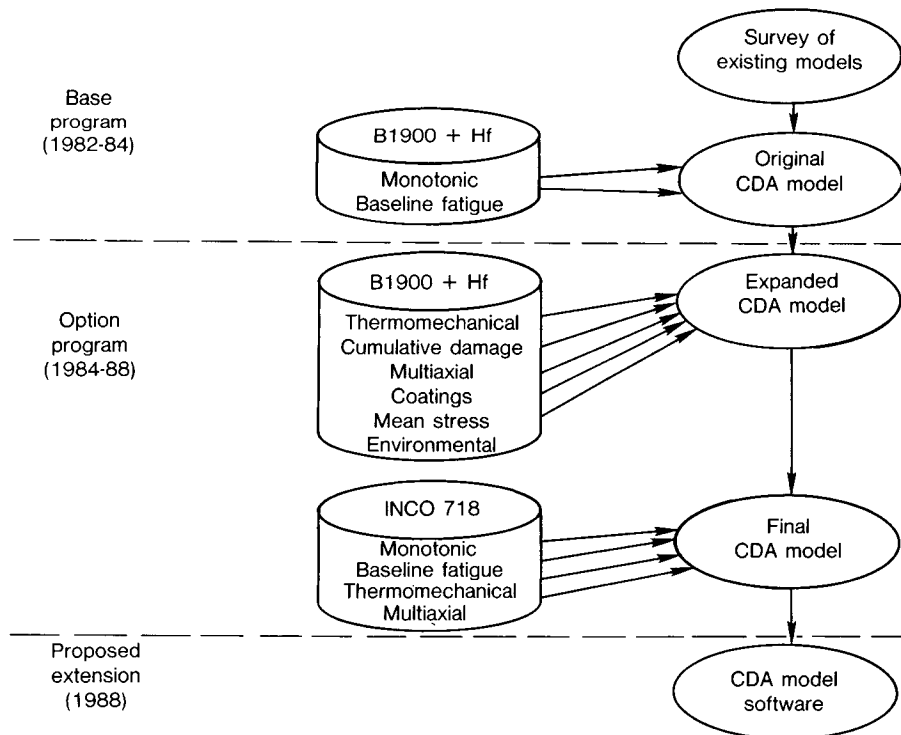
CUMULATIVE DAMAGE TESTS DEMONSTRATED THE
## USEFULNESS OF THE BASIC CDA APPROACH

One of the important features of the Cyclic Damage Accumulation (CDA) life prediction model developed during the base portion of this contract is the use of a ductility variable which represents the fatigue capability of the material as a function of the loading history. It was observed that the dislocation structure produced during the primary phase of a creep test was very similar to that which developed during fatigue. The amount of total accumulated primary creep was found to be a function of both temperature and maximum applied stress. The CDA life prediction model therefore uses primary creep ductility as a measure of fatigue capability, and the damage accumulation rates for the various temperatures are calculated using this concept.

Cumulative damage tests were completed as part of the option program, including block tests (strain ratio, temperature, and hold time), sequenced tests (strain range and rate), and interrupted tests (prior creep and interspersed exposure time). The block strain ratio results are shown below, where the level of prior loading and its duration are seen to have pronounced effects on the life of subsequent block loading. This effect is easily captured using the CDA concept of primary creep ductility, since this variable will depend on the prior loading history. The cumulative damage tests also showed the need to incorporate a non-linear damage accumulation function to predict sequence effects correctly.
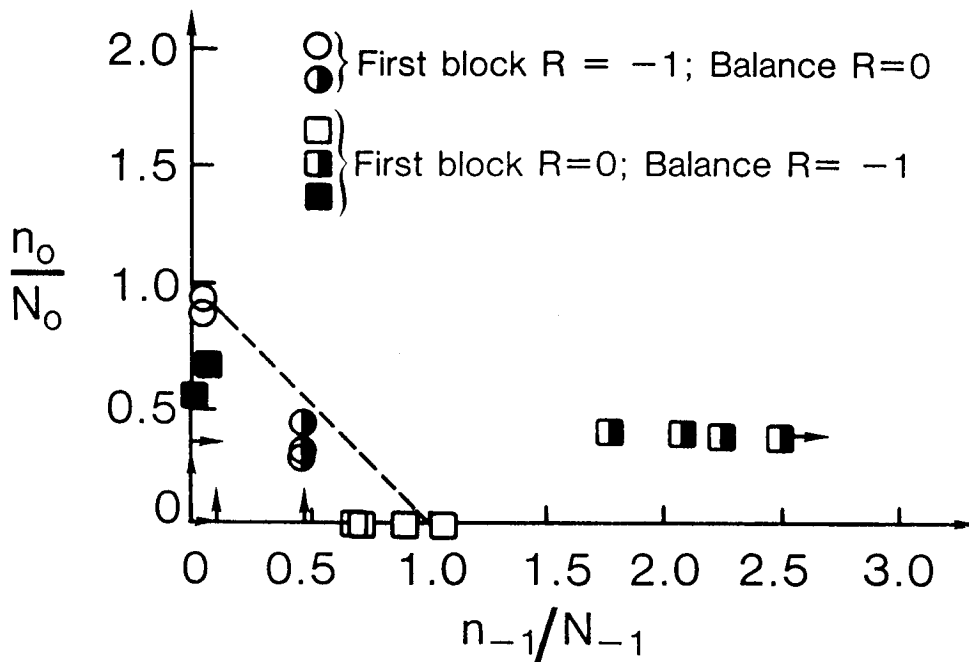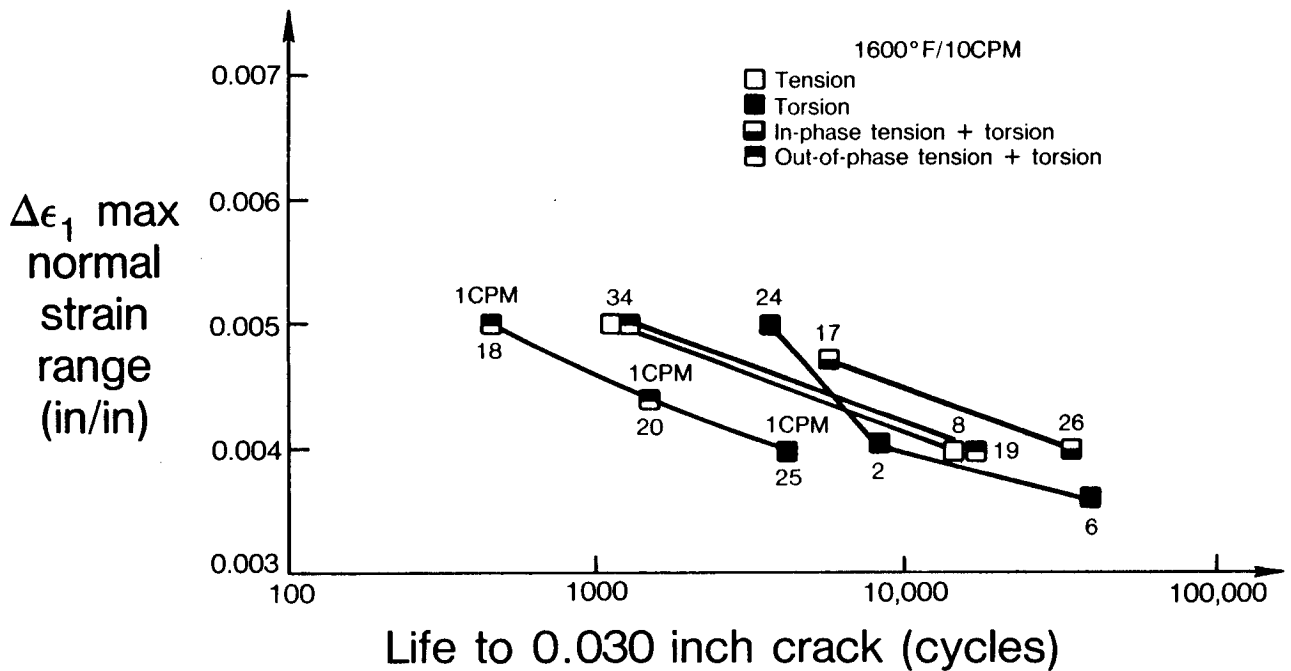
TMF LIFE PREDICTION MUST ACCOUNT FOR STRONG INFLUENCES SUCH AS COATINGS AND CYCLE PATH

Prediction of initiation life under conditions of thermomechanical fatigue is one of most important practical applications of any advanced creep-fatigue life model. Such conditions of simultaneously varying strain and temperature are typical of what is experienced by many components of modern turbomachinery and powerplants. To complicate matters further, the alloys used in such applications are often coated to prevent oxidation or other environmental attack. Such conditions were simulated during the option portion of this program using many types of strain-temperature cycle paths, including in-phase, out-of-phase, "dogleg" (non-isothermal holds), and elliptical cycles. The B1900+Hf specimens were run in one of three conditions: uncoated, overlay coated, or diffusion aluminide coated. The INCO 718 TMF specimens were run using similar strain-temperature cycles and were all uncoated. The results shown below are typical of the effects produced by such variables, indicating that successful life models must be able to account for these effects. The modifications to the CDA model currently in progress will enable it to accept completely arbitrary histories of stress-strain-temperature and thereby make accurate TMF life predictions. A constitutive and life model for coatings from a companion HOST contract will also be incorporated (Swanson et al, 1987).
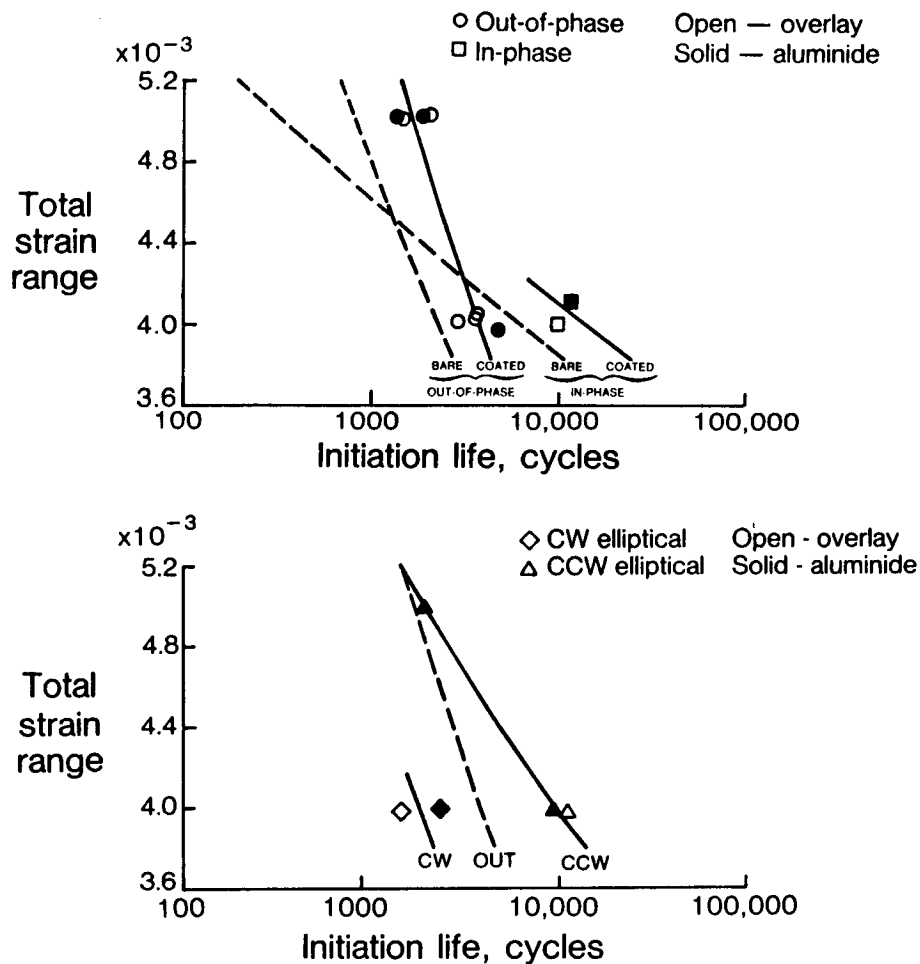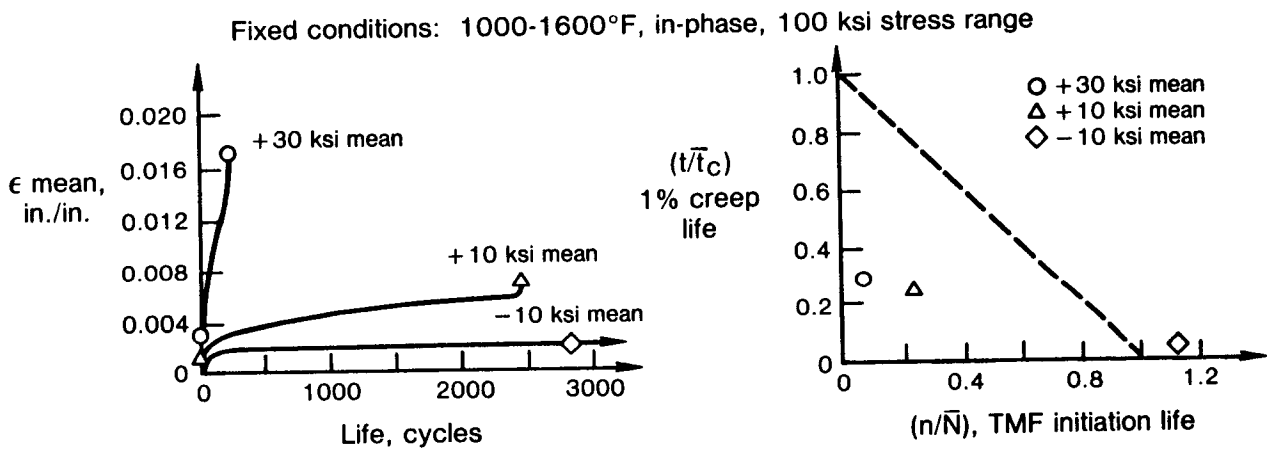
MULTIAXIAL EFFECTS HAVE BEEN INVESTIGATED
AND ARE BEING INCORPORATED INTO CDA MODEL

Certain areas of high temperature components, such as blade/platform intersections and disk webs, may be subject to loading conditions which have a high degree of multiaxiality. Also, three-dimensional analysis programs often express calculated stress and strain tensors in coordinate systems which are not aligned with the local component loads. In both of these cases, some method is needed to determine the invariant parameter(s) which best characterize the initiation life under such conditions. As part of the option program, both alloys were tested under strain controlled multiaxial conditions at elevated temperatures by Prof. Eric Jordan at the University of Connecticut. Part of the data generated for B1900+Hf are shown in the figure below, where it can be seen that maximum normal strain range does a reasonably good job of correlating the data at 871°C (1600°F). Preliminary indications are that a modified maximum shear strain range parameter will provide the best correlation for the INCO 718 multiaxial data. A preprocessor module currently being developed will allow the CDA model to incorporate the flexibility needed to adjust to such differences in modern engineering alloys.


$\Delta\epsilon_1$ max normal strain range (in/in)

Life to 0.030 inch crack (cycles)

1600°F/10CPM
☐ Tension
■ Torsion
▢ In-phase tension + torsion
▣ Out-of-phase tension + torsion

MEAN STRESS EFFECTS CAN BE NON-LINEAR
FOR BOTH ISOTHERMAL AND TMF CONDITIONS

It has been known for many years that a superimposed mean stress can have pronounced effect on fatigue life. Such conditions occur in both high and moderate temperature applications and can have different effects, depending on what types of damage modes are active at the temperatures involved. Isothermal experiments during which both the strain range and the mean stress are independently controlled are underway at the University of Rhode Island under the direction of Prof. Hamouda Ghonem. The temperatures chosen for these tests will span a range of active damage mechanisms for both B1900+Hf and INCO 718. Thermomechanical load controlled experiments have been completed on both alloys at Pratt & Whitney, and the figures shown below present the results of three of these tests. Clearly, the influence of mean stress cannot be predicted using a linear damage interaction rule combined with lives predicted for pure creep or TMF under similar conditions. The CDA model is being refined to account for this type of effect as part of its basic formulation. The inherent capability of the primary creep ductility variable will provide the basis for this work.

Fixed conditions: 1000-1600°F, in-phase, 100 ksi stress range

ϵ mean, in./in.

Life, cycles

$(t/\bar{t}_c)$ 1% creep life

O +30 ksi mean
Δ +10 ksi mean
◇ −10 ksi mean

(n/N̄), TMF initiation life

ADVANCED VISCOPLASTIC CONSTITUTIVE MODELS ARE
AVAILABLE FROM A COMPANION HOST CONTRACT

Advanced life prediction models such as CDA rely heavily on accurate knowledge of the local stress-strain conditions at the point of interest. With specimen data, these variables can be measured and used for direct correlation of the life results. For example, the figure shown below shows the measured stress response of B1900+Hf to various TMF cycles. The obvious differences in maximum stress history will significantly affect the crack initiation life and therefore must be well known. However, for design and analysis of actual components, the stress-strain behavior will generally have to be predicted using some kind of analytical method. For the base alloy from this program, two advanced viscoplastic constitutive models have been produced by a companion HOST contract (Chan et al, 1986). The basic methods used for these models can be expanded to predict the behavior of most alloys for which CDA life model constants would be desired, thus providing the framework for a complete analysis system for high temperature life prediction.
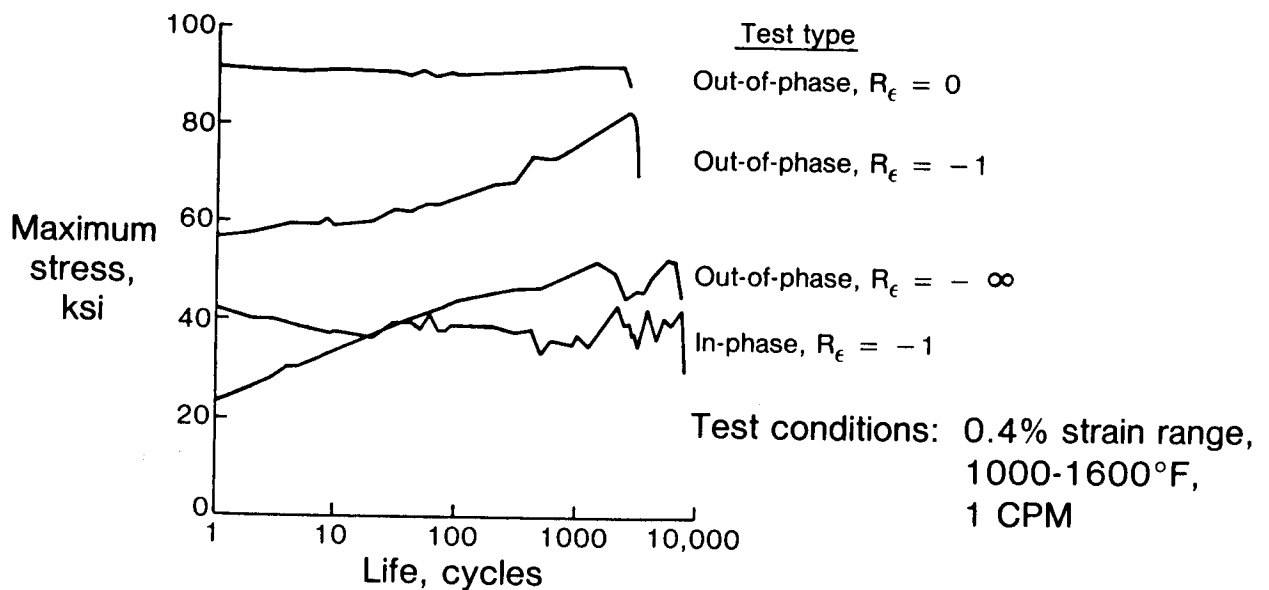
The fundamental equations of the CDA life prediction model are based on the integration of damage rates for various mechanisms for a particular material. For example, shown below are the two basic integrals which must be evaluated for the transgranular and intergranular damage modes for B1900+Hf. Note the incorporation of the primary creep ductility term and the non-linear damage accumulation function, both of which have been previously described. It is important also to note that, wherever possible, the actual calculations are based on ratios of current parameters relative to those from simple tests (the "reference" values shown in the equations with "R" subscripts). This enables the CDA life constants to be determined from low cost, simple tests rather than expensive, complex tests. Other damage modes (such as environmental) will be incorporated using the same methodology, including interaction with current modes through appropriate factors and equations. The final form of the CDA equations is still under development but will continue to include the same features. All modes for a given material will be evaluated simultaneously on a cycle-by-cycle basis using efficient adaptive techniques.

- ## Transgranular damage mode:

$$1 = \int_0^{N_i} \left(\frac{1}{\bar{\epsilon}\,p}\right)\left(\frac{1}{G_{NL}}\right)\left(\frac{dD}{dN}\right)_R \left[\left(\frac{\Delta\sigma}{\Delta\sigma_R}\right)\left(\frac{\sigma_T}{\sigma_{TR}}\right) + D_{TD}\left(\frac{fox}{fox_R}\right)\right] dN$$
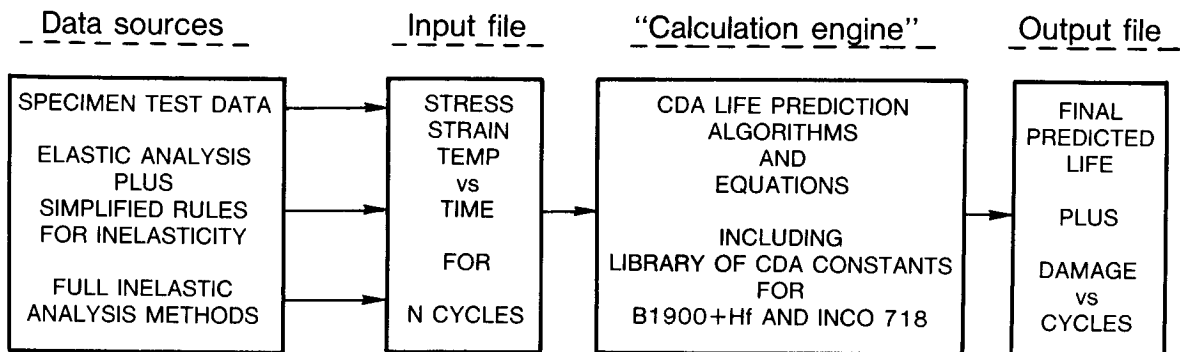
- ## Intergranular damage mode:

$$1 = \int_0^{N_i} \left(\oint_{cycle\ i} \frac{dt}{t_{cr}\,(\sigma,T)}\right)\left(\frac{fox}{fox_R}\right) dN$$

- ## Constants derived from simple tests

PROGRAM IS MODULAR TO PROVIDE MAXIMUM
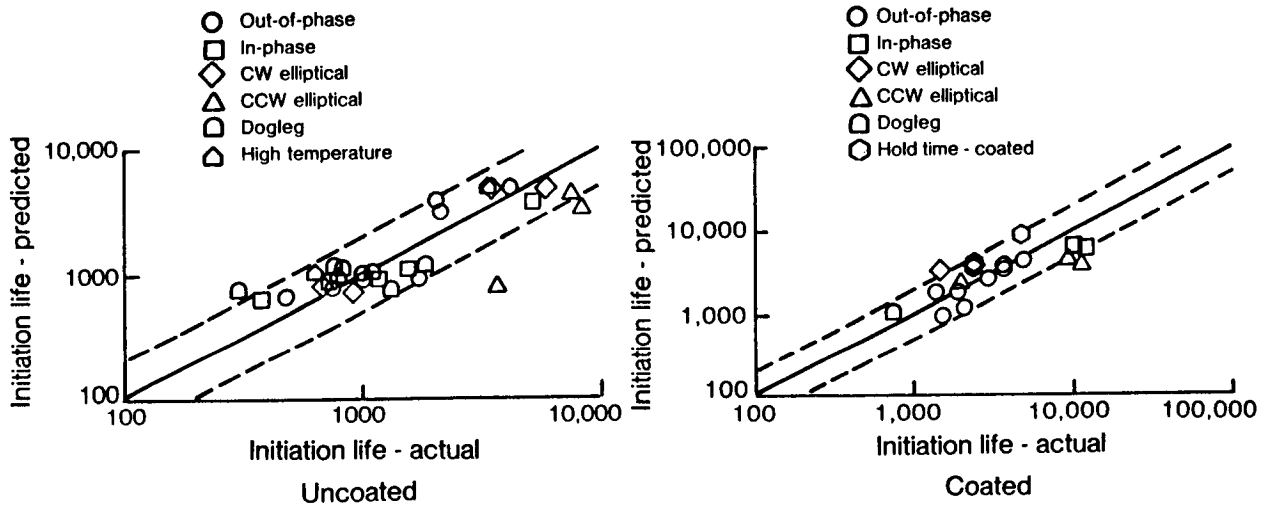## EFFICIENCY AND FLEXIBILITY FOR EXPANSION

From the very beginning of this contract, it was decided that flexibility would be very important for high temperature life prediction. It was therefore decided to keep the method to be developed as modular as possible so that only those aspects which were relevant to the particular application at hand would need to be exercised. This also permits modification or upgrading of selected portions of the method as new techniques become available. The CDA life model software currently under development is designed to reflect this philosophy and therefore incorporates several features worthy of mention. As shown in the figure below, the input will be an ASCII file which can be created as required from whatever source of information is available. Similarly, the output will be an ASCII file containing the actual life prediction(s) plus (optionally) the evolution of damage variables versus cycles. This file input/output system will permit the use of any of the many available software packages for editing, plotting, and display of these results. The internal structure will make use of generic variables and arrays which can be defined as needed by the particular damage mode being evaluated. The whole code will be written in FORTRAN-77 for use on mainframes, minis, or micros, and will be heavily commented for ease of modification by end users.

Data sources	Input file	"Calculation engine"	Output file
SPECIMEN TEST DATA ELASTIC ANALYSIS PLUS SIMPLIFIED RULES FOR INELASTICITY FULL INELASTIC ANALYSIS METHODS	STRESS STRAIN TEMP vs TIME FOR N CYCLES	CDA LIFE PREDICTION ALGORITHMS AND EQUATIONS INCLUDING LIBRARY OF CDA CONSTANTS FOR B1900+Hf AND INCO 718	FINAL PREDICTED LIFE PLUS DAMAGE vs CYCLES

PRELIMINARY TMF MODEL SHOWS GOOD CORRELATION
AND POTENTIAL FOR PRACTICAL APPLICATION

   A preliminary version of the CDA life prediction model was used to correlate
the B1900+Hf TMF data for both coated and uncoated specimens. The figures below
show that these predicted lives mostly fall within a factor of 2 relative to
the actual life data. The model used for these correlations exercised only the
basic transgranular damage mode, and work is still continuing to improve the
correlation. Also, these figures indicate the potential of the method for
improved design predictions after all damage modes are activated and integrated
into the final system.

B1900+Hf TMF data

Uncoated — legend:
- ○ Out-of-phase
- ☐ In-phase
- ◇ CW elliptical
- △ CCW elliptical
- ◖ Dogleg
- △ High temperature

Coated — legend:
- ○ Out-of-phase
- ☐ In-phase
- ◇ CW elliptical
- △ CCW elliptical
- ◖ Dogleg
- ○ Hold time - coated

Uncoated plot: Initiation life - predicted (100 to 10,000) vs Initiation life - actual (100 to 10,000)

Coated plot: Initiation life - predicted (100 to 100,000) vs Initiation life - actual (100 to 100,000)

CYCLIC DAMAGE ACCUMULATION MODEL WILL PRODUCE
ACCURATE HIGH TEMPERATURE LIFE PREDICTIONS

In summary, it should be clear that this HOST contract has produced information which is valuable to any who wish to make life predictions for structures subjected to high temperature, complex loading conditions, especially those situations which can cause creep-fatigue-environment interactions. The large, self-consistent databases for both cast B1900+Hf and wrought INCO 718 are by themselves of great value to any who wish to understand the effects of thermomechanical fatigue, cumulative damage, multiaxiality, environment, coatings, and mean stresses. The test matrices have been designed to show how the multiple damage mechanisms which are characteristic of this regime can occur and interact in actual component-relevant conditions. The development of the Cyclic Damage Accumulation life prediction model is well along and will result in a practical, accurate life model with flexibility and efficiency for many types of engineering alloys. The method is also complemented by the development of advanced viscoplastic constitutive models for stress-strain predictions for the base alloy. Finally, the availability of the CDA model as a software package will facilitate its use and further enhancement by the engineering community.

- Broad spectrum of B1900+Hf testing is nearly complete, providing consistent database for model development

- INCO 718 testing is underway to establish high temperature database for forged material

- Test results are showing how multiple damage modes occur and interact under complex loading conditions

- Model evaluation is being pursued for several types of loadings and will result in practical, accurate life prediction method

REFERENCES

Cailletaud, G., Nouailhas, D., Escaravage, C., Heliot, J., Kang, S., Grattier, J., Levaillant, C., Mottot, M., Tortel, J., 1983, "A Review of Creep Fatigue Life Prediction Methods," ONERA TP 1983-122.

Chan, K. S., Lindholm, U. S., Bodner, S. R., Hill, J. T., Weber, R. M., and Meyer, T. G., 1986, "Constitutive Modeling for Isotropic Materials (HOST)," NASA CR-179522.

Halford, G. R., 1986, "Low-Cycle Thermal Fatigue," NASA TM 87225.

Moreno, V., Nissley, D. M., and Lin, L. S., 1984, "Creep Fatigue Life Prediction for Engine Hot Section Materials (Isotropic) Second Annual Report," NASA CR-174844.

Nelson, R. S., Schoendorf, J. F., and Lin, L. S., 1986, "Creep Fatigue Life Prediction for Engine Hot Section Materials (Isotropic) Interim Report," NASA CR-179550.

Swanson, G. A., Linask, I., Nissley, D. M., Norris, P. P., Meyer, T. G., and Walker, K. P., 1987, "Life Prediction and Constitutive Models for Engine Hot Section Anisotropic Materials Program," NASA CR-179594.