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Life Prediction for a CMC Component Using the NASALIFE Computer Code

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September 2005

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Abstract

The computer code, NASALIFE, was used to provide estimates for life of a SiC/SiC stator vane under varying thermomechanical loading conditions. The primary intention of this effort is to show how the computer code NASALIFE can be used to provide reasonable estimates of life for practical propulsion system components made of advanced ceramic matrix composites (CMC). Simple loading conditions provided readily observable and acceptable life predictions. Varying the loading conditions such that low cycle fatigue and creep were affected independently provided expected trends in the results for life due to varying loads and life due to creep. Analysis was based on idealized empirical data for the 9/99 Melt Infiltrated SiC fiber reinforced SiC.

1. Introduction

Engine companies are constantly striving to improve the performance and life of their gas turbine engines. Materials are pushed to new limits as new materials and concepts are applied to gas turbines to increase operating temperatures, reduce weight, and improve aerodynamic efficiencies. Also, there is the need to reduce maintenance costs and down time making life prediction an ever more important part of the design process. The task of accurately determining the fatigue life of an engine component in service has become increasingly complex. This results, in part, from the complex missions which are now routinely considered during the design process. These missions include large variations of multiaxial stresses and temperatures experienced by critical engine parts.

NASALIFE was written in an attempt to provide a convenient software package to the designer for determining the life of a component under cyclic or variable thermo-mechanical loading. The program was developed under the National Aeronautics and Space Administration's (NASA) Enabling Propulsion Materials (EPM) and Ultra Efficient Engine Technology (UEET) programs. The EPM program and its objectives were summarized by Brewer (1999) and the UEET program overview was presented by Shaw and Peddie (2004). NASALIFE was covered in detail by Gyekenyesi, et al. (2005) with a brief overview provided earlier by Levine, et al. (2000). It should be noted that NASALIFE is not a final and all inclusive program for predicting component life, but is the part of the continuing process to improve life prediction techniques. Empirical data is used as a reference for predicting the fatigue and rupture life of a component.

In addition to the stress and lifing analysis, the high temperature ceramic matrix composite (CMC), silicon melt infiltrated (MI) silicon carbide fiber reinforced silicon carbide matrix, was developed under the aforementioned NASA programs. The MI SiC/SiC composite system was chosen for its low density, acceptable high temperature mechanical behavior, resistance to environmental attack within a gas turbine application, and potential for being processed in high volumes at an acceptable cost. The composite utilizes a silicon doped boron nitride fiber/matrix interface. The EPM program developed the composite for a gas turbine combustor application and part of the UEET program's goal was to use the composite for a gas turbine stator vane. The programs helped advance the processing methods for the CMC and provided the support for generating mechanical properties data by thermomechanical testing of the material.

Fatigue and creep at relatively high temperatures are two important material phenomena, among others, that have to be addressed when designing high temperature components for a gas turbine application. The work presented here, as one of the UEET program milestones, utilizes NASALIFE to predict an approximate number of missions a component is capable of performing prior to failure due to cyclic fatigue and/or creep rupture under a given mission loading condition. The high stress condition of a model of a thermomechanically loaded CMC stator vane, analyzed by N&R Engineering (2003), is used as the reference loading condition for the CMC. The CMC material of the vane and the corresponding data on which the analysis is based is designated as the 9/99 MI SiC/SiC composite. This work utilizes the limited empirical data generated for the 9/99 ceramic composite and the analysis capability of NASALIFE in an effort to verify the basic functionality of the life prediction program. In addition, the work provides a preliminary view to the behavior of a MI SiC/SiC stator vane with respect to life. Lastly, this work is the first step towards a sensitivity and probabilistic analysis for life prediction of the MI SiC/SiC stator vane.

2. Model and Material

The focus of this work is to approximate the life of a MI SiC/SiC stator vane. The vane is loaded at a high temperature. The highest stress at a given temperature is the reference load.

The vane is fabricated from a MI SiC/SiC composite using a silicon doped boron nitride fiber/matrix interface and a surface environmental barrier coating (EBC) with a bond coat. The composite is laminated with each laminate having a five harness satin woven fiber architecture. Tow spacing is approximately 20 ends per inch (EPI). The walls of the vane have six plies. More details of the ceramic composite are provided in the EPM Final Report (2000). A typical vane is illustrated in figure 1. The location of the highest stress is noted in the illustration also.

Mechanical and other high temperature properties are taken from the EPM Final Report (2000). In addition, some material properties were provided by Calomino (2004) and Verrilli (2004). The reported values are the statistical average. With a maximum of three specimens per condition the data exhibited significant scatter also. The scatter was typical of cyclic fatigue tests for most materials, that is, quite significant. A range of an order of magnitude or greater in the life of the material is not unusual, especially with the limited number of specimens per condition. The range of data is still limited due to the fact the material system is relatively new and is still in a state of flux. As a result, for this study the range of data was expanded by extrapolation. Higher and lower stresses were linearly extrapolated using the log of life. Due to the limitations of the MI SiC/SiC data as described above the data should be viewed only for demonstrating the functionality of NASALIFE and not be used for design purposes.

Pesting of the composite is an issue near a temperature of 1470 °F (800 °C) as noted by Ogbuji (2002). Ogbuji (2002) describes pesting as the oxidative degradation of CMCs in a service environment at intermediate temperatures. The experimental data illustrated this problem as the fatigue strength dropped significantly at 1500 °F (820 °C). For this study the data, where pesting is a concern, was not utilized. The phenomena of pesting may be incorporated in a future study.

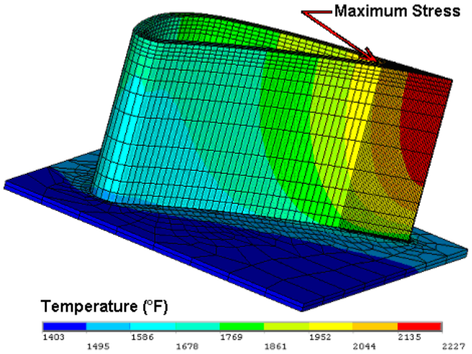

Figure 1.—MI SiC/SiC stator vane showing temperature distribution and the location of the maximum stress.

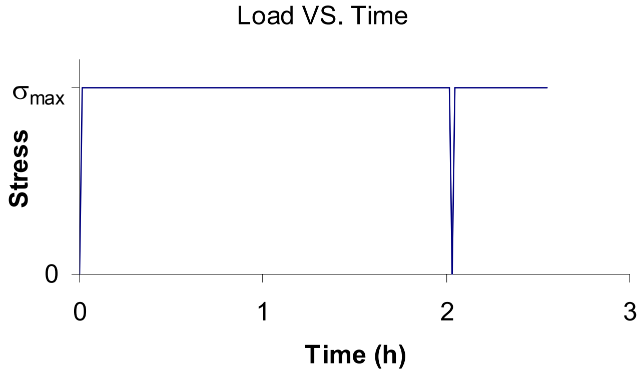

Figure 2.—Illustration of load cycles used to generate the cyclic fatigue data for the 9/99 MI SiC/SiC composite.

The low cycle fatigue (LCF) data was generated using a trapezoidal waveform loading condition on a uniaxial tensile specimen as described in the EPM Final Report (2000). The test specimen was loaded from approximately zero to the desired maximum tensile stress by ramping up to the desired load, holding for two hours, and unloading back to approximately zero. The rate of loading and unloading was such that the maximum stress or near zero stress was reached in 1 minute. Figure 2 illustrates the applied load cycle. The noted cyclic loading was repeated until complete fracture of the specimen. The complete fracture was used as the definition of failure for the cyclic fatigue and creep tests. The trapezoidal wave form load cycle was utilized to model the potential loading conditions a combustor may experience for an average duration flight. The resulting R-ratio, that is the minimum stress divided by the maximum stress, is approximately zero. Also, the resulting A-ratio, the stress amplitude divided by the mean stress, is approximately one. One should keep in mind that due to the uniaxial tensile test the coupons had a uniform stress throughout the cross section. Whereas, most modeled components will typically have some stress gradient through a cross section.

Due to the extended hold time for each cycle of the LCF tests creep deformation is a significant part of the overall failure of the composite at higher temperatures. At the current time, this is the most complete matrix of data that is available for any type of high temperature LCF information for this composite system. As such, the available data was utilized for defining the behavior under LCF conditions. DiCarlo, et al. (2004) discussed some of the issues with creep with the MI SiC/SiC CMC system. At the time of this writing a single LCF data point for the 9/99 MI SiC/SiC generated with a triangular wave form load at a frequency of 0.33 Hz was presented by Kalluri, et al. (2005). That data was used to compare properties with a single data point for a slightly modified version of the ceramic composite designated as 1/01 MI SiC/SiC. Unfortunately, the one data point is insufficient information for this study.

Figure 3 shows the LCF curves with the maximum stress, with an R-ratio of zero, as a function of cycles to failure. The curves utilize actual experimental data as the foundation but are highly massaged to provide smooth nonoverlapping curves for this study. Failure was defined as the complete fracture of the composite test specimen. The data has been modified for this work. Outlier points, due to significant scatter in the data, were deleted to provide smoother curves for this initial analysis. Points were linearly extrapolated to extend the range of the data. It is the idealized data that is illustrated in figure 3 and used for this preliminary analysis. As more tests are being conducted the developing database of the composite properties will provide a more sufficient base for design and analysis with the MI SiC/SiC composite system. It should be reiterated that available data is quite limited with significant scatter that typically comes with cyclic fatigue tests. The range in life at any one condition can be an order of magnitude or greater from the lowest to the highest number of cycles. The data presented with this work is for demonstrating NASALIFE functionality and should not be used for design purposes.

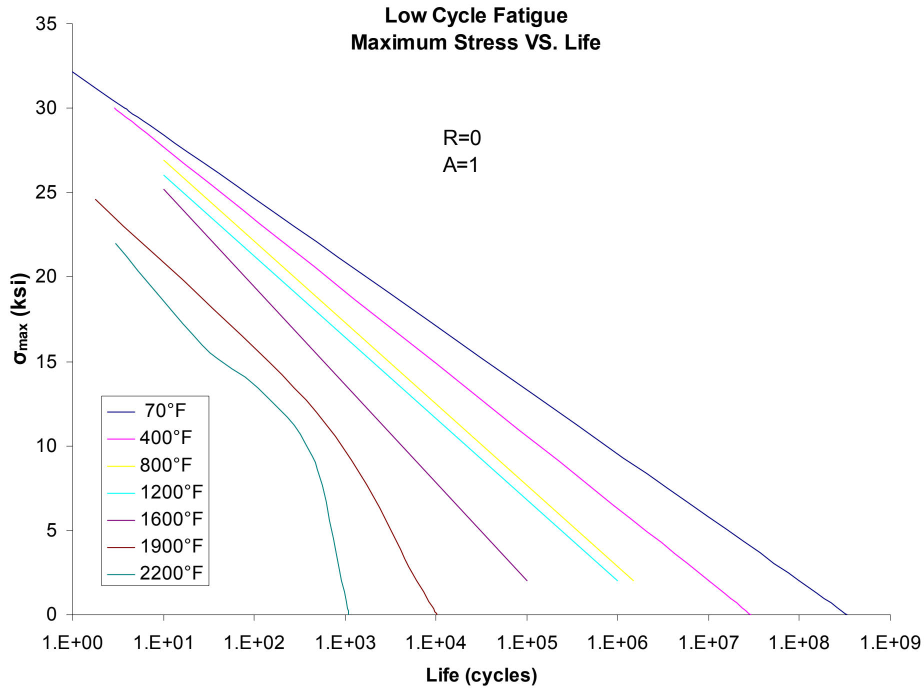

Figure 3.—Idealized low cycle fatigue curve for MI SiC/SiC. Maximum stress versus the life in cycles with an R-ratio of zero.

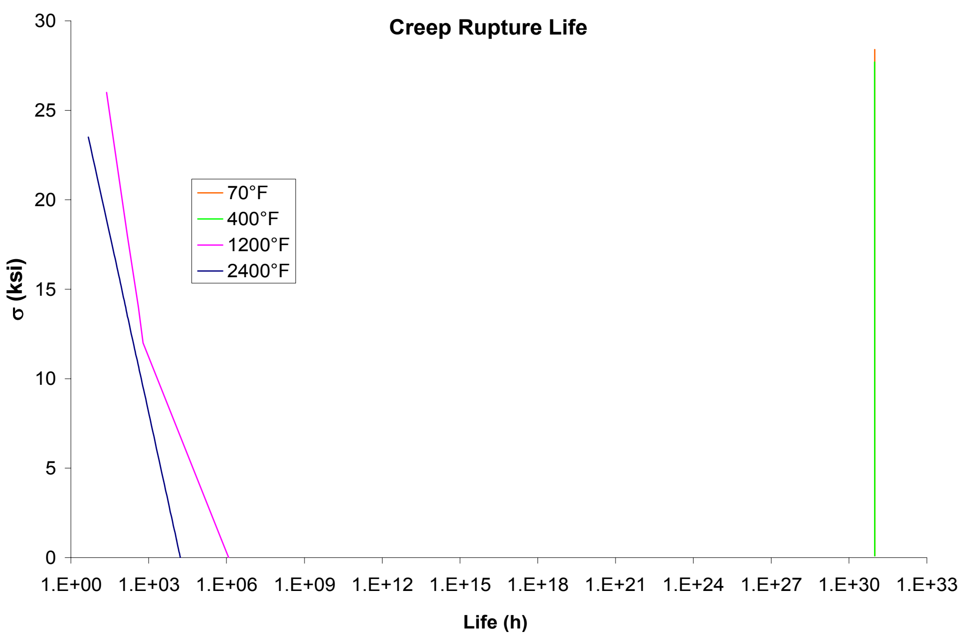

Figure 4.—Creep rupture stress as a function of time for the 9/99 MI SiC/SiC ceramic matrix composite. Creep life at 400 °F and below was set at the maximum allowable value within NASALIFE essentially indicating no creep deformation.

The MI SiC/SiC composite is being developed for high temperature applications. Another major concern with materials at high temperatures is creep deformation. Creep rupture is a significant issue along with the cyclic fatigue strength of the composite. Figure 4 presents creep rupture curves for the 9/99 MI SiC/SiC composite. Creep at 400 °F (200 °C) and below was assumed to be negligible to nonexistent.

The life at 70 °F and 0.1 ksi (0.7 MPa) was set at the maximum value that NASALIFE accepts, that is, 10^{31} hours. The other life values at the low temperatures were reduced only slightly from the maximum acceptable life within NASALIFE. As a result, the low temperature damage due to creep is effectively zero relative to the damage from the cyclic loading.

As with the LCF data the available test results for creep rupture is quite limited. The curves for the high temperature creep rupture data were extrapolated to lower stresses to extend the range of the available data. The definition of failure by creep is the same as for the LCF data, that is, the complete fracture of the specimen.

3. NASALIFE

NASALIFE is a program for predicting the life, due to LCF and creep rupture, of a thermomechanically loaded component. The program was developed to model CMCs. A detailed description was provided by Gyekenyesi, et al. (2005). The program can take a multiaxial loading condition where the load and temperature may vary and calculate an approximate life based on cyclic fatigue and creep. The output includes the damage due to the creep, damage due to the variable load, and the combined damage.

Empirical data from low cycle fatigue tests, creep rupture tests, and static tensile tests are used as the reference for predicting the number of missions a component can handle under a given thermomechanical loading condition. The creep rupture information can be entered in tabular form with stress versus life or with the use of Larson-Miller (1952) parameters.

The program uses the Walker (1970) Mean Stress model to adjust life prediction for ranges in the R-ratio. Complex load cycles are reduced by the Rainflow Counting Method as presented by both, Endo et al. (1967) and Mitsunaga and Endo (1968). In addition, the Rainflow Counting Method is covered by the American Society for Testing and Materials (ASTM) (2004) standard E 1049–85. Minor's (1945) Rule is utilized to combine the damage at different load levels. Finally, the program determines the total damage due to creep and combines it with the fatigue damage due to the cyclic loading and determines the approximate number of missions a component can handle up to failure. It should be noted that the definition of failure for NASALIFE is the same as the definition of failure used for the empirical data. The point of highest stress within the SiC/SiC vane, illustrated in figure 1, is the focus this study. At this time the changes in area due to crack propagation are ignored.

4. Mission Load Cases for Analysis

The mission loads were selected to test the output from NASALIFE as a verification process for its functionality and to provide an insight for a potential life of the modeled stator vane. The calculated maximum stress of 14.1 ksi (97 MPa) and a temperature of 2000 °F (1090 °C) within the stator vane, as determined by N&R Engineering (2003), were used as the primary reference load condition for this study. Also, the mission loads were set up like the original LCF loads with a ramp from approximately zero up to a load which was held for a duration followed by a ramp down to an approximately zero load. As noted earlier, figure 2 illustrates the load cycle. Other conditions included combinations of hypothetical situations by reducing the mean hold load to 7 ksi (48 MPa) at 2000 °F (1090 °C) and lastly, varying the 14.1 ksi (97 MPa) stress at temperatures of 400 °F (200 °C) and 70 °F (20 °C). The combination of low temperatures and high stress is noted as a hypothetical situation since it is not practical for a gas turbine engine application but a good condition for checking NASALIFE's functionality. Varying loads of different magnitudes were superimposed over the mean hold stress during the hold period. The superimposed loads over the main load of 14.1 ksi (97 MPa) may model what vibrations or localized changes in turbine gas flow may induce. The random number generator in Miscrosoft® Excel 2002 was utilized to generate the random loads for the runs that had a random load superimposed over the hold

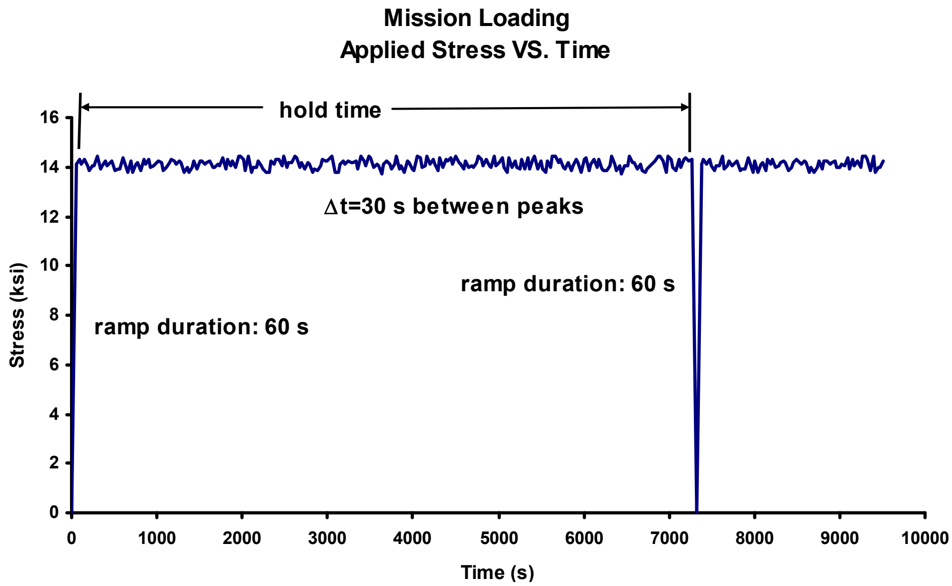

Figure 5.—A sample mission loading with a mean stress of 14 ksi and superimposed random load of ±0 to 2.5 percent. The mission consists of the ramp up, hold, and ramp down. Time increment between load peaks are fixed at 30 seconds.

stress. A typical mission with its load curve is illustrated in figure 5. The details of the individual missions will be presented in the following section along with the corresponding results for the life prediction. Appendix A illustrates one of the NASALIFE input files. The same material properties data were utilized for all the runs. The NASALIFE technical/user manual by Gyekenyesi, et al. (2005) describes all the entries of the input file.

5. Results and Discussion

The work presented here is the initial application of NASALIFE for predicting the life of a CMC component under variable thermomechanical loading conditions. As noted earlier, the runs were used to verify NASALIFE functionality and to provide an insight for a potential life of the modeled stator vane under various practical and hypothetical loading conditions.

NASALIFE utilizes empirical data as a reference for cyclic fatigue strength and creep rupture strength. Gyekenyesi, et al. (2005) provided details of NASALIFE and the theories and models within the program used to predict the number of missions to failure. It was noted earlier that the MI SiC/SiC material properties data base for NASALIFE was not ideal. The data used for fatigue contained significant creep due to the long duration hold times with the trapezoidal loading wave form. Also, the stress range of the data had to be extended by extrapolation. As the CMC continues to be characterized and more data becomes available it will be incorporated for future applications of NASALIFE.

The definition of failure is complete fracture for the test coupons used to generate the LCF and creep rupture data as per the EPM Final Report (2000). As a result, the same definition has to be applied to the stator vane. Also, one should keep in mind that each uniaxial tensile test coupon had a uniform stress through its cross section, whereas, the stator vane will have a stress gradient.

Tables 1 thru 3 provide life prediction results along with the respective load conditions. Each table is at a single temperature as indicated in the table titles. The results are grouped as cases with one condition being varied within each case. The first condition in each case is used as the reference state and is indicated in bold print. The percentage drop in life, due to the joint effect of creep and LCF, is based on the reference condition within each case. Figure 5 illustrates a typical load curve that was utilized to model a mission load cycle. Variants of the presented mission were used to generate the results with NASALIFE.

The simple load cases that ramped up to a load, held the load for a duration, and unloaded can be compared directly with figure 3 for the life prediction due to cyclic fatigue. The predicted results compared well with the expected trends of the experimental data.

The low temperature cases in table 1 at 70 °F (20 °C) and in table 2 at 400 °F (200 °C) were selected to effectively eliminate the effects of creep. Both tables of data indicate the missions to failure due to creep are large numbers showing creep damage to be essentially zero at these low temperatures.

TABLE 1.—LIFE PREDICTIONS FOR A CMC STATOR VANE WITH GIVEN MISSION LOADING CONDITIONS AT 70 °F

Mission Load Conditions	Missions to Failure: Due to Creep	Due to Cyclic Fatigue	Joint Effect	% drop relative to base condition
Vary frequency of superimposed load				
60 s ramp, 7200 s hold at 14.1 ksi, 60 s ramp	**4.89E+30**	**47433**	**47433**	
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=2400 s, 60 s ramp	4.89E+30	46000	46000	3.0
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=1200 s, 60 s ramp	4.89E+30	45982	45982	3.1
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=600 s, 60 s ramp	4.89E+30	45928	45928	3.2
Vary magnitude of superimposed load				
60 s ramp, 7200 s hold at 14.1 ksi, 60 s ramp	**4.89E+30**	**47433**	**47433**	
60 s ramp, 7200 s hold at 14.1 ksi with + 0-0.5% random and Δt=30 s, 60 s ramp	4.89E+30	44831	44831	5.5
60 s ramp, 7200 s hold at 14.1 ksi with + 0-1.5% random and Δt=30 s, 60 s ramp	4.89E+30	42155	42155	11.1
60 s ramp, 7200 s hold at 14.1 ksi with + 0-2.5% random and Δt=30 s, 60 s ramp	4.89E+30	39701	39701	16.3

bold font - reference or base condition within each case
Δt - time between sequential load peaks

TABLE 2.—LIFE PREDICTIONS FOR A CMC STATOR VANCE WITH GIVEN MISSION LOADING CONDITIONS AT 400 °F

Mission Load Conditions	Missions to Failure: Due to Creep	Due to Cyclic Fatigue	Joint Effect	% drop relative to base condition
Vary frequency of superimposed load				
60 s ramp, 7200 s hold at 14.1 ksi, 60 s ramp	**4.81E+30**	**13301**	**13301**	
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=2400 s, 60 s ramp	4.81E+30	12943	12943	2.7
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=1200 s, 60 s ramp	4.81E+30	12928	12928	2.8
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=600 s, 60 s ramp	4.81E+30	12884	12884	3.1
Vary magnitude of superimposed load				
60 s ramp, 7200 s hold at 14.1 ksi, 60 s ramp	**4.81E+30**	**13301**	**13301**	
60 s ramp, 7200 s hold at 14.1 ksi with + 0-0.5% random and Δt=30 s, 60 s ramp	4.81E+30	12027	12027	9.6
60 s ramp, 7200 s hold at 14.1 ksi with + 0-1.5% random and Δt=30 s, 60 s ramp	4.81E+30	11368	11368	14.5
60 s ramp, 7200 s hold at 14.1 ksi with + 0-2.5% random and Δt=30 s, 60 s ramp	4.81E+30	10773	10773	19.0

bold font - reference or base condition within each case
Δt - time between sequential load peaks

In reference to table 1 for the first group at 70 °F (20 °C) the frequency of the superimposed stress was varied. The hold conditions were 14.1 ksi (97.2 MPa) for 2 hours. The variable load was ±0.5 percent of 14.1 ksi (97.2 MPa). The peak to peak duration was held constant within each case. The peak to peak durations were varied between cases from 600 to 2400 seconds giving a range of three load peaks to twelve load peaks per mission. The superimposed load being a low magnitude of ±0.5 percent of the 14.1 ksi (97.2 MPa) or ±0.071 ksi (0.49 MPa) only had a minor effect on the number of missions the component can provide up to failure. The number of missions with a simple loading with a ramp from approximately zero to 14.1 ksi (97.2 MPa), hold at 14.1 ksi (97.2 MPa), and unload was 47433. The number of missions was reduced by 3.2 percent by superimposing a varying load of ±0.071 ksi (0.49 MPa) over the hold stress of 14.1 ksi (97.2 MPa) with 600 seconds between load peaks.

The next case, at 70 °F (20 °C) had a random superimposed load increase in magnitude. Runs were compared with no superimposed load going up to a varying load of 0 to +2.5 percent over the 14.1 ksi (97.2 MPa). The duration between load peaks was held at 30 seconds resulting in 240 load peaks in the 2 hours. The number of missions went from 47433 to 39701 or a 16 percent reduction in life by going from a fixed hold stress to a 0 to +2.5 percent superimposed random load with 30 seconds between peaks.

The load cases at 70 °F (20 °C) were repeated at 400 °F (200 °C). The results are presented in table 2. As with the previous case creep is insignificant. The basic load cycle of ramping from approximately zero to 14.1 ksi (97.2 MPa), holding at 14.1 ksi (97.2 MPa) for 2 hours, and ramping down was maintained. Superimposing a load of ±0.5 percent over the 14.1 ksi (97.2 MPa) load with increasing frequency reduced the life by 3 percent within the tested range.

Increasing the magnitude of the random load from no superimposed load to a varying load of 0 to +2.5 percent at 400 °F (200 °C) reduced the missions to failure by a significant 19 percent. The load peak to peak duration was held constant at 30 seconds with the superimposed variable load. The resulting number of load peaks was 240 within the 2 hour hold period. The remaining results are shown in table 3 for a temperature of 2000 °F (1090 °C). At this temperature creep becomes a significant part of the failure process when considering the life of a thermomechanically loaded component. Significant creep deformation can promote matrix cracking which exposes the constituents to the harsh environment in which a CMC component would be utilized. Upon cracking of the matrix oxidation of the constituents becomes a major concern. Lewinsohn, et al. (2000) discussed time dependent failure of nonoxide CMCs such as the SiC/SiC system. The EPM final report (2000) discusses the oxidation process and its detrimental effects on the mechanical properties of the SiC/SiC composite. The creep and oxidation effects can be observed in table 3 with the significant drop in life as loading conditions and durations under load increase.

For the first high temperature case the hold duration at 14.1 ksi (97.2 MPa) was varied from 5 seconds to 4 hours. As expected the creep damage increased as the duration increased. The number of missions relative to creep damage ranged from 22532 to 42 or a 99.8 percent reduction in number of missions to failure within the range of the study. The life relative to the joint effect of creep and LCF was reduced by 94.9 percent. The damage due to cyclic fatigue did not change as it was the duration and not the number of cycles that changed. No load frequency effect is anticipated within the range of this study.

As with the low temperature cases the frequency of the superimposed load was varied at 2000 °F (1090 °C). The holding stress was 14.1 ksi (97.2 MPa) with a ±0.5 percent load superimposed over it. Load peak to peak durations were varied from 2 hours with no superimposed load to 600 seconds with the ±0.5 percent superimposed load. Damage due to creep remained constant with 84 missions to failure. At the same time the missions to failure with respect to the cyclic loading went from 811 to 387. That is a 52 percent reduction in life with respect to the cyclic loading. The combined missions to failure ranged from 76 to 69 for a 9.2 percent reduction in the number of missions to failure.

For the next case the magnitude of the maximum load of an applied random load was increased. The range included the simple load with no superimposed load variations to a superimposed load of 0 to +2.5 percent. The load peak to peak duration was held constant at 30 seconds. The number of missions relative to creep was 84 and 85 which was relatively constant. The number of missions with respect to the cyclic loading went from 811 for the simple loading case down to 42 missions with the superimposed 0 to +2.5 percent random load. Although, just the application of a 0 to +0.5 percent random load reduced the missions to failure due to cyclic fatigue to 49.

The next trial maintained the holding stress of 14.1 ksi (97.2 MPa) for 2 hours with a 0 to +0.5 percent random load superimposed over it. The duration between load peaks was varied from 30 seconds down to 1 second. As a result, the number of load peaks ranged from 240 up to 7200 in the 2 hour hold period. The number of missions to failure due to creep held fairly constant at 84 and 85.

TABLE 3.—LIFE PREDICTIONS FOR A CMC STATOR VANE WITH GIVEN MISSION LOADING CONDITIONS AT 2000 °F

Mission Load Conditions	Missions to Failure: Due to Creep	Due to Cyclic Fatigue	Joint Effect	% drop relative to base condition
Vary hold load duration				
60 s ramp, 5 s hold at 14.1 ksi, 60 s ramp	**22532**	**811**	**782**	
60 s ramp, 30 s hold at 14.1 ksi, 60 s ramp	11715	811	758	3.1
60 s ramp, 60 s hold at 14.1 ksi, 60 s ramp	7433	811	731	6.5
60 s ramp, 7200 s hold at 14.1 ksi, 60 s ramp	84	811	76	90.3
60 s ramp, 14400 s hold at 14.1 ksi, 60 s ramp	42	811	40	94.9
Vary frequency of superimposed load				
60 s ramp, 7200 s hold at 14.1 ksi, 60 s ramp	**84**	**811**	**76**	
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=2400 s, 60 s ramp	84	668	75	1.3
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=1200 s, 60 s ramp	84	562	73	3.9
60 s ramp, 7200 s hold at 14.1 ksi with ±0.5% and Δt=600 s, 60 s ramp	84	387	69	9.2
Vary maximum magnitude of superimposed load				
60 s ramp, 7200 s hold at 14.1 ksi, 60 s ramp	**84**	**811**	**76**	
60 s ramp, 7200 s hold at 14.1 ksi with + 0-0.5% random and Δt=30 s, 60 s ramp	84	49	31	59.2
60 s ramp, 7200 s hold at 14.1 ksi with + 0-1.5% random and Δt=30 s, 60 s ramp	85	45	29	61.8
60 s ramp, 7200 s hold at 14.1 ksi with + 0-2.5% random and Δt=30 s, 60 s ramp	84	42	28	63.2
Vary frequency of random magnitude superimposed load				
60 s ramp, 7200 s hold at 14.1 ksi with + 0-0.5% random and Δt=30 s, 60 s ramp	**84**	**49**	**31**	
60 s ramp, 7200 s hold at 14.1 ksi with + 0-0.5% random and Δt=10 s, 60 s ramp	85	17	14	54.8
60 s ramp, 7200 s hold at 14.1 ksi with + 0-0.5% random and Δt=5 s, 60 s ramp	84	9	8	74.2
60 s ramp, 7200 s hold at 14.1 ksi with + 0-0.5% random and Δt=1 s, 60 s ramp	84	2	2	93.5
Vary maximum magnitude of superimposed load				
60 s ramp, 14400 s hold at 14.1 ksi, 60 s ramp	**42**	**811**	**40**	
60 s ramp, 14400 s hold at 14.1 ksi with + 0-0.5% random and Δt=30 s, 60 s ramp	42	26	16	60.0
60 s ramp, 14400 s hold at 14.1 ksi with + 0-1.5% random and Δt=30 s, 60 s ramp	42	22	15	62.5
60 s ramp, 14400 s hold at 14.1 ksi with + 0-2.5% random and Δt=30 s, 60 s ramp	42	22	14	65.0
Vary duration of hold load				
60 s ramp, 5 s hold at 7.0 ksi, 60 s ramp	**225591**	**1756**	**1742**	
60 s ramp, 30 s hold at 7.0 ksi, 60 s ramp	143545	1756	1734	0.5
60 s ramp, 60 s hold at 7.0 ksi, 60 s ramp	99931	1756	1725	1.0
60 s ramp, 7200 s hold at 7.0 ksi, 60 s ramp	1363	1756	767	56.0
Vary maximum magnitude of superimposed load				
60 s ramp, 7200 s hold at 7.0 ksi, 60 s ramp	**1363**	**1756**	**767**	
60 s ramp, 7200 s hold at 7.0 ksi with + 0-0.5% random and Δt=30 s, 60 s ramp	1364	59	56	92.7
60 s ramp, 7200 s hold at 7.0 ksi with + 0-1.5% random and Δt=30 s, 60 s ramp	1364	52	50	93.5
60 s ramp, 7200 s hold at 7.0 ksi with + 0-2.5% random and Δt=30 s, 60 s ramp	1360	48	46	94.0
Apply increased magnitude superimposed load				
60 s ramp, 7200 s hold at 7.0 ksi with ± 0-0.5% of 14.1 ksi random load and Δt=30 s, 60 s ramp	**1366**	**47**	**45**	
Vary frequency of superimposed load				
60 s ramp, 7200 s hold at 7.0 ksi with + 0-0.5% random and Δt=30 s, 60 s ramp	**1364**	**59**	**56**	
60 s ramp, 7200 s hold at 7.0 ksi with + 0-0.5% random and Δt=10 s, 60 s ramp	1364	19	19	66.1
60 s ramp, 7200 s hold at 7.0 ksi with + 0-0.5% random and Δt=5 s, 60 s ramp	1363	10	10	82.1
60 s ramp, 7200 s hold at 7.0 ksi with + 0-0.5% random and Δt=1 s, 60 s ramp	1363	2	2	96.4
Vary magnitude of hold load				
60 s ramp, 7200 s hold at 6.5 ksi, 60 s ramp	**1686**	**1905**	**894**	
60 s ramp, 7200 s hold at 7.0 ksi, 60 s ramp	1363	1756	767	14.2
60 s ramp, 7200 s hold at 7.5 ksi, 60 s ramp	1102	1627	657	26.5
60 s ramp, 7200 s hold at 13.6 ksi, 60 s ramp	98	844	88	90.2
60 s ramp, 7200 s hold at 14.1 ksi, 60 s ramp	84	811	76	91.5
60 s ramp, 7200 s hold at 14.6 ksi, 60 s ramp	72	780	66	92.6

bold font - reference or base condition within each case
Δt - time between sequential load peaks

On the other hand, missions to failure with respect to cyclic loading dropped significantly from 49 to 2 or by 96 percent. The missions to failure from the combined effect of creep and cyclic loading dropped from 31 to 2 or 94 percent.

Another case extended the hold time to 4 hours. The set compared the simple load condition with a hold stress of 14.1 ksi (97.2 MPa) with runs having a superimposed random load of 0 up to +2.5 percent. The time between load peaks was held constant at 30 seconds. The missions to failure due to creep held constant at 42. The missions to failure due to cyclic fatigue dropped from 811 for a simple load to 22 for a 0 to +2.5 percent superimposed random load. That is a 97 percent decrease due to the cyclic loading. The majority of the life reduction is just from the application of the random load. Superimposing a random load of 0 to +0.5 percent resulted in 26 missions to failure due to the cyclic loading. The combined effect of the creep and cyclic loading reduced the number of missions from 40 for a simple load to 14 with the superimposed 0 to 2.5 percent random load.

For the next few cases from table 3 the holding stress was reduced to 7.0 ksi (48 MPa). The remaining variables were adjusted in the same manner as the previous cases.

The first 7.0 ksi (48 MPa) set had the duration of the hold stress adjusted. The time ranged from 5 seconds to 2 hours. The resulting missions to failure due to creep ranged from 2.25610^5 to 1363. The missions to failure due to the cyclic stress held constant at 1756. The combined effect missions to failure ranged from 1742 to 767.

The next set compares a simple load cycle with various magnitudes of superimposed positive random loads. The maximum stress of the random loads ranged from 0.5 to 2.5 percent of 7.0 ksi (48 MPa). The hold stress duration was held constant at 2 hours as was the time between load peaks at 30 seconds. Missions to failure due to creep showed a negligible change from 1364 to 1360. The missions to failure due to the cyclic loading dropped from 1756 with a simple load curve with constant 7.0 ksi (48 MPa) to 59 with the addition of a 0 to 0.5 percent random load. From there the missions to failure dropped more gracefully to 48 as the peak load was increased to 2.5 percent. The combined effect missions to failure ranged from 767 to 46.

One case was run with a 2 hour hold stress of 7.0 ksi (48 MPa) with a superimposed positive random load ranging from 0 to 0.5 percent of 14.1 ksi. The intent is to superimpose the same magnitude stress amplitude as used with the 14.1 ksi load. Missions to failure due to creep was 1366 and missions to failure due to cyclic loading was 47. The combined effect missions to failure was 45.

The frequency of the superimposed 0 to +0.5 percent random load was varied over the 7.0 ksi (48 MPa) hold stress also. The time between load peaks was varied from 30 seconds down to 1 second. The missions to failure due to the creep remained at 1364 and 1363. Whereas, the missions to failure due to the cyclic loading exhibited a significant decrease from 59 to 2. The missions to failure due to the combined effect from creep and the cyclic loading decreased from 56 to 2 or by 96 percent.

Lastly, a simple loading situation was applied by ramping to a fixed stress, holding for 2 hours, and ramping back to a no load condition. The hold stress was varied from 6.5 ksi (45 MPa) to 14.6 ksi (101 MPa). Damage from creep and cyclic loading were significant. Missions to failure due to creep ranged from 1686 to 72 and missions to failure due to cyclic loading ranged from 1905 to 780. The combined effect of creep and cyclic loading provided missions to failure of 894 at 6.5 ksi (45 MPa) maximum stress to 66 at 14.6 ksi (101) maximum stress.

The life prediction results from NASALIFE show trends as one would expect. The missions that consist of a simple ramp up, hold stress and ramp down provide results for the missions to failure with respect to the cyclic loading that can be compared directly to the chart shown in figure 3.

The varying of the hold duration but maintaining the maximum stress did provide the expected results of a constant missions to failure due to cyclic fatigue but a reduction in missions to failure due to creep as the hold duration increased.

On the other hand, superimposing a low magnitude variable load over the hold stress and altering the frequency of the variable load had minimal effect on creep but increased the damage due to the cyclic loading.

6. Summary and Conclusions

Accurate life prediction under conditions of LCF and creep is a difficult process. The analysis requires a complete database of material behavior in fatigue and creep under different temperatures and loading conditions.

With a limited database NASALIFE is shown to provide a good estimate for life of a thermomechanically loaded structural component made of the NASA 9/99 MI SiC/SiC ceramic composite system. The output for life compares well with the LCF data when the loading condition is the same as the loading conditions used to generate the LCF data. The trends shown by NASALIFE are as expected for the loading conditions that were used for this study.

A full range of material properties data is required to make any kind of life prediction. In particular, the data must cover the operating conditions for which the analysis is to be made.

As part of the development program for the SiC/SiC composite system a full range of LCF and creep data needs to be generated. The LCF data should have a high enough frequency such that the effects of creep are significantly reduced relative to the currently available data. Also, the definition of failure may have to be revised to reflect the typical design failure that may be used for a component in a gas turbine engine.

Future work may include LCF tests with variable loading at high temperatures to verify the output of NASALIFE. Issues, such as pesting, will have to be studied and incorporated to increase life prediction accuracy, especially if there is significant operating time in the vicinity of the pesting temperature. Although, as environmental barrier coatings improve the problem of pesting may be reduced or eliminated altogether.

Also for future work it was noted earlier that this effort is the first step towards utilizing NASALIFE for sensitivity and probabilistic analysis of high temperature structural components made with the advanced SiC/SiC ceramic composite system. The program may be used in conjunction with a finite element analysis package as part of the sensitivity and probabilistic analysis.

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Appendix A

One of the NASALIFE input files is presented here. The material properties data were used for all the runs. The mission loads are at the end of the input deck. The loading conditions were varied as indicated in the tables of the results section of this work. The variables in the lines were defined in the NASALIFE technical and user manual by Gyekenyesi, et al. (2005).

```
PRIN
3 1 1 1 1 2 2 2 2 1

LCF
TITLE
Example XLIFE lcf file
ARAT
 1
TEMP FLIF SMAX FLAG
70     1.0      32.2  000
70     3.8      30.   000
70     10.0     28.4  000
70     1.0E+08   2.   000
70     3.4E+08 0.002  000
400    2.9      30.   000
400    10.0     27.7  000
400    1E+07     2.   000
400   2.927E+07  0.002  000
800    10.0     26.9  000
800   1500000.0  2.   000
1200   10.0     26.   000
1200  1000000.0  2.   000
1600   10.0     25.2  000
1600   100000.0 2.    000
1900    1.8    24.6   000
1900  482.8    12.    000
1900 6192.0     2.    000
1900 1.005E+04  0.10  000
1900 1.031E+04  0.002 000
2200    3.0    22.    000
2200   26.7    16.    000
2200  110.4    13.4   000
2200  439.8     9.4   000
2200  900.0     2.    000
2200 1.082E+03  0.10  000
2200 1.092E+03  0.002 000
EOF

RUPT
TITLE
```

Example XLIFE rupture table

```
IRUP
1
TEMP RSTR RLIF FLAG
70   28.4   9.90E+30  100
70    1.0   1.00E+31  100
400  27.7   9.66E+30  100
400   1.0   9.90E+30  100
1200 26.0  23.4       100
1200 18.0 150.        100
1200 14.0 400.        100
1200 12.0 600.        100
1200  1.0 640144.     100
2400 23.5   4.7       100
2400 15.0  90.8       100
2400 12.5 211.5       100
2400 10.0 515.2       100
2400  1.0 11647.      100
EOF

MATL
IOP1 IOP4
  1    1
TEMP  M FLAG
  60 .5 020
1300 .5 000
2200 .5 010
TEMP      E   K N  V FLAG
   70 30400 28.4 0 .13 20
  100 30400 28.4 0 .13 0
  200 30400 28.1 0 .13 0
  300 30400 27.9 0 .14 0
  400 30400 27.7 0 .14 0
  500 30400 27.5 0 .15 0
  600 30400 27.3 0 .15 0
  700 30400 27.1 0 .15 0
  800 30400 26.9 0 .16 0
  900 30400 26.7 0 .16 0
 1000 30400 26.5 0 .16 0
 1100 30400 26.3 0 .17 0
 1200 30400 26.0 0 .17 0
 1300 30400 25.8 0 .18 0
 1400 30400 25.6 0 .18 0
 1500 30400 25.4 0 .18 0
 1600 30400 25.2 0 .19 0
 1700 30400 25.0 0 .19 0
 1800 30400 24.8 0 .19 0
 1900 30400 24.6 0 .20 0
 2000 29200 24.4 0 .20 0
 2100 28000 24.2 0 .21 0
 2200 26800 23.9 0 .21 0
```

2300 25500 23.7 0 .21 0
2400 24300 23.5 0 .22 0
2500 23100 23.3 0 .22 10
EOF

TIME TEMP S11
0 2000 0.00
60 2000 14.1
1260 2000 14.1705
2460 2000 14.0295
3660 2000 14.1705
4860 2000 14.0295
6060 2000 14.1705
7260 2000 14.1
7320 2000 0.00

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13. ABSTRACT *(Maximum 200 words)*

The computer code, NASALIFE, was used to provide estimates for life of an SiC/SiC stator vane under varying thermomechanical loading conditions. The primary intention of this effort is to show how the computer code NASALIFE can be used to provide reasonable estimates of life for practical propulsion system components made of advanced ceramic matrix composites (CMC). Simple loading conditions provided readily observable and acceptable life predictions. Varying the loading conditions such that low cycle fatigue and creep were affected independently provided expected trends in the results for life due to varying loads and life due to creep. Analysis was based on idealized empirical data for the 9/99 Melt Infiltrated SiC fiber reinforced SiC.

14. SUBJECT TERMS

NASALIFE; Life; Life prediction; Fatigue; Low cycle fatigue; LCF; Creep rupture; Ceramics; Ceramic matrix composites; CMC; Silicon carbide; SiC/SiC; MI SiC/SiC; Probabilistic analysis; CMC vane; Cumulative distribution function; Probability density function; Scatter; Weibull distribution; Strength; Proportional limit; Design requirements

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