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Reliability Assessment of Thrust Chamber Cooling Concepts Using Probabilistic Analysis Techniques

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Abstract

The reliability of OFHC (Oxygen Free High Conductivity) copper and NARloy-Z thrust chambers is assessed by applying probabilistic structural analysis techniques to incorporate design parameter variability and uncertainty. Thrust chambers specifically evaluated are the cylindrical test fixtures employed in a plug-nozzle configuration at the NASA Lewis Research Center. Direct sampling Monte Carlo simulations based on a simplified life prediction methodology established probability densities of firing cycles to structural failure. Simulated cyclic lives demonstrated modest agreement to experiment. Similarly, regions of high structural failure probability were determined using a limit state approach employing calculated cumulative distribution functions for effective stress response and an assumed material strength distribution. A probability of failure of 0.012 was calculated at the center of the coolant channel hot-gas-side wall for an OFHC milled channel. Structural response was found to be sensitive to the uncertainties in the thrust chamber thermal environment and the material's thermal expansion coefficient.

Introduction

The high heat fluxes induced in the thrust chambers of liquid chemical rocket engines have driven researchers over the last several years to evaluate different cooling concepts. Numerous cooling channel designs, thrust chamber materials and fabrication techniques have been experimentally investigated.[1] These investigations have documented the cyclic life of each thrust chamber design concept under specific test conditions. At the NASA Lewis Research Center (LeRC), cyclic life data have been acquired using low-cost cylindrical thrust chamber fixtures in a plug-nozzle configuration (Fig. 1). Since testing of this configuration was initiated in the early 1970's, cooling concepts tested have included conventional milled channels, tubular bundle channels, compliant milled channels, tungsten-reinforced milled channels, milled channels with electrical discharge machined hot-gas-side slots and high-aspect-ratio channels.[2-4] Thrust chamber materials have included OFHC (Oxygen Free High Conductivity) copper, Amzirc (1/2 hard, aged), NARloy-Z and NASA-Z. Additionally, experimentation with thermal barrier coatings, such as zirconium oxide, and alternative fabrication techniques, such as electroform bonding of copper tubes[5], have been completed. Clearly, a diversified database of failure information, and hence reliability information, is readily available.

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Recognizing the value of such data in understanding the structural integrity of thrust chambers, this paper documents the initial analytical reliability assessment of the tested milled channel designs using advanced probabilistic techniques not formally utilized previously. Past analytical studies of this test fixture for milled channel designs have focussed on two- and three-dimensional finite element evaluations and simplified life predictions.[6-10] These finite element evaluations have employed both elastic-plastic and viscoplastic analysis methodologies. Life predictions have been established, mainly, through strain range data from isothermal, low-cycle, plastic strain fatigue data (i.e., a 'local strain' approach). In general, these prior analytical investigations of cylindrical thrust chambers have not, however, fully accounted for the variability that occurs in loading conditions, material behavior and geometry. Such variability or uncertainty has been documented recently in a study of flow in coolant passages. In the study, thermal stratification of the coolant fluid was postulated as more realistic of actual experimental flow than previously assumed fully-mixed conditions.[11] Uncertainty in the flow conditions such as this leads directly to uncertainty in the structural loading. By utilizing current probabilistic methodologies for reliability quantification, it is believed that the previous experimental failure investigations of cylindrical thrust chambers can be reinterpreted in the new light of quantitative structural reliability analysis.

The purpose of this paper is to describe the initial application of some probabilistic techniques for evaluating the structural reliability of cylindrical thrust chambers tested at NASA LeRC. This work is part of a larger effort to incorporate Probabilistic Risk Assessment (PRA) under a comprehensive reliability improvement program. By establishing the reliability of these chambers, comparisons can be made of the different concepts evaluated over the years, reasons for the specific reliability differences between concepts can be defined and understood through structural response sensitivity to random variable input, interpretations of the cylindrical chamber reliability results to thrust chambers that are contoured can be offered and recommendations for new design concepts can be made. Furthermore, these probabilistic techniques can serve as reliability diagnostic tools for future thrust chamber designs. This report documents the execution and results of two probabilistic analysis techniques: a direct sampling Monte Carlo method and a probabilistic finite element structural evaluation utilizing the NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) code.[12-15] Uncertainties in loadings, material properties and geometry are taken into account. Predicted thrust chamber reliability results were compared with experimentally evidenced chamber lives.

Probabilistic Analysis Techniques and Results

Direct Sampling Monte Carlo Simulation

A simplified thrust chamber life prediction methodology is employed in conjunction with a direct sampling Monte Carlo simulation to forecast thrust chamber life using normally distributed random parameters. Monte Carlo simulation combined with Porowski's life prediction scheme[16] have been previously used by both the author[17], as well as in reference 18. This paper represents the formal documentation of the author's earlier work.

The life prediction methodology calculates, in a closed form, the cyclic life of a milled channel coolant design based on one of two dominant failure modes, thermal ratcheting or low cycle fatigue. As the thrust chamber is cycled, the coolant channel hot-gas-side to coolant-side wall experiences plastic deformation (thinning) and an accumulation of plastic strain. The thermal ratcheting failure mode is predicted when the coolant channel wall has insufficient strain hardening in the area of localized thinning that the wall begins to neck under the applied stresses and eventually fails due to an inability to sustain the pressure load. With adequate strain hardening, however, thinning ceases and low cycle fatigue fails the coolant channel wall due to repetitive exposure to the maximum strain range. A hypothetical power law relationship, based on the material's strain hardening exponent, is used within the prediction methodology to determine the number of cycles till thinning ceases. Further detailed insight into the methodology can be found in reference 16.

The direct sampling Monte Carlo approach acquires data points from defined random variable distributions and then employs these values in a solution scheme. The accuracy of the result is dependent on the sophistication of the analysis, the total number of simulations and the accuracy of the random variable distributions. Table 1 presents the random parameters that were considered for the direct sampling Monte Carlo simulation used in this study. The term 'wall' in the table refers to the hot-gas-side to coolant-side wall. The mean values were reported in reference 16, and a 5% coefficient of variation (CoV) was arbitrarily assumed for each random variable. The coefficient of variation is the standard deviation divided by the mean, and represents the percent variability in the parameter. The normal distribution and 5% CoV were selected as straight forward trial attempts in characterizing the actual distributions of these inherently random variables. Actual distribution data were not available, and it is recognized that both distribution type and parameter variability may be, and probably are, different.

Fifty-thousand simulations were performed for both OFHC copper and NARloy-Z milled-channel cylindrical chambers, and their cycles-to-failure probability densities (frequency distributions) are presented in Figs. 2-4. Thermal ratcheting failures were predicted for OFHC copper cylindrical chambers resulting in a mean simulated cyclic life of 116 cycles (Fig. 2). Neglecting two exceptional data points, a mean experimental life of 166 cycles was experienced on 10 OFHC copper cylindrical thrust chambers.[2] These mean values are relatively comparable; however, the variability in the simulated life (CoV=0.156) is approximately one-half the variability observed with the experimental data (CoV=0.36).

NARloy-Z cylindrical chambers had predicted failures both due to thermal ratcheting and, with adequate strain hardening, low cycle fatigue. Of the 50,000 simulations, 45% were thermal ratcheting failures with a mean simulated life of 79 cycles (Fig. 3), and the remaining 55% were low cycle fatigue failures with a mean simulated life of 1015 cycles (Fig. 4). Based on three data points, the mean experimental cyclic life of NARloy-Z cylindrical thrust chambers was 641 cycles.[2] Due to the few experimental data points, the comparison of analytical results is not as meaningful as in the OFHC thrust chamber case. The Monte Carlo simulation does weakly suggest (55% of the simulations) that low cycle fatigue is the main failure mechanism of NARloy-Z cylindrical thrust chambers and, hence, longer cyclic lives can be anticipated relative to thermal ratcheting failures. Assuming a low cycle fatigue failure mechanism dominates, the analytical results support the experimental conclusion that NARloy-Z chambers last significantly longer than OFHC copper chambers.

The results of this type of analysis are difficult to interpret due to both the calculation scheme and limited random variable data. The simplified life prediction methodology employed can only be used as a rough estimate of milled-channel cylindrical chamber cyclic life due to the reliance of the calculation procedure on the hypothetical power law criterion for strain hardening. Furthermore, depending on the actual environment (temperature, strain rate, etc.), cyclic strain softening is more representative of actual material behavior.[19] Greater modeling sophistication is demonstrated in the next section. Probabilistic techniques offer the capability of analyzing a structure based on defined random variable distributions which account for variability and uncertainty, thus improving upon the deterministic approach in which all parameters assume a constant (uniform distribution) value. Improvements in probabilistic methods remain in defining credible random variable distributions about their deterministic mean values. More experimental data are necessary to establish a significant statistical sampling population for accurate characterization of random variable distributions and for a reduction in the variability of observed cyclic lives.

Probabilistic Structural Analysis

The NESSUS code was employed to probabilistically evaluate the structural reliability of the cylinder thrust chambers. This analysis tool, developed under NASA Lewis Research Center's Probabilistic Structural Analysis Methods (PSAM) for Select Space Propulsion System Components contract[12], incorporates inherent randomness in material properties, loading conditions and geometric variables into an overall probabilistic structural evaluation. By accounting for the independent variable uncertainties in the form of probability distributions, a structural response function can be composed in terms of uncorrelated random variables, and the probability of exceeding a particular response value is approximated by a reliability method. By evaluating the exceedance probability at several response values, a cumulative distribution function can be obtained. In the analysis that follows, effective stress and effective strain responses were calculated for each node in the finite element mesh, and the sensitivity of these responses to random variable inputs was computed. Response functions were linearly approximated, and an advanced first order reliability method was employed to generate the cumulative distribution functions.

A coarse two-dimensional finite element model of a single milled coolant channel of a cylindrical thrust chamber was constructed as illustrated in Fig. 5. The model utilizes the symmetry of the channel and consists of 20 bilinear isoparametric plane strain elements (NESSUS element type 11) with 33 total nodes. Plane strain implies the out-of-plane component of strain (z-component) is assumed negligible. The geometry is consistent with earlier analytical studies; however, the channel width (x-direction) described by nodes 13, 16 and 21, and the channel height (y-direction) described by nodes 11-13 were considered random and correlated in their respective coordinate direction fields. Such geometric variability may arise from the manufacturing and fabrication processes. All input random variable fields used in this analysis are compiled in Table 2. Again, normal distributions with 5% coefficients of variation were employed as trial attempts in characterizing the probability distributions.

Mean values of structural temperatures and pressure loadings at hot-firing conditions were acquired from reference 6 and these values were perturbed as well. Thermal loading is random due to possible combustion irregularities and injector element misalignment, and pressure loading is variable due to flow disturbances and instabilities. Mean temperature values in degrees Fahrenheit are shown in Fig. 6. The highest material temperature region is on the hot-gas-side wall at the middle of the coolant channel (node 1). The temperature field was considered fully correlated. Fully correlated implies the variability of nodal temperature throughout the coolant channel structure is influenced by a single random variable. It must be noted that the pressure and thermal loading was not incremented across an entire test cycle; the hot-fire conditions specified here were strictly used.

OFHC copper was used as the model material in the von Mises elastoplastic constitutive model. Variability in material properties arising from the manufacturing process and uncertainty in the temperature distribution was applied to the elastic modulus, thermal expansion coefficient and Poisson's ratio. All material properties were considered fully correlated. Finally, temperature dependent material properties and typical stress-strain curves[20] for OFHC copper were prepared as modeling subroutines linked to NESSUS. These subroutines added some sophistication in properly characterizing the thermal and plastic structural response of the milled channel. Material yield stress was not considered random.

The effective stress response of the milled channel model is illustrated in Figs. 7a-c. The mean stress distribution indicates that the largest stresses arise in the middle of the structural jacket and large stress gradients exist in the coolant channel rib. Effective stress is reduced along the inner chamber wall due to plastic deformation in this high strain region. The largest variability in effective stress occurs where the finite element mesh is very coarse, i.e., within the structural jacket. Coefficients of variation were approximately 11.5% in this region. Although the model is coarse for this initial reliability evaluation, the solution does provide reasonable estimates of the structural response in comparison to earlier finite element analyses (e.g., reference 10). This approximate analysis methodology has also been successfully used in evaluating Space Shuttle Main Engine (SSME) components.[21]

Structural reliability can be ascertained by using a standard limit state function approach in which failure probability is determined by the stress exceeding the material strength. The probability distribution of the effective stress incurred is reported as output from NESSUS, and is illustrated for node 1 in Fig. 8. Node 1 is used here because, as will be shown later, this is the site of highest structural failure probability. The material strength at each nodal temperature was estimated from reference 20 based on an ultimate tensile strength versus temperature curve for OFHC copper. This strength was approximated as a normally distributed random variable with a coefficient of variation of 0.05. The probability distribution for the material strength at node 1 is also shown on Fig. 8. The effective stress and material strength are considered independent random variables, and the area under the curves where stress exceeds strength is indicative of the failure probability. The power of probabilistic structural analysis techniques is demonstrated through the computation of the structural stress response distribution which defines this area for failure.

Employing the limit state function approach, the failure probability of the OFHC copper milled channel is illustrated in Fig. 7d. The greatest probability of failure, 1.2%, is located on the hot gas wall at the center of the coolant channel (node 1). This is consistent with experimental structural failure findings as evidenced in Fig. 9. Assuming a sufficiently large sample population and a 1.2% failure probability, a crack (material failure) would be initiated within 83 cycles (1/0.012). In line with experimental evidence, eventual coolant channel rupture would occur shortly thereafter as the failure probability would increase locally about this failure site. By forecasting structural failure in this manner, requirements for quality control, inspection intervals and retirement of cause for the thrust chambers can be established. Finally, it should be noted that the highest probability of structural failure is not in the region where the largest stresses are found because the material temperatures are significantly lower in the structural jacket and, hence, the material strength is significantly higher than the incurred stresses.

The sensitivity of the effective stress probability distribution at node 1 to the assumed independent random field inputs are listed in Table 3. The sensitivity factors help to define the random variable influence in the reliability model and indicate which random variables are most significant and require more careful consideration. Reporting such sensitivities demonstrates, again, the usefulness and power of probabilistic structural analysis techniques. Maximum sensitivity is represented by a value of 1.0. The results show that the dominant factors are the thermal expansion coefficient (0.788), coolant channel width (0.527) and temperature (0.279). In support of these results, reference 9 has similarly documented, for 1/2-hard Amzirc, the thermal expansion coefficient as the most influential parameter in increasing the thrust chamber fatigue life. Reducing the variability in these parameters will reduce the uncertainty in the effective stress response of the OFHC copper milled coolant channel.

The effective strain response is illustrated in Figs. 10a-c. The maximum strain regions are located near the center of the rib on the hot gas wall and at the center of the coolant-side wall. This result is consistent with other computational analyses.[6,7] The maximum strain and, hence, maximum strain range is located at node 4. The largest coefficient of variation, 0.18, is located at the node 16 in the middle of the rib on the coolant-side wall. Additionally, the sensitivity of the effective strain response at node 4 to the random field inputs is presented in Table 4. The dominant factors are temperature (0.805), thermal expansion coefficient (0.532) and channel width (0.256). It is interesting to note that the temperature is far more important to the structure's strain response than to its stress response. This is very important since the driving influence in failing thrust chamber coolant channels due to low cycle fatigue is the strain range that the material experiences.

Based on the above results, the uncertainty in loading conditions must be carefully characterized and understood to properly assess the structural reliability of coolant channels. More specifically, probabilistic fluid mechanics and thermal models need to be developed to capture the environmental variability found within rocket engine combustion chambers. One potential calculation technique is to employ a Monte Carlo method to solve modeled transport equations for the joint probability density function of velocity and composition (species mass fractions and enthalpy).[22] In this manner, a complete statistical description of the thrust chamber flow can be determined. It should also be noted that uncertainty in component and engine loadings have been addressed under a NASA LeRC contract, the Composite Load Spectra for Select Space Propulsion Structural Components.[23] Generic probabilistic models were developed and implemented for loading calculations in a probabilistic multilevel engine model. The SSME was used as a baseline model, and preliminary results for the SSME Main Combustion Chamber have confirmed the importance in describing the uncertainty in thermal modeling variables.[18,24]

Concluding Remarks

Probabilistic analysis techniques were employed in the reliability assessment of cylindrical thrust chambers tested in the plug-nozzle configuration at the NASA Lewis Research Center. These powerful techniques incorporate uncertainty within the analysis to account for variability due to natural and anomalous effects. By considering structural loading, geometry and material properties as random input fields, probability distributions of structural response and the response's sensitivity to the random variable field inputs can be determined. These results prove to be very insightful toward appraising structural reliability. This paper documents the first application of probabilistic structural analysis techniques to the cylindrical chamber test fixtures.

A direct sampling Monte Carlo technique based on a simplified life prediction methodology was employed in simulating the cyclic life of OFHC (Oxygen Free High Conductivity) copper and NARloy-Z cylindrical thrust chambers. Pressure and thermal loads, chamber material properties and coolant channel geometry were assumed normally distributed random variables with five percent coefficients of variation. Monte Carlo results indicate NARloy-Z thrust chambers have a longer mean cyclic life (1015 cycles) than OFHC (Oxygen Free High Conductivity) copper thrust chambers (116 cycles) assuming a low cycle fatigue failure mechanism for NARloy-Z. The reported simulated lives demonstrated only modest agreement with the experimental findings. Due to the strain hardening interpretation of material behavior and a reliance on a hypothetical law to distinguish between failure modes, the life prediction methodology employed here should only be used as a rough estimate of thrust chamber cyclic life. Furthermore, additional experimental data would minimize the variability in observed cyclic lives and provide better distribution definition for the random variable design parameters.

The NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) code was exercised on an approximate, two-dimensional model of an OFHC copper milled coolant channel. This application of NESSUS represents an initial attempt in forecasting the structural reliability of the cylindrical thrust chambers using a formal probabilistic structural mechanics tool. Again, pressure and thermal loads, chamber material properties and coolant channel geometry were assumed normally distributed random variables with five percent coefficients of variation. Cumulative distribution functions for effective stress and effective strain structural response were generated, with mean results comparable to more refined finite element models analyzed in a deterministic framework. Using a limit state approach based on the computed effective stress response distribution and assumed material strength distribution, a maximum failure probability of 0.012 was predicted at the center of the OFHC coolant channel on the hot-gas-side wall. By establishing such failure probabilities in critical structural areas, requirements for quality control, inspection intervals and retirement for cause can be defined. Sensitivity results indicate that uncertainty in the structure's thermal environment and the material's thermal expansion coefficient is very important to characterize and minimize in order to control your structural response and to achieve improved reliability assessments based on effective stress and effective strain responses.

These results represent preliminary findings in an effort to incorporate Probabilistic Risk Assessment (PRA) as part of a comprehensive reliability improvement program. Future directions for the present probabilistic analysis work reported here include improving the thrust chamber model sophistication within the NESSUS framework and incorporating probabilistic fluid mechanics and thermal models to minimize the uncertainty in the structure's thermal environment. These and future efforts in quantitative risk assessment are necessary to ensure an understanding of reliability drivers in space chemical propulsion systems and to subsequently enhance system reliability based on these drivers.

Acknowledgements

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Table 1. Direct Sampling Monte Carlo Simulation Random Variables

RANDOM VARIABLE	DISTR.	OFHC Copper		NARloy-Z	
		MEAN	CoV	MEAN	CoV
PRESSURE LOAD, psi	NORMAL	547	0.05	547	0.05
YIELD STRENGTH, psi	NORMAL	9000	0.05	30000	0.05
ULT. STRENGTH, psi	NORMAL	46000	0.05	55000	0.05
MODULUS OF ELASTICITY, psi	NORMAL	17E+06	0.05	18E+06	0.05
THERMAL EXPANSION COEFF., in/in/^oF	NORMAL	9.5E-06	0.05	9.5E-06	0.05
POISSON'S RATIO	NORMAL	0.3	0.05	0.3	0.05
CLOSEOUT-WALL TEMP. DELTA, ^oF	NORMAL	780	0.05	780	0.05
WALL TEMP DELTA, ^oF	NORMAL	200	0.05	200	0.05
RIB WIDTH, in.	NORMAL	0.05	0.05	0.05	0.05
1/2 WALL THICKNESS, in.	NORMAL	0.0175	0.05	0.0175	0.05
WALL LENGTH, in.	NORMAL	0.0664	0.05	0.0664	0.05

Table 2. Probabilistic Structural Analysis Random Variables

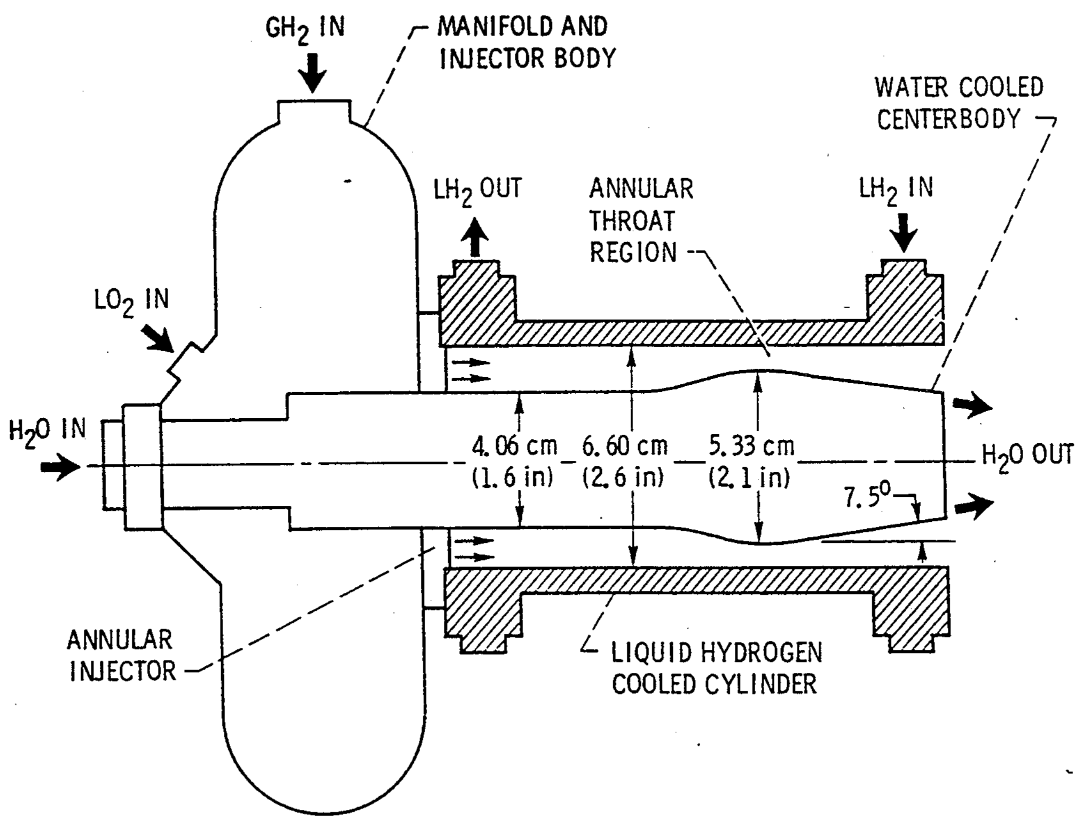
RANDOM VARIABLE	DISTRIBUTION	OFHC Copper	
		MEAN	CoV
CHAMBER PRESS., psi	NORMAL	600	0.05
COOLANT PRESS., psi	NORMAL	1200	0.05
MODULUS OF ELASTICITY, psi	NORMAL	16.6E+07	0.05
THERMAL EXPANSION COEFF, in/in/^oF	NORMAL	9.5E-06	0.05
POISSON'S RATIO	NORMAL	0.33	0.05
CHANNEL HEIGHT, in.	NORMAL	3.5E-02	0.05
CHANNEL WIDTH, in.	NORMAL	3.3E-02	0.05
TEMPERATURE, ^oF	NORMAL	**Fig. 6**	0.05

Table 3. Sensitivity Factors of Random Input Influence on Effective Stress (Node 1)

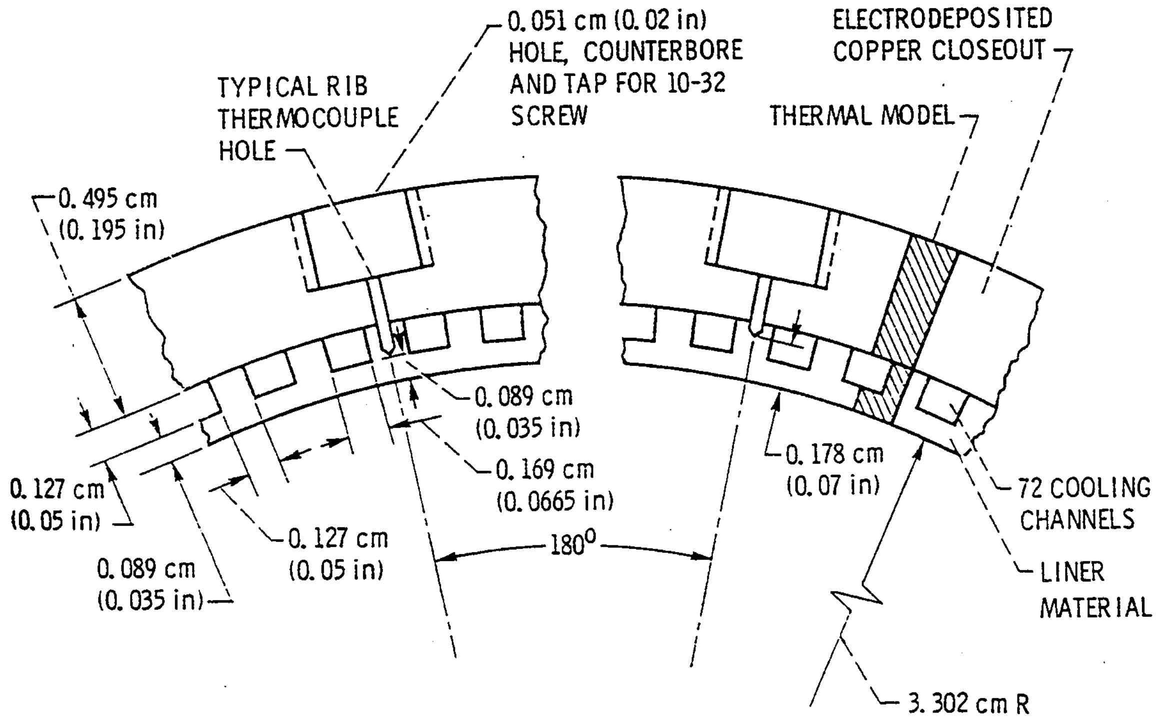
RANDOM VARIABLE	SENSITIVITY FACTOR	RANKING
CHAMBER PRESSURE	0.005	8
COOLANT PRESSURE	0.031	6
MODULUS OF ELASTICITY	0.088	5
THERMAL EXPANSION COEFF	0.788	1
POISSON'S RATIO	0.019	7
CHANNEL HEIGHT	0.118	4
CHANNEL WIDTH	0.527	2
TEMPERATURE	0.279	3

Table 4. Sensitivity Factors of Random Input Influence on Effective Strain (Node 4)

RANDOM VARIABLE	SENSITIVITY FACTOR	RANKING
CHAMBER PRESSURE	0.004	8
COOLANT PRESSURE	0.022	6
MODULUS OF ELASTICITY	0.028	5
THERMAL EXPANSION COEFF	0.532	2
POISSON'S RATIO	0.048	4
CHANNEL HEIGHT	0.020	7
CHANNEL WIDTH	0.256	3
TEMPERATURE	0.805	1



a) SCHEMATIC OF CYLINDRICAL THRUST CHAMBER ASSEMBLY



b) CYLINDER WALL CROSS SECTION

Fig. 1. Milled-channel cylindrical thrust chamber in plug-nozzle configuration.

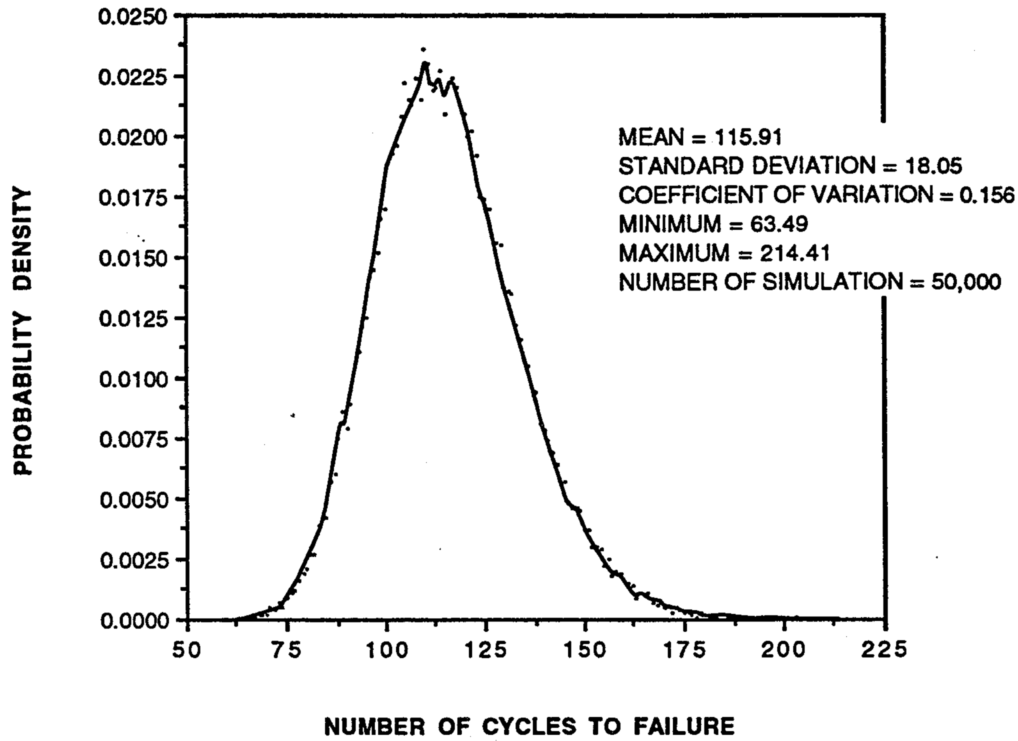


Fig. 2. Monte Carlo simulation of thermal ratcheting failure. OFHC copper milled channel.

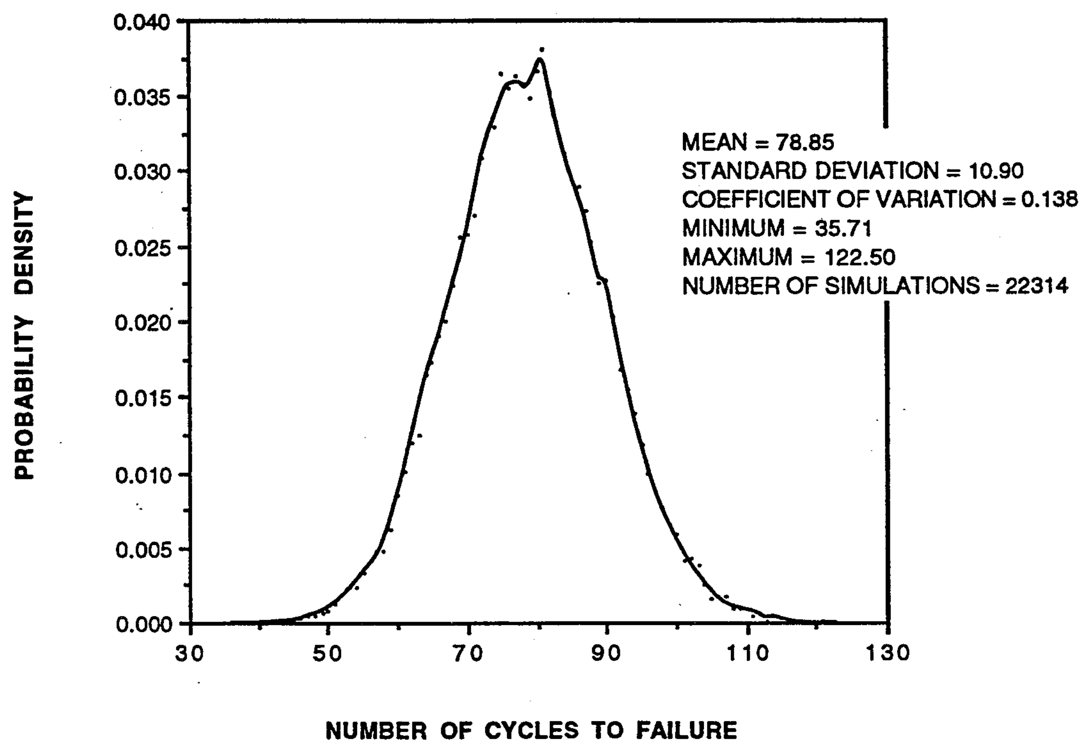


Fig. 3. Monte Carlo simulation of thermal ratcheting failure. NARloy-Z milled channel.

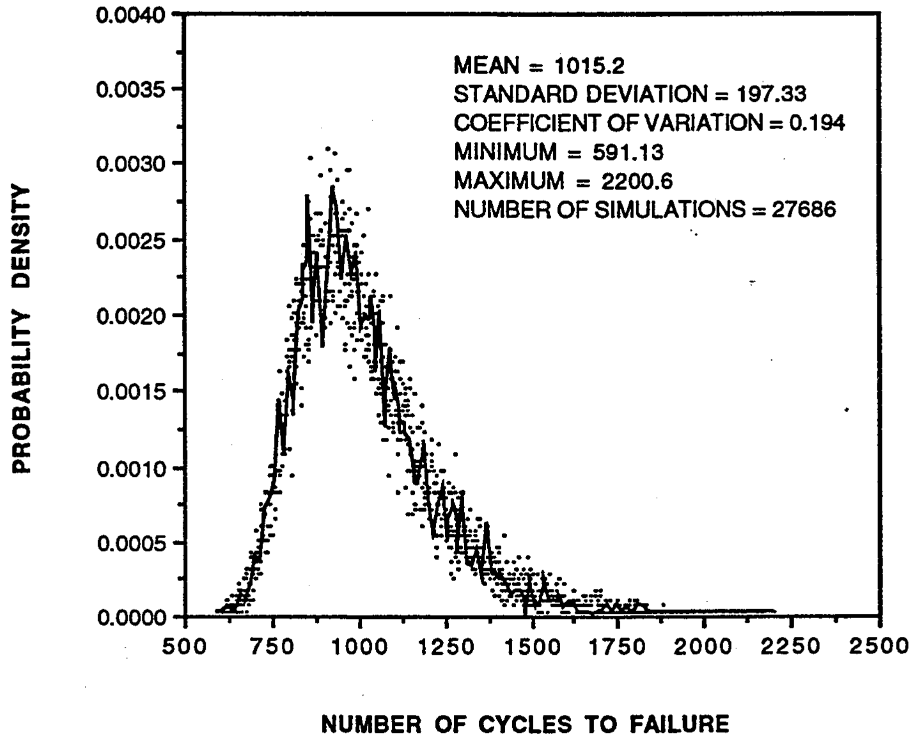


Fig. 4. Monte Carlo simulation of low cycle fatigue failure.
NARloy-Z milled channel.

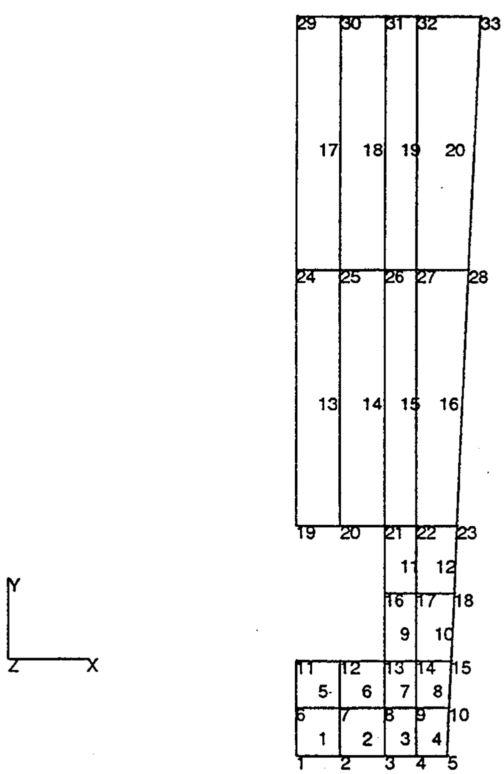


Fig. 5. Milled coolant channel.
Finite element model.

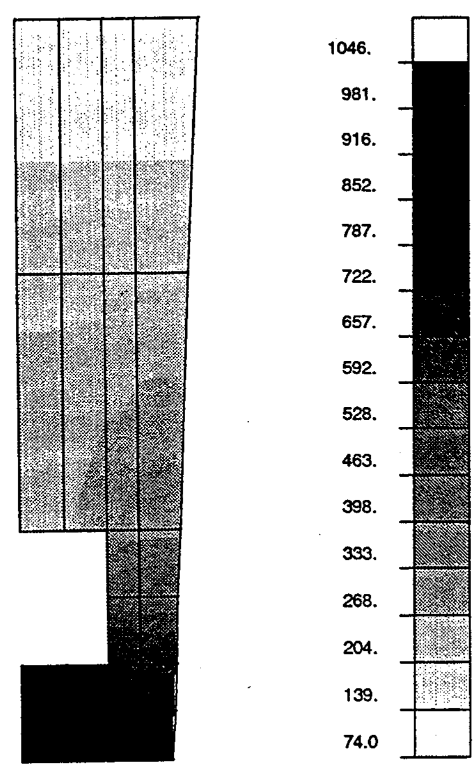
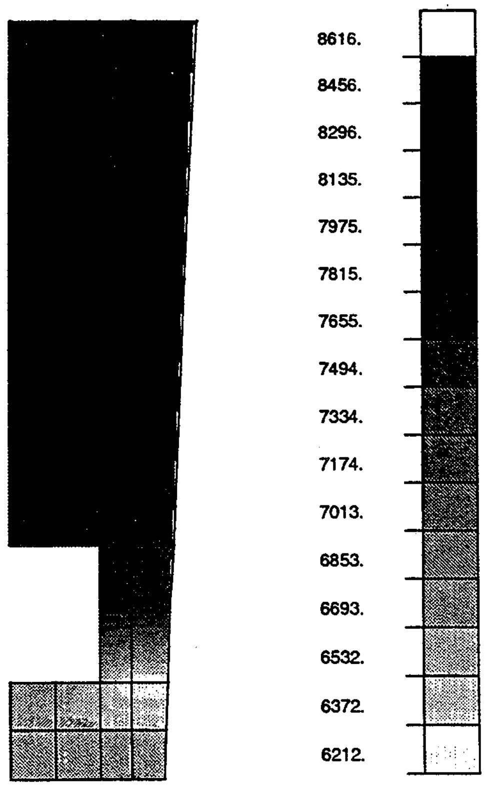
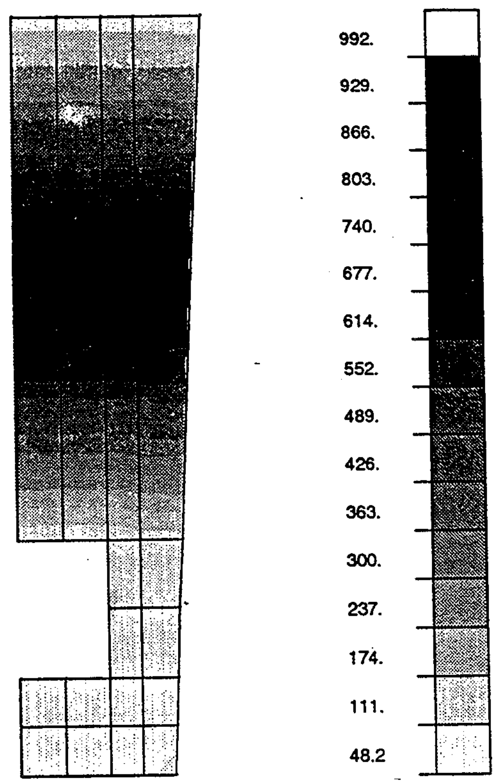


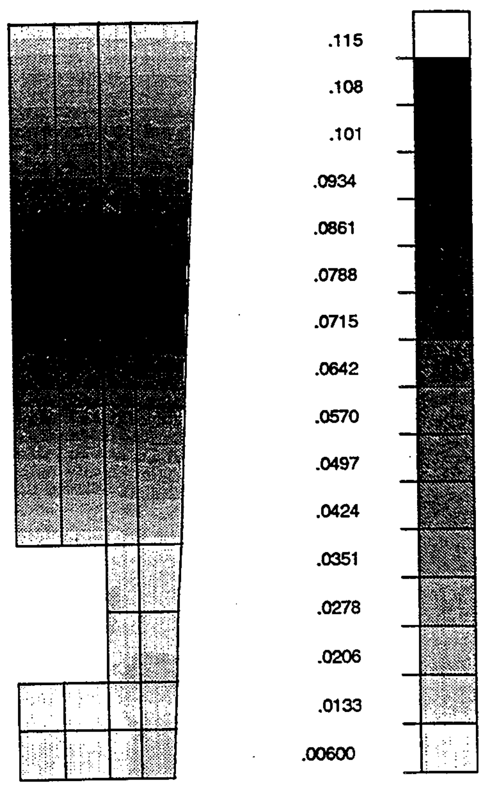
Fig. 6. Mean temperature distribution (°F).
OFHC copper milled channel.



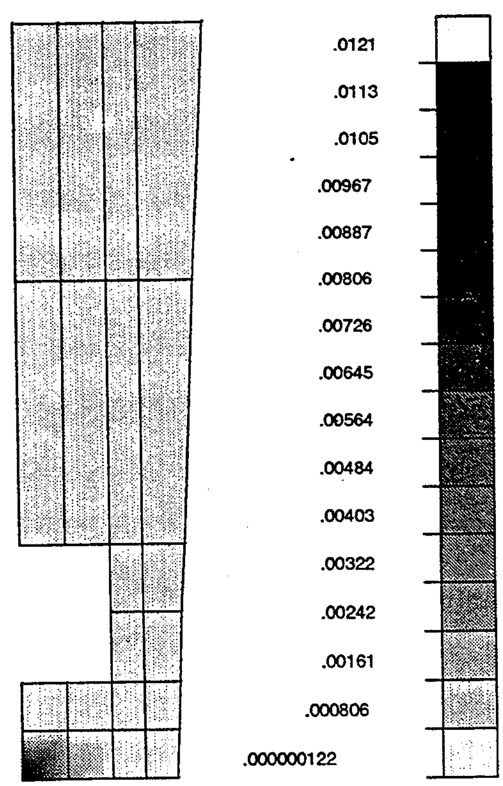
a) MEAN (psi)



b) STANDARD DEVIATION (psi)



c) COEFFICIENT OF VARIATION



d) PROBABILITY OF FAILURE

Fig. 7. Effective stress response of OFHC copper milled coolant channel

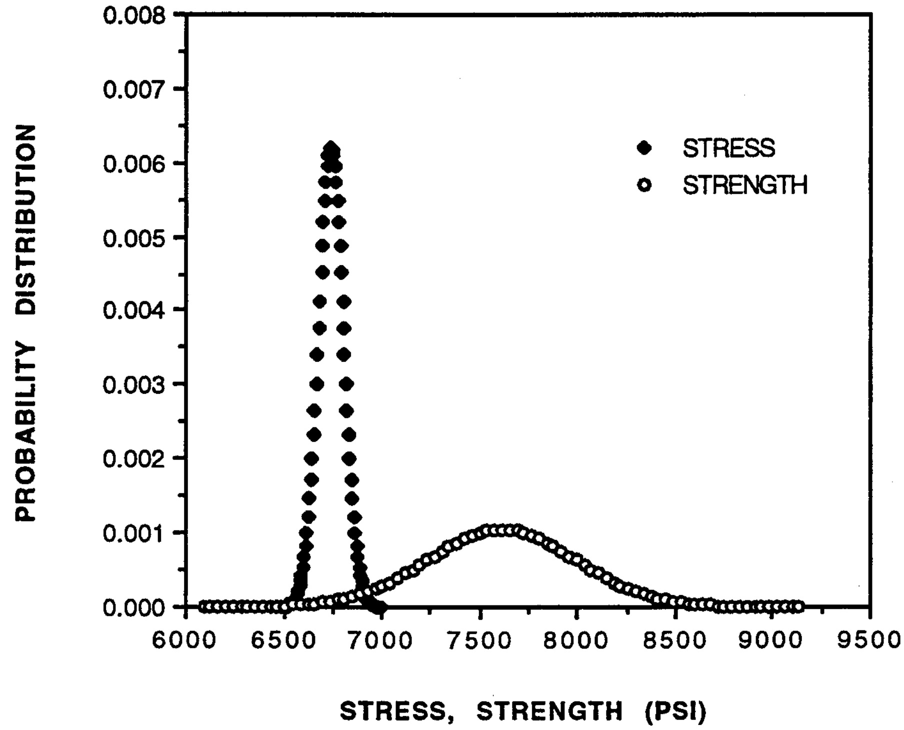


Fig. 8. Stress and strength probability distributions.
OFHC copper milled channel, Node 1, Channel center hot-gas-side wall.
Probability of failure = 0.012

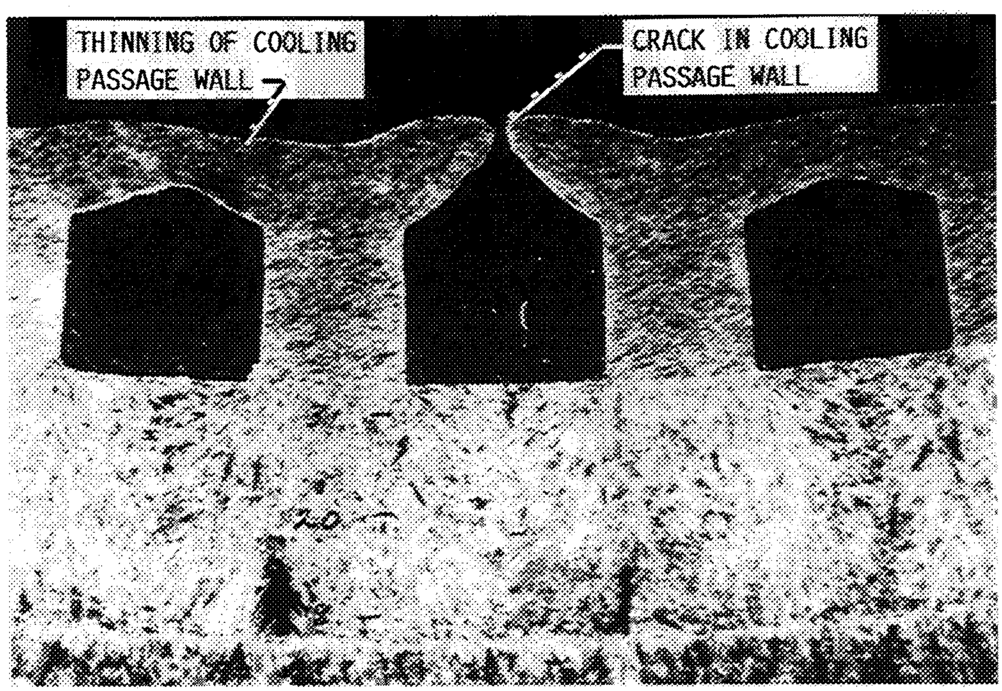
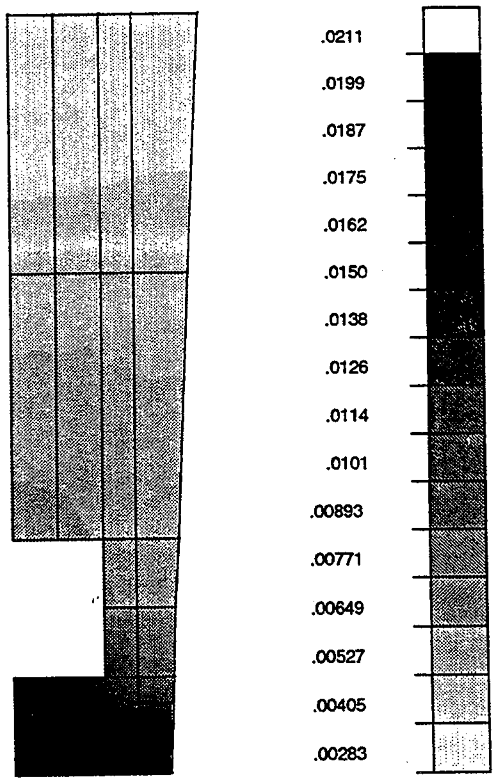
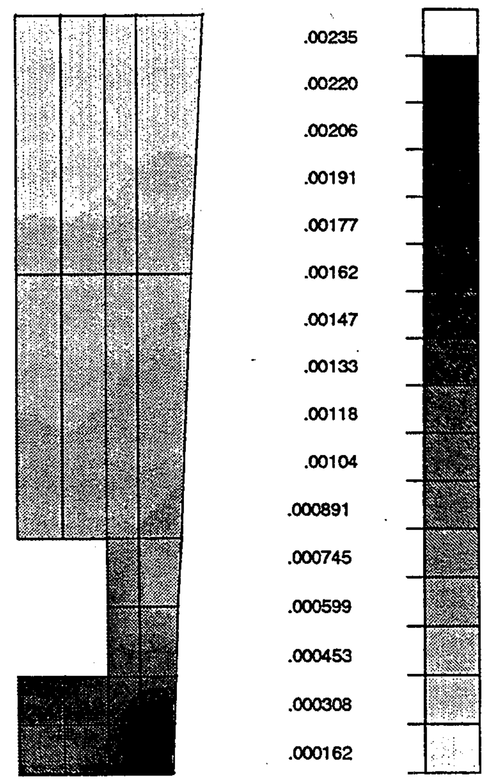


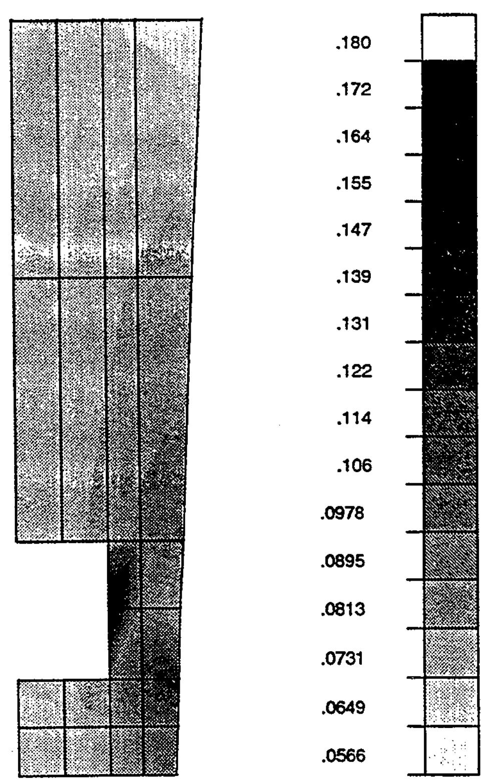
Fig. 9. Crack in combustion chamber liner wall due to thermal ratcheting.
Coolant passages were rectangular prior to cyclic testing.



a) MEAN (in./in.)



b) STANDARD DEVIATION (in./in.)



c) COEFFICIENT OF VARIATION

Fig. 10. Effective strain response of OFHC copper milled coolant channel

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13. ABSTRACT ***(Maximum 200 words)***

The reliability of OFHC (Oxygen Free High Conductivity) copper and NARloy-Z thrust chambers is assessed by applying probabilistic structural analysis techniques to incorporate design parameter variability and uncertainty. Thrust chambers specifically evaluated are the cylindrical test fixtures employed in a plug-nozzle configuration at the NASA Lewis Research Center. Direct sampling Monte Carlo simulations based on a simplified life prediction methodology established probability densities of firing cycles to structural failure. Simulated cyclic lives demonstrated modest agreement to experiment. Similarly, regions of high structural failure probability were determined using a limit state approach employing calculated cumulative distribution functions for effective stress response and an assumed material strength distribution. A probability of failure of 0.012 was calculated at the center of the coolant channel hot-gas-side wall for an OFHC milled channel. Structural response was found to be sensitive to the uncertainties in the thrust chamber thermal environment and the material's thermal expansion coefficient.

14. SUBJECT TERMS
Reliability; Thrust chambers; Monte Carlo simulation; Cyclic life; Probabilistic structural analysis; Uncertainty; Random variables

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