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A RETIREMENT-FOR-CAUSE SUTDY OF AN ENGINE TURBINE DISK

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This report describes a procedure which allows for the retirement of turbine engine disks for actual life exhaustion rather than a statistical minimum limit of a population. The procedure is applied to the third stage turbine disk of the TF33 engine for demonstration purposes. The demonstration included detailed stress and fracture analysis in addition to actual spin pit testing. All spin pit testing was done by the Navy at the Naval Propulsion Center. The effort was a technical success but could not be implemented for the TF33 engine for logistic reasons.

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FOREWORD

This report is a second printing of a technical paper that was presented at the 1978 Air Force-Navy Science and Engineering Symposium. It covers work done, in-house under project 30661236, by engineers of the Air Force Wright Aeronautical Laboratory and of the Aeronautical Systems Division during the time period, 1975 to 1978.

This report describes a procedure which allows for the retirement of turbine engine disks for actual life exhaustion rather than a statistical minimum limit of a population. The procedure is applied to the third stage turbine disk of the TF33 engine for demonstration purposes. The demonstration included detailed stress and fracture analysis in addition to actual spin pit testing. All spin pit testing was done by the Navy at the Naval Air Propulsion Center. The effort was a technical success but could not be implemented for the TF33 engine for logistic reasons.

The authors wish to thank their many Air Force colleagues who contributed during the course of this study, and are particularly indebted to Mr. Guy Mangano and his colleagues at the Naval Air Propulsion Center for the very considerable effort they devoted to the development and execution of the spin pit testing.

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SECTION I

INTRODUCTION

The design requirements of recent jet engines entering USAF service have emphasized increased performance and higher thrust/weight ratios, which, in turn, result in higher stresses and more severe environments for all components. These high stress levels have resulted in the introduction of a larger number of finite life components. In addition, these same components have rapidly increased in cost due to design complexities and by the use of advanced materials and processing techniques. To help minimize Air Force operation costs, it is imperative that ways be sought to optimize the useful service lives of these components.

In this report, an approach to achieve optimum service life, referred to as Retirement-for-Cause (RFC), is described. It is believed that this approach, which is based upon the use of a fracture mechanics analysis of a component's crack propagation phase for a safety factor, can optimize the service life and thereby minimize maintenance costs.

Using the TF33 third stage turbine disk as the test article, a program is described which details the entire RFC procedure. All aspects of the program from the analytical considerations to the spin pit verification testing considering a low cycle fatigue failure mode are discussed.

SECTION II

RETIREMENT-FOR-CAUSE

Traditionally, components whose dominant failure mode is low cycle fatigue (LCF) have been designed to a "crack initiation" criterion. Under this criterion, all components of a given population are considered to have failed as soon as a crack of some finite size, e.g., .031 inch has statistically formed in the member of the population which has minimum strength properties. No attempt is made to utilize the life associated with the remaining population members which have statistically higher properties and are therefore not cracked.

From a safety standpoint, this approach has been generally very successful since it contains a built-in safety factor by assuming all components to be "minimum." However, for real materials and for real design situations, lifetimes based on time-to-crack initiation of the minimum member tends to be extremely conservative for a component population. This may be seen by reference to Figure 1, which illustrates the LCF crack initiation behavior of Inconel 718, a typical nickel-based superalloy, at 1000°F. Because of the statistical nature of engineering materials like Inconel 718, there is significant scatter associated with the number of loading cycles required to initiate a crack at some given stress level for each specimen of material produced. For design purposes, this problem of "material scatter" is usually eliminated by degrading the failure curve to a conservative "design allowable" level where the probability of failure, i.e., crack initiation, becomes very low. For critical components such as engine disks, this probability is usually set at 0.1%. Figure 1 shows a design allowable curve established via this philosophy. In service, a component manufactured from this material would be used for the number of load (fatigue) cycles permitted by this design allowable curve and then all such components in the population would be retired. Theoretically, at this cycle count point, only one component in a population of 1000 would have actually initiated a crack and the remaining 999 components would have some undefined useful life to crack initiation remaining. Figure 1 shows that in the case illustrated, the difference between the number of cycles to reach the "design allowable" curve and the population "average" curve are significantly different and that at the design allowable limit an "average" component would have consumed only 10% or less of its potential useful life-to-crack initiation. However, under an initiation criterion as in the current Air Force system, there is no way to utilize this potential life without accepting a higher probability of failure of the minimum member.

Under the proposed system, this additional useful life can be utilized by adopting a rejection criterion that uses each component in a population until it specifically initiates a crack rather than rejecting the entire population on the behavior of the statistical minimum.

The development of fracture mechanics concepts over the last several years has permitted the degree of predictability for crack propagation rates necessary to implement such an approach on a safe basis.

Figure 2 shows the basic RFC concept. For a given component, the number of cycles, N_c, required to propagate a crack from an initial detectable size A_o to critical size A_c can be calculated and verified. An inspection interval is then established at some fraction of N_c designated N_I. The value of N_I is established by considering the non-destructive inspection threshold crack value A_o, cost effective overhaul intervals and degree of conservatism desired. It can be seen that over this interval of time, N_I, no component containing a crack equal to or smaller than A_o could fail catastrophically by reaching A_c.

In using RFC as an operating system, all components would be inspected first at the end of the initial N_I cycles, and only those components containing detectable cracks equal to or greater than A_o would be retired. All others would be returned for additional service. After additional N_I cycles, all components would again be inspected and again all components with cracks larger than A_o rejected and the remainder returned for service. In this way, the crack propagation residual life is continually reset to a safe N_c value. By following this approach, components are only rejected for cause (cracks) and each component is allowed to operate for its own specific crack initiation life. It should be noted that if a crack is missed at the first inspection interval, another chance exists to find a larger crack, A*, before A_c is achieved.

It is clear that not all fatigue-limited components may be handled in this way, and that each component must be evaluated individually to determine the economic feasibility of RFC. The inspection interval N_I (Figure 2) must be such that it does not place undue constraints on the operation of the component or that the cost of the necessary "teardown" and inspection does not negate the advantageous of the life extension gained. One thousand cycles of crack propagation may represent many years of service for one component and a fraction of a second for another. It seems unlikely that RFC can be applied to components limited by high cycle fatigue considerations, but for many high cost components limited by LCF, such as engine disks, this approach does appear to offer significant economic advantages.

It is also clear that in applying RFC, Non-destructive Evaluation (NDE) becomes a critical factor. The crack length value, A_o, in Figure 2, determines the residual life of the component and its detection is limited by the resolution and reliability of the inspection system employed. In many cases, the decision as to whether or not RFC can be applied to a component will be predicated upon the ability of available NDE approaches to detect a usable A_o with sufficient sensitivity and reliability. However, because the RFC procedure includes an in-depth stress analysis, a component's defect critical locations can be accurately predicted and verified. For this reason, NDE techniques can be selected and refined for a particular area rather than attempting to develop a technique for characterizing the quality of an entire component. This inherently increases the sensitivity of the NDE system to a level where RFC can be utilized.

Preliminary crack growth analyses indicate that the detection and elimination of cracks larger than .030 to .050 inch surface length (A_0) would provide adequate residual life for the safe application of RFC to many older disk designs, and this was the crack size of primary interest in the present study. However, it is also recognized that in some of the more advanced designs, using higher strength, lower toughness material, the acceptable level for A_0 must be much smaller for economical use of RFC.

SECTION III

DEMONSTRATION OF THE USE OF RFC ON A TF33 THIRD TURBINE DISK

1. ENGINE AND SPIN PIT STRESS ANALYSIS

In order to demonstrate RFC, an entire RFC program was initiated on the TF33 third turbine disk shown in Figure 3. The TF33 third turbine disk first was analyzed as part of the turbine low rotor system at the mission point of 105 seconds after take-off. This flight point produces the maximum centrifugal and thermal load on the disk. The analysis was done using the "ISOPDQ" family of finite element computer programs (Reference 1) developed under contract to the Air Force for the purpose of conducting stress analyses of turbine engine components. The analysis considered all blade and attachment bolt loads as well as adjacent hardware interaction.

The result of this analysis is shown as the "engine assembly" curve in Figure 4. (Only the stresses from the bore up to the bolt hole are shown). The nominal stress at the edge of the bolt hole was calculated to be 84.7 ksi. This value of stress was the value that was used as a goal in creating the spin pit test.

In order to establish the spin pit test conditions, an accurate finite element computer model of the disk was created and analyzed. Both the nominal stress and the actual stress gradients were calculated by using different models. The first model was created from a combination of axisymmetric ring elements and plane stress elements and the second model was created entirely of plane stress elements. The two models were matched through the use of equal bore displacements.

In the first model, shown in Figure 5, the properties of the plane stress element were utilized by representing the material between the bolt holes by rectangular plane stress elements. The out-of-plane direction was aligned, with the disk tangential direction (θ) and thus the in-plane stress σ_y aligned with the radial direction (R) and the in-plane stress σ_x aligned with the axial direction (Z) of the disk. The thicknesses of the plane stress elements were set equal to the average thickness of the material between bolt holes. Both the top and bottom of the plane stress elements were constrained to axisymmetric ring elements and thereby the disk bolt circle could support radial and axial loads but would not exhibit tangential stiffness nor transmit tangential load.

The entire model was analyzed at a 6000 RPM, 70^{o}F condition and resulted in an average deflection of .00488 inch at the bore. (These analysis constraints were chosen to be identical to a spin pit strain survey test which was to be conducted prior to the actual fracture tests).

The second model of the bolt hole using only plane stress elements was created as shown in Figure 6. The deflection value of .00488 inch was used as the required deflection for an equivalent load to produce on the plane stress bolt hole model. The value of the required force was determined by an iterative method to be 1883.2 pounds per nodal point in the radial direction along the top of the model.

The nodal points on each side of the plane stress bolt hole model were free from constraint in the radial direction and constrained to have zero deflection in a direction perpendicular to the radial direction. Constrained in this fashion, the boundaries of the model could only slide on a radial line. The thickness of each element was set equal to the thickness of the disk at the same location with slight adjustments being made for the disk thickness gradient. This model was also analyzed at a 6000 RPM, 70^{o} condition.

In this particular disk, only 10 of the 20 holes are used as "bolt" holes. The remaining 10 holes are "balance weight" holes and are counter sunk .090 inch and are .075 inch less in diameter than the bolt holes. Based upon a tangential plane projection comparison between the bolt holes and counterweight holes, the difference in tangential load transmittal ability is considered insignificant and thus all holes are considered to be identical in the analysis.

The results obtained using this two model procedure on the TF33 engine disk bolt hole geometry are shown in Figure 7 compared to the experimental strain data. As can be seen, there is very good agreement.

As a result of this good agreement, the two model procedure was expanded to include the actual thermal gradient effect and actual spin pit stress values were calculated for use in the fracture analysis.

Through an iterative method it was calculated that the spin pit test should be run from 0 to 6400 RPM with the thermal gradient that is labeled "Flight Profile" in Figure 8. However, this desired thermal gradient could not be achieved in the pit and, in fact, the actual test gradient had to be modified three times (shown in Figure 8 as gradient 1, 2, and 3) to reduce the spin pit cycle time. In addition, the 0 RPM engine shutdown condition could not be achieved in the pit and had to be changed to 500 RPM. All three combined stress (thermal and centrifugal) gradients for the run-up and run-down side of the three pit cycles are shown in Figure 4 for the nominal stress and in Figure 9 for the peak stress. The values from these two sets of curves are the values used in the fracture analysis.

2. FRACTURE MECHANICS ANALYSIS OF TF33 DISK

The approach taken in performing the required crack propagation analysis of a low cycle fatigue induced crack in a TF33 disk bolt hole employed the use of the well-known modified Walker equation (Reference 2). A Bowie correction was also incorporated in the solution procedure to approximate the stress field in the vicinity of the bolt hole crack as it progressed.

As previously mentioned, both an axisymmetric and a plane stress analysis were used to generate the initial conditions for the fracture mechanics analysis considering all three spin pit cycles. Since the axial stress component was found to be small in both analyses relative to the radial and tangential components in the area adjacent to the hole, an assumption of crack growth in a biaxial stress field was considered reasonable. However, before conducting the actual crack growth calculations, an understanding of the material's response was necessary. Since minimal crack growth data was available for the Incoloy 901 material at the temperatures of interest, it became necessary to generate a crack growth curve for the prescribed temperatures anticipated during testing. Figure 10 portrays the results of this effort.

For the fracture analysis, the modified Walker equation used is equation (1).

$$\frac{da}{dN} = \frac{C(\Delta K)^n}{(1-R)^{(1-M)n}} \qquad (1)$$

where: $\frac{da}{dN}$ = rate of crack growth per cycle

C = 1.537×10^{-10} } crack growth

n = 2.937 } curve parameters

M = .5 empirical weight on mean stress effect

R = minimum to maximum stress ratio

ΔK = change in effective stress intensity

The K expression used to obtain values for equation (1) was equation (2).

$$\Delta K = \Delta\sigma \sqrt{\frac{\pi a}{Q}} \; f\;(a/r) \qquad (2)$$

where: ΔK = change in stress intensity

$\Delta\sigma$ = change in applied stress

a = crack depth

Q = correction factor for geometry and stress distribution in vicinity of crack

f(a/r) = Bowie Correction Factor

Figure 11 shows the TF33 disk cross-section with the assumed elliptical starting crack superimposed. It should be noted that the Bowie correction factor used in the analysis was for an imbedded crack in a bolt hole exposed to a biaxial stress field. In addition, this expression was modified slightly to account for the fact that the radial component of the biaxial field was lesser in magnitude than the tangential stress. Some conservatism was also applied by assuming that the elliptical crack transitioned to a through-the-thickness crack when the surface length of the crack, 2c, exceeded 75% of the actual disk bolt pad thickness. This assumption appears reasonable considering the geometry of the disk in which the crack front is propagating. The aspect ratio for the crack (crack depth ÷ crack length) was arrived at by breaking open scrap TF33 disks which exhibited cracks in the bolt hole region as shown in Figure 12. Although the characteristic of the cracks in the bolt holes varied with multiple initiation sites, and appeared to propagate at a changing aspect ratio, a value of .35 was determined to best represent the average aspect ratio and was used in the analysis. Disk failure would occur when the crack depth, a, reached a critical crack depth value, a_c, which was calculated using the fracture toughness value, K_{IC}, in equation (2). These values are 0.335 inches and 110,000 psi$\sqrt{\text{in.}}$, respectively.

It will be shown that this is not truly the case but that residual life still exists once the crack goes beyond 0.335 inches.

3. SPIN PIT TESTING

For the spin pit verification, a high time TF33 third stage turbine disk which had been retired from service with an unknown history was used. The particular disk, however, had been cycled beyond the "initiation" point and contained a measured service-induced crack of 0.052 inches surface length. At an aspect ratio of .35, this surface length was the starting size used in the fracture mechanics analysis and resulted in a predicted critical crack depth of .335 inches at a propagation cycle count of 15,090 cycles with a growth rate as shown in Figure 13.

As was discussed, three different thermal gradients were used during the duration of the fracture testing. The amount of testing done under each of the three gradients was as follows: Gradient #1, Cycle 1 to Cycle 597; Gradient #2, Cycle 598 to Cycle 1500; Gradient #3, Cycle 1501 to test completion. These three gradients stress/crack propagation effects were considered in the fracture analysis assuming linear cumulative damage.

The sequence of testing was as follows:

Step 1. Apply temperature gradient.

Step 2. Spin up to 6400 RPM.

Step 3. Spin down to 500 RPM.

Step 4. Flush pit with cooling gas.

Step 5. Repeat Steps 1 through 4

The inspection interval was about every 500 cycles with the following procedure:

Step 1. Clean with solvent (each hole).

Step 2. Obtain trace of eddy current probe reading.

Step 3. Replicate with milar film.

Step 4. Assemble in pit and run next 500 cycles.

Step 5. Repeat Steps 1 through 4.

The eddy current inspection consisted of using a Dalton(R) eddy current unit modified with an automatic spiraling mechanism. As the probe transcended the hole, a trace of the signal was recorded. The crack growth was also recorded and measured through standard crack replication methods.

Testing was ended at the 13,860 cycle point after the disk could no longer be spun within acceptable balance limits. Figure 14 shows the disk after test completion.

The results of the spin pit fracture testing are shown in Figure 13 compared to the predicted growth. It should be noted that the crack growth in bolt hole #2 (.052-inch starting crack length) showed the same shape and trend as the predicted rate, but it was not the bolt hole that would cause ultimate failure. At approximately the 7500 cycle test point, bolt hole #1 indicated a crack which was also monitored for the duration of the test. Up to about 9000 cycles of testing, this crack in hole #1 grew as expected, but then it "popped" through the thickness and grew at a faster rate to become the dominant crack that ultimately caused the test to be ended. The reason for this change in behavior is not understood at this time. Effort is underway to section this test disk to determine precise aspect ratio of the cracks and to correlate the eddy current traces with the fracture surfaces. A new fracture analysis will be accomplished upon determination of the actual aspect ratio.

SECTION IV

RESULTS

It was shown through completion of the spin pit test that over 5-1/2 life times of propagation life exists for this disk as a fracture safety margin. Thus, if RFC was adopted as the replacement philosophy and the inspection interval (N_I) was set equal to one initiation life of 2500 cycles (current throwaway point), there would be five opportunities to find a crack in the disk of increasing surface length from an initial size of .031 inch. Based upon this one disk test data point, RFC would appear safe and practical for this TF33 disk. Figure 15 shows the potential for cost savings on this disk if RFC was instituted. It was not instituted by the Air Force, however, because there were no third turbine disks of TF33 design to replace the cracked disks that would be found. As a result, the Air Force had to utilize a JT3D disk in conjunction with a low turbine modification package whenever a TF33 disk needed replacement. Rather than have two different configurations and considering all cost aspects, it was beneficial to the Air Force to replace all TF33 third turbine disks at overhaul, without inspection, with the JT3D modification package. Thus, even though the RFC study was successful, it could not be utilized cost effectively on the TF33 third turbine disk. There are, however, many other LCF limited disk stages in the TF33 engine where RFC could be applied as well as many different engines in the Air Force inventory. Current studies are underway to identify which engine and which stages are the most cost effective RFC candidates.

SECTION V

DISCUSSION

The program described in this report is one of the first, if not the first, attempt to conduct a full-scale RFC validation, and to integrate the various necessary technologies into one program. As such, the results have been very valuable in assessing the state of the technology base and the requirements for implementing a RFC approach.

The primary technology areas required for RFC can be divided as follows: stress analysis, crack growth analysis, non-destructive evaluation, and mechanical testing. The following discussion examines each of these areas and attempts to define the work still required for total RFC implementation.

It is obvious that the ability to utilize an RFC philosophy depends first upon the generation of an accurate understanding of the stress field of the component's critical area(s). It is felt that the current level of stress analysis capability across the turbine engine industry is such that this aspect of the RFC method is not the limiting factor. In fact, there is even significant effort to improve the "standard design" elastic stress analysis capability to include three-dimensional inelastic time independent and dependent effects. Other areas where advances are being achieved include the determination of stress intensity factors for crack tips that are in biaxial and triaxial stress fields.

However, as demonstrated by the success of this project, one does not have to wait upon these newer technologies to come fully of age before implementing an RFC overhaul concept. A rigorous two-dimensional elastic analysis will provide data of sufficient accuracy to adequately implement RFC on many existing and development engine components that do not exhibit gross plastic flow. The components which do, however, exhibit this non-recoverable deformation will have to wait upon the validation of the newer analysis technologies prior to their inclusion in an RFC philosophy.

It was also demonstrated that an accurate fracture mechanics analysis, along with NDE, are two additionally critical requirements for the successful implementation of an RFC system. The fracture analysis performed in this study was relatively unsophisticated, and under the circumstances, it is remarkable that the correlations observed were so good. However, since 1975 when this analysis was initiated, a very significant volume of research has been devoted to high temperature fracture mechanics and the technology appears to be maturing rapidly. For example, the problems of a K-analysis of complex geometries, crack growth in complex stress fields, and the transition of part-through to through-cracks appear to be solvable through the use of linear superposition techniques (References 3, 4, 5), as well as recently developed experimental approaches for a K-analysis (Reference 6). The relationships between crack growth and many of the engine load parameters such as temperature, hold times, and stress ratios have also received considerable attention and again promising solutions appear to exist (Reference 7).

One problem exposed by this study that is currently not receiving much attention is that of multiple crack initiation. Traditionally, fracture mechanics assumes a single "engineering" crack and predicts its growth. Figure 16 shows a typical bolt hole crack observed by dye penetrant in one of the TF33 third turbine disks. As cycling proceeds, these microcracks grow individually and eventually merge into one dominating macrocrack. Observation of this phase reveals that there is an undefined interaction between the cracks that produces an accelerated growth. Since this microcracking phase persists for a significant portion of the crack growth life, it is clearly imperative that analytical approaches be developed to handle this case.

One major problem inhibiting the immediate reduction to practice of an RFC system for all components is the lack of an acceptable probabilistic prediction method for crack growth. In the present study, no attempt was made to account for materials variability, even though the material, Incoloy 901, is known to show considerable scatter in its crack growth behavior. Based upon minimal crack growth testing, observations reveal that the crack growth tended to be faster than predicted, and while this can be explained in part by the microcracking process described above, it probably suggests that the crack propagation behavior of the test disk was faster than the average values used in the analysis.

As stated earlier, NDE is a critical factor in the implementation of an RFC approach. Since with RFC the rejection of a component now becomes based on the presence or absence of a crack, it is essential that the NDE technique employed be capable of finding cracks above some defined threshold (A_0) with a very high degree of reliability. The current Air Force practice of using penetrant inspection techniques almost certainly will not provide the required sensitivity or reliability levels for an RFC system. The development of automated processes using inherently more sensitive techniques (e.g., eddy current) will be required. It would also be highly desirable to develop NDE techniques capable of more quantitative information (e.g., both length and aspect ratio of surface cracks). Finally, it is essential that the statistical aspects of NDE be included in the RFC analysis.

The spin pit verification, while costly and time consuming is a necessary step in developing the confidence levels necessary to implement the RFC approach. In the present study, considerable effort was devoted to simulating both the mechanical stress and thermal environment of the TF33 engine in order to best verify the analytical predictions. However, provided that the engine environment is well understood so that it can be handled analytically, a simpler isothermal spin pit test may probably be adequate for many disks.

In considering the application of RFC to other engine disks, it is clear that additional complexities may exist which must be considered. In the present case, the engine mission is relatively simple with few load interactions and the critical location is located in an area where fatigue/creep interactions or superimposed vibratory stresses are not likely to have an influence. In other disks, both of these factors may have to be considered in the analysis. In addition, the higher design stresses and high strength, lower toughness alloys used in many advanced engines will result in smaller critical crack sizes thus placing even more emphasis on improved NDE techniques. Nevertheless, the significant economic advantages of an RFC approach does appear to provide adequate incentive to continue the development of this approach for optimizing engine component life.

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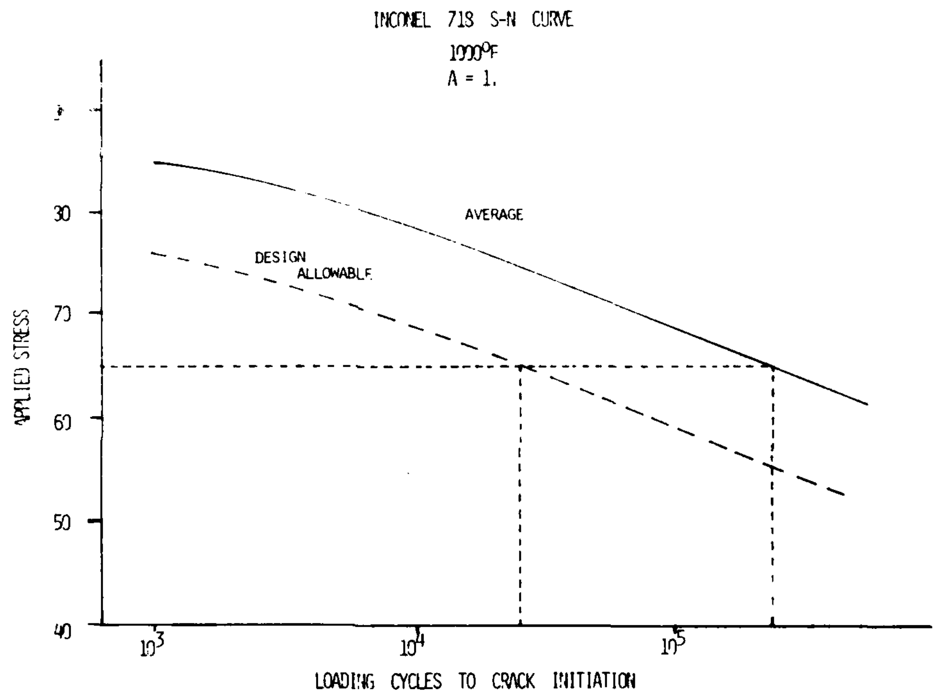

Figure 1
Inconel 718 S-N Curve

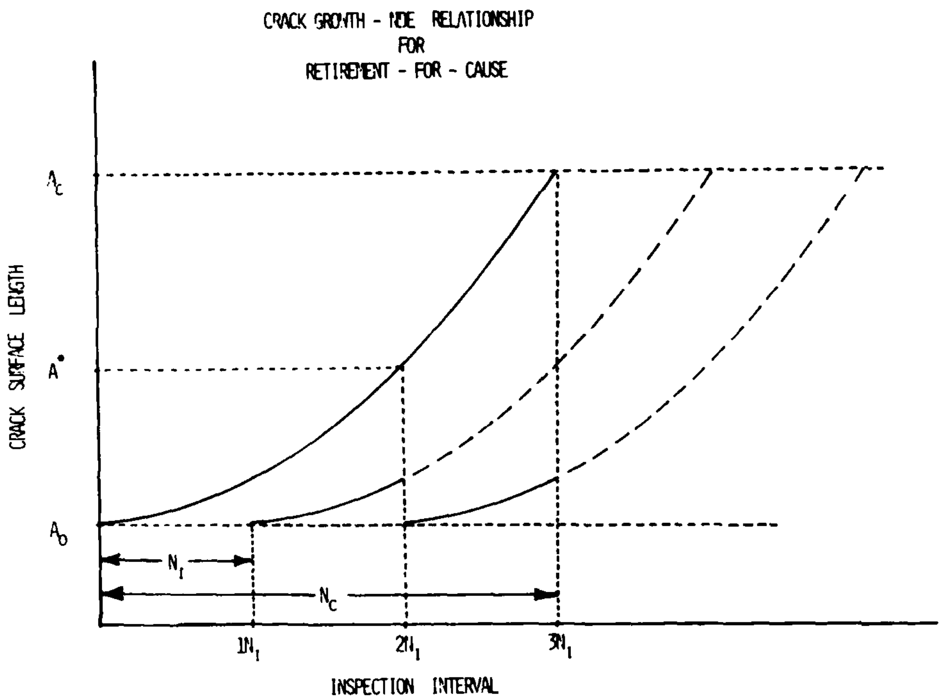

Figure 2
Crack Growth - NDE Relationship
for Retirement-for-Cause

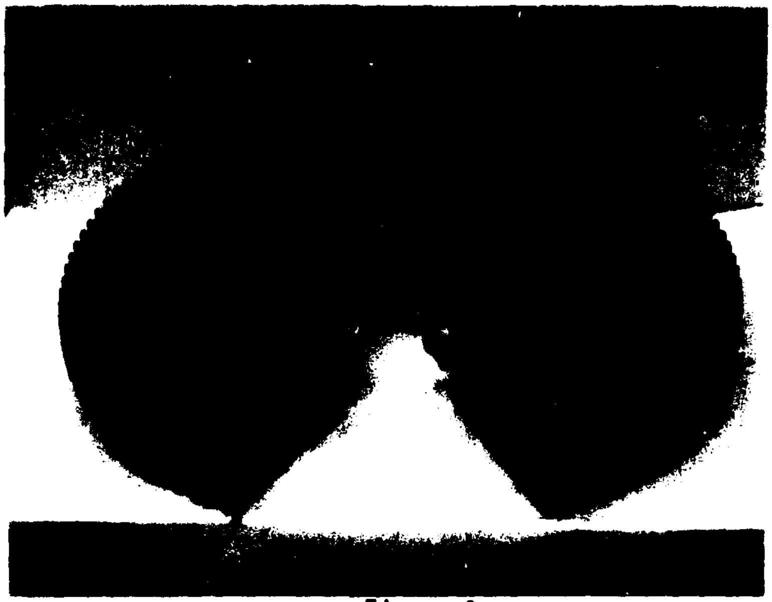

Figure 3
TF33 Third Turbine Disk

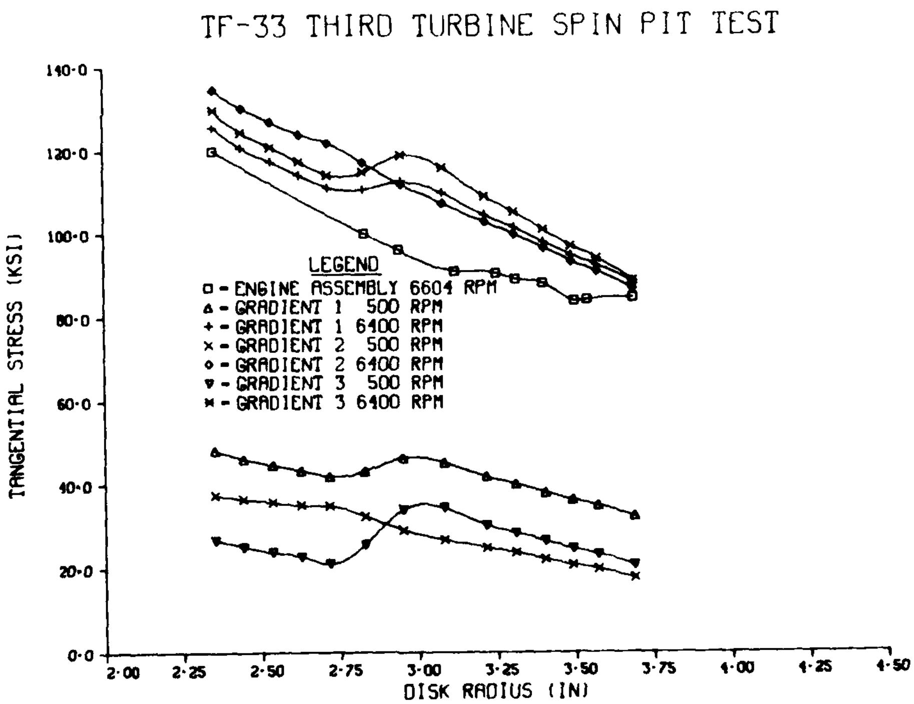

Figure 4
Nominal Stress Gradient

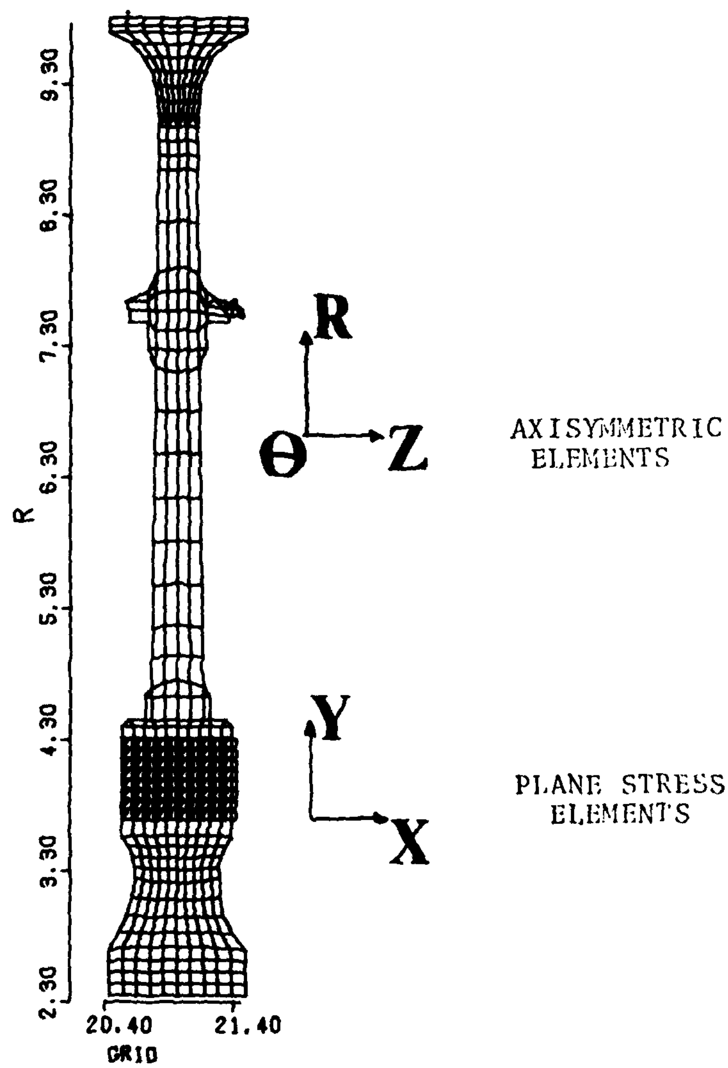

Figure 5
Disk Stiffness Model

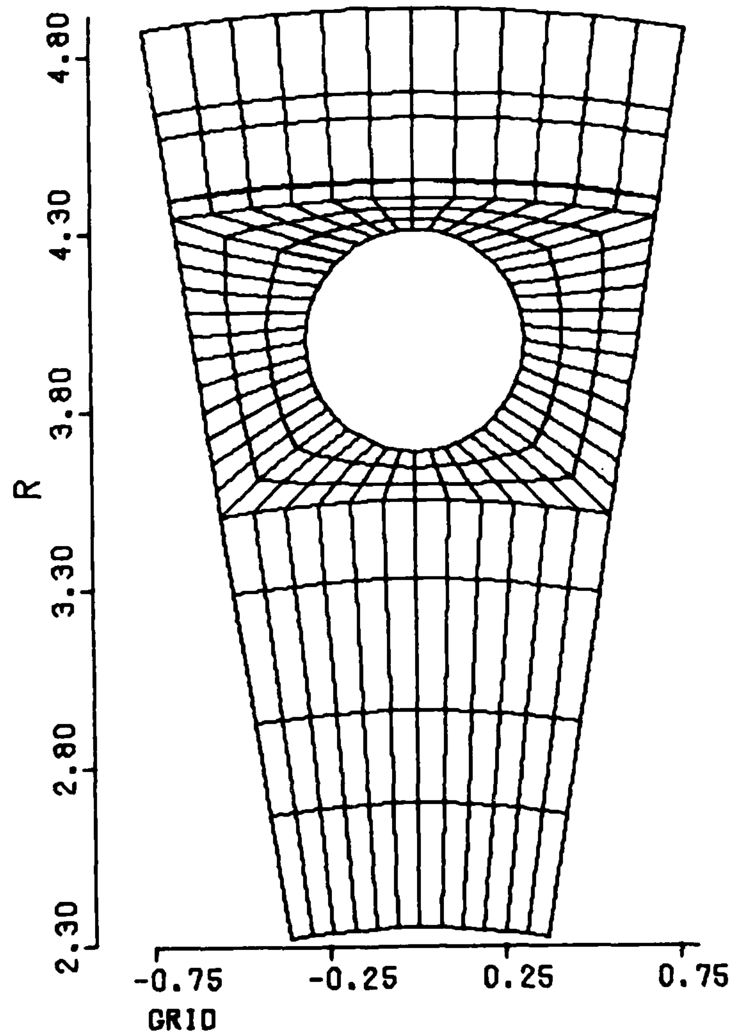

Figure 6

Plane Stress Bolt Hole Model

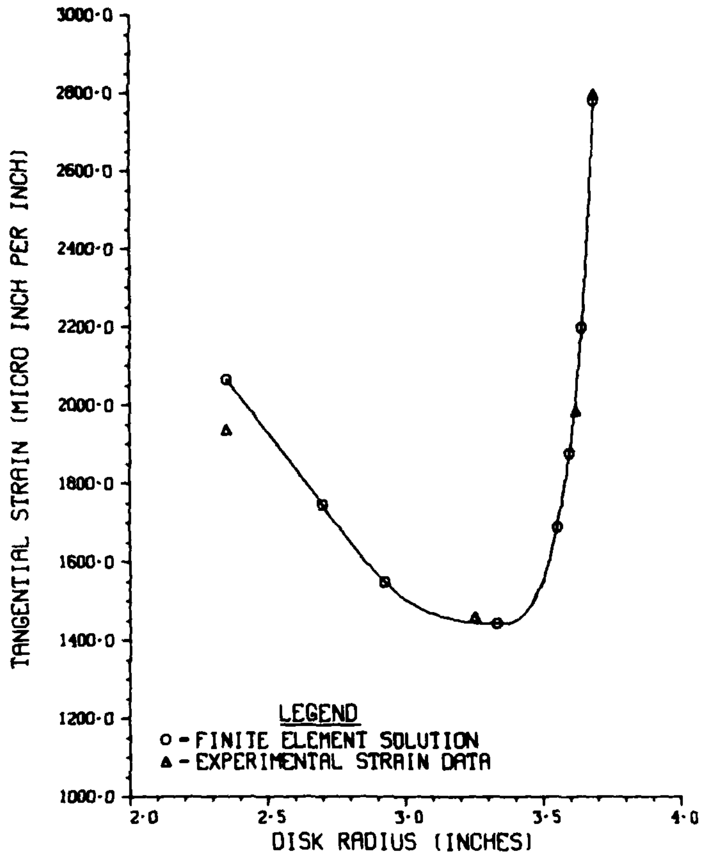

Figure 7
Spin Pit Strain Test Results

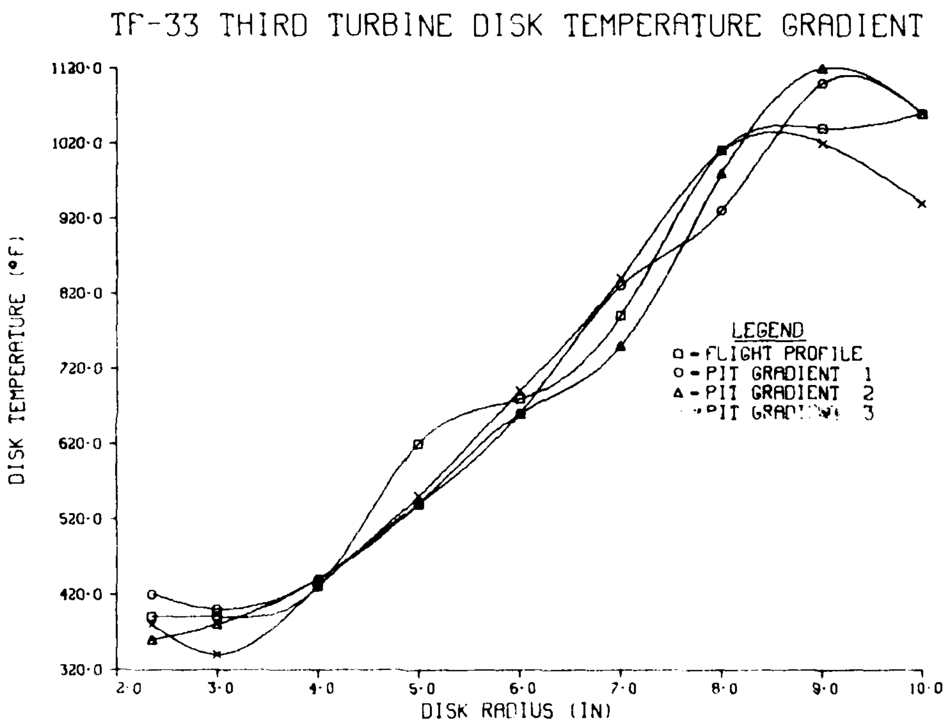

Figure 8
TF33 Third Turbine Disk Temperature

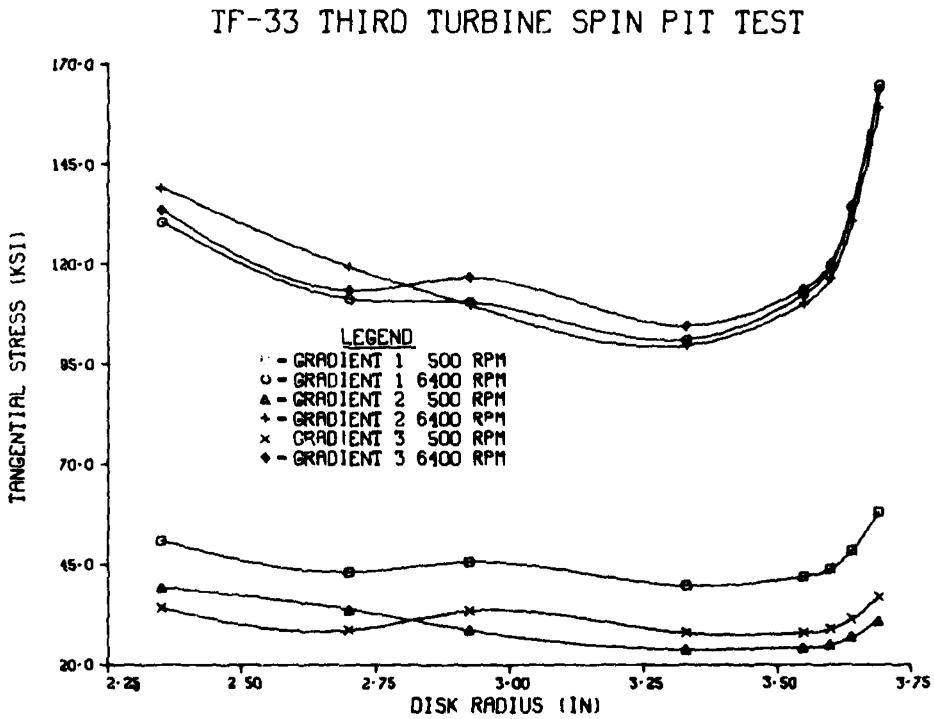

Figure 9
Peak Stress Gradient

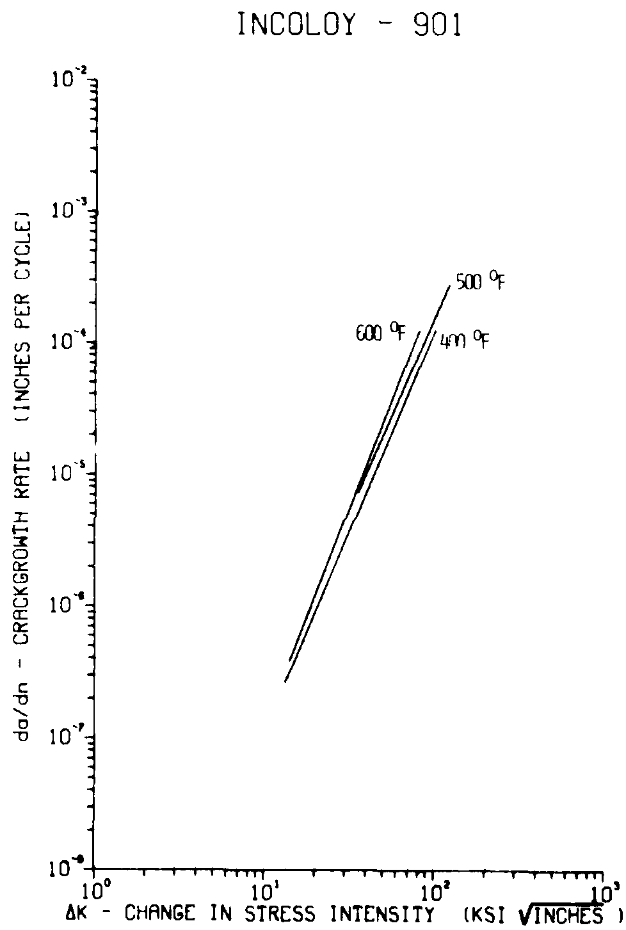

Figure 10
Crack Growth Curve

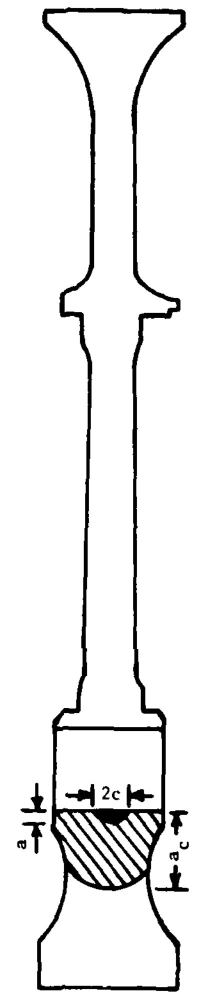

Figure 11
Bolt Hole Crack Geometry

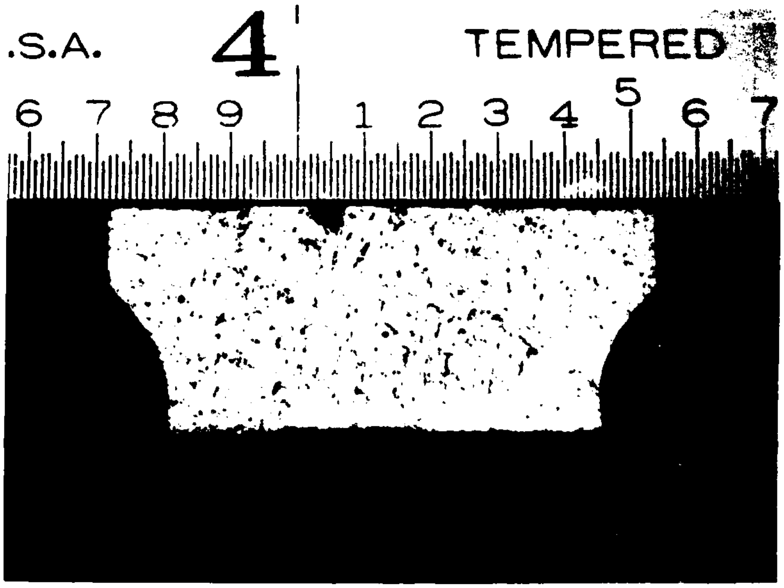

Figure 12
Typical Bolt Hole Starting Crack

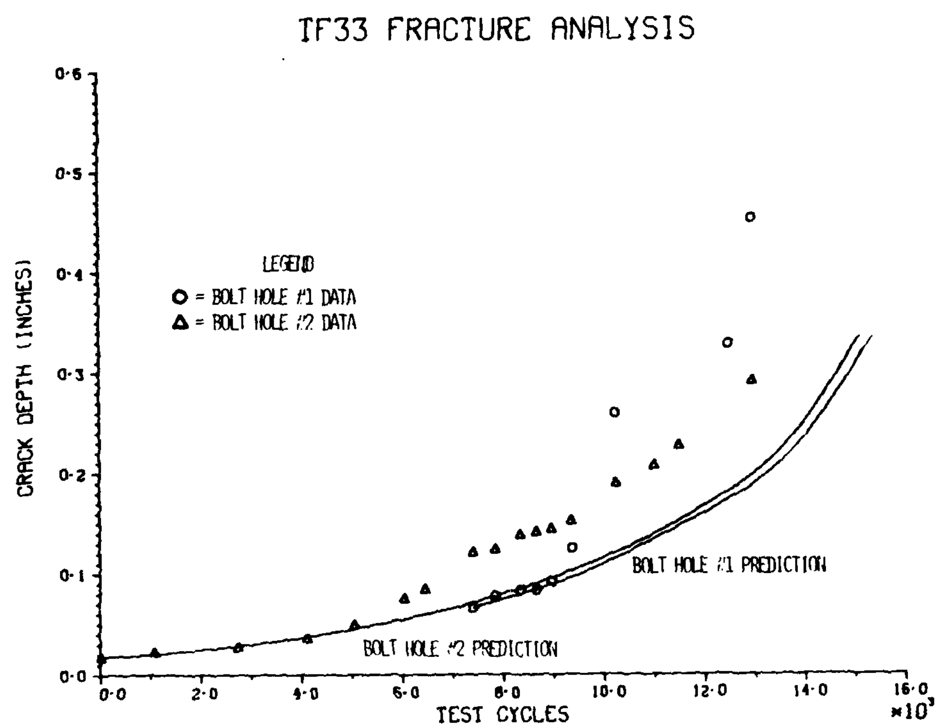

Figure 13
Spin Pit Crack Growth Test Data

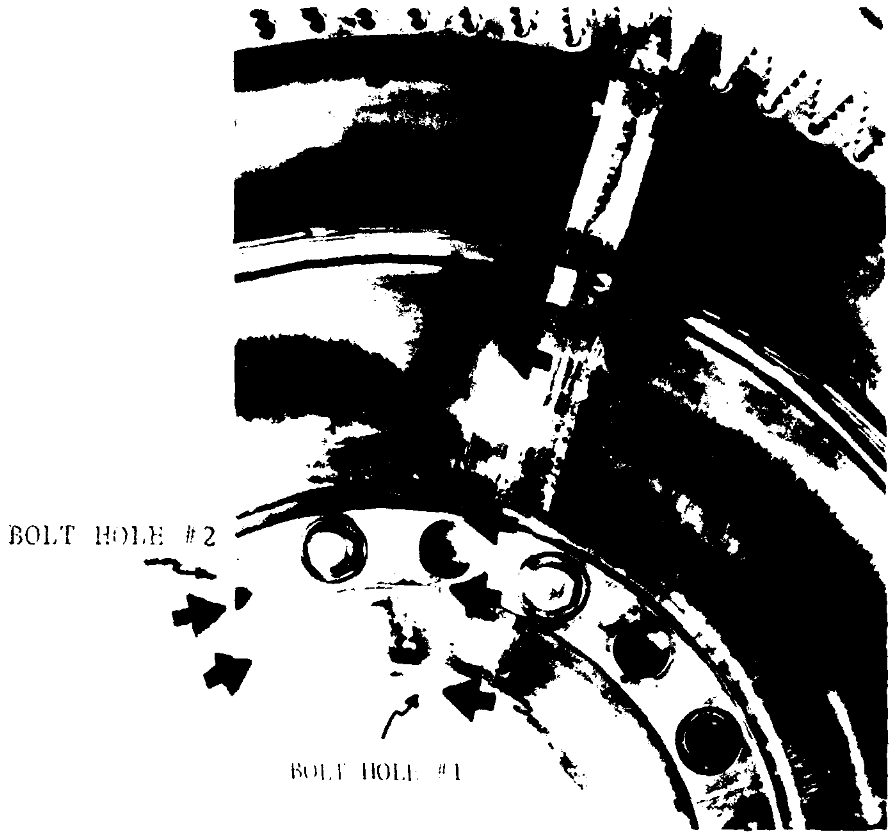

Figure 14
Bolt Hole Cracks at Test Completion

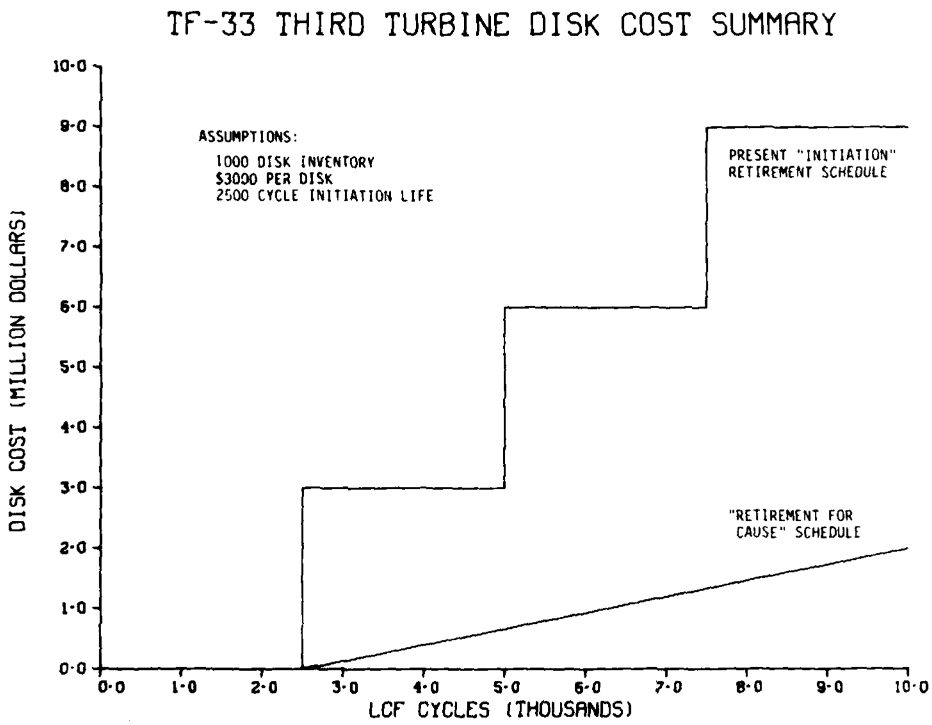

Figure 15
Disk Replacement Cost Schedules

Figure 16
Bolt Hole Surface Microcracks

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