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NASA RESEARCH BEARING ON JET ENGINE RELIABILITY

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INTRODUCTION

Turbojet engine reliability has long been an intense interest to the military users of this type of aircraft propulsion. With the recent inauguration of commercial jet transport this subject has assumed a new dimension of importance.

In January 1956 the Lewis Research Center of the NASA (then the NACA) published the results of an extensive study on the factors that affect the operational reliability of turbojet engines (ref. 1). At that time the report was classified Confidential. In July 1958 this report was declassified. It is thus appropriate at this time to present some of the highlights of the studies described in the NASA report. In no way is it intended to outline the complete contents of the report; rather it is hoped to direct attention to it among those who are directly concerned with this problem.

Since the publication of our study over three years ago, the NASA has completed a number of additional investigations that bear significantly on this subject. A second object of this paper, therefore, is to summarize the results of these recent studies and to interpret their significance in relation to turbojet operational reliability.

A third objective is to indicate several further needs -- design information, operational principles, and inspection and maintenance procedures -- that would lead to greater engine reliability. The unique opportunity afforded by the invitation of a new industry -- starting as it is with a new crop of engines and with a need for long life and utmost reliability -- to provide information of immediate use and which will help in the design of future generations of engines should not be overlooked.

In discussing the problem of jet engine reliability it is important to recognize important differences between the characteristics of this type of engine and those of the piston engine which it replaces. The concept of limited life is familiar to most engineering and maintenance personnel concerned with aircraft; but in most cases this concept relates only to rubbing contact wear and to fatigue at approximately room temperature. The severe limitations on life imposed by operation at high temperature is a new concept that must be superimposed when considering jet engine life. Not only does this factor have a profound effect on policies as to when and how to inspect for failures, but it also governs part replacement policy and the amount and type of records that must meticulously be kept if continuing maintenance of an engine is to be rational. Another difference relates to the sensitivity toward environment of the two type of engines. Foreign object damage, for example, is an unheard-of factor in the reciprocating engine, but one of the principal causes of failure in turbojet engines. The approach to an understanding of jet engine reliability must therefore begin with an acceptance that the differences between the two types of engine will entail a reorientation of the thinking of the design, operation and maintenance personnel, carrying over only those ideas that are of proven pertinence. We must start afresh, determining what parts fail, why, and what can be done about it.

The first step in our study was to examine the data on component failures compiled by the military services. These data served to indicate the components that were the principal sources of difficulty, indicated whether component failures were time-dependent, and gave some indication of the times to

failure of these components. Of course, any one particular engine may be quite different from those that were studied but the study of several served to delineate the average characteristics of the problems.

A review was then made of the theory and experimental information on the failure mechanisms of the important components obtained from NASA research and the literature. On the basis of this information, an attempt was made to discuss methods of avoiding failures, particularly those failures that could cause flight accidents.

The various failures were examined to reveal the causes of the failure, the speed with which the failure progressed from first indication of failure to final failure, and the effect of the failure of the component on the engine.

Methods of avoiding the causes of failure were then explored. When the failure causes could not be eliminated then the methods of avoiding accident in flight were explored. These methods involve scheduled inspections, scheduled replacements and warning devices.

Although the discussion in this report will emphasize primarily the contributions of NASA to this subject, mention will in several cases be made to developments of other organizations. While no attempt will be made to be complete in any area, certain outside contributions naturally fall into consideration while outlining the NASA studies.

We are indebted for the statistical data and valuable discussion to personnel in Wright Air Development Center, Air Materiel Command, Oklahoma City Air Materiel Area, Directorate of Flight Safety, Bureau of Aeronautics, and the aircraft engine industries.

STATISTICAL STUDY

It is very difficult to obtain a clear picture of the service life record to data of the turbojet engine from available published information. This is true, in part, because quoted statistics are based on overhaul records which, as we shall see, can sometimes have less significance than might be expected. It may also be due to the limited viewpoint involved in the quotations which may lead both to unusually high life or to unusually low values. In some cases a high service life of a single engine or, at most, several engines may be quoted. This life may not, however, be representative of the average engine. In other cases, high figures may be given which are specifications of maximum operating times for military engines which is the time when an engine must go to overhaul. The number of engines which complete such a service record without being sent prematurely to overhaul may be very small.

On the other hand unusually low figures may refer only to the average of the lives of these engines in overhaul without regard to the many engines in service that have not yet required overhaul. This can be illustrated by an extreme example. Assume that 100 engines are initially placed in service and after 10 hours one deficient engine requires overhaul. Examination of the average life of the engines in overhaul would indicate a figure of 10 hours. But, this ignores the other 99 engines which might operate for hundreds of hours before coming to overhaul. It is only after all the engines initially placed in service have come

to overhaul that the average life can be determined. Since available statistics do not usually include information on the engines not yet in overhaul, it is obvious that the mean life of those engines in overhaul is not a particularly meaningful figure. To avoid misrepresentations of this type, the Air Force has recently adopted what they call the Actuarial Method by which the operating times on **all** the engines in service are statistically accounted for.

Probably, however, the most important misleading factor is that statistics may be based on overhaul records without regard for the field repair program employed by the Air Force to minimize costs and engine out-time. The present practice is to permit all hot parts in most engines to be replaced at the operating base without sending the engine to overhaul. Even axial flow compressors can be reworked at the operating base, but as a rule they can be disassembled only in overhaul. Since a field repair may involve anything up to and including replacements of turbine blades, turbine disks, nozzle diaphragms, burners, etc., it is obvious that the field repairs cannot be ignored in considering overhaul statistics.

In order, therefore, to obtain a reasonably representative picture of service reliability, one must consider both the field repair program and the overhaul records. Fig. 1 shows some results obtained in reference 1, but which have been brought up to date by very recently obtained statistics. The engines and aircraft have, however, been coded for proprietary reasons. The lengths of the solid bars represent the median times to overhaul (50% of the engines go to overhaul by the median time). It is seen that the time to overhaul of the average jet engine is generally between 320 and 1120 hours. One engine has a median overhaul time of 2500 hours, but as will soon be seen it is particularly important that the interpretation of this figure include consideration of the field repair program for this engine. Also shown in the figure are the overhaul statistics for military reciprocating engines. The overhaul times lie between 460 hours and 1420 hours, with most of them above 700 hours.

The extent of the field repair program is shown in Fig. 1 by the dotted lines which represent the median times to first removal for each airplane-engine combination. The repair is frequently made at an operating base, and does not count as an overhaul. The figures are now seen to be considerably lower. An outstanding example of the influence of the field repair program on time to overhaul is the case of the C7 engine in the T1 airplane shown twice in the figure. In one case a normal number of field repairs are being accomplished in the field and the average engine goes to overhaul in 480 hours. In the second case the airplanes are being used by a command that is making an "all out" effort to accomplish replacements at the operating base. The engine then naturally exhibits a high overhaul time of 2500 hours but the time for first removal of the average engine is about the same, 200 hours.

Fig. 2 shows the number of removals per major overhaul. For the engine cited above the low overhaul time group of engines corresponds to a removal rate of 2.4, whereas the engines with the long overhaul times have a removal rate of 12.5. Also shown in this figure are the ratios of removal rates (the number of removals not including overhauls to removals for overhaul) for reciprocating engines. These are seen to be low.

It should be pointed out that the above discussion is not intended to indicate that available military records on times to overhaul are misleading. The difficulty arises because of the difference in intent between the development

of military records and their quotation for other reasons. Military records of overhaul times are developed for logistic reasons -- so that the proper number of engines will be purchased which will compensate for engine disuse during transportation to and time spent at overhaul. For their purpose, the records are quite correct and very useful. For any other use, caution should be urged.

Fig. 3 shows the principal components which are judged by the inspector at the disassembly base to be the principal reason for engine overhaul. These particular data were obtained during our 1955 study and do not reflect experience with more recently designed engines which we have not had the opportunity to review. The component is shown in the diagrammatic sketch above. Considerable spread was obtained in these statistics when considering different engines. The height of the shaded area represents the spread between the results among several engines. Thus, for all factors other than foreign object damage, the shaded area goes down to the axis indicating that in some of these engines no overhaul could be attributed to these components. By far, the most important reason for overhaul was foreign objects.

Experience has indicated that, whenever an engine is disassembled either in the field or in overhaul, a large number of component failures will be found although the cause for overhaul may be attributed to failure of only one of these components. Fig. 4 shows a sample of our findings on the part replacements made during major overhaul. It is seen, for example, that in one engine type 60% of the engines required burner component replacement during overhaul. In another engine, over 80% of the turbine sections required replacements.

The above statistics, while appearing somewhat pessimistic, should not be interpreted to imply that identical experience will be encountered in commercial application. It must be recognized that the military application is quite different from its commercial counterpart, both as to nature of service and as to factors that govern engine removal. However, it should serve as an indication that the factors which cause such removal must be determined and practices sought out which will reduce them to a minimum. Some of these factors will be discussed in this report, others will become more evident as experience is accumulated.

MECHANISMS OF FAILURE

The statistics indicated the frequency of component failure; however, little insight was provided on the reason for failure and the mechanism involved. Based on a study of failure mechanisms in test engines at the Lewis Research Center, an analysis could be made of the probable causes of the failures encountered in service. In the remainder of this discussion failure mechanisms which were observed will be outlined. These are listed in Fig. 5.

Underdesign and Defects of Materials and Manufacture

In an effort to obtain engines of low weight per unit thrust, components are designed with small margins of safety. Failures are thus usually experienced in early models, but are generally eliminated by improvements in design and manufacturing methods. A large percentage of the failures revealed in our statistical study were of the type that could be corrected by improved design by eliminating defective materials, or improving heat treatments, and by improved practices in forging, welding or other manufacturing methods. We did not therefore concern ourselves with these types of failures.

An important engine component charged with a large percentage of engine overhauls is the fuel control. The largest percentage of fuel control difficulty is due to a failure of a component within the control rather than inadequacy of the control method. No fundamental obstacle to elimination of these defects is apparent; however, a large amount of development time is required on any given control because of its large number of components. Defect elimination is hampered by the fact that control designs were changing rapidly at the time of our investigation. Improvement in the reliability of this component would greatly improve the reliability of jet engines.

Creep and Stress Rupture

A large percentage of the failures in the jet engine parts are due to high temperatures at which the engine operates. One of the failure mechanisms is creep and stress rupture. When a material is subjected to a steady load at elevated temperatures, it is found to elongate continuously with time, this being known as "creep"; and after a certain period of time rupture occurs, this being known as "stress rupture". The life of a material in a stress rupture test is very critically affected by stress and temperature as indicated in Fig. 6. Here is plotted, for a common high temperature alloy -- S-816, the rupture time or life as a function of the temperature for a stress of 15,000 psi. The slope of the curve is such that an increase in temperature of 5% cuts the life by a factor of 10, and correspondingly a decrease in temperature by 5% would increase the life by a factor of 10. Thus, we see why small temperature changes can so drastically affect the life of turbine buckets and turbine disks which are under the action of steady centrifugal stress during operation. Likewise a small increase in stress can have a large effect on the life. For one engine, a 5% increase in engine speed, maintaining the temperature, results in a change of stress rupture life in the turbine bucket of about a factor of 3. Thus, stress and temperature must carefully be controlled in such components as turbine buckets and turbine disks.

Fig. 7 illustrates a plot of method used to determine the maximum life that can be sustained by a turbine bucket. The stress and the temperature along the bucket are plotted, and, from stress rupture curves such as shown before, the life of each section of the bucket can be computed. At the base, the life is high although the stress is high because of the low temperature. At the tip, the life is again high although the temperature is high because the stress is low. Approximately midway between the base and the tip the combination of stress and temperature is such to produce minimum life. This is the section where the failure occurs when the failure is of the stress-rupture type. This minimum stress rupture life varies widely among engines of different design from less than 1000 hours to 30,000 hours.

Rarely, however, does the life of the bucket achieve its stress rupture value. Other factors, such as fatigue, both mechanical and thermal, usually reduce the life to values well below the stress rupture value. Designing for a high stress rupture life, however, increases considerably the margin of safety available for other incidental factors.

One of the problems in connection with stress rupture failure is the variability in life of presumably identical components. Stress-rupture data usually show considerable scatter and turbine buckets which are subjected to the mechanism of stress rupture will likewise show considerable scatter in

life. Fig. 8 shows the results of an investigation (ref. 2) to determine the lives of 46 buckets placed in one wheel. The wheel was operated until the first bucket failed. This bucket was replaced and the wheel operated again until other buckets failed, each blade failure was replaced by new buckets until each of the original 46 buckets had failed. The life of the first bucket was in the neighborhood of 180 hours; the last bucket to fail lasted almost 600 hours. This spread in life is typical of what happens in jet engines and from an operating standpoint illustrates an important principle regarding bucket replacement. This wheel showed a grace time of 180 hours and a set of new buckets could reasonably be expected to operate for close to this period of time without any failures. However, if upon the failure of the first bucket only this bucket is replaced, we can expect the next failure to take place after 10 hours and the next shortly afterwards. This shows the inadvisability of replacing turbine buckets one by one as they fail if the mechanism of failure is stress rupture. When blades begin to fail by stress rupture, the turbine should be rebucketed completely. It is true that a large number of useful bucket hours are lost by such bucket replacement, but no method has yet been found to distinguish in advance between the bucket that will last 200 hours and the one that will last 600 hours. This figure also points up an important factor regarding replacement practice for turbine buckets during overhaul. If, for example, an inspection period had been set at 150 hours, the first inspection would have shown no failures. By the next inspection period of 300 hours almost half the buckets would have failed. A replacement schedule for time-dependent failures must be based, therefore, not only on the appearance of the part during inspection or overhaul, but on experimentally determined life expectancy.

Another important point in connection with creep and stress rupture of turbine buckets is that the creep is highly localized because of the variation of stress and temperature shown in one of the previous figures. Fig. 9 shows the measured local elongations at various points in a turbine bucket after 9 hours and after 28 hours of operation. (This example uses a weak alloy and thus total operating times are very short.) Note, that at the section involving the critical combination of stress and temperature the local elongation may be as high as 8%. The over-all elongation is still low because of the lower elongations in other locations of the bucket. Thus, the use of the creep of a turbine bucket to warn us of impending failure (e.g., as indicated by rubbing of the squealer tips) is not completely practical. The buckets fail with an apparent low over-all elongation because the high strain is localized.

In the case of the turbine disk, creep and stress rupture can occur in the bucket fastening region and in some cases in the hub itself. Fig. 10 shows an unusual case of disk growth due to creep. In this case the creep was quite localized and most of the necking took place in the welded area between the hub and the rim regions. The problem in the case of disks can be very serious when the disk temperature is controlled by a cooling system (as is the usualy practice) and when this cooling system fails. Fig. 11 shows a photograph of a disk which burst as a result of excessive creep due to failure of the cooling system. In this case the cooling air baffles became warped and directed hot gas instead of cool air onto the disk.

When the principal failure is one of stress rupture, several obvious remedial measures can be applied. Lowering the stress or the temperature can, as previously indicated, greatly increase stress-rupture life. Thus, a slight derating of the engine may in some cases be possible which result in large

increase in stress-rupture life. In a study of one engine, for example, it was found that, if the temperature was decreased 100°F and the speed reduced 4%, the increase in the computed stress-rupture life in the turbine bucket was a factor of 44. A 6% loss in thrust was involved, but because of the greater efficiency a 4% decrease in specific fuel consumption could be realized. Careful attention must be paid to the details of the cooling system to insure its proper functioning. Warning devices to indicate when it is not functioning properly would be extremely helpful in avoiding failure. Likewise a systematic schedule of part replacements could be of great value in avoiding engine failure when the failure mechanism is stress rupture. The replacement schedule should be based on laboratory and engine test data; and should allow for the scatter in material properties and in severity of service history.

Since stress-rupture failures usually occur with little prior warning, and since the failure of a disk or of a turbine bucket, especially in the case of a multistage turbine can result in catastrophic failure of the engine, stress-rupture failure must be avoided. Preferably, the design stresses should be kept so low that the theoretical life is well beyond the expected use time of the component. This would allow, in addition, a margin for simultaneous mechanisms of deterioration such as mechanical and thermal fatigue. If, however, the press for high performance forces operation in a stress-rupture range of limited life, then the operator must be prepared to protect the engine by a replacement schedule.

Mechanical Fatigue

Another mechanism that serverely affects the life of jet engine components is mechanical fatigue. Turbine buckets, compressor blades, the fastening region of the disk, the balls and races of thrust bearings, and various sheet metal parts were found susceptible to failure by fatigue. Fig. 12 shows typical failures in a turbine bucket. When the failure is one of stress rupture, the failure cross section is rough and the failure path is in the crystal boundaries. (See top example in Fig. 12.) When the mechanism is one of fatigue, we usually have the familiar concentric rings and a smooth section where the failure is initiated. When fatigue has reduced the cross sectional area so that it can no longer sustain the load, failure usually occurs by stress rupture. This is illustrated by the middle pictures in Fig. 12. The lower pictures illustrate a case in which stress rupture initiated a crack which in turn acted as a stress raiser for ultimate failure by fatigue.

Fig. 13 shows typical fatigue failures in the compressor. The origin of failure usually occurs at the maximum camber point where the vibratory stresses are the highest. When foreign objects pass through the engine, they may nick the compressor blades introducing a stress concentration, usually in the leading edge thereby inducing subsequent fatigue failures. Stress corrosion cracks may also act as nuclei for fatigue. When the stresses are high in the fastening section, the fatigue may occur across the neck of one of the serrations.

Fig. 14 shows typical fatigue failures in bearing raceways. In the case of the bearings and the raceways, the highest shear stresses usually occur slightly beneath the surface and the failure initiates in this region. As the failure progresses outward, it releases a section of metal producing a pit. Later stages produce flaking.

Some of the components in the jet engine such as the compressor fatigue at low or moderate temperature, while other components such as the turbine bucket

fatigue at an elevated temperature. In cases involving high temperature fatigue, it appears that in many cases we cannot even count on such a thing as an endurance limit, a stress below which the material can withstand an indefinite number of cycles without failing. Fig. 15 shows some tests run on a high temperature alloy N-155. In the upper part of the figure is shown the room temperature fatigue curve, the number of cycles to failure as a function of the alternating stress. Any stress below 52,000 psi could be endured indefinitely. At 1350°F, no endurance limit was encountered even up to 10^8 cycles.

Another important characteristic of the jet engine is that in those cases involving mechanical fatigue the number of cycles that are accumulated is very high even within small operating times in the engine. For example, a turbine bucket vibrating in one of its complex modes at 10,000 cycles per second accumulates 10^7 cycles in less than 18 minutes. A typical raceway in a thrust bearing is subjected to alternating stress at a rate of 2400 cycles per second and accumulates ten million cycles in 70 minutes.

A number of remedial measures are possible when the failure mechanism is fatigue. Often an improvement in material quality will solve the problem. Fig. 16 shows how the life of thrust bearings could be improved by an increase in the quality of SAE 52100 steel of which it is made. The circles show the results of fatigue tests conducted in the early 1920's, and the square, the results of fatigue tests conducted in the late 1940's. The composition of the steel was, in both cases, the same. The cleanliness of the steel had, however, improved in the twenty year development period. The increase in life here is by a factor of 10.

The problem of material cleanliness is especially important in bearings at the present time when consideration is being directed to the use of higher temperatures at which SAE 52100 steel becomes too soft to be serviceable. Molybdenum base tool steels show promise for high temperature bearings because of their dimensional stability and high hardness over a wide temperature range. Early fatigue results with these materials were, however, quite disappointing; the room temperature life obtained with tool steel bearings was generally a fraction of that of SAE 52100 bearings. In addition, the life of tool steel bearings lubricated with synthetic oils decreased at high temperature (ref. 3). The development of very clean heats of tool steels by consumable electrode vacuum melting has produced bearings with a high temperature fatigue life comparable to that of SAE 52100 at room temperature. Fig. 17 shows a plot of fatigue tests conducted on consumable electrode vacuum melt M-50 bearings at 450°F and a typical SAE 52100 room temperature fatigue curve (data from ref. 3). The two curves show comparable fatigue lives.

Another obvious remedial measure when fatigue is the failure mechanism is to reduce the exciting force causing the alternating stress. In the case of thrust bearings, the load can be reduced by distributing the thrust among several bearings. The life can be greatly increased by small reductions in load since the fatigue life varies as the reciprocal of the cube of the load.

In the case of the turbine buckets, the vibratory force can be reduced in several ways, such as by the proper spacing between the nozzle and the turbine wheel, changing from multiple to annular combustors, or avoiding operating speeds that cause resonant vibration. It has also been found (ref. 4) that judiciously arranging the nozzle vanes so that the space between them are not all equal reduces the exciting force. The complete report (ref. 4) on this latter investigation which demonstrates the method has only recently been issued. Fig. 18(a)

shows the principle involved. In the standard nozzle diaphragm (shown in the figure as having 15 vanes, but actually having 48 vanes in the system investigated), the spacings are all equal. The rotating turbine buckets are thus subjected to regular impulses 48 times per revolution, and resonance of this exciting force with one of the many complex vibrational modes of the bucket can cause large vibrations. If the impulses are broken up the exciting forces can be reduced. A very desirable and yet practical arrangement is shown in which the 48 nozzles are divided into 3 sections, with one section having approximately 10% larger spacing than the average, and one section 10% smaller spacing. In addition a small displacement (phasing) between the sections was found desirable. In Fig. 18(b) are shown the relative exciting forces for harmonics of excitation for various selections of nozzle vane spacing. The comparison is made with the single exciting force of the 48th order which would result if the 48 vanes were equally spaced and which would appear as a relative excitation force of unity. Owing to the non-uniform spacing not only the 48th order appears but many other harmonics in the vicinity of 48. At a spacing of approximately 8.5% (i.e., 8.5% greater in one of the three segments, 8.5% smaller in another) the over-all excitation is the lowest and represents only approximately 1/3 the excitation of the uniformly spaced nozzle assembly. Thus, such an arrangement should prove promising where turbine bucket excitation by gas passage through the nozzle vanes is a problem.

In the case of compressor blades, the principal vibration exciting force is rotating stall. This is illustrated in Fig. 19 which shows that under certain conditions, usually at part rated speed, the inlet air is not a smooth continuous medium, but rather is broken up into a number of dead zones. These stall zones rotate relative to the compressor blades and act effectively as hammer blows. When the frequency of these hammer blows coincide with the natural frequency of the blade, large vibrations are induced. This subject has been under intensive study at the Lewis Research Center of the NASA. There are a number of remedial measures possible to reduce this exciting force due to rotating stall, for example, by providing an annular blocking baffle at the compressor inlet during part speed operation which is retracted at full speed operation, or by providing compressor bleed during part speed operation or by variable area guide vanes. The use of two-spool engines is also an approach toward minimizing the occurrence of rotating stall excitation at part speed conditions.

Many NACA investigations (e.g., refs. 5 to 13) have been directed at obtaining an understanding of rotating stall, its effect on vibration, and its mitigation. At the present time most engines incorporate design features which are favorable in minimizing this phenomenon. However, it would appear reasonable to expect all models of operational engines to undergo extensive strain gage vibration studies of the type used in reference 6 before it is adopted for final use. Since this phenomenon is very sensitive to many conditions -- angle of attack, inlet distortion, temperature, manufacturing tolerances, etc. -- all these conditions should be investigated.

Both in the compressor and the turbine blades, the vibratory stresses can be reduced appreciably by increasing the damping. This damping may be in the form of internal damping or it may be external by the use of special devices, some of which have been investigated at the NACA (ref. 14).

A recent investigation of combustor liners (ref. 15) has found vibration to be an important factor in these components together with thermal stress. In the particular engine studied, the vibration was induced by irregularities in air flow due to the spacing of the last two rotor stages of the axial flow compressor. It is possible, therefore, that consideration should be given to designs

involving unequal spacing and phasing of these blades as a means of minimizing this excitation.

Since the fatigue failure of a thrust bearing, of a compressor blade, or of a turbine bucket (especially in the case of a multistage turbine) can start a chain reaction leading to engine destruction, it is imperative that fatigue failures of these components be avoided. Since cycles accumulate rapidly, and a fatigue failure does not always provide a warning before it is too late, the only recourse is to reduce the vibratory stress level to a safe value by design and material selection. If a sacrifice in performance is involved, this sacrifice must be accepted if reliability is the prime criterion.

Thermal Distortion and Thermal Fatigue

Thermal stresses associated with high temperature gradients have been found to be a leading factor in causing jet engine component deterioration. For some components, the high temperature gradients occur in steady state operation; in other components, it is only in the transient conditions that high temperature gradients occur. Fig. 20 shows the conditions of operation in a typical turbine disk. The temperature in the disk is plotted as a function of the radius, both at the rated condition and in the transient condition. Five minutes after starting the engine, difference between the temperature at the center and at the rim was the greatest. At rated conditions, the ΔT was 650°F and in the transient condition an 850°F differential existed between the rim and center. Thus, the rim tends to expand much more than the center, but is prevented from the expansion by the huskier center region. The result is that under operation the disk is at very high compressive stress, usually higher than its elastic limit and compressive plastic flow occurs. Upon return to room temperature, the rim which was shortened by the compressive plastic flow now goes into a state of residual tensile stress. Alternate cycling frequently results in a condition of rim cracking shown in Fig. 21. Note the cracks at the rim which have been attributed to thermal cycling. These cracks usually start on the upstream face where the temperature gradient is the greatest. When stress concentrations are present, these cracks start in the region of stress concentrations as shown in Fig. 22. Here the stress concentrations were in the form of pin holes used for bucket retention.

In the case of inner liners, very high temperature gradients also exist under steady state operating conditions as shown in Fig. 23. Note that a temperature difference of 700°F per inch exists in some regions in the circumferential direction. These gradients result in local distortion and plastic flow which after repeated cycling produce cracking.

In the case of nozzle vanes, there are several problems: first, adjacent nozzle vanes do not operate at the same temperature, and, secondly, within a given nozzle vane high temperature gradients exist. Fig. 24 shows the temperature distribution in adjoining nozzle vanes of an engine using individual combustion cans. Note that those nozzles near the center of a given combustor operate at a temperature as much as 400°F higher than the nozzles near the junction between two combustor outlets. Thus when all of these nozzles are attached to the same inner and outer rings, the differential expansion of adjacent nozzles can cause distinct buckling and cracking, both of the nozzles and of the rings. These were commonly observed in our statistical study of several jet engine failures. Even within a given nozzle vane, the temperature in adjoining areas can vary appreciably. Fig. 25 shows typical temperature distributions in a nozzle vane and it is seen that there is a 300°F difference within the trailing edge region of

this nozzle. In the transient condition, even higher temperature gradients can be obtained. The differential expansion of adjacent parts and the constraint imposed by the cooler part on the nozzle causes compressive plastic flow, residual tensile stress, and ultimate cracking as in the case of the turbine disk.

In the turbine bucket, the thermal stresses during normal steady state operation are not high in all cases, but high stresses can be developed in the transient state.

A recent NASA investigation (ref. 16) was conducted to determine the relative importance on thermal stress fatigue of the starting, the steady state operation and the shutdown process in a typical turbojet engine. It was found that by far the most detrimental factor was the start. Fig. 26 shows the temperature distribution in the leading edge area during a normal start. A temperature difference of 840°F was observed within a 1/4 inch dimension. The thermal stresses associated with such a temperature distribution greatly exceed the elastic limit for the material and cause plastic flow of the material; cracking occurs after relatively few cycles. Fig. 27 shows typical cracks observed after several cycles of start-stop operation. The cracks have been brought out for visual emphasis by Zyglo. Although starting was the primary factor leading to cracking, steady state operation hastened the process, thus indicating the desirability of maintaining low steady-state centrifugal and thermal stresses as well as low transient thermal stresses.

One obvious solution to failures involving thermal distortion and thermal fatigue is to minimize the temperature and the temperature gradients, for example, by using more gradual and controlled starts.

In the engine study of thermal stress fatigue previously mentioned (ref. 16) an attempt was made to determine the potential increase in life of the buckets to be derived by controlling the temperature surges during start. A special fuel distributing valve was designed which supplied fuel to each combustor nozzle in sequence, thus permitting successive ignition of the individual combustors. A comparison of the exhaust gas temperatures for the gradual start and the normal start is shown in Fig. 28. No failure was induced on the buckets after 900 cycles of starting and stopping whereas 85 normal start-stop cycles were sufficient to cause crack formation. Thus it would appear that in any application not involving an urgent need for rapid starting can well take advantage of some technique of this type for limiting the rate of temperature build-up during the most critical portion of the cycle -- at least from the viewpoint of thermal stress fatigue.

Gradual starts probably would have relatively little beneficial effect on the significant thermal gradients in the disk because of its high thermal inertia. As already indicated in Fig. 20, the maximum temperature differential between the center of the disk and the rim does occur during the transient period although it requires several minutes after the engine has reached steady state full power operation for the worst condition stresswise to build up. Recognizing, however, that the stress condition at the equilibrium steady state condition is lower than in the transient period, then it would appear fruitful to examine the possibilities for reducing the transient stresses. As seen in Fig. 20, the rim reaches almost its maximum temperature very early after start because of its exposure to the hot gases. The higher temperature differentials during the early period arises because the massive central region has high thermal inertia and because heat arrives to it largely by conduction from the rim. It must be maintained at a relatively low temperature because of its proximity to the bearings.

But since, in this case, it ultimately reaches a temperature of 450°F anyway, it might be desirable to hasten achievement of this temperature thereby reducing the temperature differentials. One possible approach (although difficult to control) for achieving a more rapid increase in center temperature is to incorporate a system which will actually direct some of the hot combustion gas in this region during the early period after starting. By such an approach it may be possible to maintain the thermal stresses during the transient equal to or lower than those during the steady state condition. An approximate calculation based on the plastic flow induced by each of the two temperature distributions in Fig. 20 indicates the increase in thermal stress cycling life would be by a factor of 5.

Constraints must also be minimized if the detrimental effects of thermal stress are to be avoided. For example, the free floating design in nozzle vanes arranged such that adjacent nozzles can be expanded independently and the rings can expand independently of the vanes can help appreciably in reducing the thermal cracking problems. Provision of bellows between various parts to allow relative motion between them when temperature differences occur, is of further help in reducing thermal cracking.

Designing for low operating stress, as in the case of centrifugal stress in the turbine bucket, is of value in minimizing the danger due to thermal cracks, since such cracks will progress slowly in the absence of high operating stress and might therefore more readily be detected prior to catastrophic failure. Stress concentration should be avoided. For example, in the case of the turbine disk with the pin hole cracks previously discussed, elimination of these pin holes and utilization of another form of bucket retention can appreciably increase the life of the disk.

The use of materials with good thermal cycling characteristics should also be of great assitance. Fig. 29 shows, for example, the results of endurance tests on a number of materials conducted by Haythorne (ref. 17). In these tests, a cylinder was subjected to flame impingement in a local section and the number of cycles to failure was observed. Inconel, which has very poor conductivity, survived very few cycles. Copper alone, which has good conductivity and therefore resulted in lower temperatures and lower temperature differences between the hot and cooler sections, did not produce a greatly increased life because copper is not very durable under the temperatures involved. However, when the copper was clad with Inconel to avoid oxidation and exposure to the hot gases, the life was greatly increased. Thus, the use of sandwich materials which may have application for sheet metal parts such as combustor liners may in some cases greatly increase life. The practical difficulties such as protecting cut edges of sandwich materials must, however, be recognized where oxidation is critical.

From an operational standpoint, thermal cracks in some components are not quite as serious as other types of failures because they progress fairly slowly and in many cases may be detected prior to catastrophic failure. Thus, periodic inspection and replacement should assist in coping with the deleterious effects of thermal cracks. Knowing where to look for the cracks is an important consideration. For example, in one turbine type, we found that cracks originated in a region of the rim which was hidden when the bucket was in place. Thus, such cracks passed undetected in inspection when the bucket was not removed. When the possibility of such cracks was pointed out, buckets were removed to facilitate inspection and it was found that a large percentage of disks that would previously have passed the inspection were rejected when the inspection was properly made. Thus, experience and laboratory tests should act as a guide for intelligent inspection. Inspection should also be scheduled on a contingency basis. Hot

starts, for example, involve higher temperature gradients as previously indicated. Greater susceptibility to thermal cracking would be expected if the number of hot starts were large. It would therefore seem reasonable to schedule such inspections after a certain number of hot starts. The adoption of a replacement schedule based on experience and laboratory and engine tests would be very helpful in avoiding failure in operation from thermal distortion and thermal fatigue.

Stress Corrosion

A number of other failure mechanisms were determined to be of importance for some components. Stress-corrosion was important, for example, in compressor blades when a particular material and heat treatment was used. This condition was one of intercrystalline cracking resulting from stress (particularly residual stresses associated with fabrication and heat treatment) and moisture (particularly salt water). It appears, however, that this type of failure mechanism can be minimized by proper heat treatment to relieve the residual stresses and to soften the material but by a sacrifice in tensile strength and endurance limit. From an operational standpoint, it is important to provide proper inspections to insure that defective material, or improperly heat treated material, does not inadvertently enter the scene.

Overtemperature

Overtemperature resulting either from hot starts, drift or improper setting of the controls, fuel nozzle blockage and carbon formation in the combustor, inability of the control to account for altitude or inlet air distortion, and failure of cooling systems, has been a serious source of component failure. Although overtemperature may last for only a short period of time, the effects may be great. Some components, such as the turbine buckets, may operate at the limit of their temperature capabilities, and increases in temperature even when stresses are low can produce detrimental changes in metallurgical structure and greatly reduce life. An obvious measure of relief is to minimize those conditions known to introduce overtemperature. In the case of the controls, it would be highly desirable to develop a temperature sensing element and associated control equipment of high reliability.

Fuel Control System Malfunctions

The fuel control system is responsible for more flight accidents than any other engine component. The largest percentage of the difficulties in the control system arise from failure of a system component. This fact has already been indicated in the section entitled "Underdesign and Defects in Materials and Manufacture."

Difficulties from the control system also arise from the inability of the control system to adequately protect the engine in all of the flight conditions encountered. Following are some of the problems.

Overtemperature during starting of engine. - Many fuel systems depend on pilot control during starting to prevent overtemperature. Incorporation of a reliable gas temperature senser and associated control equipment, or possibly an accurate fuel flow scheduling mechanism, would handle this problem.

Overtemperature at maximum thrust. - Many control systems are regulated at maximum thrust by a maximum speed governor on the assumption that if rpm is held constant, then gas temperature remains constant. This is approximately correct for altitudes from sea level to about 35,000 feet. Above 35,000 feet, the gas temperature increases appreciably with altitude in spite of the fact that the engine speed is held constant. The temperature senser is hence needed for this condition also.

Surge during acceleration. - Most control systems provide some control of fuel flow during acceleration to avoid compressor stall. In most cases the control is not adequately responsive to all of the conditions encountered by the engine. In particular, it is difficult to provide adjustments for change in the surge limits of an engine caused by change in distortion of the air flow pattern at the engine inlet associated with change in flight conditions. The engine surge limits also change when the fuel flow rate is rapidly oscillated while "jockeying" the engine in a landing or air refueling maneuver. A device that sensed incipient surge would simplify the problem of surge prevention over the complex range of conditions encountered.

Flameout. - Most control systems contain some provision for limiting the minimum fuel flow rate to avoid flameout. Improvement of controls more accurately to follow the variation of flameout conditions with flight conditions is required. Improvement of the fuel spray and combustion characteristics at low fuel rates would widen the range of engine operation and help alleviate the flameout problem.

Foreign Object Damage

By far the most important environmental factor leading to premature engine removals has been the ingestion of foreign objects. Fig. 30 shows a breakdown of the foreign objects identified in one type of jet engine. The outstanding entry in this table is the "unknown" category, which for this engine is 69%, and for other engines is even higher. The known objects can further be classified as:

a. Parts and metallic debris left in the inlet by manufacturing, maintenance and operating personnel;

b. Objects originating from internal failures, such as rivets, screws, failed screens, combustor liner fragments, and nozzle diaphragm fragments;

c. Ground debris;

d. Airborne debris such as hail, flak, birds, etc.

A recent study at the NASA (ref. 18) has indicated that under certain atmospheric conditions vortices can be created, and that pressure conditions associated with the vortex can cause ground debris, such as pebbles, to be projected upward and finally sucked into the engine. The condition for such ingestion is made especially favorable if the pebble is lodged in a crack and its lateral motion is constrained. The presence of such vortices, and their role in inducing ingestion of ground debris, may be a significant factor in explaining the large incidence of foreign object damage.

Since ingestion of ground debris would seem to be an important factor, the height of the inlet from the ground would be expected to affect significantly the probability of foreign object ingestion. Fig. 31 shows the effect of inlet height on percent of engines damaged by foreign objects. There does appear to be a correlation - the greater the height, the less the probability of damage.

There is also a large difference in the amount of foreign object damage occurring on the same engine used in the same aircraft but operated at different air bases as shown in Fig. 32. This result indicates that airport cleanliness may be a very important factor.

The inlet screen is frequently relied upon for prevention of foreign object ingestion. Fig. 33 shows the effect of screen mesh size on the effectiveness of reducing foreign object damage. When used in the same engine, the screen with 1/16 inch wire spacing was better than twice as effective as the screen with the 1/4 inch wire spacing. It is also significant, however, that the coarser screen was not well fitted to the inlet, and objects of appreciable size may have entered the engine in the space between the screen and the inlet.

The study also indicated that the more rugged centrifugal engines were less susceptible to premature overhaul and to accident resulting from foreign object damage than engines of the axial flow type. In the axial flow engines, the damage was usually sustained by the compressor blades. In the centrifugal engines, foreign objects, when they were damaging, affected mainly the hot section of the engine, although disassembly records showed some damage to the compressor as well.

Since some of the foreign objects that cause damage in passing through the engine originate within the engine, or are accidentally introduced, it is important to emphasize cleanliness of design and care during maintenance. The use of screws or nut and bolts in locations where they can loosen and pass through the engine should be avoided. Repair practices must include a careful inspection to insure that no foreign matter such as fasteners, or even tools, are removed before returning the engine to service. However, since most of foreign objects enter the engine through the inlet, it is important to consider:

a. Methods of avoiding ingestion;

b. Methods of identifying the nature of the foreign matter as a guide to instituting the proper features that will reduce ingestion;

3. Methods of evaluating damage to act as a guide to decisions regarding the need to repair or replace damaged parts.

Regarding the ingestion problem, two basic approaches are possible: (1) prevent objects from reaching inlet, and (2) prevent objects which do reach the inlet from entering by the use of a screen. Cleanliness of airfields and runways would therefore appear to be of considerable importance. The finding of the significance of vortices (ref. 18) on the ingestion of foreign objects would appear to point to a need for methods which have a spoiling effect on such vortices. A recent study by the Douglas Aircraft Company (ref. 19) has indicated the potential of a "blowaway" jet or "aerodynamic screen" for this purpose. It consists of a jet of air located near the inlet of the engine and directed in such a manner as to tend to inhibit the formation of the inlet-induced vortex.

Preliminary tests have shown considerable promise, but it has not as yet been tested extensively in service.

Although it appears that the use of effective screens can appreciably reduce the problem of foreign object damage, it should be emphasized that a number of problems must be solved in connection with the use of screens. Screens produce a loss of thrust and may choke the inlet under icing conditions. In an effort to avoid icing, some screens are made retractable, but retraction of the screen may cause collected debris to be dumped into the inlet. Thus, these problems associated with screens must first be solved before screens can be regarded as effective. The use of a run-up screen on the ground during idling and immediately prior to take-off would, however, aid as a practical approach. Such screens can be made as rugged as necessary, and do not involve choking, icing or damping. Practical methods should be developed for extending its use as far into the take-off operation as possible.

Regarding the identification of the foreign objects, attention should be directed to a recent study (ref. 20) in which an emission spectroscopic method was devised to identify the chemical composition of these objects from the trace of material left behind on the damaged blade. This method can be further developed and can be of considerable assistance in providing clues for the source of the objects. The proper approaches for elimination of these sources may become more evident once the sources have been identified.

The development of guides to practices regarding the retention or replacement of parts damaged by foreign objects is an extremely important matter. The most importantly affected parts are the rotor blades in the early stages of the compressor. When the damage is severe, there is no question regarding need for replacement. It is when it consists of nicks or dents that a difficult decision must be made. It is natural to desire to replace all affected blades, but costliness points to a need for procedures for determining when replacement is really necessary. This subject has been studied to a limited extent by NASA, and the results are reported in references 21 and 22. In the latter report a specific procedure is outlined which can be of assistance to the user of a given engine to determine a reasonable replacement policy for nicked compressor blades of his engine. The approach is based on the following considerations:

(a) Only damages which would actually reduce the life under the vibratory conditions likely to be encountered in the engine require replacement. Thus it is first necessary to determine the stress distribution in the blade during vibration and in the absence of nicks. Under normal conditions, if the blade is to fatigue at all, it will fail at the location where the stress so determined is the highest. This is called the critical point. If a nick is introduced, it will be damaging only if the stress concentration due to the nick, together with the nominal stress (in the unnicked condition) at the location of the nick, causes a higher stress than is normally present at the critical point. Thus, for example, if the nick occurs in the outer 50% (approximately) of the blade span, it usually will not move the failure location from the normal critical point to its own location.

(b) The stress-concentrating factor of the nick must be considered in conjunction with the amount of vibration encountered under the worst conditions in engine use. If the vibratory stress is low, then even serious nicks can be tolerated. Thus the method involves an engine vibration study during which vibrations can readily be measured by means of strain gages.

(c) Re-working the damages -- that is straightening dents and filing or stoning the nicks to reduce stress concentrations -- is frequently adequately effective in removing their deleterious effects. A simple method is outlined for evaluating specific engines.

It thus appears that foreign object damage can be alleviated to some extent by the use of rugged engines, high air-inlet heights above the ground, by paying attention to manufacturing, maintenance, and operation to avoid left-over debris, by following good practices in air base construction and maintenance of cleanliness and possibly by the use of vortex inhibitors during ground operation. Development of rugged and effective inlet screens may be required or perhaps inertial separation devices instead of screens in which such problems as icing and thrust loss are properly handled. Ground run-up screens can possibly be very effective in preventing ingestion during ground operation where the danger of such ingestion is the greatest. If ingestion is found as a common occurrence, a study by emission spectroscopy to determine the type of objects ingested can prove helpful in suggesting remedial measures. The damaging effects of any nicks and dents so incurred should be evaluated by available methods -- and indeed the methods should be extended -- before adopting a final policy on blade replacement.

FACTORS TO BE CONSIDERED IN PROGRAM FOR DEVELOPMENT OF INSPECTION AND MAINTENANCE PROCEDURE

In our study of failure mechanisms it has been made clear that engine failure results from failure of any one of many components and that the individual lives of these components can vary greatly. Thus, it is desirable to think in terms of the lives of the individual components rather than the engine as a whole. Two approaches are obviously possible for avoiding accident due to part failure -- (1) the part should be designed and operated in such a manner that maximum life will be achieved under the conditions that must be met, and (2) the part must be replaced at the end of its useful life. The first consideration has already been briefly discussed in the section on "Mechanisms of Failure" where optimum design and operating practices were outlined. It remains now to discuss the replacement problem.

The development of a program that will lead to optimized replacement practices is urgent if conditions of safety are to be kep compatible with economic considerations. Thus, a rational approach would yield large dividends. An unusual opportunity is presently afforded by the introduction of a large number of virgin engines into service which will be operated at utilization factors heretofore rare on such engines. The flying hours per day of commercial jet engines can be expected to be 5 to 10 times as great as those of military engines. Thus a great deal can be learned even in the first year of operation that has not as yet been possible from examination of military records. Furthermore, it is urgent that this information be learned since otherwise commercial engines will soon be flying in a time range where prior experience is lacking. Since the engines are virgin, the opportunity exists to develop meaningful records unobscured by a prior replacement history of unknown extent. The object of this section is to outline very briefly the factors that should be considered in the development of a program that could be undertaken which would ultimately lead to rational procedures for engine inspection for part replacement purposes.

Desired Data

Any program of part replacement must necessarily be based on statistical data on part failures. It is important that these data be obtained and interpreted in the proper manner. For example, as already indicated, it cannot be based on statistics of only the engines found at the overhaul base, since such statistics ignore the engines which have not as yet failed. Neither should it attempt to consider all the engines in service since it would then be necessary to await equal degree of service on all engines before meaningful results are obtained. The most practical approach is to consider only those engines which have actually achieved a given life up to the beginning of a given time period, say 100 hours. The fraction of such engines that fail in the 10 hour interval, say, between 100 and 110 hours, is then plotted at the middle of the time interval (105 hours), as in Fig. 34. These plots are called "probability of failure curves", and may fall into three categories as noted on the figure.

(a) The first curve shows "wear-out" or time-dependent failure. Time dependent failure results from depletion of some material or property of the component that is essential to its proper operation. The depletion process may occur through abrasion, corrosion, or through the "using up" of life as in stress-rupture or fatigue. The probability of failure increases with age. An example of time-dependent failure is the failure of turbine buckets by stress rupture (see Fig. 8).

(b) Chance or time-independent failure results unpredictably from environmental causes. The fundamental characteristic of chance failures is that, for fixed environment conditions, the hazard of a failure-causing condition is equally likely during equal times in the operating period, i.e., the probability of failure is independent of operation time. An example of chance failure is damage resulting from foreign objects coming into the engine inlet. A foreign object is equally likely to enter the inlet at any time in the life span of the engine.

(c) Initial failure results from the fact that a component is defective at the time it is first put into operation. Such defects result, for example, from errors in manufacture or from the pre-use environment such as damage in storage, transit, or handling.

A complete engine could be expected to show a failure rate curve resulting from a combination of these three curves (Fig. 35). "Bugs" in a new engine might be expected to cause a high initial failure rate. Some components will fail as a result of variations in their environment (e.g., foreign object damage to the compressor or occasional severe overtemperature effects on turbine buckets) resulting in an element of chance appearing in the engine failure rate curve. After some time, enough components may show a time-dependent curve to reflect a gradually increasing failure rate with time for the engine.

Significance of Failure Curves

Figs. 34 and 35 show why it is desirable to consider individual components rather than the engine as a whole. Fig. 35 is an agglomeration of several factors, and therefore points neither to the specific component that must be considered, nor how to consider any one component. When plots are made for each component, the results are likely to look like one of the three curves shown in Fig. 34. Once the shape of the curve is determined, the manner of coping with the problem from a replacement standpoint becomes clear.

(a) If the curve is of the initial failure type, little is required from a replacement policy standpoint except, of course, to replace the defective parts. Proper testing or green-running should reduce the probability of initially defective components from being put into service.

(b) With chance failure, a new component is as likely to fail as an old one, and nothing can be gained by scheduling replacements or by preventive maintenance. The failure rate can be reduced only by making the component better able to withstand the environment or by reducing the severity of the environment.

To ensure flight safety, critical components that fail by the chance law must not fail suddenly or catastrophically. They must be caused to finally fail by a slow progression of a detectable incipient defect and the time from incipient failure to final failure must be greater than the time between component inspections so that defects can be found and the part replaced. This is essentially the "fail-safe" concept that has been given so much publicity for aircraft structures. (This concept is, of course, desirable for components that fail by "wear-out" as well.) Steps can be taken in the design of engines to ensure a "fail-safe" condition for most turbine engine components. For example, it has been found that as a rule turbine buckets designed for a stress-rupture life several times the required life will propagate cracks resulting from thermal fatigue very slowly whereas buckets designed for a much shorter stress-rupture life propagate any cracks to failure so rapidly that normal inspection periods are much too long to catch incipient failures.

(c) With time-dependent failures, a grace period is possible before failure begins and replacements can be scheduled; thus, it is necessary to determine the actual grace period for each part as a basis for replacement schedules. It now becomes necessary to determine how best to determine the grace period for each part.

Development of Data

The development of the necessary data to determine the nature of the failure curve for a given part is a continuous process that can, in many cases, best be achieved by a cooperative effort between the manufacturer and the user of the engine. For safety reasons, it is obviously desirable not to operate an engine in service in a time range in which no previous experience is available. Test stand operation, perhaps conducted by the engine manufacturer, can serve the purpose of staying timewise ahead of service. The records obtained from the test stand engines can then be combined with service records in a three-prong approach as follows::

(a) A group of new model engines should be tested in sea-level stands, accumulating operating time so as to have perhaps 500 hours more on critical components than the oldest engines in service. In NASA sea-level test stands, failure mechanisms observed in turbine disks, buckets, compressor blades, nozzle vanes, combustion liners, etc. of service engines (certainly those that were time- or cycle-dependent) have been consistently duplicated. In one case a particular service failure was not demonstrated but this was found to result from an unusual altitude stall condition that caused actual melting of the turbine buckets of the particular engine. Once a failure mechanism has been identified in a ground test engine, other ground engines can be inspected at short intervals to search for first signs of failure and methods of detecting these failures by inspection. A major part of inspection is to know precisely what one is looking for and where to look.

An example of this latter fact was described earlier where it was indicated that regular wheel inspections were not catching the incipient failures because the inspectors were not looking in the correct place. By repeated careful examinations of laboratory engines, it was found that if the buckets were removed and the serrations zygloed, incipient failures could be found in the serrations at the central plane of the disk. Re-examination of disks in service using the correct inspection procedure revealed large numbers of incipient failures and undoubtedly saved many lives and much valuable equipment.

The time for first occurrence of failures could be established from the ground engines and removal of these parts from flight engines could be scheduled. If the failures had been a result of a chance mechanism, the time from incipient failure to fracture could be determined and inspection periods for flight engines scheduled to be a much shorter period to ensure that in-flight failures did not occur.

This practice of continuing to operate ground test engines always in advance of flight engines has been used for at least two engine models, but is not at this time a general practice.

(b) When new engines are put into service, they should be completely disassembled at regular intervals for inspection so that incipient failures can be found. This information will superimpose the effect of the flight environment on the date of component failure rates obtained from ground test engines described in "a".

A possible approach might be as follows: When the first group of engines reach, say, 800 hours, they should be disassembled, and inspected for incipient component failures. If no incipient failures are observed, the engines can be re-assembled and replaced in service. The next inspection might be scheduled at 900 hours. Usually it will be a different group of engines that will reach 900 hours first. If, however, the already-inspected engines reach 900 hours first, and if for any reason it is not deemed desirable to disassemble the same engines again, they can be set aside until the 900 hour limit is reached by another group. When a group of engines has satisfactorily passed the 900 hour test, all engines may be taken to this time limit. The process can be repeated at perhaps 100 hour intervals.

When incipient failures are found, the defective part should be replaced and a careful record kept of the critical components that have been replaced. If experience with the test-stand engines indicates that the incipient failure will progress very slowly, and when failure does occur it will not be catastrophic, then judgment can be applied and the defective part might be permitted continued operation. In such cases, however, more frequent inspections may be needed to determine the progress of the failure.

(c) Continuing records of all replacements must be kept in order to insure knowledge of the actual service life of each part is known. If an engine is overhauled at say, 1000 hours, and the disk not replaced because it appears in good condition, it cannot be assumed that the disk will last another 1000 hours if that is the time until the next overhaul. When the service life of each critical component is known, the record of actual service time of a specific part has direct meaning in establishing a time for engine removal and part replacement.

Application of Data

As already indicated, one of the principal reasons for a test-stand and service evaluation program is to establish part replacement schedules. Although it may be desirable in some cases to remove an engine from service in order to replace a single component, it might be recognized that economic considerations will not permit disassembly and replacement on an individual part basis. The concept of "engine overhaul" will probably have to be retained, but the time for such overhaul and the parts to be replaced can be chosen on a rational basis. In addition to setting overhaul times, the records of such a program, together with supplementary studies as outlined below, would lead to a number of inter-overhaul inspections as follows:

(a) Inspection schedule on time basis. - For some of the failures the time from first indication of failure to final failure can be sufficiently long that inspections may be scheduled to detect the difficulties. In this category come such items as wear of bearings; thermal cracking of combustor liners and transition pieces, and turbine disk rims, nozzles and buckets. The records will indicate how often such inspections should be made, where to look for failures, and which incipient failures can be tolerated until the next regular inspection period. In the case of foreign objects which occur unpredictably, and with possible catastrophic consequences, every effort should be made to check for evidence of damage on a preflight basis. When extensive inspection of the compressor blades for foreign-object damage is impractical, a limited inspection, involving the screen and the early compressor stator and rotor stages, may be feasible without disassembly and may greatly reduce the probability of a failure from this source.

(b) Inspection schedule on basis of contingency. - In this category comes failures which may be considered accidental. Very rapid deterioration of the life of the components in the hot end of the engine can result from overtemperature or overspeed. Inspection of the parts in the hot end of the engine should be made when overtemperatures and overspeeds of prescribed intensity and number have been experienced as is the practice in military service. The reporting of these incidents is currently left to the pilot. An automatic recorder which gives the temperature and rpm as a function of time would provide a much more accurate basis for scheduling inspections. Not only the mean combustion gas temperature but also abnormal distributions in temperature should be indicated.

Inspection of the turbine disk should also be made when there is indication of difficulty with the turbine wheel cooling system. Evidence of excessive rim growth and changes in hardness and microstructure may be used as indications of deterioration. Inspection of the bearings and the lubrication system should be made when there is evidence of lubrication-system failure, e.g., when excessive amounts of foreign particles are detected in the oil filters.

(c) Inspections based on indications of abnormal operation . - Considerable attention should be directed toward the development of methods and devices that will warn of impending component failure. Particularly useful would be methods of checking internal parts without disassembly of the engine between regular inspections. Some possibilities along these lines such as monitoring instrumentation in the control lubricant, fuel and turbine cooling systems to warn the pilot of trouble in these systems were indicated in the text of the initial NASA report.

Three specific methods (described in ref. 23) have been developed by the Directorate of Flight Safety Research, Office of The Inspector General, USAF. They were able to cite examples where these measurements would have predicted engine failure. The methods are:

(a) Noting either increases or decreases in a continuous record of jet engine oil consumption. Increase in oil consumption might reflect seal leakage, breather or vent loss, or evaporative loss. Decrease in oil consumption might reflect restricted oil jets or oil line deficiency.

(b) Noting of a decrease in time for engine coast down. An engine which has increased friction would slow from say 65% speed to stop in less time than normal. Increaed friction might result from damaged bearings, compressor or turbine rotor rub, or failure of installed accessories.

(c) Noting changes of exhaust nozzle condition at maximum power. In some engines using an electronically-controlled exhaust-nozzle, the nozzle control seeks an optimum nozzle postion to maintain a specific average tail pipe temperature at 100% rpm. Deviation in engine effectiveness upstream of the nozzle will result in the nozzle control stabilizing at a different nozzle position. Inlet air temperature also causes a variation in exhaust-nozzle opening and changes from this cause must be compensated.

CONCLUSIONS

In conclusion, our study has indicated that overhaul times on military jet engines at the time the statistics were compiled were fairly low despite an extensive program of field repair. Foreign object damage was the most important single factor leading to premature overhaul, affecting mainly the compressor blades of the axial flow engine. The compressor, combustor, nozzle assembly, turbine buckets and turbine disks, bearings, and fuel control, were principal components in which early failure was found. The principal failure mechanisms are foreign object damage, stress rupture, mechanical fatigue, thermal distortion and thermal fatigue, overtemperature, stress corrosion, and fuel-control malfunctions.

In some cases failure can be avoided by design and material improvements. In other cases failure cannot be avoided, but the time between the initial appearance of damage and final part breakage is sufficiently long so that the incipient failure is likely to be detected during scheduled periodic inspections and overhauls. In this category comes thermal craking of combustion liners and nozzle diaphragms.

The most serious types of failures are those in which relatively little warning time is available and in which accident is likely when failure occurs. Here the principal remedy is to remove the part before its useful life is exhausted. Periodic replacement of those parts known to have finite life, following a schedule guided by laboratory studies and service experience, may avoid accident in spite of the inevitable ultimate failure if use is prolonged. In this category comes stress rupture failure of turbine disks and buckets, and fatigue failure of bearings.

In those cases where deterioration is a consequence of chance environmental factors, such as foreign object damage and overtemperature, inspection upon the occurrence of such contingency must be scheduled to guide part replacement. The engine should be designed to facilitate such inspection.
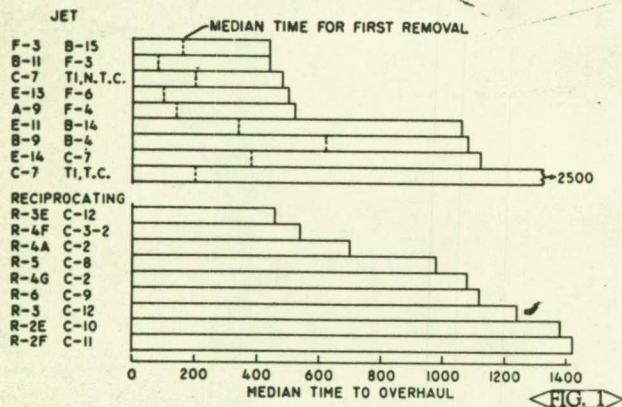
It should be emphasized that the low lives indicated by the statistical study are for military engines in which the press for high performance transcends other requirements. The frequency of component failure is closely associated with the severity of the operating conditions, and it is possible that considerable increase in life can be achieved by compromises, perhaps small ones, in performance. The user must decide on the best compromise between high performance and long life. One purpose of our study was an attempt to point out some of the factors involved in this compromise.

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COMPARISON OF MEDIAN TIME TO OVERHAUL FOR JET AND RECIPROCATING ENGINES IN MILITARY SERVICE

MEDIAN TIME FOR FIRST REMOVAL

JET

F-3	B-15
B-11	F-3
C-7	TI.N.T.C.
E-13	F-6
A-9	F-4
E-11	B-14
B-9	B-4
E-14	C-7
C-7	TI.T.C.

→2500

RECIPROCATING

R-3E	C-12
R-4F	C-3-2
R-4A	C-2
R-5	C-8
R-4G	C-2
R-6	C-9
R-3	C-12
R-2E	C-10
R-2F	C-11

0   200   400   600   800   1000   1200   1400
MEDIAN TIME TO OVERHAUL

FIG. 1

COMPARISON OF JET AND RECIPROCATING ENGINES ON THE BASIS OF NUMBER OF MINOR REPAIRS PER MAJOR OVERHAUL

12.5

NO. OF ENGINE REMOVALS FOR MINOR REPAIR PER REMOVAL FOR MAJOR OVERHAUL

JET   RECIPROCATING

FIG. 2
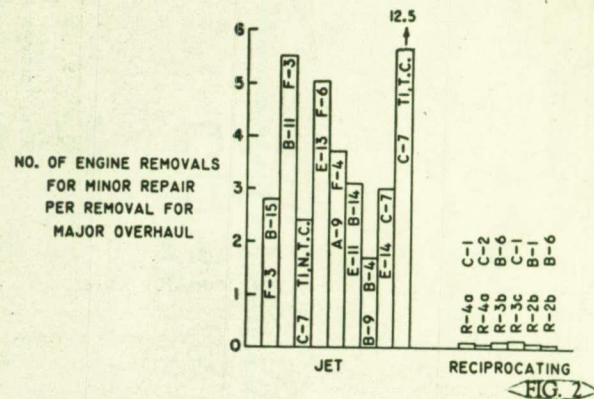
REASONS FOR ENGINE OVERHAUL FOR 6 ENGINE MODELS
(FROM DISASSEMBLY INSPECTION REPORTS)

MAXIMUM

MAXIMUM AND MINIMUM, PERCENT

MINIMUM

COMPRESSOR — BLADES, STATORS, DISKS, CASING, MISCEL.

BEARING — COMPRESSOR FRONT, COMPRESSOR REAR, TURBINE FRONT, TURBINE REAR, ACCESSORY

BURNER ASSEMBLY — OUTER SHELL, INNER LINER, TRANSITION LINER, FUEL NOZZLE

TURBINE SECTION — NOZZLE DIAPHRAGM, BUCKETS, DISKS, MISCEL.

ACCESSORY — FUEL, LUBRICATION, MISCEL.

OPERATIONAL — PERSONNEL, CRASH AND ACCIDENTS, FOREIGN OBJECTS

FIG. 3
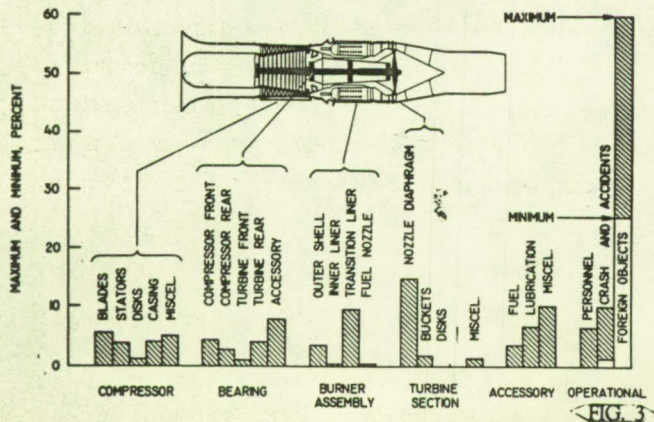
PART REPLACEMENTS MADE DURING MAJOR OVERHAUL
(FROM DISASSEMBLY INSPECTION REPORTS)

	AVG. AGE
C-7	305
A-7	160
B-3	247
B-10	88

PERCENT OF ENGINES EXAMINED

COMPRESSOR   MAIN BEARINGS   ACCESSORY BEARINGS   BURNER ASSEMBLY   TURBINE SECTION   ACCESSORIES   FOREIGN OBJECT DAMAGE

FIG. 4
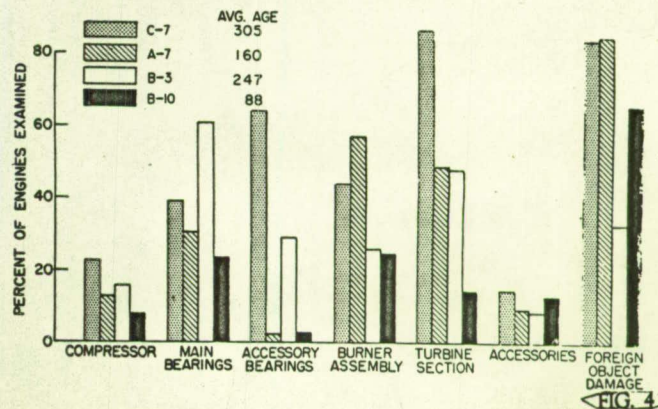
PRINCIPAL FAILURE MECHANISMS

1. UNDERDESIGN, INADEQUATE DEVELOPMENT, MATERIAL DEFECTS

2. CREEP AND STRESS RUPTURE

3. MECHANICAL FATIGUE

4. THERMAL DISTORTION AND THERMAL FATIGUE

5. CORROSION AND STRESS CORROSION

6. OVERTEMPERATURE AND OVERSPEED

7. FOREIGN OBJECT DAMAGE

FIG. 5

EFFECT OF TEMPERATURE ON TIME TO RUPTURE AT CONSTANT STRESS LEVEL (S-816 ALLOY)

15,000 PSI

LIFE CUT TO 1/10

TEMP. UP 5 %

TEMPERATURE, °F

RUPTURE TIME, HR
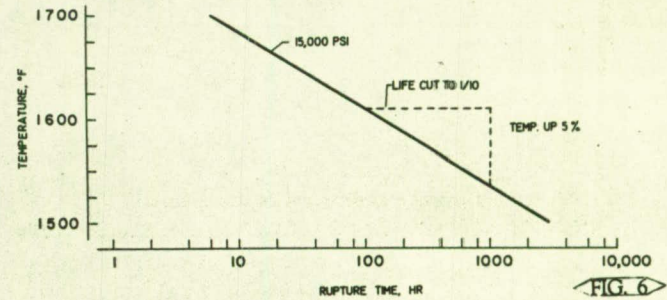
FIG. 6

STRESS & TEMPERATURE DISTRIBUTION IN BLADE DURING FULL POWER OPERATION
MAX. LIFE POSSIBLE BASED ON STRESS RUPTURE

PREDICTED BLADE LIFE (BASED ON STRESS RUPTURE PROPERTIES)

HOURS

1,000 HRS - HIGH STRESS ENGINE

30,000 HRS - LOW STRESS ENGINE

1500, °F

STRESS

TEMP, °F

13,000 PSI LOW STRESS ENGINE

22,000 PSI HIGH STRESS ENGINE

STRESS, PSI

TEMP., °F

0   2-2.5   4

DISTANCE ABOVE BASE, INCHES
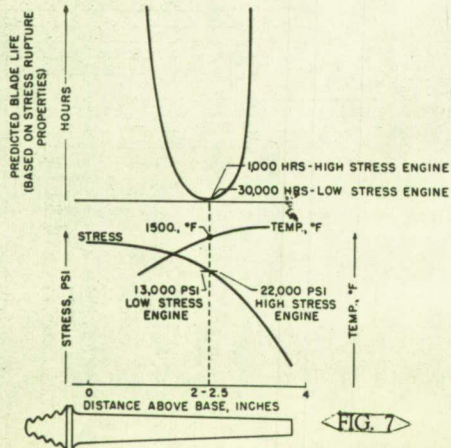
FIG. 7

TYPICAL DISTRIBUTION OF TURBINE BUCKET FAILURES

46 BUCKETS IN ONE WHEEL

NUMBER OF BUCKETS FAILED

HOURS TO FAILURE
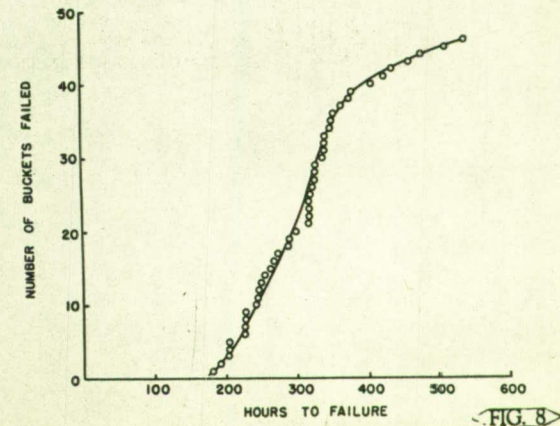
FIG. 8

ELONGATION ALONG A TYPICAL BUCKET AIRFOIL
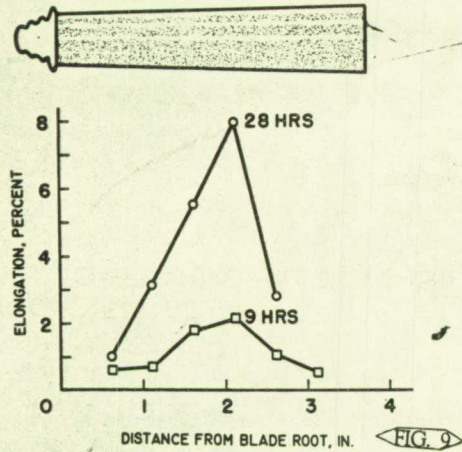
FIG. 9

GROWTH OF WELDED TURBINE DISK

ORIGINAL CONTOUR
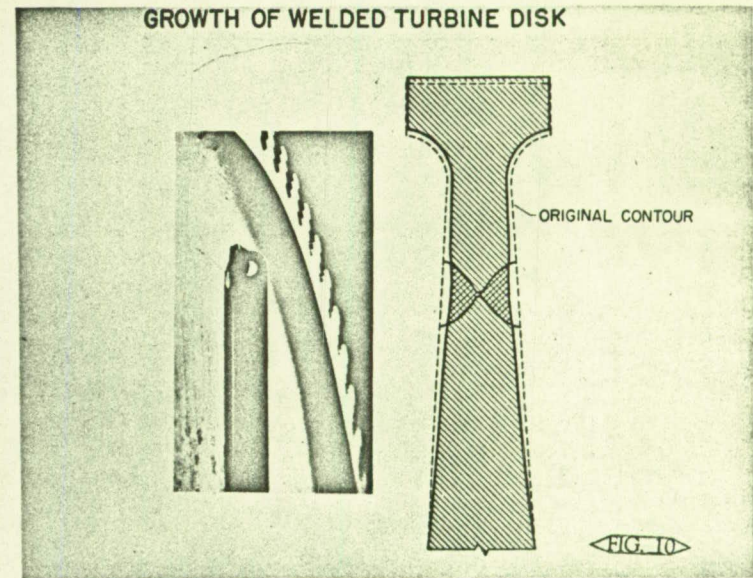
FIG. 10

TURBINE BURST DUE TO OVERTEMPERATURE
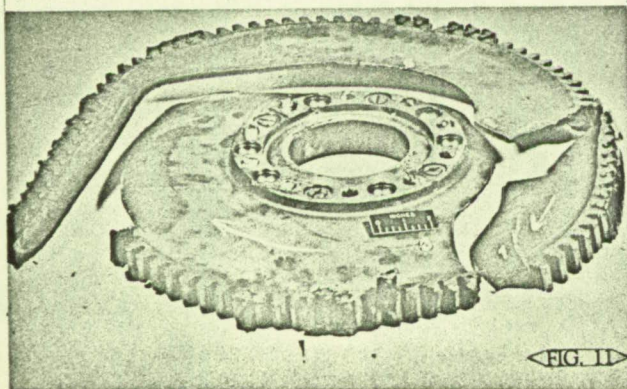
FIG. 11

TYPICAL BUCKET FAILURES

STRESS RUPTURE
(NO OR LOW VIBRATORY STRESS)

FATIGUE
(HIGH VIBRATORY STRESS)

STRESS RUPTURE FOLLOWED
BY FATIGUE
(INTERMEDIATE VIBRATORY
STRESS)

FIG. 12

LOCATION OF FATIGUE FAILURES

FIG. 13

PROGRESSIVE STAGES OF FATIGUE
IN A BALL BEARING

EARLY

LATE

FIG. 14

TYPICAL FATIGUE CURVES FOR A HIGH-
TEMPERATURE ALLOY (N-155)

FIG. 15
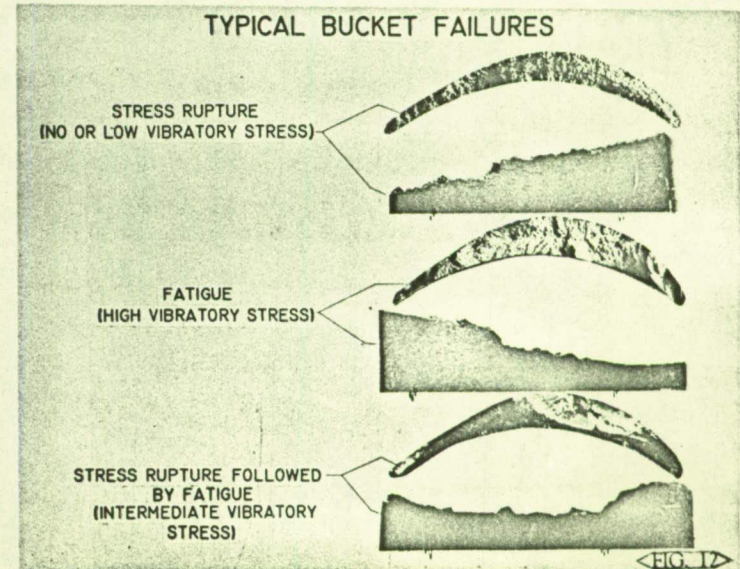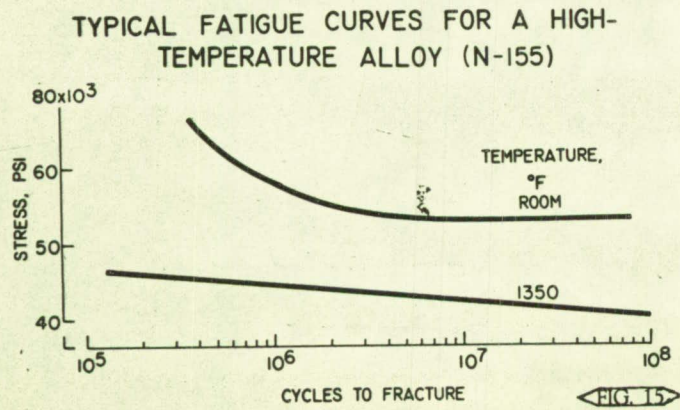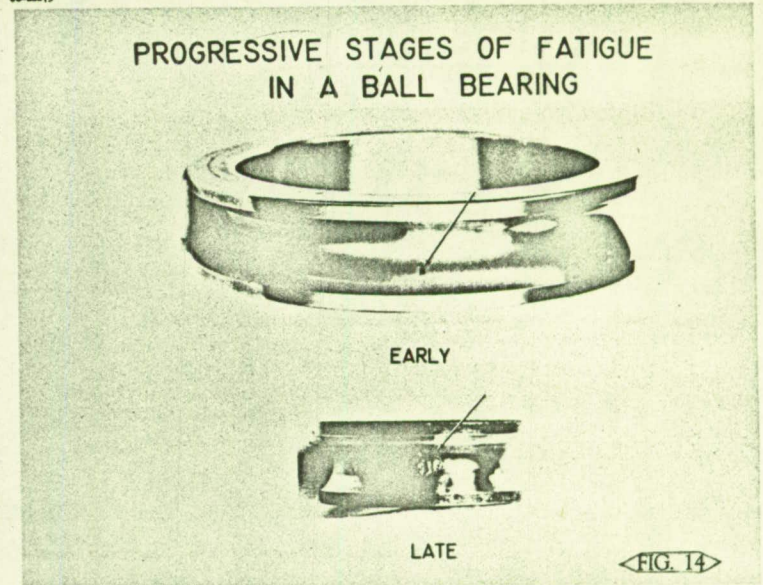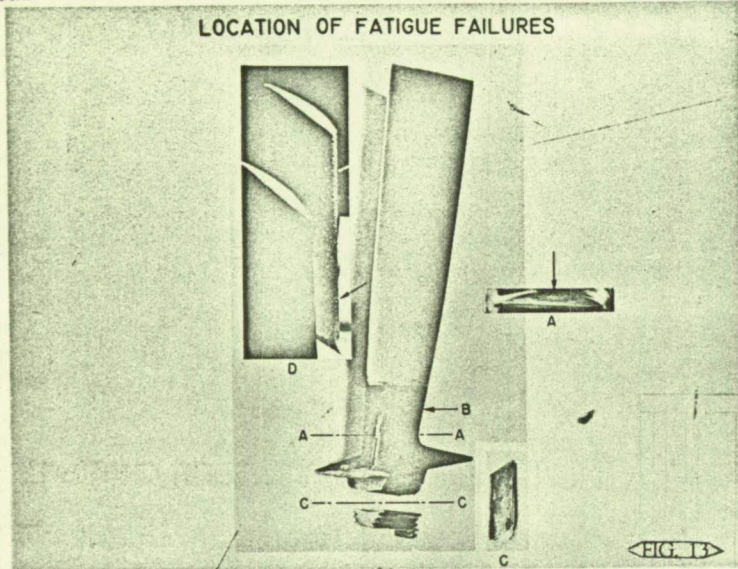
IMPROVEMENT IN FATIGUE LIFE OF SAE 52100 BEARINGS -
1920 TO 1944

FIG. 16
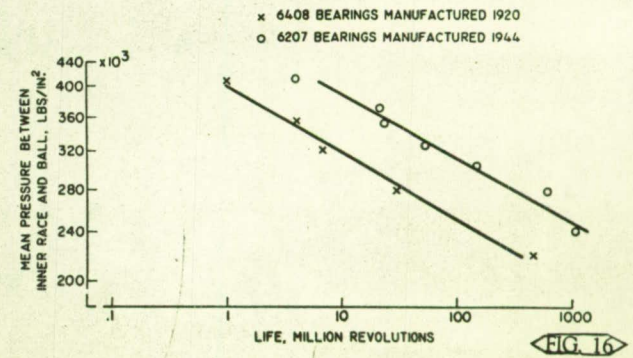
COMPARISON OF FATIGUE LIVES OF AISI M-50
WITH SAE 52100 STEELS

VACUUM MELT M-50 AT 450° F
(DATA POINTS SHOWN)

SAE 52100 AT ROOM TEMP
(BASED ON AVERAGE OF
MANY TEST GROUPS)

BEARINGS
TESTED,
%

LIFE, MILLION REVOLUTIONS   FIG. 17
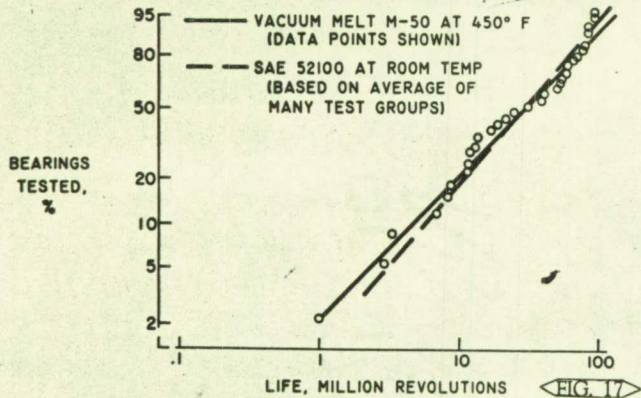
REDUCTION OF EXCITING FORCES BY VARIABLE
SPACING OF NOZZLE VANES

ORIGINAL SPACING AND MODIFICATIONS

STANDARD
EQUALLY
SPACED

SPACING CHANGE
WITHIN SEGMENTS

SPACING CHANGE
WITHIN SEGMENTS
PLUS PHASING
BETWEEN SEGMENTS

PHASING   FIG. 18A
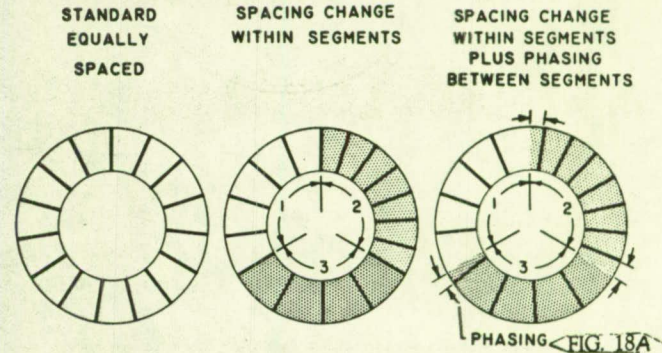
REDUCTION OF EXCITING FORCES BY VARIABLE
SPACING OF NOZZLE VANES

RELATIVE EXCITING FORCES AS FUNCTION OF SPACING

RELATIVE
EXCITATION
FORCE

PULSES PER
REVOLUTION

49

50   47   48

MINIMUM FORCE

SPACING CHANGE,
PERCENT OF STANDARD SPACING   FIG. 18B
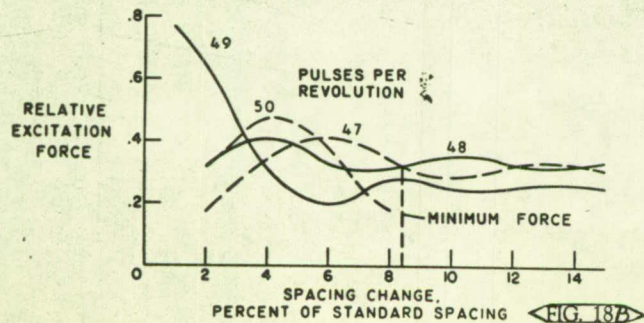
TYPES OF ROTATING-STALL PATTERNS OBSERVED

A   B   C

D   E   F   FIG. 19

TURBINE DISK TEMPERATURE
AT TRANSIENT AND EQUILIBRIUM CONDITIONS

FIG. 20

THERMAL FATIGUE CRACKS

FIG. 21

PIN HOLE CRACKS

FIG. 22
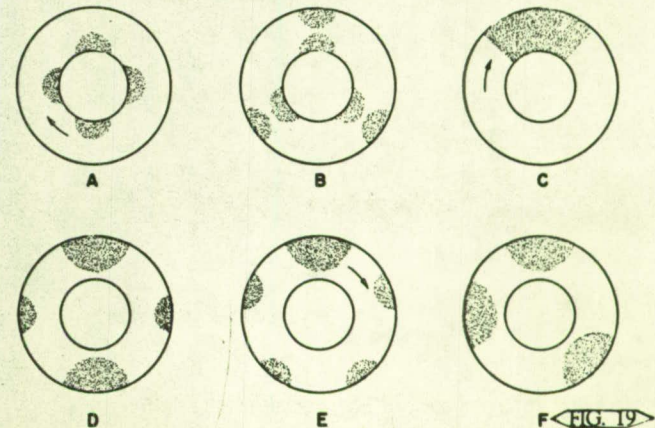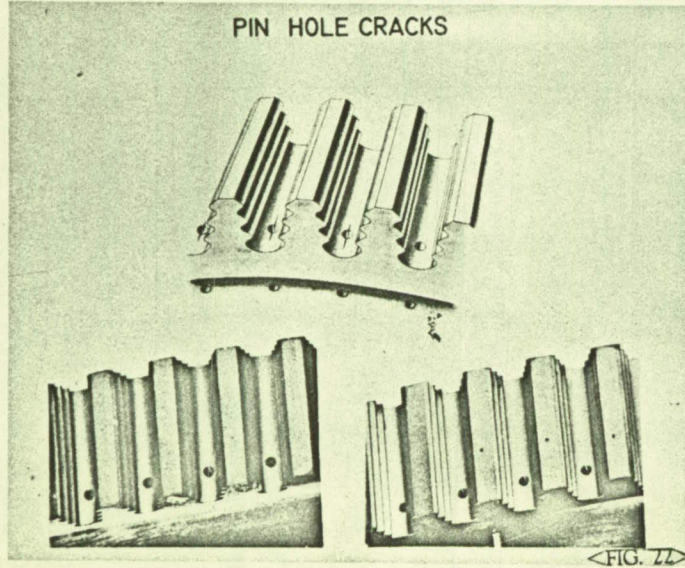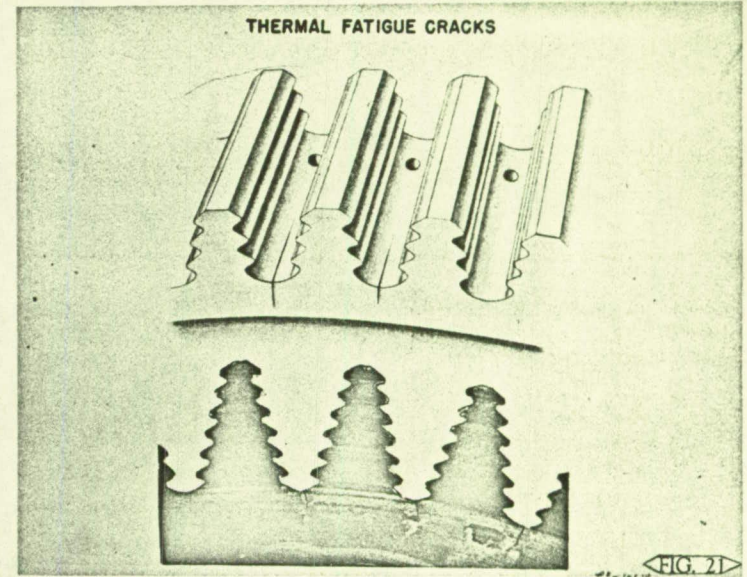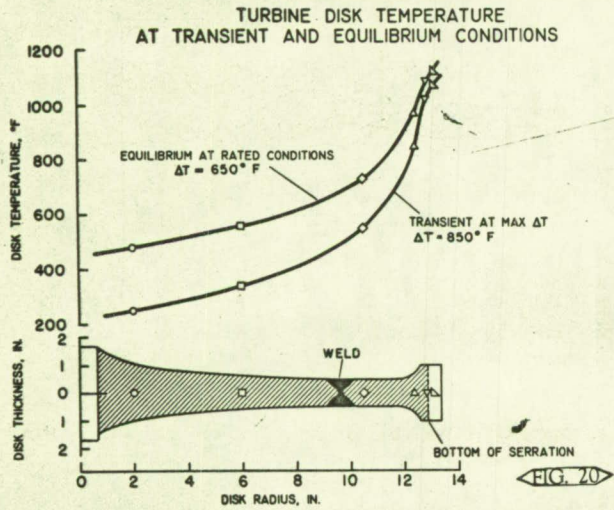
MEASURED METAL TEMPERATURES AROUND LINER

FIG. 23
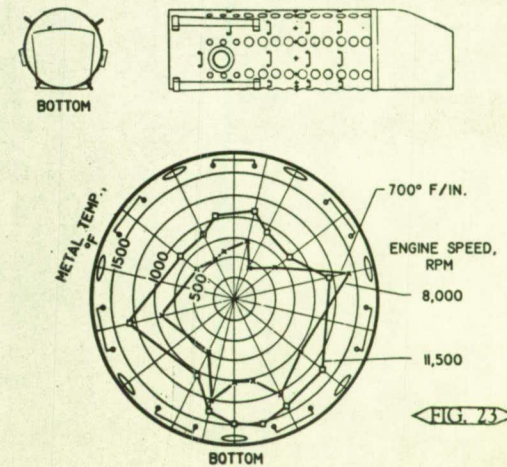
NOZZLE VANE TEMPERATURES
MEASURED AT A COMBUSTOR OUTLET

FIG. 24
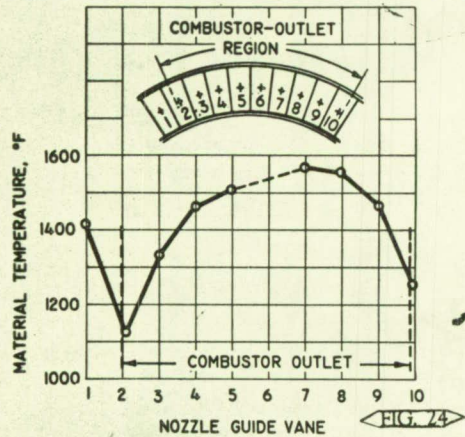
TEMPERATURE VARIATION ACROSS CHORD
OF NOZZLE VANE

FIG. 25
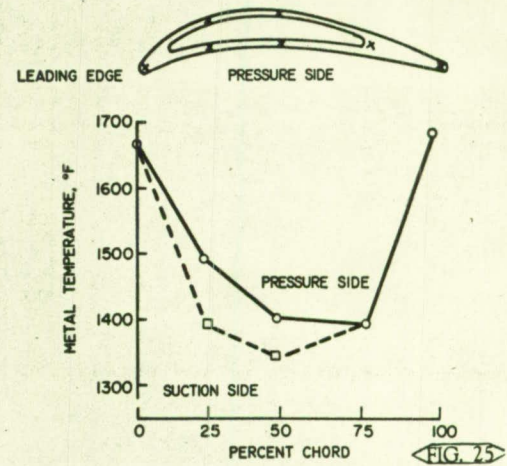
TURBINE BUCKET TEMPERATURE PROFILE
DURING START OF J-47 ENGINE

FIG. 26
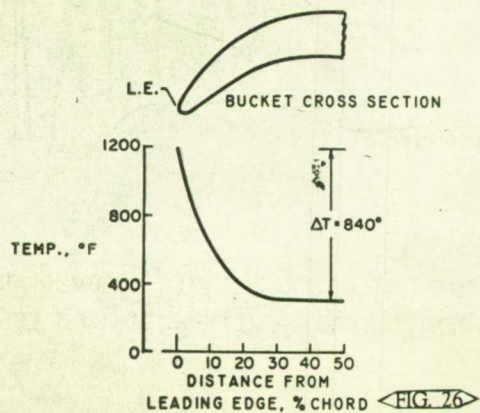
TYPICAL LEADING EDGE CRACKS

FIG. 27
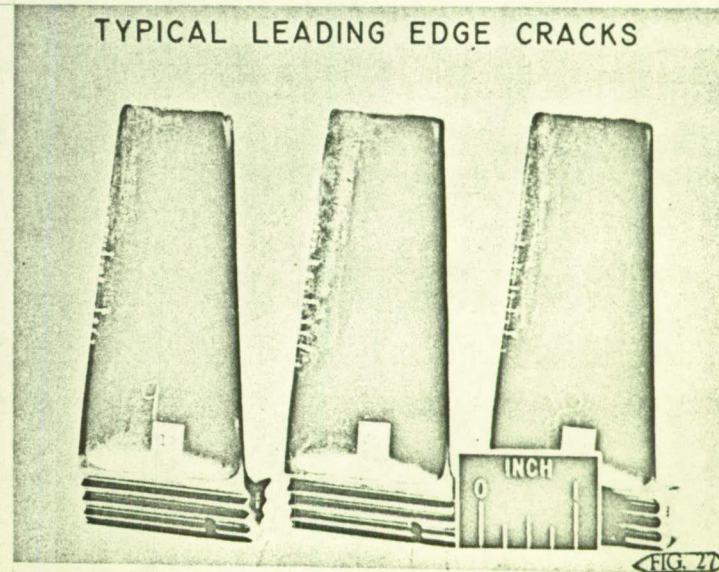
EXHAUST GAS TEMPERATURE DURING NORMAL AND GRADUAL STARTS OF J47 ENGINE

FIG. 28
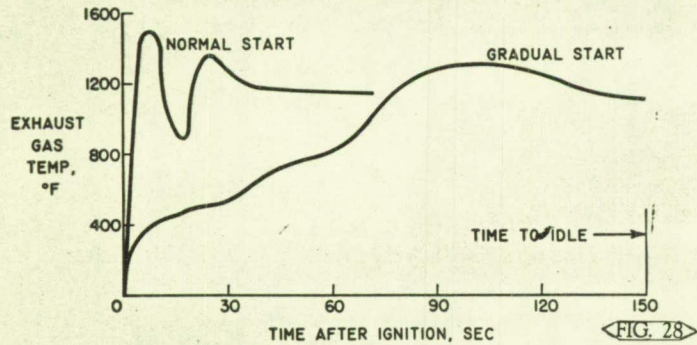
RESULTS OF FLAME IMPINGEMENT TESTS

FIG. 29
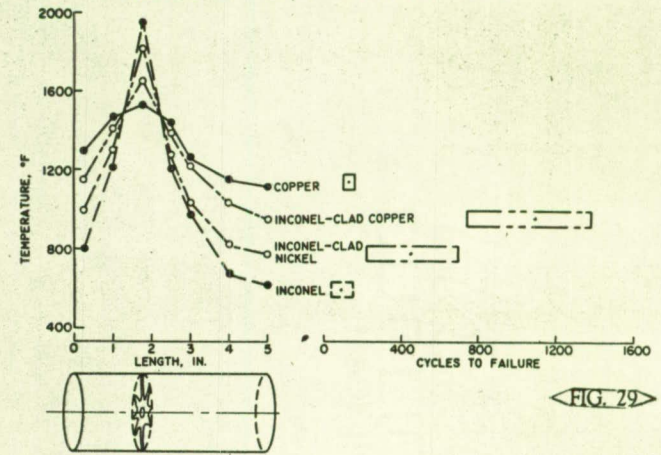
TABLE II. - IDENTIFIED OBJECTS WHICH CAUSED
THE PREMATURE OVERHAUL OF ENGINES

OBJECTS	NUMBER	PERCENT OF ENGINES OVERHAULED BECAUSE OF FOREIGN OBJECT DAMAGE
ENGINE B		
METAL PIECES	22	8.8
ROCKS AND PEBBLES	17	6.8
SCREWS AND BOLTS	12	4.8
FAILED PARTS	10	4.0
SAFETY WIRE	6	2.4
TOOLS	5	2.0
CLOTH	2	.8
BATTLE DEBRIS	1	.4
BIRD	1	.4
ANIMAL	1	.4
UNKNOWN	174	69.2
TOTAL	251	100.0

FIG. 30

VARIATION IN DAMAGE TO ENGINES WITH ENGINE INLET HEIGHT

FIG. 31
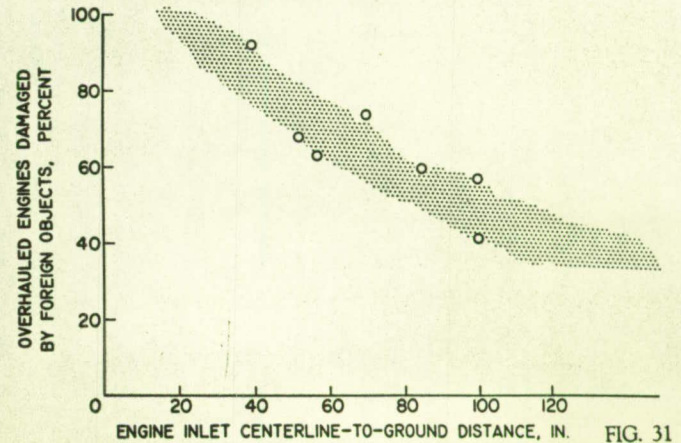
VARIATION IN ENGINE DAMAGED WITH AIRBASE
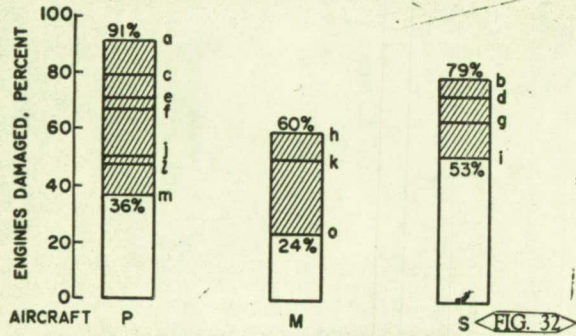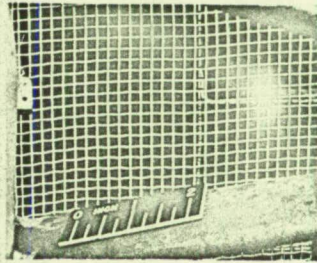
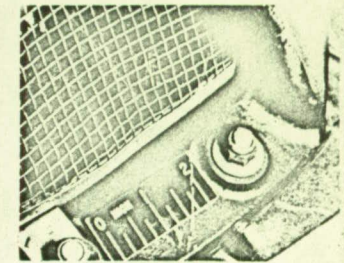AIRBASES AND AIRCRAFT ARE GIVEN IN CODE

ENGINES DAMAGED, PERCENT

AIRCRAFT P M S FIG. 32

FOREIGN OBJECT DAMAGE TO ENGINE C WITH VARIATIONS IN SCREEN INSTALLATION

AIR INLET SCREEN IN EARLY ENGINES   AIR INLET SCREEN IN RECENT ENGINES

NUMBER OF ENGINES	239	487
MESH SPACING, IN.	0.17	0.25
ENGINES DAMAGED, PERCENT	36	84

FIG. 33

CHARACTERISTIC FAILURE DISTRIBUTIONS

PROBABILITY OF FAILURE

GRACE PERIOD OF NO FAILURES

TIME   TIME   TIME

(A) WEAR-OUT (FAILURES TIME DEPENDENT)   (B) CHANCE (FAILURES TIME INDEPENDENT)   (C) INITIAL

FIG. 34
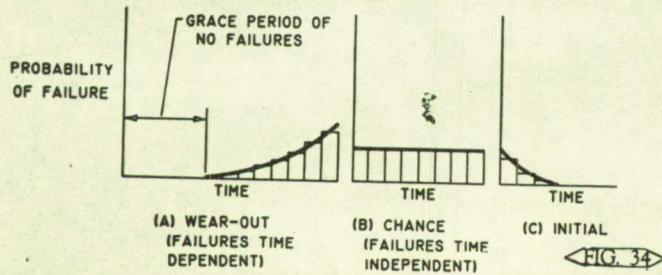
POSSIBLE ENGINE FAILURE RATE AS RESULT OF COMPONENT FAILURE RATES

PROBABILITY OF FAILURE

INITIAL   TIME DEPENDENT   CHANCE

TIME   FIG. 35