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INVESTIGATION AND ANALYSIS OF RELIABILITY AND MAINTAINABILITY PROBLEMS ASSOCIATED WITH ARMY AIRCRAFT ENGINES

K. G. Rummel, et al

Boeing Vertoi Company

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This investigation of turboshaft engine reliability and maintainability (R&M) characteristics is one of a number of continuing R&M problem investigations conducted by the U. S. Army Air Mobility Research and Development Laboratory to provide a clear understanding of the quantitative and qualitative R&M characteristics associated with Army helicopter systems. Efforts are being, and subsequently will be, pursued to determine those design criteria and concepts, test requirements, and/or advanced technology requirements to provide a quantum improvement in R&M characteristics for future systems.

This study concentrated on all factors contributing to current turboshaft engine R&M characteristics. Typical of the broad range of factors considered are design specifications/standards, technology limitations, development program inadequacies, and maintenance procedures. Both inherent and externally induced R&M problems were considered and treated separately. An attempt was made to quantify the R&M improvement potential available through the use of various program approaches (maximum attention given to R&M versus maximum attention given to performance, for example) and related part/piece design concept selections, e.g., carbon versus labyrinth seals.

This Directorate concurs with the investigation findings and specifically directs the reader's attention to that section that addresses contributing factors. It is interesting to note that a maximum of only 15% of all R&M problems are indicated as being technology oriented, while factors such as requirements documents, preliminary design efforts, detail design execution (including test), quality control, and maintenance procedures collectively constitute the remaining 85%. Results of this program are to be used as a basis for future exploratory and advanced development efforts relative to turboshaft engines.

Further investigation of the above-mentioned nontechnology factors is being initiated by this Directorate, and results will be published in late FY74. Special emphasis has been placed on test requirements as they relate to engine assembly and component reliability achievement.

This program was conducted under the technical management of David B. Cale, Technology Applications Division (Propulsion Area), with engineering support from Victor W. Welner, Military Operations Technology Division (Reliability Area).

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INVESTIGATION AND ANALYSIS OF RELIABILITY AND MAINTAINABILITY PROBLEMS ASSOCIATED WITH ARMY AIRCRAFT ENGINES

Final Report

by

K. G. Rummel
H. J. M. Smith

Prepared by

THE BOEING COMPANY, Vertol Division
Boeing Center
Philadelphia, Pennsylvania

for

EUSTIS DIRECTORATE
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13. ABSTRACT

The reliability and maintainability problems associated with gas turbine engines now operational with the U. S. military services were examined in this study. A broad spectrum of turboshaft and turboprop engines in U. S. Army, Navy and Marine helicopters and fixed-wing aircraft was examined. The study concentrated on the detailed R&M experience of the T53, T55, T58, T63, T64, T73 and T74, although data is provided on other gas turbine engines in military and commercial use. The R&M problem was quantified at the subsystem, component and failure mode levels in each of four R&M parameters and was subsequently combined into a single parameter expressing the total effectiveness, logistics and cost impact of R&M problems. All types of problems were considered, including the traditional engine-caused as well as the non-engine-caused reasons for scheduled and unscheduled events. The concept of a composite engine was introduced to describe the average R&M experience of the engines examined; problems were quantified and displayed at the failure mode, component and sybsystem levels for this composite engine. Two different approaches were taken in the subsequent analysis detailed design considerations and broader program considerations. Current experience, as described by the composite engine, was discussed in these two approaches. Individual failure modes were discussed in terms of failure mode and mechanisms, corrective actions, and the current state of the art in problem avoidance. Examples and photographs of typical failures are provided. These problems were also reviewed for the general program causal factors that contributed to the origin of the problems. Available design and program features and trends were reviewed and summarized. Categories of design features are used in order to provide visibility of their acceptability and cost and performance impacts. These features are configured into three possible future engines for the 1975-82 era. The three configurations reflect varying degrees of program emphasis on R&M. R&M levels are quantified at the failure mode and sybsystem levels for these engines.

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Theoretical composite engine						
Detailed design considerations						
Broad program considerations						
Three possible future engines						
1975-82 era						
Future remedial actions						
Recommendations for future activity						

SUMMARY

The reliability and maintainability problems associated with gas turbine engines currently operational with the U.S. military services were examined in this study. A broad spectrum of turboshaft and turboprop engines in U.S. Army, Navy and Marine helicopters and fixed-wing aircraft was examined. The study concentrated on the detailed R&M experience of the T53, T55, T58, T63, T64, T73 and T74, although quantitative R&M data is provided on other gas turbine engines in military and commercial service.

The R&M problem was quantified at the subsystem, component and failure mode levels in each of four traditional R&M parameters and was subsequently combined into a single parameter expressing the total effectiveness, logistics and costs impact of R&M problems. All types of problems were considered, including the traditional engine-caused as well as the nonengine-caused reasons for scheduled and unscheduled events.

The concept of a composite engine was introduced to describe the average R&M experience of the various engines examined, and problems were quantified and displayed at the failure mode, component and subsystem levels for this composite engine.

Two distinctly different approaches were taken in the subsequent analysis: detailed design considerations and broader program considerations.

The current experience, as described by the composite engine, was discussed in these two approaches. The individual failure modes were discussed in terms of failure mode and mechanisms, corrective actions applied to these problems, and the current state of the art in problem avoidance. Examples and photographs of typical failures are provided. These problems were also reviewed for the general program causal factors that contributed to the origin of the problems.

Currently available design and program features and trends were reviewed and summarized. Categories of design features are utilized in order to provide proper visibility of their acceptability and cost and performance impacts.

These features are configured into three possible future engines for the 1975-1982 era. The three configurations reflect varying degrees of program emphasis on R&M. R&M levels are quantified at the failure mode and subsystem levels for these engines.

Future remedial actions are considered based on the magnitude of the projected remaining problems. Recommendations for future activity are provided from both design and program standpoints.

FOREWORD

Conducted by The Boeing Company, Vertol Division, for the Eustis Directorate of the U.S. Army Air Mobility Research and Development Laboratory (USAAMRDL), Fort Eustis, Virginia, under Contract DAAJ02-71-C-0055, Task 1F162205A11902, this report investigates the reliability and maintainability problems on Army aircraft turboshaft and turboprop engines.

USAAMRDL technical direction was provided by Messrs. T. House, R. Campbell and V. Welner.

The principal investigators and authors of this study were Messrs. K. G. Rummel and H. J. M. Smith, and program management was provided by Mr. G. W. Windolph, Director and Mr. R. B. Aronson, Unit Chief of the Boeing Product Assurance staff. Also contributing to the study was Mr. K. Porter, Chief, and Mr. T. Connolly of the Propulsion Technology Group.

The authors gratefully acknowledge the significant assistance of the engineering and product support departments of the following engine manufacturers:

- Avco Lycoming - Stratford, Connecticut
- Detroit Diesel Allison - Indianapolis, Indiana
- General Electric Company - Lynn, Massachusetts
- Pratt & Whitney Aircraft - Hartford, Connecticut
- United Aircraft of Canada - Longueil, Quebec

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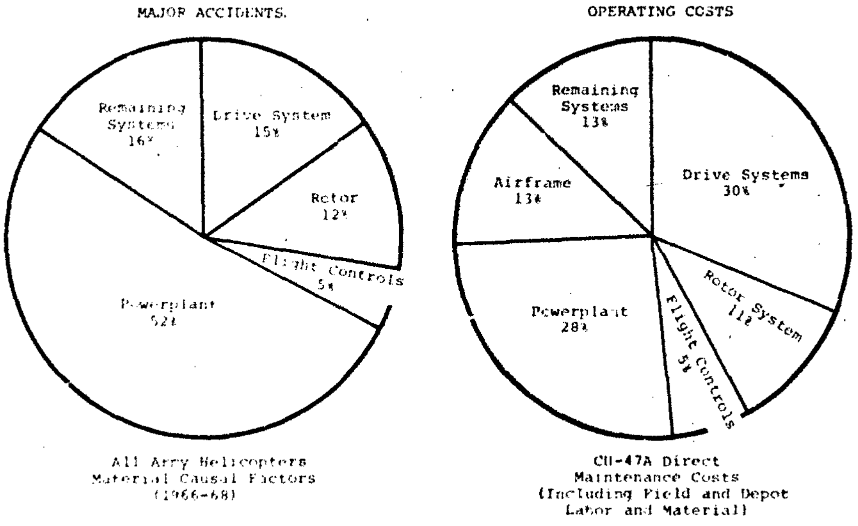
1.0 INTRODUCTION

Use of gas turbine engines in their aircraft has given the U.S. Army a significant increase in mobility. Commitment of the engines to battle conditions provided a positive measure of the gas turbine's capability in a difficult environment that included frequent operation at low altitudes in sand and dust, frequent power changes with related thermocycling, and constant exposure to the most difficult of maintenance conditions. It soon became clear that the performance benefits from the gas turbine engine were significant. It also became obvious that the anticipated reliability and maintainability (R&M) attributes of the engines were not being realized in these operations.

The impact of turbine engine reliability and maintainability is of critical concern. Review of historical safety, reliability, and maintainability data reveals that Army turbine engines contribute significantly to the total number of accidents, downtime, maintenance burden, and ownership costs of the aircraft in which they are installed. The percent of major accidents and ownerships costs attributed to powerplants is shown in Figure 1. In addition to the two parameters indicated in Figure 1, it will be shown that engine R&M levels have a significant impact on an extremely broad spectrum of cost incurring consequences.

This study utilizes extensive data from military operations to quantify the magnitude and reasons for the current level of R&M of military gas turbine engines and identifies ways to improve R&M in future engines.



All Army Helicopters
Material Causal Factors
(1966-68)

CH-47A Direct
Maintenance Costs
(Including Field and Depot
Labor and Material)

Figure 1. Helicopter Accidents and Operating Costs.

2.0 STUDY APPROACH AND PROCEDURES

This study investigates seven gas turbine engines in terms of the following R&M parameters:

- Unscheduled Engine Removal (UER) Rate
- Accident Rate (Engine-Related)
- Maintenance Man-Hour per Flight Hour Rate
- Time Between Overhaul (TBO) Interval

The study included the different dash-number variations of these basic engines:

- Lycoming T53, Figure 2
- Lycoming T55, Figure 3
- General Electric T58, Figure 4
- Allison T63, Figure 5
- General Electric T64, Figure 6
- Pratt & Whitney T73, Figure 7
- United Aircraft of Canada T74, Figure 8

CURRENT ENGINES

Problems were investigated on an engine-by-engine basis and quantified in terms of each of the individual parameters, where adequate data existed. A composite engine was developed to allow consideration of all problems on a weighted basis without undue influence by a single engine or manufacturer and without the proprietary restraints associated with specific failure modes of individual engines. A single quantified index number was developed to express the collective impact of each failure mode in terms of the traditional parameters of UER rate, major accident rate, TBO, and maintenance man-hours per flight hour. The result was a list of failure modes for the composite engine, listed in order of priority of each mode's frequency and consequence, as quantified by the index number.

Detailed failure mechanisms for each failure mode of the composite engine were examined and discussed. The study considered the program deficiencies that caused or allowed the various failure modes to exist. Program deficiencies were defined to include decisions regarding requirements, preliminary design, design execution, manufacturing and quality control, and maintenance/operation.

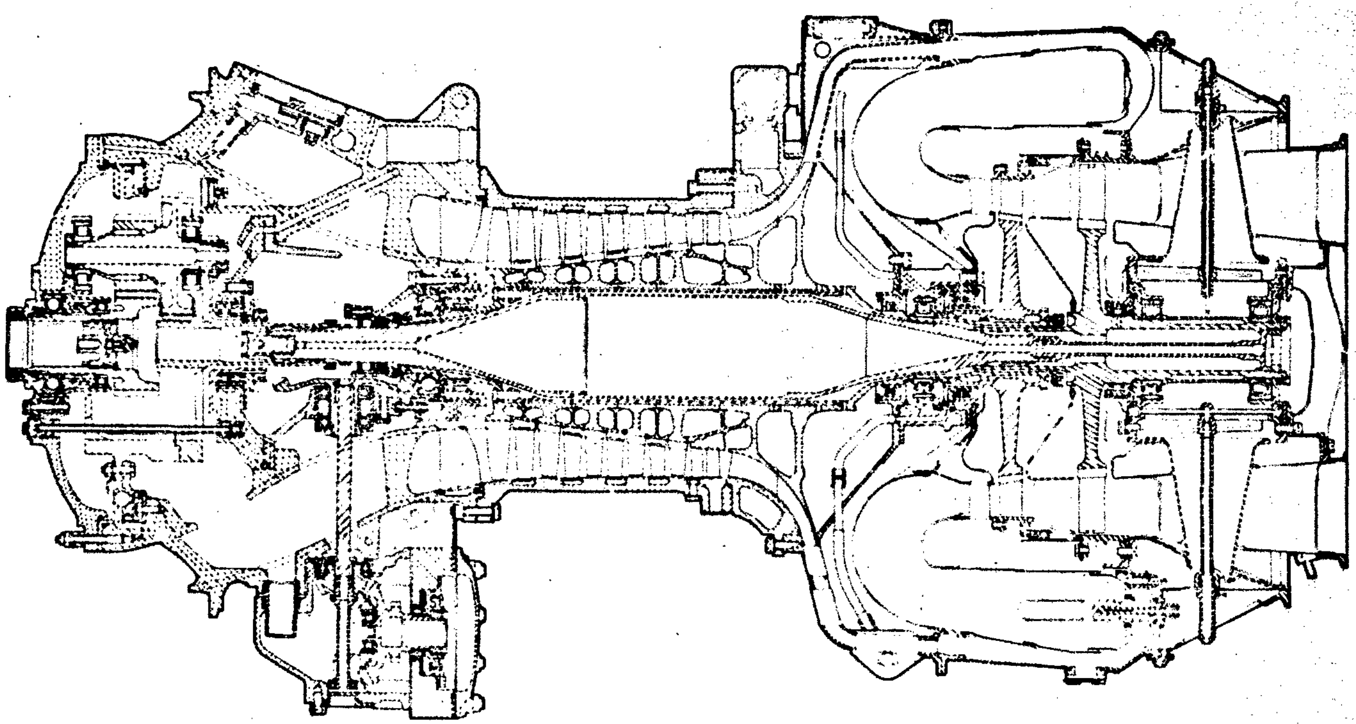


Figure 2. Avco Lycoming T53 Turbine Engine Cutaway.

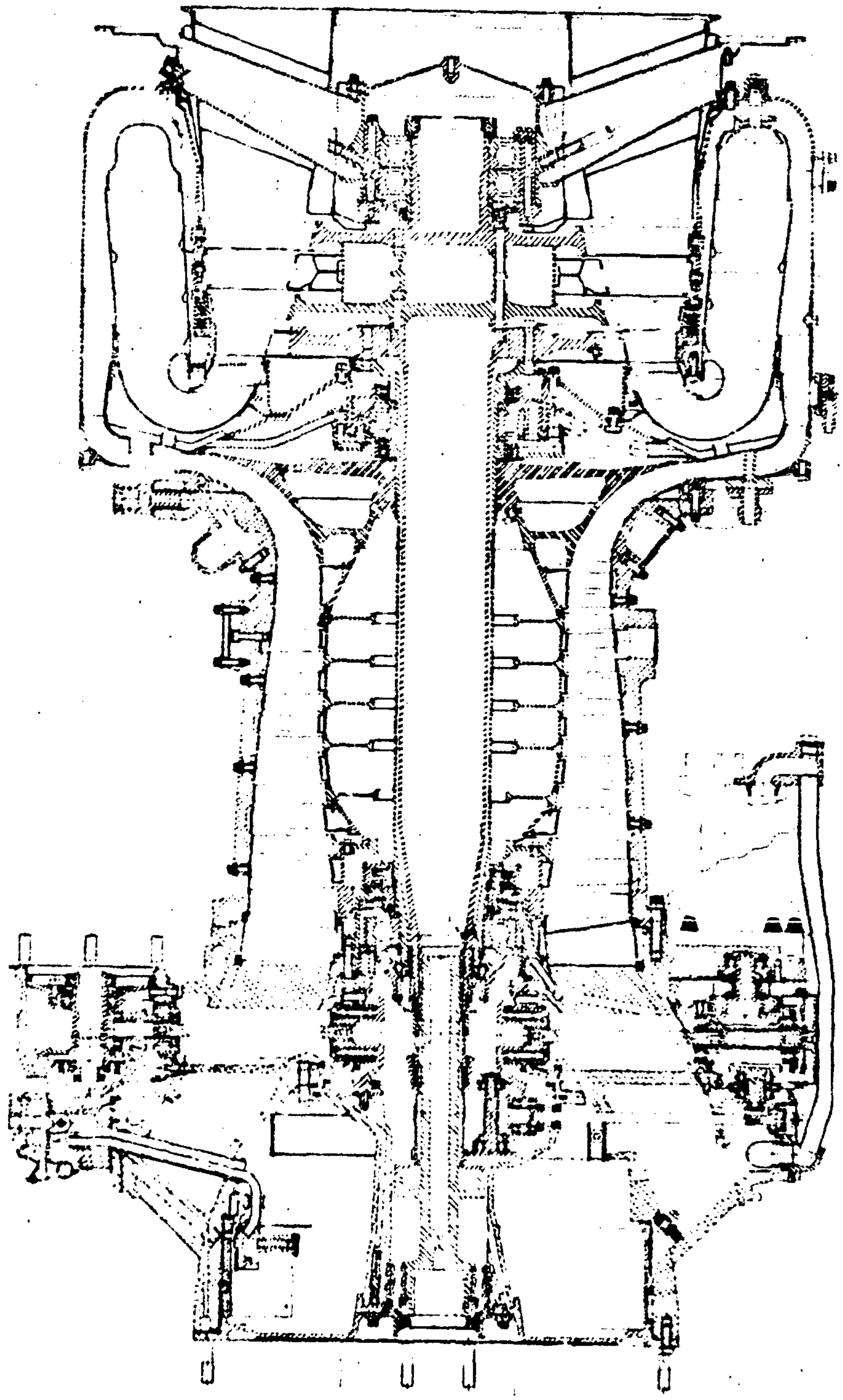


Figure 3. Avco Lycoming T55 Turbine Engine Cutaway.

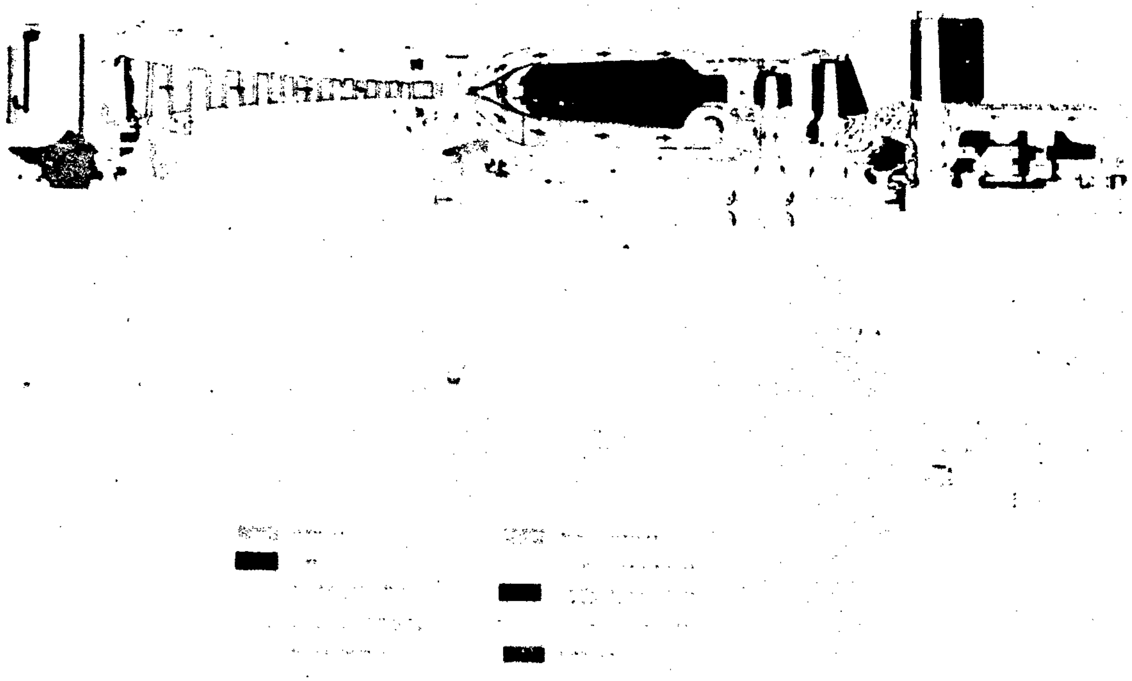


Figure 4. General Electric T58 Turbine Engine Cutaway.

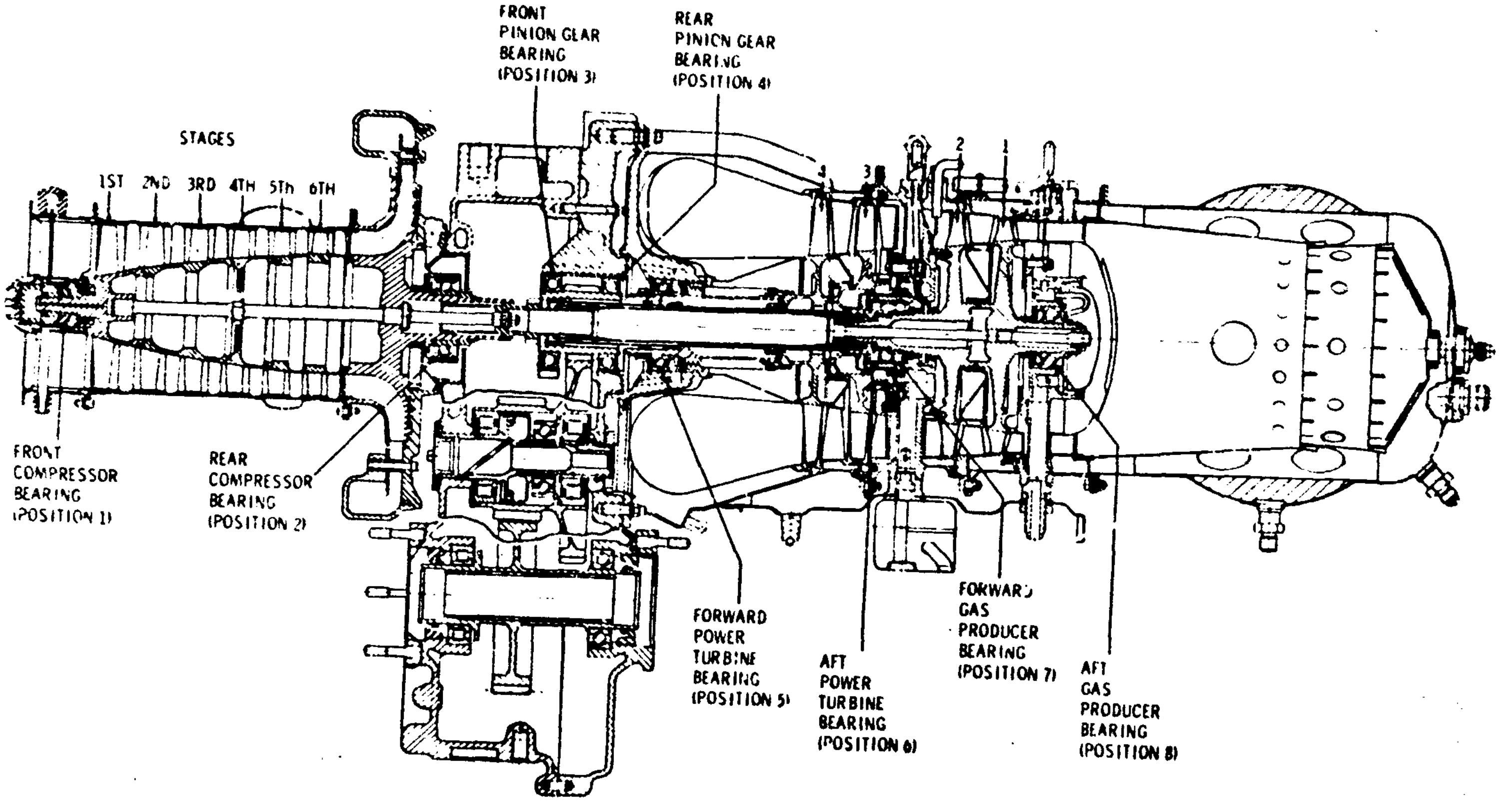


Figure 5. Allison T63 Turbine Engine Cutaway.

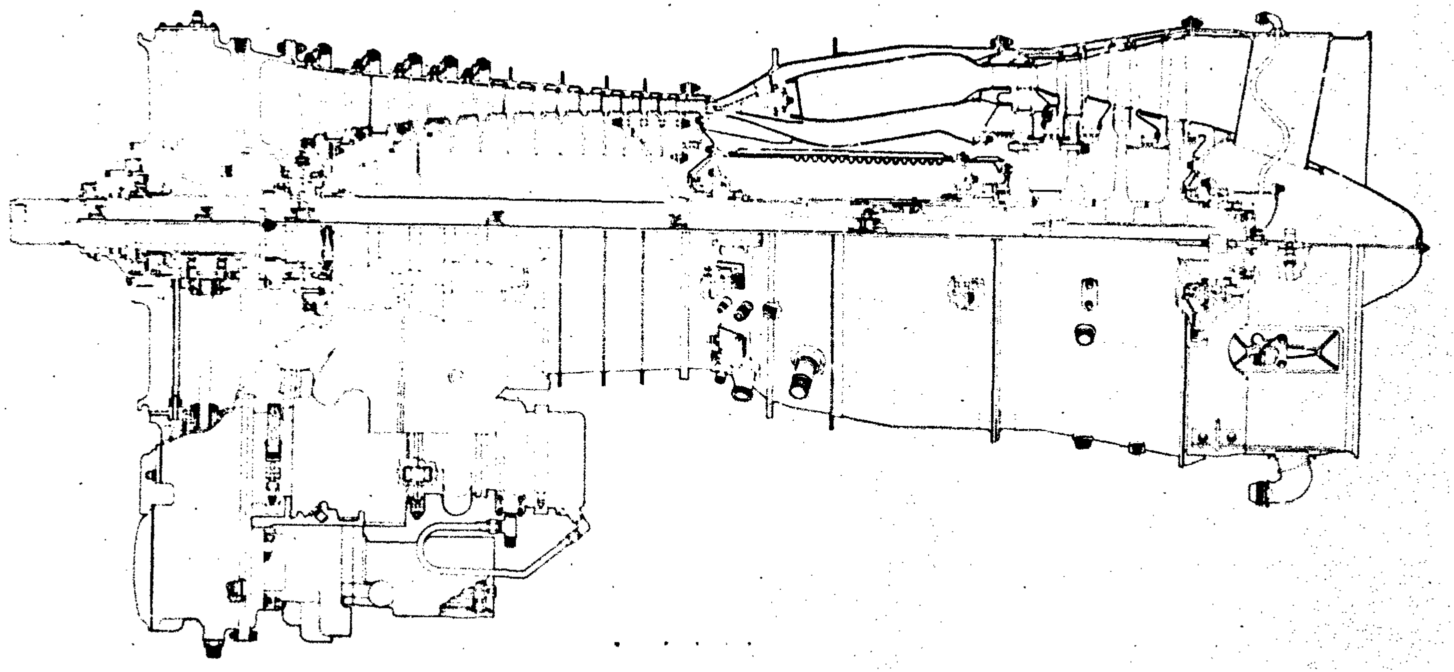


Figure 6. General Electric T64 Turbine Engine Cutaway.

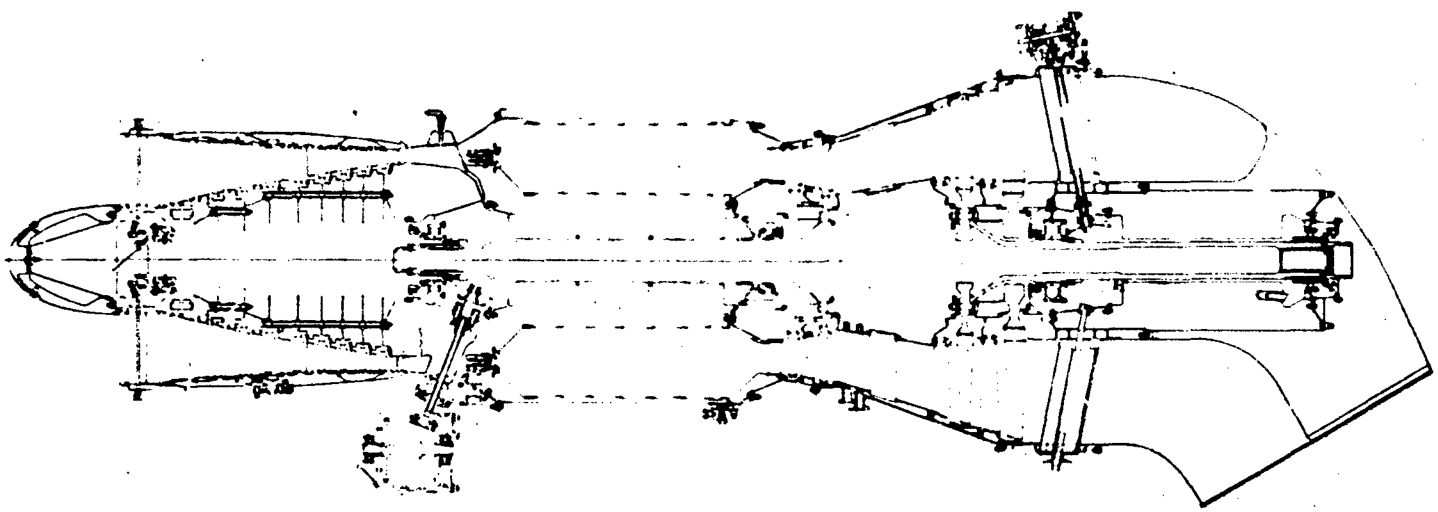


Figure 7. Pratt and Whitney T73 Turbine Engine Cutaway.

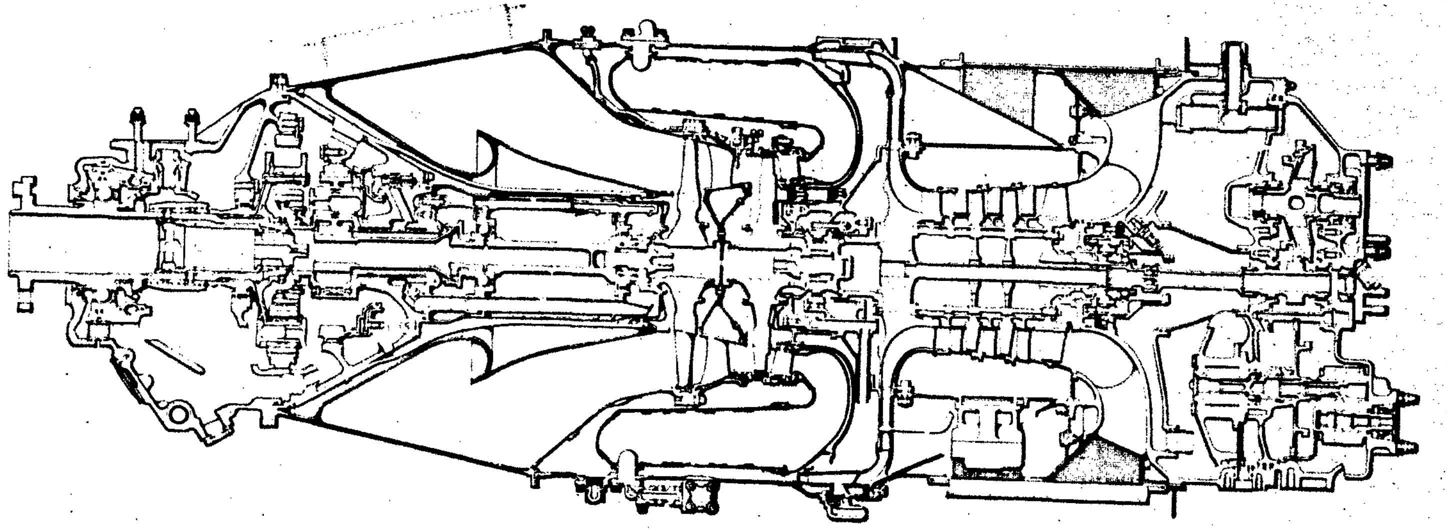


Figure 8. United Aircraft of Canada T74 Turbine Engine Cutaway.

NEAR-TERM FUTURE ENGINES

Available defined remedial actions to alleviate current engine R&M problems were tabulated and discussed for each engine subsystem. They were then selectively assigned to each of three possible near-term future engine configurations, and the R&M characteristics of these configurations were quantified. It was necessary to configure three engines because customer emphasis exerts great leverage upon product R&M. The three near-term engines (configured for the 1975-82 era) are:

- A full-performance-emphasized engine
- A full-R&M-emphasized engine
- A normal engine (representing a balance of R&M and performance)

LONG-TERM R&M REQUIREMENTS

The near-term R&M-emphasized engine still needs further R&M improvement. In general, the hardware and program corrective action does not exist today. To further improve the R&M levels, aggressive and detailed development is required for post-1982 engines. The needed improvements are identified and discussed in this report.

SELECTION OF R&M PARAMETERS

The myriad of existing parameters complicates the task of describing the magnitude of the engine R&M problem. This in turn makes it difficult to define the courses of action necessary for efficient problem solution.

The R&M-oriented parameters currently being used include:

1. Accident Rates
    - Major
    - Minor
    - Incidents
2. Schedule Accomplishment Rates
    - In-flight Shutdowns
    - Forced Landings
    - Precautionary Landings
    - Ground Aborts
    - Aircraft Availability

3. Life-Cycle Costs

- Malfunction Rate
- Unscheduled Removal Rate
- Scheduled Removal Rate
- TBO Intervals
- Maintenance Man-Hour Rate
- Operating Costs per Flight Hour

One of the study tasks was to select and integrate the optimum parameters and then provide appropriate quantification, so that a credible problem priority list could be developed. The parameters used to measure safety, reliability, and maintainability were selected by considering both their significance and their general use by the military services and the engine community. The parameters selected for use in this study are:

- Unscheduled Engine Removal (UER) Rate (all causes)
- Major Accident Rate (engine-related)
- Maintenance Man-Hour/Flight Hour (MMH/FH) (on engine systems)
- Time Between Overhauls (TBO)

These parameters quantify the safety, schedule accomplishment, and life-cycle cost domains of the engine. Table I displays how these four parameters reflect the entire spectrum of R&M consequences.

TABLE I. R&M CONSEQUENCES OF PARAMETERS SELECTED

	Selected Parameters			
R&M Consequences	UER Rate	MMH/FH	Major Accident Rate	TBO
Major Accidents	X		X	
Minor Accidents	X		X	
Incidents	X		X	
In-Flight Shutdowns	X		X	
Forced Landings	X		X	
Precautionary Landings	X			
Ground Aborts	X			
Aircraft Downtime	X	X		X
Malfunctions		X		
Unscheduled Removals	X	X		
Scheduled Removals		X		X
TBO Interval		X		X
Maintenance Man-Hours	X	X		X
Operating Costs	X	X	X	X

A number of other parameters were investigated and found to be deficient. For example, Engine Malfunction Rate is probably the best indicator of engine unreliability; however, it is not routinely collected and recorded by the U.S. Army. For those military services where engine malfunction rate is identified, the usefulness of the data is often compromised by a lack of failure mode and component identification data. In-Flight Shutdown Rate ranks high as a measure of engine reliability in commercial areas. It is collected in detail by most airlines, but not rigorously collected by the military services. Engine Returns to Depot is a parameter that has been widely collected by the U.S. Army and its contractors; however, it is strongly influenced by differing maintenance philosophies. User organizations with sophisticated maintenance philosophies and good facilities return engines to depot only as a last resort. Other organizations view the depot as a convenient place to send work. Also, the exigencies of a battle environment do not always permit engine repair to be accomplished at the maintenance level specified in military manuals.

ENGINE SELECTION CRITERIA

U.S. Army gas turbine aircraft engines are the basis for this study. The principal turboshaft engines used by Navy/Marine combat helicopters have been included to broaden the scope of the study. Inclusion of the Navy/Marine engines permits the study to include all the principal gas turbine engines currently used by U.S. military services in helicopter applications. It also permits the study to include engines from all the major engine manufacturers. Selection of a full range of engines and manufacturers makes this study a broad overview of the current turboshaft and turboprop engine spectrum.

Seven different engines were studied for this report. The principal gas turbine engines currently used by the Army are the Allison T-63 and the Lycoming T-53 and T-55 series turboshaft engines. The Pratt and Whitney T-73 turboshaft and the United Aircraft of Canada T-74 turboprop, each in limited use with the Army, are also included. The Navy/Marine engines studied are the General Electric T-58 and T-64 turboshafts.

The engines selected have a power range of 317 to 4800 horsepower; they power light observation aircraft through medium- and heavy-lift helicopters. The engines that have contributed to determining engine safety, reliability and maintainability levels, their manufacturers, and the specific applications are listed in Table II.

DATA AVAILABILITY

After selecting the parameters for study, an extensive effort was undertaken to identify compatible data for each engine.

Data was successfully obtained and analyzed for approximately 85 percent of all engine/parameter combinations as indicated in Table III.

Data was obtained from the following sources: engine manufacturers' contractual R&M reports, USABAAR accident reports, ARADMAC (Army Overhaul Facility) engine disassembly inspection reports, U.S. Navy Material and Maintenance Management Reports (3M), manufacturer Engineering Change Proposals (ECP's), powerplant and engine bulletins and changes, Boeing in-house engine data, Navy Safety Center data, EIR's and UR's. Considerable data was provided by the engine manufacturers. They also provided detailed explanations and interpretations of their data.

TABLE II. ENGINES STUDIED

Engine	Manufacturer	Application	Service
T53-L-11 T53-L-13	Lycoming	UH-1 UH-1, AH-1	U.S. Army
T55-L-7 T55-L-7C	Lycoming	CH-47 CH-47	U.S. Army
T58-8B T58-10	General Electric	CH-46, SH-3 CH-46	U.S. Navy & Marines
T63-A5A	Allison	OH-6	U.S. Army
T64-6	General Electric	CH-53	U.S. Marines
T73	Pratt & Whitney	CH-54	U.S. Army
T74	United Acft of Canada	U-21 & Commercial	U.S. Army & Commercial

TABLE III. ENGINE DATA AVAILABLE

	Data Availability			
Engine	UER Rate	Accident Rate	MMH/FH	TBO
T53	yes	yes	yes	yes
T55	yes	yes	yes	yes
T58	yes	yes	yes	yes
T63	yes	yes	no	yes
T64	yes	yes	yes	yes
T73	Partial	yes	no	yes
T74	Partial	yes	no	yes

3.0 STATUS OF CURRENT ENGINES

This section presents the results of the analyses performed on the seven current engines. Displays are provided which quantify the study parameters (UER rate, major accident rate, TBO's and MMH/FH) to the subsystem level for each engine. Although quantified only to the subsystem level in these displays, the analyses reflect component and failure mode level experience in each of the study engines. Also included in this section are discussions concerning the importance of considering the degree of engine maturity, the rationale for the particular subsystem breakdown selected, the concept of the composite engine, and the concept of the index number (a derived value which encompasses the four quantified study parameters).

The section concludes with a list of problems (in order of priority) encompassing both the component and subsystem levels as appropriate. Broad conclusions are developed from the data analysis at the subsystem level. Conclusions from analysis of data at the failure mode and component levels are developed in Section 4, Detailed Problems of Current Engines.

ENGINE MATURITY

Early in the data analysis task, it became apparent that engine maturity has a tremendous influence on the level of reliability being achieved by a particular engine. In order to make meaningful comparisons and assessments, it is essential to recognize that absolute values of reliability vary significantly over an engine's life cycle. Actual values measured are the direct result of the caliber and amount of product improvement and learning curve considerations (with respect to operator and maintenance personnel techniques).

Experience has shown that engines enter operational service after a relatively short development period. While this involves several years of effort, it rarely includes more than 10,000 hours of engine operation. After introduction into service, numerous engineering and procedural changes are usually developed as service-revealed difficulties become apparent. Following this, a much slower rate of reliability improvement occurs until the engine reaches its mature reliability. These stages in an engine's maturity are illustrated in Figure 9.

To select the most appropriate engine maturity period for all engines, consideration was given to data availability, the calendar year of maturity, and the likelihood of the engine having received the majority of its product improvement. It was concluded that an appropriate maturity level for Army engine analysis was the 1-million-engine-hour point. Most

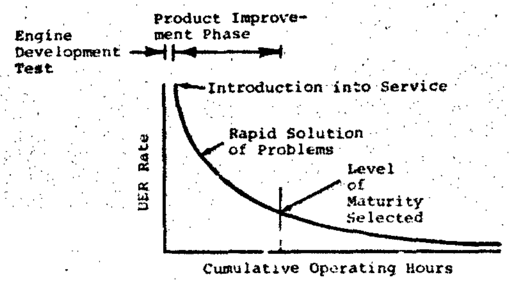


Figure 9. Engine Maturity.

military turboshaft engines reach or exceed this value; many product improvement changes have been developed, incorporated, and proven by that time; or the decision has been reached to pursue them no further.

For the current engines studied, the 1-million-hour maturity point was selected, with three exceptions. The T64 engine had only 250,000 hours of engine operation at the time of the latest available data base. The T53 and T74 engines had well in excess of 8,000,000 hours at the time of their most appropriate data with no adequate bases at the 1-million-hour point, and no acceptable method for synthesizing them. Reliability growth curves for military and commercial engines were constructed and are illustrated in Figure 10 utilizing the parameter of engine-caused unscheduled removal rate. These growth curves suggest that many factors influence engine reliability.

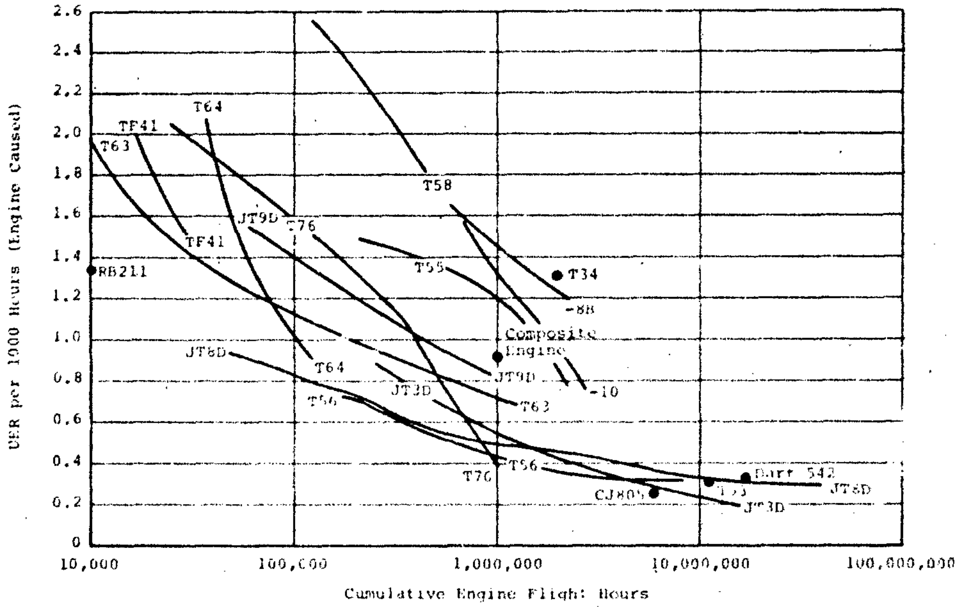


Figure 10. Engine Reliability Growth.

All engines exhibited a marked reduction in removal rate throughout their life cycle. The general trend shows a capability for an eight-fold reduction in engine-caused unscheduled removal rate from the initial value to maturity. Varying degrees of contractor product improvement effort are postulated to have a strong impact upon the engines' reliability growth process. For example, contrast the growth observed for the T56 and T34 turboprop engines. These two engines were developed in the same nominal calendar timeframe, are similar in power output, and are comparable from a complexity standpoint. Here, the similarity ends. The T56 was installed in many types of successful aircraft, acquired tremendous quantities of operating hours, and has been exposed to continuous and successful product improvement activities. The T34 engine, however, was installed only in the C-133 aircraft, which was characterized by an early-in-the-life-cycle awareness that production quantities would be quite limited.

Under these conditions it is not surprising that an aggressive product improvement program may not have been implemented. This could be the reason for the otherwise unexplainable high removal rate shown on Figure 10. This is conjecture since a complete growth curve is not available for the T34, but there is no other reason apparent why this engine should be significantly less reliable than other fixed-wing turboprop engines at an equivalent point in flight hours.

Helicopter engines can now be placed in proper perspective with fixed-wing engines by observing the cumulative engine flight hours in which significant removal rate reductions were achieved. Helicopter engines rarely exceed 2 to 3 million hours total time, while fixed-wing engines frequently exceed 10 million hours due to factors such as multiengine installations, applications of the same basic engine across many aircraft families, larger fleet sizes, and historically higher utilization rates. This allows the fixed-wing engine to reap the benefits of extended product improvement programs and permits it to achieve far more dramatic levels of reliability than most helicopter engines.

Another observation concerns the differences in reliability characteristics between various engine configurations. There appears to be a rather tight band of reliability for military and commercial fixed-wing engines whether they are turbojet, turbofan, or turboprop. The band for helicopter turboshaft engines is much broader and of greater mean value; however, the lower boundary is within the fixed-wing band. Therefore, it appears that the application of an engine has a greater impact on its reliability than does its configuration. Figure 10 also provides perspective to the legendary high reliability of the commercial turbofan engine. To attribute this to configuration rather than aggressive product improvement effort is unrealistic.

The wide variation of removal rates for helicopter applications warrants comment. Without doubt, the band is a function of both reliability and maintainability factors. Reliability is degraded by more abusive climatic and mechanical environments and/or a shorter mission length which produces more thermocycles per hour. Maintainability aspects (such as poor accessibility) drive certain helicopter applications to the high side of the band.

Of particular interest is the observation that there appears to be no discernible reliability difference between military and commercial usage. Although Figure 10 does not show commercial helicopter data, the fixed-wing data suggests that the difference is, at most, minimal. Further analysis should be undertaken to clarify this continuing controversy.

With this general perspective of turbine engine reliability, it is appropriate that the subsystems, components, and failure modes which compose and define helicopter turboshaft engine R&M characteristics be examined in detail.

SUBSYSTEM DEFINITION

Establishment of a suitable engine subsystem breakdown is a prerequisite to an organized identification of engine R&M problems. After evaluating the subsystem breakdowns being used by the engine manufacturers, it was concluded that a functional breakdown was the most suitable for this study. This breakdown was arranged to include the grouping of engine main-shaft bearings and seals under individual headings. The display of the large impact of these components on engine reliability is the principal reason for this exception. Other systems were arranged functionally so that direct comparisons of lubrication systems, fuel systems, etc., were possible.

Although the engine manufacturers did not agree on a common subsystem breakdown, there was complete agreement on the need to separate engine removals into two categories: engine-caused and non-engine-caused. Engine-caused removals are those in which a malfunctioning component of the engine itself necessitates a removal. A non-engine-caused removal is one in which some external reason (such as FOD or improper maintenance) was the cause. For engine-caused removals, definition of the problem is usually available down to the component level. For non-engine-caused removas, information is not routinely displayed below the failure cause (for example, airframe induced).

It is postulated that the extremely rigorous categorization by the manufacturers between engine-caused and non-engine-caused removals is prompted by their seeing a need to identify those failures for which they feel directly responsible. Unfortunately, this directs attention to only a portion of engine unreliability. The impact of poor R&M dictates that all causes should be addressed with the diligence appropriate to their numerical rates. Full definition and details of the subsystem and category breakdowns used in this study are given in Table IV.

TABLE IV. SUBSYSTEM DEFINITION

Category	Subsystem	Components
Engine-Caused Events	o Bearings	Main Shaft Bearings
	o Seals	Main Shaft Seals, Assembly Seals
	o Compressor	Discs, Blades, Stators, Shafts, Diffuser, Scrolls, Bleed Bands, VIGV Actuators, Bleed Valves
	o Combustion	Liners, Housings, Support Hardware, Air Swirl Components
	o Turbine	Nozzles, Blades, Shrouds, Wheels, Shafts, Shaft Couplings
	o Cases	Outer Casing, Inlet Housing, Fittings
	o Lubrication	Pump, Valves, Lines, Filters, Coolers
	o Fuel	Fuel Control Units, Pump, Purifier, Drain Valves, Manifold, Lines, Nozzles
	o Air	Anti-Ice, Seal Pressurizing, Cooling Lines and Valves
	o Accessory	Gears, Drives, AGB Housing
	o Torquemeter	Rotors, Drives, Rollers, Transmitters, Pistons, Valves
	o Electrical	Ignitor Units, Harness, Power Management Amplifier
	o Exhaust	Exit Vanes, Tailpipe Mounting Flanges, Exhaust Cones
	o Power-Train Reduction	Output Bearings, Gears
Non-Engine-Caused Events	o Foreign Object Damage	Events caused by ingestion of foreign objects other than sand or dust
	o Erosion	Events caused by sand and dust ingestion
	o Environmental	Events caused by corrosion, fuel and oil contamination
	o Operator Induced	Events caused by hot starts, overtemp, overspeed conditions
	o Improper Maintenance	Events caused by improper procedures/lack of skill
	o Convenience	Events caused by cannibalization, poor engine component accessibility
	o Battle Damage*	
	o Airframe Related	Events caused by mounting, cooling, drive and start interfaces, removals to gain access to airframe components
	o Unsubstantiated/unknown	

*Provided for information only, not used in study

UNSCHEDULED ENGINE REMOVAL (UER RATE)

The parameter of unscheduled engine removal rate from the airframe was defined to include engine removals for all causes except TBO changes and hot end inspections. In terms of impact on an operational military unit, the unscheduled removal of an entire engine from the aircraft structure is most heavily felt. This unplanned event involves considerable manpower expenditure and usually a requirement for a replacement engine.

A factor favoring the unscheduled removal rate as one of the preferred reliability parameters is that it is the closest to being universally understood and accepted and is one of the few that extends to commercial operations. This has allowed comparisons to be drawn between the rates applicable to turboshaft military engines and turboprop and turbofan engines in both military and commercial operations. Construction of the engine maturity curves was also possible for this reason. However, since this parameter is driven by factors other than reliability, conclusions based on comparisons between engines should only be drawn with caution. Considerations such as maintainability, accessibility in the aircraft, environment, and logistics all affect the UER rate, although it is not possible to quantify their separate effects.

In the case of the maintainability factors , for instance, modularization tends to decrease the number of unscheduled removals if failures are repaired with the engines installed. The accessibility of an engine also has considerable impact on its removal rate. This was commonly seen on the fuel subsystem, for example, where working on the fuel control unit is difficult when the complete engine is installed in the airframe. The engine logistics situation impacts convenience removals. Many removals are generated by the need to remove a serviceable engine from one aircraft to install it in another aircraft when no other engines are available.

Other non-engine-caused subsystem UER rates are also affected by operational environment, personnel skill levels, and engine configuration in terms of FOD and erosion protection equipment. For these reasons, direct comparisons of non-engine-caused or total UER rates are not appropriate.

Despite these shortcomings, the parameter of unscheduled removal rate should be considered one of the prime measures of engine R&M characteristics. The unscheduled removal rates for a variety of military and commercial turboprop, turbojet, turbofan, and turboshaft engines are displayed in Table V.

TABLE V. UNSCHEDULED ENGINE REMOVAL RATES

Subsystem	T53-L-11/11B CH-1 FY'67	T53-L-13/13A CH-1 FY'68	T55-L-7C 1971	T58-8B CH-46(SEA) 1/68-1/69	T58-8B CH-3 1/68-12/68	T58-10 CH-46(SEA) 1/69-2/70	T63-A-5A OH-6(SEA) 1/69-12/70	T64-6 CH-53(SEA) 1/68-12/69	T73 CH-54(SEA) 3/62-12/70	T74 Comm/Military 6/70-5/71
Bearings	0.108	0.106	0.207	0.063	0.055	0.086	0.170	0.230	0.081	0.085
Seals	0.074	0.346	0.245	0.018	0.073	0.138	0.158	0.097	0.081	-
Compressor	0.036	0.026	0.164	0.059	0.032	0.007	0.116	0.180	0.062	0.036
Combustion	0.068	0.002	0.190	0.117	0.038	0.007	0.002	0.033	-	-
Turbine	0.046	0.091	0.103	0.176	0.037	0.058	0.034	0.049	-	0.012
Cases	0.005	0.001	0.019	0.116	0.089	0.014	0.008	0.049	0.225	0.001
Lubrication	0.009	0.036	0.041	0.107	0.025	0.031	0.067	0.032	-	0.009
Fuel	0.303	0.006	0.071	0.380	0.166	0.163	0.038	0.032	-	0.003
Air	-	-	-	0.019	-	0.046	0.015	0.016	-	-
Accessory	0.008	0.003	0.063	0.049	0.012	0.029	0.016	0.048	-	0.010
Torquemeter	0.004	-	0.228	-	-	-	0.005	-	-	0.003
Electrical	-	-	-	0.039	0.011	0.065	-	0.016	-	0.009
Exhaust	-	-	0.006	-	-	-	0.007	-	0.021	0.009
Power-Train Reduction	0.006	0.016	-	-	-	-	-	-	-	0.010
Unknown*	0.018	0.051	0.151	0.241	0.012	0.352	0.226	0.170	0.141	0.010
TOTAL - Engine-Caused	0.526	0.703	1.479	2.212	0.598	0.650	0.834	0.959	0.604	0.117
Foreign Object Damage	[illegible]	1.096	[illegible]	[illegible]	0.122	0.591	0.203	0.542		0.017
Erosion	[illegible]	[illegible]	[illegible]	0.476	-	0.065	0.009	0.132		-
Environmental	[illegible]	[illegible]	[illegible]	0.246	0.057	0.104	0.046	0.016		0.011
Operator Induced	[illegible]	[illegible]	0.145	0.203	[illegible]	0.104	0.190	0.398		0.078
Improper Maintenance	0.095	[illegible]	0.411	0.750	0.212	0.305	0.120	0.608		0.013
Convenience	0.158	0.192	1.667	0.360	0.038	0.645	0.115	0.657		-
Battle Damage/Crash	0.084	0.097	0.097	0.586	-	0.215	0.532	0.033		0.041
Airframe Related	0.036	[illegible]	0.121	0.407	0.045	0.423	0.002	0.130		0.005
Unknown*	0.090	[illegible]	0.176	0.446	0.025	0.194	[illegible]	0.407		[illegible]
TOTAL - Non-Engine-Caused	1.392	[illegible]	[illegible]	4.041	0.539	2.486	1.975	2.753	0.906	0.153
TOTAL - All Cause *	1.920	2.934	4.515	6.253	1.137	3.136	2.809	3.712	1.510	0.270

*Unknowns prorated proportionally to engine-caused and non-engine-caused UER's.

MAJOR ACCIDENT RATE

Major accidents are defined as those engine-related accidents classified as major in accordance with AR385-40 for the U.S. Army, or OPNAVINSTR 3750.6H for the U.S. Navy. These events involve loss of life or aircraft damage above a specified man-hour value for each particular aircraft. They specifically exclude events due to combat. The parameter has been expressed in engine operating hours rather than aircraft operating hours. Accordingly, for multiengined aircraft, the aircraft accident rate is obtained by multiplying the per-engine operating hour rate by the number of installed engines.

Very comprehensive data has been collected by each of the U.S. military services on aircraft accidents. Since this parameter measures a completely unplanned event with 100 percent data reporting, it represents a precise quantification of the most serious consequence of R&M problems. Major accidents involve high costs or loss of life. Their acute psychological impact often provides the motivation for immediate engineering changes where the same failure modes manifested in the other reliability parameters would not provide sufficient motivation. Since engines contributed to over 50 percent of Army and Navy material-caused major accidents, any study of engine R&M should examine this parameter intensively. The accident rate parameter, like the unscheduled engine removal rate parameter, is driven by factors over and above that of engine reliability alone. These factors include aircraft configuration, type of mission, environment, pilot skills, and aircraft and engine hardware characteristics.

The configuration issue is one primarily of the number of engines. The type of mission involves both its aerodynamic requirements in terms of altitude and speed and its physical characteristics such as internal versus external load, nature of the landing sites, etc. The environmental effects include those of adverse weather, local terrain in which either no or inadequate emergency landing sites may be available, contaminated fuel and oil, FOD, etc.

The skill level of the flight crew can have a signficant impact on the outcome of an in-flight emergency, particularly when a power-loss-caused forced landing is concerned.

The final factor of aircraft and engine hardware characteristics addresses both the failure progression and containment characteristics of the engine as well as the propensity of the aircraft itself to an accident, given an emergency situation. The amount of single engine power available on twin engine aircraft can also affect the accident rates.

Of all these factors, engine reliability, number of engines, power available and type of mission appear to be most influential in the engine-related accident rate. Figure 11 demonstrates the relationship between the total UER rate and the corresponding accident rate for a variety of Army and Navy aircraft. The effects of the two largest factors in determining accident rates, engine reliability and number of engines installed, are obvious in this figure. The scatter of points within the single or twin engine family however, suggests that other variables such as available power and mission requirements are also important.

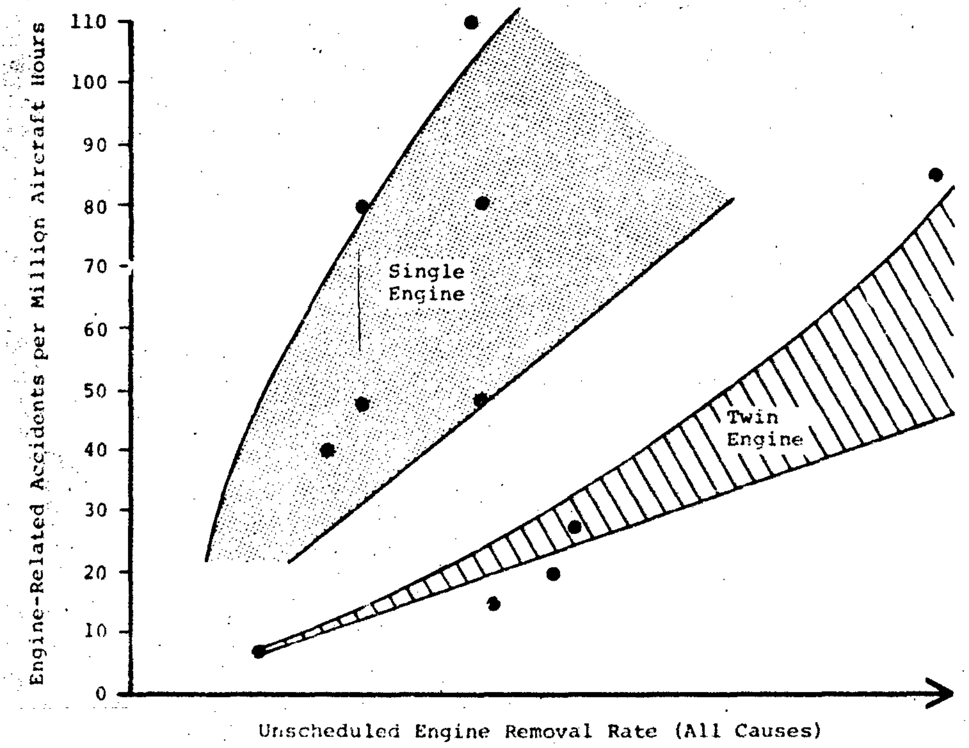


Figure 11. Factors Affecting Major Accident Rates.

Engine-related accident rates for a variety of helicopters are listed at the subsystem level in Table VI. Only data bases that consisted of 6 or more accidents were included for realistic subsystem distributions. The absolute rates are displayed in bar graph form in Figure 12 and the percentage rates in Figure 13.

TABLE VI. ENGINE-RELATED MAJOR ACCIDENT RATES*

Subsystem	Single-Engine Helicopter I	II	III	Average Rate	Average Percent	Twin-Engine Helicopter I	II	III	IV	Average Rate	Average Percent
Bearings	4.4	2.0	15.0	7.1	10.6	0	0	0	6.9	1.7	9.0
Seals	0.2	0.5	0.8	0.5	0.7	0	0	1.2	0	0.3	1.6
Compressor	4.4	16.1	7.5	9.3	13.9	1.1	0	1.2	0	0.6	3.2
Combustion	0	0	0	0	0	0	0	0	0	0	0
Turbine	6.3	1.3	3.4	3.7	5.5	0.6	4.4	0	0	1.3	6.9
Cases	0	0	0.8	0.3	0.5	0	0	0	0	0	0
Lubrication	0	0.2	3.4	1.2	1.8	0	0	0	0	0	0
Fuel	1.0	0.7	29.3	9.8	14.6	1.1	0	1.2	0	0.6	3.2
Air	0	0	0	0	0	0	0	0	0	0	0
Accessory	0	0.2	0	0.1	0.1	0	4.4	0	0	1.1	5.8
Torquemeter	0	0	0	0	0	0.6	-	-	-	0.6	3.2
Electrical	0.2	0	0	0.1	0.1	0	0	0	0	0	0
Exhaust	0	0	0	0	0	0	0	0	0	0	0
Power-Train Reduction	0.2	0	0.8	0.3	0.5	-	-	-	-	-	-
Foreign Object Damage	5.3	5.5	5.0	5.3	7.9	0	4.4	1.2	0	1.4	7.4
Erosion	1.7	0.5	0.8	1.0	1.5	0	8.7	0	0	2.2	11.6
Operator Induced	2.7	2.4	0.8	2.0	3.0	1.1	0	0	0	0.3	1.6
Improper Maintenance	2.9	3.6	0	2.2	3.3	1.1	0	1.2	3.4	1.4	7.4
Airframe Related	0.7	1.4	0	0.7	1.0	0	0	0	0	0	0
Unknown	16.6	13.6	40.2	23.5	35.0	3.5	21.6	1.2	3.4	7.4	39.2
TOTAL	46.6	48.0	108.0	67.1	100.0	9.1	43.5	7.2	13.7	18.9	100.0

*Major accidents per 1,000,000 engine hours

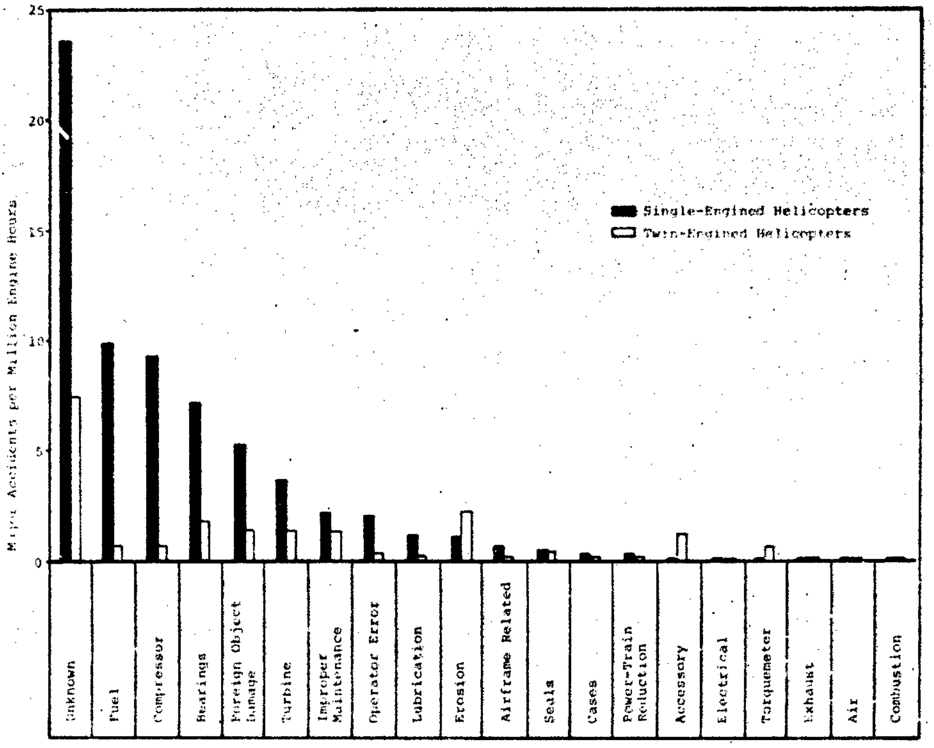


Figure 12. Composite Engine Major Accident Rates by Subsystem.

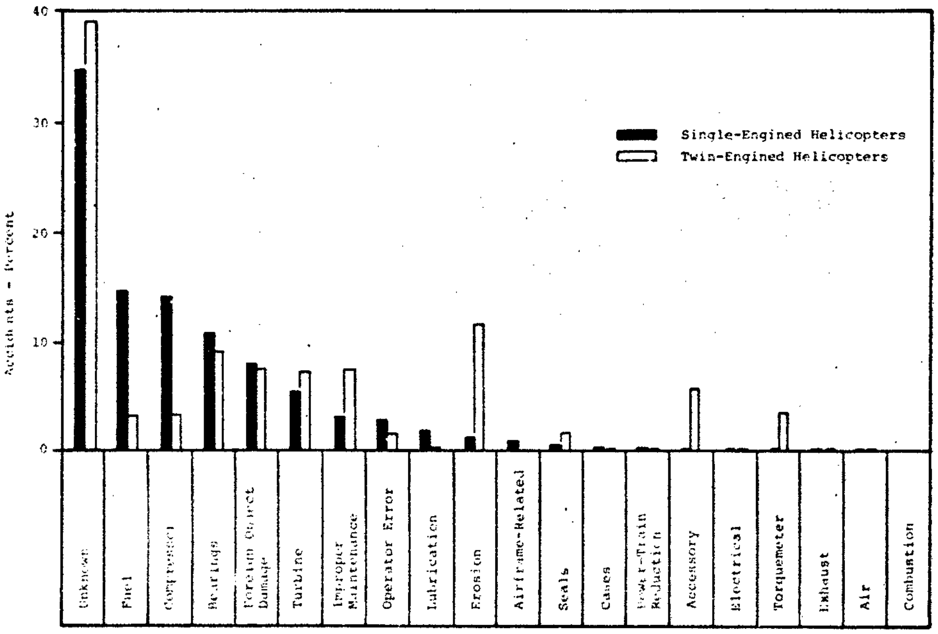


Figure 13. Composite Engine Major Accident Percentage Distribution by Subsystem.

MAINTENANCE MAN-HOUR PER FLIGHT HOUR

This parameter expresses the maintenance man-hour per flight hour expenditure in performing three major tasks involving engines:

- Engine removal from the airframe and replacement
- Engine repairs and adjustments with the engine installed in the airframe
- Engine hot-end inspections

The levels of maintenance included are the Organizational and Direct Support levels in the U.S. Army and Organizational and partial Intermediate levels in the U.S. Navy.

The only significant man-hour expenditures which are not included are those expended at the Intermediate or Direct Support levels on the repair of detailed components or subassemblies on an engine, and the man-hours expended at the overhaul depot. Omission of these man-hours is not significant, since their equivalent costs have been used to quantify the impact of the UER rate parameter.

The apparent value of this parameter lies in its familiarity rather than the significance of its actual cost impact. The Navy and Air Force routinely collect man-hour data through their 3M and 66-1 systems. Many individuals have become accustomed to the use of this parameter as a means of expressing both reliability and maintainability.

One of the prime difficulties with this parameter is the lack of accurate and comprehensive man-hour data in U.S. Army operations. In this study, two data bases for Army operations were analyzed. Both of these were from limited sampling prorams conducted outside the normal Army reporting system, but funded by the Army.

Another factor tending to degrade the significance of this parameter is the real-world requirement that manpower be available to meet peak demands of maintenance. The implied maintenance man-hours that can be eliminated through improved R&M on any specific problem may be merely artificial savings, since the only real savings are those achieved through direct reduction of TOE maintenance personnel.

Man-hours per flight hour for three helicopter engines are presented in Table VII at the subsystem level expressed as man-hours per 1000 engine hours. The assumption was made that the turbine and combustor systems share the manpower requirement equally for scheduled hot-end inspections.

TABLE VII. MAINTENANCE MAN-HOUR RATES*

	T53-L13/A/B			T55-L7/B/C			T64		
System	Unscheduled Removals/ Failures	Scheduled Hot Ends	Total	Unscheduled Removals/ Failures	Scheduled Hot Ends	Total	Organizational Only	Scheduled Hot Ends	Total
Bearings	2.5		2.5	4.5		4.5	3.5		3.5
Seals	5.8		5.8	6.9		6.9	1.5		1.5
Compressor	1.3		1.3	6.3		6.3	7.0		7.0
Combustion	-	18.5	18.5	0.8	19.0	19.8	1.5	19.0	20.5
Turbine	1.7	18.5	20.2	0.5	19.0	19.5	1.0	19.0	20.0
Cases	-		-	-		-	-		-
Lubrication	0.5		0.5	3.2		3.2	2.5		2.5
Fuel	2.2		2.2	4.8		4.8	22.5		22.5
Air	0.1		0.1	-		-	0.5		0.5
Accessories	0.7		0.7	2.3		2.3	4.0		4.0
Torquemeter	-		-	2.0		2.0	-		-
Electrical	0.2		0.2	0.4		0.4	11.0		11.0
Exhaust	-		-	-		-	2.0		2.0
Power-Train Reduction	-		-	-		-	-		-
Miscellaneous	6.1		6.1	9.2		9.2	-		-
Unknown	0.5		0.5	4.3		4.3	10.0		10.0
Foreign Object Damage	9.5		9.5	10.6		10.6	8.5		8.5
Erosion/ Cleaning	0.9		0.9	4.3		4.3	2.0		2.0
Environment	-		-	-		-	-		-
Improper Operation	2.2		2.2	1.1		1.1	1.5		1.5
Improper Maintenance	4.9		4.9	8.3		8.3	9.5		9.5
Airframe Related	2.2		2.2	1.9		1.9	3.0		3.0
Convenience	5.4		5.4	15.0		15.0	8.0		8.0
			85.0			131.0			138.0

*MMH per 1000 hours: unscheduled maintenance and hot-end inspections only

TIME BETWEEN OVERHAULS (TBO)

A TBO is an operating time interval at which an engine is removed on schedule and returned to depot for replacement and/or overhaul of one or more of its components. A combination of hardware and administrative factors determines TBO intervals on engines. From the hardware aspect, a TBO is established to minimize the appearance of some new failure mode or the prevention of a frequency increase in an already evident failure mode. The failure modes that are of concern are usually catastrophic failures or failures which cause substantial internal damage. TBO's for engines at an early point in their life cycle reflect concern for the unknown. TBO's at the 1-million-hour maturity point can be related to specific component areas. Components or failure modes that established a hot-end-inspection inverval were appropriately penalized in the previous parameter of maintenance man-hours where the impact of hot-end inspections was quantified. Thus, only subsystems which required the actual overhaul of the engine or component replacement/repair were considered in the TBO parameter. Most engines analyzed in this study had TBO limitations that could be traced to one or more components or failure modes.

The administrative sources for TBO levels involve a variety of reasons which may be unrelated to the actual reliability experience of the hardware. These include a desire to cycle engines back to an overhaul facility for configuration or model upgrading or a desire to maintain a steady workload in overhaul/repair facilities. An indication of how great these administrative influences can be is displayed in Figure 14 where the TBO levels for a variety of commercial and military engines are plotted against cumulative engine flight time. It is readily apparent that commercial operators assign TBO levels that are three times the TBO levels assigned for the same engine in military service.

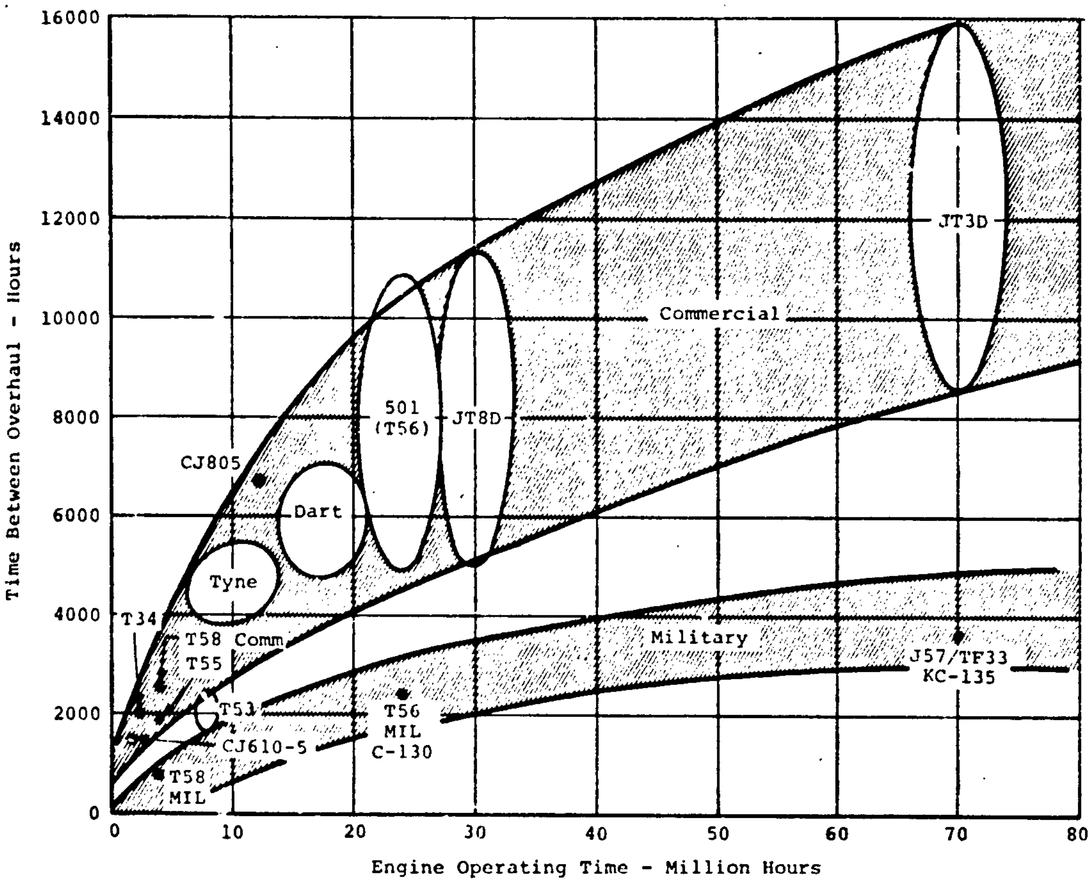


Figure 14. TBO Progression.

The TBO's of helicopter turboshaft engines have been identified on Table VIII. The TBO level chosen to represent each model is considered to be the value of the largest portion of the fleet at the 1-million-hour point. Newer models may incorporate design changes which allow higher TBO's. The TBO for a given model is increased as confidence is established. Thus, the TBO levels shown are not to be rigorously identified to each specific model or family, since they are subject to continuous update. The major subsystems that limited these TBO levels are indicated on Table VIII.

TABLE VIII. SUBSYSTEMS THAT LIMIT TBO INTERVALS

	Engines					
	T53-11	T53-13	T55	T58	T63	T64
TBO →	1200	600	1200	800	750	800
Bearing						X
Compressor	X	X		X	X	X
Turbine			X		X	

This table indicates that generally only one subsystem (usually only one mode within that subsystem) defines the TBO interval on each engine. In the following paragraphs the concept of a composite engine will be introduced. It represents the average of the study engines with a TBO of 800 hours and the assigned contributions of the subsystems as bearings 12 percent, compressor 63 percent, and turbine 25 percent.

THE COMPOSITE ENGINE

Having quantified the R&M characteristics of the individual engines in this study by utilizing the four selected parameters, the concept of a composite engine is now introduced. Fundamentally, the composite engine is simply an average of the numerical rates experienced on individual engines analyzed in this study and shown in Tables V, VI, VII, and VIII. As such, it has finite values of unscheduled removal rate, major accident rate, maintenance man-hour rate and TBO level. These values are shown on Table IX.

TABLE IX. THE COMPOSITE ENGINE

	Subsystem	UER Rate ($\times 10^{-3}$)	Accident Rate ($\times 10^{-6}$)	MMH Rate ($\times 10^{-3}$)	TBO* (800 Hr)
Engine Caused	Bearings	0.107	4.0	3.5	12%(0.02)
	Seals	0.205	0.4	4.7	
	Compressor	0.072	4.3	4.9	63%(0.13)
	Combustion	0.040	0	19.6	
	Turbine	0.058	2.3	19.9	25%(0.05)
	Cases	0.054	0.1	1.5	
	Lubrication	0.034	0.5	2.1	
	Fuel	0.085	4.8	9.8	
	Air	0.010	0	0.2	
	Accessories	0.025	0.7	2.3	
	Torquemeter	0.048	0.2	0.7	
	Electrical	0.014	0.1	3.9	
	Exhaust	0.004	0	0.7	
	Power-Train Reduction	0.013	0.3	0.4	
	SUBTOTAL	0.759	17.7	74.2	100%(0.20)
Non-Engine-Caused	Foreign Object Damage	0.368	3.1	9.5	
	Erosion	0.140	1.7	2.4	
	Environmental	0.059	0	-	
	Operator Error	0.122	1.0	1.6	
	Improper Maintenance	0.305	1.7	7.6	
	Airframe Related	0.148	0.3	2.4	
	Convenience	0.495	0	9.5	
	Unknown	0.356	14.3	8.5	
	TOTAL	2.782	39.8	115.7	

*TBO interval of 800 hours is converted into removal rates and allocated to subsystems in Appendix I.

The composite engine should be viewed not as a specific engine configuration but as an overview of the total R&M problem of Army/Navy turboshaft engines. It allows consideration of the problems from all engines on a weighted basis, without undue influence by a single engine or manufacturer, and without the proprietary restraints associated with consideration of specific failure modes on individual engines.

Integration of Parameters - Index Numbers

The composite engine combined the R&M experience of individual engines. This produced occurrence rates in each of four R&M parameters for each subsystem of the engine. To further simplify the determination of the priority of subsystems and failure modes, the four R&M parameters are integrated into a single expression. This expression, termed the index number, is on a dimensionless scale of 0 to 10 where 10 is the most severe problem.

The complete rationale and numerical development of index numbers is provided in Appendix II. Briefly, index numbers are constructed by converting numerical rates for each subsystem in each parameter to a 0 to 10 value, called a scale factor. These scale factors are then combined into the index number through the application of weighting multipliers. These weighting multipliers reflect the relative impact and frequencies of events between the various parameters.

As an example of the procedure, it was determined that a single accident is 25 times more costly than an unscheduled removal of a composite engine; however, the removal frequency is 75 times greater than the accident frequency. The resulting relative significance of UER scale factors to accident scale factors is 3. Similar steps were used to relate the other parameters.

Subsystem Quantification

Index numbers were established for each subsystem as shown in Table X. Although the composite engine integration and the index number quantification process were both performed at the subsystem level, they reflect the combined impact of the numerous individual failure modes encountered. Table XI shows the contribution of each failure mode against the subsystem index numbers.

TABLE X. COMPOSITE ENGINE SUBSYSTEM INDEX NUMBERS

		Unscheduled Removal Rate	Accident Rate	Maintenance Man-Hour Rate	TBO		
	Subsystem	Weighting Multiplier 100	Weighting Multiplier 33	Weighting Multiplier 1	Weighting Multiplier 50	Index Number	Percent of Total
Engine Caused	Bearings	3	9	2	2	3.80	6.33
	Seals	6	1	3	0	3.46	5.76
	Compressor	2	9	3	7	4.63	7.71
	Combustion	2	0	10	0	1.14	1.90
	Turbine	2	5	10	3	2.86	4.76
	Cases	2	1	1	0	1.27	2.12
	Lubrication	2	1	2	0	1.28	2.13
	Fuel	3	10	5	0	3.45	5.75
	Air	1	0	1	0	0.55	0.92
	Accessories	1	2	2	0	0.91	1.50
	Torquemeter	2	1	1	0	1.27	2.12
	Electrical	1	1	2	0	0.73	1.22
	Exhaust	1	0	1	0	0.55	0.92
	Power-Train Reduction	1	1	1	0	0.72	1.20
	SUBTOTAL	-	-	-	-	26.62	44.34
Non-Engine-Caused	Foreign Object Damage	10	7	5	0	6.71	11.19
	Erosion	4	4	2	0	2.90	4.83
	Environmental	2	0	0	0	1.09	1.82
	Operator Error	4	2	1	0	2.54	4.23
	Improper Maintenance	8	4	4	0	5.09	8.47
	Airframe Related	4	1	2	0	2.36	3.93
	Convenience	10	0	5	0	5.46	9.09
	Unknown						12.10
	TOTAL					60.03	100.00

Table XI also shows the UER rate for these same elements. Inclusion of these values was not intended to dilute the worth of the index number, but simply to provide a frame of reference to a parameter whose dimensions are universally understood. Tables XII and XIII present the top 20 failure modes, expressed in terms of index numbers and UER rate, respectively.

TABLE XI. COMPOSITE ENGINE SUMMARY MATRIX

Subsystem/Failure Mode	Index Number			Unscheduled Removals		
	Value	Subsystem Percent	All Causes Percent	Rate	Subsystem Percent	All Causes Percent
Bearings	3.80		6.33	0.107		3.85
Spalling - Classical (B-10)	0.42	11	0.70	0.006	6	0.22
Spalling - Nonclassical	1.86	49	3.10	0.033	31	1.18
Race Rotation/Displacement	0.61	16	1.02	0.032	30	1.15
Cage Wear/Cracking	0.50	13	0.83	0.018	17	0.65
Roller Skidding	0.30	8	0.50	0.013	12	0.47
Miscellaneous	0.11	3	0.18	0.005	5	0.18
Seals	3.46		5.76	0.205		7.37
Carbon-Seal Leakage	3.28	95	5.46	0.189	93	6.84
Labyrinth Seals	0.07	2	0.12	0.004	2	0.14
Static Seals and O Rings	0.08	2	0.13	0.009	4	0.32
Miscellaneous	0.03	1	0.05	0.002	1	0.07
Compressor	4.63		7.71	0.072		2.59
Vane Failures - Erosion, Corrosion	[illegible]	24	1.85	0.028	38	[illegible]
Blade/Disc Fatigue Failure	2.40	52	4.00	0.006	8	0.22
Diffuser Cracking	0.28	6	0.47	0.022	30	0.79
Compressor Lining Wear	0.04	1	0.07	0.004	6	0.14
Variable Stator and Bleed	0.09	2	0.15	0.006	9	0.22
Miscellaneous	0.70	15	1.17	0.006	9	0.22
Combustion	1.14		1.90	0.040		1.44
Liner Cracking/Warping	0.19	17	0.32	0.007	17	0.25
Support Structure Cracking	0.19	17	0.32	0.007	17	0.25
Housing and Fitting Corrosion, etc.	0.58	50	0.96	0.020	50	0.72
Swirl Cup Wear/Cracking	0.17	15	0.28	0.006	15	0.22
Miscellaneous	0.01	1	0.02	-	1	
Turbine	2.86		4.76	0.058		2.08
Nozzle and Band Cracking	0.57	20	0.96	0.016	27	0.58
Nozzle Sulfidation/Burning	0.17	6	0.28	0.005	8	0.18
Support Structure and Fittings	0.54	19	0.90	0.025	44	0.88
Blade and Wheel Cracks	1.17	41	1.96	0.001	2	0.04
Shaft and Couplings	0.23	8	0.38	0.003	6	0.11
Miscellaneous	0.17	6	0.28	0.008	14	0.29
Cases	1.27		2.12	0.054		1.94
Corrosion	0.27	21	0.45	0.012	23	0.43
Secondary Structural Cracks	0.45	35	0.75	0.017	31	0.62
Bosses, Fittings, etc.	0.47	37	0.79	0.021	39	0.75
Miscellaneous	0.08	[illegible]	0.13	0.004	7	0.14
Lubrication	[illegible]		[illegible]	0.034		1.22
Pump Failures	[illegible]	[illegible]	[illegible]	0.017	49	0.61
Filters, Coolers, etc.	0.26	[illegible]	[illegible]	0.004	13	0.14
Tubes and Fittings	0.22	[illegible]	[illegible]	0.007	21	0.25
System Problems and Miscellaneous Hardware	0.20	16	0.33	0.006	17	0.22
Fuel	[illegible]		[illegible]	[illegible]		[illegible]
Fuel Control Units	2.58	75	[illegible]	[illegible]	68	[illegible]
Pumps, Valves, etc.	0.52	15	0.87	0.020	24	0.72
Tubes, Lines and Fittings	0.18	5	[illegible]	0.002	2	[illegible]
Miscellaneous	0.17	[illegible]	0.29	0.005	6	0.18
Air	[illegible]		0.42	[illegible]		[illegible]
Control Valve Binding, Leak	[illegible]	70	[illegible]	0.007	70	0.25
Tubes, Fittings, and Miscellaneous Hardware	0.17	30	0.25	0.003	30	0.11
Accessory	0.97		1.50	0.025		0.90
[illegible]	[illegible]		2.12	0.048		1.72
High-Speed System	[illegible]	95	2.02	0.046		1.65
Low-Speed Systems	0.06	5	0.10	0.002		0.07
Electrical	[illegible]		1.22	0.014		[illegible]
Ignition System Components	0.26	15	0.43	0.005	35	[illegible]
Power Management Systems	[illegible]	22	0.27	0.003	22	0.10
Wiring and Thermocouples	0.31	43	0.52	0.006	43	0.22
Exhaust	[illegible]		[illegible]	0.004		0.14
Power-Train Reduction	0.72		1.20	0.013		0.47
[illegible] Air Separation	-		-	-		-
[illegible]	-		-	-		-
TOTAL - [illegible]	[illegible]		44.34	[illegible]		[illegible]
Foreign Object Damage	[illegible]		[illegible]	[illegible]		[illegible]
Erosion	2.90		4.83	0.140		5.03
Environmental	1.09		[illegible]	[illegible]		2.12
Operator Induced	2.54		[illegible]	0.122		[illegible]
Improper Maintenance	[illegible]		[illegible]	[illegible]		[illegible]
Airframe Related	2.36		3.93	[illegible]		[illegible]
Convenience	5.46		9.09	0.495		17.79
TOTAL - Non-Engine Caused	[illegible]		43.56	1.657		59.56
Unknown	[illegible]		[illegible]	[illegible]		[illegible]
TOTAL - All Causes	[illegible]		100.0	2.782		

TABLE XII. COMPOSITE ENGINE - PROBLEM AREAS IN ORDER OF PRIORITY (INDEX NUMBERS)

Priority	Subsystem/Failure Mode	Index Number	All Causes, Percent	Cumulative Percent
1	Foreign Object Damage	6.71	11.19	11.19
2	Improper Maintenance	5.09	8.47	19.66
3	Carbon-Seal Leakage	3.28	5.46	25.12
4	Erosion	2.90	4.83	29.95
5	Fuel - Fuel Control Unit	2.58	4.30	34.25
6	Operator Induced	2.54	4.23	38.48
7	Compressor - Blade/Disc Fatigue	2.40	4.00	42.48
8	Airframe Related	2.36	3.93	46.41
9	Bearings - Nonclassical Spalling	1.86	3.10	49.51
10	Torquemeter - High-Speed Systems	1.21	2.02	51.53
11	Turbine - Blade and Wheel Cracks	1.17	1.96	53.49
12	Compressor - Vane Failures (Erosion, Corrosion)	1.11	1.85	55.34
13	Environmental	1.09	1.82	57.16
14	Accessory - All	0.91	1.50	58.66
15	Power-Train Reduction	0.72	1.20	59.86
16	Compressor - Miscellaneous	0.70	1.17	61.03
17	Bearings - Race Rotation Displacement	0.61	1.02	62.05
18	Lubrication - Pump Failures	0.60	1.00	63.05
19	Turbine - Nozzle and Band Cracking	0.58	0.96	64.01
20	Combustion - Housing and Fitting Corrosion	0.57	0.96	64.97
21	Exhaust - All	0.55	0.92	65.89
22	Turbine - Support Structure and Fittings	0.54	0.90	66.79
23	Fuel - Pumps, Valves, etc.	0.52	0.87	67.66
24	Bearings - Cage Wear/Cracking	0.50	0.83	68.49
25	Cases - Bosses and Fittings	0.47	0.79	69.28
26	Cases - Secondary Structural Cracks	0.45	0.75	70.03
27	Bearings - Classical (B_{10}) Spalling	0.42	0.70	70.73
28	Air - Control Valve Binding/Leaking	0.38	0.64	71.37
29	Convenience	5.46	9.09	80.46
30	Unknown	7.26	12.10	92.56

TABLE XIII. COMPOSITE ENGINE - PROBLEM AREAS IN ORDER OF PRIORITY (UER'S)

Priority	Subsystem/Failure Mode	Unscheduled Removal Rate	All Causes, Percent	Cumulative Percent
1	Foreign Object Damage	0.388	13.95	13.95
2	Improper Maintenance	0.305	10.96	24.91
3	Carbon-Seal Leakage	0.189	6.84	31.75
4	Airframe-Related	0.148	5.32	37.07
5	Erosion	0.140	5.03	42.10
6	Operator Induced	0.122	4.39	46.49
7	Environmental	0.059	2.12	48.61
8	Fuel Control Units	0.058	2.08	50.69
9	Torquemeter - High Speed Systems	0.046	1.65	52.34
10	Bearings - Spalling (Non-classical)	0.033	1.18	53.52
11	Bearings - Race Rotation/Displacement	0.032	1.15	54.67
12	Compressor - Vane Failures (Erosion/Corrosion)	0.028	1.00	55.67
13	Accessory - All	0.02[illegible]	0.9[illegible]	56.[illegible]7
14	Turbine - Support Structure and Fittings	0.025	0.86	57.45
15	Compressor - Diffuser Cracking	0.022	0.79	58.24
16	Cases - Bosses and Fittings	0.022	0.75	58.99
17	Combustion - Housing and Fitting Corrosion	0.020	0.72	59.71
18	Fuel - Pumps, Valves, etc.	0.020	0.72	60.43
19	Bearings - Cage Wear/Cracking	0.018	0.65	61.08
20	Cases - Secondary Structural Cracks	0.017	0.62	61.70
21	Lubrication - Pump Failures	0.017	0.61	62.31
22	Turbine - Nozzle and Band Cracking	0.016	0.58	62.89
23	Bearings - Roller Skidding	0.013	0.47	63.36
24	Power-Train Reduction - All	0.013	0.47	63.83
25	Cases - Corrosion	0.012	0.41	64.26
26	Seals - Static Seals/O Rings	0.009	0.32	64.58
27	Turbine - Miscellaneous	0.008	0.29	64.87
28	Combustion - Liner Cracking/Warping	0.007	0.25	65.12
29	Convenience	0.49[illegible]	17.79	82.91
30	Unknown	0.[illegible]6	12.80	95.71

SUMMARY OF CURRENT-ENGINE STATUS

With engine R&M problems defined and quantified, several intermediate conclusions are apparent. These range from general reliability growth issues to limitations of data reporting and from the evaluation of individual R&M parameters to the specific hardware failure modes. Issues of both a philosophical and design nature have emerged:

- Over 30 percent of engine removals were for unknown and convenience reasons. While these represent the two largest single contributors to the total rate, they have not been included in the priority tables, since they have no unique failure modes or causes. Unknowns are largely represented by data collection problems, and convenience removals are driven by various administrative, logistic, and local conditions. The magnitude of unknown and convenience removals indicates that improvements in logistics systems and data reporting is as appropriate as hardware type improvements.

- Excluding the convenience and unknown categories, the following 10 major problem areas for current turboshaft engines represent 52 percent of the problem:

  - Foreign Object Damage
  - Improper Maintenance
  - Carbon-Seal Leakage
  - Erosion
  - Fuel Control Unit
  - Operator Induced
  - Compressor Blade/Disc Fatigue
  - Airframe Related
  - Mainshaft Bearing Spalling (Nonclassical)
  - High-Speed Torquemeter Systems

- Identified engine-caused removals have been responsible for only 28 percent of the total unscheduled removals. The total removal rate appears to be a function of the engine-caused rate. A higher engine-caused rate appears to cause a significantly higher total rate.

- The engine problems which contribute most heavily to aircraft accidents are generally not the same as those that cause high unscheduled removal rates. A significant exception is FOD, which contributes heavily to both.

- Failure modes which define TBO intervals are generally the same as those which cause major accidents.

- The military philosophy concerning the establishment of TBO intervals requires intensive examination in view of the commercial operators' experience with higher TBO levels on the same hardware.

- Engines experience similar reliability growth trends primarily due to aggressive product improvement programs.

- Turbojet, turbofan, and turboprop engines installed in fixed-wing aircraft have demonstrated higher reliability than turboshaft engines installed in helicopters. While there is insufficient direct evidence available to conclusively prove the point, it appears that the application rather than the configuration (jet/fan/shaft) has the greater impact on reliability. The more adverse engine-operating/mission environment of the helicopter may explain much of the difference.

- The technology to achieve higher reliability is currently available. An engine comprised of the most reliable subsystems seen on individual engines would have at least a 50 percent reduction in unscheduled removals from that encountered with current turboshaft engines.

4.0 DETAILED PROBLEMS OF CURRENT ENGINES

This section provides an in-depth analysis of failure modes and rates at the component level for each subsystem of the study engines. The impact of each failure mode, expressed quantitatively, forms much of the basis for identification of required design and program improvements. The presentation format for each subsystem, engine- or non-engine-caused, is similar. The scale factors for the particular subsystem are extracted from Table X and presented as a reminder of the importance of the subsystem in the four R&M parameters and in the overall index number. Discussion of these values follows. A breakdown into the significant failure modes is presented as percentages of each mode that contributes to each R&M parameter. Both of these displays are of the composite engine. A display is shown of how the total subsystem problem and mode distribution, where possible, vary among selected engines in the UER parameter. Usually the display is on the same five engines on which detailed failure mode information was available. The rate of UER for the composite engine is transposed from Table IX and shown on this UER figure as the symbol, *. Discussion of the individual failure modes follows in a magnitude usually proportionate to the size of the problem.

BEARINGS

The bearing subsystem contribution in terms of the four R&M parameters is shown below:

Bearings	UER	Accidents	TBO	MMH	Index
Scale Factor	3	9	2	2	3.80

This chart indicates that bearings are a major contributor to accidents and a significant contributor to unscheduled removals. The high rating for causing accidents is due more to an adequacy of failure detection than to the structural consequences of bearing failure. Most bearing failures generate sufficient debris to cause an in-flight warning which results in a forced or precautionary landing. Historical data shows how many accidents have occurred at the time of the actual landing. Thus, the specific failure progression of the bearing, which normally would be relatively benign, is not the driving factor for the high accident scale factor. It can be concluded that any failure mode which is highly detectable in flight can cause accidents if emergency landing techniques and sites are not adequate. The failure modes for bearings which contribute to the total subsystem values shown above are given in Table XIV.

TABLE XIV. BEARING FAILURE MODES

Failure Mode	UER	Accidents	TBO	MMH	Index
Classical Spalling	6	10	30	6	11
Nonclassical Spalling	31	65	60	31	49
Race Rotation/Displacement	30	7	-	30	16
Cage Wear/Cracking	17	11	10	17	13
Roller Skidding	12	6	-	12	8
Miscellaneous	4	1	-	4	3
Total	100%	100%	100%	100%	100%

This table indicates that the failure modes which generate in-flight-detectable debris (such as spalling and cage break-up) are the greatest contributors to accidents (86 percent). The relative contribution to TBO levels of classical and nonclassical spalling is an approximation. In cases where the TBO has been limited by bearings, it is seldom clear whether it has been due to a calculated B_{10} life (classical spalling) or to actual service problems (nonclassical spalling).

The distribution of these failure modes among selected engines is shown in Figure 15 for the UER rate parameter. This figure indicates that bearing UER rate and the distribution of modes are similar for each engine. Detailed discussions of each bearing failure mode follow.

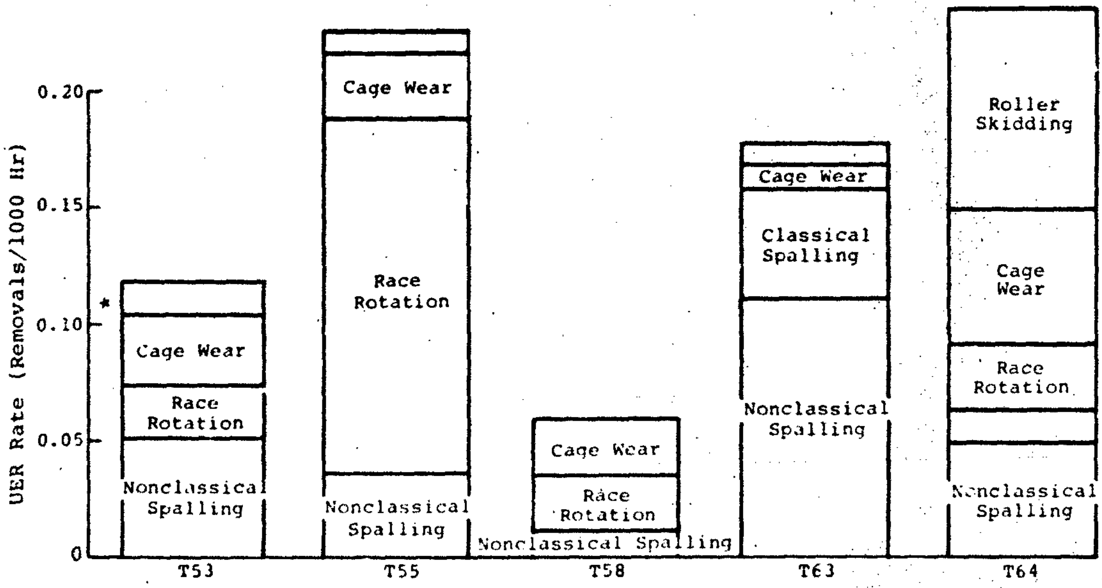


Figure 15. Bearing UER Rate for Various Engines.

Classical Spalling

Classical spalling involves bearing failures of a subsurface fatigue nature which result from the design loads imposed on the bearing. These are termed B_{10} failures and are usually random in their frequency distribution. These failures are predicted during the initial design using standard or modified AFBMA life calculations, with some B_{10} life being considered acceptable. There is concern that these life-calculation methods do not accurately predict service failure frequencies for current bearing materials, since the basic equations were based on and confirmed by tests of 52100 steels. Multiplying factors (sometimes referred to as material factors) are used to increase the life values from AFBMA calculations. These are usually related to the materials and processing characteristics of the bearing. These factors as well as the effects of lubrication, speed, and misalignment have been quantified in a recent comprehensive review of the bearing life calculation technology.[1]

Because the design loads can be closely predicted, actual failures for this mode are low. For the study engines, the contribution of this mode to bearing-caused unscheduled removals was only 6 percent and to bearing index number was only 11 percent. Even these percentages are artificially high, since the only significant failure rate (see Figure 15) was from an application where a limited capacity ball bearing was used to replace a roller bearing to solve a servere skidding problem. Similar observations were made for commercial turbojet and turbofan engines[2] where only 6 percent of all bearing failures are due to pure fatigue. While this classification does not precisely match the classical spalling failure mode, it does suggest that classical spalling is not the prime bearing reliability problem.

Nonclassical Spalling

Nonclassical spalling represents the largest single failure category for bearings. It describes failures involving race or rolling-element spalling whose occurrence was not anticipated. The sources of these problems have been inadequate lubrication, excessive loads, or manufacturing/quality errors.

Inadequate lubrication, which causes approximately 32 percent of the failure rate for this mode, has involved insufficient flow to properly cool the bearing elements, or inadequate filtration which allowed debris scoring damage or debris/carbon blockage of oil jets.

Excessive loads, which caused approximately 52 percent of this mode's failure rate, have originated from three basic sources. First, there have been excessive radial and axial loads that occurred due to unanticipated thermal expansion of bearing support housings. Second, there have been excessive loads from external sources such as shock loads, maintenance procedures (excessive preload), or failures of the piston balancing system (faulty check valves). The third source of excessive loads has been the misalignment of modules and lock up of working splines.

Manufacturing or quality errors caused the remaining 16 percent of the nonclassical spalling failures. Variations in dimensions and improper heat treatment of material have been the primary factors in this category.

The failures that contribute to this mode do not exhibit a precisely similar mechanism of failure. Usually, spalling-type failures are either surface initiated by distress or subsurface initiated by fatigue. The important common characteristic is that the basic causes were unanticipated. Often these causes appear to arise from inadequate interface between the bearing designer and other subsystem design areas. Limitations in the complete understanding of the effects of extreme temperature variations upon bearing support structure, the lubrication and cooling characteristics of the oil system, the source and magnitude of all possible internally or externally induced loads, and the control of the manufacture and assembly of bearing assemblies are all factors which have led to this failure mode.

Detailed discussion of individual problems in individual engines would reveal a wide variety of specific causes. As shown in Figure 15, each engine has a significant rate for this mode. Many individuals in the engine community view failures of this type as developmental in nature, which can be detected and corrected in the developmental test program or early in service experience. There is some merit to this view, since correction of these type problems has usually been highly effective. Since their origin lies in the detailed execution of the design and does not reflect a basic load or sizing issue, incorporation of fixes once the problem has been revealed has not usually required excessive redesign. There is no doubt that the manufacturers' ability to solve problems in this category contributes to the large improvement in engine reliability shown in Figure 10. However, despite this suggested ease of resolution, the magnitude of this problem remains quite high even after 1 million hours of operation. This failure mode is a prime candidate for further action.

Race Rotation or Displacement

Race rotation or displacement involves problems related to the positioning of bearing inner and outer races. Included are failures of retaining keys or pawls and axial displacement of inner or outer races as well as the more familar circumferential movement or rotation of the outer race. This mode has exhibited more benign consequences than the other failure modes in the bearing subsystem, as shown in Table XIV. Outer-race rotation, which represents 80 percent of this mode category,is usually detected by the slow accumulation of fine debris in filters. It does not, therefore, result in an inflight warning.

This category also included a small portion (7 percent) for inner-race displacement. This occurred when a locking tang instead of a locknut was used to retain the inner race of a differential bearing. This introduced a greater susceptibility to maintenance error. The remaining 13 percent of this category involves wear on antirotation keys of positively retained outer races. This occurred on a bearing with oil-film viscous damping which undoubtedly contributed to the problem.

Five of the six bearing locations in the study engines which exhibited problems in this category involved roller bearings. The primary reason for the susceptibility of roller bearings is that ball bearings normally have a more secure means of axial retention since they carry thrust loads. A secondary reason is that radial damping is usually accomplished on roller bearings. When the damping approach is an oil film between the outer race and the housing, additional retention problems are introduced. A third reason for roller bearings having a greater outer-race problem is the high rotation forces generated when an elliptical outer race is used to preclude a roller skidding problem. There does not appear to be a consistent policy of inner- and outer-race retention within the engine community or even within individual companies.

Race rotation represents a large percentage of the failures in the relatively mature (1 million hour) bearing subsystem, and like nonclassical spalling, is even higher during the development and early service phases. The rationale that this is a benign mode which can be quickly identified and for which corrective action can be readily developed should be reexamined in light of this high rate after 1 million hours. Bearing designers should recognize that bearing installation considerations require the same attention as internal bearing loads and configurations.

Positive mechanical retention of bearing outer races has the potential for significant rate reduction if incorporated at initial design. Despite this potential, many contractors are reluctant to incorporate this feature during initial design. Their hesitation stems from the following concerns:

- Bearing outer race spinning problems encountered during development testing or early service experience can be quickly corrected.

- The positive retention devices may themselves introduce problems. Instances of pawl wear or race cracking through the pawl slot have been known to occur. In addition, there is a possibility that additional maintenance problems may occur due to the lack of installation or misinstallation of the pawl or locking device.

- The anticipated value in allowing the outer race to creep around, thereby distributing a steady radial load throughout the outer race circumference and theoretically extending the outer race fatigue life.

- The cost of installing this feature.

- The further complication that arises if viscous damping of rotors is desired. Viscous damping is normally obtained by an oil film between the outer race and the bearing housing. Under these conditions, the method of outer race retention may compromise the success of the damping function.

Considering all of these factors, the concensus appears to be that positive mechanical retention should be incorporated on high-speed main shaft bearings whenever high reliability is desired. The specific methods for positive retention are as numerous as are their applications. An extreme is the approach of bolting through an integral flange of the outer race. This approach is used by several manufacturers for small bearings in the AGB section and has been used for all main shaft ball and roller bearings by one manufacturer. Other means such as pawls, keys, pins, etc., are more widely used and usually appear to be an effective means of preventing race rotation problems. No specific design approach can be recommended without further research to identify the cost and reliability characteristics of each method.

Cage Wear and/or Breakup

This mode has a consistent rate in the study engines as shown in Figure 15. Like nonclassical spalling, the causes of cage failure do not appear to be well understood by the engine designers. The same unusual loads, thermal variations, or inadequate lubrication create cage wear and fatigue cracking. Wear is generally at the interface with the ball or roller. Occasionally, cage-to-race wear is seen. Since the sources of cage problems are factors such as misalignment, spline locking, and maintenance damage, the issue is basically one of application and installation which routine life calculations do not address.

Most cages for main-shaft bearings have been one-piece machined designs. A few have been two-piece riveted designs. Stamped and riveted cages are inexpensive and allow a full ball complement without splitting the inner or outer race. These designs have presented problems involving rivets breaking, and consequently they are seeing less frequent use. The design of reliable cages appears to be an art rather than a science. A trade-off is involved between wear characteristics and strenght. S-Monel (nickel-copper), silicon bronze, and basic steels are all prevalent materials. Silver plating has been added to many cages with excellent results.

Roller Skidding

Data show that roller skidding is a problem encountered early in the development cycle of most engines, but one which is usually corrected by the time a significant number of field hours is accrued. Figure 15 shows that the T64 still has a significant roller skidding problem, but it had considerably less than 1 million hours accrued at the time of data analysis. Roller skidding is a phenomenon associated with lightly loaded roller bearings at any DN value above 1.0×10^6. Under low radial load conditions, the rollers may not maintain sufficient tractive contact with the driving race (usually the inner race), and cage slip and roller skidding can occur. The mechanism of this failure mode, the factors affecting the amount of slip, and the degree of race or roller damage are discussed in detail in Reference 3.

Elliptical or out-of-round outer races have been a familiar solution to roller-bearing skidding problems. By deforming the outer race roller, control is maintained continuously and cage slip reduced or eliminated. Much research has been directed at the problem of roller skidding because the device of elliptical outer race bearings is not considered an optimum solution. The disadvantages of elliptical outer races are a higher cost of procurement, a theoretically reduced fatigue life, and installation problems, since the bearing should be installed in a specified radial position.

The research to find a more suitable solution has taken two directions. The first investigates new or different bearing configurations, including engine designs which avoid the use of roller bearings completely through the use of axially, spring-mounted ball bearings. Other investigations have been directed at new roller bearing internal configurations, cited in Reference 4, which studies the concept of a few circumferentially spaced, preloaded, annular rollers whose preload would always drive the cage. The referenced study suggests that this approach would result in serious fatigue life compromises. More promise is likely in the other direction of current research. This involves an analytical understanding of the mechanism of roller skidding with the resultant ability to control elements such as internal clearances, cage balance, external radial loads, oil film thickness and other factors which are found to be important.

The analysis results in models which are designed to indicate the amount of cage slip that results from a given set of input data. In some cases the models produce the oil film thickness at the roller contact. This film thickness can then be evaluated in terms of adequacy. Because of obvious measurement problems, little correlation has been established between the results of these models and empirical data. Models to calculate cage slip appear to be quite accurate. In References 3 and 5, analytical data is compared to test data with a high degree of correlation indicated. Less clear is the amount of slip or oil film thickness that may be a borderline condition. The value of 10 percent cage slip is suggested in Reference 3 as the limit value, although there are many instances of bearings operating successfully with up to 30 to 40 percent slip. Conversely, bearings with as little as 6 percent have had serious skidding damage. The real issue is, of course, that there is a distinction between skidding and skidding damage. Relationships between the amount of slip and actual failure causing skidding damage are most likely related primarily to the amount, type, and particle size of the debris entrapped in the bearing or circulating in the lubrication system. This latter point will continue to be examined in future research with documentation and dissemination of test results and analytical studies, allowing a wider acceptance of design limitations.

SEALS

The contribution of seals to the engine R&M problem in terms of the four parameters is:

Seals	UER	Accidents	MMH	TBO	Index
Scale Factors	6	1	3	0	3.46

The chart indicates that seals are high contributors to unscheduled removals but cause few accidents and do not limit TBO intervals. Seal leakage is usually detected during ground operations or inspections and thus does not cause precautionary or forced landings (with the attendant potential for accidents upon landing). In-flight seal leakage rarely depletes the entire oil supply. The failure modes of seals which contribute to the total subsystem values are shown in Table XV.

As can be seen, the problem is basically one of main-shaft oil-sump carbon-seal leakage, regardless of the parameter

TABLE XV. SEAL FAILURE MODES

Failure Mode	UER	Accidents	MMH	TBO	Index
Positive-Contact (Carbon) Seal Leakage	93	100	90	-	95
Labyrinth-Seal Abradable Surface Wear	3	-	2	-	2
Static Seals (O Rings and Gaskets)	3	-	5	-	2
Miscellaneous (other rotating seals)	1	-	3	-	1
Total	100%	100%	100%	0	100%

examined. The labyrinth-seal leakage rate reflects both oil sump (oil-to-air) and interstage (air-to-air) seal applications. Static seals contribute a slightly higher percentage in the man-hour parameter due to many repairs/replacements of static seals without removal of the engine from the airframe. Because the man-hour parameter is so weak (after weighting), the higher percentage does not affect the index number percentage. The distribution of these failure modes among selected engines is shown on Figure 16 for the UER rate parameter.

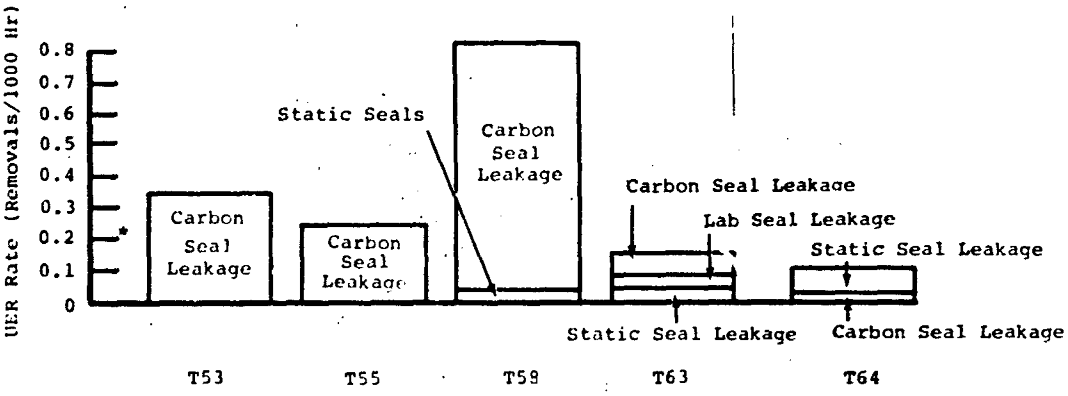
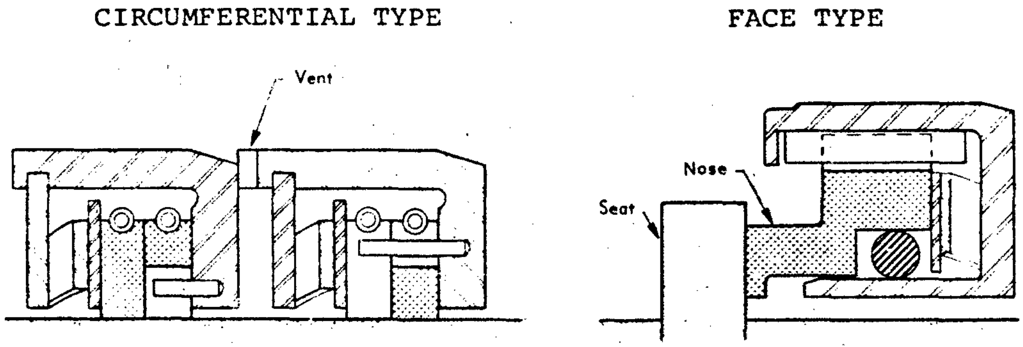


Figure 16. Seal UER Rate for Various Engines.

This display indicates that carbon-seal leakage rates have varied considerably among the study engines. This chart does not reflect the failure rates on a per-seal basis, since the number of carbon seals in each of the study engines varies considerably. The T53, T55, and T64 engines use carbon seals for main-shaft oil sumps throughout, while the T58 and T63 use combinations of labyrinth and carbon seals. The T73 and T74, used in the calculation of the composite engine rate but not shown above, have all carbon seals and all labyrinth seals respectively. Discussion of each of the major failure modes follows.

Carbon-Seal Leakage

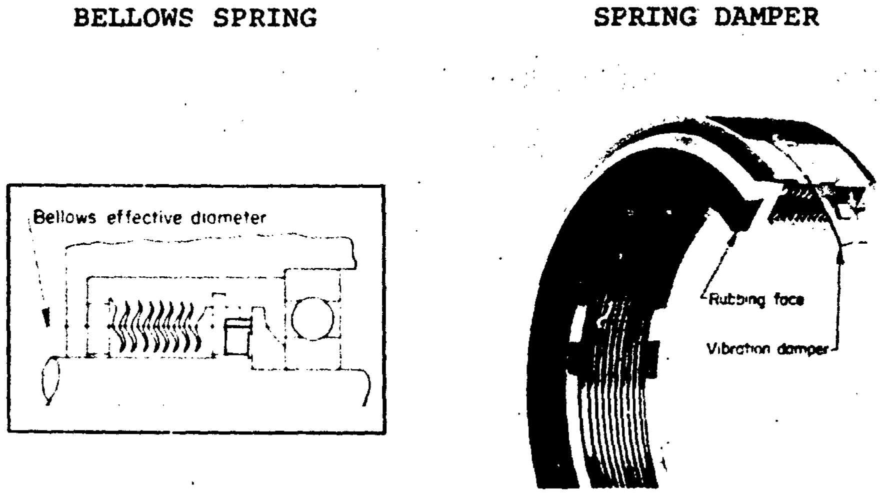
The carbon seals that failed in the engines examined were of both the face and circumferential types. These are shown in Figure 17. The usual failure mechanism of the face seal was surface damage to the carbon element or out-of-flatness conditions of the runner. Face seals have experienced a particularly high degree of sensitivity to maintenance damage, since the two elements (runner and carbon body assembly) are separated during disassembly, thus providing opportunities for contamination, surface damage, or runner distortion. Circumferential types usually fail to seal when the ring segments become clogged with carbonized oil which prevents the segments from assuming a tight seat on the shaft. Other failure mechanisms have involved the antirotation pins or other components within the seal assembly.


CIRCUMFERENTIAL TYPE

FACE TYPE

Figure 17. Carbon Seals.

In most cases, there appeared to be unique conditions which caused these failures. Face-seal runners distorting upon installation on the shaft, inadequate oil scavenging causing excessive heat, and exposure of the seal face to excessive contamination are typical conditions leading to seal failures. One interesting failure mechanism was a resonant condition of a bellows spring used in a face seal (see Figure 18). This resonance caused the sealing element to lift off the runner with ensuing leakage. This problem was corrected with the installation of a damper, as also shown in Figure 18.



BELLOWS SPRING

SPRING DAMPER

Figure 18. Face Seal Bellows.

These specific failure mechanisms and causal effects on individual seal installations have not formed any clear patterns or trends. Certain general application criteria have been used to suggest operating limits for both face and circumferential carbon seals. Differential air pressures, operating temperatures, face pressures, and running velocities are the usual means of describing the applicability of various types of mechanical seals. For instance, Reference 6 gives 420 feet per second as the limit for carbon seals and Reference 7 gives 300 feet per second. The rationale for these particular limits is not discussed in the available literature. Face seals, since they can be pressure balanced, are usually used where a high pressure differential exists. Circumferential seals must be used where significant axial motion will occur. A preliminary analysis of the individual failure rates of the seals in the study engines was performed; the results are shown in Figure 19 as a plot of failure rate versus running speed. Both face and circumferential configurations are used in this analysis, and the trend clearly indicates the increasing probability of failure with higher running speeds. This is the general trend, but there are cases of extremely high failure rates (approximately 0.2 per 1000 hours) with relatively low running speeds (170 feet per second), as well as excellent reliability histories (0.001 per 1000 hours) with nearly equivalent speeds (210). Extreme environmental conditions or unique maintenance procedures are cited as reasons for the unusually high values and extraordinary maturity as the reason for the low value. There is no apparent reliability difference between face and circumferential seals from this analysis.

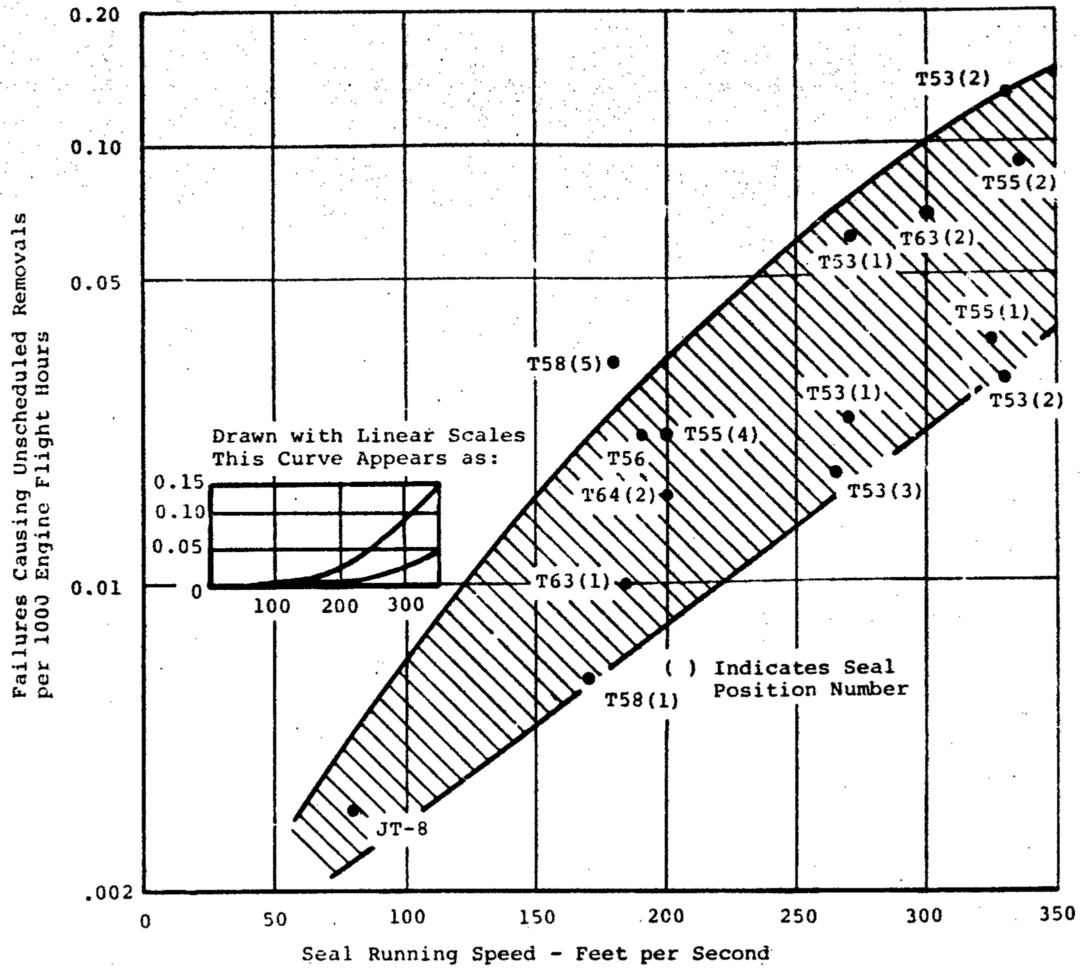


Figure 19. Carbon-Seal Reliability.

The choice of mechanical positive-contacting seals appears to be the result of a decision-making process that is independent of the reliability history of these seals. Carbon seals, even more than bearings, are viewed in a somewhat proprietary light with little reliability data exchanged. The choice of this type of seals has been basically driven by the need to provide positive sealing, over a range of engine attitudes in a small envelope, and with the minimum of airflow losses. Alternative seal configurations, such as close-contact or labyrinth seals, are being used instead of the positive contact seal in new engine designs.

The carbon seal has developed (and deserves) an image of unreliability in view of its 95 percent contribution to our current problem. Despite claims by seal designers that problems of the past have been solved, many individuals as well as entire engine companies have elected to develop the close-contact or labyrinth seal and accept the penalties of increased engine weight and size. Only in instances where the competition is clearly on the basis of performance and/or weight are carbon seals being utilized.

Labyrinth Seal Abradable Material Wear

Despite the dramatically higher reliability of labyrinth seals, their failure modes merit discussion. The bulk of the labyrinth-seal leakage problem has been as oil sump seals. Since they are normally noncontacting, wear is normally nonexistent. There have been some instances, however, where excessive radial displacement of the spool has caused contact and wear of the adjacent surfaces. These displacements occurred on spools whose supporting bearings were flexibly mounted to provide damping during operation at critical speeds. Another source of wear has been unpredicted differential thermal growth causing interference between rotating and nonrotating elements. Some small degree of erosion of the abradable surface and knife edges has also been observed.

A maintainability problem relating to labyrinth seals has been the lack of repairability of seal "knives" in instances where they were machined as an integral part of a wheel or disc. Under these conditions, wear or damage to the knives would require replacement of the expensive wheel or disc. The obvious corrective action in these cases was the use of a separate element (ring) containing the knives.

Static Seals

Static seals, both "O" rings and gaskets, do not exhibit a high rate in any of the study engines. Most failures are due to a combination of installation procedures or elementary design oversights such as sharp edges on "O"-ring lead-ins. The effect of static-seal leakage is usually an air pressure loss, oil weepage, or corrosion of the sealing surfaces.

Miscellaneous Seals (Rotating, Non Main Shaft)

The rates for rotating seals other than those on the main shaft are infinitesimal. Seals, usually of the lip variety, used for accessory or output shafts operate at sufficiently low speeds and cool environments such that only random failures occur. They are probably of a manufacturing or installation origin.

COMPRESSORS

The compressor subsystem contribution to engine R&M problems in terms of the four parameters is:

Compressor	UER	Accidents	MMH	TBO	Index
Scale Factors	2	9	3	7	4.63

The chart indicates that, although compressors have been a relatively low contributor to unscheduled removals, their impact as an accident-causing component has been significant. Compressor failures usually cause either partial or complete loss of power with the subsequent initiation of either a precautionary or forced landing, which presents an opportunity for a major accident. This possibility is further increased if the failure mode is one where the compressor wheel or disc loses structural integrity. Under these circumstances, containment of the high-speed rotating mass is usually not possible, and the result is airframe/control damage or fire and severe damage to the aircraft. Compressor components also were the limiting items in the establishment of TBO intervals in many of the study engines (see Table VII). The failure modes which contribute to the total subsystem values shown above are given in Table XVI.

TABLE XVI. COMPRESSOR FAILURE MODES

Failure Mode	UER	Accidents	MMH	TBO	Index
Corrosion/Erosion Induced Vane Fatigue	38	20	30	20	24
Blade/Disc Fatigue	8	70	6	60	52
Diffuser Cracking	30	-	30	-	6
Lining Wear/Cracking	6	-	7	-	1
Variable Stator/Bleed System	9	-	18	-	2
Miscellaneous	9	10	9	20	15
Total	100%	100%	100%	100%	100%

Table XVI confirms that the losses of compressor blades, vanes, or wheels are the prime accident-causing failure modes. This is not surprising, since the compressor and turbine are the two major rotating components in which large quantities of kinetic energy are stored. The effects of significant unbalance are manifested in either an accident or engine removal. The high proportion of accidents caused by undetected blade/disc failures (70 percent) and the low percentage of unscheduled removals (8 percent) indicate the serious consequences of these failures. Other problems in the compressor subsystems are largely nuisance items or performance-loss-causing failure modes of a passive nature (e.g., liner wear/cracking and compressor diffuser cracking). The distribution of these failure modes among selected engines is shown in Figure 20 for the UER rate parameter.

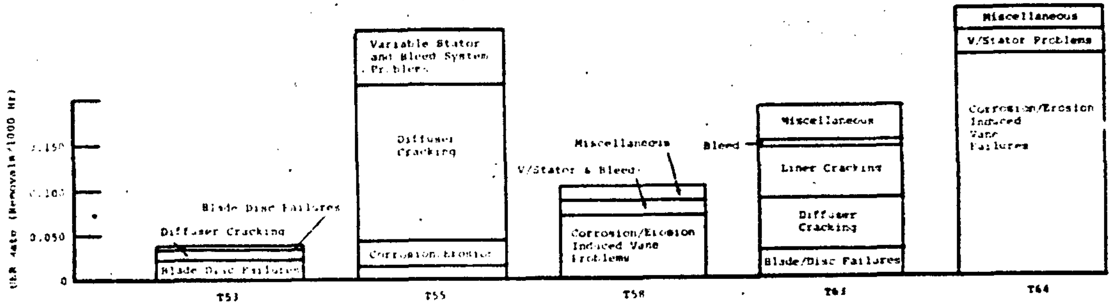


Figure 20. Compressor UER Rate for Various Engines.

This illustration shows a vastly different distribution of modes among the study engines. Only the T58 and T64 had significant corrosion/erosion-induced vane failures. Only the T55 and T63 had significant diffuser cracking problems. Compressor lining cracking was only seen in the T63, which has a unique plastic lining on the inside of the compressor case. These differences stem from the different basic compressor configurations in the study engines. The T58 and T64 are all-axial designs. The T53, T55, and T63 are axial/centrifugal designs. The thin blades/vanes inherent in the latter stages of axial compressors lead to erosion and corrosion problems which progress into failures. Centrifugal designs have the attendant complexity of large diffusers. It is because of these offsetting characteristics that conclusions regarding the relative R&M of axial versus centrifugal compressors should be drawn with caution. The average rates for the two axial flow engines and the two axial/centrifugal designs (disregarding the T53 whose rates are at a significantly different point on the maturity curve) are within 15 percent of each other. A more discernible difference, however, between axial and centrifugal compressors will become apparent when considering the failure mode (subsystem) of erosion in the non-engine-caused subsystems.

Corrosion/Erosion-Induced Vane Failures

This mode appears primarily on two engines: both, all axial flow designs. Classification of these failures as engine-caused as opposed to non-engine-caused (erosion) arises from the mechanisn of failure involved. The sequence of failure was erosion of the vane protective coating, followed by erosion of the base material to the point where the resonant frequency of the vane was excited by the operating frequency of the engine. Operation under these conditions produced high stress so that even minor corrosion pits were sufficient to cause fatigue failures. Corrective action for both engines was incorporation of more corrosion-resistant metals (AM355/INCO718 replaced 403 stainless) with additional emphasis on field procedures for compressor cleaning and application of preservatives.

Thus, the magnitude of this mode was driven by a combination of design, environment, and maintenance-procedure factors. Analyses were not adequate in that the inevitable loss of corrosion-preventive coatings was not considered. On some compressor designs in an abrasive environment, this mode could limit TBO intervals. The close relationship between this mode and the usual power-loss erosion mode suggests that environmental requirements and environmental testing should fully consider the progressive effects of erosion.

Blade/Disc Fatigue Failures

This mode, as shown on Table XVI, contributes a small percentage of unscheduled removals (8 percent) but has been a major factor in causing accidents and TBO limitations. Three specific types of failures that were observed are classified under this failure mode. First are blade fatigue failures due to resonance producing higher stress levels than anticipated. These frequencies were either mechanically or aerodynamically induced. Aerodynamic sources include cases where localized inlet blockage by airborne debris (grass) created an aerodynamic disturbance which, in combination with the proper rotating speed, excited blades at their natural frequency. A mechanical source was the accessory drive-train gear mesh. Failures usually were limited to blade loss, with no progression into the wheels. Even then, however, significant secondary damage to other compressor blades occurred to result in immediate power loss.

The second type of failure involved the blade-to-wheel retention devices. Failures were due to stress corrosion, fretting, or, in some cases, maintenance damage. There were some occurrences of wheel cracking as the failures progressed beyond the tenon area of the wheel.

The third type of failure originated in the wheel itself. It involved low cycle fatigue and manufacturing variations of wheels with intergrally cast blades. These failures are catastrophic, since compressor cases can rarely contain disc portions. TBO limits were usually established for this mode.

Diffuser Cracking/Leakage

The diffuser cracking problem occurs only on engines which utilize the centrifugal compressor design, and involves a variety of locations. Inclusion of this mode in the compressor subsystem allows a more equal comparison between axial and centrifugal compressors.

The failure mechanisms contributing the largest diffuser cracking rate were fatigue failures of the forward and aft faces of the diffuser, as shown in Figures 21 and 22. The precise causes of these failures have not been agreed upon. Factors such as aircraft-induced vibration, local degradation of the face material due to welding procedures, and local thermal gradients are considered to individually or collectively contribute to the cracking. Improved materials and use of castings have significantly reduced the rate of this problem.

Another diffuser problem was cracking of the oil and air lines routed through the air path. Cracking at the forward or aft diffuser face requires engine replacement. The fittings for these lines were tack-welded onto the diffuser face (see Figure 22) and fabricated from three separate elements. One of the primary causes of failure was the suspected use of both lines as handholds by maintenance personnel, with resulting high loads on the welds.

A failure mode on another engine with diffuser problems was related to the unique airpath utilized. In this case, compressor-discharge air was collected in the diffuser scroll, routed through two tubes to the rear of the engine, and then into the aft-mounted combustion chamber. The connection of the diffuser scroll to these two tubes was a slip-joint configuration using piston rings of a design similar to the piston-ring concept in an automobile engine. Distortion of the diffuser scroll would cause misalignment, with the piston rings locking and binding on the tube surface, thus pulling the ring assembly out of the scroll and allowing air leakage. This distortion was caused by a combination of air pressure and the thermal expansion characteristics of magnesium.

These failure modes may not appear to be related to the basic compressor function, but collectively they represent the actual problems encountered with use of the centrifugal configuration and the attendant diffuser. Routing of oil and air lines through this structure and the attachment of the many vanes are more difficult with this diffuser than with the straight-through case and inserted-vane design of axial flow compressors.

Compressor Lining Wear or Cracking

This failure mode has only appeared in any magnitude on one engine, and reflects its unique design approach. To achieve low cost and high efficiency in a small engine, an approach was taken which involved brazing of individual vanes directly

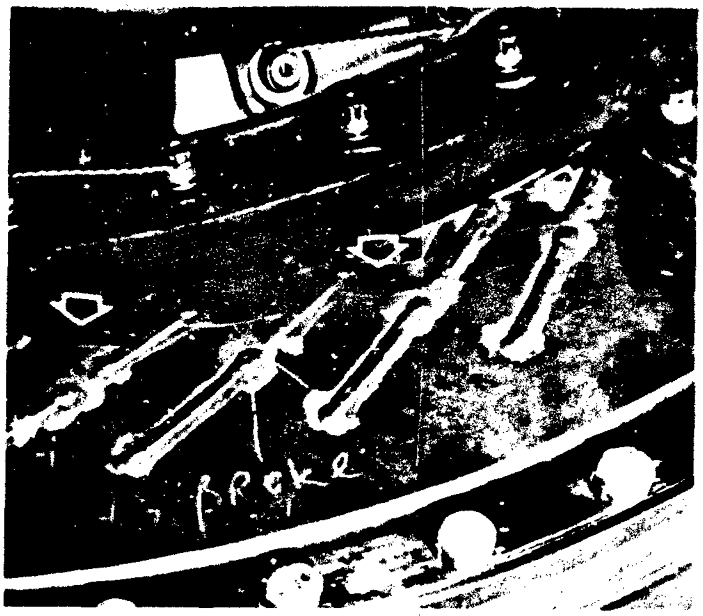


Figure 21. Cracking of Forward Diffuser Face.

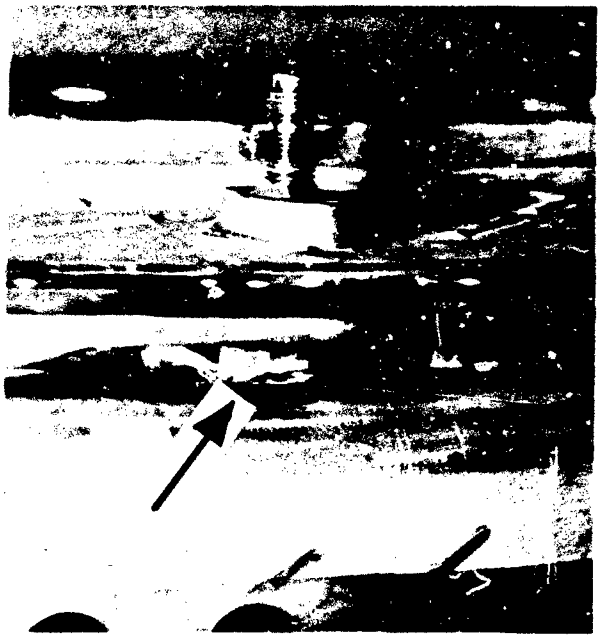


Figure 22. Cracking of Aft Diffuser Face.

onto the compressor case and utilizing a plastic lining to achieve maximum aerodynamic efficiency. This plastic was applied through a centrifuging process which caused the denser elements to separate out near the compressor case and allowed the softer elements to be exposed to the erosive effects of compressor air. Cracking was induced by an inadequate case bond and the effects of thermal cycles. Corrosion was also evident on the compressor case due to this inadequate bond.

This specific instance of failure is obviously related to the unique approach. The traditional design approach of using insertable metallic rings between the vane rows has not exhibited any measurable problem other than some small amount of erosion on magnesium cases that did not utilize abradable rings. This mode, however, is properly considered in the erosion subsystem.

Variable Stator and Bleed System Problems

When examining this mode, the repairability of variable-geometry stator and compressor bleed system hardware without requirements for removal of the complete engine must be remembered. The UER rate for this mode in no manner relects the basic failure rate of these items. There have been many problems with this hardware, the primary mode being binding and subsequent breaking of the actuating rings, levers, and attaching hardware. A typical failure caused by the presence of FOD (a bolt) is shown in Figure 23. Binding due to dirt and debris resulted in excessive loads which caused fatigue or ultimate failures. Excessive looseness was also observed which allowed inconsistent stator positioning around the circumference. Material changes, use of dirt shields, and use of dual (180-degree-displaced) actuators were typical corrective actions. Engine performance is usually tolerant to problems in this area, and in-flight detection is unusual.

Figure 23. Failed Variable Stator Vane Mechanism Due To FOD.

Bleed system problems usually involve the control valves. The most frequent mode is binding of spools from contamination. A few cases of mechanical linkage wear inside the valves, without the presence of contamination, were also observed.

COMBUSTOR

The combustor subsystem contribution to engine R&M problems in terms of the four parameters is:

Combustion	UER	Accidents	MMH	TBO	Index
Scale Factors	2	0	10	0	1.14

The chart indicates that the only significant impact that the combustion subsystem has had as an R&M problem has been in the maintenance man-hour parameter. This is due mainly to continuing requirements for hot-end inspections. These inspections, which are normally required to check turbine blades, nozzles, and combustion system components, account for relatively large maintenance man-hour expenditures. No accidents were caused by combustion system components, and no TBO limitations were imposed by them. This latter point is academic, since a hot-end inspection can be construed as an interim TBO, which provides an opportunity to change combustion system components where necessary.

The low index number assigned to this subsystem is a direct result of the relative weakness of maintenance man-hour expenditures as a parameter in the total spectrum of R&M problems. The failure modes which contribute to the total subsystem values are shown in Table XVII.

TABLE XVII. COMBUSTOR FAILURE MODES

Failure Modes	UER	Accidents	MMH	TBO	Index
Liner Cracking/Warping	17	-	17	-	17
Liner Support Structure Cracking	17	-	17	-	17
Housing Cracking/Corrosion Fitting Problems	50	-	50	-	50
Swirl Cup Problems	15	-	15	-	15
Miscellaneous	1	-	1	-	1
Total	100%		100%		100%

This table indicates that those failure modes which cause unscheduled removals are also responsible for man-hour expenditure. This is expected, since unscheduled engine removals are one consequence of problems that justify the imposition of a hot-end inspection. The failure modes in the combustion subsystem are passive and were usually detected by a gradual power loss or during a hot-end inspection. The distribution of these failure modes among selected engines is shown in Figure 24 for the UER rate parameter.

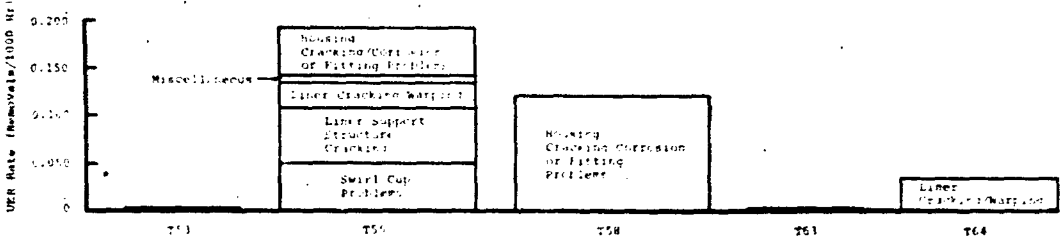


Figure 24. Combustor UER Rate for Various Engines.

The extreme values of rates among the study engines warrant comment. The low rate for the T53 is somewhat explainable by its higher flight-hour accumulation than the rest of the study engines. The T63 combustion system is a single chamber mounted on the rear of the engine with the minimum of attachments, fittings and structural complexity. The remaining engines (T55, T58 and T64) represent a more appropriate level of R&M problems for the average engine of intermediate size and a maturity point of 1 million hours. The effect of various combustor configurations may also be indicated by these rates. The T53 and T55 possess a folded combustor, while the T58 and T64 have the straight-through type. The suggestion that the folded combustor design introduces additional primary and secondary structural complexity may have some merit. The specific failure modes observed in this subsystem are discussed as follows.

Liner Cracking/Warping

Although this mode is usually viewed as the primary reliability issue, the data indicates that it only accounts for 17 percent of the combustor problem. A better understanding of materials capability and aerodynamics of cooling flows has been obtained over the years from the extensive use of combustor test rigs. This technology has played an effective role in maintaining basic liner integrity within the temperatures and overhaul intervals of existing engines. Typical cracking is shown on Figure 25. It is usually associated with thermal fatigue in the area of louvers, holes, or complex curvatures, such as in the header or dome area.

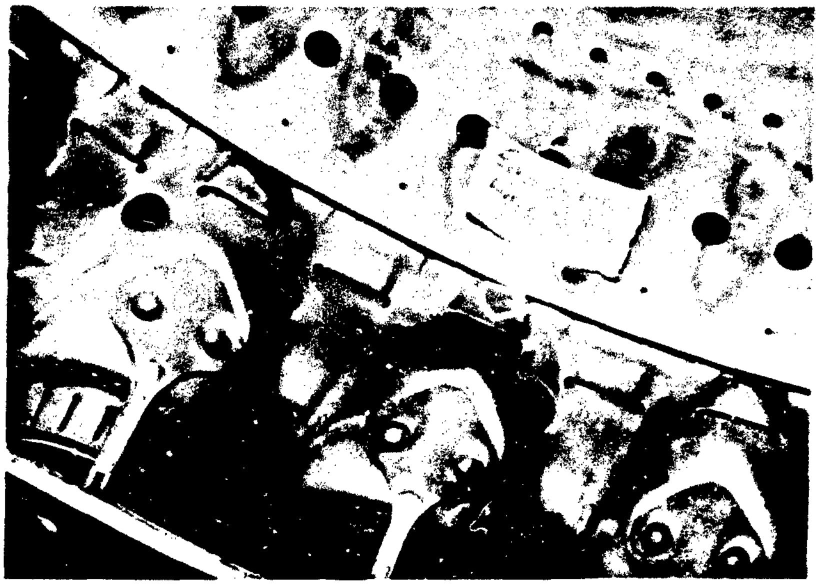


Figure 25. Typical Combustor Liner Cracking.

Liner Support Structure Cracking

This mode has been experienced by only one engine in the study. The problem occurred on brackets supporting the liner assembly, as is illustrated in Figure 26. In this particular instance,

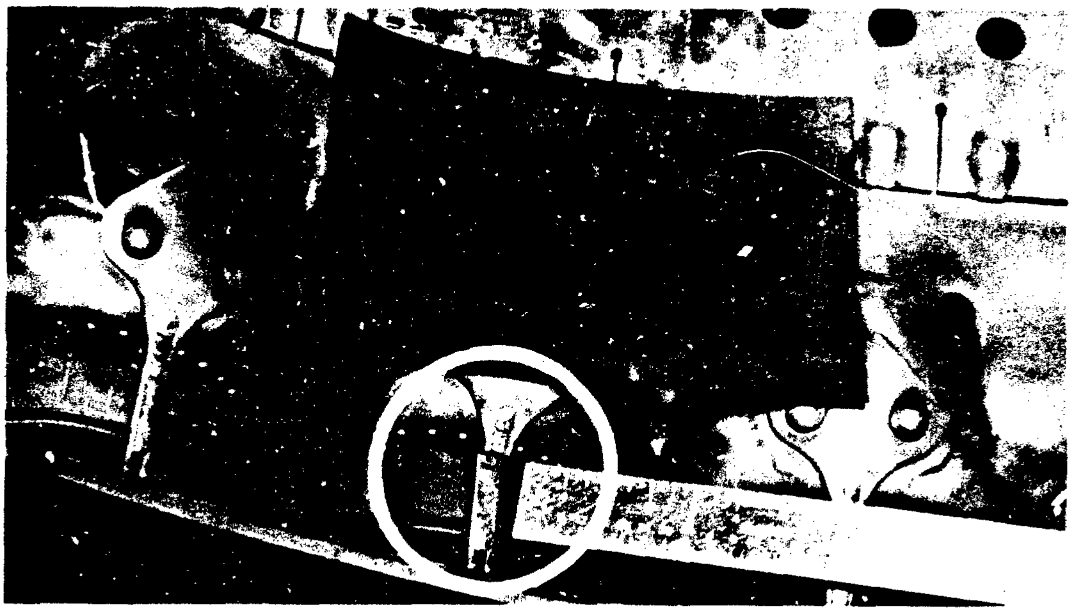


Figure 26. Combustor Liner Support Bracket Cracking.

aircraft vibration was determined to be a primary source of fatigue failures. The thin design of the supports was intended to minimize airflow distortion and was not adequate from a strength standpoint. This failure mode was not observed during early development testing but was later reproduced in the same test rig after imposing a one-per-rev rotor vibration on the assembly. This problem illustrates the need to specify expected airframe-induced vibration levels prior to full-scale engine testing and to perform endurance tests with external vibration levels imposed.

Housing Cracking, Corrosion, and Fitting Problems

The failures that contributed to this category represent a variety of modes. Combustor drain valves and ignitor plugs were a large portion of the problem due to corrosion and cracking of the fitting attachments to the combustor housing. An example of an ignitor plug fitting failure is shown in Figure 27. These failures were usually related to inadequate detail design. In one instance, an internal weld fillet was machined flat for aerodynamic cleanliness, with inadequate quality control of the amount of fillet removed. In many cases application of excessive force on the attaching lines by maintenance personnel was suspected to contribute to problems. In cases involving drain-valve boss cracking, the primary factor was corrosion leading to strength deterioration. In this instance, engine drying cycles were not rigorously accomplished after washing. This accelerated the corrosion. Seizure of bolts and studs due to corrosion was also encountered. These problems indicate that much of the R&M problem arises from lack of attention to a wide variety of small design details.

Figure 27. Ignitor Plug Fitting Failure.

Swirl-Cup Problems

This is another problem experienced by only one of the engines studied. The failure mode was wear and cracking of the swirl-cup mounting spacers, as shown in Figure 28. The design requirement for the swirl-cup mounting system dictated provisions for swirl-cup displacement relative to the mounting on the combustion liner to accept the fuel nozzles mounted on the outer case and whose position would vary in relation to the swirl cups. Production variability and differential thermal growth cause this shift in relative position.

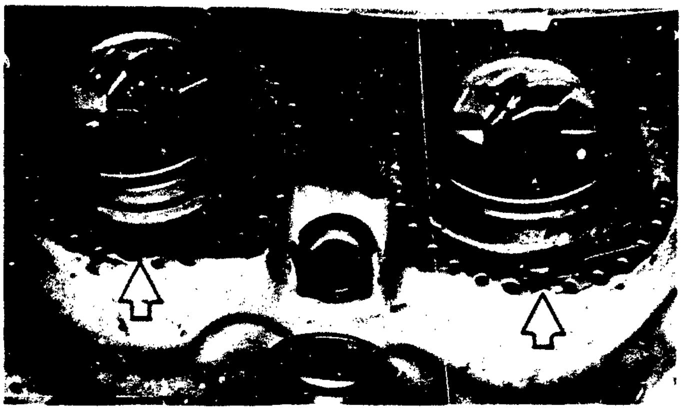


Figure 28. Swirl-Cup Mounting Spacer Cracking.

To provide this displacement capability, the swirl cups were designed to be mounted with a spring type spacer retaining the swirl cup against the liner with a snug fit which allowed radial positioning. The initial design utilized tolerances which provided adequate retention, and the early testing with these components indicated the adequacy of the design. Subsequent to the development testing and for reasons of manufacturing and assembly economy, the tolerances were increased. These larger tolerances on the stackup allowed excessive looseness between the swirl cup and mounting surface.

The resultant swirl-cup motion, encouraged by the soft swirl-cup mounting system, leads to swirl-cup mounting flange wear, elongation of the swirl-cup key slots (Figure 29), and eventual swirl-cup spacer cracking (Figure 28). The swirl cups would then drop into the combustion chamber. Alternately, the swirl cups rubbed or vibrated against the nozzles, causing wear (Figure 30).

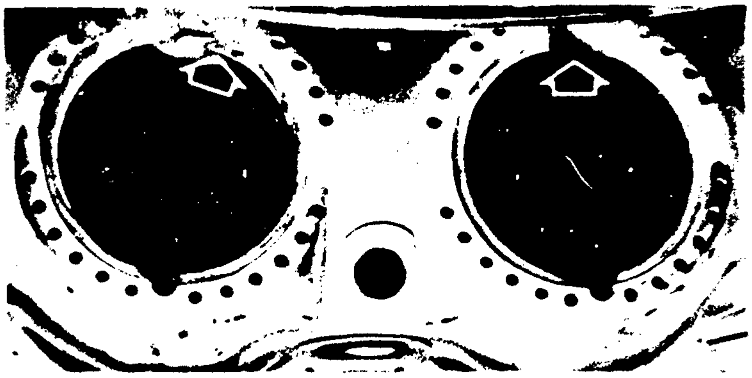


Figure 29. Mounting Flange Wear and Key Slot Elongation.

Figure 30. Fuel Nozzle Wear by Swirl Cups.

TURBINE

The turbine subsystem contribution to engine R&M problems in terms of the four parameters is:

Turbine	UER	Accidents	MMH	TBO	Index
Scale Factors	2	5	10	3	2.86

The chart indicates that the turbine subsystem has a broad impact in all the selected R&M parameters. Its prime impact is apparent in the accident and maintenance man-hour parameters. The predominant reason for its high rating in maintenance is due to continuing requirements for engine hot-end inspections. The major reasons for hot-end inspections are to inspect for continued serviceability of turbine blades and nozzles and for certain combustion subsystem component serviceability. The turbine subsystem's importance as a potential cause of accidents is highlighted by its appearance as a TBO-limiting subsystem. Those subsystems having a significant accident record also contribute to engine TBO.

Although the turbine subsystem has traditionally been considered the prime offender from an engine R&M standpoint, this study does not confirm the belief. Four subsystems, namely compressor, bearings, seals, and fuel, are more significant R&M restraints (see Table X). The failure modes for components which contribute to the total subsystem values are shown in Table XVIII. Table XVIII indicates that approximately 90 percent of the unscheduled removals are caused by nonrotating components. The smaller percentage of accidents due to these components (31 percent) reflects the passive nature of failures in this area. In general, these failures result in gradual power degradation.

TABLE XVIII. TURBINE FAILURE MODES

Failure Mode	UER	Accidents	MMH	TBO	Index
Nozzle Band Cracking	27	23	30	-	20
Nozzle Erosion/Oxidation Sulfidation	8	8	10	-	6
Nozzle Support Structure Wear/Cracking	44	-	40	-	19
Blade/Wheel Cracks	1	54	-	100	41
Shafts/Coupling/Hardware	6	15	5	-	8
Miscellaneous	14	-	15	-	6
Total	100%	100%	100%	100%	100%

Failures of rotating components, on the other hand, contributed to only 7 percent of the unscheduled removals but caused nearly 70 percent of the accidents. These components were also the only items within the turbine subsystem to limit the TBO intervals. The instantaneous power losses and high kinetic energy involved with turbine blade and disc failures and the inability of the case to contain disc failures are the reasons for this modes's potential for causing accidents. The distribution of turbine subsystem failure modes among selected engines is shown in Figure 31 for the UER rate parameter. The study engine modes are generally similar in terms of both type and rate.

Nozzle Inner/Outer-Band and Partition Cracking

This mode appeared in every study engine examined at a rather consistent rate. Cracking has been evidenced in both the inner and outer bands as well as in the nozzles or partitions themselves. An example of inner-band cracking is shown in Figure 32. The cracking is usually most severe on first-stage gas-producer turbine nozzles (where the temperatures are

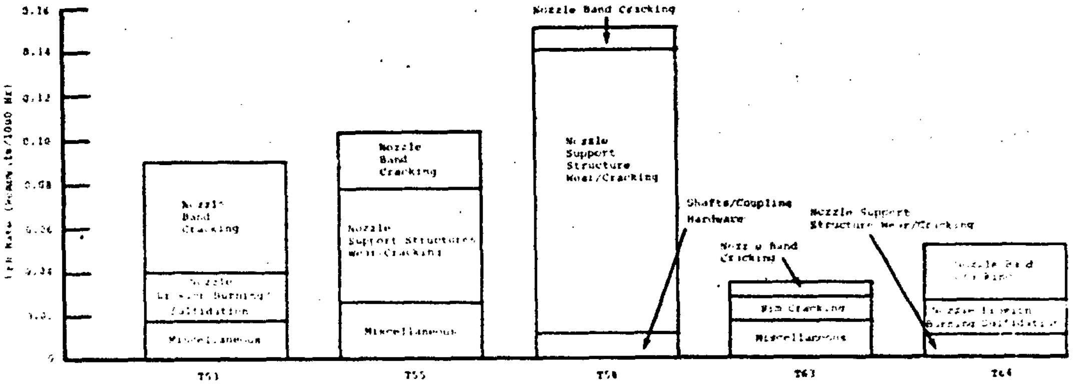


Figure 31. Turbine UER Rate for Various Engines.

highest). It appears at the discontinuities of fabricated assemblies and is attributed to thermal stresses. All engines studied except one had brazed nozzle assemblies fabricated out of separate inner bands, outer bands, partitions, related flanges, etc. The alternative design approach, an integral casting, has been demonstrated to be superior from a reliability standpoint. The absence of discontinuities reduces stress concentrations at the brazed joints, particularily at the vane-to-shroud intersections. Virtually every engine in this study which began with fabricated nozzles has either incorporated or proposed cast nozzles as the corrective action for its cracking problem. The initial incorporation of integrally cast assemblies, however, was not considered practical, since it allows virtually no flexibility in vane shapes, angles, or basic throat areas. Initial tooling costs are very high for castings, although on a large-scale production basis, fabricated assembly unit costs are higher. Unfortunately, evaluations of competing engines are performed with the ground rules of limited production quantities. This emphasizes the impact of initial tooling cost differences, thereby penalizing the cast designs.

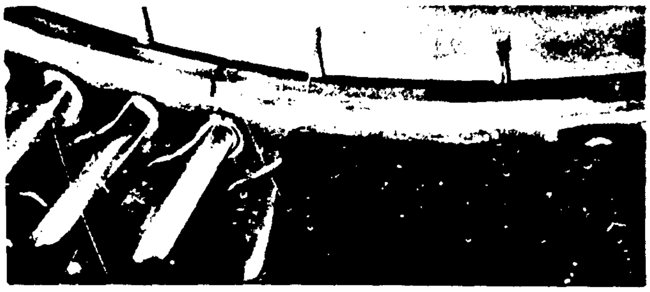


Figure 32. Turbine Nozzle Inner-Band Cracks.

Another corrective action applied to in-service engines to resolve nozzle cracking problems has been the slotting of the inner or outer bands or shrouds. This slotting, usually between groups of 3 to 7 vanes, minimizes the low-cycle stresses that result from thermal expansion of the separate elements. Although this slotting should theoretically lower the fatigue life of the assembly, no such degradation was apparent.

In addition to the manufacturing technique selected, the basic choice of materials played a major role in the resultant nozzle reliability. Most of the engines examined utilized either cobalt-based X-40 alloy (AMS-5382) or the nickel-based INCO 713C alloy for the basic vane material. The choice of material is basically a trade-off of strength versus hot-corrosion resistance. The nickel-based alloys have superior strength at high temperatures but are more susceptible to sulfidation or hot-corrosion attack than are cobalt-based materials. This trade will be discussed in more detail under Nozzle Erosion/Oxidation/Sulfidation.

The magnitude of the cracking problem is particularly high on turbine engines in helicopters because of the frequent thermocycles experienced during typical helicopter missions. This will become more critical as turbine inlet temperatures increase.

Nozzle Erosion/Oxidation/Sulfidation

This failure mode category includes all of the mechanisms of failure of turbine nozzles or blades that involve chemical actions rather than pure stress actions. Included in this category are problems of oxidation and sulfidation which are sometimes described as either burning or erosion. A severely corroded turbine blade is shown in Figure 33.

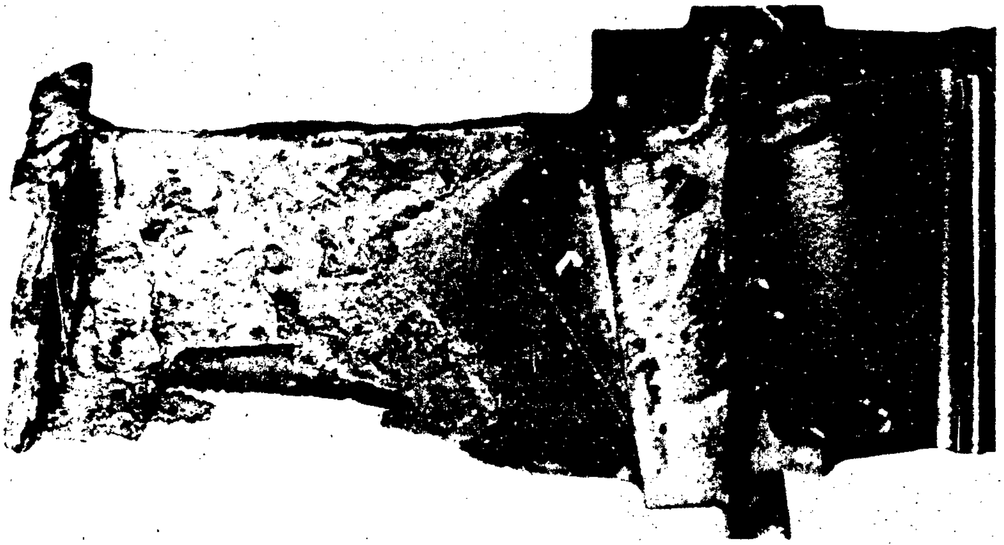


Figure 33. Corroded Turbine Blade.

Oxidation reflects the classical limit of materials in high-temperature applications. It involves the formation of oxides on the surface of the metal which can progress to penetrate the structure, causing element diffusion and subsequent loss of strength. Sulfidation is a more complex phenomenon that requires the presence of sodium sulfates. These sulfates are a constituent of sea salt and can be ingested directly from the atmosphere; or they can be produced in the combustion process by the combination of sodium chloride in sea air reacting with sulfur contained in engine fuel. At high temperature, sodium sulfate reacts with any oxide scale, causing it to become unprotective. Once the oxide film has been disrupted, sodium sulfate reacts rapidly with the base materials to form sulfides and large amounts of sodium oxide. The sodium oxide prevents reformation of a protective metal oxide scale, thus permitting the corrosion process to continue at an accelerating rate. Although these mechanisms have not caused unscheduled removals to any large degree (only 8 percent), they are one restraint to the continual demand for higher operating temperatures and will, most likely, become the limiting element to "on-condition" maintenance in future engines.

Because of the performance penalties associated with the use of cooling air to reduce metal temperatures, much past and current research is directed at increasing the capability of metals and developing coatings to resist the effects of higher temperatures. This research has been extensive, and it is neither possible nor necessary to describe it all here. However, an overview is in order since these modes will become a larger portion of the total problem as turbine temperatures increase, unless continued emphasis is applied.

Somewhat oversimplified, the problem is that contemporary turbine-blade materials suffer degradation from sulfidation at 1650° to 1750°F and higher and from oxidation at 1800° to 1900°F and higher. The use of appropriate coatings can raise these values approximately 100°F. Since both of these mechanisms are time dependent, with attack severity depending on component material, coatings, and in the case of sulfidation, the presence of other elements from the atmosphere or fuel, rigorous absolute limits cannot be set. Some research has indicated that the most severe temperature range for sulfidation is between 1550°F and 1650°F,[8] although the test conditions may not have precisely represented actual turbine operations.

The primary metals used for many years in turbine blades and vanes (nozzles) were nickel-based alloys. The trend of decreasing the chromium content in these metals to achieve better high-temperature strength compromised oxidation and sulfidation resistance.[9] Relief from these restraints has taken several paths. The cobalt-based superalloys were developed and are now extensively used in stationary components such as nozzles. Cobalt-based alloys are generally recognized as having a higher resistance to sulfidation. They are also considered to possess superior oxidation capabilities[10] to the nickel-base metals, although some research indicates this may not hold universally, particularly in uncoated states.[11]

A second path has been the development of coatings for the protection of both nozzles and blades. The most widely used are intermetallic alumide diffusion coatings under a wide range of product names, most of them proprietary. These coatings are highly effective in extending life (or allowing higher temperatures), but they suffer the disadvantages of being erodible by airborne contaminants, are expensive, and present problems in overhaul/repair at military depots.

The third approach to avoiding these problems is the use of new blade-vane cooling techniques. The trend from convection, film/convection, and impingement/film to transpiration cooling methods has allowed significant increases in T5 with only modest increases in metal temperature. Turbine inlet temperatures of 2200°F are now possible with metal temperatures remaining at 1700°F.[12]

The technology is adequate to eliminate this mode in future engines. This, plus other controls (such as preventing the use of alkali metal-based agents for cleaning engines, the source of some problems experienced in the study engines), should be sufficient to prevent the appearance of these modes, even at the desired high operating intervals, providing conservative operating-temperature increases are postulated for growth engines.

Nozzle Support Structure Cracking

This failure category is the largest contributor to unscheduled removals in the turbine subsystem. Similar to other problems with a large magnitude, it does not consist of a single failure mode or location, but represents a variety of individual failure instances on the study engines. The common element of these failures is that they occur in stationary components outside the main gas stream. They are frequently unrelated to the primary functional purposes of the turbine section and are coded in this turbine subsystem more from a proximity standpoint.

An example of this category is the cracking of oil-delivery tubes at the joint with the basic nozzle assembly (see Figure 34). The connection points for antirotation pins are also shown in this figure. On several study engines, these pins have exhibited wear and breakage. In some instances, all pins were broken and the nozzle (not the configuration shown) began to rotate inside the casing. The specific sources of these failures were never precisely isolated. Aircraft-induced vibration, aerodynamic loading, production variations in component dimensions, and even maintenance damage were all candidates for causal factors both singly and in combination. The oil tube cracking problem used as an example was most likely due to improper maintenance (inadequate double wrenching of fittings and mounting nuts).

Another example of this failure category is illustrated in Figure 35, showing cracks that appeared in the nozzle assembly support structure. In this instance, the primary problem source was a variation in weld fillet which caused unpredicted dynamic responses of the assembly. These weld fillet variations were not within permissible drawing tolerances but were not detected by quality control. Each of these failures appears to be sensitive to small design details.

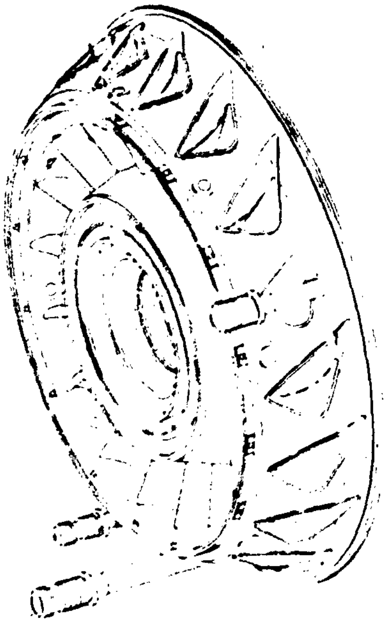


Figure 34. Turbine Nozzle With Integral Oil Tubes.

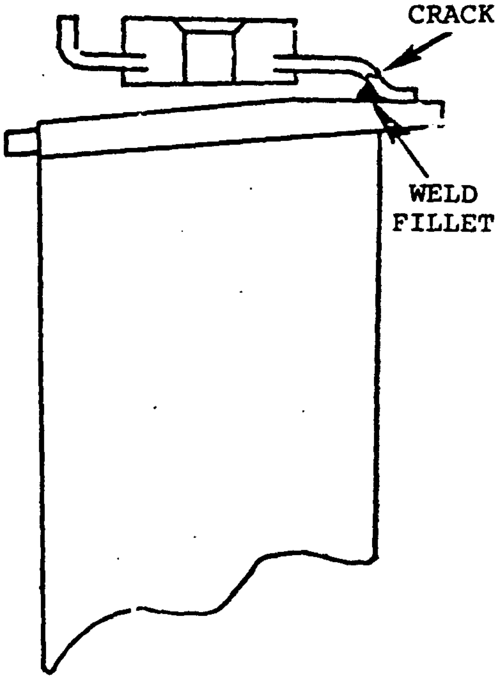


Figure 35. Cracked Turbine Nozzle Support Structure.

Blade/Wheel Cracking

This category was the largest single problem area in the turbine subsystem. It includes failure mechanisms of both turbine blades and the wheels or discs. This mode has been traditionally considered the most critical R&M issue in turbine engines, although this study found that it has had a problem magnitude only half that of compressor blade and wheel failures (see Table XI).

The specific failure instances that defined this category have many similarities to those experienced in the compressor section. This included low-cycle fatigue cracking of the wheels, high-cycle fatigue failures of the blades, fretting and/or stress corrosion at the blade-to-wheel connection, and problems initiated by the blade retention devices. Sources of problems unique to the turbine section included excessive temperature gradients on wheels due to inadequate control of cooling air, and blade to shroud rubs which changed the basic damping characteristics of the blades.

The technology demanded to properly design rotating turbine components is probably the most complex of all engine mechanical areas. It has received a great deal of research attention directed at improving analytical techniques as well as obtaining improved materials and manufacturing techniques. The key to future improvements in reliability is the development of analytical techniques to recognize not only the classical sources of loads, such as low frequency thermal cycling, but also the obscure problems with cooling air variations and other similar lessons from field experience.

CASES

The case subsystem contribution to engine R&M problems in terms of the four parameters is:

Cases	UER	Accidents	MMH	TBO	Index
Scale Factor	2	1	1	-	1.27

The chart indicates that cases do not have a major contribution to the overall R&M problem. The unscheduled engine removal parameter is the only parameter of signficance. The failure modes for components which contribute to the total cases subsystem problem are shown in Table XIX. This table indicates that case corrosion has necessitated both unscheduled engine removals and maintenance man-hours to prevent and fix the corrosion, but it has had no influence on aircraft accidents. The largest single contributing mode had been

TABLE XIX. CASE FAILURE MODES

Failure Mode	UER	Accidents	MMH	TBO	Index
Case Corrosion	23	-	30	-	21
Case Cracking	31	65	20	-	35
Tube, Boss, & Fitting Cracks and Loose Inserts	39	35	40	-	37
Miscellaneous	7	-	10	-	7
Total	100%	100%	100%	-	100%

cracking of external tubes, bosses, and fittings and problems with loose inserts. These problems have been of a relatively low rate and random nature, but their collective impact is considerable. The distribution of case failure modes among selected engines is shown in Figure 36 for the UER rate parameter.

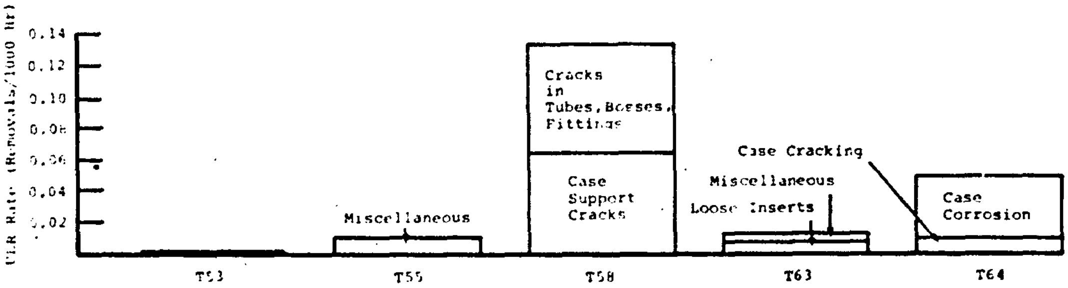


Figure 36. Case UER Rate for Various Engines.

The unusually high rate for a single engine in Figure 36 may be somewhat artificial. The definition of the case subsystem is not precise. Failure modes on the remaining engines, which were coded in other subsystems, could just as reasonably have been coded into the case subsystem. For instance, in the T55 compressor system, there are approximately 0.06 removals per 1000 flight hours due to failures of air and oil line fittings on the compressor diffuser that could be considered equivalent to some of the modes shown here in the cases subystem.

Case Corrosion

The rate for this mode is due primarily to the appearance of significant corrosion on only one engine. This engine was used in a Navy application where the environmental conditions were conducive to corrosion. The problems usually occurred in tapped holes in the steel frame where various connections and equipment are mounted. Corrosion in these holes resulted in either seized bolts/studs or the inability to apply proper seating pressure on gaskets, thus allowing air leakage.

These failure locations suggest that the source of the problems is more in the susceptibility of the base material to corrosion than the adequacy of the coatings that were applied. Coatings are difficult to apply and maintain to threaded holes, on mating surfaces, etc., and corrosion is likely to occur, particularly where a continuous oxygen supply is present (as in the case of air valve mounting pads) and where proper preventative maintenance procedures have not been utilized. Corrective actions for these corrosion problems consisted of the replacement of both the coatings and the base material.

Any discussion of corrosion would not be complete without addressing the use of magnesium. The two Navy engines in this study did not utilize any magnesium. However, the three Army engines whose failure modes were examined in detail used extensive amounts of magnesium in the inlet and compressor area. Corrosion on these engines was coded by the two engine manufacturers involved in the non-engine-caused subsystem entitled environmental, reflecting their belief that extreme environmental conditions caused the corrosion and that under normal usage, the coatings utilized would be sufficient. Without debating this rationale, the reader is cautioned that the generic rates for corrosion should reflect rates evident in both of the subsystems of cases and environmental. In general, the use of magnesium has not presented a large corrosion problem over traditionally used steels. Difficulties that were experienced with the use of magnesium were more related to their thermal expansion characteristics, resulting in problems coded in the subsystems of bearings and compressors.

Case Cracking

The case cracking observed in the study engines was usually in the joint areas where bearing-housing mounting struts connected to the casing assemblies. These problems are usually attributed to fatigue caused by radial cyclic thermal growth and/or to excessive drive-train vibration. The two engines with the highest case-cracking failure rates, the T58 and the T73, are both rear-drive engine configurations. This arrangement may magnify the effects of drive-train misalignment or

unbalance on the case structure. Rear-drive engines usually have the power-turbine output shaft bearings mounted in housings which are cantilevered out rearward from the main case. This mounting introduces bending loads on the strut to housing/case joints not normally experienced when the bearing housing is axially located under the main case structure.

Tube, Boss, and Fitting Cracking and Loose Inserts

The above failure modes are similar to failures coded in the compressor and combustion subsystems as a function of the specific engine involved. Failure locations, component causal factors, and corrective actions are similar to those modes previously discussed. The drain-valve boss problem, for example (described in the combustion subsystem), is similar to a failure mode whose rate is coded in this subsystem. The boss-cracking problem here was due to a riveted fitting with inadequate strength. Another failure mode was insert looseness in a magnesium case. These inserts were used to mount the compressor assembly where looseness would promote misalignment and cause subsequent bearing failures. The looseness resulted from a differential expansion with temperature change involving steel and magnesium. The desire to have a minimum number of compressor module mounting bolts may have contributed to the problem. This is one indication of a potential penalty associated with designing for increased modularization.

LUBRICATION

The lubrication subsystem contribution to engine R&M problems in terms of the four parameters is:

Lubrication	UER	Accidents	MMH	TBO	Index
Scale Factors	2	1	2	0	1.28

The chart indicates that the lubrication subsystem does not have a major contribution to the overall engine R&M problem. The unscheduled engine removal parameter is the only parameter of significance. Because [illegible] the great variety of failure modes experienced in this system, failures have been organized by component classes rather than failure modes and are shown in Table XX.

This table indicates that the majority of the problems with the lubrication subsystem have been associated with lube pump and check valve failures. Although the failure rate was relatively low, it is a common one for all the engines in this study. The only accident-causing mode was, surprisingly,

TABLE XX. LUBRICATION FAILURE MODES					
Failure Mode	UER	Accidents	MMH	TBO	Index
Pump, Valve Failures	49	-	40	-	47
Tubes, Lines, Fittings, and Vents	13	100	23	-	17
Filters and Coolers	21	-	17		20
System Problems	17	-	20	-	16
Total	100%	100%	100%	-	100%

failures of the lube lines, fittings or "O" rings. The distribution of these failure modes among selected engines is shown in Figure 37 for the UER rate parameter.

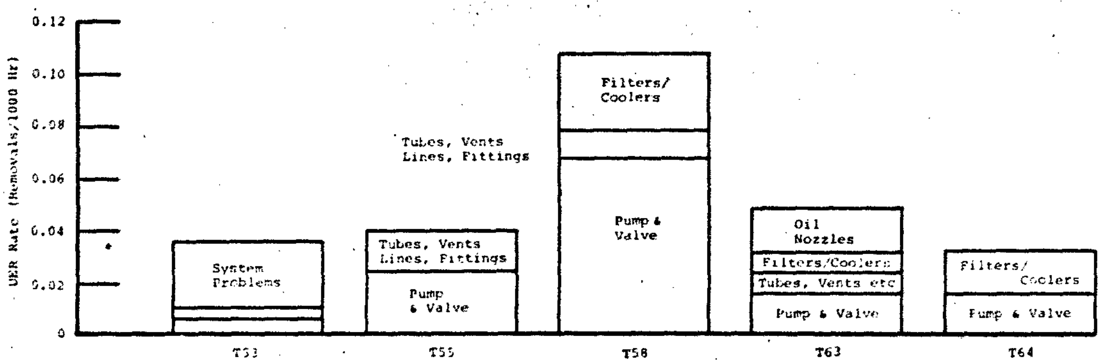


Figure 37. Lubrication UER Rate for Various Engines.

This figure indicates that removals caused by lubrication system components are generally similar among the study engines. The rate for the T58, which is approximately twice the average rate, is a reflection of its poor accessibility in certain applications. Normally, most lubrication system failures do not require engine removal, since individual components can be replaced. Poor accessibility to these components causes the T58 engine to be removed in a greater percentage of lubrication failures. Discussion of the major categories of failures follows.

Pump and Valve Failures

This category is the largest contributor to lubrication system problems and includes failures of the main pump and assorted valves contained in the body of the pump unit. In instances where the oil reservoir is mounted above the engine, a check valve is required to prevent sump flooding during engine shutdown. Problems associated with this design have included contamination-induced leakage of the check valve and inadequate scavenge pump pressure at low engine speeds, both of which caused sump flooding. The contamination problem was due to the location of the check valve upstream of the filter.

Other than specific identified failure modes such as these, there have been many instances where failures of related lubrication system components were mistakenly attributed to the main pump or the control valves. Many system type problems would have been eliminated if complete system testing had been performed during the development phase. This would have been difficult for three engines in the study which required airframe-mounted components (reservoirs, coolers).

Tubes, Lines, Fittings, and Vents

These failures were almost entirely of components mounted outside the engine which did not normally require engine removal for resolution. That these failures did cause engine removals can only be attributed to the lack of accessibility, spare parts, or insufficient maintenance time or skills. The failures evidenced in this mode were the most routine of tube and hose leakage and chafing. No dramatic or unusual mechanisms were evident. Basic inattention to design details, including routing, clamping, possible maintenance damage, and the effects of vibrations, was the only identifiable cause of most of these failures. The few accidents caused by the lubrication system were due to line, tube, and O-ring leakage and were due more to precautionary landings that became out of control on the ground than to the actual functional nature of the leaks. In only one case did a failure of a line cause oil depletion and engine oil starvation.

Filters and Coolers

The major problems experienced in this category were with coolers. High oil temperatures which necessitated preventative engine removals were suspected to be due to clogged oil coolers, for several study engines. Leakage of oil coolers was also observed. Filters were a rather small problem. Collapsed screen elements and binding bypass valves were the only identifiable filter failure modes.

FUEL SYSTEM

The fuel subsystem contribution to the R&M problem is shown below in terms of the four R&M parameters:

Fuel	UER	Accidents	MMH	TBO	Index
Scale Factors	3	10	5	0	3.45

This chart indicates that the fuel subsystem is a high contributor to three of the four parameters. There is only one engine-related subsystem that causes more unscheduled removals and two that cause more man-hour expenditures. The fuel subsystem causes more accidents than any other subsystem (engine-related or not). The reason for the high accident-causing potential of this subsystem should be readily apparent. Any failure mode which can cause a sudden interruption of power has a potential for causing accidents. The failure modes of the fuel subsystem, as in the case of lubrication subsystem failure modes, do not form any meaningful patterns. Further breakdown as to the major types of fuel system components involved is shown in Table XXI.

TABLE XXI. FUEL FAILURE MODES

Failure Mode	UER	Accidents	MMH	TBO	Index Number
Fuel Controls Units	68	85	80	-	75
Other Components: Pumps, Valves, etc.	24	8	15	-	15
Tubes and Hoses	2	5	2	-	5
Miscellaneous	6	2	3	-	5
Total	100%	100%	100%	-	100%

As the table shows, the fuel subsystem problem is largely a fuel control unit problem. Fuel controls are 75 percent of the total problem, with nearly equivalent percentages in each separate parameter. The distribution of the failure modes among selected engines for the UER rate parameter is shown in Figure 38.

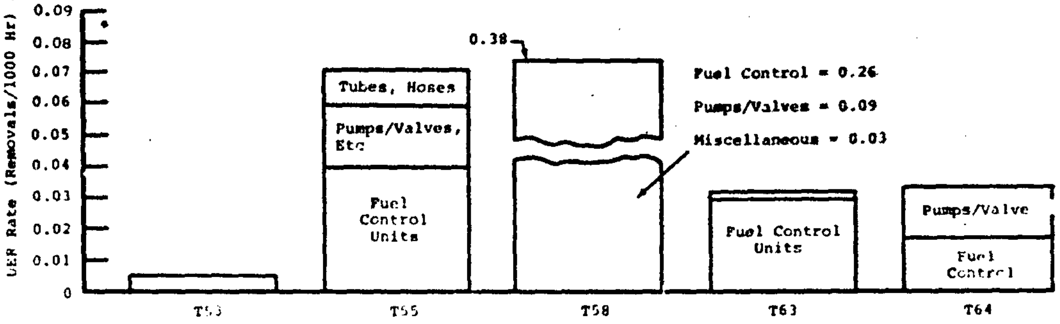


Figure 38. Fuel UER Rate for Various Engines.

This figure indicates that the 0.085 composite rate for the fuel subsystem is strongly influenced by the unusually high rate for one engine. The rate for this engine is approximately 10 times the magnitude of the average of the other engines. This installation, as indicated in the lubrication subsystem discussion, has poor accessibility characteristics (the lubrication system caused engine removals at twice the rate of other study engines). The 10:1 ratio for the fuel subsystem suggests that there are more differences that affect the T58 removal rate than just accessibility. These factors will be reviewed during the following discussion of major individual failure areas.

Fuel Controls

This category of failures is the fifth highest single problem in the engine. Despite their large contribution to the fuel subsystem R&M problem (75 percent), information on fuel control failure modes is less complete than data on any other turbine engine problem. This situation is directly related to the fact that the prime engine manufacturer does not usually perform the detailed design, manufacture, or overhaul of the fuel control. Although the corrective action cycle for service problems involves the engine manufacturer, detailed records describing the various failure modes and their frequency were not available from the engine manufacturers involved in this study. Because of the past tendency for the overhaul/repair of failed fuel controls to be contracted to agencies or companies which did not manufacture the units, this information is not available from the fuel control manufacturers. In a study conducted by the Naval Air Propulsion Test Center on the state of the art of fuel controls, the following conclusion was offered:

> "Fuel control and engine manufacturers are not adequately informed of fuel control problem areas and degree of maintenance required, especially after acceptance of the engine and performance of overhaul operations by the using service."[13]

With this background, it is not possible to provide a numerical allocation of the relative contributions of various failure modes to fuel control problems. In general, the failure modes observed in the study engines can be grouped into the following categories:

- Contamination from the actuating media or from the fuel itself causing sticking and binding of spools, leakage of valves, and clogged orifices
- Wear on moving or contacting elements
- Fatigue failures of springs, bellows, retention devices, etc.
- Misadjustment, erroneous troubleshooting, etc.

The magnitude of the last category has been estimated by one engine manufacturer to be as high as 50 percent.[13] The contribution of the first category depends on the type of actuation system used in the fuel control unit. Fuel control units used in the study engines are hydro-mechanical, except for one pneumatic-mechanical system. The pneumatic system experienced many air contamination problems, but its easy accessibility prevented an unusually high engine removal rate.

The fuel control which contributed approximately 10 times as many unscheduled removals as the average (Figure 38) is significantly more complex than the average. This complexity arises from the several functions it possesses over equivalent fuel controls including its integration into a complete power-management system. This unit is larger than average; it accounts for 7.2 percent of total engine weight as compared to the 2 to 3.5 percent of engine weight for typical fuel controls.[13] This factor, coupled with the general inaccessibility of the fuel control on this installation, contributed to the large UER rate.

Since good failure-mode information was not available, little further discussion on the factors driving the R&M characteristics appears warranted. It is clear that there is not an adequate baseline of R&M history on these components to allow either effective corrective action on existing fuel controls or meaningful trade-offs of functions, mounting arrangements, or types of systems for future designs.

Pumps, Valves, and Other Components

Fuel pumps, purifiers and filters, and associated fuel system components (such as divider assemblies, manifolds, and nozzles) are the three areas that equally share the responsibility for unscheduled removals in this category.

The usual failure modes of fuel pumps are shaft-seal leakage and drive-spline wear. Spline wear appears to be more prevalent on those configurations where the fuel pump and control are mounted in series, with the fuel control driven by shafts and splines extending through the pump, or vice versa. This arrangement reduces the radial size of the engine and eliminates a takeoff pad from the accessory gearbox with its attendant gears, bearings, and seals. Unfortunately, these apparent advantages appear to be outweighted by the spline-wear problem that arises from greater loads, possibilities of misalignment, maintenance damage, or a combination of these factors when the pump and fuel control are mounted in series. Inadequate lubrication was cited as a frequent cause of spline wear which in turn was due to poor preventative maintenance or fuel seal leaks which washed the lubricants from the splines.

Purifier and filter failures have primarily involved purifiers in the study engines. Failure modes included wear of the housing due to interferences when interchanging covers during cleaning, wear of drive shaft pins, elongation of quick disconnect mounting clamps which allowed fuel leakage (see Figure 39), and breaking of mounting flanges (see Figure 40). The sources of these problems were varied. Some wear was due to the interchanging of noninterchangeable components by maintenance personnel; other wear and shearing of the drive shaft pins were due to improper hardness pins (a manufacturing and quality control problem). Breaking of the mounting lugs was

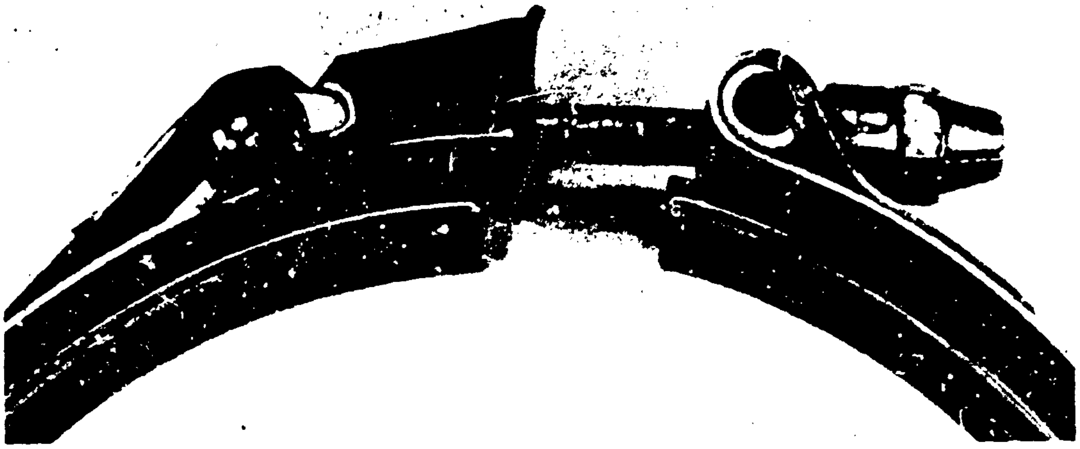


Figure 39. Elongated Rivet Hole on Purifier "V" Band Clamp.

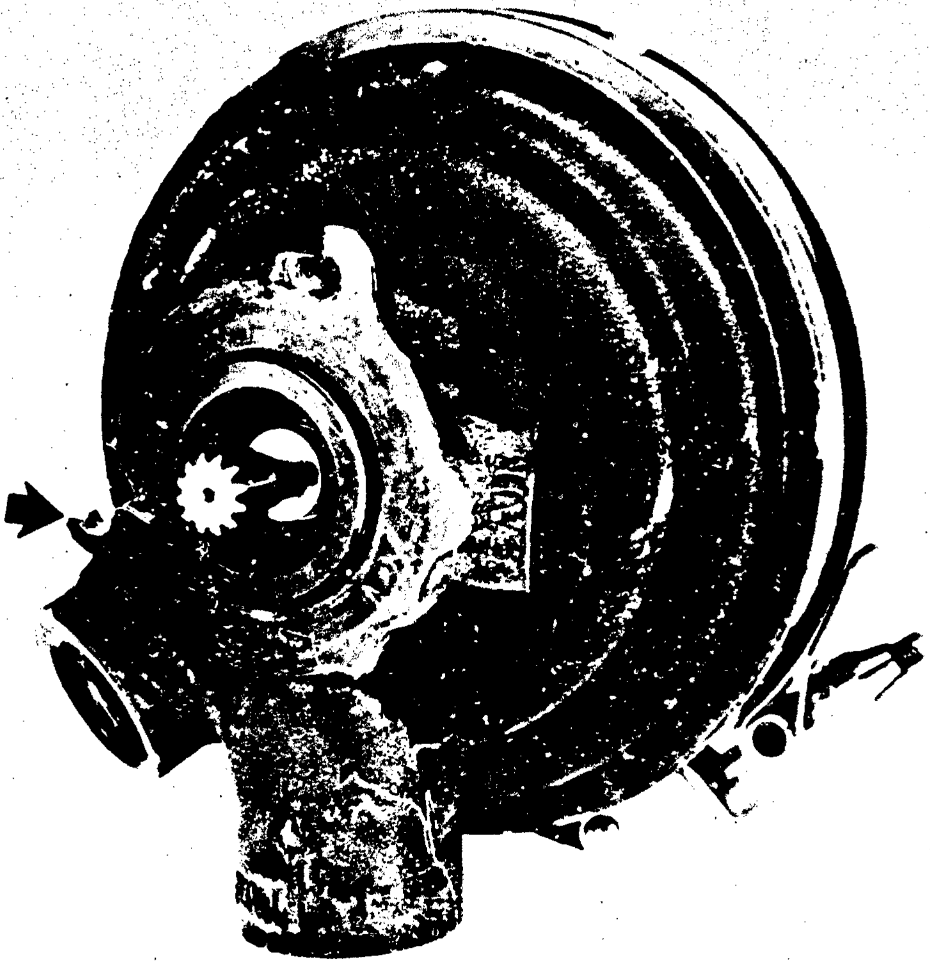


Figure 40. Purifier With Broken Mounting Flanges.

an installation problem where the exposed purifier would contact the airframe or transport stand during engine replacement. Elongation of a quick-disconnect clamp was a straightforward design error which specified an upper limit to the installation torque which would yield the pin hole brackets.

The failure modes of the other components in the fuel system are just as varied as in purifiers and filters. Fatigue failures of clamps mounting manifolds to the engine housings resulted in fuel spillage. Dividers failed due to bellows guide wear. No particular pattern is evident in this grouping of fuel system problems. There will be an increasing tendency for problems with increasing hardware complexity. The effect of poor accessibility has been clearly shown. Engine removal rates are 3 times as high as normal if accessibility is poor.

AIR SYSTEM

The air subsystem contribution to the engine R&M problem in terms of the four parameters is:

Air	UER	Accidents	MMH	TBO	Index
Scale Factors	1	0	1	0	0.55

The problem is clearly a minimal one. Since this subsystem consists only of anti-icing, cooling, or balance air systems and usually involves components which can be repaired or replaced without engine removal, this conclusion should not be surprising. Since no failure mode pattern was evident, further breakdown of this subsystem is performed only on the type of component involved (see Table XXII).

TABLE XXII. AIR FAILURE MODES

Failure Mode	UER	Accidents	MMH	TBO	Index Number
Control Valves	71	-	60	-	70
Tubes, Hoses, Fittings, etc.	29	-	40	-	30
Total	100%	-	100%	-	100%

The distribution of these failure categories among the engines studied for the UER parameter is shown in Figure 41. No conclusions are evident from this figure. Since the small rates represent only one or two occurrences, no failure pattern is evident. No discussion of the failure categories is warranted. The only failure mode which was documented was binding of valves due to air contamination.

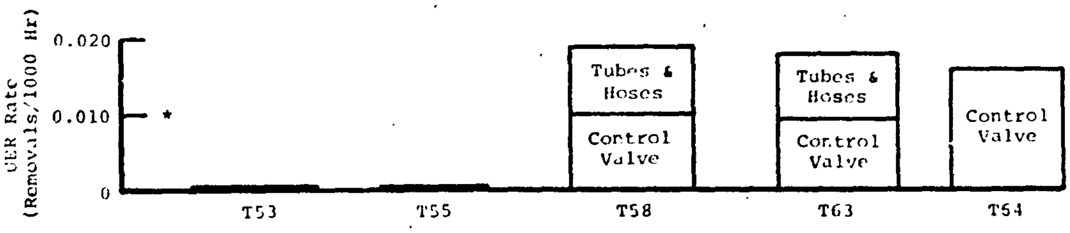


Figure 41. Air UER Rate for Various Engines.

ACCESSORY

The accessory contribution to the engine R&M problem is shown below.

Accessory	UER	Accidents	MMH	TBO	Index
Scale Factors	1	2	2	-	0.91

These scale factors indicate that the accessory subsystem is not a major problem area despite the relatively large number of components involved. The higher scale factor for accidents than removals reflects the fact that failures of the accessory drive train to drive the fuel control or fuel pump can cause immediate power loss.

The types of failures experienced in this subsystem by each of the study engines were so varied that no common patterns were evident to suggest a logical further breakdown. Accordingly, Figure 42 shows the total accessory subsystem contribution to unscheduled engine removals for the engines studied. This figure indicates that the rate for this subsystem is generally consistent among the study engines although somewhat higher than the composite rate of 0.025 removals per thousand hours.

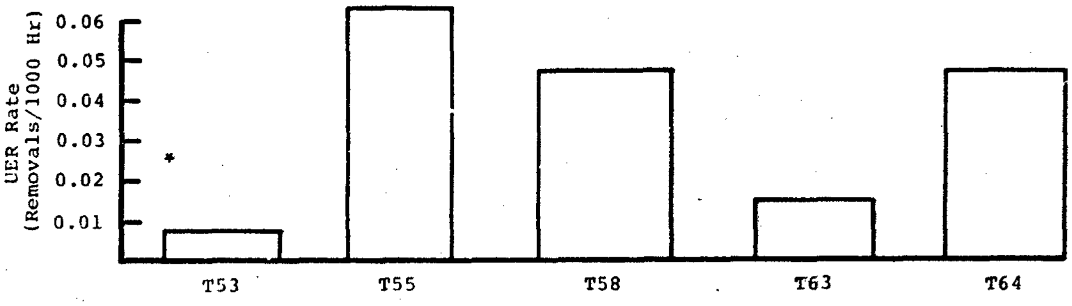


Figure 42. Accessory UER Rate for Various Engines.

The one causal factor that was repetitive among the study engines was inadequate consideration of the effect of the starting cycle on the accessory system. Specifically, problems of gear scoring occurred in one engine due to inadequate lubrication of the gears during engine start-up. In another engine there were problems due to the loads imposed on accessory drive bearings. Failures of the hydraulic starter imposed excessive axial loads on these bearings in one case, while high impact loads of electric starters contributed to bearing failures in the same engine on another aircraft.

Maintenance damage was also prevalent in the accessory system, with failures due to individual unique situations. One problem involved the careless installation of the AGB onto the basic engine, with damage to the accessory drive shaft resulting. A second problem involved unauthorized turning of the compressor by the mechanics using a bearing retention bolt. This caused bolt looseness and loss of axial retention of the gear train. Other failure modes evident were spinning of bearing inner race spacers and shaft/gear Woodruff key wear and/or breakage. Since the accessory subsystem includes such a large number of components, the experienced rate can be considered acceptable.

TORQUEMETER

The torquemeter subsystem contribution to the engine R&M problem is shown below in terms of the four study parameters.

Torquemeter	UER	Accident	MMH	TBO	Index
Scale Factors	2	1	1	0	1.27

To conclude from this chart that the torquemeter subsystem is a significant contributor to the engine R&M problem would be erroneous. The scale factors shown are only as high as they are because of the influence of one specific torquemeter design approach, which was installed in only one study engine. Specifically, an engine that did not include an integral reduction gearbox made use of an electro-mechanical system, which became a significant R&M problem. All of the other engines that use torquemeters also include integral reduction gearing, thus permitting the use of the well-understood conventional hydraulic-type system, which involves sensing the axial displacement of a helical gear. The distribution of torquemeter component failures is reflected in Table XXIII.

TABLE XXIII. TORQUEMETER FAILURE MODES

Failure Mode	UER	Accident	MMH	TBO	Index Number
High-Speed Mechanical System	93	100	93	-	95
Low-Speed Mechanical System	7	-	7	-	5
Total	100%	100%	100%	-	100%

The greater percentage value for accidents than for unscheduled removals for the high-speed system has no significance. Failures of low-speed systems were so infrequent that the relatively small accident data bases did not statistically permit a single accident to occur due to low-speed systems.

The influence of the single high-speed system on the UER rate parameter is also illustrated in Figure 43. Since the T58 and T64 did not have integral torquemeters, their displays have been replaced by displays for two turboprop engines, the T56 and T74. The T56 features a shaft torsional-displacement system (high speed). The T74 incorporates the normal hydraulic (gear axial-displacement) type. The figure shows the influence of the single high-speed system on the composite rate of 0.048 removals per thousand hours. The remaining systems have a generally consistent rate of 0.003 to 0.005 removals per thousand hours.

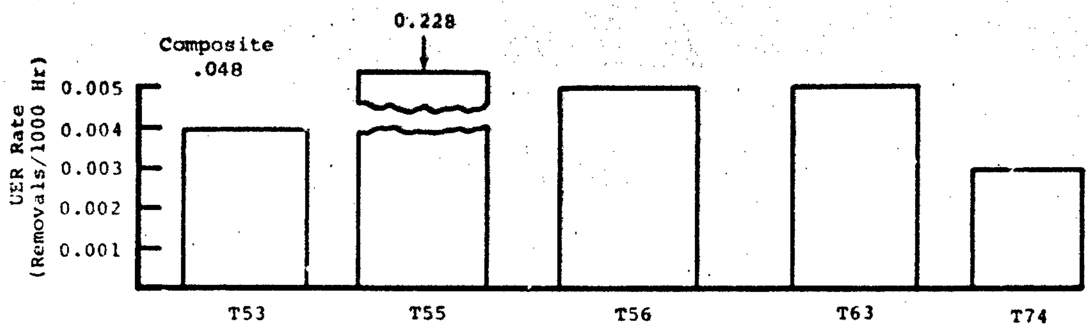


Figure 43. Torquemeter UER Rate for Various Engines.

The high-speed mechanical system is complex (see Figure 44). Spalling was experienced in the bearings, and wear was evident at various locations. One point of wear is illustrated in Figure 45. Maintenance damage was also prevalent in this configuration. Removal of the power turbine shaft required disengagement of the entire torquemeter assembly from the shaft. The tendency for maintenance damage is discussed in more detail under Improper Maintenance.

In contrast to the high-speed mechanical configuration, the hydraulic system is relatively simple (see Figure 46). The failure rates of the hydraulic systems are so low that they only produced one- or two-time occurrences in the data bases used in this study. The only genuinely repetitive failure mode was binding of the spool due to oil contamination.

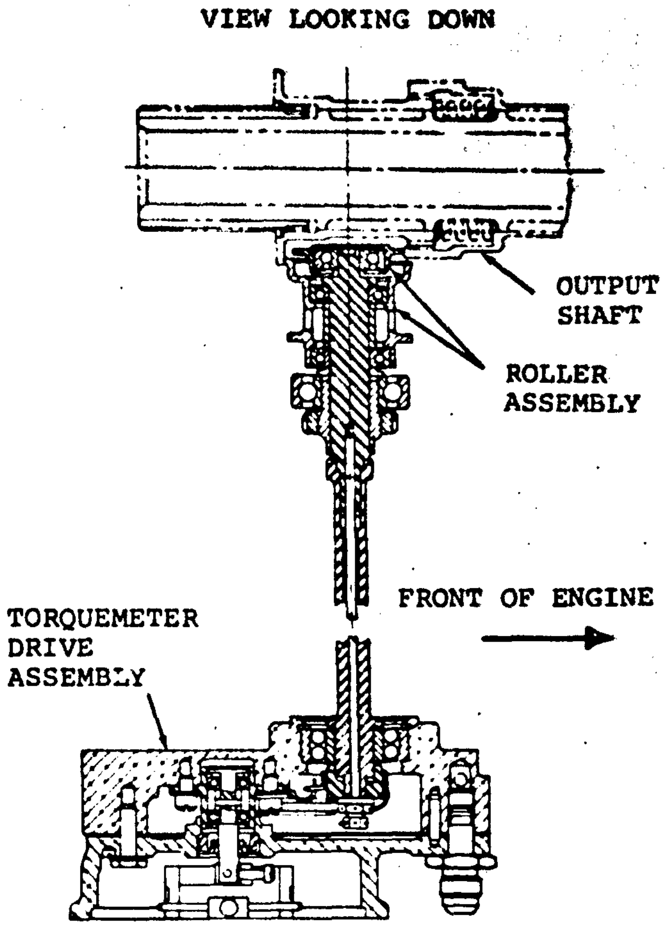


Figure 44. High-Speed Mechanical Torquemeter System.

Figure 45. Wear in a High-Speed Mechanical System.

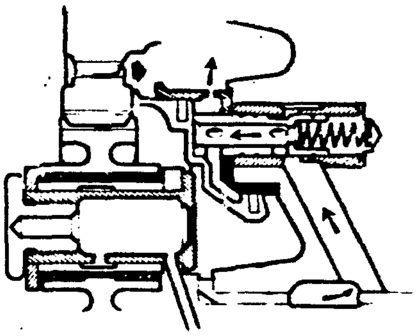


Figure 46. Hydraulic Torquemeter System.

ELECTRICAL

The electrical subsystem contribution to the total R&M problem is shown below for the four study parameters.

Electrical	UER	Accidents	MMH	TBO	Index
Scale Factors	1	1	2	-	0.73

The electrical subsystem is not a significant problem area. This reflects the relative ease of repair of most of the electrical subsystem components without need for engine removal. The electrical subsystem problem is divided among three components. Table XXIV shows the percentage contribution of these components in the four study parameters.

TABLE XXIV. ELECTRICAL FAILURE MODES

Failure Mode	UER	Accidents	MMH	TBO	Index Number
Ignition Components	47	-	40	-	35
Power Management Systems	18	-	50	-	22
Wiring and Thermocouples	35	100	10	-	43
Total	100%	100%	100%	-	100%

The numerical value assigned to wiring and thermocouples as accident causal factors is misleading; it reflects a very small frequency of occurrence in a relatively small accident data base. The distribution of problems among the study engines for the UER rate parameter is shown in Figure 47. Deviations from the average reflect varying levels of engine accessibility in the airframe (T58 and T63) and maturity (T53). A discussion of specific problems follows.

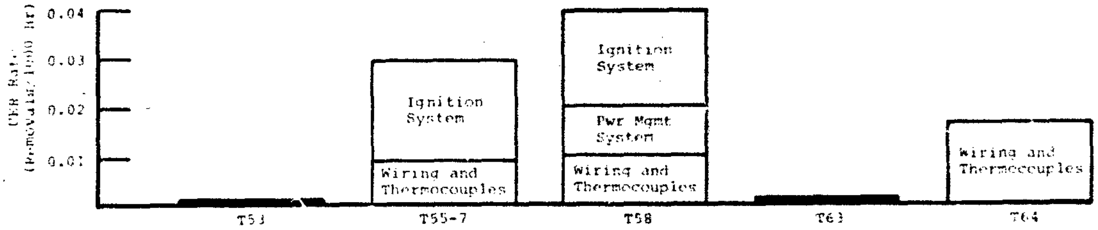


Figure 47. Electrical UER Rate for Various Engines.

Ignition Components

The ignition components which caused unscheduled engine removals were primarily elements of the ignition subsystem black boxes and reflected poor accessibility of the black boxes as installed in the aircraft. The failure modes of black-box elements varied from shorted internal wiring to malfunctioning transformers and filters. Ignitor plugs did not cause any measurable rate of UER's on the study engines.

Power Management Subsystems

Only one of the study engines contained a power management subsystem. Its functions included T5 limiting and assuring equal load sharing in a twin-engine installation. The specific failure modes encountered include relay contact failures in the main amplifier box, moisture-shorted wires at connectors, sensitivity to radio frequency signals, and problems reflecting misrigging or poor troubleshooting of the subsystem.

Wiring and Thermocouples

This problem is the most repetitive mode across all engine models and is largely a thermocouple problem. Failures of thermocouples have taken many forms. Among the modes experienced were sulfidation of the probe tip, fuel/oil entrance into the sheaths causing insulation breakdown and shifting resistance, connector wire breakage, and cracking of mounting housings or sleeves. An example of the latter mode is shown in Figure 48.

Figure 48. Cracked Thermocouple Sleeve.

Engine wiring problems, in contrast to thermocouple problems, are more routine in their failure modes. Moisture entrance into plugs, breakage of wires at the junction to the connectors, and ordinary chafing have been the predominant modes. The causes of these problems are usually traced to inadequate environmental and movement protection. Maintenance damage and aircraft/engine vibration are usually cited as contributing causes. An example of wire chafing is shown in Figure 49.

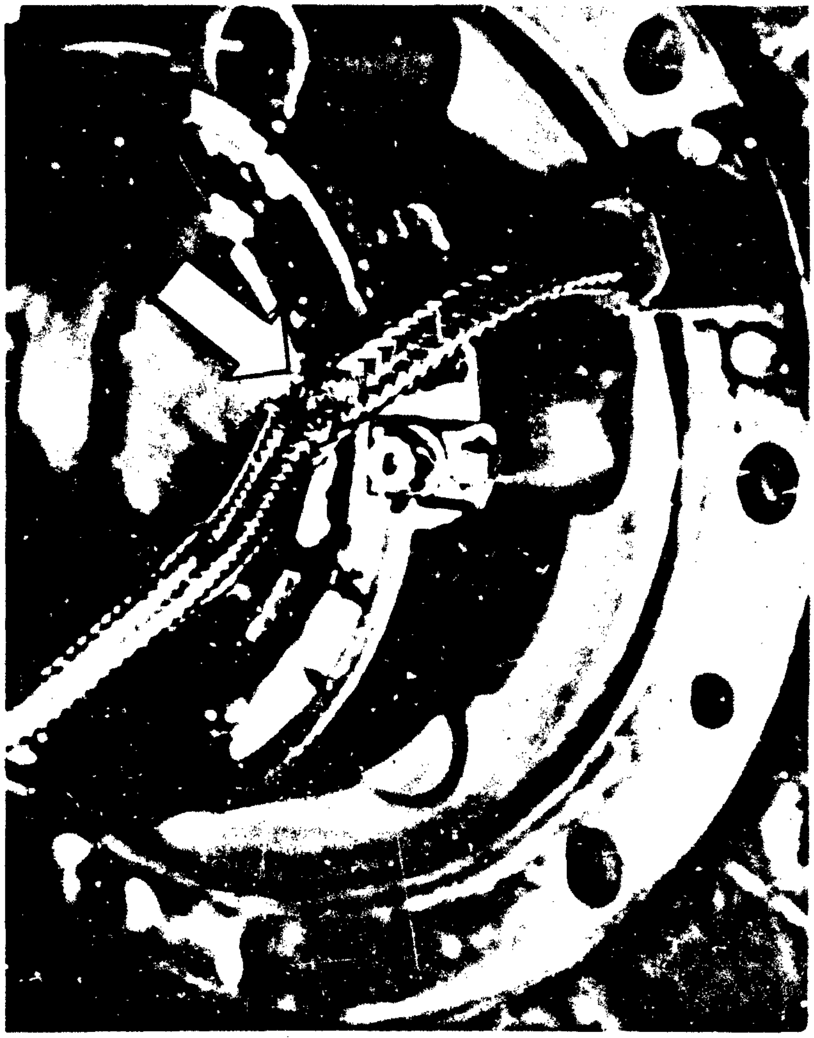


Figure 49. Alternator Cable Chafing.

POWER-TRAIN REDUCTION

The contribution of the power-train reduction subsystem is shown below in the four R&M parameters.

Power-Train Reduction	UER	Accident	MMH	TBO	Index
Scale Factors	1	1	1	-	0.72

The chart shows that this subsystem is a small contributor to the R&M problem, with only two subsystems (air and exhaust) having lower index numbers. Since some of the engines examined in this study did not have an integral power-train reduction function, the above scale factors represent an average from only those engines with this feature. If the scale factors represented the average of all engines, the value would be approximately half that shown. Therefore, this subsystem's contribution to the total R&M problem is small.

Because of these low rates, insufficient failures were experienced to establish any clear failure patterns. Figure 50 shows the rates for the total subsystem for the 3 engines with integral gearboxes. Two models of the T53 are shown: the basic -11 series which has previously been discussed and the -13 which is an uprated model. The removal rate for the speed-decreaser gearbox for the T58 when installed in the UH-1F is also shown for general interest. This gearbox is used in conjunction with the T58 when installed in both the UH-1F and H-2 series aircraft. The rates for the T63 are those experienced by the power-train reduction components but which were coded into the subsystems of bearings or seals.

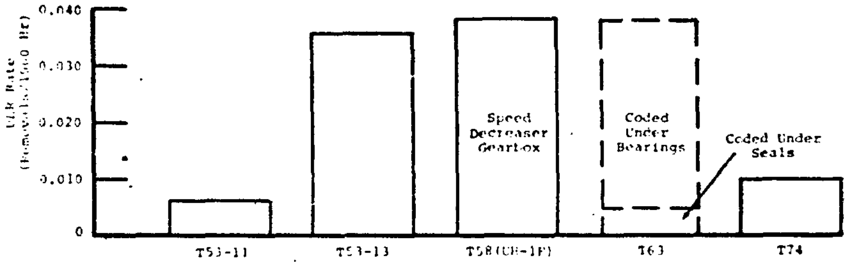


Figure 50. Power-Train Reduction UER Rate for Various Engines.

Figure 50 indicates that reduction-gearbox-caused removal rates are generally consistent; the two exceptions, the T53-11 and T74, are explained on the basis of being more mature than the other engines studied. The failure modes experienced can be grouped into three categories: bearings, retention hardware, and seals. Further discussion is not possible due to the lack of failure-mechanism definition.

EXHAUST

The contribution of the exhaust subsystem to the total engine R&M problem is shown below.

Exhaust	UER	Accident	MMH	TBO	Index
Scale Factors	1	0	1	0	0.55

This chart indicates that the exhaust subsystem is a minor problem compared to other engine subsystems. This subsystem and the air subsystem have the lowest index numbers of any subsystems. The low frequency of occurrence experienced in the study engines did not permit any pattern or classification of failures to be established. The distribution of the total rate among the study engines is shown in Figure 51.

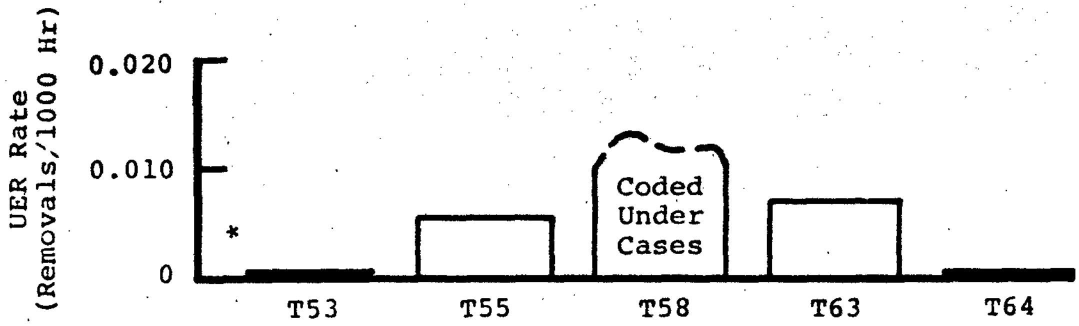


Figure 51. Exhaust UER Rate for Various Engines.

There is a generally consistent rate among the study engines, with exceptions reflecting either high maturity (T53) or a subsystem definition problem (T58). Since it is a rear-drive engine, the T58 exhaust casing also serves as the main support for the power turbine assembly. As such, it is considered as primary casing, and all problems associated with this assembly on the T58 were coded in the case subsystem. In the discussion concerning the relative rates of the case subsystem among the study engines, it was suggested that the rear-drive configuration created additional problems since the T58 and T73 experienced high case-caused removal rates. This suggestion is somewhat reinforced here with the T73 experiencing a removal rate of 0.021 (approximately 5 times the composite rate). The two engines with amidships exhaust configurations (T63 and T74) experienced exhaust rates slightly above the average. The T74 exhaust rate was .009 (see Table V).

Problems with exhaust components have usually been fatigue failures of structure at the intersection of exit guide vanes or struts. Some minor problems have been experienced with the retention systems of the inner cones on engines possessing that configuration. Both of these problem areas appear more often early in the development cycle. They are the kind of problem where adequate design analytical predictive techniques do not appear to exist but are relatively easy to resolve early in the test program. By the 1-million-hour point, they have usually been corrected; hence the rates displayed here are relatively low.

FOREIGN OBJECT DAMAGE

The contribution of foreign object damage (FOD) to the total engine R&M problem is shown below in the four R&M parameters:

FOD	UER	Accident	MMH	TBO	Index
Scale Factors	10	7	5	-	6.71

This problem has the highest index number of any single subsystem or failure cause in the engine. It has caused more unscheduled removals for failure than any other subsystem or cause and ranks fourth in listings of both accidents and man-hour expenditures. Since it represents random occurrences (not a function of component operating time), impositions of TBO's are not appropriate as a means of rate control.

The FOD problem is basically one of compressor damage. Over 90 percent of the incidents reported are caused by compressor vane or blade damage.[14] The sources of FOD can be classified in four categories:

- Objects with an origin outside the engine which are unrelated to the engine or aircraft (such as birds, ice, ordnance, etc.)
- Ground debris (such as rocks, pieces of failed tires, debris from accidents, hardware, etc.)
- Aircraft-originated objects (such as probes, fasteners, covers, etc.)
- Items left in the engine area during repairs or inspections (tools, flashlights, cloths, nuts, bolts, etc.)

These categories are based on the origins of the objects rather than the types of objects. This identification of FOD sources is necessary for effective corrective action in the future. The first two categories are operational hazards whose origins are basically uncontrollable. The second two categories are the product of either the design of the aircraft or the procedures of the maintenance personnel. Each requires its own particular corrective action. Categorization of all FOD into these four groups has been difficult in the past. Frequently, the object that caused the damage is unrecognizable or has been consumed in the process of combustion. When the object is recognizable, its origin may not be obvious (i.e., a bolt could have come from the ground, the aircraft, or from prior maintenance in the engine area itself). Thus, it is usually easier to identify the nature or type of the object than its origin.

The only available quantification of types of FOD is provided in a series of periodic reports published by the Naval Air Technical Services Facility.[14] A summary of the types of FOD, where identification was possible, is provided in Figure 52 which represents 70 events over a 6-month period ending in December 1967. The lack of origin identification is obvious when examining this figure. The largest category (tools and hardware) could originate either from inside the engine area or from external sources. The same situation applies to the second largest category (rags, cloths, etc.). Nearly half (43 percent) of the FOD has origins that cannot be isolated. The relatively small contribution of aircraft/engine inlet components (7 percent) may reflect the nature of the data base which included mostly fighter, transport, and patrol and attack fixed-wing aircraft with only a relatively small number of incidents from helicopter engines (10 percent). Fixed-wing aircraft do not normally utilize screens or other protective devices and are therefore not subject to the failures historically attendant to these devices.

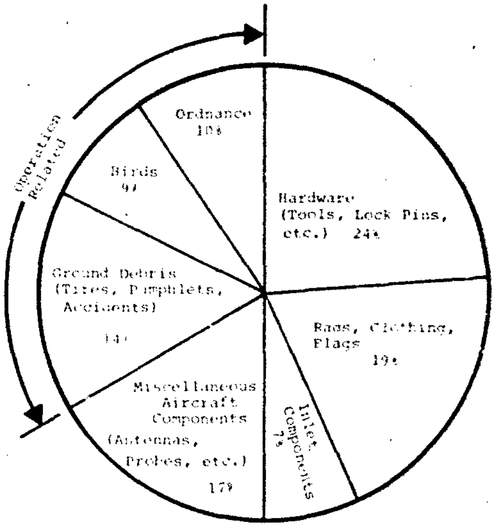


Figure 52. Sources of FOD.

Despite our inability to quantify the exact sources of FOD to turbine engines, the resultant effects in terms of accidents, unscheduled removals, and maintenance man-hours have been quantified. This quantification was shown in Table IX to represent the experience of the composite engine. The engines in the data bases examined were equipped with various degrees of protection. Some engines had no protection devices, some had devices installed on only part of the fleet, and others were equipped with filters or screens throughout the fleet.

To provide more perspective on the quantitative effects of FOD, the rates of unscheduled removals for FOD on a variety of Army, Navy, and Air Force aircraft are displayed in Figure 53. Not all of the engine data points shown were used to calculate the composite engine rate. Three basic divisions are shown on Figure 53: helicopters without any specific FOD protection devices, helicopters with some type of protection (whether it be screens, full barrier filters, or panel type inertial separators), and fixed-wing aircraft, which normally do not possess protection devices (the exception is the T74 which has an integral protective screen around its center body air intake). The engines are arranged within these three divisions in descending order of rates. Efforts were made to obtain data on the same engines in different aircraft with and without protection and performing a variety of missions.

Analysis of this data suggests that there are six basic factors which affect the FOD rates experienced:

- Mission type
- Environment
- Aircraft installation
- Extent of protection
- Engine compressor design
- Sortie length

These factors affect the FOD rates in varying degrees. Full extremes of variations were experienced in some factors. For example, the mission category included assault missions from unprepared sites as well as ASW missions from prepared sites, of long durations over water. Other factors, such as the extent of protection, are not complete in that the FOD rates when using second-generation engine-integral self-purging inertial separators are not available. Also, the factor of compressor design is not complete in that an FOD rate on an all-centrifugal compressor design was not available. Despite these limitations, an estimate was made of the separate

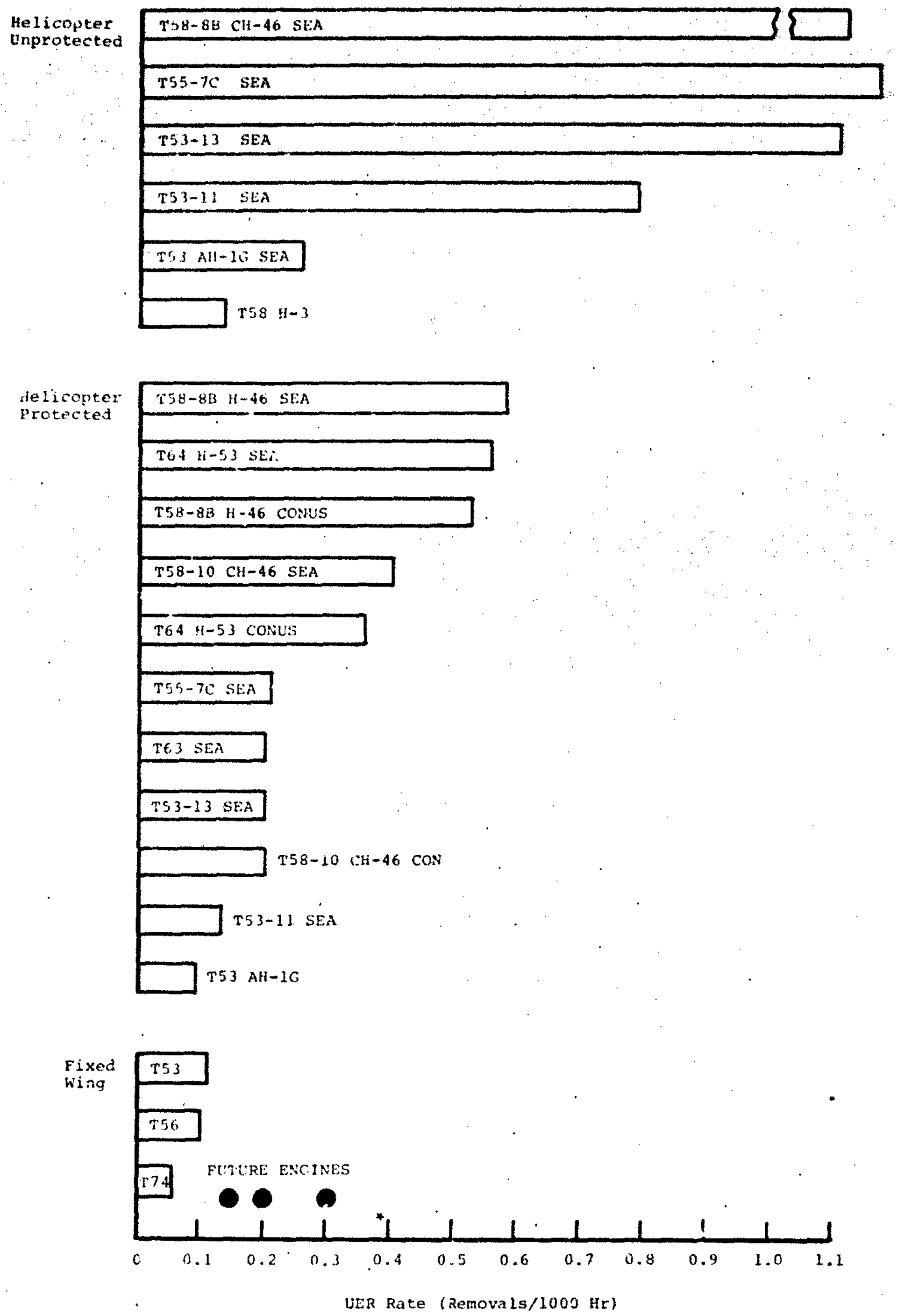


Figure 53. FOD UER Rate for Various Engines and Aircraft Installations.

effects or contribution of each of the six factors based on the available data. The effects are expressed as multiplying values in Table XXV.

TABLE XXV. FACTORS THAT AFFECT FOD

	Maximum Effect	Minimum Effect
Mission	8	-
Environment	2	1.6
Acft. Installation	2	1.5
Protection	6	3
Compressor Design	3	-
Sortie Length	3	-

Mission, environment and sortie length are intrinsic to operational requirements; therefore, sources of relief must be found by the variables of protection, compressor design, and to a lesser extent, aircraft installation features.

The extent of protection area offers the most potential for reduction of FOD rates. The composite rate represents the current mixture of protection devices. They range from the simplest of coarse screens mounted remote from the engine at the aircraft intake to screens mounted on and surrounding the actual engine, and from full-barrier filters with no bypass capability (in terms of the basic screen) to panel-type inertial separators with bypass doors. The extent to which each of these configurations has reduced the FOD from the four basic sources previously mentioned is not obvious without the further identification of the actual FOD objects. It is clear that while there have been significant reductions in FOD rate from the incorporation of these devices, they have also introduced their own problems. Latch, fastener, and actual mesh/ filter/separator failures have caused FOD. These devices may also encourage maintenance-induced FOD due to the frequency of scheduled cleaning/inspections and the additional difficulties of observing tools or hardware left in the intake area. They are also subject to combat damage due to gunfire where the unit either breaks up or retains the projectile. In several instances the installation of the protective devices did not assure a complete barrier due to gaps in connection of the device to the airframe. These gaps permitted FOD.

Compressor design can be very influential in determining FOD rates. The differences in the inherent abilities of certain compressor designs to withstand the entrance of foreign objects are obvious in examining Figure 53. The axial/ centrifugal compressors appear to be two to three times more resistant than the axial designs. No data from all-centrifugal designs were available for inclusion in the analysis.

Aircraft installation features also play a significant role in determining FOD rates. Whether the engine intake is high or low on the aircraft, its proximity to high-frequency maintenance work areas, and whether it is mounted in a pod outboard of the fuselage or near the centerline (where the fuselage acts as a shelf to collect and route debris into the intake), are all factors which have been shown to influence FOD rates.

Foreign object damage (its current sources, the effectiveness of past and current remedial actions, and its future magnitude) is an extremely complex subject which has only recently been approached with any sophistication. Analysis of available data shows that the simple answer of screen installation is obviously inadequate. The inability to understand and quantify all of the factors affecting FOD rates will make it difficult to predict the magnitude of the problem for future engines.

Without this prediction cpability the necessary trade-offs that must be performed in the near future cannot be accomplished in a conclusive manner. Specifically, several production aircraft/engine configurations with particle separators are currently being designed. Whether these configurations require FOD screens in addition to the particle separators is a question largely unresolved. The lack of a complete and thorough documentation of the FOD problem and the technology of potential improvements is most likely the cause of continued conflicts of opinions in this area.

EROSION

The contribution of the erosion problem to the total R&M problem is shown below for each of the four R&M parameters:

Erosion	UER	Accidents	MMH	TBO	Index
Scale Factors	4	4	4	0	2.90

This chart indicates that the magnitude of the erosion problem is significant. It is the fifth highest UER problem and has the fourth highest index number. Where this mode, primarily a power loss issue, combines with erosion/corrosion-induced fatigue failures of vanes and blades (discussed under the compressor subsystem), the problem takes on an even greater magnitude.

Usually, erosion of turbine engines is a very gradual process which is apparent through a loss of available power at a given operating temperature. As such, this mode should not normally cause accidents. However, erosion of compressor components also has the effect of reducing the compressor-surge margin. In certain compressor designs, this loss is more critical than the loss of steady-state power. Table VI indicates that the high scale factor shown for accidents is due to one engine/airframe installation with a relatively high accident rate due to erosion. This rate was due to accidents which usually occurred during a flared landing where a sudden application of power on eroded engines caused surging and loss of full power. This erosion loss of surge-margin should be considered when establishing new requirements and testing procedures.

Although the erosion phenomenon is a time-dependent mode (unlike FOD which is a random occurrence), it has not influenced TBO intervals in the past because, although the amount of erosion damage is cumulative and increases with operating time, the process only occurs if the engine is exposed to an erosive environment. Thus, it would be inappropriate to establish a fleet-wide TBO interval for engines when they see only partial or no erosive environment. Additionally, the effect of erosion in terms of power loss is usually very detectable and thus allows removal of engines before they reach a point of threshold deterioration. The problem of inadequate surge margin is an exception.

Erosion is primarily due to the passage of sand and dirt (below 1000 microns) through the engine and is basically a compressor performance issue. Engine removal from service is almost exclusively due to losses in compressor performance, although a few sand-related turbine problems have been experienced during specialized test programs such as accumulation of semimolten material on the first-stage turbine vanes[15] or erosion of the protection coatings on turbine blades and vanes.[16] The T64 experienced field erosion of the honeycomb turbine shroud which contributed to nearly 40 percent of the total performance loss.[17] Normally, however, compressor blades (see Figure 54) and vanes (Figure 55) are the most critical items.

The magnitude of the erosion problem, as represented by the composite engine rate, results from a combination of engine designs, aircraft installations, and degrees of protection. In order to provide perspective of the impact of the factors affecting erosion rates, the erosion-causing removal rates of a variety of engines installed on fixed-wing aircraft and helicopters are shown in Figure 56. Two basic divisions are shown: those rates experienced on aircraft which do not incorporate any means of protection or filtration, and those which do. The rates displayed on this figure (like the FOD rates displayed in Figure 53) are dependent on the exposure to specific environments, in this case sand and dirt. Also, since the

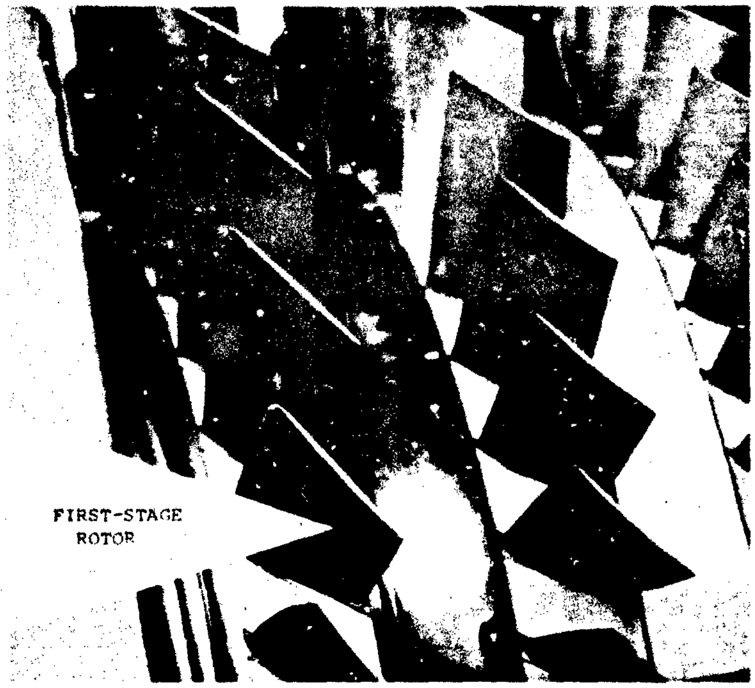


Figure 54. Erosion of Compressor Blades With Curled Leading Edges.

Figure 55. Erosion of Compressor Vanes After Severe Test Conditions.

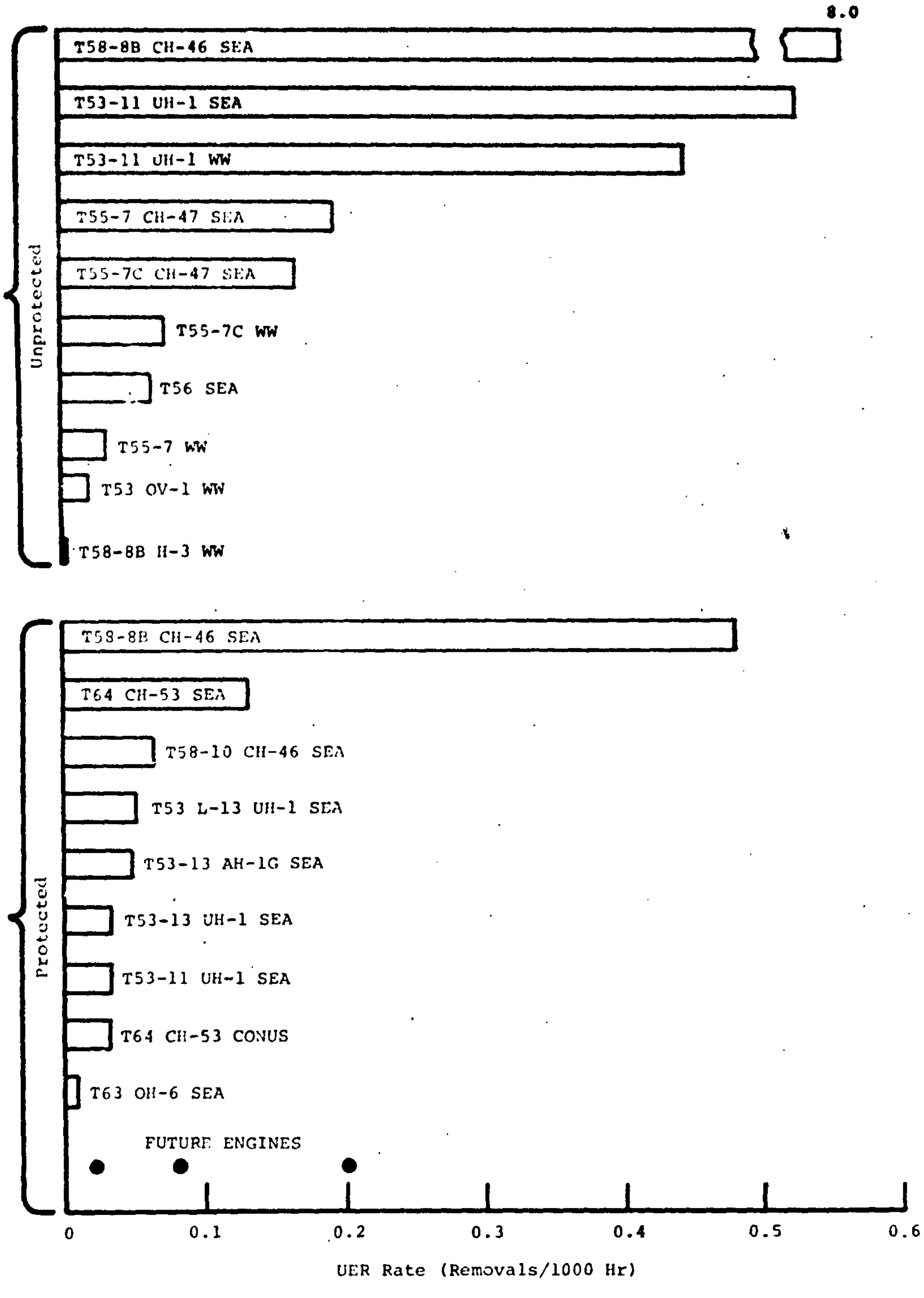


Figure 56. Erosion UER Rate for Various Engines and Aircraft Installations.

erosion process is cumulative and therefore has an increasing failure characteristic with operating time, the TBO level on the engines will affect the actual UER rates due to erosion. Since the aircraft/engines used in the analysis could not experience the precisely same environment and had varying levels of TBO, caution should be used when comparing the rates.

The various factors which ultimately define a UER rate for erosion are similar to those which determine FOD rates:

- Mission type
- Ground environment
- Aircraft installation
- Extent of protection
- Engine compressor design
- Sortie length

The separate effects on erosion of each of these factors have been quantified by the industry to a further degree than they have been for FOD. Considerable time and funds have been allocated to quantifying and understanding these effects.

The ground environment has been addressed in a host of studies and papers too numerous to reference. Both the particle size and chemical distribution of ground environments throughout the world have been described.

The aircraft downwash and recirculation pattern effects on both the contaminant concentration and particle size distribution are less well known. Studies have indicated that the effect of rotor disc loading and hover height upon the concentration and particle distribution can be significant factors in determining what contaminants will be ingested into the intake.[15]

The specific design of the engine/airframe interface and the height and location of the intake are other factors that have been shown to be important. Designs which scoop or trap airborne particles and direct them to the engine are obviously inferior to remote pod-mounted designs, where the rotor downwash can be used to sweep the engine intake area clear of airborne particles.

The extent of protection is one of the most important considerations. It is a factor with a high erosion reduction potential and one over which the customer and contractor have direct control. The evaluation of filters and particle-separator hardware has been accompanied by an increasing ability to quantitatively predict their benefits. The normal means of expressing the effectiveness of these devices is by measuring the percent by weight of various size particles removed.

Is is not possible to review all of the developments in the evolution of protection devices. It is sufficient for review purposes to indicate that efficiencies approaching 98 or 99 percent are being achieved on the latest separator designs at their optimum particle size. The past levels of efficiencies experienced in the engines shown in Figure 56 were considerably less (60 to 80 percent). Despite these low efficiencies, reductions of rates from unprotected to protected by factors of 10 to 15 are evident. Clearly, the technology for achieving significant benefits from the installation of protection devices is available.

Engine compressor design is nearly as influential as the extent of protection. While the maximum effect of extremes of compressor designs on FOD rates was shown to be only 3 (see Table XXV), the maximum effect for erosion is as high as 8 or 10. The factors which define the compressor's ability to withstand erosive particles are both aerodynamic and mechanical. The aerodynamic trends toward high efficiencies in compressors have been accomplished by the use, in some instances, of axial flow compressors with thin blades and vanes in the latter stages and minimum air leakages through reduced clearances. In a study concerned primarily with the aerodynamic factors in compressor designs,[18] analysis of existing engines indicated that the relative tolerance of axial compressors could be related to expressions which basically describe the work performed by each stage. Stage relative tangential velocities were also found to be a good indicator of total erosion resistance (as well as a means of isolating critical stages). From a mechanical standpoint, the blade and vane materials and coatings are perhaps the most critical. Limited tests have shown that titanium has a lower wear resistance than steel by a factor of at least 1.4[19], and aluminum is another factor of 2 lower than titanium.[16]

The relative erosion characteristics of axial versus centrifugal compressors have not been well quantified. Despite the importance of this understanding in engine configuration development, few tests or analyses have been performed that would allow direct comparison. One of the few studies available[19] indicated that under similar concentrations and particle distributions, a centrifugal design would take twice as long to reach the same power loss as an axial design for the same mass flow and pressure ratio.

The capability of an engine to withstand the induction of erosive particles is usually described by a finite weight of material that can be ingested before a given percent of power degradation is reached. This is possible, since tests have demonstrated that erosion is independent of the concentration of the contaminant in the air. The total weight, however, is specified for a given distribution of particle sizes and materials, since they have been shown to have a significant effect on the erosion rate. Generally, the larger size particles cause greater erosion for a given total weight.

When the erosion characteristics of engines are described in this manner, the variables of airborne concentration, sortie length (exposure time to sand and dirt), and the effectiveness of protection devices need not be specified. Goals are established in terms of total weight of sand and dirt at a given distribution, and accelerated tests can be performed to verify compliance.

The effect of many various compressor approaches has been relatively well quantified through the analysis of field data, and more importantly, from controlled tests. Although not documented into one single report or analysis, the technology appears to exist to calculate the compressor erosion tolerance requirement based on:

- Separator efficiency
- Required minimum removal rate
- Percent of time exposed to sand
- Ingestion concentration

An approach for graphically relating these five variables is given in Reference 20 which allows solution for any one variable when given the other four.

Erosion is an extremely complex subject whose full technology cannot be adequately summarized in this short treatment. The major point is that erosion is a failure mode, and it can be predicted and therefore controlled, to higher degrees of accuracy than many other areas of the engine R&M problem.

ENVIRONMENT

The contribution of this subsystem to the total R&M problem is shown below for the four parameters:

Environmental	UER	Accidents	MMH	TBO	Index
Scale Factors	2	0	0	0	1.09

The significant difference in the scale factors for accidents as opposed to UER's does not reflect a passive nature for failures in this subsystem. Rather, it reflects a coding problem. While significant numbers of unscheduled removals are attributed to factors termed environmental causes, few accidents are as clearly identified. This problem, typical of many non-engine-caused problems, suffers from a lack of sufficient detail that would allow consistent categorization among engines and among the four parameters. Additionally, when events cause accidents instead of merely unscheduled removals, a further contributing factor of pilot or maintenance error is involved. Corrosion that has progressed to a point where it causes an accident has usually been overlooked by maintenance personnel. Contamination that is large enough to cause oil-jet blockage and oil starvation is frequently due to maintenance errors (such as chipped O-rings, foreign objects, etc.) rather than fine airborne dirt associated with environmental caused UER's.

Environmental problems can be subdivided into several major failure modes. The distribution is shown in Figure 57. The distribution of these modes for the study engines is shown in Figure 58. Figure 57 indicates that the composite rate of 0.059 UER's per 1000 hours is driven strongly by one (T58) or to a lesser extent, two (T63), engines in the analysis. The rate for the T63 is clearly higher because of hot starts. This rate is additive to the hot starts shown in the operator-induced area and represents occurrences when the ambient conditions, not pilot technique, were the primary cause. Without the hot-start rate, the T63 would have a rate close to the apparent generic rate of 0.020 UER's per 1000 hours. An additional discussion of this mode was given in the Operator-Induced Removals section.

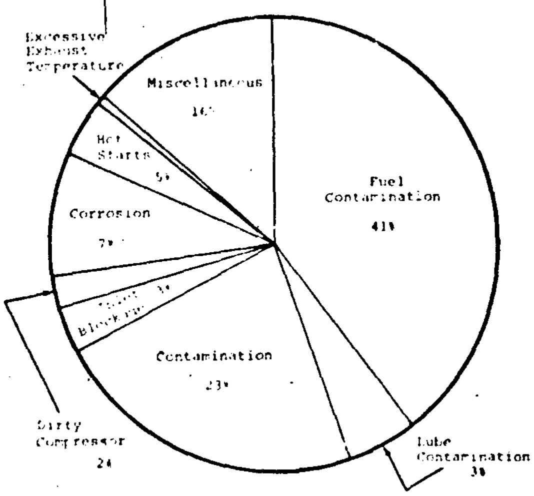


Figure 57. Environmental Failure Modes.

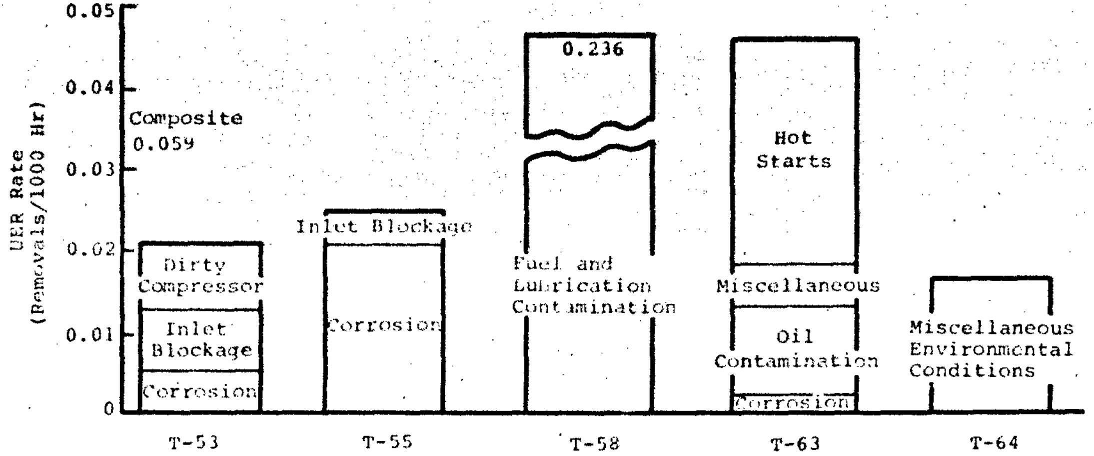


Figure 58. Environmental UER Rate for Various Engines.

The unusually high rate for the T58 warrants more discussion than the data permits. While a factor of two can be attributed to the poor engine accessibility when installed in the CH-46, there is still a factor of 5 that requires explanation. Since the T58 rate was not separable into fuel and oil contamination, the relative contributions cannot be estimated. The source of oil contamination is frequently not uncovered during teardown of the engines. Reports show that over 50 percent of engines removed for oil contamination were erroneously removed. Whether the use of labyrinth seals on the T58 allowed excessive airborne contamination of the lubrication system or the seals themselves were contributing to the contamination as they wore in is not known.

Fuel contamination was known to be a problem and was significantly reduced with the incorporation of an airframe fuel filter.

The comparatively high corrosion rates for the T53 and T55 are due to the large amounts of magnesium used in the inlet and compressor sections. While the coatings which have been developed appear adequate for normal use, they may be subject to erosion or maintenance damage (scratches). The T63, which uses magnesium for compressor components, also experienced some corrosion. The T58 and T64 contain no magnesium.

Additional discussion of the failure modes in this subsystem is difficult because of the lack of definitive information. It is unlikely that the environments encountered by these engines were significantly more severe than those outlined in their basic specifications. Hence, there appears to be little rationale for any significant rate in this area. The coding of problems in this area reflects the inability to identify the actual problem more than the severity of the environment.

Future R&D programs must provide more detail on these non-engine-caused removals to allow precise identification of problems.

Operator-Induced Removals

This subsystem's contribution to the total engine R&M problem is shown below in the four parameters.

Operator Induced	UER	Accidents	MMH	TBO	Index
Scale Factors	4	2	1	0	2.54

The operator-induced area is only a medium-sized problem area, when considered in terms of index number. Yet, it causes more unscheduled engine removals than any engine-caused subsystem except seals. It does not cause many accidents, since most removals in this area are precautionary, and no actual hardware discrepancy is observed.

Operator-induced removals can be caused either intentionally or unintentionally, although the events themselves cannot always be categorized in this manner due to inadequate description of the circumstances surrounding the incidents. This lack of good data reporting, coupled with the lack of priority that non-engine-caused problems appear to receive, prevents a conclusive distribution of failure modes being established. However, based on limited samples and discussions with representatives from the various engine manufacturers, the following breakdown is suggested for unscheduled removals:

. Hot starts	25 percent
. Overspeed/overtemp	20 percent
. Low power	
. Not confirmed	15 percent
. Miscellaneous	40 percent
Total	100 percent

These modes do not usually contribute to accidents, since they are normally only precautionary removals. Accidents occur due to situations such as inadvertent fuel shutoff, fuel exhaustion, or misuse of engine controls. The use of leaded gas, which caused several accidents, is considered a maintenance error and is coded in the Improper Maintenance section. We recognize that some of these incidents occurred due to operator actions, particularly under emergency situations, and should be coded in this section; once again however, inadequate description of accompanying circumstances prevents this distinction. The breakdown of failure modes above does not provide a clear perspective of intentional versus nonintentional events. The three identifiable modes and the many modes which contribute to the miscellaneous 40 percent can each be generated by deliberate actions. The distribution of these failure modes and the absolute rates in the UER parameter are shown in Figure 59.

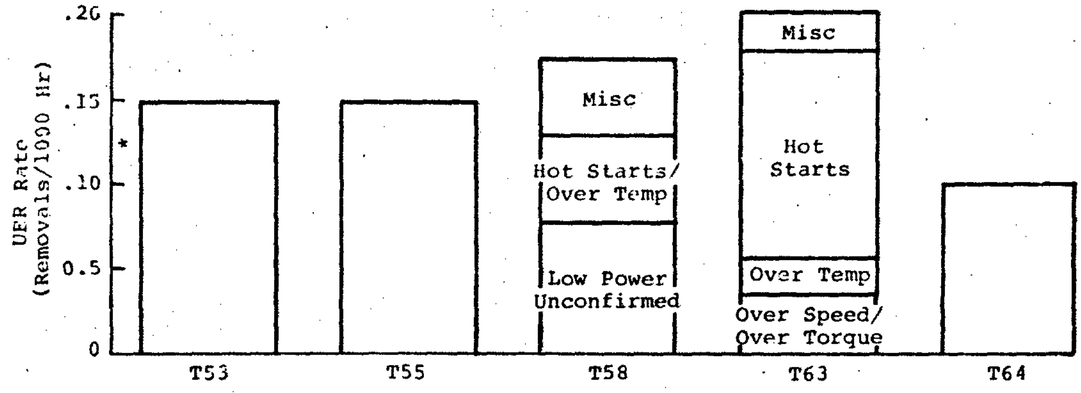


Figure 59. Operator-Induced UER Rate for Various Engines.

This figure indicates that the rate of unscheduled removals due to this mode is relatively constant among the study engines, and suggests that the rates may be due more to the personnel operating engines than to the design itself. Certain higher-than-average rates, however, reflect certain design characteristics of the engines. Specifically, the T63 had an unusually high hot-start rate, which can be traced back to a fuel mixture problem during starting which was later corrected by fuel control system modification. The significant portion of unconfirmed low power on the T58 was no doubt related to the high erosion rates experienced on this engine as shown in Figure 56. Complete mode distribution was not performed on the remaining engines due to insufficient detail of the reported events. This subsystem is a prime example of a collection of failure events which require more attention in future R&M data-collection programs, if future engines and operators are to benefit from past experience.

Improper Maintenance

The contribution of this subsystem to the total R&M problem is shown below for each of the four parameters.

Imp. Maint.	UER	Accidents	MMH	TBO	Index
Scale Factors	8	4	4	-	5.09

As the chart indicates, this subsystem contributes heavily to each of the parameters except TBO limitations. It is the third highest identifiable cause of unscheduled removals and is also high in causing accidents. The data includes only those events where improper maintenance was proven to be the cause. It is probable that many more events involved improper maintenance, but positive proof could not be established. In actuality, the real contribution is probably considerably higher.

Maintenance errors take many forms; some are errors of commission, while others are errors of omission. Future corrective action requires a more detailed definition of the specific mechanisms of maintenance errors. Toward this objective, large samples of unscheduled removals on each of the study engines were examined in order to identify common failure mechanisms. Based on over 350 actual cases of improper maintenance on the five study engines, the distribution shown in Figure 60 was identified.

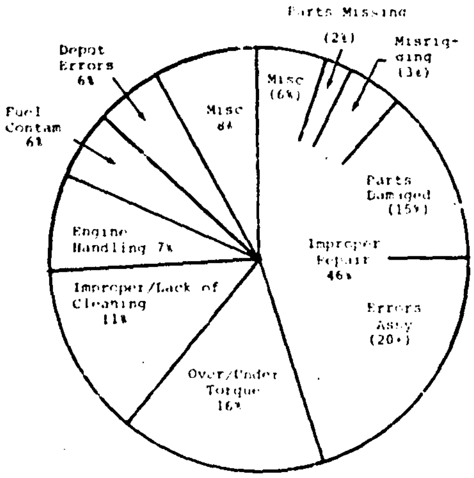


Figure 60. Improper Maintenance-Caused Removals.

These categories are largely self-explanatory, with the category of improper repair being a general one that represents actual damage to the hardware in the process of repair. The category of over/under torque is also damage during repair, but its high contribution as a single identifiable mechansim appeared to warrant separate categorization. The category of depot errors could also be actual damage, but past interest in this source of problems also justifies a separate listing. This distribution of problem areas is rather consistent for each engine examined, although the absolute rates varied considerably. The distributions for various engines are shown as a percentage of the total in Figure 61.

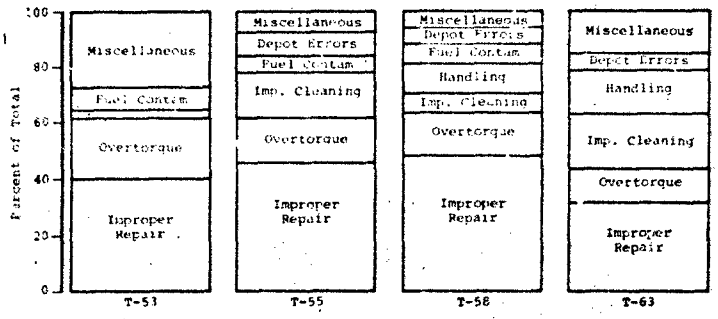


Figure 61. Distribution of Improper Maintenance UER's - Various Engines.

The fact that the distribution is consistent among the engines examined suggests that the rate of maintenance error is not due to uniquely poor design characteristics of any engine, but is more a function of the general skill and motivation levels of the maintenance personnel. The suggestion is supported by Figure 62 which plots the rate of unscheduled removals due to maintenance errors against the total unscheduled removal rates due to engine causes.

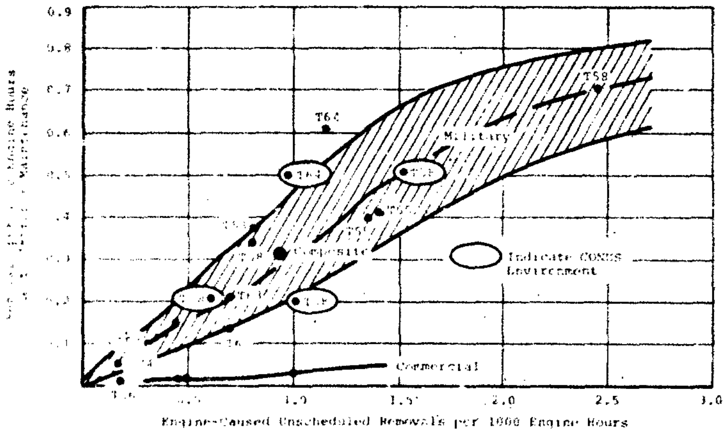


Figure 62. Improper Maintenance UER Experience.

The high degree of correlation suggests that the magnitude of the maintenance-error problem is directly related to the frequency of total maintenance exposure of the engine. If a more direct measurement of total touch frequency were available, an even better correlation might be evident. Another observation available from Figure 62 is that there does not appear to be any discernible difference in the maintenance error rate between the various military services or, even more surprising, no discernible difference between a combat environment, such as Southeast Asia, and CONUS.

An additional observation concerns the significant difference between the military band of data points and the few points from commercial usage. Much of this difference may be due to the significant disparity in sortie lengths between the military and commercial data groups. The military data is largely helicopter experience of short sortie lengths, while the commerical data is fixed-wing experience with considerably longer sorties lengths. Since maintenance damage only occurs while an engine is being repaired or inspected (therefore, on the ground), longer sortie lengths would have the effect of decreasing the events-per-hour rate. Nevertheless, Figure 62 surely suggests that there may be inherent limitations to either the skills or motivation of maintenance personnel on military engines. The magnitude of the difference demands that further analysis be performed to understand the specifics of this situation and to determine if the limitations arise from a lack of adequate training, tools, manuals, or some other factor.

This emphasis on maintenance personnel should not, however, diminish the fact that engine designs have been characterized by features that are susceptible to maintenance error. Many of these features or design details have been identified previously in the various discussions on each engine subsystem. For example, the mechanical torquemeter system illustrated in Figure 44 was responsible for over 70 percent of the improper repair category on the T55. Similarly, engines with nonmetallic compressor linings such as the T63 could be expected to present problems when improper cleaning agents were used.

Thus, the improper-maintenance-caused problem is shown to be a function of three variables:

- The basic reliability of the engine and the associated opportunities for error
- The skill and motivation of the maintenance personnel
- The susceptibility of the engine to maintenance error

The first two factors were identified as the primary contributors, with little observable difference in hardware characteristics among the study engines.

Airframe-Related Removals

The contribution of this area to the total engine R&M problem is shown below for each of the four R&M parameters.

Airframe-Related	UER	Accidents	MMH	TBO	Index
Scale Factors	4	1	2	0	2.36

This chart indicates that the airframe-related area ranks as a medium-sized problem largely due to the unscheduled-removal portion. Few accidents are caused by failures in this area. This grouping of problems consists of two distinctly different types. The first type is actual damage to the engine due to airframe or non-engine equipment. The second type is merely removals from the airframe in order to gain accessibility to airframe-related components in the general area of the engine. Clearly, accidents can be caused by problems in the first category only. Also, the second category does not require engine repair. Since the weighting factor applied to the rate of unscheduled removals presumes repair or overhaul, its usage in this area provides a somewhat higher priority rating to the airframe-related area than it actually warrants.

The division of airframe-related unscheduled removals into these two categories (damage or mere accessibility) could not be precisely determined. It is estimated to be split 20 to 30 percent actual damage and 70 to 80 percent accessibility-induced. More definitive allocations were not possible due to inadequate data reporting.

The two types of problems included in this subsystem arise from different sources. The damage type is a hardware reliability issue involving not only the frequency of failures but also their progression and detectability. Examples of airframe-related engine damage include oil leakage into the engine from hydraulic starters mounted in the inlet area (on rear-drive engines) or from airframe responsible transmissions mounted in the same inlet area. Misalignment or unbalance of high-speed airframe output shafts has caused engine bearing or housing failures and also contributes to seal leakage. Normally, aircraft rotor-induced vibration levels are not identified as the prime causal factor to engine failures and therefore do not contribute to this subsystem.

The accessibility type of removal is a function of the complexity and failure rate of the airframe equipment in the nacelle area, as well as the ability to gain access to these components for replacement, repair, or adjustment. Even though accessibility is not rigorously quantifiable, it appears to be the prime variable in determining removal rates in this subsystem. Hence, an attempt at a qualitative assessment of accessibility was made for each engine installation. This assessment was used to construct a curve relating removal rate to the degree of accessibility as shown in Figure 63. It should be noted that a given engine has different degrees of accessibility as installed in different aircraft, and that this difference can have a significant effect upon the removal rate.

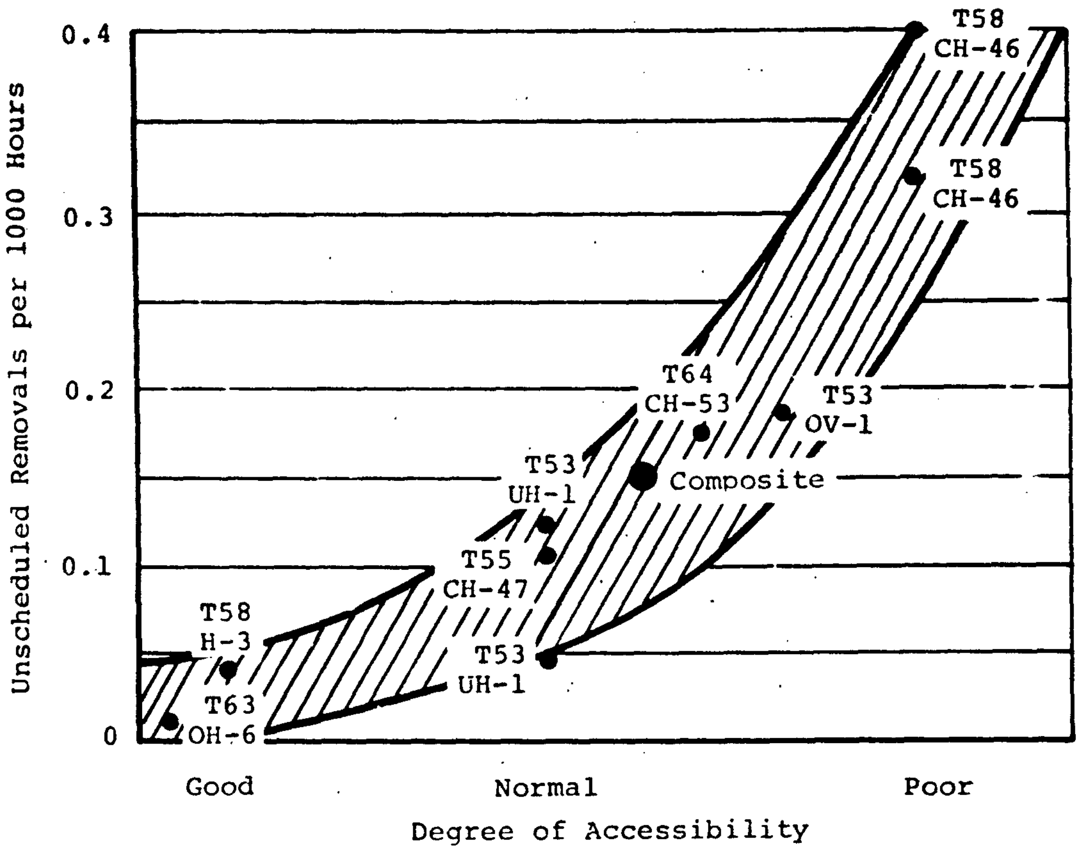


Figure 63. Airframe-Related UER Experience.

Convenience Removals

The contribution of this area to the total R&M problem is shown below for each of the four parameters:

Convenience	UER	Accidents	MMH	TBO	Index
Scale Factors	10	0	5	0	5.46

Removals for convenience occur when an operative engine is removed from an airframe so that the engine can be installed in another airframe, or for a special engine modification. This causes more unscheduled removals than any other single subsystem (engine- or non-engine-caused). This is solely responsible for its high index number (second only to FOD as an identifiable problem area). Since convenience removals are not failures of the engine itself, accidents are not appropriate in this investigation. And since repair or overhaul is performed in only a small percentage of convenience removals, the weighting factor for removals overstates the priority of this problem.

The largest percentage of convenience removals are due to cannibalization, and therefore a relationship might be suspected between the rate of convenience removals and the rate of all removals. An approximation of this relationship is shown in Figure 64, which indicates that total unscheduled engine removal rate correlates well with the rate of convenience removals. However, the effect of the logistics system is also apparent. Cannibalization occurs when insufficient spare engines or parts are available, and the range of resultant convenience removals is seen to be quite large.

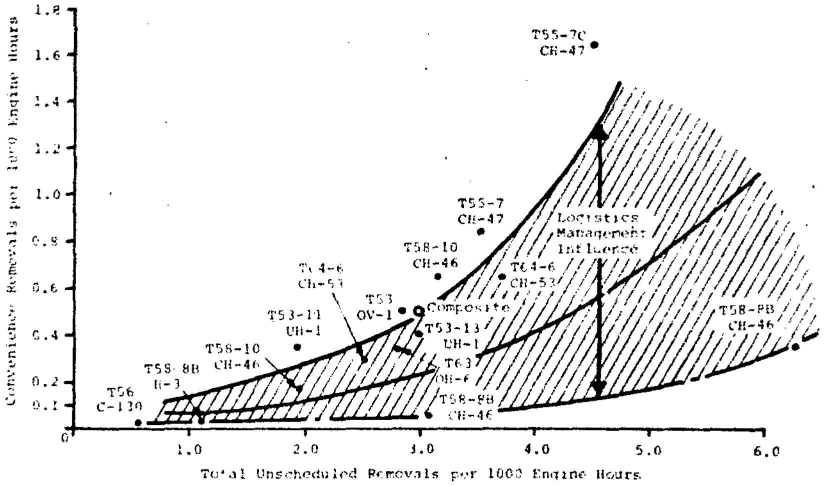


Figure 64. Convenience UER Experience.

Unknown

The contribution of this category of problems is shown below for each of the four parameters.

Unknown	UER	Accidents	MMH	TBO	Index
Scale Factors	10	10	5	-	7.26

This chart indicates that the number of removals and accidents for unknown reasons is significant. The factors that cause a removal or accident to be unknown are more likely related to the effort made in determining the cause, rather than the nature or detectability of the failure itself. Many engines do not receive the intensive analysis that allows definition of problem cause. This may occur because of the economics of the situation, where repairs or overhauls are performed by agencies who do not have a specific responsibility for problem definition. It also occures when engines are not returned for repair or analysis, such as in the case of a severe accident where the extent of damage or cost to recover is excessive.

Assuming that the unknown problem is merely the lack of positive identification of already-defined problems, there should be a correlation between the rate of unknown problems and the rate of all other problems combined. This relationship is plotted in Figure 65, which supports this contention. Various engine manufacturers treat unknown or unsubstantiated problems differently, with some classifying them all as engine-caused and others as all non-engine-caused. The rates shown on Table V proportioned the total unknown unscheduled removals between engine-caused and non-engine-caused.

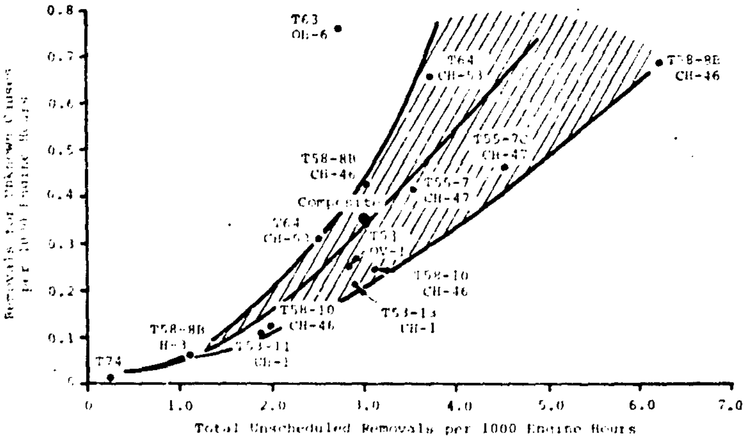


Figure 65. Unknown UER Experience.

SUMMARY OF CURRENT-ENGINE PROBLEMS

Based on the examination of the detailed failure modes experienced by the study engines and the preceding discussion of the specific mechanisms, causal factors, and numerical rates, the following conclusions are appropriate.

Many of the failure modes with the largest rates are the direct result of specific design approaches or criteria adopted during the development phases of the engine. Significant examples of failure modes in this category are bearing outer-race rotation, carbon-seal leakage, compressor blade and vane erosion, compressor FOD, turbine-nozzle-band cracking, turbine-vane sulfidation, case cracking and corrosion, and torquemeter system problems. In most of these cases, the resultant problems could not have been predicted at the time of initial design due to the lack of either historical experience or sufficiently advanced analytical prediction techniques.

Other failure modes appear to be common to all design approaches. Examples include nonclassical bearing spalling; case fitting problems; and fuel, oil, and electrical subsystem problems.

Certain failure modes are intimately related to the climatic and mechanical environment and appear to be largely independent of the design or configuration of engines. Fuel and oil contamination, operator-induced and maintenance-error-caused problems are examples of significant magnitude.

All of these three failure mode categories have been addressed by corrective action during the operational phase of the study engines. Corrective action usually involves only minor redesign of the local failure area, particularly when directed at problems classified as engine caused. Non-engine-caused problems frequently involve more extensive actions, such as the addition of screens or separators.

Precise identification of the causes of many failure modes is frequently impossible. The separate effects of normal engine operating loads, improper manufacturing or quality control, maintenance abuse, and environmental conditions are not clearly evident in many cases. Often the allocation of an incident to engine- or non-engine-caused subsystems involves an assumption of what is considered a normal environment, whether this environment is climatic, mechanical, or personnel related.

The inherent R&M characteristics of many various design approaches are not clearly identifiable from this analysis. Design alternatives such as rear versus front drive, axial versus centrifugal compressors, face versus circumferential carbon seals, and others did not exhibit sufficiently consistent R&M rates to allow quantification of their inherent differences. The limited number of engine configurations examined undoubtedly contributed to this lack of discrimination capability.

Certain subsystems, or groups of problems, were related to the total removal rate of the engine. These subsystem problems were improper-maintenance-caused removals, convenience removals, and removals for unknown reasons.

5.0 CURRENT ENGINE PROGRAM CONSIDERATIONS

The engine-contractor's design/test program and manufacturing/quality control capability, the airframe-contractor's installation, the encountered environments and stresses, and the services' operational/maintenance practices all combine to directly produce the R&M levels exhibited by military turboshaft engines.

The R&M problem areas are influenced by a complex set of program considerations. The program for a specific engine development/production project will influence the specifications and requirements; detailed design and testing; and the engines' manufacturing and quality control and installation. Broad program considerations also have an effect on downstream operations and maintenance practices. This section describes how these program considerations affect R&M problems.

The specific R&M problems discussed in Section 4 will be examined from a broader customer/contractor program management viewpoint to identify considerations that influenced the R&M of the study engines. A review of the background of individual R&M problems will determine what in the requirements, design development, and operational phases contributed to the problem. The contribution of these factors to the composite engine will be quantified and discussed.

Five program-oriented causal factors were identified which, collectively, can be considered to represent 100 percent responsibility for problems. Against these five factors, over 163 different case histories of individual R&M problems in five of the study engines (T53, T55, T58, T63 and T64) were examined. The relative influence of each factor was then determined in conjunction with the manufacturer of each engine.

DEFINITION OF CAUSAL FACTORS

Requirements

All engine design commences with a requirement and a set of specifications. The detailed requirements and specifications establish the basic sizing, cost, and technology level for the engine and thereby influence its R&M characteristics. The stipulation of specific R&M beneficial design features and/or the imposition of R&M levels are direct influences. Indirect influences occur when no R&M requirement is imposed or the requirement for the engine is driven at the expense of good R&M by performance or cost considerations. R&M is a competing parameter with the engine performance and sizing parameters such as SHP, SFC, weight and space envelope. Reliability and maintainability is therefore a by-product of other actions where there is no contractual requirement to design it into an engine. Further requirements which influence R&M include prime design requirements of low cost, modularization, or tight scheduling.

Preliminary Design

This represents the broad design selection made by the engine manufacturer to meet the customer-specified requirements which conceptually define the engine. During this phase of engine design the physical arrangement of the engine is formulated and fixed. This includes decisions on such intrinsic requirements as the selection of centrifugal versus axial flow compressors, straight versus folded combustors, number of shafts, number of compressor and turbine stages, and relative positioning of the compressor in relation to the turbine and combustor section and gearbox. The preliminary design stage molds significant reliability features into an engine design. A decision, for example, to use carbon-face, main shaft seals would prohibit any subsequent engine redesign to utilize labyrinth seals. Basic pressure loss allowables, bearing thrust balancing, bearing cooling, bearing sump size and other important variables would have been predicated on the use of carbon seals. Decisions made at the preliminary design stage will have a significant effect on the engines' reliability potential and on the alternatives available to achieve it during later detailed design stages.

Design Execution and Developmental Test

With the basic layout, sizing and design decisions made in the preliminary design phase, the next phases of R&M are detailed design and test. Here the detailed design effort and decisions are made, tests are formulated and detailed drawings are issued. Drawing board decisions now directly affect engine R&M and will reflect the basic emphasis of the original requirements. Materials choice, structural application and thermostructural analytical techniques, and experience of past problems are applied in the design execution stage. Tests are conducted to verify performance and improve the reliability at the component level. Subsequently, similar tests are conducted on the complete engine for extended durations under a variety of operating and environmental conditions. These tests can detect R&M problems not anticipated during the design and serve as a backup to the analytical process. Reliability and maintainability problems may originate during the design execution and development test phase. During this phase these problems can be found and eliminated with developmental tests.

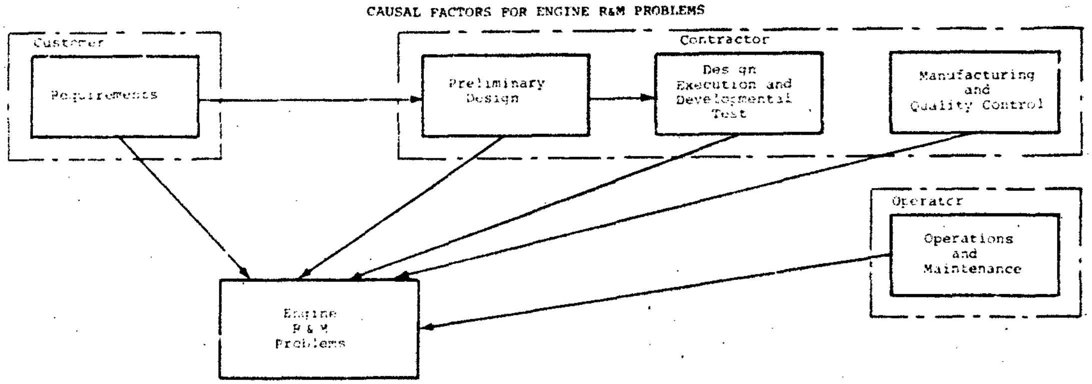
Manufacturing and Quality Control

R&M problems can also be created during the manufacturing and quality control phases. Specific problems were noted during the conduct of this study as originating from excessive tolerances, inadequate care during assembly, or inadequate inspection of components or assemblies. In these situations the inherent reliability can be significantly degraded. Manufacturing and quality control problems are usually transient, since they are normally identified and resolved rapidly. Generally, this category contributed least to the R&M problems.

Operations and Maintenance

Many problems have traditionally first appeared during the operational phase. Problems such as induced high soak-back temperatures into the engine due to improper engine shutdown techniques and ingestion of FOD have caused extreme difficulty during operational use. During this stage of engine use, maintainability problems become more apparent, the effect of human error becomes critical and the distinction between engine-caused and non-engine-caused R&M problems first appears. Earlier conclusions regarding the magnitude of the non-engine-caused problem clearly indicated that strong corrective action is required.

Figure 66 presents R&M problem causal factors and includes a summary of the detailed factors included in each category.



Significant Examples:

Requirements

- Emphasis on Cost
- Emphasis on Weight
- Urgency of Schedule
- Performance Dictates Affected Compressor and Seal Design
- Lack of Aggressive Bearing [illegible] Requirements
- Emphasis on Modularization
- Nose-up Installation
- All Ambient Conditions Not Specified

Preliminary Design

- Bearings with Inner Race Integral with Shaft
- High-Speed Carbon Seal
- No [illegible] Vanes [illegible] Wheels and [illegible]
- [illegible] of Oil Lines [illegible] Hot Turbine Area
- Oil Pump Mounted Inside Gearbox
- No Integral FOD Screen Considerations

Design Execution and Developmental Test

- No Positive Retention of Bearing Outer Races
- Inadequate Lube Oil Filtration
- Seal Mating Ring Flatness Inadequate
- Failure to Recognize Seal Bellows Natural Frequency
- Excessive Shaft Excursions
- Vane Resonance
- Incorrect Choice of Materials
- Effects of Thermal Gradients Not Adequately Analyzed
- Excessive Tolerance Buildup
- Inadequate Compressor Lining Material

Manufacturing and Quality Control

- Inadequate Attention to Shaft Installation During Engine Build
- Problems with Manufacturing Process of Compressor Liner

Operations and Maintenance

- Operator Error
- Maintenance Error

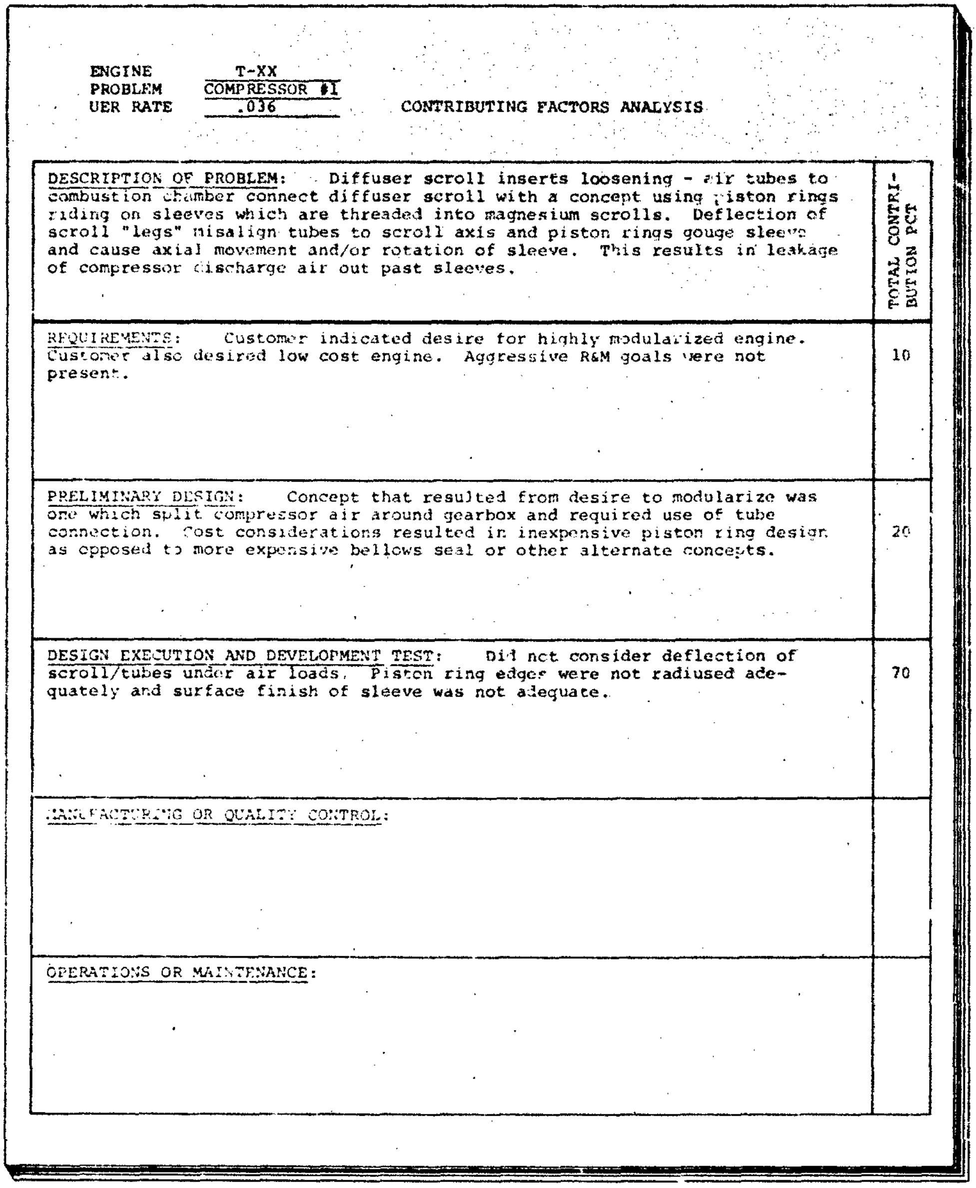
Figure 66. Interrelationships and Examples of Causal Factors.

This figure details the broad areas in which the actions of customer, contractor, and operator are responsible for engine R&M problems. An interaction between requirements, preliminary design and design execution has been indicated in Figure 66. This interaction reflects a progressive, time-sequenced relationship to problem creation. Even when the specification of R&M requirements is deficient, the R&M hardware need not be irrevocably compromised since an opportunity may exist, in the ensuing preliminary design phase, to salvage R&M. Correspondingly, when R&M-compromising decisions are reached in preliminary design, some opportunity may exist to recover, if the contractor chooses, during the ensuing detailed design or test phase. In assessing causal factors for specific problems, it was frequently found that the origin of the problem might have been deficient R&M specifications or requirements; but it was also recognized that subsequent failure to make use of opportunities present in preliminary design and detailed design/test also contributed to the problem.

The following example is illustrative of this phenomenon. In one study engine, the customer specified the requirement for a low-cost, highly modularized engine which resulted in a preliminary design concept with an unorthodox arrangement of the major sections of the engine. This involved the transfer of compressor air around a mid-section gearbox. The continuing requirement for low cost led to detailed design features for the transfer air joints which were not optimum from an R&M standpoint. Problems soon followed. Analysis of the causal factors for this problem showed that, although it was predominantly one of detailed design execution, both the requirements and preliminary design phases contributed to the failures. Although the problem was initiated from a specific customer's requirement, the preliminary design phase offered an opportunity to preclude the requirement from inducing an R&M problem. The detailed design phase offered alternatives to avoid the problem. More development testing would have identified this problem prior to release of the engine to operational use. This example is not unique. It serves to illustrate the interaction of R&M problems experienced at the requirements, preliminary design and design execution phases of an engine program.

QUANTIFICATION OF CAUSAL FACTORS

In order to determine the relative impact of the five causal factors on the overall R&M problem, 163 individual case histories were investigated. The percentage of the problem due to each contributing factor was assigned in cooperation with the engine manufacturers. An example of this process is shown on Figure 67 which illustrates the case cited above. The contribution of each factor was measured according to the magnitude of the basic problem in each of the four R&M parameters.



ENGINE T-XX
PROBLEM COMPRESSOR #1
UER RATE .036

CONTRIBUTING FACTORS ANALYSIS

DESCRIPTION OF PROBLEM: Diffuser scroll inserts loosening - air tubes to combustion chamber connect diffuser scroll with a concept using piston rings riding on sleeves which are threaded into magnesium scrolls. Deflection of scroll "legs" misalign tubes to scroll axis and piston rings gouge sleeve and cause axial movement and/or rotation of sleeve. This results in leakage of compressor discharge air out past sleeves.	TOTAL CONTRIBUTION PCT
REQUIREMENTS: Customer indicated desire for highly modularized engine. Customer also desired low cost engine. Aggressive R&M goals were not present.	10
PRELIMINARY DESIGN: Concept that resulted from desire to modularize was one which split compressor air around gearbox and required use of tube connection. Cost considerations resulted in inexpensive piston ring design as opposed to more expensive bellows seal or other alternate concepts.	20
DESIGN EXECUTION AND DEVELOPMENT TEST: Did not consider deflection of scroll/tubes under air loads. Piston ring edges were not radiused adequately and surface finish of sleeve was not adequate.	70
MANUFACTURING OR QUALITY CONTROL:	
OPERATIONS OR MAINTENANCE:	

Figure 67. Example of Contributing Factors Analysis.

The problems on five of the study engines formed the basis for this task. Using the composite engine index number values shown on Table XI as a basis, the results of the causal factor analysis were summarized on Figure 68 which displays the data at the total engine level. Table XXVI illustrates the results at the subsystem level and Table XXVII details the impact of the causal factors at the failure mode level.

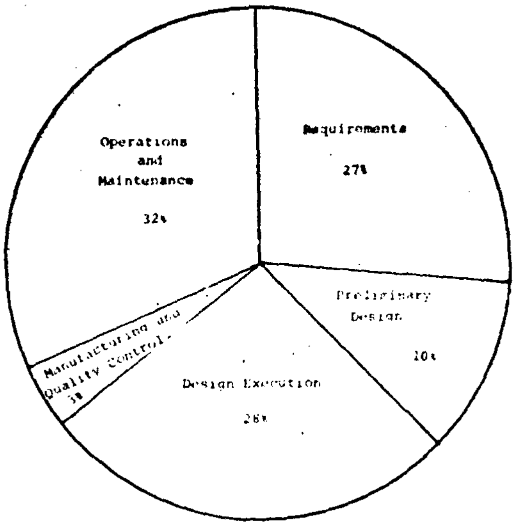


Figure 68. Summary Results of Contributing Factors.

TABLE XXVI. CONTRIBUTING FACTORS SUBSYSTEM SUMMARY MATRIX

Subsystem or Mode	Index	Contributing Factors									
		Requirements		Preliminary Design		Design Execution		Manufacturing and Quality Control		Operation and Maintenance	
		Percent	Value	Percent	Value	Percent	Value	Percent	Value	Percent	Value
Bearings	3.80	12	0.45	9	0.34	67	2.55	7	0.27	5	0.19
Seals	3.46	20	0.69	22	0.76	50	1.74	5	0.17	3	0.10
Compressor	4.63	34	1.57	6	0.28	44	2.04	9	0.42	7	0.32
Combustion	1.14	28	0.32	7	0.08	55	0.63	7	0.08	3	0.03
Turbine	2.86	46	1.31	3	0.09	42	1.20	3	0.09	6	0.17
Cases	1.27	22	0.29	2	0.03	56	0.71	-	-	19	0.24
Lubrication	1.28	4	0.05	22	0.36	44	0.57	5	0.06	19	0.24
Fuel	3.45	24	0.83	22	0.76	28	0.97	1	0.03	25	0.86
Air	0.55	10	0.06	-	-	65	0.35	10	0.06	15	0.08
Accessory	0.91	-	-	-	-	80	0.73	20	0.18	-	-
Torquemeter	1.27	20	0.25	19	0.24	42	0.54	-	-	19	0.24
Electrical	0.73	19	0.14	-	-	29	0.21	-	-	52	0.38
Exhaust	0.55	44	0.24	21	0.12	33	0.18	-	-	2	0.01
Power-Train Reduction	0.72	40	0.29	10	0.07	30	0.22	10	0.07	10	0.07
Total - Engine-Caused	26.62		6.49 24%		3.13 12%		12.64 48%		1.43 5%		2.92 11%
Foreign Object Damage	6.71	70	4.70	10	0.67	5	0.34	-	-	15	1.01
Erosion	2.90	70	2.02	15	0.44	5	0.15	-	-	10	0.29
Environmental	1.09	-	-	20	0.22	-	-	-	-	80	0.87
Improper Operation	2.54	10	0.25	10	0.25	15	0.38	-	-	65	1.66
Improper Maintenance	5.09	10	0.51	5	0.25	5	0.25	5	0.25	75	3.83
Airframe Induced	2.36	5	0.12	10	0.24	45	1.06	-	-	40	0.94
Convenience	5.46	-	-	-	-	-		-	-	100	5.46
Total - Non-Engine Caused	26.15		7.60 29%		2.06 8%		2.18 8%		0.25 1%		14.06 54%
Unknown	7.26										
Total - Engine	60.03		14.09 27%		5.19 10%		14.82 28%		1.68 3%		16.99 32%

TABLE XXVII. CONTRIBUTING FACTORS FAILURE MODE MATRIX

Subsystem/ Failure Mode	Index Number	Percent	Contributing Factors - Percent				
			Requirements	Preliminary Design	Design Execution and Testing	Manufacturing and Quality Control	Operations or Maintenance
Bearings	1.80	–	[illegible]	6	67	7	5
Spalling - Classical/Prior	0.42	21	48	–	48	–	4
Spalling - Nonclassical	[illegible]	49	8	15	56	8	11
Race Rotation Displacement	0.61	16	12	8	70	10	–
Cage Wear/Cracking	0.55	15	10	–	78	7	5
Roller Skidding	0.10	6	–	12	88	–	–
Miscellaneous	0.11	3	–	–	–	–	–
Seals	1.46	–	20	22	50	5	3
Carbon Seal Leakage	1.28	[illegible]	20	22	50	5	3
Labyrinth Seals	0.07	2	40	50	10	–	–
Static Seals - O Rings	0.08	4	10	20	50	10	10
Miscellaneous	0.03	3	–	–	–	–	–
Compressor	4.63	–	34	4	44	5	7
Vane Erosion - Failures	1.11	24	45	–	35	–	20
Blade Disc Fatigue	2.40	52	31	8	47	14	–
Diffuser Cracking	0.28	6	34	5	52	–	9
Compressor Lining Wear	0.04	1	10	20	50	20	–
Variable Stator and Bleed	0.09	2	–	20	60	–	20
Miscellaneous	0.71	15	–	–	–	–	–
Combustion	1.14	–	28	7	55	7	3
Liner Cracking Warping	0.19	17	–	–	100	–	–
Support Structure Cracking	0.19	17	20	20	60	–	–
Housing Corrosion and Fittings	0.58	51	43	7	38	5	7
Swirl Cup Problems	0.17	15	20	–	60	20	–
Miscellaneous	0.01	1	–	–	–	–	–
Turbine	2.86	–	46	3	42	3	6
Nozzle and Band Cracking	0.57	20	58	6	36	–	–
Nozzle Burning Sulfidation	0.17	6	73	–	19	–	8
Support Structure and Fittings	0.54	19	13	6	53	16	12
Blades and Wheels	1.17	41	60	–	40	–	–
Shafts, Couplings	0.23	8	–	–	56	–	44
Miscellaneous	0.17	6	–	–	–	–	–
Cases	1.27	–	23	2	56		19
Corrosion	0.27	21	10	–	71	–	19
Secondary Structural Cracking	0.45	35	29	–	50	–	21
Bosses, Fittings, etc.	0.47	37	27	4	51	–	18
Miscellaneous	0.08	7	–	–	–	–	–
Lubrication	1.28	–	4	28	44	5	19
Pump Failures	0.60	47	–	45	45	–	10
Filters, Coolers, etc.	0.26	20	10	10	50	–	30
Tubes, Fittings, etc.	0.22	17	10	20	40	–	30
System and Miscellaneous Hardware	0.20	15	–	10	40	30	20
Fuel	1.45	–	24	22	28	1	5
Fuel Control Units	[illegible]	75	30	20	30	–	[illegible]
Pumps, Valves, etc.	0.52	15	2	40	10	5	41
Tubes, Fittings, etc.	[illegible]	5	–	–	50	–	50
Miscellaneous	[illegible]	5	–	–	–	–	
Air	[illegible]	–	6		65	16	13
[illegible]	[illegible]	70	[illegible]	–	80	[illegible]	
Tubes, Fittings, Miscellaneous Hardware	[illegible]	30	–	–	50	–	50
Accessory	[illegible]	–			80	20	[illegible]
Instrumentation	[illegible]	–	25	13	43		19
[illegible] System	[illegible]	[illegible]	20	[illegible]	[illegible]	–	20
[illegible] System	[illegible]	5	–	–	100	–	–
Electrical	[illegible]	–	19	–	29	–	52
Ignition System Components	[illegible]	35	33	–	50	–	20
Power Management System	0.16	22	40	–	30	–	30
Wiring and Thermocouples	0.31	43	–	–	10	–	90
[illegible]	[illegible]	–	44	21	[illegible]		2
[illegible]	[illegible]	–	40	10	30	10	10
TOTAL [illegible]	[illegible]	–	25	12	47	5	11
[illegible]	[illegible]	–	[illegible]	[illegible]	[illegible]	–	[illegible]
[illegible]	[illegible]		75	15	5	–	10
[illegible]	[illegible]	–	–	20	–	–	80
[illegible]	2.54	–	20	[illegible]	15	–	65
Improper Maintenance	[illegible]	–	10	5	5	5	75
Airframe Related	[illegible]	–	[illegible]	10	[illegible]	–	40
[illegible]	[illegible]	–	–			–	100
TOTAL [illegible]	[illegible]	–	[illegible]	8	[illegible]		[illegible]
[illegible]	[illegible]	–	–	–	–		–
TOTAL [illegible]	[illegible]	–	27	10	[illegible]	[illegible]	[illegible]

DISCUSSION OF RESULTS

Certain of the causal factors have a more powerful influence than others in the establishment of the R&M characteristics. In the case of the engine-caused category of R&M problems, two causal factors predominate - requirements and design execution. Two causal factors also dominate the non-engine-caused problems - requirements, and operations and maintenance. When the total engine R&M problem is considered, three causal factors of relatively equal magnitude (requirements, design execution, and operations and maintenance) are collectively responsible for almost 90 percent of the total problems. The following sections will discuss the significance of each of the five causal factors.

Significance of Requirements on R&M Achievement

The requirements phase for the study engines was in the 1950 to 1960 time period. It was noted in discussions with the engine manufacturers that these engine programs did not have formal or even any specific reliability and maintainability requirements at the commencement of the design phase. The engine reliability achieved under these circumstances was the result of R&M receiving lower priority in the trade-off decisions than contractual parameters of performance and weight.

A lack of requirements is the principal reason why requirements were seen to be responsible for over 25 percent of past engines' R&M problems. Reiterating, when the detailed requirements do not include R&M, the resulting effects on R&M of the other parameters will probably be deleterious. Several instances of this situation were noted in the study. On one study engine, the requirement for a high-performance, small, lightweight engine led to design decisions to use carbon-seal main shaft bearing seals to minimize compressor air losses. The decision to use carbon seals which caused reliability problems was made on the basis of a requirement that did not include a reliability parameter. On another study engine, particular compressor-liner material was used on the basis of a cost requirement. Again, there was no R&M requirement. In both examples, the absence of specific reliability requirements did not allow R&M to be treated with adequate emphasis during critical design decisions.

Significance of Preliminary Design on R&M Achievement

The preliminary design phase represents the first tangible engine manufacturers' response to given customer requirements. It is almost always possible to propose more than one engine design configuration to meet a requirement, and some basic engine layouts have a lower probability of causing R&M problems at later design stages than others. At the preliminary design stage, several of the basic reliability-affecting variables are decided upon and fixed. Included in these basic variables are the number of engine shafts, number and types of bearings and main shaft seals, engine materials and similar major design decisions. The preliminary concept selected by the engine designer utilimately defines the mature, generic reliability rate attainable for that engine after all reasonable reliability improvement changes have been incorporated.

The preliminary design phase allows the manufacturer to incorporate beneficial R&M features and thereby reduce the probability of problems later. Alternately, some problems resulting directly from the preliminary design phase were noted. One study engine coupled the fuel pump, fuel control unit and purifier in series. Significant problems occurred with drive spline wear and inadequate spline lubrication. Since there were no known requirements specifying this arrangement, the preliminary design was mainly responsible for this problem.

The impact of the preliminary design phase on the achievement of good R&M levels was relatively low. Its main impact was on defining the detailed design features necessary to satisfy the requirements phase and determining the difficulties of the design execution phase.

Design Execution and Development Test Impact on R&M Achievement

The effort expended during this stage of engine development cycle is important in determining the R&M levels ultimately found in field operations. This effort consists of not only the actual design of the hardware, but the entire spectrum of analysis and testing that is applied in support of the design effort. The actual drawing process is a complex interaction and integration of requirements imposed, available technology, past experience, and the skills of the project and design personnel.

This phase contributed to nearly one-half (47 percent; see Table XXVII) of the engine-caused problem, but to only 8 percent of the non-engine-caused problem. In the engine-caused area, nearly every subsystem was significantly influenced by this factor. Bearing problems were particularly prevalent, with most failure modes having traceable origins to inadequate design efforts and testing. Typical bearing problems were excessive axial or radial loads caused by inadequate calculations of housing/case thermal growths, outer race rotation caused by lack of positive retention, and roller skidding due to excessive clearances or insufficient radial load. Other problem subsystems due to this factor are seals, compressor, turbine and fuel. Most of the many failure modes in these subsystems follow a pattern of wide variety similar to that displayed for bearings.

To better understand this factor, specific failure modes which were due, wholly or in part, to this factor were reexamined to establish lower-level visibility. This additional analysis resulted in the discovery of four basic faults as follows: 55 percent analysis test procedures available but not utilized; 20 percent past R&M experience/history not utilized; 15 percent alternate design or materials not available; 10 percent analysis test procedures not available. This suggests that the prime cause (75 percent) was a lack of application of existing and available analysis/test or historical experience. Limitations that appear to be most critical are development time and funding, not technological restraints. This explains why engines can experience such large improvements in reliability over a relatively short time frame. Little new technology has been made available; operational experience was used to replace analysis during design.

The effect of design execution and development test in the non-engine-caused areas are minimal. Once the base requirements have been established (for example, not to have a screen or separator), the preliminary design chosen (for example, an axial-flow compressor design) and the operational environment fixed, there is little that can be done during this phase to increase the resultant reliability. Only the detailed installation of airframe components on or near the engine contributes any significant effect. The importance of this factor in engine R&M should not be minimized in spite of the great variety of failure mechanisms and specific causes evidenced by examining various engines.

Significance of Manufacturing and Quality Control on R&M Achievement

This phase during which R&M problems can be induced in an engine tends to receive more vocal comment than its importance warrants. Table XXVI indicates the low contribution that manufacturing and quality control represents to the total R&M dilemma. The problems that occur are usually transient and are quickly resolved.

Manufacturing problems have been associated with assembly difficulties rather than with the production of detail parts. Several examples of this situation were noted in this study. One engine which used the engine power turbine shaft as an integral inner roller bearing race experienced externally induced damage which occasionally led to bearing failures because of difficulty installing the shaft into the bearing assembly.

Another engine utilizing a differential bearing in a main shaft application had considerable problems from the difficulty of installing the retaining ring for the bearing outer race. Improper seating of this bearing outer race with subsequent lack of retention by its retaining ring allowed axial movement of the bearing.

A new manufacturing technique for installing compressor liner material was partly responsible for later R&M problems. This process involved the centrifuging of the plastic lining onto the case, which caused separation of the denser elements of the mixture out to the case surfaces. This produced a nonhomogeneous mixture and allowed softer elements of the plastic to become exposed to compressor air, with subsequent liner cracking.

An assembly-induced problem was that proper inspection was either extremely difficult or impossible following completion. Occasional quality control problems were encountered. Typically, a grinding operation removed much of the weld material securing a drain boss to a combustor housing. Several problems unique to military overhaul depot activities were also noted. Prime among these was that a metal flame spray technique which did not produce an adequate surface finish was used as the bearing inner race, and the incorporation of this rework technique caused severe bearing problems. This problem reflected a military overhaul-activities emphasis on cost and time savings which in some cases was instrumental in causing R&M problems.

Most manufacturing and quality control problems appeared to be related to general personnel and facilities limitations and hence were largely independent of the requirements, preliminary design and design execution phases of any specific engine.

Significance of Operations and Maintenance on R&M Achievement

The introduction and use of engines in operational service usually generate a new series of R&M problems not previously encountered. Operation of the engine under field conditions begins to reveal situations that result from actual operational environments which may be more adverse than those of the test program. Table XXVI illustrates that the majority of problems to which operations and maintenance have a significant impact are non-engine-caused.

Several of these non-engine-caused problems, specifically FOD, erosion and airframe-related, where major responsibility lay in requirements or design execution, were magnified by maintenance personnel action. As an example, engines have been operated without the specified FOD screens or particle separators installed.

The other categories of non-engine-caused problems (operator induced, improper maintenance and environmental) were principally the result of personnel action or inaction. These problems were exaggerated by factors largely unrelated to the particular engine. With maintenance-induced R&M problems, the problems included skill levels of the personnel and the adequacy and utilization of equipment and facilities. The operator-induced problems included both deliberate overtemperature operations and unintentional engine hot starts. Assessing the causal factors for these types of problems, it is obvious that they were universally unrelated to a particular engine. To what extent specific design features led to these rates is not altogether obvious. Certainly the application of features to prevent hot starts could provide one solution to that problem; but flight crews will always require the option of overtemping an engine to extract additional power if the emergency warrants. More than 50 percent of maintenance-induced problems were unrelated to the particular engine being worked on, but were really a more general type that could have occurred on any engine.

Operations and maintenance also affect, to a lesser degree, engine-caused problems. Analyzing the R&M problem causal factors for engine-caused problems, the operation and maintenance phase was somewhat contributory to many failure modes. Many fuel system problems originated in the operational reality of contaminated fuel. Another engine-caused problem occurred in the electrical system during abusive field-operations/maintenance. The mechanical torquemeter system provided another classic example of this phenomenon. Here one manufacturer did encounter both reliability and maintainability problems during test cell operations, but these were considered tolerable. However, the problem took on significantly large proportions when the engine was released to the field where the general operational and maintenance environments were not as adequate as those in the manufacturers' facilities.

The R&M problems that have occurred in this operations and maintenance phase of the engines life cycle warrant close examination of how program management can prevent them. Later sections of this report will propose some considerations for this purpose.

6.0 IMPROVEMENTS AVAILABLE TO DESIGNS AND PROGRAMS

Detailed discussions of individual failure modes and problem areas and the program deficiencies which caused or allowed them to exist have been presented in Sections 4 and 5 for Army gas turbine engines designed and developed during the 1950 to early 1960 era. This section is a compendium of known design and program improvements which are available to designers and program managers for application to 1975-1982 era engines. The section is divided into two parts. The Design Features section presents, by engine subsystem, all of the hardware changes and analytical tools which are completely developed today or can be realistically developed through current R&D programs. Under the Program Trends section, new concepts in program management are presented that are sufficiently well understood to be deemed useful to program managers of today (given significant customer reliability requirements for the hardware).

DESIGN FEATURES

The hardware changes available today for use in 1975-1982 era gas turbine engines can be divided into categories which will facilitate the compilation of subsystem listings of candidate changes. The categories used are Experience Trends, Technology Trends, and Design Options. How these three categories interact to define future engines is shown in Figure 69.

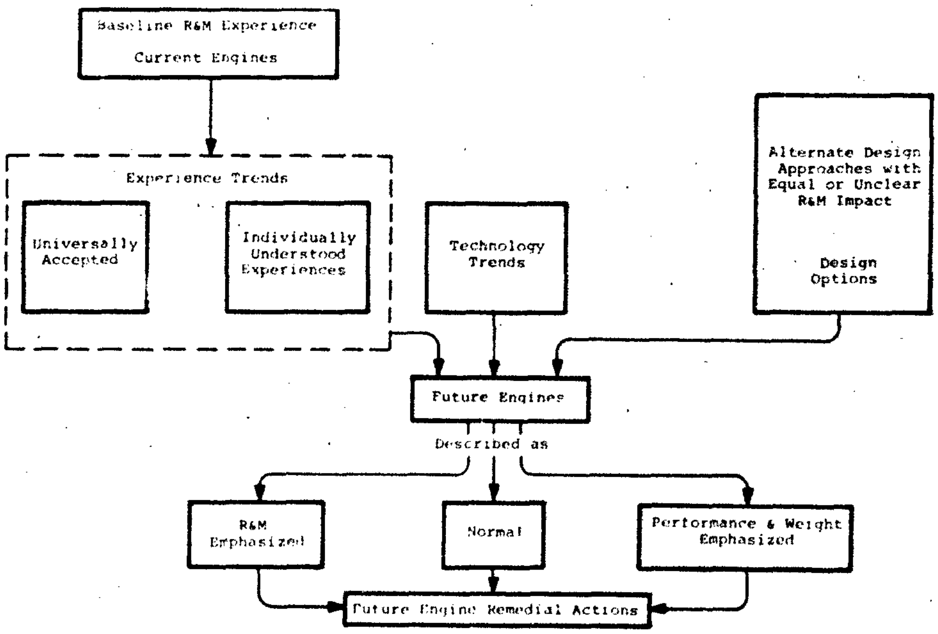


Figure 69. Future Engine Activity Flow Chart.

Experience Trends

An experience trend is a design approach or material usage which is known to the majority of engine manufacturers and has been proven superior through service experience. Experience trends generally stem from the development of corrective action for R&M problems that are common to the majority of engines in a given era. Since the problems are common, the solutions are relatively common, and as such, they represent lessons learned throughout the industry. However, sometimes companies, and agencies or individuals within companies or agencies, disagree that a given design approach or material usage is preferred from an R&M standpoint. This would not prevent their consideration as experience trends, since the majority of the members of the engine design community consider them advantageous.

For example, the mechanical retention of a bearing outer race to prevent rotation in its liner or housing is an experience trend because it is common to all engines. Where a problem is unique to one engine due to a specialized design approach, material selection, or configuration requirement, the problem solution is not considered to represent an experience trend, since it is very unlikely that the lesson was learned throughout the industry.

Technology Trends

A technology trend is an advanced design approach which typically results from a new concept, new analytical technique, or new manufacturing approach. These advanced approaches may have resulted from Government and industry R&M investments in techniques and materials. They include technology changes necessitated by the continued demand for higher power, reduced specific weight, and decreased specific volume, in addition to improved R&M. Recent requirements for IR suppression and noise and smoke attenuation are considered to impact R&M as technology trends.

There are two basic sources of technology trends. The first is the direct influences representing advancements in materials capability, etc., of the component or subsystem in question. The improvement in turbine alloys, which permits higher turbine inlet temperatures, is an example. The second type of technology trend is indirect in nature. An example is the concept of a two-spool compressor design to improve engine acceleration and specific fuel consumption (SFC) which in turn requires additional bearings and seals with their attendant impact on R&M.

Design Options

Design options are engineering features whose incorporation is at the discretion of the designer because alternative means of accomplishing the same objective are available. The key element of the design option as used in this study is that the R&M characteristics of the design feature are not obvious, either because of a lack of agreement between manufacturers or agencies concerning the R&M levels associated with a particular approach or because entirely different ways of achieving the same objective may have similar R&M levels.

The design option category is created with reluctance. There is no doubt that most design options have one alternative with better R&M characteristics than the others, but the lack of experience with the alternatives prevents rigorous identification of the superior approach.

Each of the engine subsystems has been examined for possible design changes. These changes are summarized in tables accompanied by a brief discussion of the overall trend. All of the changes listed may not be incorporated in future engines for several reasons: first, the item may not appear to be sufficiently developed for incorporation in near-term engines (gas bearings is an example) or the feature may be an alternative to another feature (refinements in carbon-seal design would not be applicable if all labyrinth seals are used).

Bearings

The candidate changes for future engines that affect the bearing subsystem largely result from R&M problems in past engines or from engine configuration changes. The most R&M-significant changes stem from corrective actions applied to past engines in response to problems. Other changes involve materials or configuration improvements which apparently are initiated so that the bearing can handle greater loads. Changes of this type are not expected to have significant R&M impact. Of more importance are the indirect changes which result from overall engine configuration changes, such as use of multispool compressors and the resultant additional number of bearings. Changes that affect future bearing R&M are presented in Table XXVIII.

Seals

Changes in the seal subsystem will result from the need for considerable improvement in reliability. Historically, this subsystem has been one of the largest contributors to engine removals. It appears that future engine reliability should be the direct result of the incorporation of changes identified in this section.

TABLE XXVIII. POTENTIAL CHANGES IN THE BEARING SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
• Pinned Bearing Outer Races • Machined Bearing Cages • Improved Thrust Load Control • Improved Lube Filtration • Elliptical Outer Races	Internal • Improved Analytical Models for Cage Slip • Advanced Materials • New Bearing Configurations - Gas - Ceramic - Tapered Rollers - Hollow Balls & Rollers • Exotic, Improved Lubricants External • Higher Bearing Speeds Condition Monitoring • Impregnation of Trace Materials • Increased Modularization (Adverse Effect on Misalignment) • Multi-speed Compressor (Additional Number of Bearings)	• **Differential Bearings** • **Integral Inner Races** • **Race or Jet Lubrication** • Co-rotation vs. Counter Rotation Inner Race Riding Cages

The commonly used carbon seal will give way to various forms of noncontact labyrinth or close-contact seals. The popularity of the carbon seal has been due to its very low bleed-air demand for seal pressurization and its low air leakage characteristics. This seal, however, has been prone to assembly damage, oil contamination and coking, and other reliability problems. There are definite limits to its effectiveness at surface running speeds of approximately 300 feet per second and greater. Although bleed air losses are being reduced with more refined forms of labyrinth seals, these losses and the difficulty of providing static sealing capabilities for oil sumps remain the major barriers to their universal application for all air/air and air/oil seals in turbine engines. Therefore, continued improvements will be evident in the design and reliability of carbon and other types of positive or close-contact seals.

The important issue in this subsystem is the selection of various seal concepts for main shaft bearings, rather than detailed improvements in any one seal concept. Changes that affect future seal R&M are presented in Table XXIX.

Compressors

The principal changes in the compressor subsystem will result from the increased efficiency that will be available for future engine compressors. Analytical and developmental research has continued on both axial and centrifugal compressors, and progressive improvements in compressor efficiency are being achieved. Advances made in aerodynamic efficiency have caused renewed interest in the centrifugal compressor, particularly for the smaller turboshaft engines. They provide a means of

TABLE XXIX. POTENTIAL CHANGES IN THE SEALS SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° Increased use of Labyrinth Seals ° Continued but reduced number of Carbon Seals ° Improvements in Static Seal Materials, Configurations & Installations ° More extensive use of Piston Ring Seals	External ° Higher Seal Speeds ° Additional Seals (Due to multi-spool compressor) ° Oil coking problem will become more significant as soak back temps increase ° Contaminant levels will be reduced - improved oil filtration - integral air inlet separator Internal ° Refinements in Labyrinth Seal designs ° Refinements in Carbon Seal designs	° Fluid damping of shafts may cause seal difficulties over mechanical damping ° Bore vs. face carbon seals ° Tighter seals - less leakage as a means of obtaining more performance ° Fewer static seals if air/oil lines integrally routed ° Co-rotation vs. counter rotation ° Greater potential for static seal leakage with use of centrifugal compressors

avoiding small blades and vanes with their attendant manufacturing difficulties.

It is probable that higher stage loadings, and pressure ratios will be required for future engine compressors as well as increased bleed-air requirements, including those for engine sump and balanced air labyrinth seals. In addition, the increasing requirements for turboshaft engines to have more efficient partial power operating conditions are almost certain to lead to more complex compressor bleed systems. Noise reduction and ecological considerations will influence compressor design and may result in greater complexity.

To offset some of the R&M degradation resulting from these performance-oriented changes, significant improvements in analytical techniques will be available to preclude some of the major reliability problems experienced in the past. Those of particular note concern the prediction of low-cycle fatigue and blade/vane resonance. Changes that affect future compressor R&M are presented in Table XXX.

Combustion

Changes in the combustion subsystem will result from a series of relatively minor problems that have been encountered in current engines. From the R&M standpoint, combustor design remains an art, rather than science, and history has demonstrated the need for considerable component development testing.

Nuisance problems predominate. Problem solution is relatively straightforward once the problem has been adequately identified. Most problems resulted from the nonpredictability of thermal stresses on components in the combustor assembly. Typical nuisance problems encountered included combustor liner cracking, louvre cracking, nozzle support structure cracking, and the cracking of miscellaneous fittings.

TABLE XXX. POTENTIAL CHANGES IN THE COMPRESSOR SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
• Erosion Res. Blade/Vane Mtls • Dual Actuator - variable stators • Low cycle fatigue & blade resonance analytical methods	• Higher stage loadings • Higher pressure ratios • Improved analyt. tech. for resonance • Improved low cycle fatigue prediction techniques • Improved blade/vane coat - corrosion • Increase use of effective separators - with integral screen • Increased complexity compressor control systems - part power • Composite/fiber/filament wound disc • Higher demand for bleed air requires additional complexity of bleed extraction hardware • Noise attenuation may add complexity	• Variable stators vs. bleed systems • Rub-in strips for performance • Higher aspect ratio blades • Integral casting of blades/disc • Centrifugal vs. axial compressors • Diffuser difficulties resulting from use of centrifugal compressor

Future engines will require higher combustor temperatures to fulfill the demands for higher specific powers and efficiencies. Improved coating materials and detailed design techniques are being developed to accommodate these higher temperatures. Improved analytical techniques for heat distribution patterns are being developed. The resulting decrease in pattern factors should favorably impact reliability problems. Nevertheless, the most fruitful technique for determining and reducing R&M problems in the combustor subsystem will continue to be vigorous and representative component testing. Changes that affect future combustion R&M are shown in Table XXXI.

TABLE XXXI. POTENTIAL CHANGES IN THE COMBUSTION SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
• Improved component testing necessary	• Higher combustor temperatures • Improved coating materials (zirconate type materials) • Improved analytical techniques for heat distribution patterns (TVR reduced) • Double wall liners • Cast liners • Smoke-free operation and improved liner materials	• Folded vs. straight combustor • Vaporizing vs. atomizing fuel nozzles

Turbines

Problems with current turbine subsystems have centered in four areas, all of which have received R&M attention. The most critical problem has been fatigue cracks of the turbine blades and wheels. The most prevalent problem has been nozzle band cracking. Other problems have concerned nozzle support structure cracking, and blade and vane sulfidation. In addressing these problems, advances have been made in prediction techniques for low-cycle fatigue, in improved materials and coatings to resist sulfidation, in the incorporation and use of slotted inner and outer nozzle bands, and in the use of castings (as opposed to weldments) to minimize the effects of thermal gradients and local stresses.

The turbine subsystem will receive prime attention in technology developments to achieve higher specific powers and efficiency. These will include higher turbine inlet temperatures, higher pressure ratios, incorporation of new blade cooling techniques, and use of variable geometry nozzles. The impact of these performance-oriented changes is expected to offset the reliability gains. Changes that affect future turbine R&M are shown in Table XXXII.

TABLE XXXII. POTENTIAL CHANGES IN THE TURBINE SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° Use of cast nozzles ° Improved materials & coatings to resist sulfidation ° Use of slotted inner/outer nozzle bands	° Higher turbine inlet temperatures & advanced blade metallurgy ° Possible application of ceramics ° New cooling techniques ° Variable geometry nozzles ° More sophisticated blade/vane design from cooling requirements ° Higher pressure ratios ° Use of directional solidified alloys ° Lower sulfur contents in fuel ° Improved low cycle fatigue prediction techniques	° Radial inflow turbines ° Materials selections (cobalt vs. nickel based metals)

Cases

Changes in the case subsystem will result from R&M emphasis to offset the additional complexity expected in future engines, and from the detailed correction of difficulties revealed in past service. Difficulties arose in instances where thin-wall casings or magnesium castings have been used. Corrosion problems were encountered. Bosses and fittings have proven to be a major source of unreliability for this subsystem. Detailed design attention will reduce this problem. Anticipated changes include improvements in corrosion protection and an increasing trend toward incorporation of integral bosses and fittings in castings and machinings.

This latter point will become increasingly important as diagnostic systems in engines become more comprehensive with an increased number of interface points. The decreasing emphasis on thin wall casings will allow more robust structure capable of accommodating these design details.

The requirements for engine noise attenuation are expected to complicate engine cases. Cases are a prime example of an area in which very careful detailed design will be necessary to avoid R&M problems. Changes that affect future cases R&M are given in Table XXXIII.

TABLE XXXIII. POTENTIAL CHANGES IN THE CASES SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° Less emphasis on thin wall casings ° Improved corrosion protection ° Bosses & fittings should be **integrally** cast ° Magnesium should not be used for any structural support	° Increased modularization ° Increased case temperatures ° Additional bosses/fittings for both internal and external diagnostics ° Additional bosses/fittings for extra bleed controls ° Noise attenuation requirements may complicate cases ° Improved erosion characteristics	° Hard vs. soft mounting of engines ° Different materials

Lubrication

The need for improved filtration and protection from minor debris will necessitate changes in the lubrication subsystem. Experience has proven that the majority of problems encountered were contaminant related, either from metallic debris and carbon contamination, or from mixing of contaminated seal-pressurizing air with the engine oil.

Demands on the lubrication system will become more severe as engine operating temperatures and soak-back temperatures increase. The trend toward the use of more labyrinth seals will increase the need for improved filtration and involve the use of more complex air/oil separators. Problems encountered with lubrication system operation (such as check valves sticking, marginal scavenge capabilities, and fitting leakage) have demonstrated the need for increased system testing. Changes that affect future lubrication system R&M are presented in Table XXXIV.

Fuel

Changes in the fuel subsystem will result from the necessity of improving filtration protection and improving accessibility and maintainability of the fuel control unit. While the fuel control unit has been the major contributor to system unreliability and will probably continue to be, several factors will reduce this rate on future engines. Contamination of this

TABLE XXXIV. POTENTIAL CHANGES IN THE LUBRICATION SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° Use of labyrinth seals will necessitate more complex oil/air separation ° No quick disconnects ° Increased system testing of lubrication systdm ° More attention to scavenge capabilities ° Additional requirements for filtration	° Additional cooling requirements ° Potential soak-back temperature problem from increased T.I.T.'s ° Higher operating oil temperature and use of more temperature stable lubricants	° Internal vs. external location of oil pump

component has been a major problem, and filtration will be improved. The reduction of impurities in turbine fuels will further reduce the contamination problem. Problems with drive splines for fuel control units, pumps, purifiers, etc., have substantiated the need for positive spline lubrication.

Overall trends for the fuel system will be toward increased complexity as power management, compressor bleed control, power margin indicators, variable turbine controls, and other advanced features are incorporated. Fuel system changes are shown in Table XXXV.

TABLE XXXV. POTENTIAL CHANGES IN THE FUEL SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° Additional filtration required ° Increased accessibility to fuel control ° Positive lubrication of fuel pump/cont splines	° More complex fuel control units incorporating automatic functions, bleed control & diagnostic functions ° Additional control functions for variable turbine geometry ° Increasing use of power management systems ° Increasing use of electronics and fluidics ° Reduction of impurities in turbine fuels affecting hot section components (sulphur, etc.)	° Electronic vs. electro-mechanical vs. pneumatic fuel control units

Air

The air subsystem will become increasingly complex as the requirements for more sophisticated compressor bleed systems and more extensive anti-icing systems to provide for integral air particle separators become incorporated on future engines. The trend will be toward increasing utilization of compressor bleed air for particle separator jet pumps, compressor and turbine stator control functions, and the like. R&M improvements to be incorporated in the subsystem will be minimal. They will consist of detailed changes to improve the durability of components. See Table XXXVI.

TABLE XXXVI. POTENTIAL CHANGES IN THE AIR SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
• More rugged construction of external lines and fittings	° More complex air systems for compressor bleed (part power performance and aircraft systems power) ° More extensive anti-icing systems for use on particle separators ° Need for built-in low pressure air supply for nacelle cooling and IR suppression	• Integral versus external passages for anti-icing, piston balancing, and cooling

Accessory

The trend for future accessory subsystems will be toward an increased number of component drives. Experience has indicated that tandem grouping of accessories from a single drive has caused problems. The trend will be toward more individual accessory drives for this purpose and to provide mechanical drives for particle separator blowers and like purposes. The operating environment for the accessory system will become more severe as engine case temperatures rise. Changes in the accessory subsystem are given on Table XXXVII.

TABLE XXXVII. POTENTIAL CHANGES IN THE ACCESSORY SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° More individual drives instead of series (Accessibility & Vulnerability)	° Additional components (particle separator blowers, etc.) ° Higher ambient temperatures	° Higher speed pumps, gen., etc could reduce accessory drive size & complexity (use a function of engine size)

Torquemeter

The trend of torquemeter subsystems for future engines will become more reliable and more accurate. Experience indicates that high-speed mechanical and remote airframe-mounted torquemeter systems have neither adequate reliability nor accuracy. It is unlikely that either type will be used on future engines. Features of future engine torquemeter systems are likely to include integral high-speed electrical/electronic systems with self-checking capability for torquemeter calibration. Changes that will affect future torquemeter system R&M are given in Table XXXVIII.

TABLE XXXVIII. POTENTIAL CHANGES IN THE TORQUEMETER SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° Purely mechanical systems are unlikely to be used ° Small high-speed turbines will continue to incorporate hydro-mechanical systems	° All engines will have integral torquemeters ° Self-check (pwr. margin ind.) of torque system will be required ° Need for improved accuracy	° Electronic vs. electro-mechanical on larger engines

Electrical

Electrical systems will become more complex to provide for the increasing use of power management systems and more comprehensive built-in engine diagnostic systems. The operating environment for the electrical system will become more severe as ambient temperatures rise due to higher engine operating temperatures. Changes that affect future electrical subsystems are presented in Table XXXIX.

TABLE XXXIX. POTENTIAL CHANGES IN THE ELECTRICAL SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° More rugged mounting of electrical lines & components	° Additional complexity due to diagnostics power management ° Higher ambient temperatures from higher engine temps (>250°F)	° Integral generators (shaft driven) on smaller engines

Exhaust

The general trend for the exhaust system will be toward simplification as the conventional front-shaft-drive configuration becomes more universal on medium and large engines. Small engines are likely to continue to show the diversity of exhaust configurations apparent on current engines. IR suppression is not likely to impact the exhaust-system removal rates since mounting and load-carrying provisions will be part of the airframe and will, most likely, be maintained as a separate module. Table XL shows the changes that will affect future systems.

TABLE XL. POTENTIAL CHANGES IN THE EXHAUST SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° Redundant retention mounting of exhaust cones		° Front-drive engines generally simplify exhaust configuration

Power-Train Reduction

Small engines with very high turbine shaft speeds will continue to employ power-train reduction gearing for helicopter drive systems. Changes in this subsystem will occur to take advantage of advanced gear and bearing materials. No overall change in reliability is foreseen. The introduction of integral particle separators may force reduction gearing to be offset from the engine centerline. Factors affecting future R&M are given in Table XLI.

TABLE XLI. POTENTIAL CHANGES IN THE POWER-TRAIN REDUCTION SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
	° Advanced gear and bearing materials • Integral separator may force reduction gearing to be offset	• Higher speed outputs would lead to less reduction gearing

Foreign Object Damage

The major trend toward preventing the FOD problem will be the universal application of FOD screens. Improvements can be expected in screen size optimization and design of more rugged attaching hardware. The development of second-generation inertial particle separators may provide the basis for a suitable alternative to FOD screens. The separator provides an overboard flow path for sand and dust, and it may be capable of handling large objects in the same manner. Studies and development efforts will determine this through analysis and testing under various power conditions with a variety of FOD sources.

Experience shows that design of compressors to withstand erosion and FOD can provide considerable benefit (see Figure 53). Engine configurations with an emphasis on durability and ruggedness will be characterized by compressor designs which are more tolerant of FOD and will result in significant reductions in removals due to FOD. Table XLII shows changes that will affect engine FOD.

TABLE XLII. POTENTIAL CHANGES IN THE FOD SUBSYSTEM

EXPERIENCE TRENDS	TECHNOLOGY TRENDS	DESIGN OPTIONS
° FOD screens mandatory ° Optimized screen size ° Improved screen-attaching hardware	° Reduced inlet losses ° Anti-iced screens ° Inertial separators instead of screens	° FOD-resistant compressor designs

Erosion

General trends in erosion damage reduction will be in the direction of mandatory incorporation of inertial particle separators and further refinement of these devices. Second-generation air particle separators with increased separator efficiencies and reduced ram air losses will be available. The past generation of add-on separators will be superseded by an era in which the air particle separator is designed by the engine manufacturer as an integral portion of the engine assembly. It is being recognized that the design of the compressor can have an R&M improvement potential nearly as great as the installation of particle separators. Erosion-resistant compressor designs will be considered for future engines where R&M is emphasized over performance and weight.

Several of the study engines were considerably more erosion tolerant than others. This tended to reduce the index number assigned to the composite engine. If R&M emphasis in 1975-1982 era engines does not outweigh performance emphasis, it is possible that these engines will experience erosion rates in excess of that assigned to the composite engine. Changes that will improve engine R&M through reduction of erosion are listed in Table XLIII.

TABLE XLIII. POTENTIAL CHANGES IN THE EROSION SUBSYSTEM

Experience Trends	Technology Trends	Design Options
o Particle separators are mandatory	o Increased separator efficiency	o Power sources for scavenging particle separators (hydraulic, electric, compressor air)
o Self-purging separators	o Reduced ram air losses o Separators integral with engine	

Environment

The trend for the environment domain will be toward more effective protection against identified problems. It is unlikely that contaminant levels present in fuel or oil from external sources will be significantly reduced. Similarly, environmental conditions leading to corrosion will not change. Operations will continue in adverse environments.

Activities are under way to more closely identify the specific conditions causing fuel and oil contamination. This effort parallels the efforts to improve fuel and oil filtration capabilities. Fuel and oil systems can also be designed to better accommodate current levels of contamination. Corrosion problems can be reduced by reducing the use of magnesium and using improved corrosion-resistant coatings. Engine problems resulting from start-up under adverse altitude and temperature conditions can be reduced by the incorporation of automatic overtemperature cutoffs. Changes that will reduce environmental problems are presented in Table XLIV.

TABLE XLIV. POTENTIAL CHANGES IN THE ENVIRONMENTAL SUBSYSTEM

Experience Trends	Technology Trends	Design Options
o Improved fuel filtration	o Improved corrosion resistant materials	
o Improved oil filtration	o Automatic power management systems to avoid overtemps	
o Less use of magnesium	o Additional complexity to fuel controls due to new functions	

Operator-Induced Problems

Operator-induced problems are classified as either intentional or unintentional. In future engines, it will not be possible to significantly reduce the category of intentional problems; they are caused by extraordinary demands on an engine to save the aircraft in dangerous situations or emergencies. The pilot will always require the option of extracting all possible power from an engine under extreme circumstances.

In the category of unintentional problems, engine starting techniques are expected to become more demanding as engine complexity increases. Also, higher operating temperatures may necessitate more involved shutdown procedures to preclude high soak-back temperatures. These two problems, which raise operator-induced failure rates, can be offset by the incorporation of automatic starting and power management systems and more extensive incorporation of diagnostic equipment to verify engine condition. Changes that will affect operator-induced engine R&M problems are presented in Table XLV.

Improper Maintenance

The magnitude of this problem was shown in Section 6 to be generally a function of the total engine reliability level. Thus, any trend in this area will be largely the result of changes incorporated in the other engine systems. If the total reliability is improved on future engines, the magnitude

TABLE XLV. POTENTIAL CHANGES IN THE OPERATOR-INDUCED SUBSYSTEM

Experience Trends	Technology Trends	Design Options
	o Higher operating trends with greater soak-back temp problems o Increased engine performance sophistication with more complicated starting techniques o Automatic starting o Condition monitoring	o Contingency power

of this problem will be reduced accordingly. Thus, R&M emphasis throughout the engine will influence the magnitude of problems caused by improper maintenance.

In addition to this indirect relationship, a direct improvement is possible through the stringent application of maintenance engineering disciplines to the design of turbine engines. This benefit from this improvement alone can be substantial. Examination of specific instances of maintenance damage (as discussed in Section 5) indicates that there are several areas that can profit from increased attention. Certain of these changes are shown in Table XLVI. Other improvements can result from close attention to detailed design and from recognition of past maintainability problems. All changes to reduce the magnitude of this problem will require significantly more emphasis on R&M than has been manifested in the past.

TABLE XLVI. POTENTIAL CHANGES IN THE IMPROPER MAINTENANCE SUBSYSTEM

Experience Trends	Technology Trends	Design Options
o Standardized and stronger studs and bolts o Integral wash manifolds o Reduction of blind installations o Components designed so that they cannot be installed backwards o Improved maintenance manuals o Careful selection of fuel and oil filter/screen locations o Additional maintenance durability tests	o Increased engine modularization o Improved engine diagnostics	o Level of repair capability

Airframe-Related Problems

Only slight improvements are expected in this area in the near future. The magnitude of the reduction will be a function of the overall emphasis on R&M. Since the bulk of removals in this category are due to poor accessibility of airframe-mounted components, the application of rigorous maintainability analysis to engine compartment design can be of significant value.

The emergence of formal interface agreements between airframe and engine manufacturers can provide a means of reducing failures caused by airframes. Engine/airframe interfaces (starting system, drive-train output connections, nacelle cooling, fuel filtration, mounting techniques, etc.) can be more closely controlled under these agreements.

The requirement to specify airframe-induced vibration levels will permit endurance testing in an environment similar to that which will be experienced on the aircraft. Detection and resolution of potential vibration-induced problems will then be possible. Table XLVII lists the changes that affect airframe-related R&M problems.

TABLE XLVII. POTENTIAL CHANGES IN THE AIRFRAME-RELATED SUBSYSTEM

Experience Trends	Technology Trends	Design Options
o Engine testing with A/C vibration levels o Improved accessibility o Rigorous maintainability analysis	o Improved airframe/engine interfaces o Development of drive system dynamics analysis techniques	o Hard vs soft mounting of engines

Convenience Removals

The two dominant factors that influence this problem were shown to be the overall reliability of the engine and the management of the logistics system. Since the magnitude of this problem in future engines will be the indirect result of basic engine reliability, it will reflect the specific emphasis on R&M given to each program. In addition to this indirect benefit, significant reductions in this rate can be obtained by an improvement in the logistics system. Specifically, the nonavailability of spare engines or engine components has been shown to be the significant factor in convenience removals. Improvements in the skills of logistics management should provide considerable relief to this problem. The magnitude of improvement will be greatest on those engines which are most unreliable and least on those which are most reliable, as shown on Figure 63. Improved accessibility can provide for more in-place repair, thus avoiding unnecessary engine removals. This accessibility improvement will result from increased R&M emphasis. Changes that will reduce convenience removals are shown in Table XLVIII.

TABLE XLVIII. POTENTIAL CHANGES IN THE CONVENIENCE SUBSYSTEM

Experience Trends	Technology Trends	Design Options
o Improvements in logistics management o Influenced strongly by engine accessibility	o Improved accessibility o Grouping of accessories	

PROGRAM TRENDS

In the previous section the individual R&M problems of current engines were examined to determine general program deficiencies. This portion of Section 6 reviews contemporary program trends to identify activities that can effectively offset the impact of past program deficiencies in future (1975-82 era) engines.

There are five major areas that influence the R&M of any engine. The first three (Specifications and Requirements, Development Design and Testing, and Operational Use and Product Improvement) relate to the development and use of specific engine models. The fourth and fifth areas (Environment and Materials and Design Concepts Technology) are not related to specific engines, but to engines in general.

Prior to discussing these areas, it would be valuable to review the various approaches that could be used to improve R&M. The term approach is used to indicate that there can be significantly different roles assumed by the customer and manufacturer in the total cycle of engine development. The spectrum of approaches can best be visualized by outlining the two extremes.

One extreme concentrates the achievement of R&M in the establishment of numerical objectives at the total engine level with minimal customer contact with the detailed design. Associated with these objectives are formal contractual demonstration requirements with economic incentives and penalties. This approach utilizes the design and management skills of the engine manufacturer to determine appropriate design concepts, execute the detail design, plan and perform the testing program, evaluate the need for corrective action, and conceive and implement design changes. Customer activity is limited to the establishment of initial requirements and confirmation that the objectives are achieved.

The other extreme requires that the customer be intimately involved with all phases of the program - establishing detailed design requirements, reviewing design approaches and analyses, exercising close and authoritative monitoring of the test, determining the need for corrective action, and assuring the adequacies of the corrective action.

The first approach has the advantages of simplicity, minimum costs, and minimum coordination. However, little or no knowledge of contractor progress is available to the customer, and contractual penalties notwithstanding, it is unlikely that the customer could ever completely recover the reliability growth schedule or the life-cycle cost objectives if the contractor's R&M program were deficient.

The second approach involves lower risks but requires much more customer effort. Customer evaluation and auditing at the detailed design level require skill across the full spectrum of engine design. A possible disadvantage is that this level of interface could essentially relieve the engine manufacturer of responsibility for achieving the R&M objectives.

Selecting the superior approach becomes even more complex when demonstration of the various R&M parameters that might be of interest is examined. It is relatively easy to perform a demonstration test of erosion characteristics. It is more difficult to demonstrate a removal rate for all causes. It is nearly impossible to demonstrate a safety-affecting failure rate, due to the low frequencies of occurrence and long demonstration times involved. The timing of the demonstration in relation to production go-ahead decisions and the customer's basic model evaluation and selection process are two other areas that must be considered in adopting a basic approach.

The two roles described are extremes and may not ever represent actual programs. They indicate the contrasts in emphasis that could affect future activities. Contemporary programs suggest that a combination of the two approaches is being taken with emphasis on numerical demonstration. Selected design features are being specified (such as erosion resistance, blade containment, accessory mounting locations, and similar characteristics) which can be separately demonstrated, usually through testing. General customer monitoring of the design and testing phases will provide some indication of goal achievement, but will not alleviate the contractor's basic responsibility for attaining the R&M objectives. A program approach midway between the two extremes is assumed in the discussion of the five program areas.

Specifications and Requirements

There is growing recognition that specifications and requirements is the prime area where the customer can influence major R&M characteristics. Later phases, especially the Operation and Product Improvement period, produce numerous detailed improvements; but by that time, the ability to make the major changes that grossly affect R&M has been lost due to the extreme costs involved. Consistent with the overall program approach of customer noninvolvement with design details, R&M objectives can presently be established with the following characteristics:

- Individual, realistic objectives for each engine
- Use of clearly understood parameters for which historical data is available
- Formal demonstration tests for each objective

R&M requirements for engines can and should be unique for a particular engine, just as weight, performance, SFC, and other characteristics are unique for a particular engine. This approach places the R&M objectives in the individual model specification rather than in general specifications such as MIL-E-5007, General Specification for Turbojet and Turbofan Aircraft Engines, which does include a numerical objective. General specifications should not include actual numerical values since R&M characteristics are so intimately related to other program issues (such as performance and weight requirements, development program effort, and state of the art in technology at the time of development).

Realistic numerical requirements are essential. Unrealistic or unquantified requirements will inevitably be ignored. The R&M objectives can be consistent with what is achievable, based on simultaneous consideration of past experience, current available technology, and other engine requirements from noise to performance. The numerical value can have a time dimension which denotes when in the life cycle of the engine the numerical value is to be reached. Both this time dimension and the numerical values can realistically reflect the schedule and planned extent of the developmental effort.

The requirement that the parameters be clearly understood and have historical data available has an importance that cannot be minimized. The value of historical data in the specific parameter enables the contractor and customer alike to honestly evaluate the design against the requirement. This requirement can be satisfied today for many parameters.

Finally, demonstration is required to make the other requirements meaningful. Formal demonstration of objective achievement is the ingredient that makes improved R&M a reality.

Demonstration of R&M objective achievement can be in the form of tests or analyses. Some parameters lend themselves to verification thru tests. Among these are erosion rates, fuel contamination resistance, total malfunction rate, maintenance task times, tool and GSE requirements, some failure progressions including containment, dry-lube operation, and others. Characteristics that are dependent on factors which can be understood and controlled are likely candidates for formal tests. Other characteristics driven by factors such as aircraft installation, maintenance concept, mechanics skills, pilot judgement, and local logistics and environmental conditions are difficult to demonstrate with the conclusiveness appropriate to a contractual obligation.

These elements are the prerequisites for effective R&M requirements and are generally available today for application to 1975-82 e[illegible] engines. They help R&M to compete effectively against other engine requirements that are universally understood and immediately demonstrable.

For current engines developed in the 1950-60 era, inadequate, misdirected, or absent specifications were directly responsible for 27 percent of the engine R&M problem. The individual subsystems/modes which were the source of this percentage are shown (Table XXVI). As indicated in the discussion, specifications were directly influential in a relatively few, but nevertheless important, modes and subsystems. However, inadequate specifications and requirements have an indirect effect upon the contributing factors Preliminary Design and Design Execution, and these factors influence every mode and subsystem. Thus, the potential improvement of R&M from more rigorous numerical specifications can be significant.

The direction of contemporary engine development programs should be examined against this background. Based on recent engine specifications, data presented at symposiums, and the various studies performed under contract to military customers, the following observations are offered:

- Numerical requirements at a specific point in the maturity cycle are being imposed at the engine-caused level in many parameters. Several of these parameters lack either historical data or the ability to be demonstrated through tests. Others are extremely sensitive to issues unrelated to the design (such as maintenance concept and skill levels).

- Several of these numerical values are to be demonstrated through testing. There appears to be a growing appreciation of the mathematical relationships involved with reliability demonstration tests, and this has enabled more meaningful tests to be established.

- Economic incentives and penalties are being associated with achievement of R&M goals.

- In addition to overall numerical objectives, specific design features are being specified and quantitative requirements established for specific failure modes. Erosion resistance, operation with contaminated fuel, low-cycle fatigue lives, no-lube operation, bearing B_{10} lives, and blade containment are being controlled. Certain design features, such as pinned bearing outer races, are being required. Other features that may also fall into this category are type of oil seals, case and compressor materials, type of torquemeter, fuel control actuating media, installation of FOD screens, sizes of fluid, air, and mechanical connections, and location and sequence of accessory mounting. Establishing these design features as requirements forces initial proposals to address these features directly and, where alternates are proposed, forces the proposers to justify, from an R&M standpoint, their decision to propose an alternate.

- Appropriate durations for demonstration tests are being recognized. Demonstration tests for overall engine reliability that require longer durations than practical for the development phase are being scheduled to occur in the production phase.

- Some engine programs are requiring that the configuration utilize an existing core. This approach capitalizes on the "Volkswagen principle" and is an effective method of obtaining good R&M by benefitting from the experience on already mature designs. This approach, if accompanied by restraints in increasing the operating temperatures and in the whole definition of "existing," can achieve both improved R&M as well as lower development costs.

In general there appear to be significant improvements in contemporary specifications and requirements. These improvements should produce future engines with R&M characteristics superior to the study engines.

Developmental Design and Testing

Consistent with the program approach discussed in previous paragraphs, participation of the customer in development design and testing should be limited primarily to observation and assistance. The responsibility for developing the basic design approaches, executing the detailed design, planning and performing the test program, and initially evaluating the resultant product should be the manufacturer's. The degree of freedom of the manufacturers in this area should be consistent with the contractual obligations they have assumed.

Essential to the process of developing the optimum engine for the given requirement is an understanding of the relative characteristics of alternative design approaches, materials, etc., and the ability to utilize these characteristics in meaningful trade-off studies. The inherent R&M characteristics of many design alternatives have not always been well defined. Most engine manufacturers possess a rather limited data bank that is restricted to the field experiences of their own engines and the tests of research programs they have conducted. This has severely limited their exposure to a wide range of configurations, designs, and materials with known R&M attributes, and thus has resulted in trade studies of confined scope. This lack of interchange of data among the engine manufacturers extends into other areas such as exchange of analytical techniques. Associations such as the SAE, AGMA, and many Government agencies contribute some relief from this problem. Much more effort is required. This is discussed under Material and Design Concepts Technology.

The problem has not been merely accessibility to R&M data. Even when data bases are available, the R&M qualities of alternate designs may not be evident due to variations in overlapping designs, environmental or usage differences, or dissimilar points on maturity curves. The design option category of engine features included many important and controversial design alternatives available to the engine designer. Significant questions such as the relative erosion characteristics of axial and centrifugal compressors have not been conclusively answered through either field or test data. This prevents the designer from relating a compressor design decision to a numerical goal for erosion resistance. It is felt that the study reported herein may represent a step toward alleviation of these problems, in that it represents both a compendium of field data and manufacturers' experience for a wide variety of turboshaft engine designs. Exposure to the R&M experience from growing families of engine configurations is assisting engine manufacturers in evaluating the design characteristics of at least the alternative approaches they have utilized in their own products.

It was suggested in Section 5 that only 25 percent of the problems arising from design execution were due to a technology or data limit. The remaining 75 percent were due to the omission of analytical calculations, disregard of clear historical experience, or failure to plan or execute test programs adequately. Thus, it is appropriate to suggest that what may be missing is an escalation in application rather than technology. This reflects again the indirect effects of inadequate R&M objectives and specifications. When the technology exists to adequately perform the design and testing phases and is not utilized, it can only be attributed to a lack of time, funds, or R&M emphasis. The current tendency, reported under Specifications and Requirements, toward meaningful numerical objectives with a contractual obligation to demonstrate achievement should cause the contractors to utilize their available analytical tools to a far greater extent in the design of contemporary engines.

The role of complete assembly testing in the development phase requires discussion at this point. Development testing, as opposed to demonstration testing, should be viewed as a backup to the design analytical process. It should never be considered as less than an integral element of the total developmental effort in response to a given requirement. As such, it reflects not only the uniqueness of a given configuration but the manufacturer's engineering and management skills as well as his total facilities and financial situation. The engine design, management, and procurement community is, unfortunately, not currently able to size a test program in terms of a stated reliability objective without making certain assumptions concerning initial design reliability, problem detectability in the test stands, and the contractor's ability to recognize, understand and correct problems. Assumptions such as these may be quite subjective.

Given this uncertainty on the required test program, the current trend is that minimum test durations and basic operating conditions are being specified by the customer. There are two basic reasons for this trend.

The first relates to the initial proposals by various competitors for the development contract award. Since the test program represents such a large portion of the development costs, it affords the individual manufacturer an opportunity for significant cost reductions through abbreviated efforts in this area. Given the inexact science of reliability prediction and control, military customers have chosen to establish a finite value of test duration in order to obtain comparable cost and schedule estimates. This eliminates one variable from the evaluation process but prevents any offeror from realizing his due competitive advantage from a superior reliability approach. Inherently more reliable design features, use of existing mature components or subsystems, or more sophisticated analytical procedures would be reflected only in the obscurity of an heretofore unprovable higher reliability level instead of the more obvious lower cost program.

The second reason for specified minimum test durations is related to the first in that it reflects the current inability to size a test program based on a reliability goal. Minimum test durations have been escalating throughout the years with the hope that higher reliability would be achieved. Durations are currently between 9000 and 14,000 hours on new engines.

There is a natural reluctance to reduce these durations, at a time when good R&M is the dominant theme. This may result, however, in higher development program costs than are actually required.

The growing concern for minimum costs, when coupled with the concurrent desire for improving the reliability levels, has produced an interest in developing methods for relating reliability and testing requirements. An approach for relating test requirements to reliability objectives for helicopter transmissions and other major dynamic components is available today for application to the design of test programs for contemporary engines.[23] Application of these principles would result in a more efficient development test program, by tailoring the level and duration of the tests to the R&M requirements.

The following is a summary of current trends in the development design and testing area:

- o Design and testing has been and will be primarily the contractor's responsibility. The customer is generally assuming a passive role in the evolution and execution of the detailed design, but a more aggressive role in the testing area by specifying minimum test durations. Methods are appearing to aid in the establishment of test requirements.
- o Relationships between testing duration and reliability objectives are becoming better understood. Rigorous sizing of test programs requires some improvements in our ability to predict anticipated initial design reliability, test detection effectiveness, and time required for corrective action.
- o Information relating to the R&M characteristics of alternate design approaches or materials has been severely limited due to the general lack of widely available published field and test data. Exposure to available analytical techniques is similarly limited. Steps are being taken to relieve this problem, and material is available for application to contemporary engines.

In general, development design and testing is a fertile area for activities that will apply, expand, and upgrade the resources for improving the R&M of future engines.

Operational Use and Product Improvement

This phase represents the activities occurring after the engine has been fielded for operational use. The emphasis applied to the product improvement program affects the slope (rate of improvement) of the growth curves. Depending on the precise nature of the developmental and production contracts in the area of R&M goals, the responsibility for R&M improvement in this phase may lie with either the contractor or the customer. It has been suggested that, in an era of formal R&M demonstrations, most of the responsibility for corrective action will rest with the contractor until the point of demonstration. However, there will still be a significant opportunity for improvement after this point, with prime responsibility for implementation, if not initiation, resting with the customer.

Unfortunately, past production programs have not been models of efficiency or effectiveness. Three areas of these programs require remedial action:

- The evaluation process for initiating and implementing design changes to correct reliability problems
- The system for the uprating of the basic model for higher powers through changes in speeds, operating temperatures, or additional stages
- The procedures for establishing initial TBO intervals and progression programs

The entire process of product support has suffered because of weaknesses in both the contractor and customer roles. On the contractors' part, the design and support teams tend to be disbanded after the initial development phase is completed. Thus, the response to service-identified problems has not been characterized by the same talents and enthusiasms encountered in the development of a new design.

On the other hand, even when the contractor has responded quickly to the indication of a problem, the customer sometimes fails to approve the corrective action or to have it incorporated into field engines in a timely manner. The problems on both fronts arose from the lack of clear reliability growth objectives for the hardware and the difficulties of evaluating the need for, or value of, specific corrective action for problems.

Two basic approaches have been followed in the past for identifying problems; each has its own merits. The first concentrates the R&M program in the collection of quantitative data and the periodic publishing of this failure data in order to identify existing and potential problems. The second relies more on qualitative judgements formulated during periodic joint conferences between the contractor and the several customer organizations involved.

Both systems have their faults: the first, with its emphasis on numerical expression, tends to minimize or at least discourage a good description and discussion of the mechanisms of failure. And many times, the collection and display of several R&M parameters fail to emphasize the consequences of a single failure mode in each of these parameters. The disadvantage of the second approach is that a tendency exists for individuals to emphasize problems of which they are locally or immediately aware regardless of their actual magnitude or consequences. It has been difficult to determine priority of problems under these circumstances.

Recent product improvement programs appear to have recognized the basic advantages and disadvantages of the two extremes noted above and have developed data reporting systems which have combined the advantages of both. More qualitative descriptions of problems are provided, but the basic numerical expressions are maintained. It would appear that for contemporary engines, these new reporting systems will be used more as working documents than in past programs and will be correspondingly more effective in achieving rapid visibility of problem cause and magnitude, and in providing a more efficient product improvement program. The data reporting systems for the T63 in the U.S. Army and the TF41 in the U.S. Navy are two examples of this improvement trend.

The second major problem area, the development of reliable and maintainable uprated models, has been as serious as the first problem area. Several dramatic instances have occurred in the last decade where significant problems accompanied the introduction of uprated models. Failure modes were experienced that caused accidents and unscheduled removals at rates much greater than those for the basic model.

These problems arose essentially from a lack of adequate verification testing. Confidence that the new model was similar to the existing design led to an overreliance on analysis techniques as opposed to testing. Frequently, the schedule became a dominant restraint to further activities, with the new airframe becoming available prior to the new engine model with the attendant pressures to accelerate the introduction of the engine.

The technology that achieves the required level of R&M in new development engines will be adequate to achieve it in uprated models, if it is applied. What has been lacking is recognition that an uprated model of an existing engine needs the same R&M attention during specification, design, detail, and testing as did the basic model. The concept of numerical objectives and demonstration requirements for uprated models is available today for application to the derivatives of contemporary engines.

The third area, TBO interval establishment, has traditionally been the joint domain of the developmental and production phases. Objectives for TBO intervals have not been clearly established in the basic specifications. Terminology has been inconsistent, and no rigorous means of verification has been suggested. Even when TBO objectives were quantitatively established, no programs were defined for extending the intervals beyond the initial levels after the aircraft/engines were tested and introduced into operational service.

The actual TBO progressions have been the responsibility of various committees representing a wide range of technical and administrative assignments. In some cases, decisions have been made based on samples returned from normal operational aircraft; while in other cases, a specialized accelerated test activity was utilized. In either case, the criteria for detailed component evaluation were ill-defined or inconsistent for different engines or evaluating agencies.

Recent efforts at the Naval Air Integrated Logistics System Command (NAILSC) and the Eustis Directorate, United States Army Air Mobility Research and Development Laboratory (USAAMRDL), are directed at establishing the hardware, criteria, and mathematical procedures for determining appropriate TBO intervals. When developed, these procedures must be incorporated into the basic R&M program and applied throughout the life cycles of the engines.

The following trends are apparent:

- There is some indication of improvement in procedures and responsibilities for the identification and correction of service-revealed problems. Data reporting systems and their documentation are more oriented to the rapid detection and correction of problems than in past programs.
- There are current activities being directed at upgrading the logic and mathematical tools required for TBO establishment. Rigorous procedures will soon be available for application to engines now in service.

Environment

This area pertains to all engines and represents the total environment (climatic, mechanical and personnel) to which engines are subjected. In spite of its universality of effect, insufficient resources have been addressed to this area.

In the previous subsystem discussions, the effect of the environment on individual failure modes was noted, and specific remedial actions were defined. It should be recognized, however, that the effect of environment on individual problems is normally minimized; the dialogue usually concentrates on the means of correcting the problem. The impact of environment requires increased attention by customer agencies chartered to improve R&M, but not involved with specific engine model development programs.

It may be presumptuous to suggest that environment could be significantly changed. However, there has been a growing recognition that there is a very real value in better definition of environment as a prerequisite to defining adequate design criteria.

Climatic environment involves terrain-related topics such as sand types and concentrations as well as atmosphere-related issues such as humidity and salt concentrations. The impact of variations in these elements on engine R&M has previously been discussed for specific failure modes. Specialized studies (such as Reference 22 which quantifies the salt deposits on compressor blades and vanes) aid in understanding specific problem areas. Of even more value are the Conferences on Environmental Effects on Aircraft and Propulsion Systems sponsored by the Naval Air Propulsion Test Center. These conferences provide a forum where military and commercial interests can publish and discuss the results of climatic environment analyses and tests.

Activities such as these provide a means by which configurations and materials can be selected for contemporary engines which permit them to achieve reliability objectives.

The mechanical environment consists primarily of the aircraft-imposed loads on the engine. Aircraft vibration levels and drive-train torque or alignment fluctuations have contributed to engine failures. This mechanical environment, significantly more severe for helicopters than for fixed-wing aircraft, is probably a major reason for the differences in reliability indicated in Figure 10. Heated discussions of problem responsibilities (engine versus airframe) have done little to provide a solid data bank of helicopter vibration levels for future engine design criteria. Recent effort by the Helicopter Powerplant Committee of the SAE (S-12) to standardize vibration measurement techniques is a start toward such a data bank. Progress has been made in reducing rotor-induced vibration levels in helicopters of recent designs.

Other physical dimensions of the environment that should be mentioned in this category include fueling equipment and the array of ground support equipment at all levels of maintenance. The impacts of contaminated fuel and maintenance damage have previously been shown to be substantial.

The effect of the physical limitations of fuel nozzles or fueling locations on the contamination problem needs to be explored. Actual fuel and oil contamination levels experienced in the field have not been adequately defined. Recent requirements for aircraft pressure fueling systems should diminish the fuel contamination problem, and design improvements in oil filtration devices will contribute some relief to the oil contamination problem.

The personnel who maintain and operate turbine engines have had an even greater effect on engine R&M. Analyses indicated that 32 percent of the problem was directly attributable to operations and maintenance, with approximately 40 percent operator-induced and 60 percent maintenance-induced. Over 65 percent of this operations and maintenance contribution was experienced in the Improper Maintenance, Operator-Induced and Convenience modes. The inevitability of this people problem requires emphasis for all types of hardware.

It should be clear that military helicopter turbine engines have not experienced the required step function improvement in their ability to operate reliably within the people environment that exists. A clear recognition of the performance characteristics of operating and maintenance personnel will be essential to this upgrading. While undoubtedly more difficult than a definition of the sand environment, any effort to establish some type of baseline of human performance has a potential for large reductions in the R&M problem. Individual skills, maintenance concepts, and pilot workloads are a few of the factors that should be examined. The impact of the volunteer army may provide some relief to the maintenance- and operator-induced problem, although the benefit may be nominal. More gain may be achieved through the application of human factors engineering to the manual and handbook software as well as to the design itself.

The climatic environment is receiving the bulk of industry's attention. Progress is apparent in that sector and will favorably impact contemporary engines. Additional attention needs to be given to the personnel and mechanical aspects of the environment. Progress is evident in vibration reduction.

Materials and Design Technology

This area is intended to represent the development of design concepts and materials technology that is performed independently of specific engine programs. No rigid distinction is implied here, since much research is funded by specific engine programs. The required research encompasses investigations into the properties, characteristics, and applications of new and existing materials or design concepts. There are three basic domains of this research:

- Subsystem- or component-oriented research
- General engine configuration or sizing studies
- Engine-related topics such as improved fuels and lubricants

Subsystem-oriented research has received the bulk of the R&D effort with nearly every subsystem being considered. The Detailed Problems of Current Engines section cited studies covering topics ranging from turbine vane materials[10] to high-speed fuel pumps[23] and air bearings.[24] Investigations in these new areas are valuable, since they allow the engine design team to choose from an expanding pool of design techniques. When funded and published by Government agencies, they dilute the effects of the not-invented-here syndrome. Unfortunately, most of this research is primarily directed at reducing size, weight or costs, and secondarily if at all, at improving reliability or maintainability. Of more interest to those concerned with R&M are the studies that address trade study issues, involving the application of existing alternative design approaches or materials. For example, the performance penalties associated with the use of labyrinth seals have been quantified.[25] Studies such as these assist in the practical selection of designs with proven reliability or maintainability characteristics.

The additional emphasis that should be applied to studies of this type should not be postponed because of a prevalent attitude that increased R&M demands new materials, design concepts, or significant increases in available technologies. There are many areas that are candidates for these studies; it was noted in the Developmental Design and Testing section that many design features used to configure future engines had to be classified as design options because their inherent R&M characteristics were not fully understood.

Other research has been directed at more general engine design areas such as the feasibility of regeneration or recouperation[26] or the applicability of diagnostics and condition monitoring. Additional topics that should be pursued in this category include a formal methodology for engine TBO establishment, realistic examination of the concept of an expendable engine, and optimum engine output speeds based on considerations of the entire drive train. However, this engine research category is not nearly as critical to future R&M as is the previous area of more detailed component research.

The third area of research is in subjects relating to engines but not directly to their design. The most notable examples here are the research programs directed at improved fuels and lubricants. These activities are usually intended to improve performance, with little consideration given to improving R&M. An exception is the current research directed at improved load capacities of lubricants.

Studies directed at describing the R&M problem of turbine engines in general have not been undertaken by the full variety of agencies and interests with active responsibilities in engine development and design. Other than the study reported herein, the authors are aware of only one other comprehensive study of turbine-engine R&M.[27] That study, however, described only turbojet engines designed in the 1940's and operated in the 1950's. The study is, however, valuable due to the depth of design discussion in several of the major subsystems.

The many forums, symposiums and conferences that promote the exchange of existing and newly developed reliability-oriented design technology warrant discussion. These Government and professional-society sponsored meetings provide a necessary technical interchange of information directly applicable to the development of contemporary engines. The Mechanical Failures Prevention Group meetings held three times a year under the sponsorship of the Office of Naval Research and the annual R&M Conference sponsored by the SAE, ASME, and the AIAA are excellent examples.

These categories encompass a vast array of effort in the public and private sectors of engine development. This area has made available considerable technology for application to 1975-82 era engines and will continue this contribution for subsequent developments. This area is second only to Specifications and Requirements in its potential benefit to improved engine R&M.

7.0 NEAR-TERM ENGINE PROJECTION

The previous section outlined the probable changes that will or could be incorporated in 1982 engines. No clear pattern has emerged to define the degree of emphasis that will be placed on R&M in 1982 engines. Some of the changes that were outlined, particularly in the Experience Trend group, had a significant R&M impact, while others, particularly in the Design Options group, had no apparent R&M impact.

The engines that will emerge in 1982 will represent some combination of features that were outlined in the previous section. The R&M levels that will be achieved depend on the particular emphasis placed on these characteristics by the customer, and in turn by the manufacturer, during the design and developmental stages. It is possible to define two extremes of options that exist: first, an engine with a full and rigorous R&M emphasis, sufficient to dominate all other considerations in the trade-offs; and second, an engine in which performance receives the predominant emphasis, and R&M features are included only where they do not compromise performance. The configurations and designs of the individual engines intended to meet these two different objectives would be quite different. Since engineering endeavors usually involve a more judicious balance of emphasis during trade-offs, a third configuration will be defined which incorporates the anticipated balance of R&M features in its design. This 1982 normal engine will have a configuration and R&M level that lie between the extremes of full-R&M-oriented and full-performance-oriented engines.

ENGINE MATURITY

Earlier sections of this study presented the effects of product improvement efforts upon the R&M levels that were measured on individual engines at any particular time. It was shown that considerable reliability improvements were observed following the completion of development testing and after inservice introduction (see Figure 9).

In order to make a valid comparison between R&M values measured for current engines and those predicted for 1975-82 era engines, it is necessary to compare them at a common point of maturity. The composite engine developed earlier in the study was assumed to be at the reliability level appropriate for 1 million engine hours. Therefore, the three future engines to be defined will each be considered to have 1 million hours of operation. The importance of this point is twofold. First, all component and engine development testing will have been accomplished; many of the major design oversights, deficiencies, etc., will have been detected and eliminated; and the engine will have been fielded for large-scale operation.

Second,the engine will have benefitted from the elimination of major service-revealed difficulties, benefitted from product improvement programs, and essentially, it will be well toward its mature reliability rate.

SPECIFIC CONFIGURATIONS

The three configurations investigated have been designated Full-R&M-Emphasized Engine, Full-Performance-Emphasized Engine and Normal Engine. The detailed engine configurations are outlined in Tables XLIX through LXVIII. These configurations present selections of features from those provided in Section 6. Many of the features contained in the Experience Trends (category) were applied to all three engines, since they provide increased reliability with little or no performance penalty. The features categorized as Technology Trends found their greatest application in the full-performance-emphasized engine. Design options found applications in all three engines.

TABLE XLIX. FUTURE ENGINE FEATURES - BEARINGS

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Pinned bearing outer races	o Pinned bearing outer races	o Pinned bearing outer races
o One-piece machined cases	o One-piece machined cases	o One-piece machined cases
o Improved thrust load control	o Improved thrust load control	o Improved thrust load control
o Improved lube filtration level		
o Inner race riding cages	o Inner race riding cages	o Inner race riding cages
o Elliptical outer races		o Elliptical outer races
o Improved analytical models for cage slip	o Improved analytical models for cage slip	o Improved analytical models for cage slip
o Advanced materials	o Advanced materials	o Advanced materials
	o New bearing configurations	
	o Exotic lubricants	
o Impregnation of trace materials	o Impregnation of trace materials	o Impregnation of trace materials
	o Higher bearing speeds	
o Condition monitoring	o Condition monitoring	o Condition monitoring
o Increased modularization		o Increased modularization
	o Differential bearings	
	o Integral inner races	
	o Additional bearings	
	o Counterrotating shafts	
o Corotating shafts		o Corotating shafts

TABLE L. FUTURE ENGINE FEATURES - SEALS

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
	o Oil coking problem will become more significant as soak-back temperatures increase	
o Contaminant levels will be reduced due to improved oil filtration & integral air inlet separator		o Contaminant levels will be reduced due to improved oil filtration & integral air inlet separator
o Refinements in labyrinth seal designs		o Refinements in labyrinth seal designs
	o Refinements in carbon seal design	o Refinements in carbon seal design
o Fluid damping of shafts may cause seal difficulties over mechanical damping	o Fluid damping of shafts may cause seal difficulties over mechanical damping	o Fluid damping of shafts may cause seal difficulties over mechanical damping
	o Tighter seals - less leakage as a means of obtaining more performance	
o Fewer static seals if air & oil lines integrally routed		
o More static seals from increased modularization		o More static seals from increased modularization
o Corotating shaft seals		o Corotating shaft seals
	o Additional shaft seals	
	o Counterrotating shaft	
o Greater potential for static seal leakage with use of centrifugal compressor		o Greater potential for static seal leakage with use of centrifugal compressor
o Increased use of labyrinth seals		o Increased use of labyrinth seals
	o Continued use of carbon seals	
		o Reduced number of carbon seals
o Improvements in static seal materials, configurations, & installations	o Improvements in static seal materials, configurations, & installations	o Improvements in static seal materials, configurations, & installations
o More extensive use of piston ring seals		o More extensive use of piston ring seals
	o Higher seal speeds	

TABLE LI. FUTURE ENGINE FEATURES - COMPRESSOR

Full-R&M-Emphasis	Full-Performance	Normal Engine
o Erosion-resistant blade and vane materials		o Erosion-resistant blade and vane materials
		o Dual actuator - variable stators
	o Higher stage loadings	o Higher stage loadings
	o Higher pressure ratios	o Higher pressure ratios
o Improved analytical techniques for resonance	o Improved analytical techniques for resonance	o Improved analytical techniques for resonance
o Improved low-cycle fatigue-prediction techniques	o Improved low-cycle fatigue-prediction techniques	o Improved low-cycle fatigue-prediction techniques
o Improved blade/vane coatings for corrosion		o Improved blade/vane coatings for corrosion
o Increased use of effective air separators	o Increased use of effective air separators	o Increased use of effective air separators
	o Increased complexity compressor control system for part power considerations	
	o Composite/fibre/filament wound disc	
o Higher demand for bleed air requires additional complexity of bleed extraction hardware	o Higher demand for bleed air requires additional complexity of bleed extraction hardware	o Higher demand for bleed air requires additional complexity of bleed extraction hardware
o Additional complexity for noise attenuation	o Additional complexity for noise attenuation	o Additional complexity for noise attenuation
	o Higher aspect ratio blades	
	o Integral casting of blades/disc	

TABLE LII. FUTURE ENGINE FEATURES - COMBUSTOR

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Improved component testing necessary	o Improved component testing necessary	o Improved component testing necessary
	o Higher combustor temperatures	o Higher combustor temperatures
	o Improved coating materials	
o Improved analytical techniques for heat distribution patterns (TVR reduced)	o Improved analytical techniques for heat distribution patterns (TVR reduced)	o Improved analytical techniques for heat distribution patterns (TVR reduced)
	o Double wall liners	
o Cast liners		
o Straight combustor	o Straight combustor	

TABLE LIII. FUTURE ENGINE FEATURES - TURBINES

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Use of cast nozzles	o Use of cast nozzles	o Use of cast nozzles
o Improved materials and coatings to resist sulfidation	o Improved materials and coatings to resist sulfidation	o Improved materials and coatings to resist sulfidation
o Use of slotted inner/outer nozzle bands		o Use of slotted inner/outer nozzle bands
	o Higher TIT's	o Higher TIT's
	o Possible application of ceramics	
	o New cooling techniques	o New cooling techniques
	o Variable geometry nozzles	
	o More sophisticated blade/vane design from cooling requirements	o More sophisticated blade/vane design from cooling requirements
	o Higher pressure ratios	
o Use of directional solidified alloys	o Use of directional solidified alloys	o Use of directional solidified alloys
o Lower sulfur contents in fuel	Lower sulfur contents in fuel	o Lower sulfur contents in fuel
o Improved low-cycle fatigue-prediction techniques	o Improved low-cycle fatigue-prediction techniques	o Improved low-cycle fatigue-prediction techniques

TABLE LIV. FUTURE ENGINE FEATURES - CASES

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Less emphasis on thin wall casings		o Less emphasis on thin wall casings
o Improved corrosion protection		o Improved corrosion protection
o Bosses & fittings integrally cast		o Bosses & fittings integrally cast
o Magnesium minimized as structural support		o Magnesium minimized as structural support
o Increased modularization		o Increased modularization
	o Increased case temperatures	
o Additional bosses/ fittings for both internal and external diagnostics	o Additional bosses/ fittings for both internal and external diagnostics	o Additional bosses/ fittings for both internal and external diagnostics
o Additional bosses/ fittings for extra bleed control	o Additional bosses/ fittings for extra bleed control	o Additional bosses/ fittings for extra bleed control
o Noise attenuation requirements may complicate cases	o Noise attenuation requirements may complicate cases	o Noise attenuation requirements may complicate cases

TABLE LV. FUTURE ENGINE FEATURES - LUBRICATION

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Use of labyrinth seals will necessitate more complex air/oil separation		
o No quick disconnects	o No quick disconnects	o No quick disconnects
o Increased system testing		o Increased system testing
o More attention to scavenge capabilities		o More attention to scavenge capabilities
o Additional requirements for filtration		o Additional requirements for filtration
	o Additional cooling requirements	
	o Potential soak-back temperature problem from increased TIT	

TABLE LVI. FUTURE ENGINE FEATURES - FUEL

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Additional filtration required	o Additional filtration required	o Additional filtration required
o Increased accessibility to fuel control	o Increased accessibility to fuel control	o Increased accessibility to fuel control
o Positive lubrication of fuel pump/control splines		
	o More complex fuel control units incorporating automatic functions, bleed control, & diagnostic functions	o More complex fuel control units incorporating automatic functions, bleed control, & diagnostic functions
	o Additional control functions for variable turbine geometry	
	o Increasing use of power management systems	o Increasing use of power management systems
	o Increasing use of electronics and fluidics	
o Reduction of impurities in turbine fuels (affecting hot section components)	o Reduction of impurities in turbine fuels (affecting hot section components)	o Reduction of impurities in turbine fuels (affecting hot section components)
o Power margin indicator	o Power margin indicator	o Power margin indicator

TABLE LVII. FUTURE ENGINE FEATURES - AIR

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o More rugged construction of external lines and fittings		
o More complex air systems for compressor bleed (partial power performance & aircraft system power)	o More complex air systems for compressor bleed	o More complex air systems for compressor bleed
o More extensive anti-icing systems for use on particle separators	o More extensive anti-icing systems for use on particle separators	o More extensive anti-icing systems for use on particle separators

TABLE LVIII. FUTURE ENGINE FEATURES - ELECTRICAL

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o More rugged mounting of electrical lines and components o Additional complexity due to diagnostics and power management	o Additional complexity due to diagnostics and power management o Higher ambient temperatures from higher engine temperatures (>250°F)	o Additional complexity due to diagnostics and power management

TABLE LIX. FUTURE ENGINE FEATURES - TORQUEMETER

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Purely mechanical systems are unlikely to be used	o Purely mechanical systems are unlikely to be used	o Purely mechanical systems are unlikely to be used
o Small high speed turbines will continue to incorporate hydro-mechanical systems	o Small high speed turbines will continue to incorporate hydro-mechanical systems	o Small high speed turbines will continue to incorporate hydro-mechanical systems
o Engines will have integral torquemeters	o Engines will have integral torquemeters	o Engines will have integral torquemeters
o Self checking of torque system will be required	o Self checking of torque system will be required	o Self checking of torque system will be required

TABLE LX. FUTURE ENGINE FEATURES - ACCESSORIES

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o More individual drives instead of series types	o More individual drives instead of series types	o More individual drives instead of series types
o Additional components (particle separator blowers, etc.)	o Additional components (particle separator blowers, etc.)	o Additional components (particle separator blowers, etc.)
	o Higher ambient temperatures	

TABLE LXI. FUTURE ENGINE FEATURES - POWER-TRAIN REDUCTION

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Advanced gear and bearing materials o Integral separator may force reduction gearing to be offset	o Advanced gear and bearing materials o Integral separator may force reduction gearing to be offset	o Advanced gear and bearing materials o Integral separator may force reduction gearing to be offset

TABLE LXII. FUTURE ENGINE FEATURES - FOD

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Inertial separators o Screens installed o Optimized mesh size o Improved screen attaching hardware o FOD-resistant compressor (max)	o Inertial separators o Screens installed o Optimized mesh size o Improved screen attaching hardware	o Inertial separators o Screens installed o Optimized mesh size o Improved screen attaching hardware o FOD-resistant compressor (max)

TABLE LXIII. FUTURE ENGINE FEATURES - EROSION

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Inertial separators o Increased separator efficiency o Erosion-resistant compressor	o Inertial separators o Increased separator efficiency	o Inertial separators o Increased separator efficiency o Erosion-resistant compressor

TABLE LXIV. FUTURE ENGINE FEATURES - ENVIRONMENTAL

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Improved lube filtration o Improved fuel filtration o Less use of magnesium	Improved fuel filtration o Automatic power mgmt o More use of magnesium o Additional complexity of fuel controls with potential for contamination	o Improved lube filtration o Improved fuel filtration o Automatic power mgmt

TABLE LXV. FUTURE ENGINE FEATURES - OPERATOR INDUCED

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Improved condition monitoring o Multiengine power matching	o Improved condition monitoring o Multiengine power matching o Automatic power management o Emergency power capability o Higher operating temperatures	o Improved condition monitoring o Multiengine power matching

TABLE LXVI. FUTURE ENGINE FEATURES - IMPROPER MAINTENANCE

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Improved engine diagnostics o Clearer maintenance manuals o Improved studs & bolts o Integral wash manifolds o Reduction of blind installations o Murphy-proof designs o Optimum screen/filter locations o Maintenance durability tests	o Improved engine diagnostics o Clearer maintenance manuals	o Improved engine diagnostics o Clearer maintenance manuals

TABLE LXVII. FUTURE ENGINE FEATURES - AIRFRAME RELATED

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Engine/airframe interface agreements o Improved accessibility o Rigorous maintenance analysis o Engine testing with acft/vibration levels	o Engine/airframe interface agreements	o Engine/airframe interface agreements o Improved accessibility

TABLE LXVIII. FUTURE ENGINE FEATURES - CONVENIENCE

Full-R&M-Emphasis	Full-Performance-Emphasis	Normal Engine
o Improved logistics mgmt o Benefits from improved reliability o Improved accessibility	o Improved logistics mgmt	o Improved logistics mgmt

QUANTIFICATION OF R&M LEVELS IN NEAR-TERM (1975-82 ERA) ENGINES

The previous tables defined the specific features expected in 1975-82 era engines. This section quantifies the reliability of the features at the subsystem and failure mode levels. Two separate quantifications are developed, namely index number and UER rate. These are provided in Table LXIX at the subsystem level and in Table LXX at the failure mode level.

The reliabilities listed represent the extremes of an engine with a rigorous emphasis on R&M and one with a full emphasis on performance. The decision to pursue R&M versus performance as the prime objective will have been made prior to the detailed design phase. The assumption has been made in this study that both the full-reliability-emphasized and full-performance-emphasized engines will have received similar attention to R&M during development testing and operational use. Thus, the shapes of the maturity curves are considered to be similar to those experienced in the past. The predictions represent an RVN (combat, climate, etc.,) type environment.

TABLE LXIX. FUTURE ENGINES SUMMARY MATRIX - SUBSYSTEMS

SUBSYSTEM	COMPOSITE ENGINE		FUTURE ENGINES					
			RELIABILITY/ MAINTAINABILITY EMPHASIZED		PERFORMANCE/ WEIGHT EMPHASIZED		NORMAL GROWTH	
	INDEX VALUE	UER	INDEX VALUE	UER	INDEX VALUE	UER	INDEX VALUE	UER
BEARINGS	3.80	0.107	2.65	0.057	4.68	0.127	2.80	0.062
SEALS	.346	0.205	0.26	0.020	5.25	0.303	2.41	0.144
COMPRESSOR	4.63	0.072	3.47	0.051	4.68	0.067	3.76	0.057
COMBUSTION	1.14	0.040	0.94	0.033	1.02	0.035	0.98	0.034
TURBINE	2.86	0.058	2.24	0.047	3.03	0.082	2.24	0.047
CASES	1.27	0.054	0.83	0.039	1.42	0.063	0.91	0.041
LUBRICATION	1.28	0.034	1.03	0.028	1.21	0.028	0.98	0.026
FUEL	3.45	0.085	2.73	0.070	3.37	0.084	3.12	0.078
AIR	0.55	0.010	0.58	0.011	0.61	0.011	0.61	0.011
ACCESSORY	0.91	0.025	1.00	0.028	1.04	0.029	1.00	0.028
TORQUEMETER	1.27	0.048	0.43	0.016	0.43	0.016	0.43	0.016
ELECTRICAL	0.73	0.014	0.71	0.013	0.77	0.015	0.76	0.014
EXHAUST	0.55	0.004	0.28	0.002	0.28	0.002	0.28	0.002
POWER-TRAIN REDUCTION	0.72	0.013	0.72	0.013	0.72	0.013	0.72	0.013
INLET AIR SEPARATION	-	-	0.50	0.013	0.50	0.013	0.50	0.013
TOTAL - ENGINE CAUSED	26.62	0.769	18.37	0.441	29.01	0.887	21.50	0.586
FOREIGN OBJECT DAMAGE	6.71	0.388	2.59	0.150	5.02	0.290	3.12	0.180
EROSION	2.90	0.140	0.29	0.020	2.90	0.200	1.16	0.080
ENVIRONMENTAL	1.09	0.059	0.87	0.047	1.16	0.063	0.89	0.048
OPERATOR INDUCED	2.54	0.122	2.54	0.122	2.54	0.122	2.54	0.122
IMPROPER MAINTENANCE	5.09	0.305	2.50	0.150	5.85	0.350	3.85	0.230
AIRFRAME RELATED	2.36	0.148	1.60	0.100	2.40	0.150	1.92	0.120
CONVENIENCE	5.46	0.495	0.77	0.070	2.18	0.200	1.10	0.100
TOTAL - NON ENGINE CAUSED	26.15	1.657	11.16	0.659	22.05	1.345	14.58	0.860
UNKNOWN	7.26	0.356	1.23	0.060	5.90	0.290	2.65	0.130
TOTAL - ALL CAUSES	60.03	2.782	30.76	1.160	56.96	2.522	38.73	1.596

TABLE LXX. FUTURE ENGINES SUMMARY MATRIX-FAILURE MODES

	Current Engines				1972-82 Era Engines					
	Composite Engine				Reliability and Maintainability Emphasized		Performance/ Weight Emphasized		Normal Growth	
	Index Number		Unscheduled Removals		Index Number	Unscheduled Removals	Index Number	Unscheduled Removals	Index Number	Unscheduled Removals
Subsystem Failure Mode	Value	Percent	Rate	Percent	Value	Rate	Value	Rate	Value	Rate
Bearings	3.80	—	0.137		[illegible]	[illegible]	1.68	0.127	2.80	[illegible]
Spalling - Classical (B_{10})	[illegible]42	11	0.006	6	[illegible]	0.003	0.53	0.008	0.28	0.008
Spalling - Nonclassical	[illegible]65	49	0.033	31	1.76	0.031	2.88	0.350	1.76	0.031
Race Rotation Displacement	[illegible]62	16	[illegible]	[illegible]	[illegible]	0.003	0.26	0.014	0.07	[illegible]
Cage Wear Cracking	[illegible]	13	[illegible]18	[illegible]	0.35	0.012	0.47	0.017	0.35	[illegible]
Roller Skidding	[illegible]33	8	[illegible]	[illegible]	[illegible]	[illegible]	0.48	0.021	[illegible]	[illegible]
Miscellaneous	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]14	0.007	[illegible]	[illegible]
Seals	[illegible]	—	[illegible]		[illegible]	[illegible]	5.25	0.303	2.41	0.244
Carbon-Seal Leakage	1.26	97	[illegible]	91	-	-	[illegible]	[illegible]	2.22	[illegible]
Labyrinth Seals	[illegible]	2	[illegible]004	2	[illegible]	0.013	[illegible]	0.004	[illegible]	[illegible]
Static Seals and O Rings	0.08	2	0.009	4	0.07	[illegible]	0.06	0.007	0.09	0.010
Miscellaneous	0.03	1	0.002	1	0.03	0.002	0.03	0.002	0.03	0.002
Compressor	4.63	—	[illegible]		[illegible]	[illegible]	4.68	0.067	3.76	[illegible]
Vane Failures - Erosion/ Corrosion	1.22	24	[illegible]	8	[illegible]	0.008	0.95	0.022	0.62	[illegible]
Blade Disk Fatigue Failure	2.40	52	0.006	8	[illegible]	0.004	2.41	0.005	1.88	0.004
Diffuser Cracking	[illegible]	6	[illegible]	[illegible]	[illegible]	0.022	[illegible]	0.022	0.31	0.022
Compressor Casing Wear	[illegible]04	1	[illegible]004	6	[illegible]	0.004	[illegible]	0.004	[illegible]	0.004
Variable Stat and Bleed	0.09	2	[illegible]	[illegible]	0.08	0.007	0.14	0.008	0.12	0.007
Miscellaneous	0.70	15	[illegible]006	9	[illegible]	0.006	0.78	0.006	0.78	0.006
Combustor	[illegible]	—	[illegible]		0.94	[illegible]	[illegible]	[illegible]	0.98	[illegible]
Liner Cracking/Warping	[illegible]	17	[illegible]	17	[illegible]	0.006	[illegible]	0.008	[illegible]	0.006
Support Structure Cracking	[illegible]	17	[illegible]	17	[illegible]	0.005	0.17	0.005	[illegible]	0.006
Housing and Fitting (Cracks, etc.)	0.58	[illegible]	[illegible]	52	0.46	[illegible]	0.46	0.016	0.46	[illegible]
[illegible] Wear Cracking	[illegible]	15	0.006	15	0.17	0.006	0.17	0.006	0.17	0.006
Miscellaneous	0.01	1	-	[illegible]	0.01	-	0.01	-	0.01	-
Turbine	2.86	—	[illegible]58		[illegible]24	[illegible]	3.03	[illegible]	[illegible]	[illegible]
Nozzle and Band Cracking	[illegible]	[illegible]	[illegible]	[illegible]	0.24	[illegible]	0.48	[illegible]	[illegible]	[illegible]
Nozzle Oxidation, Burning	[illegible]	6	0.005	4	[illegible]	0.003	0.10	0.004	[illegible]	[illegible]
Support Structure and Fittings	1.34	19	[illegible]	44	0.49	0.025	1.03	0.052	0.49	0.025
Blade and Wheel Cracks	[illegible]	41	[illegible]	[illegible]	[illegible]	[illegible]	1.06	[illegible]	[illegible]	[illegible]
Shaft and Couplings	[illegible]	8	[illegible]	6	[illegible]	0.003	[illegible]	[illegible]	0.21	[illegible]
Miscellaneous	[illegible]	6	[illegible]	14	[illegible]	0.008	0.15	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	—	[illegible]		[illegible]	[illegible]	1.44	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Secondary Structural Cracks	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.45	[illegible]	[illegible]	[illegible]
Bosses and Fittings, etc.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]24	0.62	0.030	[illegible]	[illegible]
Miscellaneous	[illegible]08		[illegible]4		[illegible]	[illegible]004	[illegible]	0.004	[illegible]	[illegible]
[illegible]	[illegible]	—	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	47	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Miscellaneous Hardware	[illegible]	16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	—	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Lines and Fittings	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Miscellaneous	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Miscellaneous Hardware	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	—	[illegible]		[illegible]	[illegible]	1.04	[illegible]029	[illegible]	[illegible]
[illegible]	[illegible]	—	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Speed Systems	[illegible]	[illegible]	[illegible]		0.36	[illegible]	0.36	[illegible]	[illegible]	[illegible]
[illegible] Speed System	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] System Components	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Management Systems	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Wiring and Thermocouples	[illegible]	[illegible]	[illegible]	41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	—	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	-	-			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

1975-82 ERA ENGINE SUMMARY

Examination of the summary matrix (Table LXX) for the 1975-82 era engines indicates that a factor of two improvement in engine reliability can be achieved over that measured for current engines, provided that the user is prepared to pay the weight and performance price for this benefit. The means to achieve this reliability improvement are available now and require no quantum jumps in technology. Further examination of Table LXX reveals that the reliability of engines with full performance emphasis will not be significantly different from today's engines. This represents a significant increase in life-cycle costs above that of the full-R&M-emphasis engine.

The normal engine is shown to achieve a level of reliability that represents a 30 percent increase over today's engines, but which still leaves considerable room for improvement. The normal engine configured and quantified in this study cannot represent a hard and fast configuration. In this study, it is structured by a median consideration of R&M, performance, cost, weight, volume, schedule and other dictates of engine design. This engine's reliability level is fully variable between the two extremes, and only with very careful attention to reliability details will it tend toward the full R&M emphasized engine.

This section has shown how major R&M benefits can be achieved in near-term 1975-82 era engines through the incorporation of certain design features or approaches reflecting a program emphasis on R&M. Significant differences were indicated between the R&M-emphasized engine and the full-performance engine as indicated on Table LXIX and summarized below in Table LXXI.

TABLE LXXI. SUMMARY OF FUTURE ENGINES

	UER Rate Expressed in Removals/1000 Hr							
	R&M Emphasized		Full Performance		Normal		Composite	
	Index	UER Rate	Index	UER Rate	Index	UER Rate	Index	UER Rate
Engine Caused	18.37	.441	29.01	.887	21.50	.586	26.62	.769
Non Engine Caused	11.16	.659	22.05	1.345	14.58	.860	26.15	1.657
Unknown	1.23	.060	5.90	.290	2.65	.130	7.26	.356
Total	30.76	1.160	56.96	2.522	38.73	1.596	60.03	2.782

The reader is cautioned, however, that these predictions rest on the assumption that all engines, including the full-performance engines, will have benefitted from the inclusion of certain R&M features which should be available for these engines. Incorporation of these features, however, is not inevitable, and conscious effort will be required to insure their inclusion.

The full-R&M-emphasized engine, and to a lesser degree the normal engine, require the inclusion of features which are in general of greater reliability significance than those features applied to the full-performance-emphasized engine. The 20 most significant changes listed in order of priority by index number are shown in Table LXXII.

The cumulative effect of incorporation of these 20 remedial actions represents a 57 percent improvement in reliability from the current composite engine and is 98 percent of the total reduction from the composite engine to the R&M-emphasized engine. The individual effects of some remedial actions on the three configurations of future engines are different, principally because the configurations differ from each other. The probable applicability of each remedial action to a particular configuration of future engine has also been indicated on Table LXXI.

The conclusions that may be drawn from Table LXXII vary widely as a function of the reader's past knowledge of turbine engine R&M and preconceived ideas about where problems lie. The most disturbing observation is that many of the remedial actions which provide large reductions are addressed to non-engine-caused failure modes/subsystems, and are intimately related to the external environment. FOD, erosion, fuel and oil contamination, and logistics and management are problems that require significantly different approaches from those applied against classical internal failure modes. The acknowledged difficulty in initiating and implementing corrective action in these areas was fully accounted for in estimating benefits. Nevertheless, these conservative estimates produce numerical rate improvements which are very high and indicate that improvements in these non-engine-caused subsystems must be undertaken through a combination of customer and supplier actions.

The high ranking of bearing and seal remedial actions may also be surprising to some. Many in the engine design, management, and procurement communities tend to minimize the bearing and seal problem and correspondingly downplay the value of improvements in these subsystems. The significant benefits to be gained through remedial actions in these areas indicated in Table LXXII should provide better perspective of the cost effectiveness of improved bearing and seal reliability.

A third observation involves the rapid decrease in numerical

TABLE LXXII. R&M IMPROVEMENT ACTIONS AND BENEFITS APPLICABLE TO 1975-82 ERA ENGINES

		R&M Benefit		Incorporation in 1975-82 Era Engines		
	Remedial Action	Index Number	UER Rate**	Full R&M	Full Performance	Normal
1	Use of Labyrinth Seals	3.19	0.183	✓		*
2	Foreign Object Damage Resistant Compressor	2.42	0.138	✓		*
3	Use of High Efficiency Particle Separators in Lieu of Filters	1.74	0.080	✓	✓	✓
4	Improved Foreign Object Screen Arrangements	1.70	0.100	✓	✓	✓
5	Erosion/Corrosion Resistant Compressor	1.61	0.060	✓	*	*
6	Improved Maintenance Durability	0.9[illegible]	0.055	✓		
7	Positive Retention Bearing Outer Races	0.85	0.029	✓	✓	✓
8	Elimination of High-Speed Mechanical Torquemeters	0.84	0.032	✓	✓	✓
9	Improved Engine and Component Accessibility	0.76	0.048	✓		*
10	Improved Fuel Filtration	0.53	0.017	✓	✓	✓
11	Improved Analytical Techniques for Blade/Disc Resonance Predictions	0.52	0.002	✓	✓	✓
12	Integral Bosses on Casings	0.34	0.012	✓		✓
13	Use of Elliptical Face Roller Bearings	0.30	0.007	✓	✓	✓
14	Elimination of Thin Wall Casings	0.28	0.012	✓		✓
15	Improved Fuel Control Accessibility	0.26	0.006	✓	✓	✓
16	Improved Thrust Load Control on Main-Shaft Bearings	0.22	0.006	✓	✓	✓
17	Improved Logistics Management	(Full Perf Ben) 1.80	0.170	*	✓	*
18	Use of Cast Turbine Inlet Nozzles	0.15	0.005	✓		✓
19	Use of Slotted Inner/Outer Nozzle Bands	0.14	0.004	✓	✓	✓
20	Improved Lubricant Filtration	0.12	0.004	✓		✓

✓Indicates that feature is fully incorporated
*Indicates that feature is partially incorporated and numerical benefit is less than shown
**UER rate expressed in removals/1000 hours

benefit proceeding down the list of remedial actions. After the first 11 remedial actions, there is only 1/10 of the benefit that the first item provided. The first 5 remedial actions alone contribute approximately 50 to 60 percent of the total difference between the composite engine and the R&M-emphasized engine. This suggests that future activity in improving engine reliability can be focused on a few problem areas without fear that significant problems would be overlooked.

In comparing Table LXX to the basic problem summary matrix (Table XI), a question may arise regarding improvement in the unknown, maintenance caused, and convenience categories. These rank high in both index number and UER. Yet, only one remedial action is specifically directed at them. This is discussed below.

INDIRECT EFFECT OF R&M IMPROVEMENTS

It has been shown previously that a relationship exists between total engine removal rates and the associated convenience, maintenance-caused and unknown removal rates (see Figures 62, 64, and 65). This means, in effect, that any time specific R&M improvements are made in the various subsystems, an indirect benefit will be realized in the three subsystems noted above.

The relationship is definitive enough so that an estimate of its magnitude can be made for each remedial action for the two parameters, index number and UER rate. The indirect benefits are shown in Table LXXIII expressed as an additive percentage.

TABLE LXXIII. INDIRECT BENEFITS

Parameter	Indirect Percentage Additive
Index Number	64
Unscheduled Engine Removals	82

Therefore, the actual anticipated benefit of any of the remedial actions shown on Table LXXII will be nearly twice the values shown when considering the indirect benefit. It should be noted that the total engine rates on Tables LXIX, LXX, and LXXI already include this indirect benefit, since the subsystems of unknown, convenience, and improper maintenance are included in the total.

8.0 LONG-TERM FUTURE-ENGINE DESIGN AND PROGRAM REQUIREMENTS

Improvement of R&M beyond that indicated for the near-term engines will require considerable effort. Program management, design skills, and support programs must be upgraded. This section identifies specific areas of potential improvement. Two discussions are presented. Specific failure modes remaining in the 1975-82-era full-R&M-emphasized engine are identified, and analyses and research that must be directed toward their reduction or elimination are discussed. The accompanying program-type activities that must be applied to the same 1975-82-era engine to improve R&M are also presented.

DESIGN CONSIDERATIONS

The significantly different remaining rates for the R&M-emphasized engine and the performance-emphasized engine primarily reflect design priorities and failure to incorporate certain R&M design features in the full-performance engine. It is appropriate to utilize the residual rates in the R&M-emphasized engine as the basis for identifying priorities for future research. There is no doubt, however, that some available R&M features may not be incorporated into future engines because their full impacts in weight, cost, or performance are not fully understood. In these cases, it is appropriate that on-going studies be directed at the quantification of weight and performance penalties so that these features can be incorporated when they match the objectives of a specific set of requirements.

The residual rates at the subsystem and failure mode level for the R&M-emphasized engine were given in Table LXX. The highest 10 problems in terms of index number have been extracted and are presented in Table LXXIV. For convenience, the associated UER rate for each mode is also shown. The following discussion addresses these remaining problem areas.

TABLE LXXIV. REMAINING PROBLEMS OF THE FULL-R&M-EMPHASIZED ENGINE

Priority	Remaining Problem	Problem Magnitude	
		Index Number	UER
1	Foreign Object Damage	2.59	0.150
2	Operator Induced	2.54	0.122
3	Improper Maintenance	2.50	0.150
4	Compressor Blade/Disc Fatigue Failures	1.88	0.004
5	Fuel Control Units	1.81	0.040
6	Bearings - Nonclassical Spalling	1.76	0.031
7	Airframe Related	1.60	0.100
8	Turbine Blade/Wheel Cracks	1.06	0.001
9	Accessory	1.00	0.028
10	Environmental	0.87	0.047

Foreign Object Damage (FOD)

The magnitude of the FOD problem remaining reflects the industry's uncertainty of the sources and types of foreign objects. Without this knowledge, it will be difficult to justify additional remedial actions. The remedial actions listed in Table LXXII already include screens in addition to particle separators, improved detailed designs for mounting the screens, and more rugged compressor configurations. The residual rate may only represent FOD from operation with the screens removed or bypass doors open; tools or debris left in the engine intake during maintenance; or enemy gunfire not properly identified as being due to combat. Under these conditions, further action may not be cost-effective or warranted.

It remains to be confirmed, however, that these will be the only remaining sources of FOD. A more comprehensive definition of FOD sources is required from current aircraft equipped with varieties of screens and separators, operating in various locations, and performing various missions. This could be accomplished through an examination of engines during overhaul/repair or perhaps by the collection of debris scavenged from inertial-type separators. The data-collection program previously conducted by the Naval Air Technical Services Facility[14] should be reinstituted.

It is assumed that present attention to the FOD problem will determine answers to such issues as optimum mesh size, detailed mounting and fastening techniques, and effective anti-icing systems. The recommendation to define the erosion resistance characteristics of axial versus centrifugal compressors also applies for FOD resistance.

It may be that the residual rate of 0.15 removals per 1000 engine hours must be accepted for helicopter applications. A generic rate of approximately 0.07 has been observed for fixed-wing aircraft. It may be reasonable to expect a factor of 2.0 or higher for helicopters, based on the relative frequencies of landings.

Operator Induced Problems

This area is deliberate or unintentional engine abuse or uncertainity as to the engine's condition. Since this may be the indirect result of basic reliability problems, some benefit may occur as those problems are corrected. Removals due to a suspected low power condition that is later unconfirmed may decrease if the erosion characteristics of engines are improved.

Perhaps the only clearly identifiable improvement is the development of a reliable device to measure the power available from an engine. Although some development effort is currently being applied to such a device, it was not considered sufficiently advanced for application in the 1975-82 generation of engine installations. This research should be accelerated, since a significant portion of the removals in this subsystem were attributable to suspected low power.

A more general remedial action is the thorough exploration of starting and shutdown procedures and responses during the development phase. Early testing in this area should be expanded, particularly in light of the advent of the three-engined helicopters with their attendant power management complexity. The application of human factors engineering would be productive in establishing analysis and testing criteria.

A concluding comment that applies to many of the other non-engine-caused removal categories is that more problem definition should be required in R&M reporting programs on this subsystem. Further reduction of this rate requires a more detailed understanding of the precise mechanisms, personnel intentions, and contributing circumstances involved with operator-induced problems.

Improper Maintenance

The magnitude of the improper maintenance problem was shown to be primarily a function of the basic reliability of the engine (Figure 62) and largely independent of the particular military service. Examination of the figure reveals no obvious differences in the damageability of various engines. The specific sources of improper maintenance were reviewed in Section 5 with the conclusion that no significant single characteristic or area of engine design could be isolated as being particularly sensitive to maintenance damage. It was also shown that depot-originated maintenance errors were a small percentage of the total, and therefore a shift in overhaul/repair to the admittedly higher quality contractor facilities could not provide a significant improvement in the rates.

To further reduce the magnitude of this problem requires aggressive action in two areas. First, the specific instances of improper maintenance should be researched and published at a greater level of detail than provided in this report. A study of this type could profitably extend into other aircraft systems and still provide benefit to engine design. Analysis of this history would provide the general trends or patterns as well as specific design details which should be avoided in future engine designs.

The second area involves the skills, procedures, and tools utilized during actual engine maintenance. The dramatic difference between the military and commercial trends (Figure 62) suggests that improvements in the military maintenance environment are necessary. The question of whether the military maintenance environment can approach the commercial environment is an issue requiring in-depth analysis. Maintenance concepts, skill/task allocations, and facilities should all be examined.

Compressor Blade/Disc Fatigue

The magnitude of this problem in the 1975-82 engine reflects our inability to adequately understand the precise state of the art of fatigue analysis methods employed throughout the industry. The magnitude of this problem in past and current engines has certainly led to significant improvements in analysis techniques and application within the individual engine companies. Greater attention to potential resonance situations, emphasis on low-cycle fatigue, and improved awareness, if not control, of production variabilities of machined and cast components will reduce this problem.

Since much of this technology is both complex and proprietary, we are reluctant to recommend any general cataloguing of analysis methods. From the customer's standpoint, the most effective action is the imposition of low-cycle fatigue-life requirements during the specification stage of engine development. Since the frequency of failure of this mode is low, demonstration tests are impractical. Existing specifications adequately require blade containment, although disc containment appears to impose a weight penalty which is unwarranted on the basis of the low probabilities of occurrence.

The increasing use of titanium for compressor design has caused a great deal of attention to be directed to its properties. It offers significant weight savings at the expense of erosion resistance. Stress corrosion and fretting are two failure mechanisms which have received particular emphasis. It is believed that this technology is progressing at an adequate pace and no additional emphasis need be applied.

The potential use of composites, however, is of concern. Filament designs that would afford slower crack-progression rates are being considered for advanced designs. The production variability of these composites is of concern. The strength distribution of mass-produced units should be thoroughly explored before incorporation into production engines.

Fuel-Control Units

The lack of quantification of the various fuel-control problem areas was noted previously. Future R&M trends were calculated based on external changes such as fuel and air filtration improvements and a few internal improvements such as positive lubrication of driving splines. Beyond these, no identifiable changes were apparent. The additional complexity of future fuel controls and the potential for problems causing accidents, as well as frequent component and engine removals, demand that this area be subject to intensive examination.

A recently released contract from the Eustis Directorate of USAAMRDL to examine the current and future R&M characteristics of fuel controls should provide a baseline for identifying future remedial actions.

Nonclassical Bearing Spalling

Since few specific remedial actions were identified for this failure mode, the residual failure rate is quite high. This lack of corrective action stems from the great variety of detailed causes and failure mechanisms. Experience retention is difficult in this area, since the individual bearing installation details that cause the problems vary greatly. These failures are unpredictable by current classical bearing analysis methods.

Failure rate reductions, therefore, require compilation of the details of failure for as many engine bearing installations as possible. Analysis of these data by skilled bearing designers may reveal patterns that have not been identified up to now.

The emergence of the air bearing concept for gas turbine engines is a promising development. Analysis, fabrication, and testing should continue in this area. A word of caution is appropriate: Design glitches that cause nonclassical-spalling problems in rolling-element bearings could also degrade air bearing reliability. Various mounting and installation approaches should be explored, and extensive tests should be conducted over a wide range of engine sizes and configurations to prevent this.

Airframe-Related Problems

It has been assumed that future engines will have generally good accessibility. Therefore, the relatively large remaining rate results more from the airframe and the environment causing suspected or actual engine damage, rather than from removals of the engine to perform maintenance on airframe components. Accordingly, the most productive future remedial action is the strengthening of the engine/airframe manufacturer interface agreements which have recently been developed on engine/airframe programs. These agreements, although quite familiar on commercial programs, are still somewhat new to military systems and will require some experience before maximum benefit can be expected.

One specific area of these agreements that will require further definition is particularly pertinent to helicopter installations. This is the effect of aircraft vibration on engine reliability. Specification of maximum aircraft vibration levels prior to airframe development will in turn require a level of predictive capability that has yet to be demonstrated. Research into the state of the art would be useful.

These activities, coupled with anticipated improved reliability of airframe components, should allow further reduction of this problem.

Turbine Blade/Disc Fatigue Failures

The magnitude of this problem in the 1975-82 engine is the same as in current engines because specific remedial actions could not be quantified, although some improvements in methodology and application are recognized.

The additional complexity of turbine mechanical design due to thermal effects has resulted in a corresponding effort to improve the prediction and control techniques for thermal and fatigue life of turbine components. The success of these efforts is evidenced by the continued escalation in turbine inlet temperatures, more complex blade cooling system, and more weight-efficient discs with no observable decrease in reliability. Literature is extensive on these efforts, although the detailed effect on reliability of this rapidly evolving technology is not well understood. Some of the materials, cooling, and analysis improvements in turbine design technology are summarized in Reference 12. More detailed information on specific areas such as transpiration-cooled blades is provided in Reference 28.

The sources of turbine blade/disc failures in past engines have not been directly attributable to fatigue in the purest sense. The sources, as described in Detailed Problems of Current Engines (Section 4), were such factors as blade-to-disc fretting or a decay in vibration damping characteristics due to wear. Since these factors are not routinely addressed as an element of the classical fatigue calculations, the previously suggested improvement in analysis capability and materials may not directly reduce the magnitude of this problem. If anything, they may allow further refinement of turbine weight, size and performance to the detriment of safety margins heretofore designed into turbines through the natural conservatism that accompanies inadequate technology.

Based on this discussion, it is recommended that a state-of-the-art review of the analysis methods be undertaken in conjunction with an analysis of past turbine blade and disc failures. Since this technology, like the compressor blade/disc fatigue technology, is extremely complex and highly proprietary, this recommendation may not be practical. Thus, a close review of this area by the customer during the development stages of specific engine programs is also suggested.

Accessory

The specific failure modes in the accessory subsystem were of a varied nature with no one area or failure mode consistently high. It was suggested that this rate may be considered a generic rate based on the number of individual components and the relatively low operating loads of the gears, bearings, and other elements of the accessory system.

Thus, the only apparent action that could alleviate this problem is a reduction in the complexity of the accessory systems. This can be accomplished through the integration of drive functions (such as tandem mounting of fuel pump and fuel controls) or through the elimination of drive functions (such as air impingement starting systems). The potential for mounting a high-speed fuel pump on the main shaft has been explored,[23] and other accessories could possibly serve as candidates for similar research.

Environmental Conditions

Over 50 percent of the residual rate represents fuel control contamination. Even with the increased fuel filtration anticipated in all future engines, control unit contamination will continue, due to filter bypass and/or accumulation of contaminants passing through the filters. Lubrication system contamination and structure/case corrosion are other modes in this category; each contributes approximately 10 percent.

Further remedial action for fuel contamination requires a more definitive statement of the degree of contaminants actually experienced in aircraft. This would allow further optimization of filter mesh sizes.

Closed loop fueling systems would reduce fuel contamination in the field. Gravity refueling into an open fuel filler tube with helicopter rotors turning is not conducive to fuel cleanliness. Pressure refueling, gravity close-loop, or simply better nozzle-to-filler sealing are the responsibilities of both the customer and the airframe manufacturer. Engine requirements should be more clearly expressed by the engine manufacturer in order that the airframe fuel systems be improved.

Lubrication system contamination could increase over that experienced in the current engines if extensive use is made of labyrinth seals. To preclude this problem and reduce scheduled maintenance on oil filter systems, devices should be developed which would continuously clean the oil to the 10-micron level and have a self-cleaning capability. One such device is discussed in Reference 29.

Some degree of corrosion has been experienced on all engines examined in this study. Usually the incidents are recorded as being due to unusually severe environmental conditions. They were only experienced in any magnitude on engines utilizing extensive amounts of magnesium. Although the one company using magnesium extensively has developed a rather effective (proprietary) protective coating, its benefits are lost where erosion takes place. If erosion is reduced in the future, the corrosion problem will be reduced without further remedial action.

PROGRAM CONSIDERATIONS

The program elements that contributed to past R&M problems were reviewed in Section 5; current improvements in programs were examined in Section 6. This discussion will suggest areas of the program that require additional remedial action and will utilize the five program elements previously introduced in Section 6:

- Specifications and Requirements
- Development Design and Testing
- Operational Use and Product Improvement
- Environment
- Materials and Design Concepts Technology

Specifications and Requirements

Two remedial actions in the specifications area are appropriate. First, overall R&M objectives should be strengthened through the selection of well-understood parameters with numerical values enforced by contractual demonstrations. Second, the restrained and selective imposition of design requirements should be exercised at the detailed level. Specific recommendations along these lines are as follows.

Three main R&M parameters should be adopted to describe the total engine. These are unscheduled engine removal (UER) from the airframe, time between overhaul (if appropriate) and hot-end inspection intervals, and maintenance task times on selected tasks. All other parameters either have insufficient historical data available or are undemonstrable.

Specific individual subsystems/failure modes should be controlled through separate quantitative requirements. These failure modes are erosion, fuel contamination, turbine vane sulfidation, no-lube operation, blade containment, and compressor and turbine fatigue. Each of these modes, as well as maintanance task times or tool requirements, can be demonstrated by testing under accelerated or controlled conditions. The criteria for acceptance can be clearly defined in each instance.

Certain design features should be specified where the trade-off aspects are clearly understood. The R&M, cost, weight, performance, space, and schedule implications of a legislated design feature must be acknowledged in the total engine numerical objectives.

All requirements must be demonstrated through either test or analysis. Emphasis should be placed on test verification, with minimum of subjectivity in acceptance criteria. Tests for overall engine reliability may require longer durations than would be practical in the development phase and thus should be conducted in a downstream production or operational phase. Since these two phases are usually authorized by separate contracts, arrangements must be devised so that the obligation of demonstrations is clearly manifested in the development contract.

Developmental Design and Testing

Although the prime responsibility for hardware improvements in this area rests with the engine manufacturer, certain recommendations are appropriate for engine customers. These suggestions require customer initiation and funding for maximum effectiveness.

First priority should be given to providing the engine designer with the tools necessary for meaningful trade-off decisions. The customer can accomplish this through expanded data collection systems on in-service engines with the data made routinely available to all engine manufacturers. Periodic summaries of reduced data should be published. This is a prerequisite to vigorous prediction, evaluation, and control of engine R&M in the future.

A series of studies of the detailed design problems in the various engine subsystems should be accomplished. As a casebook of past problems, the studies would contribute to experience retention that should avoid the repetition of certain failure modes. These studies would be integrated with the subsystem design studies recommended in the Materials and Design Concepts Technology discussion.

A general relationship between reliability and development testing should be established. A study of turbine engines similar to that performed on helicopter dynamic components [21] would allow the engine contractor to realistically size the test program to the reliability requirements. This study could also examine the present specifications relating to PFRT and MQT testing and clarify acceptance criteria and test conditions.

Operational Use and Product Improvement

Improvements in this area should cause a decrease in R&M problems as large as that expected from improved specifications.

An R&M program to control the operational phase product improvement of every engine should be defined. It must reflect specific contractual responsibilities and specify the details of data reporting, meeting, timing and personnel attendance, criteria for problem identification and correction, and TBO growth criteria. It is most important that an attitude of commitment to identifying, acknowledging, and fixing problems, and increasing the TBO quickly be generated.

The R&M data-collection system on a specific engine program should collect data on parameters in addition to those specifically recommended in the specifications and requirements paragraphs and those required for demonstration purposes.

These additional parameters should be:

- o Maintenance man-hours
- o In-flight and ground aborts
- o Unscheduled engine removals requiring depot return
- o Component or module removals
- o Total malfunctions

Current and near-term future programs should collect this data in anticipation of the expansion of R&M quantification.

Contractor data-collection teams should be used to provide quantitative rates and failure-mode and mechanism detail.

Members assigned to operating units, field repair activities, and depot level facilities would contribute necessary information to the reporting system and could expedite retrieval of failed units for engineering analysis.

Uprated models should receive R&M controls similar to the basic model. Numerical R&M goals and demonstration tests should be utilized, with the contractor deciding the appropriate mix of analysis and testing.

Environment

No specific recommendations are given in this area other than that additional effort should be applied in the mechanical and personnel areas. Vibration levels of today's helicopters should be measured, collected and published. Realistic performance capabilities of maintenance and operating personnel should be quantified. The effects of an all-volunteer Army should be predicted in terms of skills, morale, and motivation.

More generally, non-project-aligned Government agencies should continue to define the total environment. With this definition, the nature and magnitude of the environments impact on R&M will be better understood. Future R&M control programs, including demonstration tests, require this understanding for problem responsibility assignment and cost-effective corrective action. The physical and human environment will most likely change little - what is ultimately required is the design of equipment to withstand conditions heretofore called abusive but now recognized as normal.

Materials and Design Concepts Technology

The following recommendations may generate many specific areas of design or analysis research and provide a real foundation for a logical industry-wide program for improved R&M in future engines.

A series of R&M oriented state-of-the-art studies should be directed at the major subsystems of the engine. These studies, conducted by design specialists, would review the R&M history of the particular subsystem, evaluate alternative design approaches, discuss current research and future trends, and provide specific recommendations for future anticipated engine requirements.

Government agencies should increase their sponsorship and encourage wide attendance of forums and conferences in an effort to maximize the exposure to design lessons learned throughout the industry.

9.0 CONCLUSIONS AND RECOMMENDATIONS

Current engine R&M problems have been identified and quantified. Fifty problem areas have been used to describe the causes of current and predictions of future engine R&M problems.

Non-engine-caused problems are responsibile for two-thirds of all unscheduled engine removals. These problems must be alleviated in new engine/aircraft programs.

Engine programs have been continually improved through product improvement programs as service experience is gained.

The significance of advanced technology in new engines can be assessed against current engine problem areas.

More R&D is required to evaluate the R&M characteristics of many design features and approaches.

Engines typically have experienced extensive improvement after service introduction. This implies that more development could economically eliminate future service problems.

Firm and realistic specification of requirements for design, test and quality control are essential for new engine programs.

A number of design features and approaches have R&M advantages. These are available for consideration in design trade studies.

The following recommendations are appropriate:

- The combination of approximately 20 design features identified in this study that can reduce the current R&M problem should be considered in future engines requiring improved reliability.
- A series of studies on selected, advantageous R&M changes should be undertaken to quantify the full impact of these changes over a range of engine sizes and configurations. The performance, weight, cost and developmental schedule characteristics of R&M beneficial changes must be understood and developed to achieve the rapid and effective incorporation of these changes into future designs.
- Non-engine-caused reliability problems must be closely identified; engineering changes must be implemented to reduce their rate.

- Procuring agencies, at the initiation of requests for proposals and design/development work on new engines, should implement the following actions to improve the R&M characteristics:

  - Provide clear, precise requirements and objectives for program requirement documents and hardware specifications that are realistic in terms of the numerical rates and parameters selected and are demonstrable within prescribed time limits.

  - Establish reliability growth goals for each engine.

  - Require formal R&M demonstration tests at prescribed points in the life cycle.

  - Require contractors to develop R&M plans to allow for R&M growth through adequate consideration of R&M in the trade-off process, accomplishment of analyses that reflect realistic environments, reliability testing to identify problems, development of timely corrective action, and verification of corrective action effectiveness.

- The reliability of an engine should continue to be monitored after it is committed to production and fielded for operational use. This will provide a logical basis for the assessment of engine product improvements necessary to achieve the engine's long-term reliability goals.

- The customer should establish a uniform and organized R&M data collection system for each engine program. Information gathered should sufficiently establish the causes and frequency of all problems. The parameters measured should include as a minimum:

  - Unscheduled engine removals

  - Maintenance man-hours

  - Total malfunction rates

  - Abort rates

- The reliability objectives for uprated-power engine models should be clearly specified at the initiation of the uprating program. Adequate, additional reliability testing on the complete engine should be provided and demonstrations should be required to ensure that these objectives are met.

- TBO growth program for each engine should be established, based on rigorous analytical techniques including the consequences, detectability and rate of progression of failures and the shape of the hazard function.

- Engine modularization policy should be reexamined. Existing modularization in Army engines is not being fully utilized. Potential reliability, weight, cost and performance penalties are associated with extensive engine modularization. A reappraisal of organizational and direct support level engine maintenance tasks should be initiated to determine if current levels of modularization are warranted. If not warranted, they should be reduced.

- Study and development efforts should be completed on the following specific topics which adversely affect current R&M levels:

  - FOD - Identify origins and types of FOD, optimize screens as an interim step, and investigate alternate concepts for FOD prevention.

  - Operator and maintenance error - Identify common factors in operation and maintenance errors and develop proposals to reduce/eliminate them.

  - Vibration environment - Identify vibration frequencies/amplitudes imposed on engines and their effects on engine components. Determine the relative merits of hard versus soft mounting of engines.

- Unique design features have been identified whose R&M characteristics are either unknown or potentially adverse. Studies and hardware development programs to include R&M considerations are recommended on the following:

  - Variable geometry turbine nozzles and their associated operating hardware.

  - Air bearings in engine main shaft applications.

- Studies should be implemented to develop the relationship between the necessary testing duration and the engine reliability requirements and objectives.

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APPENDIX I

CONVERSION OF TBO INTERVAL INTO RATES

Three of the four R&M parameters used in this study are expressed as rates (events per unit time). The TBO parameter is, however, usually expressed as intervals (hours) and must be converted into a rate for integration with the other parameters.

The rate desired is the scheduled removal rate. It is important to understand that, since premature removals prevent engines from reaching their designated TBO interval, the scheduled removal rate is not the reciprocal of the TBO. Instead, the scheduled removal rate is obtained by subtracting the unscheduled removal rate (measured) from the total removal rate (calculated). This total removal rate is obtained by using the following formula which is applicable with an exponential distribution:

$$\text{Total Removal Rate} = \frac{1}{\left[\frac{1}{\text{UER Rate}}\right]\left[1 - e^{-(\text{TBO})(\text{UER Rate})}\right]}$$

Specifically:

$$\text{Total Removal Rate} = \frac{1}{\left[\frac{1}{0.00278}\right]\left[1 - e^{-(800)(0.00278)}\right]}$$

$$= 0.00298$$

Scheduled Removal Rate = Total Removal Rate - Unscheduled Removal Rate

= 0.00298 - 0.00278 = 0.00020 Scheduled Removals Per Engine Flight Hour (or 0.200 Removals Per 1000 Engine Hours)

This total scheduled removal rate is apportioned to the various subsystems as shown in Table IX where 12% of the TBO was considered due to bearings, 63% to compressors, and 25% to turbines. Thus:

Bearings = (12%)(.20) = .024 use .02 removals per 1000 hours
Compressor = (63%)(.20) = .126 use .13 removals per 1000 hours
Turbine = (25%)(.20) = .050 use .05 removals per 1000 hours
Total .20

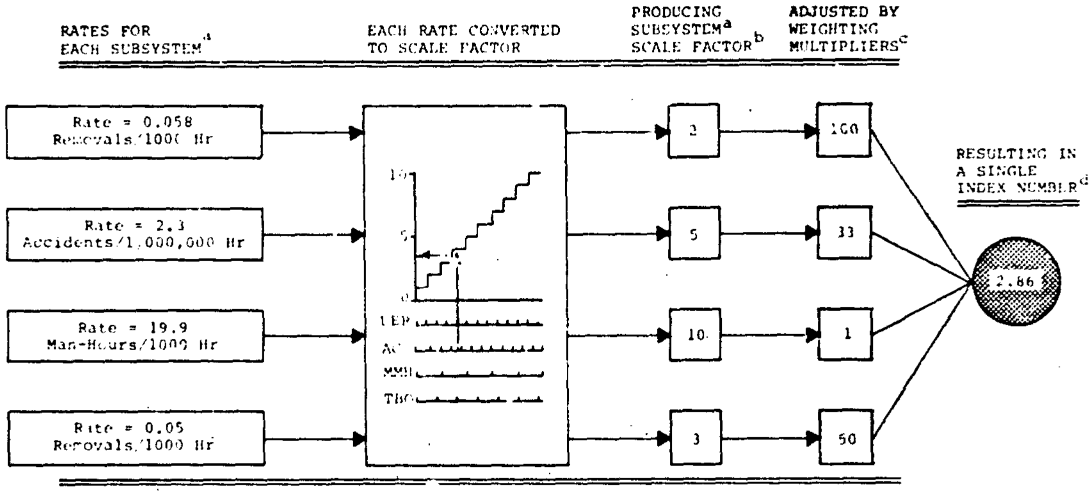
APPENDIX II

DEVELOPMENT OF INDEX NUMBERS

THE CONCEPT

The index number is designed to integrate the frequencies and consequences of failure modes and/or subsystems in each of four separate R&M parameters. The use of the index number results in a single value for each failure mode or subsystem on a dimensionless scale of 0 to 10.

Construction of the index numbers is a straightforward three-step process involving first, the conversion of the numerical rate for all problems (subsystems) within each parameter to a scale factor; second, the creation of weighting multipliers which consider the relative frequencies and consequences of events among the four parameters; and third, the application of the weighting multipliers to the scale factors to produce the index numbers. This process is illustrated in Figure 70.



[a]Example used is of turbine subsystem.

[b]Scale factors give visibility to major problems within a parameter and in which parameter problem has impacted.

This ratio is calculated by comparing the frequency of two parameters at the same scale factor.

$$^{c}\text{Weighting multiplier} = \frac{\text{Frequency}_{\text{Parameter I}}}{\text{Frequency}_{\text{Parameter II}}} \times \frac{\text{Consequence}_{\text{Parameter I}}}{\text{Consequence}_{\text{Parameter II}}}$$

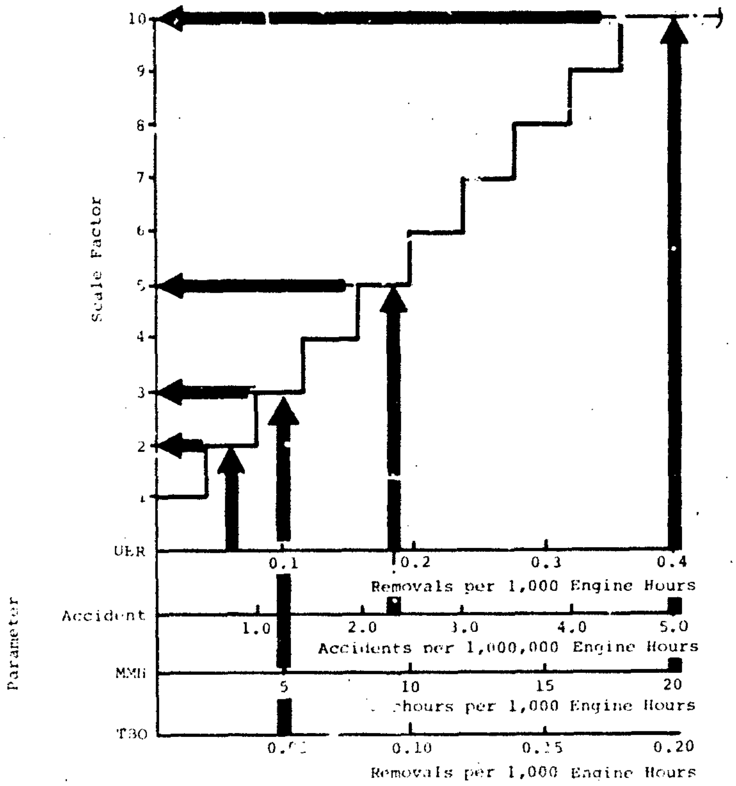
This is calculated by comparing the costs of a single event in each parameter.

[d]Index number reflects the magnitude of problem considering all parameters.

Figure 70. Development of the Index Number.

SCALE FACTOR

Assignment of the scale factors is the first step in the process of deriving index numbers. The scale factor is, as is the index number, a value of 0 to 10 which reflects the frequency of occurrence of each problem (subsystem) within each parameter. The relationships between scale factors and frequencies for each parameter are shown on Figure 71. The numerical relationships on Figure 71 are constructed so that usually the scale factor of 10 is set equal to the largest single subsystem value observed in each parameter. Subsystems with lower occurrence rates then, have a proportionately lower scale factor. The resulting scale factors for each subsystem in each parameter are shown in Table X.



EXAMPLE: The turbine system has these numerical rates from Table IX : UER - 0.058 Accidents - 2.3
MMH - 19.9 TBO - 0.05

These are read as: UER - 2 Accidents - 5
MMH - 10 TBO - 3

Figure 71. R&M Parameter Scale Factors.

WEIGHTING MULTIPLIERS

Establishing the weighting multipliers for each parameter is a process somewhat more complex than for the scale factors. Since the scale factor merely reflects the relative frequencies of problems within an individual parameter, consideration of both the relative consequences and relative frequencies from one parameter to another is handled by the weighting multiplier. Calculation of the relative frequencies of the four R&M parameters is performed through an examination of Figure 71 which relates scale factors to a frequency of occurrence for each parameter. The ratios of frequencies for a common scale factor are shown below in Table LXXV.

TABLE LXXV. RATIOS OF FREQUENCY OF OCCURRENCE

Parameter	Frequency Ratio to Accidents
Unscheduled Removals	75
Major Accidents	1
Maintenance Man-Hours	3400
Scheduled Removals	37

Calculation of the relative consequences of the four parameters is performed by examining the impact of a specific event (a single major accident, a single maintenance man-hour, or a single scheduled or unscheduled removal) in each of the four parameters and relating these impacts.

Several measures of consequences were considered as potential evaluators of the relative impact among the four R&M parameters. Among those considered were:

- Program response criteria: the number of similar events that have been historically necessary in order to initiate and implement corrective action
- Impact on availability: the loss in available flying time that each event consumes

These and other parameters were considered but discarded due to either a requirement for an excessive amount of subjectivity to be applied or a lack of applicability across all four R&M parameters.

Cost as a consequence was chosen for the evaluation of the relative impact among the four parameters. The cost parameter chosen consists principally of direct costs incurred from each event. They were quantified using existing published data.

The calculations of the relative cost consequences are presented in the following manner:

1. The costs per event in each of the four parameters are calculated. In most cases the costs vary over a range of engine/aircraft sizes.

2. An average aircraft is chosen.

3. Ratios of costs per event among each of the parameters are established.

COSTS OF AN UNSCHEDULED ENGINE REMOVAL (UER)

The cost impact of an unscheduled removal is dominated by the cost incurred during overhaul or major repair. In the Army, overhaul/repair is usually accomplished at the depot level. While the Navy and Air Force utilize intermediate levels of maintenance to perform repairs involving the complete disassembly of the engine, this practice has not been effectively implemented by the Army despite recent efforts to utilize the general support level of maintenance. In actuality, approximately 70-80% of Army turbine engines removed from the airframe are returned to a depot level activity for final disposition/repair/overhaul.

The material and labor costs to overhaul gas turbine engines at the depot level are described in one study[30] as being related to the acquisition costs of the engines. This study arrived at a cost equation which is expressed mathematically as:

$$\frac{\text{overhaul cost}}{\text{acquisition cost}} = .2646 + .00000\ 18429\ (\text{acquisition cost})$$

Expressed in graphic form the equation appears as shown in Figure 72.

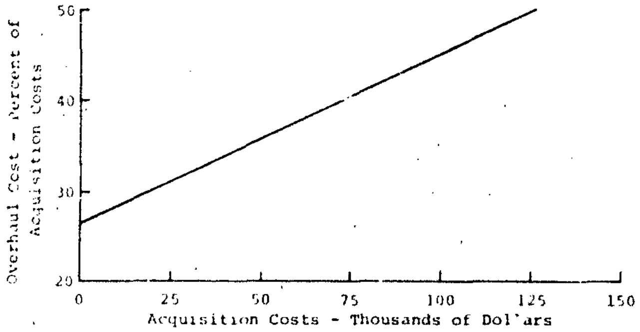


Figure 72. Overhaul Cost Ratios of Turbine Engines.

Utilizing this curve (equation) and the acquisition prices of engines (in 1968 dollars) the range of overhaul costs is shown on Figure 73 as a function of the empty weight of the aircraft in which the various engines are installed.

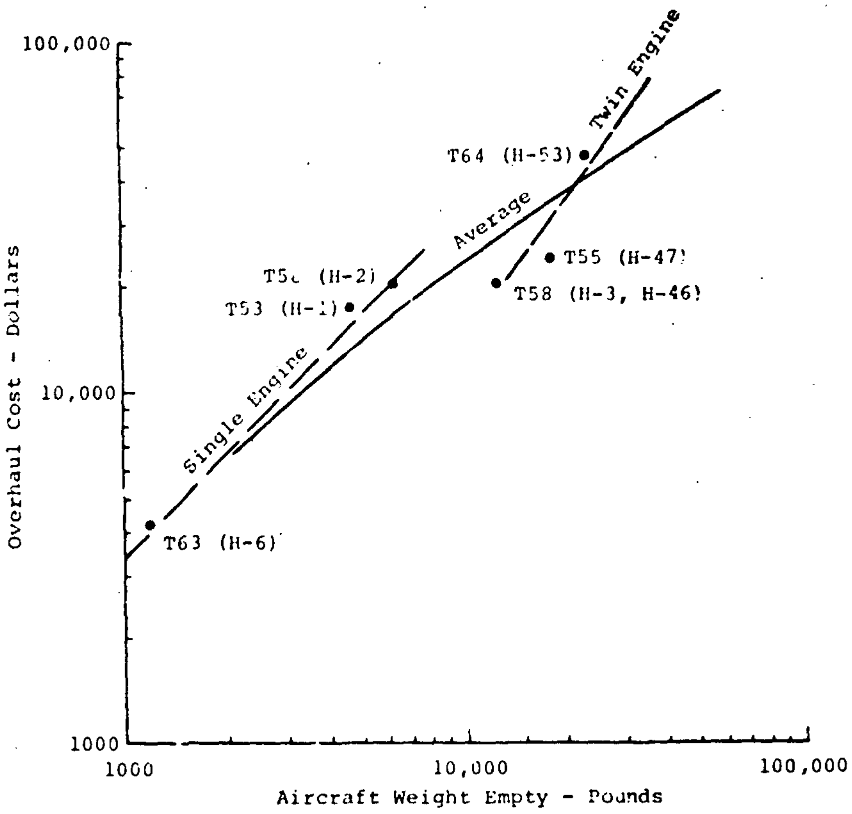


Figure 73. Overhaul Costs of Turbine Engines.

COSTS OF A MAJOR ACCIDENT

The cost of a major accident must consider the aircraft material costs (repair or attrition) and the costs of any fatalities that occur from the accident.

Aircraft material costs for a major accident vary as a function of the size of the aircraft. Army Regulation AR385-40 and OPNAVINSTR 3750.6 for the Navy define major accidents as having occurred when a specific value of man-hours to repair has been incurred or when a fatality of the crew or passengers is associated with the event. Thus, each aircraft size family has its own man-hour threshold. This is shown in Figure 74 which plots man-hours against aircraft weight empty for the Army definition.

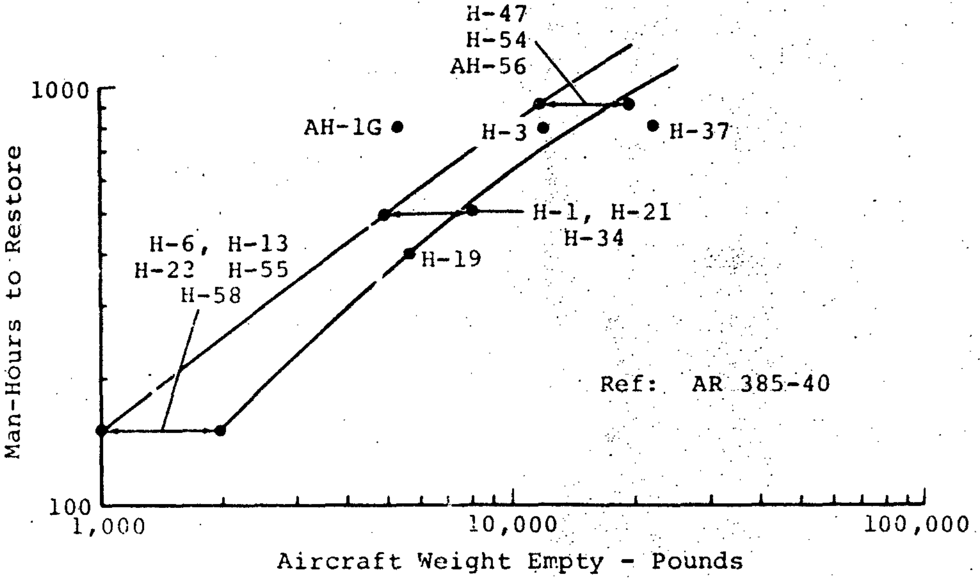


Figure 74. Repair Criteria for Classification as a Major Accident.

The specific cost threshold for each aircraft is exceeded, naturally, whenever the aircraft is stricken as a result of an accident. Figure 75 shows the ratio of strikes to major accidents as a function of aircraft weight empty. It is plotted using both Army and Navy data as published in Reference 31.

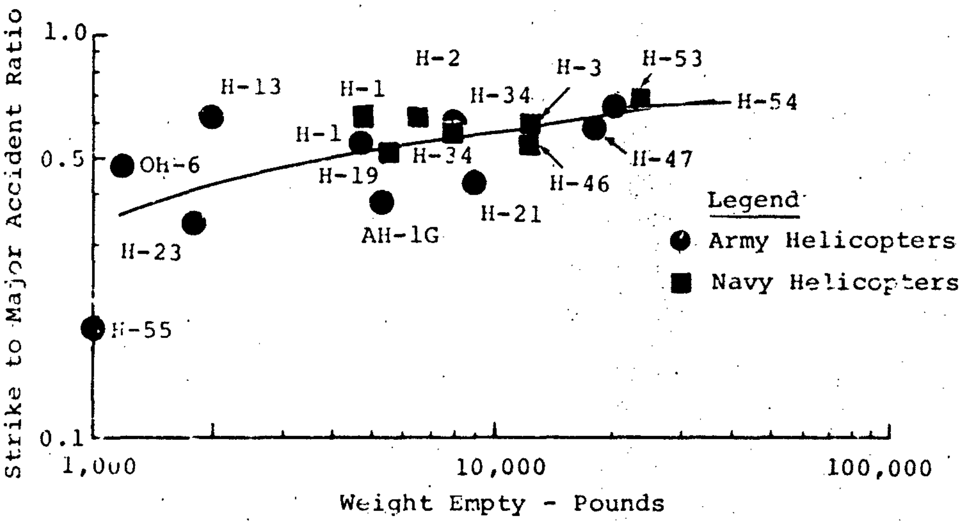


Figure 75. Strike to Major Accident Ratios for Army and Navy Helicopters.

The acquisition cost of the aircraft (plotted on Figure 76 as a function of weight empty) is used to represent the cost of a strike.

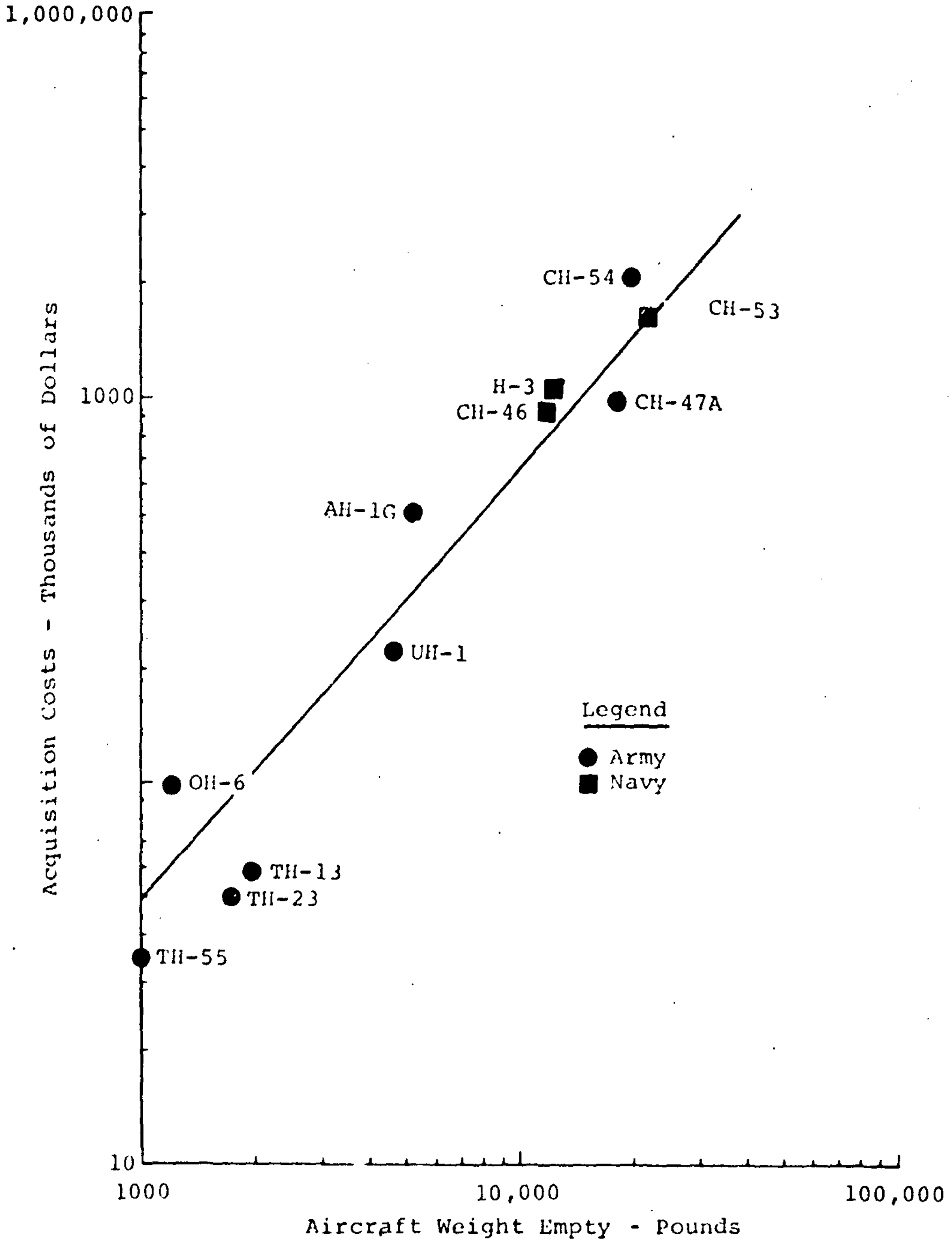


Figure 76. Helicopter Acquisition Costs.

The aircraft which were involved in major accidents which were repaired and returned to service (not attrited) incurred costs which were obtained from the U.S. Army Agency for Aviation Safety (USAAAVS). Average costs by aircraft model are shown on Figure 77 plotted against aircraft weight empty.

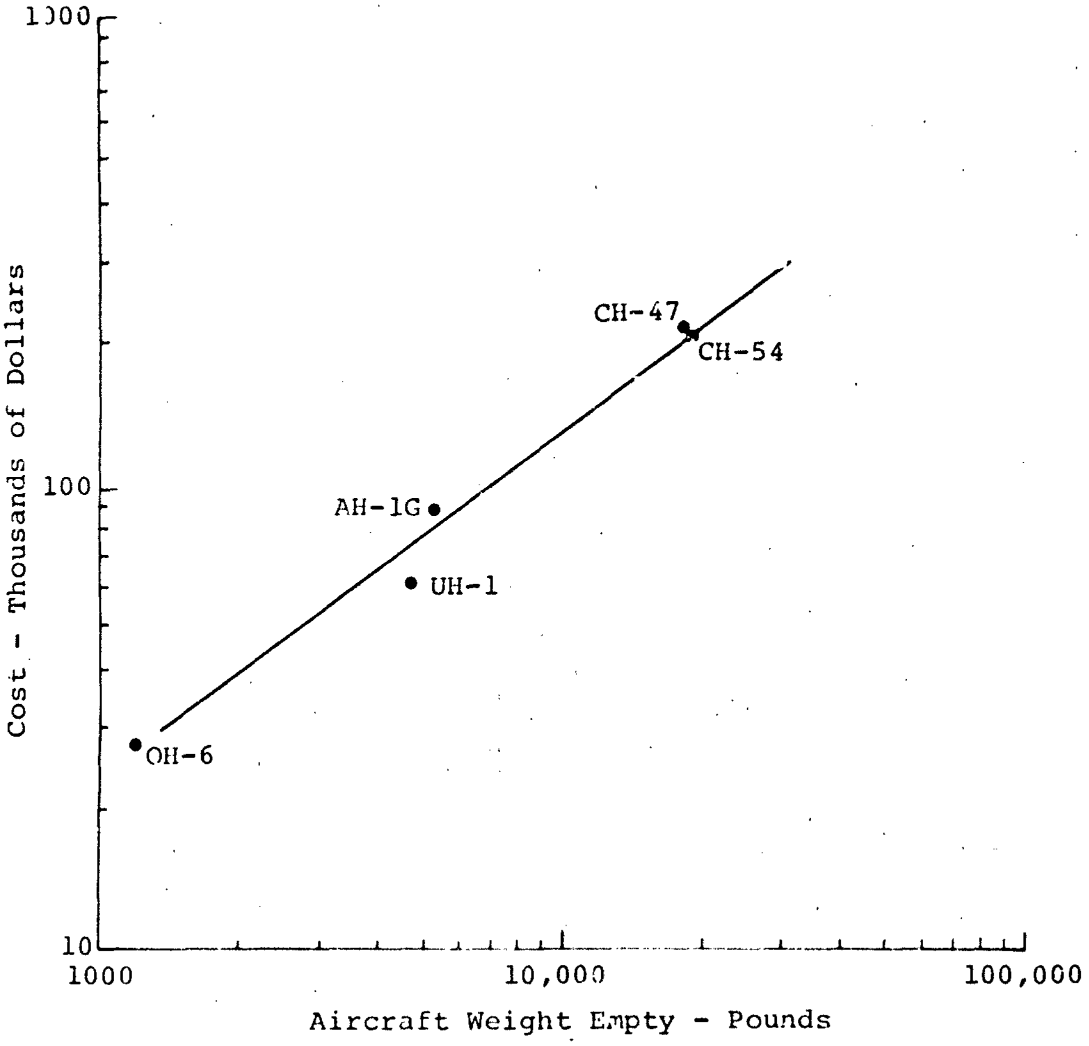


Figure 77. Costs of Non-Attrited Major Accidents.

Historical data was reviewed to determine the average number of fatalities per major accident. These fatalities were divided into three groups:

- Aviators - (pilots and copilots)
- Non-Aviator Flight Crew - (crew chiefs, gunners, observers)
- Passengers - (military and civilian)

The results are expressed in fatalities per major accident, in each of these three personnel categories, for individual aircraft models as a function of aircraft weight empty. These data are plotted in Figures 78 through 81.

The costs per death were considered to have two elements: compensation costs, and retraining costs. Compensation costs include Social Security benefits, death gratuities, dependency and indemnity compensation, and funeral costs. Some of these costs vary as a function of the rank or grade of the individual fatality. Retraining costs represent the costs of replacing the deceased person, from a training standpoint. Table LXXVI shows the compensation and training costs for aviator fatalities, based on an estimated distribution of ranks.

The costs of non-aviator flight crew and passenger fatalities are shown below in Table LXXVII.

Considering the fatality rates shown on Figure 81 and the costs per fatality in Tables LXXVI and LXXVII, the fatality costs of a major accident are shown on Figure 82.

Using the equipment costs from Figures 76 and 77 and the fatality costs from Figure 82, the total cost per major accident in the U.S. Army is shown on Figure 83 as a function of aircraft weight empty. Figure 84 is the same data as Figure 83 except that costs are plotted with a linear scale.

COSTS OF A MAINTENANCE MAN-HOUR

The cost (in 1968 dollars) of a maintenance man-hour is assumed to be $4.00.

COSTS OF A TBO (SCHEDULED) REMOVAL

The labor and material costs of a scheduled removal are considered to be the same as for an unscheduled removal (as shown in Figure 74).

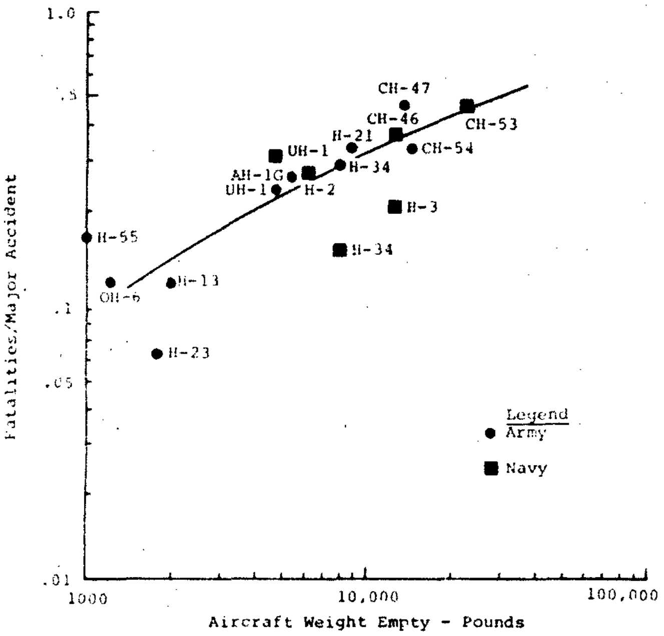


Figure 78. Aviator Fatalities per Major Accident.

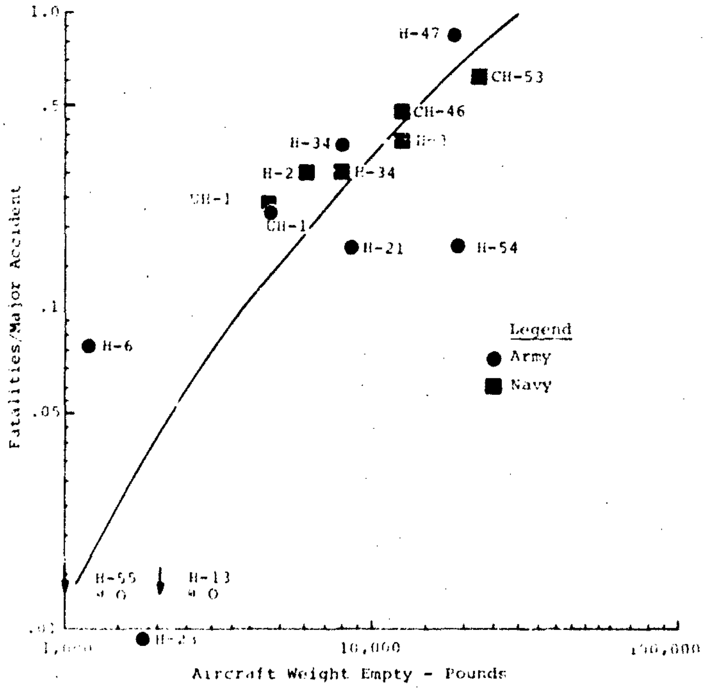


Figure 79. Non-Aviator Flight-Crew Fatalities per Major Accident.

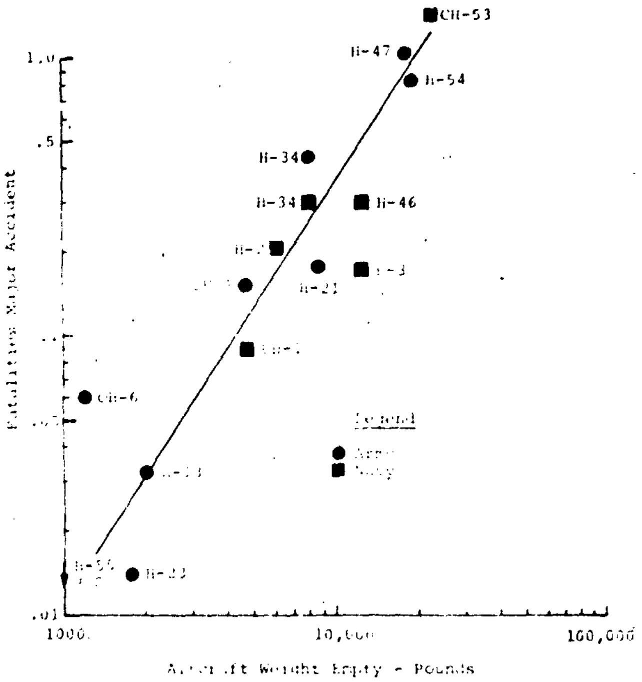


Figure 80. Passenger (Non-Crew) Fatalities per Major Accident.

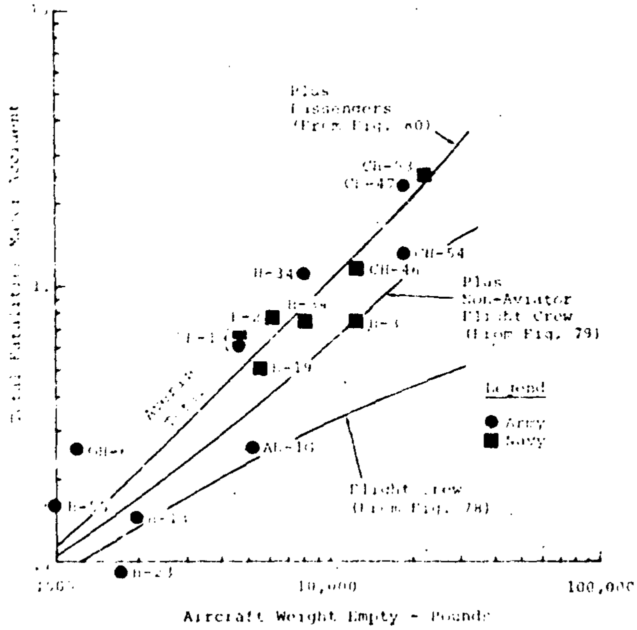


Figure 81. Total Fatalities by Type per Major Accident.

TABLE LXXVI. COSTS OF AVIATOR FATALITIES[a]

Rank	Comp. Cost[b] (dollars)	Retrng. Cost[c] (dollars)	Total	Aviator Fatalities (pct)	Aviator Fatalities (est. dist.)
W01	4,073	55,000	59,073	-	-
W02	47,068		102,068	20	20,414
W03	61,183		116,183	30	35,000
W04	111,911		166,911	10	16,691
2LT	4,118		59,118	10	5,912
1LT	42,894		97,894	15	14,684
CPT	69,324		124,324	10	12,432
MAJ	58,238		113,238	5	5,662
LTC	51,526		106,526	-	-
COL	33,559	55,000	88,559	-	-

[a] Avg. aviator $110,795 [b] Ref. 32 [c] Ref. 33

TABLE LXXVII. COST OF NON-AVIATOR CREW AND PASSENGER FATALITIES

	Comp. Cost[a] (dollars)	Retrng. Cost[b] (dollars)	Total
Non-Aviator Flight Crew	52,000	15,000	67,000
Passenger	37,000	11,000	48,000

[a] Est. from Ref. 32 [b] Ref. 33

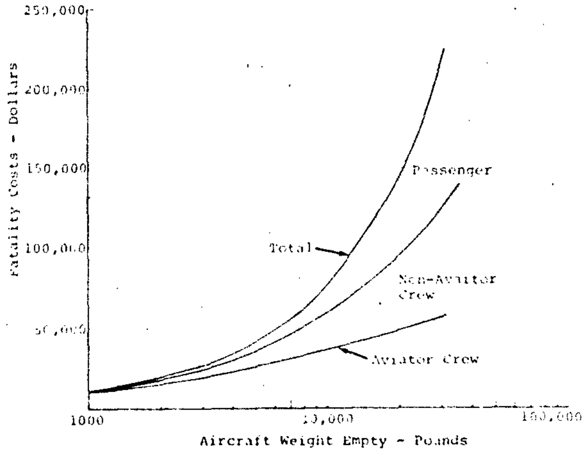


Figure 82. Costs of Fatalities per Major Accident.

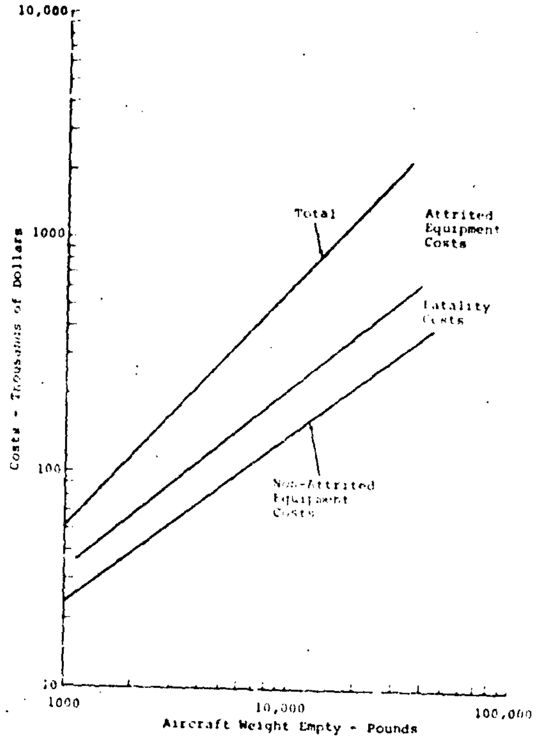


Figure 83. Costs of a Major Accident.

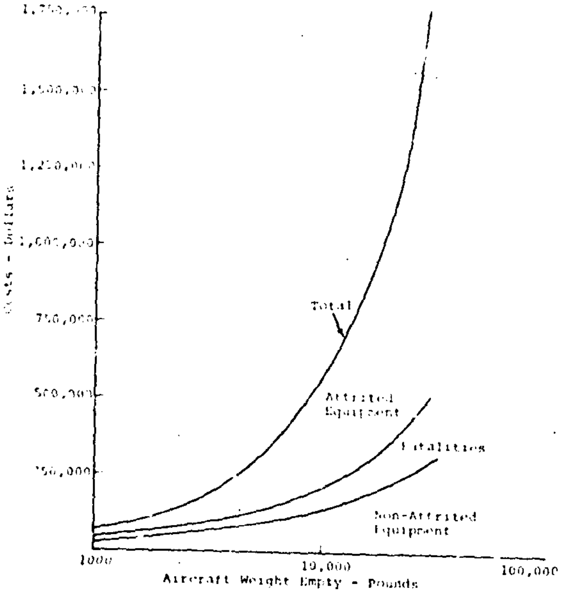


Figure 84. Costs of a Major Accident (Linear Scale).

SELECTION OF AN AVERAGE AIRCRAFT

Since the costs per event for three of the four parameters vary over a range of engine/aircraft size, an average size aircraft must be chosen to facilitate subsequent calculations. For the purposes of this study, a helicopter of 7,000-pound weight empty was selected as being typical of past U.S. Army helicopter experience. Figure 85 illustrates the weight range of Army helicopters, and the average size aircraft chosen.

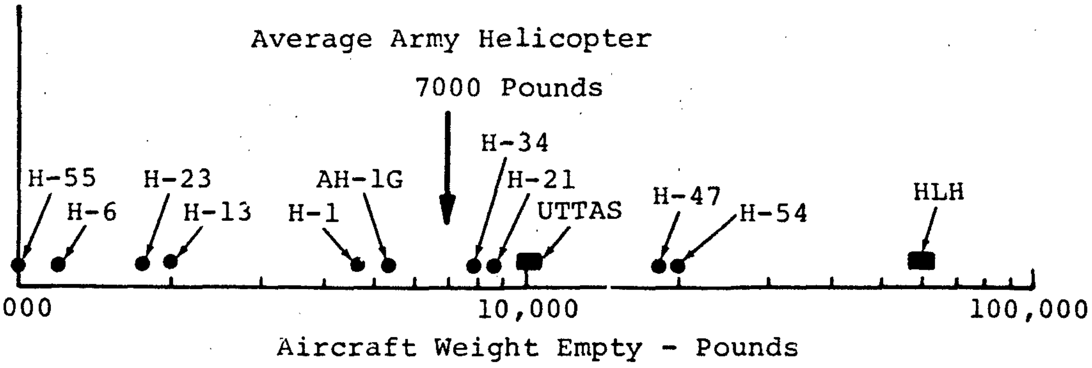


Figure 85. Weight of Army Helicopters.

DETERMINATION OF COST RATIOS

At the 7,000-pound weight empty point, the cost per event and associated ratios for each of the four R&M parameters are shown on Table LXXVIII.

TABLE LXXVIII. COSTS AND RELATIONSHIPS

Parameter	Cost per Event (dollars)	Cost Ratio to Accidents
Unscheduled Removals	16,000	1/25
Major Accidents	400,000	1
Maintenance Man-Hours	4	1/100,000
Scheduled Removals	16,000	1/25

DETERMINATION OF WEIGHTING MULTIPLIER

Determination of weighting multipliers involves combining the relative severity of each event with the relative frequency of occurrence of events. Thus the process is simply the multiplication of the ratios from Table LXXVIII (ratios of cost per event) and Table LXXV (ratio of frequency of occurrence). This process is shown below in Table LXXIX.

TABLE LXXIX. DERIVATION OF WEIGHTING MULTIPLIER

Parameter	Ratio of Costs	Ratio of Frequencies	Weight. Multi.	
			ACC Set at 1	MMH Set at 1
UER	1/25	75	3	100
ACC	1	1	1	33
MMH	1/100,000	3400	00.03	1
TBO	1/25	37	1.5	50

CALCULATION OF INDEX NUMBERS

The calculation of index numbers involves adjusting the scale factor for each subsystem by the weighting multiplier. In mathematical terms the process is:

$$\text{Ind. No.} = \frac{(\text{UER SF})(\text{UER WM})+(\text{ACC SF})(\text{ACC WM})+(\text{MMH SF})(\text{MMH WM})+(\text{TBO SF})(\text{TBO WM})}{\text{UER WM}+\text{ACC WM}+\text{MMH WM}+\text{TBO WM}}$$

where SF = scale factor

WM = weighting multiplier

An example of this process is provided by the turbine subsystem (see Figure 70):

$$\frac{(2)(100)+(5)(33)+(10)(1)+(3)(50)}{100 + 33 + 1 + 50} = \frac{525}{184} = 2.86$$

This calculation was performed on each subsystem and the resultant index numbers are provided in Table X.