# Reliability-Centered Maintenance

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# 1. Chapter one - Reliability-centered maintenance

THE TERM reliability-centered maintenance refers to a scheduled-maintenance program designed to realize the inherent reliability capabilities of equipment. For many years maintenance was a craft learned through experience and rarely examined analytically. As new performance requirements lead to increasingly complex equipment, however, maintenance costs grew accordingly. By the late 1950s the volume of these costs in the airline industry had reached a level that warranted a new look at the entire concept of preventive maintenance. By that time studies of actual operating data had also begun to contradict certain basic assumptions of traditional maintenance practices.

One of the underlying assumptions of maintenance theory has always been that there is a fundamental cause-and-effect relationship between scheduled maintenance and operating reliability. This assumption was based on the intuitive belief that because mechanical parts wear out, the reliability of any equipment is directly related to operating age. It therefore followed that the more frequently equipment was overhauled, the better protected it was against the likelihood of failure. The only problem was in determining what age limit was necessary to assure reliable operation.

In the case of aircraft it was also commonly assumed that all reliability problems were directly related to operating safety. Over the years, however, it was found that many types of failures could not be prevented no matter how intensive the maintenance activities. Moreover, in a field subject to rapidly expanding technology it was becoming increasingly difficult to eliminate uncertainty. Equipment designers were able to cope with this problem, not by preventing failures, but by preventing such failures from affecting safety. In most aircraft all essential functions are protected by redundancy features which ensure that, in the event of a failure, the necessary function will still be available form some other source.

A major question still remained, however, concerning the relationship between scheduled maintenance and reliability. Despite the time honored belief that reliability was directly related to the intervals between scheduled overhauls, certain studies based on actuarial analysis of failure data suggested that the traditional hard-time policies were, apart from their expense, ineffective in controlling failure rates. This was not because the intervals were not short enough, and surely not because the teardown inspections were not sufficiently thorough. Rather, it was because, contrary to expectations, for many items the likelihood of failure did not in fact increase with increasing operating age. Consequently a maintenance policy based exclusively on some maximum operating age would, no matter what age limit, have little or no effect on the failure rate.

At the same time the FAA, which is responsible for regulating airline maintenance practices, was frustrated by experiences showing that it was not possible for airlines to control the failure rate of certain types of engines by any feasible changes in schedule-overhaul policy. As a result, in 1960 a task force was formed, consisting of representatives from both the FAA and the airlines, to investigate the capabilities of scheduled maintenance. The work of this group led to an FAA/Industry Reliability Program, issued in November 1961. The introduction to that program stated:*

"The development of this program is towards the control of reliability through an analysis of the factors that affect reliability and provide a system of actions to improve low reliability levels when they exist.... In the past, a great deal of emphasis has been placed on the control of overhaul periods to provide a satisfactory level of reliability. After careful study, the Committee is convinced that reliability and overhaul time control are not necessarily directly associated topics; therefore, these subjects are dealt with separately. Because the propulsion system has been the area of greatest concern in the recent past, and due to powerplant data being more readily available for study, programs are being developed for the propulsion system first, as only one system at a time can be successfully worked out."

This approach was a direct challenge to the traditional concept that the length of the interval between successive overhauls of an item was an important factor in its failure rate. The task force developed a propulsion-system reliability program, and each airline involved in the task force was then authorized to develop and implement reliability programs in the area of maintenance in which it was most interested. During this process a great deal was learned about the conditions that must be obtained for scheduled maintenance to be effective.** It was also found that in many cases there was no effective form of scheduled maintenance.

## 1.1. The evolution of RCM analysis

At United Airlines an effort was made to coordinate what had been learned from these various activities and define a generally applicable approach to the design or maintenance programs. A rudimentary decision-diagram was devised in 1965 and was refined over the next few years. This technique was eventually embodied in a document published under the title "Handbook: Maintenance Evaluation and Program Development", generally known as MSG-1. MSG-1 was used by special teams of industry and FAA personnel to develop the initial program issued by the FAA Maintenance Review Board for the Boeing 747. As described by the FAA, these teams:

... sorted out the potential maintenance tasks and then evaluated them to determine which must be done for operating safety or essential hidden function protection. The remaining potential tasks were evaluated to determine whether they were economically useful. These procedures provide a systematic review of the aircraft design so that, in the absence of real experience, the best [maintenance] process can be utilized for each component and system.

The Boeing 747 maintenance program so developed was the first attempt to apply reliability-centered maintenance concepts. This program has been successful.

Subsequent improvements in the decision-diagram approach led in 1970 to a seco0nd document, MSG-2: Airline/Manufacturer Maintenance Program Planning Document, which was used to develop the scheduled maintenance programs for the Lockheed 1011 and the Douglas DC10. These programs have been successful. MSG-2 has also been applied to tactical military aircraft such as the McDonnell F4J and the Lockheed P-3, and a similar document prepared in Europe was the basis of the initial scheduled-maintenance programs for such recent aircraft as the Airbus Industrie A-300 and the Concorde.

The objectives of the techniques outlined by MSG-1 and MSG-2 was to develop a scheduled maintenance program that assured the maximum safety and reliability of which the equipment was capable and would meet this requirement at the lowest cost. As an example of the economic benefits achieved with this type of program, under traditional maintenance policies the initial program for the Douglas DC-8 included scheduled overhaul for 339 items, whereas the initial program for the DC-10, based on MSG-2, assigned only seven items to overhaul. One fo the items no longer subject to an overhaul limit in the later program was the turbine engine. Elimination of this scheduled task not only led to major reductions in labor and materials costs, but also reduced the spare-engine inventory required to cover shop activities by more than 50 percent. Since engines for larger airplanes now cost upwards of $1 million each, this is a respectable saving.

As another example, under the initial program developed for the Boeing 747 it took United airlines only 66,000 manhours on major structural inspections to reach an inspection interval of 20,000 hours. In contract, traditional maintenance policies led to an expenditure of over 4 million manhours before the same interval was attained for structural inspections on the smaller and les complex Douglas DC-8. Cost reduction on this scale are of obvious importance to any organization responsible for maintaining large fleets of complex equipment. More important, they are achieved with no decrease in the reliability of the equipment; in fact, a clearer understanding of hte failure process has actually improved operating reliability by making it easier to pinpoint signs of imminent failure.

The specific developments that led to RCM concepts as a fundamental approach to maintenance planning are described in detail in Appendix B. Although MSG-1 and MSG-2 were short working papers, intended for use by a small number of people with extensive back-grounds in aircraft maintenance, further clarification of the basic principles has resulted in a logical discipline that applies to maintenance programs for any complex equipment.

## 1.2. The basis of RCM decision logic

The principles of reliability-centered maintenance stem from a rigorous examination of certain questions that are often taken for granted:

- How does a failure occur?
- What are its consequences?
- What good can preventive maintenance do?

One of the chief drawbacks of the old hard-time approach to scheduled maintenance is that the resulting teardown inspections provided no real basis for determining when serviceable parts were likely to fail - that is, there was no objective means of identifying reduced resistance to failure. More than any other single factor, recognition of the specific need to identify potential-failure conditions has been responsible for the change from scheduled overhauls to on-condition inspections for signs of imminent failure.

Unfortunately, not all items can be protected by this type of maintenance task. In some cases the failure mechanism is imperfectly understood, in others it is random, and in yet others the cost of such inspections exceeds the benefits they might provide. In fact, preventive maintenance si nto possible for many items of modern complex equipment. Nor, in all cases, is it necessary. Failures which could jeopardize the safety of the equipment or its occupants must be prevented. Under modern design practices, however, very few items fall into this category, either because an essential function is provided by more than one source or because operating safety is protected in some other way. Similarly, hidden functions must be protected by scheduled maintenance, both to ensure their availability and to prevent exposure to the risk of a multiple failure.

In all other cases the consequences of failure are economic, and the value of preventive maintenance must be measured in economic terms. In some cases these consequences are major, especially if a failure affects the operational capability of the equipment. Whenever equipment must be removed from service to correct a failure, the cost of failure includes that loss of service. Thus if the intended use of the equipment is of significant value, the delay or abandonment of that use will constitute a significant loss - a fact that must be taken into account in evaluating the benefit of preventive maintenance. Other failures will incur only the cost of correction or repair, and such failures may well by tolerable, inthe sense that it is less expensive to correct them as they occur than to invest in the cost of preventing them.

In short, the driving element in all maintenance decisions is not the failure of a given item, but the consequences of that failure for the equipment as a whole. Within this context it is possible to develop an efficient scheduled-maintenance program, subject to the constraints of satisfying safety and environmental requirements and meeting operational-performance goals. However the solution of such an optimization program requires certain specific information which is nearly always unavailable at the time an initial program must be developed. Hence we also need a basic strategy for decision making which provides for optimum maintenance decisions, given the information available at the time. The process of developing an initial RCM program therefore consists of the following steps:

Partitioning the equipment into object categories to identify those items that require intensive study. Identifying significant items, those whose failure would have safety or major economic consequences for the equipment as a whole, and all hidden functions, which require scheduled maintenance regardless of their significance.

- Evaluating the maintenance requirements for each significant item and hidden function in terms of the failure consequences and selecting only those tasks which will satisfy those requirements.
- Identifying items for which no applicable and effective task can be found and either recommending design changes if safety is involved or assigning no scheduled-maintenance tasks to these items until further information becomes available.
- Selecting conservative initial intervals for each of the included tasks and grouping the tasks in maintenance packages for application.
- Establishing an age-exploration program to provide the factual information necessary to revise initial decisions.

The first of these steps is intended, as a purely practical matter, to reduce the problem of analysis to manageable size and to focus it according to areas of engineering expertise. The next three steps are the crux of RCM analysis. They involve a specific sequence of decision questions, worded to indicate the information required for a yes/no answer in each case. Where this information is not available, a default answer specifies the actions that will best protect the equipment until there is a basis for some other decision. This decision-diagram technique, described in full in Chapter 4, not only provides an orderly basis for making decisions with limited information, but also results in clear audit trail for later review.

In the airline industry all scheduled-maintenance programs are, of course, subject to FAA review and approval. The initial program for each new type of equipment is promulgated by the FAA Maintenance Review Board. This document, developed in conference with the equipment manufacturers and the purchasing airlines, forms the basis of the initial program submitted by each airline for FAA approval. Organizations operating other equipment in the civilian and military spheres may define their initial maintenance programs differently, but some comparable review procedure is usually involved.

Because any initial scheduled-maintenance program must be developed and implemented in advance of actual operational data, an important element of RCM programs is age exploration, a procedure for systematic gathering of the information necessary to determine the applicability of some maintenance tasks and evaluate the effectiveness of others. As this information accumulates, the same decision diagram provides a means of revising and refining the initial program. Much of this information is already available, of course, for equipment that has been in service for some time. Although the specific data needed may have to be retrieved from several different information systems, and the remaining useful life of the equipment will be a factor in certain decisions, RCM analysis under these circumstances will result in fewer default decisions, and hence a near-optimum program at the outset. Such programs usually include a larger number of on-condition inspections than the programs arrived at under older policies, and fewer of the scheduled rework tasks which had been included simply because there was no evidence that they should not be done.

An effective scheduled-maintenance program will realize all the reliability of which the equipment is capable. However, no form of preventive maintenance can alter characteristics that are inherent in the design. The residual failures that occur after all applicable and effective preventive tasks have been implemented reflect the inherent capability of the equipment, and if the resulting level of reliability is inadequate, the only recourse is engineering redesign. This effort may be directed at a single component to correct for a dominant failure mode or it may be directed at some characteristic that will make a particular preventive technique feasible. Product improvement of this kind takes place routinely during the early years of operation of any complex equipment. Thus, although reliability-centered maintenance is concerned in the short run with tasks based on the actual reliability characteristics of the equipment, it is also concerned with improvements that will ultimately increase delivered reliability.

## 1.3. Reliability Problems in Complex Equipment

Failures are inevitable in any complex equipment, although their consequences can be controlled by careful design and effective maintenance. The reason for this failure incidence is apparent if we consider some basic differences between simple and complex equipment. Simple equipment is asked to perform very few different functions. Such equipment therefore consists of only a few systems and assemblies, and these may in turn be so simple that some are exposed to only one possible failure mode. In most cases this simplicity extends to the structural elements as well, and both the structure and the various items on the equipment are relatively accessible for inspection.

As a result, simple equipment has certain distinct failure characteristics. Because it is exposed to relatively few failure possibilities, its overall reliability tends to be higher. For the same reason, these failures tend to be age-related; each type of failure tends to concentrate around some average age, and since only a few types of failure are involved they govern the average age at failure. However, in the absence of redundancy and other protective features, such failures may have fairly serious consequences. Thus simple equipment is often protected by "overdesign"; components are heavier and bulkier than necessary, and familiar materials and processes are used to avoid uncertainty associated with more complex high-performance equipment.

All in all, the traditional idea that failures are directly related to safety and that their likelihood varies directly with age is often true for simple equipment. In any case, it is fairly easy to make an exhaustive study of such equipment to determine its scheduled-maintenance requirements.

The situation is quite different with complex equipment in use today. The general-aviation aircraft of the 1930s usually had a simple reciprocating engine, a fixed-pitch propeller, fixed landing gear, and no wing flaps. The modern airplane may have several turboprop or turbojet powerplants, a retractable landing gear, movable high-lift devices, an airframe anti-icing system, pressure- and temperature-control systems for the cabin, extensive communications and navigation equipment, complex cockpit instrumentation, and complex ancillary systems to support all these additional items. This increased complexity has greatly expanded the safe operational capability of the aircraft. The simple airplane of the 1930s was restricted to trips of a few hundred miles under reasonably favorable weather conditions. The higher performance capability demanded of modern equipment, however has greatly increased not only the number of items that can fail, but the types of failure that can occur.

Each new design of any high-performance equipment is essentially an attempt to make earlier designs technologically obsolete, with the usual measure of improvement being potential operating capability (including costs). In other words, this is the operating capability expected in the absence of any failures that might change the circumstances. The basis for evaluating new aircraft designs usually includes performance factors such as the following:

- The maximum payload (military or commercial) that can be carried over a distance
- The maximum distance over which a given payload can be carried
- The minimum size of the vehicle that can carry a given payload over a given distance
- The highest speed that can be attained under defined payload/range conditions
- Special capabilities, such as the ability to traverse rough terrain, operate from short runways, or withstand punishment

In some cases these factors are weighed against the anticipated direct operating costs (including maintenance costs) associated with attaining such capabilities, since a major objective may be to achieve the minimum cost per unit of payload transported. In other cases performance takes precedence over cost. This is true not only of military equipment but of certain types of civilian equipment, where there is an adequate market for specialized capability despite its cost.

Another aspect of performance demands, of course, is the trend toward increasing automation. Examples are everywhere - automatic flight-control systems in aircraft, including automatic approach and landing equipment; automatic transmissions in automobiles; automated traffic-control systems from rapid-transit trains; and automatic aperture-setting devices in cameras.

The design of complex equipment, therefore, is always a tradeoff between achieving the required performance capability and acceptable reliability. This tradeoff entails an intentional compromise between the lightness and compactness required for high performance and the weight and bulk required for durability. Thus it is neither economically nor technologically feasible to produce complex equipment that can sustain trouble-free operation for an indefinite period of time. Although the reliability of certain items that perform single functions may be improving, the number of such items has been vastly multiplied. It is therefore inevitable that failures will occur - that is, that certain parts of the equipment will lose the capability of performing their specified functions.

Our concern is not with the number of these failures, but with the consequences of a given failure for the equipment as a whole. Will the loss of a particular function endanger the equipment or its occupants: If not, is it necessary to abort the mission or take the equipment out of service until repairs can be made? Or can unrestricted operation continue and the repair be deferred to a convenient time and place: The ability to defer failure consequences depends largely on the design of the equipment. One strategy is the use of redundancy and fail-safe construction. Another strategy is failure substitution, the use of a minor failure to preempt a major one, as in the use of fuse and circuit breakers. The latter concept extends to maintenance activities in which potential failures are used to preempt functional failures. Thus the design may include various instrumentation to give some warning of an impending failure or other features which facilitate inspection for possible deterioration. All these features actually increase the number of failure possibilities in the sense that they add more items that could fail. However, they greatly reduce the consequences of any single failure.

## 1.4. An overview of maintenance activity

The activities of a maintenance organization include both the scheduled work that is performed to avoid failures and the corrective work that is performed after failures have occurred. Our present concern is with preventive maintenance, the program of scheduled tasks necessary to ensure safe and reliable operation of the equipment. The complete collection of these tasks, together with their assigned intervals, is termed the scheduled-maintenance program. This program includes only the tasks that are scheduled in advance - servicing and lubrication, inspection, and scheduled removal and replacement of items on the equipment. Exhibit 1.1 lists some typical tasks in such a program.

In order to accomplish the anticipated corrective and scheduled maintenance, an operating organization must establish an overall support plan which includes the designation of maintenance stations, staffing with trained mechanics, provision of specialized testing equipment and parts inventories, and so on. The overall maintenance plan of an airline is typical of that for any transportation system in which each piece of equipment operates through many stations but has no unique home station.

**Exhibit 1-1 Typical scheduled maintenance tasks for various items on aircraft. Some scheduled tasks are performed on the aircraft at line-maintenance stations and others are performed at the major maintenance base, either as part of a larger maintenance package or typical scheduled maintenance tasks for various items on aircraft. Some scheduled tasks are performed on the aircraft at line-maintenance stations and others are performed at the major maintenance base, either as part of a larger maintenance package or as part of the shop procedure whenever a failed unit is sent to the maintenance base for repair.**

| Nature of item | Scheduled-maintenance task | Task interval |
|---|---|---|
| **SYSTEMS ITEMS** | | |
| Fuel-pump assembly (Douglas A4) | On-condition (on aircraft): Inspect filter for contamination | 60 operating hours |
| | On-condition (on aircraft): Inspect drive shaft for spline wear | 1000 operating hours |
| Brake assembly, main landing gear (Douglas DC-10) | On-condition (on aircraft): Inspect brake wear indicators | During overnight stops and walkaround checks |
| | On-condition (in shop): Test automatic brake adjuster | Whenever brake assembly is in shop |
| **POWERPLANT ITEMS** | | |
| Compressor rear frame (General Electric CF6-6) | On-condition (on aircraft): Inspect front flange for cracks emanating form bolt holes. | 500 flight cycles or phase check (134 days), whichever is first |
| Nozzle guide vanes (Pratt & Whitney J8D-7) | On-condition (on aircraft): Perform borescope inspection for burning, cracking, or bowing of guide vanes | 1000 operating hours |
| Tenth-stage compressor blades (Pratt & Whitney J8D-7) | Scheduled rework: Shot-peen blade dovetail and apply anti-galling compound | 6000 operating hours |
| Stage 3 turbine disk (Pratt & Whitney J8D-7) | Scheduled discard: Replace turbine disk with new part | 15000 flight cycles or 30000 operating hours, whichever is first |
| **STRUCTURAL ITEMS** | | |
| Rear spar at bulkhead intersection (Douglas DC-10) | On-condition (on aircraft): Inspect specified intersections in zones 531, 631, 141, 142 for cracks and corrosion | Primary strength-indicator areas 5000 operating hours, internal fuel-tank areas 20,000 hours |
| Shock strut, main landing gear (Boeing 737) | On-condition (in shop): Strip cadmium plate and inspect for cracks and corrosion | 19,500 hours |

A large proportion of the failures that occur during operation are first observed and reported by the operating crew. Some of these must be corrected after the next landing, and a few are serious enough to require a change in flight plan. The correction of many other failures, however, can be deferred to a convenient time and location. Those line stations with a high exposure to the need for immediate corrective work are designated as maintenance stations and are equipped with trained mechanics, spare-parts inventory, and the facilities necessary to carry out such repairs. United Airlines serves 91 airline stations with 19 such maintenance stations.

The decision to designate a particular station as a maintenance station depends chiefly on the amount of traffic at that station and the reliability of the aircraft involved. A station at which the greatest volume of repairs is expected is the logical first choice. However, other considerations may be the frequency with which the operating schedule provides overnight layovers, the relative ease of routing other aircrafts to that station, the availability of mechanics and parts to support other types of aircraft, the planned volume of scheduled-maintenance work, and so on.

Line-maintenance stations themselves vary in ssize and complexity. The facilities needed for immediate corrective work establish the minimum resources at any given maintenance station, but operating organizations generally consolidate the bulk of the deferrable work at a few of these stations for greater economy. To simplify the control of scheduled maintenance, individual tasks are grouped into a fairly small number of maintenance packages for execution. Like deferrable corrective work, these scheduled-maintenance packages can be assigned to any convenient maintenance station. Thus the more involved work is generally assigned to those line stations already equipped with the staff and inventories for extensive corrective work.

Not all scheduled-maintenance tasks can be carried out at line stations. Major structural inspections, scheduled rework, and inspections which entail extensive disassembly are best handled at a major maintenance base equipped with shop facilities. The major base also repairs failed units that are removed form aircraft at the line stations. Few such maintenance bases are needed, and reliability considerations generally determine their size and manpower requirements, rather than their location. Many large airlines operate efficiently with only one maintenance base. The work performed at a maintenance base is generally termed *shop maintenance* to differentiate it from *line maintenance,* which consists primarily of replacing failed units rather than repairing them.

The entire process by which a detailed support plan is developed is beyond the scope of this volume. Suffice it to say that a detailed plan is necessary in order to implement a scheduled-maintenance program. Our concern here is with the development of such a program – or rather with the principles underlying its development. In the following chapters we will examine the nature of failures, the basis on which their consequences are evaluated, and the specific criteria that determine the applicability and effectiveness of a given type of preventive task. With this framework established, we will consider the decision logic that results in a scheduled-maintenance program based on the actual reliability characteristics of the equipment. This reliability-centered approach ensures that the inherent safety and operating capability of the equipment will be realized a the minimum cost, given the information available at any time.

The chapters in Part Two illustrate the application of RCM decision logic to specific hardware examples and discuss some of the information processes involved in the continuing evolution of the maintenance program after the equipment enters service. All these illustrations are drawn from commercial-aircraft applications. However, it should be clear from the discussion in Part One that the basic principles of RCM programs extend not just to other operating contexts, but to maintenance programs for any complex equipment.

# PART ONE
## Theory and principles

## 2. Chapter Two - The nature of failure

The parts of any mechanical equipment are subject to wear, corrosion, and fatigue which inevitably result in some deviation from the conditions that existed when the equipment was new. Ultimately the deviation will become great enough that the equipment, or some item on it, no longer meets the required performance standards – that is, it fails. The role of scheduled maintenance is to cope with the failure process. For years, however, the chief focus has been on anticipating the age at which things were likely to fail, rather than on how they fail and the consequences of such failures. As a result there has been insufficient attention to the failure process itself, and even less attention to the question of precisely what constitutes a failure.

One reason for this lack of attention has been the common assumption that all equipment “wears out” and inevitably becomes less reliable with increasing operating age. This assumption led to the conclusion that the overall failure rate of an item will always be reduced by an age limit which precludes operation at ages where the likelihood of failure is greater. In accordance with this hard-time policy, all units were taken out of service when they reached a specified age and were sent to the major maintenance base for complete disassembly and overhaul, a procedure intended to restore each part to its original condition.

It is now known that the reliability of most complex items does not vary directly with operating age, at least not in such a way as to make hard-time overhaul a useful concept. Procedures directed at obtaining some precise evidence that a failure is imminent are frequently a far superior weapon against failure. However, to understand the specific nature of such procedures as they pertain to an RCM program, it is necessary to take a closer look at the entire concept of failure. Without a precise definition of what condition represents a failure, there is no way to either assess its consequences or to define the physical evidence for which to inspect. The term failure must, in fact be given a far more explicit meaning than “an inability to function” in order to clarify the basis of reliability-centered maintenance.

In this chapter we will examine the problem of defining failures and some of the implications this has for the analysis of failure data. We will also see how failure consequences are evaluated, both in terms of single failures and in terms of multiple failures. Finally, we will discuss the process of failure itself and see why complex items, unlike simple items, do not necessarily wear out.

## 2.1. The Definition of Failure

Each of us has some intuitive notion of what constitutes a failure. We would all agree that an automobile engine, a fuel pump, or a tire has failed if it ceases to perform its intended function. But there are times when an item does continue to function, although not at its expected level. An automobile engine may run powerfully and smoothly, but its oil consumption is high; a fuel pump may pump fuel, but sluggishly; a tire may hold air and support the car, but its bald tread indicates that it will do neither much longer.

Have these items failed? If not, how bad must the condition become before we would say a failure has occurred: Moreover, if any of these conditions is corrected, the time required for unanticipated repairs might force a change in other plans, such as the delay or cancellation of a trip. In this event could it still be argued that no failure occurred?

To cover all these eventualities we can define a failure in broad terms as follows:

**A failure is an unsatisfactory condition**

In other words, a failure is any identifiable deviation from the original condition which is unsatisfactory to a particular user. The determination that a condition is unsatisfactory, however, depends on the consequences of failure in a given operating context. For example, high oil consumption in an aircraft engine may pose no problem on short or medium-range flights, whereas on long range flights the same rate of consumption would exhaust the oil supply. Similarly, engine-instrumentation malfunctions that would not disrupt operations on multi-engine equipment would be clearly unsatisfactory on a single engine plane, and performance that is acceptable in a land-based environment might not be good enough for carrier operation.

In short, the exact dividing line between satisfactory and unsatisfactory conditions will depend not only on the function of the item in question, but on the nature of the equipment in which it is installed and the operating context in which that equipment is used. The determination will therefore vary from one operating organization to another. Within a given organization, however, it is essential that the boundaries between satisfactory and unsatisfactory conditions be defined for each item in clear and unmistakable terms.

**Functional failure**

The judgment that a condition is unsatisfactory implies that there must be some condition or performance standard on which this judgment can be based. As we have seen, however, an unsatisfactory condition can range from the complete inability of an item to perform its intended function to some physical evidence that it will soon be unable to do so. For maintenance purposes, therefore, we must classify failures further as either functional failures or potential failures.

**A functional failure is the inability of an item (or the equipment containing it) to meet a specified performance standard.**

A complete loss of function is clearly a functional failure. Note, however, that a functional failure also includes the inability of an item to function at the level of performance that has been specified as satisfactory. This definition thus provides us with an identifiable and measurable condition, a basis for identifying functional failures.

To define a functional failure for any item we must, of course have a clear understanding of its functions. This is not a trivial consideration. For example, if we say that the function of the braking system on an airplane is to stop the plane, then only one functional failure is possible – inability to stop the plane. However, this system also has the functions of providing modulated stopping capability, providing differential braking for maneuvering on the ground, providing antiskid capability, and so on. With this expanded definition it becomes clear that the braking system is in fact subject to a number of different functional failures. It is extremely important to determine all the functions of an item that are significant in a given operating context, since it is only in these terms that its functional failures can be defined.

### Potential Failure

Once a particular functional failure has been defined, some physical condition can often be identified which indicates that this failure is imminent. Under these circumstances it may be possible to remove the item from service before the point of functional failure. When such conditions can be identified, they are defined as *potential failures*:

**A potential failure is an identifiable physical condition which indicates a functional failure is imminent.**

The fact that potential failures can be identified is an important aspect of modern maintenance theory, because it permits maximum use of each item without the consequences associated with a functional failure. Units are removed or repaired at the potential-failure stage, so that potential failures preempt functional failures.

For some items the identifiable condition that indicates imminent failure is directly related to the performance criterion that defines the functional failure. For example, one of the functions of a tire tread is to provide a renewable surface that protects the carcass of the tire so that it can be retreaded. This function is not the most obvious one, and it might well be overlooked in listing of tire functions; nevertheless, it is important from an economic standpoint. Repeated use of the tire wears away the tread, and if wear continues to the point at which the carcass cannot be retreaded, a functional failure has occurred. To prevent this particular functional failure, we must therefore define the potential failure as some wear level that does not endanger the carcass.

The ability to identify either a functional or a potential failure thus depends on three factors:

- Clear definitions of the functions of an item as they relate to the equipment or operating context in which the item is to be used
- A clear definition of the conditions that constitute a functional failure in each case
- A clear definition of the conditions that indicate the imminence of this failure

In other words, we must not only define the failure; we must also specify the precise evidence by which it can be recognized.

## 2.2. The detection of failures

The role of the operating crew
Evident and hidden functions
Verification of failures
Interpreting failure data

Both functional failures and potential failures can be defined in terms of identifiable conditions for a given operating context. In evaluating failure data, however, it is important to take into account the different frames of reference of several sets of failure observers – the operating crew, the line mechanic, the shop mechanic, and even passengers. Understanding how and when the observer sees a failure and how he interprets it is crucial both to operating reliability and to effective preventive maintenance.

The detection and reporting of failures depends on two principal elements:

- The observer must be in a position to detect the failure. This "right" position may be a physical location, a particular moment in time, or access to the inspection equipment that can reveal the condition.
- The observer must have standards that enable him to recognize the condition he sees as a failure, either functional or potential.

### The role of the operating crew

Members of the operating crew are the only people in a position to observe the dynamic operation of the equipment in its normal environment. Whereas as airplane in a maintenance facility is in a static environment, during flight its systems are activated and the whole machine is subjected to air loads and to both low atmospheric pressure and low outside temperatures. As a result, the operating crew will be the first to observe many functional failures. Such failures are often detected at the time a crew member calls on a function and finds that it is impaired.

In most complex equipment the crew's ability to observe failures is further enhanced by extensive instrumentation, warning lights, or other monitoring devices. In some cases these indicators make failures evident at the moment they occur, when otherwise they might go undetected until the function was needed. Such early warning provides more time for changes in operating strategy to offset the consequences of the failure. For example, certain engine malfunctions may require the shutdown of one engine and perhaps the selection of an alternate landing field, or an auxiliary hydraulic pump may have to be turned on after one of the main ones fails. Even when the flight can be continued without incident, the crew is required to record the failure as accurately as possible in the flight log so the condition can be corrected at the earliest opportunity.

This instrumentation also permits the crew to determine whether items that are still operative are functioning as well as they should. In some cases reduced performance is an indication of an imminent failure, and these conditions would also be examined later to see whether a potential failure exists.

Not surprisingly, the operating crew plays a major role in detecting failure conditions. This is illustrated by a study of the support costs on a fleet of Boeing 747s over the first ten months of 1975 (a total of 51,400 operating hours). In this case 66.1 percent of all failure reports while the plane was away from the maintenance base originated with the operating crew, and these failures accounted for 61.5% of the total manhours for corrective line maintenance. The other 33.9 percent of the reported failures included potential failures detected by line mechanics, along with other failures not normally evident to the operating crew.

## Hidden-Function Items

Although most functional failures are first detected by the operating crew, many items are subject to failures that the crew is not in a position to observe. The crew duties often include special checks of certain hidden-function items, but most such failures must be found by inspections or tests performed by maintenance personnel. To ensure that we will know when a failure has occurred, we must know that the observer is in a position to detect it. Hence for maintenance purposes a basic distinction is made between *evident* and *hidden functions* from the vantage point of the operating crew:

**An evident function is one whose failure will be evident to the operating crew during the performance of normal duties.**

**A hidden function is one whose failure will not be evident to the operating crew during the performance of normal duties.**

An item may have several functions, any one of which can fail. If the loss of one of these functions would not be evident, the item must be classified from the maintenance standpoint as a hidden-function item.

Hidden functions may be of two kinds:

- A function that is normally active but gives no indication to the operating crew if it ceases
- A function that is normally inactive, so that the crew cannot know whether it will be available when it is needed (usually the demand follows some other failure)

The fire detection system in an aircraft powerplant falls into the first category. This system is active whenever the engine is in use, but its sensing function is hidden unless it detects a fire; thus if it fails in some way, its failure is similarly hidden. The fire-extinguishing system that backs up this unit has the second kind of hidden function. It is not activated unless a fire is detected, and only when it is called upon to operate does the crew find out whether it works.

In addition to inspecting for potential failures, maintenance personnel also inspect most hidden-function items for functional failures. Thus the operating crew and the maintenance crew complement one another as failure observers.

## Verification of Failures

Operating crews occasionally report conditions which appear unsatisfactory to them, but which are actually satisfactory according to the defined standards for condition and performance. This is a basic principle of prevention. The operating crew cannot always know when a particular deviation represents a potential failure, and in the interests of safety the crew is required to report anything questionable. In most airlines the operating crew can communicate directly with a central group of maintenance specialists, or controllers, about any unusual conditions observed during flight. The controllers can determine the consequences of the condition described to them and advise the crew whether to land as soon as possible or continue the flight, with or without operating restrictions. The controllers are also in a position to determine whether the condition should be corrected before the plane is dispatched again. This advice is particularly important when a plane is operating into a station which is not a maintenance station.

Once the plane is available for maintenance inspection, the maintenance crew is in a better position to diagnose the problem and determine whether a failure condition actually does exist. Thus the suspect item may be replaced or repaired or marked "OK for continued operation." The fact that failure observers have different frames of reference for interpreting the conditions they see often makes it difficult to evaluate failure reports. For example, a broken seat recliner is recognizable to any observer as a failure. Frequently a passenger will notice the condition first and complain about it to the flight attendant. The line mechanic at the next maintenance station will take corrective action, usually by replacing the mechanism and sending the failed unit to the maintenance base, where the shop mechanic will record the failure and make the repair. In this case all four types of observer would have no difficulty recognizing the failure.

The situation is somewhat different with an in-flight engine shutdown as a result of erratic instrument readings. Although the passengers would not be aware that a failure had occurred, the operating crew would report an engine failure. However, the line mechanic might discover that the failure was in the cockpit instruments, not the engine. He would then replace the faulty instrument and report an instrument failure. Thus the crew members are the only ones in a position to observe the failure, but they are not in a position to interpret it. Under other circumstances the situation may be reversed. For example, on certain engines actual separation of the turbine blades – a functional failure – is preceded by a perceptible looseness of one or more blades in their mounts. If the blades separate, both the operating crew and the passengers may become abruptly aware of the functional failure, but since the engine functions normally with loose blades, neither crew nor passengers have any reason to suspect a potential failure. In this case the crew members might be able to interpret the condition as a potential failure, but they are not in a position to observe it.

The line mechanic who inspects the engine as part of scheduled maintenance will check for loose blades by slowly rotating the turbine assembly and feeling the blades with a probe (typically a length of stiff rubber or plastic tubing). If he finds any loose blades, he will report a failure and remove the engine. The mechanics in the engine-repair shop are in an even better position for detailed observation, since they must go inside the engine case to get at the faulty blades. (On occasion they may be the first to observe loose blades in an engine removed for other reasons.) If they confirm the line mechanic's diagnosis, they will report the failure as verified.

Of course, the situation is not always this clear cut. Often there are no precise troubleshooting methods to determine exactly which component or part is responsible for a reported malfunction. Under these circumstances the line mechanic will remove several items, any of which might have caused the problem. The practice is sometimes referred to as "shotgun" troubleshooting. Many of these suspect items will show normal performance characteristics when they are tested at the maintenance base. Thus, although they are reported as failures at the time they are removed from the equipment, from the shop mechanic's frame of reference they are unverified failures. By the same token, differences between the testing environment and the field environment will sometimes result in unverified failures for items that are actually suffering functional failures in the field.

Units removed from equipment either as potential failures or because of malfunctions are termed premature removals. This term came into use when most equipment items had a fixed operating-age limit. A unit removed when it reached this limit was "time-expired," whereas one removed because it had failed (or was suspected of having failed) before this age limit was a "premature" removal.

## Interpreting Failure Data

The problem of interpreting failure data is further complicated by differences in reporting policy from one organization to another. For example, one airline might classify an engine removed because of loose turbine blades as a failure (this classification would be consistent with our definition of a potential failure). This removal and all others like it would then be counted as failures in all failure data. Another airline might classify such removals as 'precautionary,' or even as 'scheduled' (having discovered a potential failure, they would then schedule the unit for removal at the earliest opportunity). In both these cases the removals would not be reported as failures.

Similar differences arise as a result of varying performance requirements. The inability of an item to meet some specified performance requirement is considered a functional failure. Thus functional failures (and also potential failures) are created or eliminated by differences in the specified limits; even in the same piece of equipment, what is a failure to one organization will not necessarily be a failure to another. These differences exist not only form one organization to another, but within a single organization over a long calendar period. Procedures change, or failure definitions are revised, and any of these changes will result in a change in the reported failure rate.

Another factor that must be taken into account is the difference in orientation between manufacturers and users. On one hand, the operating organization tends to view a failure for any reason as undesirable and expects the manufacturer to improve the product to eliminate all such occurrences. On the other hand, the manufacturer considers it his responsibility to deliver a product capable of performing at the warranted reliability level (if there is one) under the specific stress conditions for which it was designed. If it later develops that the equipment must be frequently operated beyond these conditions, he will not want to assume responsibility for any failures that may have been caused or accelerated by such operation. Thus manufacturers tend to "censor' the failure histories of operating organizations in light of their individual operating practices. The result is that equipment users, with some confusion among them, talk about what they actually saw, while the manufacturer talks about what they should have seen.

## 2.3. The Consequences of Failure

While failure analysis may have some small intrinsic interest of its own, the reason for our concern with failure is its consequences. These may range from the modest cost of replacing a failed component to the possible destruction of a piece of equipment and the loss of lives. Thus all reliability-centered maintenance, including the need for redesign is indicated, not by the frequency of a particular failure, but by the nature of its consequences. Any preventive-maintenance program is therefore based on the following precept:

**The consequences of a failure determine the priority of the maintenance activities or design improvement required to prevent its occurrence.**

The more complex any piece of equipment is, the more ways there are in which it can fail. All failure consequences, however, can be grouped in the following four categories:

- Safety consequences, involving possible loss of the equipment and its occupants
- Operational consequences, which involve an indirect economic loss as well as the direct cost of repair
- Nonoperational consequences, which involve only the direct cost of repair
- Hidden-failure consequences, which have no direct impact, but increase the likelihood of a multiple failure

### Safety Consequences

The first consideration in evaluating any failure possibility is safety:

**Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?**

Suppose the failure in question is the separation of a number of turbine blades on an aircraft engine, causing the engine to vibrate heavily and lose much of its thrust. This functional failure could certainly affect the safety of a single-engine aircraft and its occupants, since the loss of thrust will force an immediate landing regardless of the terrain below. Furthermore, if the engine is one whose case cannot contain ejected blades, the blades may be thrown through the engine case and cause unpredictable, and perhaps serious, damage to the plane itself. There is also danger from hot gases escaping from the torn engine case. In a multiengine plane the loss of thrust would have no direct effect on safety, since the aircraft can maintain altitude and complete its flight with one engine inoperative. Hence the loss of function is not in itself cause for alarm. However, both plane and passengers will still be endangered by the possible secondary damage caused by the ejected blades. In this case, therefore, the secondary effects are sufficient reason to classify the failure as critical.

A *critical failure* is any failure that could have a direct effect on safety. Note, however, that the term *direct* implies certain limitations. The impact of the failure must be immediate if it is to be considered direct: that is, the adverse effect must be one that will be felt before planned completion of the flight. In addition, these consequences must result from a single failure, not from some combination of this failure with one that has not yet occurred. An important fact follows from this:

- All critical failures will be evident to the operating crew. If a failure has no evident results, it cannot, by definition, have a direct effect on safety

It may be necessary to remove a plane from service to correct certain failures before continuing operation, and in some cases it may even be advisable to discontinue the flight. However, as long as the failure itself has no immediate safety consequences, the need for these precautionary measures does not justify classifying this failure as critical.

Not every critical failure results in an accident; some such failures, in fact, have occurred fairly often with no serious consequences. However, the issue is not whether such consequences are inevitable, but whether they are possible. For example, the secondary effects associated with ejected turbine blades are unpredictable. Usually they do not injure passengers or damage a vital part of the plane – but they can. Therefore this failure is classified as critical. Similarly, any failure that causes an engine fire is critical. Despite the existence of fire-extinguishing systems, there is no guarantee that a fire can be controlled and extinguished. Safety consequences are always assessed at the most conservative level, and in the absence of proof that a failure cannot affect safety, it is classified by default as critical.

In the event of any critical failure, every attempt is made to prevent a recurrence. Often redesign of one or more vulnerable items is necessary. However, the design and manufacturer of new parts and their subsequent incorporation in in-service equipment takes months, and sometimes years. Hence some other action is needed in the meantime. In the case of turbine-blade failure an identifiable physical condition – loose blades – has been found to occur well in advance of actual separation of the blades. Thus regular inspection for this condition as part of scheduled maintenance makes it possible to remove engines at the potential-failure stage, thereby forestalling all critical functional failures. Note that this preventive-maintenance task does not prevent failures; rather, by substituting a potential failure for a functional failure, it precludes the consequences of a functional failure.

## Operational Consequences

Once safety consequences have been ruled out, a second set of consequences must be considered:

**Does the failure have a direct adverse effect on operational capability:**

Whenever the need to correct a failure disrupts planned operations, the failure has operational consequences. Thus operational consequences include the need to abort an operation after a failure occurs, the delay or cancellation of other operations to make unanticipated repairs, or the need for operating restrictions until repairs can be made. (A critical failure can, of course, be viewed as a special case of a failure with operational consequences.) In this case the consequences are economic: they represent the imputed cost of lost operational capability.

A failure that requires immediate correction does not necessarily have operational consequences. For example, if a failed item on an aircraft can be replaced or repaired during the normal transit time at a line station, then it causes no delay or cancellation of subsequent flights, and the only economic consequence is the cost of the corrective maintenance. In contrast, the plane may be operational, but its reduced capability will result in such costs as high fuel consumption. The definition of operational consequences will therefore vary from one operating context to another. In all cases, however, the total cost of an operational failure includes the economic loss resulting from the failure as well as the cost of repairing it. If a failure has no operational consequences, the cost of corrective maintenance is still incurred, but this is the only cost.

If a potential failure such as loose turbine blades were discovered while the plane was in service, the time required to remove this engine and install a new one would involve operational consequences. However, inspections for this potential failure can be performed while the plane is out of service for scheduled maintenance. In this case there is ample time to remove and replace any failed engines (potential failures) without disrupting planned operations.

## Nonoperational Consequences

There are many kinds of functional failures that have not direct adverse effect on operational capability. One common example is the failure of a navigation unit in a plane equipped with a highly redundant navigation system. Since other units ensure availability of the required function, the only consequence in this case is that the failed unit must be replaced at some convenient time. Thus the costs generated by such a failure are limited to the cost of corrective maintenance.

As we have seen, potential failures also fall in this category. The purpose of defining a potential failure that can be used to preempt a functional failure is to reduce the failure consequences in as many cases as possible to the level o f direct cost of replacement and repair.

## Hidden-failure Consequences

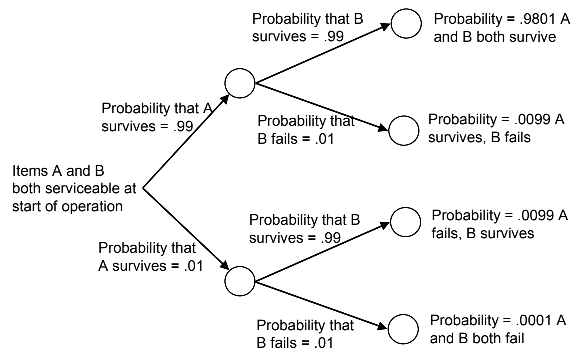
Another important class of failures that have no immediate consequences consists of failures of hidden-function items. By definition, hidden failures can have no direct adverse effects (if they did, the failure would not be hidden). However the ultimate consequences can be major if a hidden failure is not detected and corrected. Certain elevator-control systems, for example, are designed with concentric inner and outer shafts so that the failure of one shaft will not result in any loss of elevator control. If the second shaft were to fail after an undetected failure of the first one, the result would be a critical failure. In other words, the consequence of any hidden-function failure is increased exposure to the consequences of a multiple failure.

## 2.4. Multiple failures

Failure consequences are often assessed in terms of a sequence of independent events leading to a multiple failure, since several successive failures may result in consequences that no one of the failures would produce individually. The probability of a multiple failure is simple to calculate. Suppose items A and B in Exhibit 2.1 both have a probability of 0.99 of surviving a given two-hour flight (this would correspond to one failure per 100 flights, which is in fact a very high failure rate). If items A and B are both functioning at takeoff time, there are only four possible outcomes:

| | |
|---|---|
| Item A survives and item B survives: | P = 0.99 x 0.99 = 0.9801 |
| Item A survives and item B fails: | P = 0.99 x 0.01 = 0.0099 |
| Item A fails and item B survives: | P = 0.01 x 0.99 = 0.0099 |
| Item A fails and item B fails: | P = 0.01 x 0.01 = 0.0001 |

**Exhibit 2-1Tree diagram showing the probability of the multiple failure of two items during the same flight when both items are serviceable at takeoff**




In other words, the probability that A and B will both fail during the same flight is only 0.0001, or an average of once in 10,000 flights. If we were considering a multiple failure of 3 items, the average occurrence, even with the high failure rate we have assumed here, would be once every million flights.

| Nature of failure consequences | | | | Effective on the previous failures in sequence |
|---|---|---|---|---|
| **First failure** | **Second failure** | **Third failure** | **Fourth failure** | |
| Critical | | | | The critical nature of the first failure supersedes the consequences of a possible second failure. |
| Operational | Critical | | | A second failure would be critical; the first failure must be corrected before further dispatch and therefore has operational consequences. |
| Nonoperational | Operational | Critical | | A third failure would be critical; the second failure must be corrected before further dispatch, but correction of the first failure can be deferred to a convenient time and location |
| Nonoperational | Nonoperational | Operational | Critical | A fourth failure would be critical; the third failure must be corrected before further dispatch, but correction of both the first and second failures can be deferred |

**Exhibit 2-2. The consequences of a single failure as determined by the consequences of a possible multiple failure. A failure that does not in itself affect operating capability acquires operational consequences if a subsequent multiple failure would be critical.**

Note the difference, however, if item A is in a failed state when the flight begins. The probability that B will fail is 0.01; thus the probability of a multiple failure of A and B depends only on the probability of the second failure – 0.01, or an average of one occurrence every 100 flights. This becomes a matter of concern if the combination has critical consequences. Because of the increased probability of a multiple failure, hidden-function items are placed in a special category, and all such items that are not subject to other maintenance tasks are scheduled for failure-finding tasks. Although this type of task is intended to discover rather than to prevent, hidden failures, it can be viewed as preventive maintenance because one of its objectives I to reduce exposure to a possible multiple failure.

To illustrate how the consequences of a multiple failure might be evaluated, consider a sequence of failures all of which are evident. If the first failure has safety consequences, there is no need to assess the consequences of a second failure. This first critical failure is the sole concern, and every effort is made to prevent its occurrence. When the first loss of function is not critical, then the consequences of a second loss of function must be investigated. If the combined effect of both failures would jeopardize safety, then this multiple failure must be prevented by correcting the first failure as soon as possible. This may entail an unscheduled landing and will at least require taking the equipment out of service until the condition has been repaired. In this case, therefore, the first failure has operational consequences.

Note in Exhibit 2.2 that multiple-failure consequences need to be assessed only in terms of two successive failure events. If a third loss of function would be critical, the second failure has operational consequences. However, the first failure in such a sequence can be deferred to a convenient time and place; thus it has no operational consequences. Hidden-function failures are assessed on the same basis. If the first failure under consideration is a hidden one, scheduled maintenance is necessary to protect against a multiple failure. The intensity of this maintenance, however is dictated by the consequences of the possible multiple failure. If the combination of this failure with a second failure would be critical, every effort is made to ensure that the hidden function will be available.

What we are doing, in effect, is treating any single failure as the first in a succession of events that could lead to a critical multiple failure. It is this method of assessing failure consequences that permits us to base a maintenance program on the consequences of single failures.

# 2.5. The Failure Process

One reason for identifying unsatisfactory conditions at the potential-failure stage is to prevent the more serious consequences of a functional failure. Another reason, however, is that the removal of individual units on the basis of their condition makes it possible to realize most of the useful life of each unit. To see how this procedure works consider a simple item such as the airplane tire in Exhibit 2.3. Although a tire has other functions, here we are concerned with its retread capability. Hence we have defined a functional failure as the point at which the carcass plies are exposed so that the carcass is no longer suitable for retreading. The remaining tread is thus the tire's *resistance to failure* at any given moment. The *stresses* to which the tire is subjected during each landing reduce this resistance by some predictable amount, and the number of landings is a measure of the total *exposure* to stress. With increasing exposure in service, the failure resistance is gradually reduced until there is a functional failure – visible plies.

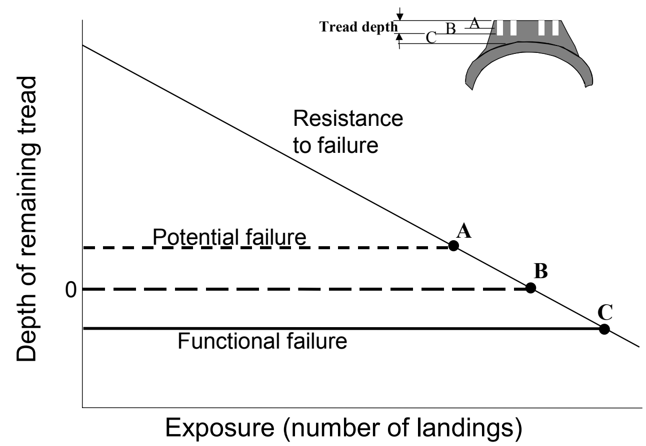



**Exhibit 2-3 Tire tread wear as an illustration of the failure process in a simple item. The potential-failure condition is defined in this case and the tread depth at point A. At point B, when the tire is smooth, it can still be removed as a potential failure, but if wear continues to point C the carcass will no longer be suitable for retreading, and the loss of this function will constitute a functional failure.**

Because the reduction in failure resistance is visible and easily measured, it is usual maintenance practice to define a potential failure as some wear level just short of this failure point. The tires are inspected periodically, usually when the aircraft is out of service, and any tire worn beyond the specified level is replaced. To allow for periodic inspections, the condition we choose as the potential-failure stage must not be too close to the functional-failure condition; that is, there must be a reasonable interval in which to detect the potential failure and take action. Conversely, setting the potential-failure limit too high would mean replacing tires that still had substantial useful life.

Once the optimum potential-failure level has been defined, inspections can be scheduled at intervals based on the expected amount of tread wear over a given number of landings. Exhibit 2.4 shows a smooth tread noticed at inspection 5. At this point the tire is replaced, and if its carcass is sound, it will be retreaded. Retreading restores the original resistance to failure, and a new service cycle begins.

Failure resistance, as we are using the concept here, is somewhat analogous to the structural engineering practice of determining the stresses imposed by an applied load and then adding a safety factor to determine the design strength of a structural member. The difference between the applied load load and the design strength is then the resistance to failure. The same principle extends to servicing and lubrication requirements, for example, where a specified oil quantity or lubrication film represents a resistance to functional failure. Similarly, loose turbine blades are taken as a marked reduction in failure resistance. There is a subtle difference, however, between this latter situation and the tire example. In the case of the tire the decline in failure resistance is visible and the approximate unit of stress (average tread wear per landing) is known. In the case of turbine blades the unit of stress is unknown and the decline in failure resistance is not apparent until the resistance has become quite low.

## A Model of the Failure Process

So far we have discussed a reduction in failure resistance that is evidenced by some visible condition. The more general failure process involves a direct interaction between stress and resistance, as shown in Exhibit 2.5. The measure of exposure may be calendar time, total operating hours, or number of flight or landing cycles, depending on the item. Because the measurable events occur over time, it is common to refer to total exposure as the *age* of an item. Possible measures for the stress scale are even more varied. Stresses may include temperature and atmospheric conditions, vibration, abrasion, peak loads, or some combination of these factors. It is often impossible to separate all the stress factors to which the item is subjected ina a given operating context.

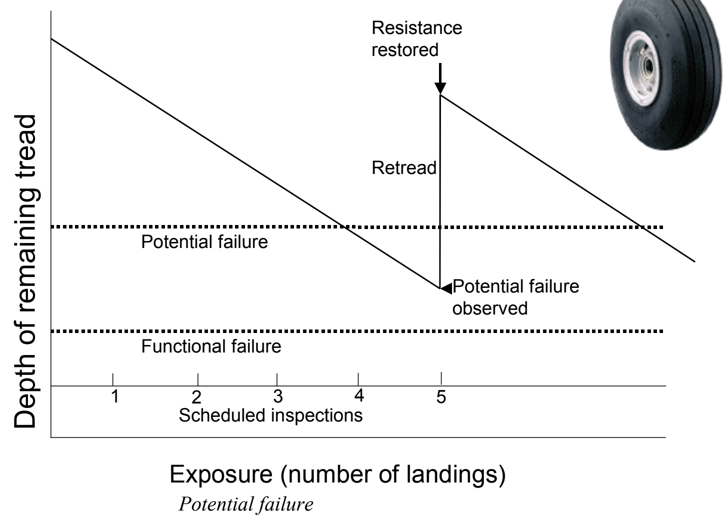



**Exhibit 2-4 The use of potential failures to prevent functional failures. When tread depth reaches the potential-failure stage, the tire is removed and retreaded (recapped) . This process restores the original tread, and hence the original failure resistance, so that the tire never reaches the functional-failure stage.**

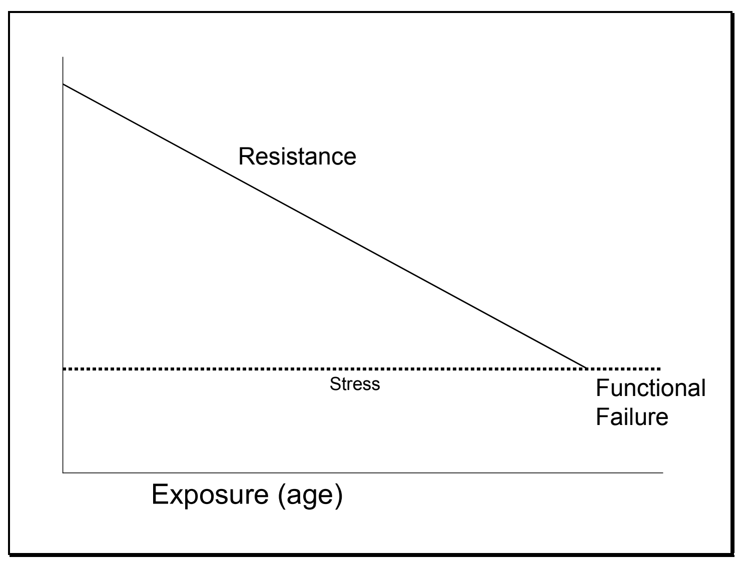



**Exhibit 2-5 Generalized model of the failure process. Resistance to failure is assumed to decline steadily with exposure to stress, measured over time as operating age, flight cycles, and so on. A functional failure occurs when the amount of stress exceeds the remaining failure resistance. In reality both stress and resistance can fluctuate, so that there is no way to predict the exact age at which the failure point will be reached.**

The primary age measure for most aircraft is operating hours, usually "off-to-on" (takeoff to landing) flying hours. Some failure modes, however, are related to the number of ground-air-ground stress cycles, and in these cases age is measured as number of landings or flight cycles. Flight cycles are important, for example, in determining the number of stress cycles experienced by the aircraft structure and landing gear during landing. They are also of concern for powerplants. Engines undergo much more stress during takeoff and climb than during cruise, and an engine that experiences more takeoffs in the same number of operating hours will deteriorate more rapidly.

For this reason all aircraft is monitored in terms of both operating hours and flight cycles, usually on the basis of total flying time and total flight cycles for the entire aircraft. Thus if an engine is installed in a plane that has accumulated 1000 operating hours and is removed at 1543 hours, the engine has aged 543 hours since installation. If that engine was 300 hours old when it was installed, its age at removal is 843 hours.

Some military aircraft are equipped with acceleration recorders which also monitor the number of times the structure is stressed beyond a certain number of G's during operation. The loads can be counted and converted to an equivalent number of flight hours at the plane's design operating profile. Like operating hours or flight cycles, these "spectrum hours" provide a basis for estimating the reduction in resistance to a particular failure mode.

A functional failure occurs when the stress and resistance curves intersect – that is, when the stress exceeds the remaining resistance to failure. Either of these curves may take a variety of different shapes, and the point at which they intersect will vary accordingly (see Exhibit 2-6). Until they do intersect, however, no functional failure occurs. In practice this failure model can be applied only to *simple items* – those subject to only one or a very few failure modes – and to individual failure modes in complex items. The reason for such a limitation becomes apparent if we consider some of the variables in just a single failure mode.

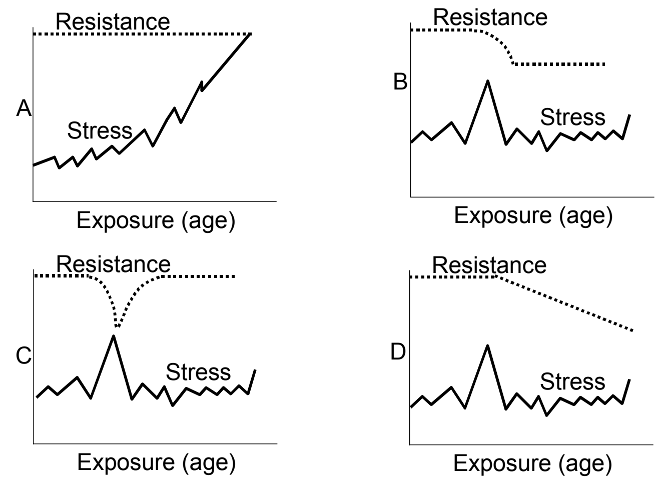



**Exhibit 2-6 Variability of stress, failure resistance, and age at failure. In example A the resistance remains constant over time, but a sudden peak in stress causes failure to occur. In B the stress and resistance curves do not intersect, but the peak in stress has permanently lowered the remaining failure resistance. In C the reduction in failure resistance caused by the peak stress is temporary. In D the peak stress has accelerated the rate at which the remaining resistance will decline with age.**

## The Age at Failure

Our examples thus far imply that any given component, such as a tire, has a well-defined initial resistance to failure and that the rate of decline in this resistance is more or less known and predictable. It follows that the time of failure should be predictable. In reality, however, even nominally identical parts will vary both in their initial failure resistance and in the rate at which this resistance declines with age. Suppose we have two nominally identical units of a simple item, or perhaps two identical parts in a complex item. To simplify matters further, let us say they are exposed to only one type of stress and are subject to only one type of failure. On this basis we might expect their failure resistance to decline at the same rate and therefore expect both units to fail at approximately the same age. However, all manufactured components are produced to specified tolerance limits, which results in a variation in initial resistance. These variations are insignificant from a performance standpoint, but the result is that two units will begin their service lives with slightly different capacities to resist stress, and these capacities may decline at somewhat different rates.

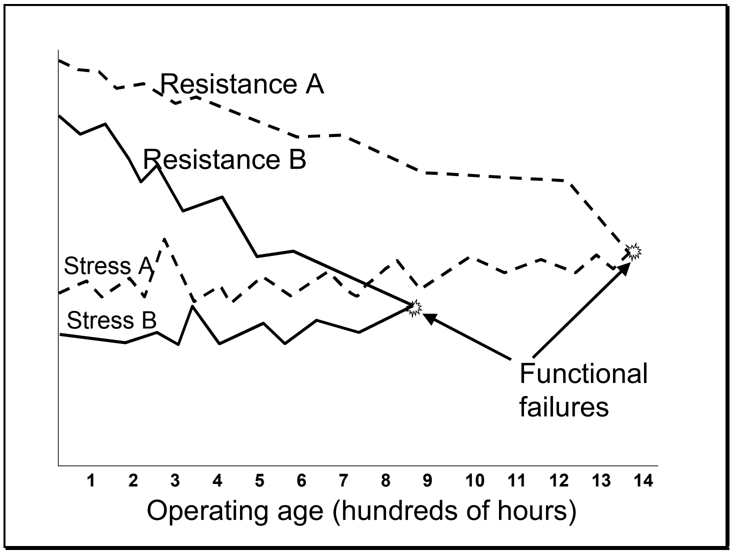



**Exhibit 2-7 The difference in failure age of two nominally identical parts subjected to similar stress patterns. The two units begin their service lives with comparable initial resistance to failure, but unit B is exposed to greater stress peaks and reacts to them consistently. Unit A behaves less accountably; its resistance is unaffected by stress peaks at 600 and 1120 hours but declines rapidly between 1200 and 1300 hours. As a result, one unit fails at 850 hours and the other at 1300 hours.**

Stress also varies form moment to moment during operation, sometimes quite abruptly. For example, the different loads exerted on an aircraft structure by atmospheric turbulence can vary markedly even in the course of a short flight. Moreover, the effect of these stresses will be further influenced by the condition of the item at the particular moment it is stressed. As a result, each component will encounter a different stress pattern even if both are operating as part of the same system. Although the variations in either stress or resistance may be slight, their interaction can make a substantial difference in the length of time a given component will operate before failing. Units A and B in Exhibit 2-7 are relatively alike in their initial resistance, and the stress placed on each does not vary much from the constant stress assumed in the generalized model. However, the time of failure is the point at which the stress and resistance curves intersect; thus unit B failed at an age of 850 hours, whereas unit A survived until 1300 hours.

Despite the variation in the failure ages of individual units, if a large number of nominally identical units are considered, their failures will tend to concentrate about some average age. For purposes of reliability analysis, however, ti is necessary to employ statistical techniques that describe the variation about this average age.

It is also important to recognize that the actual age at failure depends on the stress the unit experiences. The wing-to-fuselage joints of an aircraft will stand up to normal air turbulence for a very long time, but perhaps not to the loads encountered during a tornado. The fan blades of a turbine engine can withstand thousands of hours of normal stress, but may not be able to tolerate the ingestion of a single goose. In nearly all cases random stress peaks markedly above the average level will lower the failure resistance. This reduction may be permanent, as when damage to several structural members lowers the failure resistance of a wing, or resistance may be affected only at the time the stress exceeds a certain level. In some cases resistance may change with each variation in stress, as with metal fatigue. From th standpoint of preventive maintenance, however, the important factor is not a prediction of when an item is likely to fail, but whether or not the reduction in failure resistance can be identified by some physical evidence that permits us to recognize an imminent failure.

Many functional failures are evident at the time they occur, and in these cases the exact age at failure is known. Unless a failure is evident to the operating crew, however, it is impossible to determine precisely when it occurred. A potential failure detected by mechanics is known to have occurred some time between the last inspection and the inspection at which it is observed. Similarly, although there is some exact age at which a hidden function fails, the only age we can pinpoint is the time at which the failure is discovered. For this reason the *age at failure* is defined, by convention, as the ate at which a failure is observed and reported.

## 2.6. Failure in Complex Items

A *complex item* is one that is subject to many different failure modes. As a result, the failure processes may involve a dozen different stress and resistance considerations and a correspondingly tangled graphic representation. However, each of these considerations pertains to a single *failure mode* – some particular type of manner of failure. For instance, a bearing in a generator may wear; this causes the unit to vibrate, and ultimately the bearing will seize. At this point the generator will suffer a functional failure, since it can no longer rotate and produce electric power. Generators can also fail for other reasons, but the failure mode in this case is bearing seizure.

Of course, the bearing itself is also subject to more than one failure mode. It may wear as a result of abrasion or crack as a result of excessive heat. From the standpoint of the generator both conditions lead to the same failure, bearing seizure. However, the maintenance analysis must know the physical circumstances leading to a particular failure in order to define an identifiable potential-failure condition. The manufacturer also needs to know that the bearing is prone to failure and that a modification is needed to improve the reliability of the generator. Such a design modification is obviously desirable if one particular failure mode is responsible for a significant proportion of all the failures of the item. Such failure modes are called *dominant failure modes*.

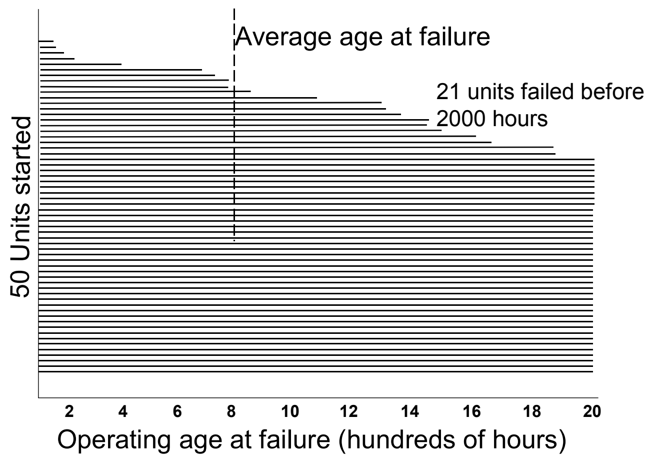



**Exhibit 2-8 Experience with 50 newly installed Pratt & Whitney JT8D-7 engines of the first 2000 operating hours. The 21 units that failed before 2000 hours flew a total of 18,076 hours, so the total operating time for all 50 engines was 18,076 hours plus 58,000 or 76,076 hours. The mean time between failures was therefore 76,076/21, or 3,622 hours. The average age of the failed engines, however, was only 861 hours (United Airlines)**

As with failures in simple items, the failure ages for a single failure mode tend to concentrate about an average age for that mode. However the average ages for all the different modes will be distributed along the exposure axis. Consequently, unless there is a dominant failure mode, the overall failure ages in complex items are usually widely dispersed and are unrelated to a specific operating age. This is a unique characteristic of complex items. A typical example is illustrated in Exhibit 2-8. In a sample of 50 newly installed Pratt & Whitney JT8D-7 engines, 29 survived beyond 2,000 operating hours. The disparate failure ages of the 21 units that failed, however, do not show any concentration about the average age of 861 hours.

Nevertheless, even in complex items, no matter how numerous the failure modes may be, the basic failure process reduced to the same factor – the interaction between stress and resistance to failure. Whether failures involve reduced resistance, random stress peaks or any combination of the two, it is this interaction that brings an item to the failure point. This aspect of the failure process was summed up in a 1960 United Airlines report:[1]

> The airplane has a whole, its basic structure, its systems, and the various items in it are operated in an environment which causes stresses to be imposed upon them. The magnitudes, the durations and the frequencies with which specific stresses are imposed are all very variable. In many cases, the real spectrum of environmentally produced stresses is not known. The ability to withstand stress is also variable. It differs from piece to piece of new nominally identical equipment due to material differences, variations in the manufacturing processes, etc. The ability to withstand stress may also vary with the age of a piece of equipment.
>
> It is implied that an instance of environmental stress that exceeds the failure resistance of an item at a particular time constitutes failure of that item at that time.

## 2.7. Quantitative Descriptions of Failure

Any unanticipated critical failure prompts an immediate response to prevent repetitions. In other cases, however, it is necessary to know how frequently an item is likely to fail in order to plan for reliable operation. There are several common reliability indexes based on the failure history of an item. Methods for deriving certain of these measures are discussed in detail in Appendix C, but it is helpful at this point to know what each measure actually represents.

### Failure Rate

The failure rate is the total number of failures divided by some measure of operational exposure. In most cases the failure rate is expressed as failures per 1,000 operating hours. This if six failures have occurred over a period of 9000 hours, the failure rate is ordinarily expressed as 0.667. Because measures other than operating hours are also used (flight cycles, calendar time, etc), it is important to know the units of measure in comparing failure-rate data.

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[1] F. S. Nowlan, A Comparison of the Potential Effectiveness of Numerical Regulatory Codes in the Fields of Overhaul Periodicity, Airplane Strength, and Airplane Performance, United Airlines Report POA-32, April 14, 1960. These remarks paraphrase a report prepared by D.J. Davis of the Rand Corporation in 1950, which offered intensive analysis of failure data. For an excellent detailed discussion of the physical processes present in the failure mechanism, see Robert P. Haviland, *Reliability and Long Life Design*, Van Nostrand Company, Inc., New York, 1964.

The failure rate is an especially valuable index for new equipment, since it shows whether the failure experience of an item is representative of the whole state of the art. It is also useful in assessing the economic desirability of product improvement. Early product-improvement decisions are based on the performance of units that have been exposed to fairly short individual periods of time in service, and this performance is adequately measured by the failure rate.

## Mean Time Between Failures

The mean time between failures, another widely used reliability index, is the reciprocal of the failure rate. Thus with six failures in 9000 operating hours, the mean time between failures would be 9000/6, or 1500 hours. This measure has the same uses as the failure rate. Note that mean time between failures is not necessarily the same as the average age at failure. In Exhibit 2-8, for example, the average age of the failed engines was 861 hours, whereas the mean time between failures was 3622 hours.[1]

## Probability of Survival

With more extended operating experience it becomes possible to determine the *age-reliability characteristics* of the item under study – the relationship between its operating age and its probability of failure. At this stage we can plot a survival curve, showing the probability of survival without failure as a function of operating age. This curve relates directly to the generally accepted definition of reliability:

**Reliability is the probability that an item will survive to a specified operating age, under specified operating conditions, without failure.**

For this reason the survival curve is commonly referred to as the reliability function.

Exhibit 2-9 shows a typical survival curve for an aircraft turbine engine. The curve represents the percentage of installed engines that survived to the time shown on the horizontal axis, and this is usually the best estimate of the probability that any individual engine will survive to that time without failure.

A survival curve is more useful than a simple statement of the failure rate, since it can be used to predict the percentage of units that will survive to some given age. If the engines in Exhibit 2-9 were scheduled for removal at 1000 hours, for example, 69 percent of them would survive to that age limit, whereas 31 percent could be expected to fail before then. The area under the survival curve is equal to the average life of the item under consideration – the case of this engine it is 1811 hours. Now suppose a hard time age limit of 1000 hours were applied. Then the average life is only 838 hours.

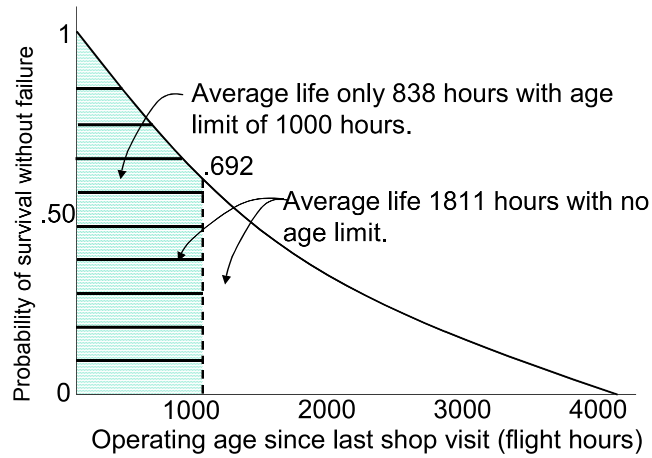


**Exhibit 2-9 Survival curve for the Pratt & Whitney JT8D-7 engine of the Boeing 737, based on 58,432 total operating hours from May 1 to July 31, 1974. The average life is computed by partitioning along the vertical axis to form small incremental areas whose sum approximates the area under the curve. With an age limit of 1000 hours, only the shaded area enters into this computation, since no engines can contribute to the survival curve beyond this limit, despite the fact that they would have survived had they been left in service. (United Airlines)**

The average lives that would be realized with other age limits in this case are as follows:

| Age limit | Average realized life |
|---|---|
| 1000 hours | 838 |
| 2000 hours | 1393 |
| 3000 hours | 1685 |
| No limit | 1811 |

## Probability Density of Failure

The probability that an engine in Exhibit 2-9 will survive to 1000 hours is .692 and the probability that it will survive to 1200 hours is .639. The difference between these probabilities, .053, is the probability of a failure during this 200-hour interval. In other words, an average of 5.3 out of every 100 engines can be expected to fail during the interval from 1200 to 1400 hours. This measure is called the *probability density* of failure.

Exhibit 2-10 shows the probability densities for each 200-hour age interval, plotted from the probabilities of survival at each age. A decreasing percentage of the engines will fail in each successive age interval because a decreasing percentage of engines survives to enter that interval.

[1] For a further discussion of this distinction, see Appendix C.

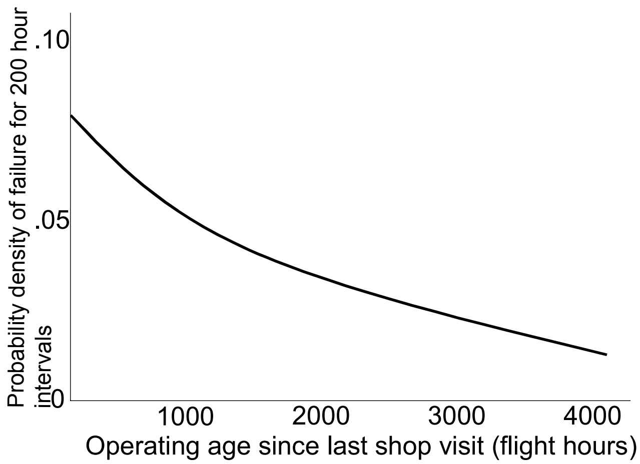


**Exhibit 2-10 Probability density of failure for the Pratt & Whitney JT8D-7 engine of the Boeing 737. Density values are plotted at the midpoint of each 200-hour interval and represent the probability that a failure will occur during this interval. (United Airlines)**

## Conditional Probability of Failure

The most useful measure of the age-reliability relationship is the probability that an item entering a given age interval will fail during that interval. This measure is usually called the *conditional probability of failure* – the probably of failure given the condition that the item enters that age interval. Sometimes it is also referred to as the hazard rate or the local failure rate.[1] The conditional probability is related to both the probability of survival and the probability density. For example, an engine beginning at zero time has a probability of .692 or reaching the age of 1000 hours; once it has reached this age, the probability density of failure in the next 200-hour interval is .053. Each engine that survives to 1000 hours therefore has a conditional probability of failure between 1000 and 1200 hours of .053/.692 = .077.[2] The complete conditional-probability curve for this engine is shown in Exhibit 2-11.

If the conditional probability of failure increases with age, we say that the item shows *wearout characteristics* and immediately wonder if an age limit would be effective in reducing the overall failure rate. (Note that the term *wearout* in this context describes the adverse effect of age on reliability; it does not necessarily imply any evident physical change in individual units.) With an age limit of 1000 hours the average realized life of the engine in question is 838 hours. The probability that an engine will survive to this age is .692, so the failure rate with this limit would be the probability of failure (.308) divided by the average life, or a rate of 0.37 failures per 1000 hours.[3]

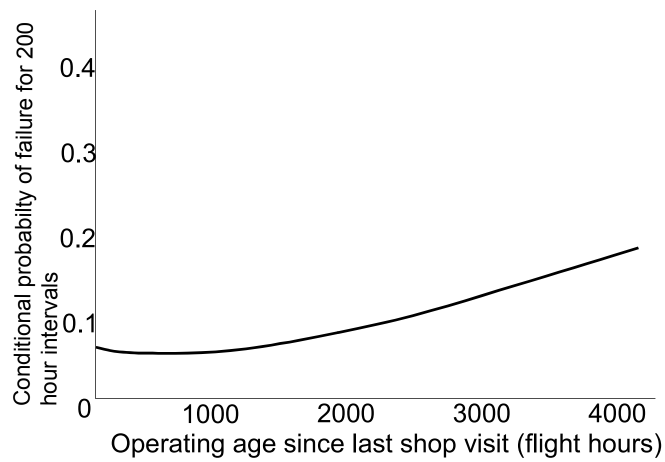


**Exhibit 2-11 Conditional probability of failure for the Pratt & Whitney JT8D-7 enigne of the Boeing 737. Probability values are plotted at the midpoint of each 200-hour interval and represent the average probability that an engine that survives to enter the interval will fail during this interval (United Airlines)**

Exhibit 2-12 shows this failure rate plotted as a function of various age limits. If the age limit is raised from 1000 to 2000 hours, the overall failure rate is .42, an increase of only 13.5 percent due to the second thousand hours of operations. However, the conditional probability of failure in the 200-hour interval just before each of these age limits goes up from .075 to .114, an increase of 52%. The *rate of increase* in the in the failure rate falls off with age because it depends on the conditional probability for each interval weighted by the probability of survival to that interval – and there is a continual reduction in the probability of survival.

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[1] In some literature these terms are defined in a narrower sense to mean the value obtained by computing the limit of the ratio as the age interval goes to zero.

[2] Explanation: Let A be the probability of surviving to 1000 hrs and B be the probability of surviving the next 200 hr interval. Then by definition the conditional probability of B given A is $P(B \mid A) = B \cap A / A$. But $B \cap A$ is just B since B includes A.

[3] Remembering that he failure rate is the total number of failures divided by some measure of operational exposure, 308 out of 1000 engines will fail before the 1000 hour cutoff. 1000 engines will have a total exposure of 838000 hours. Therefore the failure rate is 308/838000 = .00037 failures / hour or .37 failures per 1000 hours

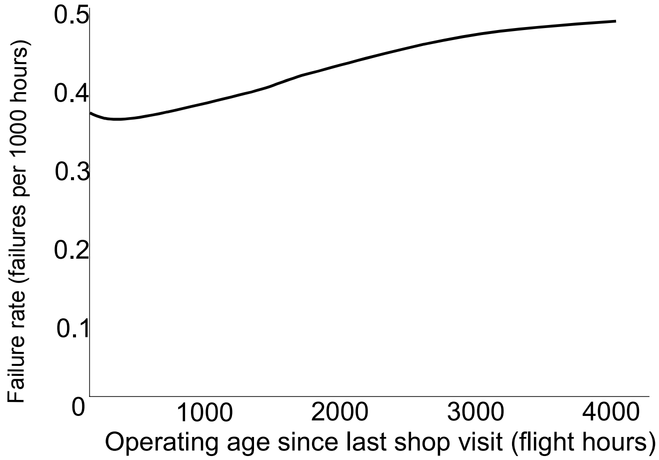


**Exhibit 2-12 [2-12] Relationship between the failure rate and various age limits for ht Pratt & Whitney JT8D-7 engine of the Boeing 737. (United Airlines)**

What this means is that the effectiveness of an age limit in controlling failure rates depends not only on large increases in conditional probability at higher ages, but also on a high probability of survival to those ages. It follows that the desirability of an age limit on any item cannot be investigated until there are sufficient operating data to construct the survival and conditional-probability curves.

# 2.8. Age-Reliability Characteristics

At one time it was believed that all equipment would show wearout characteristics, and during the years when equipment overhaul times were being rapidly extended, United Airlines developed numerous conditional-probability curves for aircraft components to ensure that the higher overhaul times were not reducing overall reliability. It was found that the conditional-probability curves fell into six basic patterns shown in Exhibit 2.13. Pattern A is often referred to in reliability literature as the *bathtub curve*. This type of curve has 3 identifiable regions:

- An infant-mortality region, the period immediately after manufacture or overhaul in which there is a relatively high probability of failure
- A region of constant and relatively low failure probability
- A *wearout region, in which the probability of failure* begins to increase rapidly with age.

If the failure pattern of an item does in fact fit this curve, we are justified in concluding that the overall failure rate will be reduced if some action is taken just before this item enters the wearout zone. In these cases allowing the item to age well into the wearout region would cause an appreciable increase in the failure rate. Note, however, that such action will not have much effect on the overall rate unless there is a high probability that the item will survive to the age at which wearout appears.

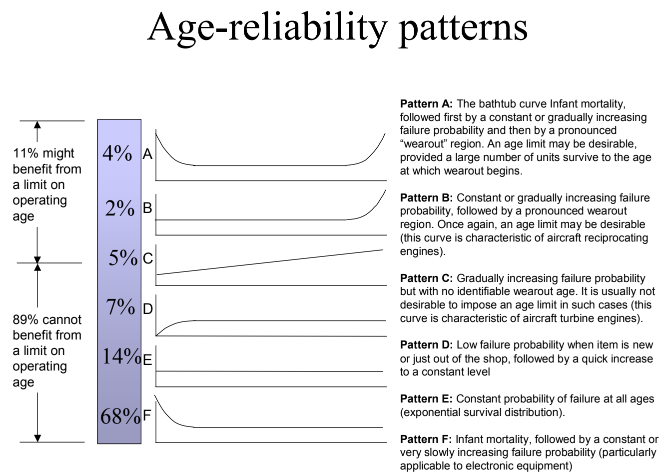


**Exhibit 2-13 Age-reliability patterns. In each case the vertical axis represents the conditional probability of failure and the horizontal axis represents the operating age since manufacture, overhaul, or repair. These six curves are derived from reliability analysis conducted over a number of years, during which all items analyzed were found to be characterized by one or another of the age-reliability relationships shown. The percentages indicate the percentage of items studied that fell into each of the basic patterns (United Airlines)**

The presence of a well-defined wearout region is far from universal; indeed, of the six curves in Exhibit 2-13, only A and B show wearout characteristics. It happens, however, that these two curves are associated with a great many single-celled or simple item s – in the case of aircraft, such items as tires, reciprocating-engine cylinders, brake pads, turbine-engine compressor blades, and all parts of the airplane structure.

The relative frequency of each type of conditional-probability curve proved especially interesting. Some 89 percent of the items analyzed had no wearout zone; therefore their performance could not be improved by the imposition of an age limit. In fact, after a certain age the conditional probability of failure continued on at a constant rate (curves D, E, and F). Another 5% had no well-defined wearout zone (Curve C) but did become steadily more likely to fail as age increased. For a very few of these items an age limit might prove useful, provided that it was cost effective.

Only 6%of the items studied showed pronounced wearout characteristics (curves A and B). Although an age limit would be applicable to these items, as we have seen, its effectiveness depends on a high probability that the item will survive to that age. However, the conditional-probability curves make it possible to identify those items that might benefit from such a limit, and the question of effectiveness can then be investigated. Although it is often assumed that the bathtub curve is representative of most items, not that just 4% of the items fell into this pattern (curve A). Moreover, most complex items had conditional-probability curves represented by curves C to F – that is, they showed no concentration of failures directly related to operating age.

The basic difference between the failure patterns of complex and simple items has important implications for maintenance. Usually the conditional-probability curve for a complex item will show some infant mortality; often the probability of failure rate after installation is fairly high. Usually, also, the conditional-probability curve shows no marked point of increase with increasing age; the failure probability may increase gradually or remain constant, but there is no age that can be identified as the beginning of a wearout zone. For this reason, unless there is a dominant failure mode, an age limit does little or nothing to improve the overall reliability of a complex item. In fact, in many cases scheduled overhaul actually *increases* the overall failure rate by introducing a high infant-mortality rate in an otherwise stable system.

In contrast, single-celled and simple items frequently do show a direct relationship between reliability and increasing age. This is particularly true of parts subject to metal fatigue or mechanical wear and items designed as consumables. In this case an age limit based on some maximum operating age or number of stress cycles may be highly effective in improving the overall reliability of a complex item. Such limits in fact play a major role in controlling critical-failure modes, since they can be imposed on the part or component in which a given type of failure originates.

It is apparent from our discussion thus far that most statements about the "life" of equipment tell us little about its age-reliability characteristics. For example, the statement that an aircraft engine has a life of 2000 operating hours might mean any of the following:

- No engines fail before reaching 2000 hours
- No critical engine failures occur before 2000 hours
- Half the engines fail before 2000 hours
- The average age of failed engines is 2000 hours
- The conditional probability of failure is constant below 2000 hours
- Some part in the engine has a life limit of 2000 hours
- N% of the engines fail before 2000 hours

The definition of reliability is the probability that an item will survive a given operating period, under specified operating conditions, without failure. In discussions of reliability, therefore, it is insufficient to state an operating period alone as the "life" of an item. This statement has no meaning unless a probability of survival is associated with it.

It should also be apparent by now why the failur rate plays a relatively unimportant role in maintenance programs: it is too simple a measure. Although the frequency of failures is useful in making cost decisions it tells us nothing about what tasks are appropriate or the consequences that dictate their objective. The effectiveness of a particular maintenance solution can be evaluated only in terms of the safety or economic consequences it is intended to prevent. By the same token, a maintenance task must be applicable to the item in question in order to have any effect at all. Hence we must now consider the possible forms of preventive maintenance and see how an understanding of the failure process and the age-reliability characteristics of an item permit us to generate maintenance tasks on the basis of explicit criteria.

# 3. Chapter Three - The four basic maintenance tasks

RCM programs consist of specific tasks selected on the basis of actual reliability characteristics of the equipment they are designed to protect. All of these tasks can be described in terms of four basic forms of preventive maintenance, each of which is applicable under a unique set of circumstances:

- Scheduled inspection of an item at regular intervals to find any potential failures
- Scheduled rework of an item at or before some specified age limit
- Scheduled discard of an item (or one of its parts) at or before some specified life limit
- Scheduled inspection of a hidden-function item to find any functional failures

The first types of tasks are directed at preventing single failures and the fourth at preventing multiple failures. Inspection tasks can usually be performed without removing the item from its installed position whereas rework and discard tasks generally require the item be removed from the equipment and sent to a major maintenance base

The development of a scheduled maintenance program consists of determining which of four tasks if any are applicable and effective for a given item. Applicability depends on the failure characteristics of the item. Thus an inspection for potential failures can be applicable only if the item has characteristics that make it possible to define a potential failure condition. Similarly an age limit task will be applicable only if the failures at which the task is directed are related to age. Effectiveness is a measure of the results of the task; the task objective, however, depends on the failure consequences involved. A proposed task might appear useful if it promises to reduce the overall failure rate but it could not be considered effective if the purpose in applying it was to avoid functional failures altogether.

For inspection tasks the distinction between applicability and effectiveness is usually obvious: the item either does or does not have characteristics that make such a task applicable for age-limit tasks, however, the distinction is sometimes blurred by the intuitive belief that the task is always applicable and therefore must also be effective. In reality imposing an age limit on an item does not in itself guarantee that its failure rate will be reduced. The issue in this case is not whether the task can be done but whether doing it will in fact improve reliability.

## 3.1. scheduled on-condition tasks

Scheduled inspections to detect potential failures are commonly termed *on-condition tasks* since they call for the removal or repair of individual units of an item "on the condition" that they do not meet the required standard. Such tasks are **directed at specific failure modes** and are based on the feasibility of defining some **identifiable physical evidence** of a reduced resistance to the type of failure in question. Each unit is inspected at regular intervals and remains in service until its failure resistance falls below a defined level – that is until a potential failure is discovered. Since on-condition tasks discriminate between units that require corrective maintenance to forestall the functional failure and those units that will probably survive to the next inspection, they permit all units of the item to **realize most of their useful lives**.

This type of task is applicable to tires, brakes, many parts of an aircraft powerplant, and much of its structure. Many routine servicing tasks, such as checking oil quantity and tire pressure, are on-condition tasks. The applicability of an on-condition task depends to some extent on both maintenance technology and the design of the equipment. For example, borescope and radiostope techniques have been developed for inspecting turbine engines, but these techniques are of value chiefly because **the engines have been designed to facilitate their use**. If on-condition tasks were universally applicable, all failure possibilities could be dealt with in this way unfortunately they are many types of failures in which the failure mode is <u>not clearly understood</u> or is <u>unpredictable</u> or <u>gives insufficient warning</u> for preventive measures to be effective. And there are three criteria that must be net for an on-condition task to be applicable:

- It must be possible to detect reduced failure resistance for a specific failure mode.
- It must be possible to define a potential-failure condition that can be detected by an explicit task.
- There must be a reasonably consistent age interval between the time of potential failure and the time of functional failure.

As an example, suppose a visible crack is used as a measure of metal fatigue, as shown in Exhibit 3-1. Such an item is most failure resistant when it is new (point A). Resistance drops steadily with increasing age and is already somewhat reduced by the time a crack appears (point B). Therefore it is possible to monitor the growth of the crack and define a potential-failure point C far enough in advance to permit removal of the item before a functional failure occurs (point D). Once a crack has appeared, the failure resistance drops more rapidly; hence the <u>rate of crack growth</u> in this item must be known in order to establish an inspection interval $\Delta T$ that will effectively control this failure mode.

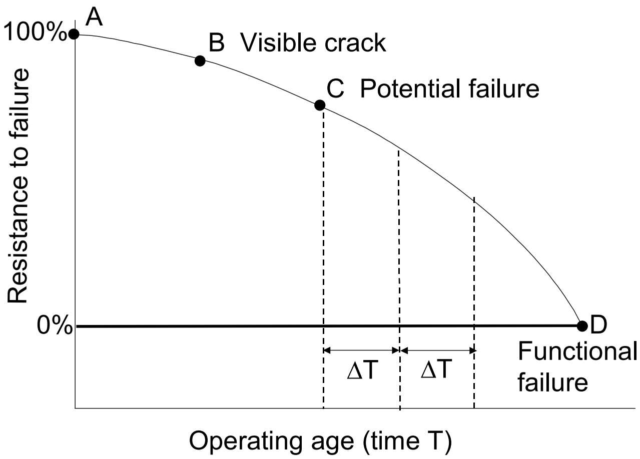


**Exhibit 3-1 Determining the interval for an on-condition inspection of an item subject to metal fatigue. once the rate of decline in failure resistance has been determined, and inspection interval ΔT is established, that provides ample opportunity to detect a potential failure before a functional failure can occur.**

The data for the entire population of this item would define a range of failure ages rather than 1 specific age. Hence both the defined potential failure and the frequency of inspections depends on the objective of the task. If a functional failure would have safety consequences, then the objective is to prevent all such failures. In this case and on-condition task may be applicable, <u>but it would be considered effective only</u> if it minimized the likelihood of a critical failure. If the failure does not involve safety, effectiveness is measured in economic terms – that is, the task is effective only if it is cost-effective. In the case of operational consequences this means that the cost of finding and correcting potential failures must be less than the combined cost of the operational consequences plus the cost of repairing the field units. It follows from this that when an on-condition task is effective in reducing the failure rate, and hence the frequency of operational consequences, it is usually also cost-effective, since the cost of inspection is relatively low.

**Exhibit 3-2 Examples of on-condition inspection tasks as specified for maintenance mechanics, (United Airlines)**

1. **Low-pressure turbine section**
   check for failed air seal tie bolts.

   Note: Airseal tie bolts between fourth- and fifth-stage and six-stage rotors (last three stages) are failing. These broken bolts are trapped in the air seal between the rotors and cause a rattling sound as they role when the turbine is slowly rotated.

   A. Have fan rotated 180 degrees very slowly. Repeat 180-degree rotation as often as necessary.
   B. Listen at tailcone for rattling sound costs by broken bolts rolling around (do not confuse with clanking sound of blades). Attempt to determine the number of broken bolts by counting the rattles.
   C. Failed-bolt limits. Three or fewer broken bolts: and gin may remain in-service. Four or more broken bolts: engine must be borescoped within 75 hours.
   D. Supply the following information:
      a. Plane number, engine position, engine time since last shop visit
      b. Number of broken bolts estimated from "listening" check
   E. Send DIS*P5106 SH and getting above information.

2. **First-stage nozzle guide vanes**
   Borescope inspection (Boeing 747 JT9D power plant).
   A. perform initial borescope inspection of first-stage nozzle guide vanes and 600 hours. Perform repeat inspections at 600, 200,75, or 30 hours, depending on conditions found.
   B. Distress limits as giving in MM/OV 72-00-99:
      i. Trailing-edge cracks: maximum of 5 cracks per vane extending to window (slot) leading edge. If distress exceeds this limit, remove engine; otherwise, repeat inspection in 600 hours.
      ii. Trailing-edge erosion: If burning-surface burn-through does not exceed one-half by one-half inch, repeat inspection in 600 hours; if burn-through does not exceed three quarters by three-quarters inch, repeat inspection in 200 hours; if burn-through does not exceed one by one inch, repeat inspection in 75 hours. If surface burn-through is up to 5/8 inch from leading edge, repeat inspection in 30 hours. **Note: 30-hour limit is a maximum fly-back limit, to be used one time only.**

3. **Fire-detector installations**
   Intensified inspection of installations, leads, and

connections.

A. check for minimum clearance of 1/16 inch between sensing elements and engine, as well as between various engine components. Provide necessary clearance.
B. Check for any signs of wear.
C. Wear limits:
Acceptable: flat spots not exceeding 0.035 in. in width; Any length acceptable
Not acceptable: flat spots exceeding 0.035 inch in width 4 worn spots exposing inner conductor or composition material between inner conductor and motor sensing-element shell.
Note: nominal diameter is 0.070 in.

4. **Brake assembly, main landing gear**
Check brake-lining wear at each assembly, using small-scale.
A. Set parking brakes.
B. Measure wear-indicator pin extension at both indicator pins.
C. Wear limits:
If either team is < 0.25 inch in length, replace brake assembly.
Note: replacement may be deferred, with approval from SFOLM, provided wear-indicator pin measures longer than 13/64 inch. I f wear-indicator pin length is 13/64 inch or less, immediate replacement is required.

5. **Pneumatic drive units, leading edge flap**
check will level and service as required.
Note: dry units are numbered from a look forward to inboard, one to four, left and right-wing.
A. Check will level in proper sight glass. It will level is visible in sight glass. No service is required.
B. If oil is not visible, slowly and loyal (Oil 2380) through fill port until sight glass is filled. Use 53769 oil dispenser.
C. Allow excess oil to drain out before installing fill plug.

In the third example potential failure may be either lack of adequate clearance or visible wear on fire-detector sensing elements and leads. The fourth and fifth example will involve less judgment in the inspection process. Exact limits are given for the brake wear indicator in the first case and oil level in the pneumatic unit in the second case. Both will require a clear-cut response on the part of the inspecting mechanic.

Whenever an on-condition task is applicable, it is the most desirable type of preventive maintenance. Not only does it avoid the premature removal of units that are still in satisfactory condition, but the cost of correcting potential failures is often far less than the cost of correcting functional failures, especially those that cause extensive secondary damage. For this reason on condition inspection tasks are steadily replacing older practices for the maintenance of airline equipment.

## 3.2. scheduled rework tasks

Many single-celled and simple items display wear out characteristics – that is, the probability of their failure becomes significantly greater after a certain operating age. When an item does have an identifiable wearout age, its overall failure rate can sometimes be reduced by imposing a hard-time limit on all units to prevent operation at the ages of higher failure frequency. If the item is such that its original failure resistance can be restored by rework or remanufacture, the necessary rework task may be scheduled at appropriate intervals.[1] For example, the airplane tire in Exhibit 2.4 could have been scheduled for rework after a specified number of landings, since retreading restores the original failure resistance. However, this would have resulted in a retreading of all tires at the specified age limit, whether they needed it or not, and would not have prevented functional failures in those tires that failed earlier than anticipated.

Where no potential-failure condition can be defined on-condition inspection of individual units is not feasible. In such cases be rework task may be applicable, either for a simple item or to control a specific failure mode in a complex item. As we saw in chapter two failures in complex items are the results of many different failure modes, each of which may occur at a different average age. Consequently the overall failure rate of such items remains relatively constant; in some cases reliability decreases gradually with age, but there is no particular age that can be identified as a wearout zone. Thus, unless there's a dominant failure mode which is eliminated in the course of rework, complete rework of a complex item will have little or no effect on the overall failure rate.

A rework task can be considered applicable to an item only if the following criteria are met:

- there must be an identifiable age at which the item shows a rapid increase in the conditional probability of failure.
- A large proportion of the units must survive to that age.
- It must be possible to restore the original failure resistance of the item by reworking it.

[1] This term *overhaul* has the connotation that the unit is completely disassembled and remanufactured part by part to restore it as nearly as possible to a "like-new" physical condition. Rework refers to a set of maintenance operations considered sufficient to restore the unit's original resistance to failure. Thus rework for specific items may range from replacement of the single part to complete remanufacture.

Because the information required to develop survival and conditional probability of an item is not available when equipment first goes into service, scheduled rework tasks rarely appear in a prior to service maintenance program (only seven components were assigned to scheduled rework in the initial program developed for the Douglas DC-10). Often, however, those items subject to very expensive failures are put into an age-exploration program to find out as soon as possible whether they would benefit from scheduled rework.

Even when scheduled reworked is applicable to an item, very often it does not meet the conditions for effectiveness. A reduction in the number of expected failures, for example, would not be sufficient in the case of safety consequences, and in the case of economic consequences that task must be cost-effective. Moreover, since an age limit lowers the average realized age of an item, it always increases the total number of units sent to the shop for rework.

As an example, consider the effect scheduled rework what have on the turbine engine discussed in section 2.7. With no age limit, the failure of these engines is 0.552 failures per 1000 hours. Thus over an operating period of one million hours an average of 552.2 field units (1000 000/1811) are sent to the shop for repair (see Exhibit 3.3). A rework age limit of 2000 hours will reduce the failure rate to 0.416; however, it will also reduce the average realized age from 1811 hours to 1393 hours. Since 42 percent of the units survive to 2000 hours, over the same operating period, an average of 717.9 would be sent to the shop – the 416.3 units that failed plus the additional 301.6 scheduled removals. In other words, there would be about 135 fewer failures, but 166 more engines that required rework. On this basis scheduled rework at 2000-hour intervals would not be cost-effective unless the rework cost for scheduled removals were substantially lower than the cost of repairing failures (in this case the rework costs would have to be less than 135.9/301.6, or 45.1 percent, of the repair costs).

| Age limits (hours) | Failure rate (per 1000 hours) | Percentage of units surviving to age limit | Average realized engine age (hours) | Shop workload per 1,000,000 engine hours | | |
|---|---|---|---|---|---|---|
| | | | | Failed engines | Scheduled removals | Total workload |
| 1000 | 0.3681 | 69.2 | 838 | 368.1 | 825.2 | 1193.3 |
| 2000 | 0.4163 | 42.0 | 1393 | 416.3 | 301.6 | 717.9 |
| 3000 | 0.4871 | 17.9 | 1685 | 487.1 | 106.4 | 593.5 |
| None | 0.5522 | 0 | 1811 | 552.2 | -- | 552.2 |

**Exhibit 3-3 Effect of several reworking age limits on shop workload. The total number of engines sent to the shop is computed by dividing the total hours of engine operation by the average realized age for each age limit. The number of schedule removals is then the percentage of this total that survives to the age limit in question.**

Of course, the direct cost of rework is not the only economic factor to be taken into account. If the failure is one that has operational consequences, the reduction in the number of failures may more than offset the additional cost of rework. Determining the economic desirability of a proposed reworking age limit will be discussed in greater detail in the next chapter. In general, however, the effect of at least four possible reworking intervals must be analyzed before an optimum limit can be determined – if indeed one does exist. In most cases our rework task will not prove cost-effective unless the item has an unusually expensive failure mode or the cost of functional failure includes economic losses other than the direct cost of repair.

# 3.3. Schedule discard tasks

The scheduled rework of items at a specified age limit is one type of hard-time task; the other is scheduled discard of items or certain of their parts at some specified operating age. Such tasks are frequently termed *life-limit* tasks. Life limits may be established to avoid critical failures, in which case they are called *safe-life* limits, or they may be established because they are cost-effective in preventing noncritical failures, in which case they are called *economic-life limits*.

## Safe-life limits

A safe-life limit is imposed on an item only when safety is involved and there is no observable condition that can be defined as a potential failure. In this case the item is removed at or before the specified maximum age and is either discarded or disassembled for discard of a time-expired part. This practice is most useful for simple items or individual parts of complex items, such as pyrotechnic devices in ejection seats, which have a limited shelf life, and turbine-engine disksys or nonredundant structural members, which are subject to metal fatigue.

The safe-life limit itself is usually established by the equipment manufacturer on the basis of developmental testing. A component whose failure would be critical is designed, to begin with, to have a very long life. It is then tested in a simulated operating environment to determine what average life has actually been achieved, and a conservatively safe fraction of this average life is used as the safe-life limit.

Safe-life items are nearly always single-celled parts, and their ages at failure are grouped fairly closely about the average. However, the correlation between a test environment and the actual operating environment is never perfect. Moreover, because testing a long-lived part to failure is both time consuming and expensive, the volume of test data is often too small to permit us to draw a survival curve with much confidence. For this reason safe-life limits are usually established by dividing the average failure age by a large arbitrary factor – sometimes a factor as large as 3 or 4. The implication is that the conditional probability of failure at this limit is essentially zero; that is, a safe-life limit is based on a 100 percent probability of survival to that age. The difference between a safe-life limit and the average age at failure is illustrated in Exhibit 3.4.

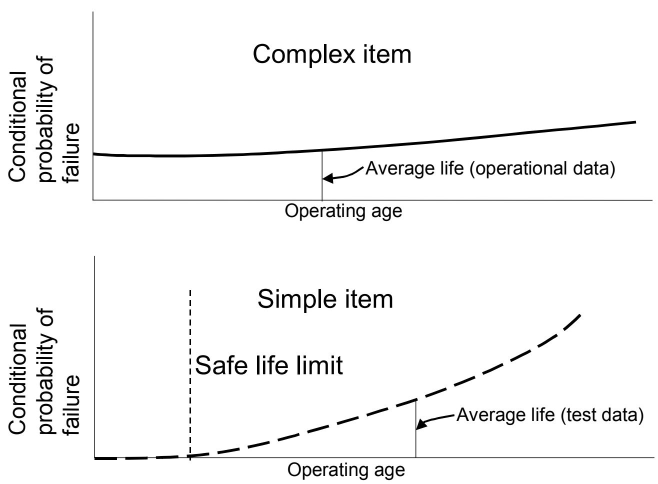


**Exhibit 3-4 Comparison of the average age at failure (average life) determined from the operating data, top and a safe-life limit determined on the basis of test data, bottom.**

A safe-life discard task is applicable only under the following circumstances:

- The item must be subject to a critical failure.
- Test data must show that no failures are expected to occur below the specified life limit.

Since the function of a safe-life limit is to avoid the occurrence of a critical failure, the resulting discard task is effective only if it accomplishes the objective. Thus the only information for assessing effectiveness in this case will be the manufacture's test data. Sometimes these tests have not been completed at the time the initial program is developed, but until a limit can be established, the available test data must show that the anticipated in-service aging of the item will be safe. An operating organization rarely has the facilities for further simulation testing that might justify increasing a safe-life limit, nor is there usually a reasonable basis for reducing it, unless failures occur.

## Economic-life limits

In some instances extensive operating experience may indicate that scheduled to discard of an item is desirable on purely economic grounds. An economic-life limit, however, is established in the same manner as an age limit for scheduled rework; that is, it is based on the actual age-reliability relationship of the item, rather than on some fraction of the average age and failure. Whereas the objective of a safe-life limit is to avoid accumulating any failure data, the only justification for an economic-life limit is cost effectiveness. Thus the failure rate must be known in order to predict how the total number of scheduled removals at various age limits would affect the cost-benefit ratio.

In general, an economic life task requires the following three conditions:

- The item must be subject to a failure that has major economic (but not safety) consequences.
- There must be an identifiable age at which the item shows a rapid increase in the conditional probability of failure.
- A large proportion of the units must survive to that age.

Although an item that meets the first criterion may be put into an age-exploration program to find out if a life limit is applicable, there rarely sufficient grounds for including this type of discard task in an initial scheduled-maintenance program.

# 3.4. Schedule failure-finding tasks

Whenever an item is subject to a functional failure that would not be evident to be operating crew, a scheduled task is necessary to protect the availability of that function. Although hidden-function failures, by definition, have no immediate consequences, failures that are undetected increase the exposure to a possible multiple failure. Hence, if no type of maintenance task is applicable and effective, hidden function items are assigned *failure-finding tasks*, scheduled inspections for hidden failures. Although tasks are intended to locate functional failures rather than potential failures, they can be viewed as a type of on-condition maintenance, since the failure of a hidden-function item can also be viewed as a potential multiple failure. The chief difference is in the level of item considered; a functional failure of one item may be only a potential failure for the equipment as a whole.

Most items supported by failure-finding inspections remain in service until a functional failure is discovered. Some items, however, have several functions, of which only one or two are hidden. Such items will be removed from service to correct evident failures, and if the removal rate is sufficient to ensure adequate availability of the hidden function, the shop specifications may include a failure-finding inspection at that time. Other items may not require scheduled failure-finding tasks because the operating crew is required to check them periodically. Many hidden functions, especially in systems, are made evident by the addition of instrumentation, so that a separate inspection for hidden failures is unnecessary.

A scheduled failure-finding task is applicable to an item under the following two conditions. Note that the second criterion is in fact a default condition:

- The item must be subject to a functional failure that is not evident to the operating crew during the performance of normal duties.
- In the item must be one for which no other type of task is applicable and effective.

The objective of a failure-finding task is to ensure adequate availability of a hidden function. The level of availability that is needed, however, depends on the nature of the function and the consequences of a possible multiple failure. Some hidden functions, such as the fire-warning system in an aircraft powerplant, are sufficiently important that they are tested before every flight.

Appropriate intervals for failure-finding tasks cannot be determined as exactly as those for other types of tasks. In the case of emergency equipment hidden-function items which are replaced at specific intervals, such as pyrotechnic devices, are tested prior to rework or discard to see if they would have functioned had they been needed. The test results at any given interval provide a basis for increasing or decreasing the interval. In other cases in the expected availability of a hidden function can be approximated by assuming that the age-reliability relationship is exponential,[1] assigning a conservatively high failure rate, and then determining the probability of survival across a given inspection interval.

As an example, suppose some hidden function has an anticipated failure rate of 0.5 per 1000 hours. The mean time between failures is then 2000 hours. If the proposed inspection interval is 500 hours, a unit that is serviceable at 1 inspection we'll have aged 500 hours by the next inspection. The probability that it will survive 500-hour interval (1/4 of the mean time between failures) is .78 on an exponential curve (Exhibit 3.5). The average availability would thus be

$$\frac{1.00 + 0.78}{2} = 0.89$$

or a probability of .89 that the item will function if it is needed. If this degree of reliability is inadequate, the inspection interval must be reduced. Failure-finding tasks are always effective if the inspection interval is short enough.

[1] If the conditional probability of failure is nonincreasing. this is a conservative assumption.

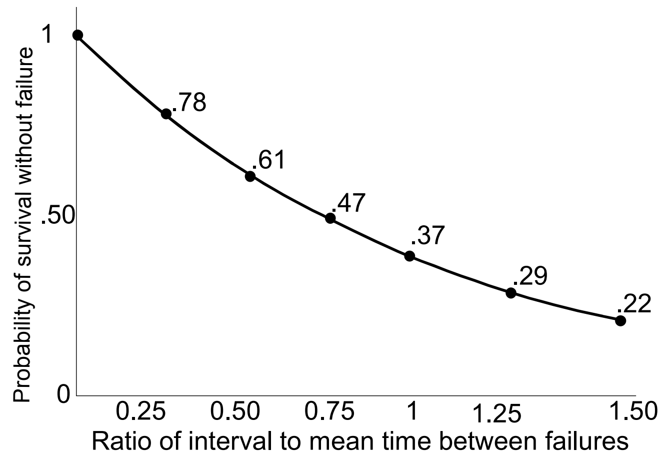


**Exhibit 3-5 Establishing the interval for a failure-finding inspection. The age-reliability relationship of an item is assumed, in the absence of information, to be exponential over operating age. Thus at an inspection interval equal to one-fourth of the mean time between failures, the probability that the item will survive that interval is .78. This is true of the interval between any two inspections, regardless of the age of the item. On the basis of this inspection interval, the average availability of the unit would be 89 percent. And interval that represented a smaller fraction of the expected to mean time between failures would yield a high air average availability.**

To be considered effective a failure-finding task must ensure the required level of availability. However, this task must also be cost-effective with respect to the three other types of maintenance tasks – that is, it must be the least expensive means of ensuring the necessary level of availability. When a possible multiple failure is not related to safety, and availability a goal of 95 percent is often used. Alternatively, the economic consequences of the multiple failure can be balanced against the costs of inspection to determine the most cost-effective interval and availability level.

Exhibit 3.6 shows some typical failure-finding tasks for the commercial aircraft. In each case the scheduled task is designed to identify a functional failure. In the second example the failure might or might not be evident to the operating crew, depending on whether a complaint was received from a passenger.
defended

**Exhibit 3-6 Examples of failure-finding inspection tasks as specified for airline maintenance mechanics. In this case the mechanic is required only to replace the failed units. (United Airlines)**

| **1. Smoke goggles** |
|---|

Replace missing or damaged goggles (not repairable) as required by the following conditions:

A. plastic-foam face seal not adhering to goggle rim
B. lens not retained within goggle groove
C. Dirt or scratches on lens
D. Any other detrimental condition

**2. Reading lights, passenger-service system**

Test lights in zones A to E:

A. At positions 1, 2, 3, and 4 on right attendant's panel, position switches as follows:
PES-OFF, PSS-OFF,CH-OFF,ATTND CALL-TEST (to illuminate blue)

B. For zone being checked, rotate reading-light switch to ON position:
(1) All reading lights in that zone should illuminate
(2) Master call light should not blink.

C. Rotate reading-lite switch to OFF position:
(1) All reading lights in that zone should not illuminate
(2) Master call light should not blink.

D. Rotate reading-light switch to SEAT position:
All reading lights in that zone should return to individual seat CTL selector.

**3. Exterior lights**

A. Turn on beacon, navigation, and wing-illumination lights, and at night turn on logo lights.
B. Walk around exterior of aircraft and check lights.
C. Turn off lights.

# 3.5. Characteristics of the basic tasks

The four types of scheduled-maintenance tasks employed in an RCM program differ both in terminology and in concept from traditional approaches to scheduled maintenance. In the airline industry, for example, it is customary to refer to 3 "primary maintenance processes": *on-condition, hard time,* and *condition monitoring.* All scheduled tasks are considered to be either on-condition or hard-time. On-condition tasks are defined by FAA regulations as:

… restricted to components on which a determination of continued airworthiness may be made by visual inspection, measurement, tests, or other means without a teardown inspection or overhaul. These "On-Condition" checks are to be performed within the time limitations prescribed for the inspection or check.

Although the term *hard tim*e is not specifically defined, it is implied by a number of FAA requirements. Airline maintenance specifications must include "time limitations, or standards for determining time limitations, for overhauls, inspections and checks of airframes, engines, propellers, appliances, and emergency equipment," and the basic principle for establishing these time limits is:

… that the inspections, checks, maintenance or overhaul be performed at times will within the expected or proven service life of each component of the aircraft.

**Exhibit 3-7 Comparison RCM task terminology and current regulatory usage**

| RCM terminology | Current regulatory usage |
|---|---|
| **Inspection tasks:** | |
| On-condition tasks (to detect potential failures) | On-condition process |
| Failure-finding tasks (to detect hidden function failures) | Condition-monitoring process (inspection of hidden-function items) |
| **Removal tasks:** | Hard-time process |
| Scheduled rework | Scheduled overhaul |
| Scheduled discard | Life limit |
| **Servicing tasks:** | servicing |
| No scheduled maintenance | Condition-monitoring process (no scheduled tasks |

The process termed *condition monitoring* is one that is characterized by the absence of preventive-maintenance tasks. An item is said to be maintained by condition monitoring if it is permitted to remain in service without preventive maintenance until a functional failure occurs. However, since condition of monitoring is oriented to after the fact detection of failures, this designation may refer in some instances to failure-finding tasks assigned to hidden-function items and in other instances to items assigned to no scheduled maintenance.

Despite the overlap in terminology, there are certain fundamental differences in concept between the tasks performed under traditional maintenance policies and the explicit task definitions required by an RCM program. The hard-time approach was based on the assumption that complex items do have an "expected or proven service life" – that is, that their overall reliability invariably decreases with age. On this premise overhaul specifications usually required that all units which had survived to the specified time limit be disassembled down to their smallest constituent parts and inspected in detail for signs of deterioration. Technical experts examined each part and formed opinions about whether a given component could have continued to operate satisfactorily to a projected new overhaul interval; in other words, they made judgments about the age at which the item was likely to fail.

These teardown inspections might at first appear to qualify has on-condition inspections. However, such inspections were rarely focused on the specific conditions required by an on-condition task. Unfortunately it is usually beyond human capability to look at a used part and determine what its likelihood of failure will be at some later age. As a result, the initial overhaul intervals for new equipment were short and were extended only by very small increments. At one point, in fact, the FAA limited extensions of the interval for engine overhauls to a maximum of 100 hours and required a period of at least three months between successive extensions.

Note that the traditional type of scheduled overhaul also fails to satisfy the criteria for a rework task. Shop specifications calling for the part-by-part remanufacture of complex items to restore them to "like-new" condition were intended to avoid operation in the age period at which failures were expected to be more likely. As we have seen, however, this expectation does not hold for most complex items. Consequently we cannot expect periodic overhaul at any operating age to make a noticeable difference in their reliability. Furthermore, even when a complex item does meet the applicability criteria for a rework task, it is difficult to satisfy the conditions for effectiveness. For this reason complete rework of items such as turbine engines is now relatively rare, and many organizations have abandoned rework of other rotating machinery, which was once considered a prime candidate for scheduled overhaul.

## The basis of task preference

The applicability of any maintenance task depends on the failure characteristics of the item. However, the characteristics of the tasks themselves suggest a strong order of preference on the basis of their overall effectiveness as preventive measures. The first choice is always an on-condition inspection, particularly if it can be performed without removing the item from the equipment. This type of preventive maintenance has a number of advantages. Because on-condition tasks identify individual units at the potential-failure stage, they are particularly effective in preventing specific modes of failure. Plus they reduce the likelihood both of critical failures and of the operational consequences that would otherwise result from that failure mode. For the same reason, they also reduce the average cost of repair by avoiding the extensive secondary damage that might be caused by a functional failure.

The fact that on-condition tasks identify individual units at the point of potential failure means that each unit realizes almost all of its useful life. Since the number of removals for potential failures is only slightly larger than the number that would result from functional failures, both the repair costs and the number of spares necessary to support the repair process are kept to a minimum. The scheduling of on-condition inspections at a time when the equipment is out of service concentrates the discovery of potential failures at the maintenance stations that perform the inspections. This fact, together with the lower probability of functional failures, further reduces the inventory of spare units that would otherwise have to be kept available at each line station.

If no applicable and effective on-condition task can be found, the next choice is a scheduled rework task. Scheduled rework of single parts or components leads to a marked reduction in the overall failure rate of items that have a dominant failure mode (the failures resulting from this mode would be concentrated about an average age). This type of task may be cost-effective if the failures have major economic consequences. As with on-condition inspections, the scheduled removals can be concentrated at a few maintenance stations, thus reducing the exposure of all line stations to the need to remove units after they have failed. A rework age limit usually includes no restriction on the remanufacture and reuse of time-expired units; plus material costs are lower than they would be if the entire unit had to be discarded.

Any scheduled rework task, however, has certain disadvantages. Because the age limit applies to all units of an item, many serviceable units will be removed that would otherwise have survived to higher ages. Moreover, as we saw in Section 3.2, the total number of removals will consist of failed units plus scheduled removals. Hence the total workload for this task is substantially greater than it would be with on-condition inspection, and a correspondingly larger number of spare units is needed to support the shop process.

Scheduled discard is economically the least desirable of the three directly preventive tasks, although it does have a few desirable features. A safe-life limit on simple components can prevent critical failures caused by certain failure modes. Similarly, an economic-life limit can reduce the frequency of functional failures that have major economic consequences. However, a discard task is in itself quite costly. The average life realized by an item subject to a safe-life limit is only a fraction of its potentially useful life, and the average life of an item subject to an economic-life limit is much less than the useful life of many individual units. In addition, a discard task involves the cost of replacement; new items or parts must be purchased to replace the time-expired units, since a life limit usually does not permit remanufacture and reuse.

Hidden-function failures have no immediate consequences; hence our interest is in the least expensive means of ensuring the necessary level of availability for the item. When none of the other tasks is applicable, the default action for hidden-function items is a failure finding task. Otherwise, the choice of task is determined by cost effectiveness.

| Characteristic | On-condition task | Scheduled rework task | Scheduled discard task | Failure-finding task |
|---|---|---|---|---|
| Applicability criteria | Reduced resistance to | Conditional probability | For safe-life limits | The occurrence of the |

| Characteristic | On-condition task | Scheduled rework task | Scheduled discard task | Failure-finding task |
|---|---|---|---|---|
| | failure must be detectable; rate of reduction in failure resistance must be predictable. | of failure must increase at an identifiable age; a large proportion of the units must survive to that age. [For safety related failure modes, 100% of the units must survive to that age] | conditional probability of failure must be zero below life; for economic-life limits conditional probability of failure must increase at an identifiable age and a large proportion of units must survive to that age. | functional failure must not be evident to the operating crew. |
| Effectiveness criterion | For critical failures the task must reduce the risk of failure to an acceptable level; in all other cases the task must be cost-effective. | For critical failures that task must reduce the risk of failure to an acceptable level (a rework task alone is unlikely to meet this requirement); in all other cases that task must be cost-effective. | A safe-life limit must reduce the risk of failure to an acceptable level; and economic-life limit must be cost-effective. | The task must result in the level of availability necessary to reduce the risk of a multiple failure to an acceptable level. |
| Usual availability of required information | Applicability prior to service; effectiveness after age exploration. | Applicability after age exploration; effectiveness after age exploration. | Safe-life applicability and effectiveness prior to service; economic-life applicability and effectiveness after age exploration. | Applicability prior to service; effectiveness after age exploration. |
| Effect on occurrence of functional failures | Failures due to specific failure mode eliminated or greatly reduced in frequency. | Frequency of failures somewhat less than with no scheduled maintenance. | Failures due to specific failure mode eliminated (safe-life limit) or reduced in frequency (economic-life limit). | No effect on item inspected, but frequency of multiple failures greatly reduced |
| Distribution of removals | Removals for potential failures concentrated at few stations where inspections are performed; removals for functional failures at any station. | Scheduled removals concentrated at the very few stations; removals for functional failures at any station. | Scheduled removals concentrated at a very few stations; removals for functional failures (economic-life limits) at any station. | Removals concentrated at stations where inspections are performed; no removals at other stations. |
| Effect on shop volume | Slightly greater than with no scheduled maintenance. | Much greater than with on-condition or no scheduled maintenance. | Not applicable. | Minimal. |

**Exhibit 3-8 Comparison of various characteristics of the four basic scheduled-maintenance tasks.**

## Items that cannot benefit from scheduled maintenance

In the process of evaluating proposed maintenance tasks for an item there will be a number of instances in which no applicable task can be found – that is, items for which there is no evidence that a particular task will improve reliability. There will be far more instances, however, in which an applicable task does not satisfy the conditions for effectiveness. This may be because the failure has such minor consequences that the task is not cost-effective or because it has such major consequences that the task does not reduce the risk of failure to the required level. If safety consequences are involved, the objective of any task is to minimize the probability of a failure, and in this case all applicable tasks are assigned as preventive maintenance. Since most essential functions in well-designed equipment are protected by redundancy, the safety hazard is usually the possible secondary damage. However, the number of failure modes in which this is a factor is relatively small.

When an item cannot benefit from scheduled maintenance, in some cases product improvement may be necessary before the equipment goes into service. More often the chore of determining what preventive maintenance might accomplish for each item helps to clarify specific modifications that would improve reliability in subsequent designs.

Where safety consequences are not involved, any applicable task must be cost-effective, and this condition is usually difficult to satisfy unless the failure has operational consequences. Once again, the design often employs redundancy to limit the number of items subject to such failures. As a result, there are tens of thousands of items on complex equipment for which scheduled maintenance provides no advantage. Since such items cannot benefit from preventive maintenance, they are left in operation until a functional failure occurs. This strategy permits each unit to realize its maximum useful life.

Items that cannot benefit from scheduled maintenance are characterized by two properties:

- Such items have no hidden functions; hence a failure is evident to the operating crew and will therefore be reported and corrected.
- The failure is one that has no direct adverse effect on operating safety.

A further characteristic of such items is that many of them are complex. One reason for this is that when there is no evidence that a proposed task will actually improve the reliability of a complex item, there is always the possibility that it will introduce new problems, either by upsetting a stable state or, in some cases, by introducing workmanship problems. Thus where a complex system cannot be protected by on-condition inspections, from a purely practical standpoint the default action would be no scheduled maintenance. This is usually the case, for example, with electrical and electronic systems.

## 3.6. The dimensions of the scheduled-maintenance program

### The role of the basic tasks

The maintenance activities required to support any type of complex equipment include routine servicing, periodic inspections, and the performance of any corrective maintenance necessary when a condition is found to be unsatisfactory. Scheduled tasks are selected, however, on the basis of the ways in which a particular item can fail. In considering all the known or anticipated failure modes of each item we find that many major components cannot benefit from any type of preventive maintenance, some will require a single task, and others will require several different tasks. The maintenance tasks assigned to a complex item such as an aircraft turbine engine, for example, are quite numerous. Following are just a the inspection tasks performed while the engine is installed:

- Oil-screen inspection to detect metal particles
- Borescope inspection of the combustor to detect signs of metal fatigue
- "sniff test" of the fuel manifold to detect fuel odors
- "broomstick check" to detect loose turbine blades
- inspection of the fan blades and front compressor blades for possible damage
- inspection for rattling noise to detect broken tie bolts
- radiostope inspection of nozzle guide vanes for deformation
- spectrographic oil analysis to detect metallic indications of wear

Recognition of the criteria for applicability of scheduled rework has led to a great reduction in the number of items removed and sent to the shop for routine overhaul. Items are still removed from equipment and sent to the maintenance base, however, either because they have failed or because they contain parts that require rework or discard. In this case it is necessary to decide the extent of the work to be done before these items are returned to service. Within the frame of reference dictated by the applicability of rework tasks, there are only four circumstances under which rework would be specified:

- Single parts may require rework as the result of an inspection for potential failures that can be performed only when an item is disassembled in the shop. This applies to certain types of turbine blades.
- Single parts may require rework because their failure characteristics show that they will benefit from an age limit. This is the case with some fuel manifolds.
- Single parts may have to be discarded because they have reached a specified life limit. This applies to the safe-life limits imposed on most compressor and turbine disks.
- Single parts may have to be reworked or discarded because shop inspection discloses a functional failure that was not observable when the item was installed on the equipment.

The amount of work specified as part of shop maintenance depends, of course, on the nature of the item. With some the direct cause of a failure is corrected, and if the component can then meet its performance standards, it is returned to service.

This practice is sometimes referred to as *conditional overhaul.* Other items, such as turbine engines, may have a great deal of additional work done on them while they are out of service . The work performed, however, is very much less than that done under hard-time overhaul policies. As a result, the RCM approach to rework tasks has substantially decreased engine maintenance costs, not only by reducing the volume of the units flowing through the maintenance base, but also by reducing the amount of work required when they are there.

The propulsion system is not the only complex item on an aircraft; however, it is a system closely associated with operating safety, and the largest part of the maintenance costs for any aircraft stem from scheduled or unscheduled work on engines. Because of this, on-condition inspections play a major role in power plant maintenance programs, and scheduled removals, when they are necessary, are set at the maximum interval that will allow satisfactory operation.

## Servicing and lubrication

Complex equipment requires numerous scheduled servicing and lubrication tasks to maintain satisfactory operation. There is usually no question about which tasks are required and whether they are applicable and effective. However, it is interesting to review this aspect of maintenance in light of our discussion thus far.

Lubrication, for example, really constitutes scheduled discard of a single-celled item (the old lubrication film). This task is applicable because the film does deteriorate with operating age and does show wearout characteristics. Usually the condition of the film cannot be determined; hence conservatively short intervals are assigned for its replacement with new lubricants. Such tasks are also cost-effective. An item is lubricated whether it needs lubrication or not because the cost is minuscule in comparison to the costs that would result from inadequate lubrication. In fact, the cost of this task is too low to justify studies to determine the most economical task interval. As a result, lubrication is rarely isolated for in-depth analysis in developing a maintenance program.

Whereas lubrication constitutes a discard task, the servicing tasks – checking tire pressure or fluid levels in oil and hydraulic systems – are on-condition tasks. In this case potential failures are represented by pressure or fluid levels below the replenishment level, and this condition is corrected in each unit as necessary.

## Zonal inspections and walkaround checks

In contrast to servicing and lubrication tasks, zonal inspections and walkaround checks of aircraft structures do not fall within the realm of RCM task definition. Walkaround checks are intended to spot accidental damage and fluid leaks and hence might be viewed as combination on-condition and failure-finding inspections. In fact, they do include a few specific on-condition tasks, such as a check of brake wear indicators. However, damage can occur at any time and is unrelated to any definable level of failure resistance. As a result, there is no basis for defining an explicit potential-failure stage or a predictable interval between a potential failure and a functional failure. Similarly, a check for leaks is not based on the failure characteristics of a particular item, but rather is intended to spot any unforeseen exceptions in failure behavior.

Zonal inspections are even less specific. They are not directed at any particular failure mode, but are merely a survey of the general conditions within a given zone, or area, of the equipment. The zonal inspections include a check of all the system subassemblies and connecting lines in each zone for security (loose parts), obvious signs of the damage or leaks, and normal wear and tear as a result of other maintenance activities. In the power plant this inspection includes looking into the engine tailpipe and inlet, opening the cowling and examining all the engine-mounted accessories, and so on. Such inspections play an important role in structural maintenance, since they also include a general inspection of the internal structural areas that can be seen with all installations in place. Thus they complement, but are not a substitute for the program of detailed on-condition inspections developed for structurally significant items.

Although zonal-installation inspections do not need the applicability criteria for any of the four basic tasks, their cost is such a small part of the total cost of scheduled maintenance that they are economically justified if they result in the discovery of the even a few potential failures. For this reason any RCM program is supplemented by a separate program of scheduled zonal inspections.

| | Corrective work | | | |
|---|---|---|---|---|
| Location of work performed | Scheduled work | Flight-crew reports | Mechanic reports | Total man hours per flight hour |
| **On the airplane** | | | | |
| At stations | | | | |
| Below A-check level | -- [1] | 2.1 | 0.2 | 2.3 |
| At A-check level | $\frac{0.2}{0.2}$ [2] | $\frac{-}{0.2}$ [3] | $\frac{0.2}{0.4}$ | $\frac{0.4}{2.7}$ |

[1] Workload was not significant.
[2] Workload at checks was prorated, with one-half assigned to schedule inspections and servicing and one-half assigned to corrective work.
[3] A-check figures were adjusted to include only scheduled-maintenance work and the corrective work it generated.

| | | | | |
|---|---|---|---|---|
| At main maintenance base | | | | |
| Phase check (combination of B and C checks) | 0.7[9] | -- | 0.7 | 1.4 |
| D check (heavy structural inspection) | 0.8 / 2.4 [9,1] | -- / -- | 0.8 / 1.5 | 1.6 / 3.0 |
| **Off the airplane** | | | | |
| At main maintenance base | | | | |
| Repair of failed engines | -- | 2.3[2] | 6.9 | 9.2 |
| Repair of other failed items | -- / -- | 3.9 / 6.2 | --[8] | 3.9 / 13.1 |
| | 1.7 | 8.3 | 8.8 | 18.8 |
| | | | | |

**Exhibit 3-9 A breakdown of the total maintenance workload of 18.8 man-hours per flight hour on the United Airlines fleet of Boeing 747's. Data are for January – Nov. 1975 and do not include manhours expended to accomplish modifications. (United Airlines)**

## The total maintenance workload

The total maintenance workload required to support complex equipment consists of all the work performed as scheduled maintenance, plus the corrective-maintenance work required to repair failed units. Exhibit 3.9 illustrates the ratio of these two aspects of maintenance for an aircraft supported by a scheduled-maintenance program that is essentially the same as an RCM program. The scheduled tasks comprised somewhat less than 10 percent of the total man hours spent on maintenance, yet these tasks ensured realization of all the reliability of which the equipment was capable. Additional scheduled work would have increased costs, but it would not have improved reliability.

Approximately 75 percent of the corrective work was done at the major maintenance base as a result of the line-maintenance practice of replacing failed units with serviceable ones. About half the corrective work was done on engines. The only way corrective workload can be reduced is by design changes that improve the inherent reliability of the items that are failing. Such changes are usually directed at the dominant failure modes in items whose failure has safety or major economic consequences. In this case the engine failures do have serious economic consequences, and this and is still undergoing intensive development.

The absolute size of the scheduled workload for this aircraft will not change very much from its 1975 value, but the corrective workload will decrease substantially as product improvement overcomes those problems which require high man-hour expenditures. Consequently the relative proportions of the workload components may change in the next several years. At some time in the future both components may increase again as a result of conditions that do not occur until much later ages.

## 3.7. Product improvement as preventive maintenance

Over the years aircraft manufacturers have incorporated a number of design features that have increased the inherent capability of the equipment for reliable operation. In most cases these practices are intended not to prevent failure, but to reduce its consequences to the cost of corrective maintenance. Thus most systems items are designed with a high degree of redundancy to ensure that if one unit fails, the necessary function will still be available. On the same principle, structures are designed with multiple load paths so that they are damage-tolerant. Protective devices may also consists of entirely separate components, as in the case of emergency equipment – fire extinguishers, automatically released oxygen equipment in passenger aircraft, and ejection seats in single-engine military aircraft.

Another common practice is failure substitution. This may be the substitution of a minor functional failure to preempt a major one, as in the use of automatic shut off devices. Or it may be a feature included to permit easy identification of a potential failure; for example, the outer skin and an aircraft may be designed to crack before the structural member beneath it fails, so that there is evidence of an imminent failure that can be detected by visual inspection. Inspection features such as borescope ports in engines also facilitate the detection of potential failures that would otherwise be difficult to check for.

All these features are important from the standpoint of preventive maintenance, since they determine both the feasibility of certain tasks and the failure consequences by which task effectiveness is measured. On a short-term basis, however, any scheduled-maintenance program must be built around the reliability characteristics of the equipment as it exists. In the case of new equipment, therefore, it is important to bear in mind a basic conflict between certain design goals

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Corrective work resulting from flight-crew reports is aggregated with other below-A-check work

1 The D check figure is not typical. During the reporting. There were two sample D checks for age-exploration purposes. A longer reporting. Would lead to a smaller D check number.

2 The corrective engine to work was prorated, with one-quarter assigned to pilot reports and the remainder assigned to mechanic findings.

and reliability goals. This problem is nowhere more apparent than in modern aircraft, where the requirement for lightness and compactness is in direct opposition to the strength and bulk that is necessary for failure resistance. A further difficulty is posed by the rush to new technology, since this means that the designer is often working with new components and even new materials whose reliability has not been proved by experience.

There are several pitfalls here. Designing for lightness, for example, correspondingly reduces the initial margin between resistance and stress. Even with familiar materials, the actual strength of a material may be less than its nominal strength, or the rate at which its failure resistance declines may be greater than expected. With unfamiliar materials and processes the likelihood is increased in both these areas. The design goal of compactness may lead to the same results and two other problems as well. In a more compact area an item that functioned well in a different environment, may be exposed to higher temperatures or to vibration from neighboring components. Such items are also likely to be more difficult to reach for inspection and replacement.

Where reliability problems are inherent in the design itself, there are ways of coping with the failure process:

- Increasing the initial resistance to failure
- Reducing the rate at which failure resistance decreases
- Reducing the stress to which the item is exposed

All three of these effects are shown in Exhibit 3.10.

Reliability improvement in each of these areas can take any number of forms. In some instances the solution may be a modification in operating procedures. For example, the use of more reverse thrust and less brakeing to slow and airplane after it has landed will reduce stress on the brakes (although it increases the cumulative stress on the reverser). Since this procedure will also increase the life of the tires, it has several implications for maintenance. In general, however, when unsatisfactory reliability characteristics result in exposure to critical failures or excessive operational or maintenance costs, the only effective form of prevention is redesign – either to alleviate the problem or to mitigate its consequences.

When a critical-failure mode is involved, and no form of scheduled maintenance can be found that will effectively control it, product improvement is mandatory. Otherwise the desirability of redesign depends on an assessment of the costs involved on both sides. Since this information is ordinarily not available until after the equipment has been in service for some time, items that mean ultimately be redesigned on the basis of actual operating costs are often assigned to know scheduled maintenance in a prior-to-service program.

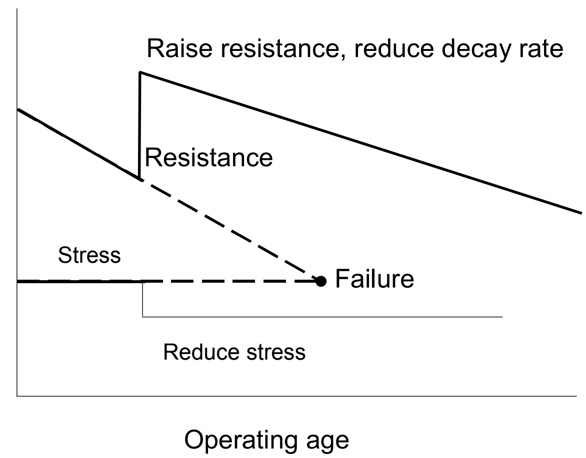



**Exhibit 3-10 Methods of coping with the failure process. An item may be redesigned to increase its initial failure resistance, to reduce the rate at which failure resistance decays, or both. At the same time, various strategies may be employed to reduce stress to which the item is exposed. Any or all of these procedures will improve reliability by moving the point of functional failure farther into the future, and thus increasing the mean time between failures.**

# 4. Chapter Four - Developing the initial program

An initial scheduled-maintenance program must be developed for new equipment long before it enters service. While it might be possible to obtain a small mountain of test data on every part, assembly, and subsystem, the information about their actual reliability comes only from operating experience. Thus the problem in basing a maintenance program on reliability characteristics might appear to be a lack of the very information that is needed. In reality the problem is not a lack of information; rather, it is knowing what information is necessary in order to make decisions.

The RCM solution to this problem is a structured decision process based, not on an attempt to estimate the reliability of each part, but on the consequences of functional failures for the equipment itself. The decision process thus proceeds from the top down, first to identify those items whose failure is significant at the equipment level and then to determine what scheduled maintenance can do for each of these items. At each step of the analysis decision is governed by the nature of the failure consequences. This focus establishes the priority of maintenance activity and also permits us to define the effectiveness of proposed maintenance tasks in terms of the results they must accomplish. Once this determination has been made, we are in a position to examine each of the four possible forms of preventive maintenance to see which tasks, if any, are both applicable and effective for the item under consideration.

The process of evaluating failure consequences and maintenance tasks is facilitated by a decision-diagram technique which employs an ordered set of priorities – in the case of failure consequences and task selection – with the questions at each level worded to define the information required for that decision. In many cases the answer will be obvious from engineering expertise, the manufacture's test data, and previous experience with similar items. However, in developing a prior-to-service maintenance program a strategy is required for decision making when the appropriate information is not available. Thus the decision logic also provides for default answers to meet this situation. For an item subject to critical failures, the default leads ultimately to redesign. Where the consequences of failure are economic, the default decision may be to do nothing (no scheduled maintenance) until operating experience provides the information to justify some other choice.

The results of RCM analysis is a scheduled-maintenance program that includes all scheduled tasks necessary to ensure safety and operating economy, but only those tasks that will do so. Where there is no basis for determining whether a particular task will prove applicable and effective, the default strategy provides the most conservative answer, and as the maintenance program evolves, these initial decisions are systematically modified on the basis of actual operating data. This process continues throughout the service life of the equipment, so that the decision structure provides for an optimal program in terms of the information available at any time. In this chapter we will examine the decision process as it relates to commercial aircraft. However, the decision logic itself is general and applies to any complex equipment that requires a maintenance support program designed to realize maximum operating reliability at the lowest cost.

# 4.1. The nature of significant items

A transport plane consists of a vast number of parts and components, all of which have specific functions. All these items can be expected to fail at one time or another, but some of the failures have more serious consequences than others. Certain kinds of failures are a threat to safety, and others have a direct effect on operating capability. However, there are tens of thousands of items whose failure has no immediate impact on the equipment as a whole. The failures are simply corrected soon after they occur, and the only consequence is the cost of repair. These items have no significance from the standpoint of preventive maintenance in the sense that their consequences are tolerable. It is less expensive to leave them in-service until they fail then it would be to prevent the failures. Thus the initial decision for these tens of thousands of items is no scheduled maintenance.

The information on which to base this decision ordinarily comes from the manufacturer, who has had to face the problem of failures during the design and development of the equipment. In order to qualify the aircraft for airworthiness, the manufacturer will have conducted a failure modes and effects analysis (FMEA) for all the major assemblies, subsystems, and systems to demonstrate how the equipment will perform when serious items fail. In addition, the purchasing airlines will have knowledge of operating experience with similar items in the past, as well as knowledge of the failure consequences in the particular operating context in which the equipment is to be used.

The failures that are of concern are those which have serious consequences. Thus an RCM program directs tasks at a relatively small number of items – those systems, subsystems, and assemblies whose functional failure would be significant at the equipment level, either immediately or downstream in the event of a hidden failure.

## Identifying significant items

The first step in the development of a scheduled-maintenance program is a quick, approximate, but conservative identification of a set of *significant items:*

**A significant item is one whose failure could affect operating safety or have major economic consequences.**

The definition of "major economic consequences" will vary from one operating organization to another, but in most cases it includes any functional failure that has a direct effect on operational capability or involves a failure mode with unusually high repair costs.

So far we have used the term *item* in a very general sense to refer to some component of the equipment. An item can, in fact, be of any size; the entire aircraft might be viewed as an item, as might any one of its parts. However, the larger and more complex the item, the more unwieldy the set of failure possibilities that must be taken into account. To reduce the problem of analysis to manageable size, it is customary to partition the equipment into three major divisions – systems, powerplant, and structure – each of which involves different areas of engineering expertise. Each division is then partitioned in descending order of complexity, with successively fewer failure possibilities at each level.

The chore now is to sort through the functions and failure possibilities of the various components and eliminate all the obvious non-significant items. To ensure that borderline cases and items for which information is lacking will always receive further study, any items eliminated at this stage must be demonstrated to be non significant. Items may be classified as non significant because their functions are unrelated to operating capability or because they are replicated, so that a functional failure would not affect operating capability. Many items can be eliminated because their failures can be repaired quickly and therefore involve no operational consequences. Other items may be rolled out later because they are not candidates for on-condition or safe-life tasks and hence cannot benefit from scheduled maintenance (there is usually no information on the applicability of rework tasks at this time). At this stage, however, all the items that might benefit from scheduled maintenance must be listed for further study.

During the process of classifying items as significant or non significant certain items will be identified that have hidden functions. All these items will require scheduled maintenance regardless of their significance. Although the loss of a hidden function has no direct effect on safety or operating capability, an undetected failure exposes the equipment to the risk of a multiple failure which might have serious consequences. Hence hidden-function items are subjected to the same intensive analysis as significant items.

Note that all items will in fact be included by this procedure, since the partitioning process itself has the following properties:

- Any item containing a significant item is itself significant.
- Any nonsignificant item is contained in a higher-level significant item.
- Any lower-level item contained in a nonsignificant item is itself nonsignificant.

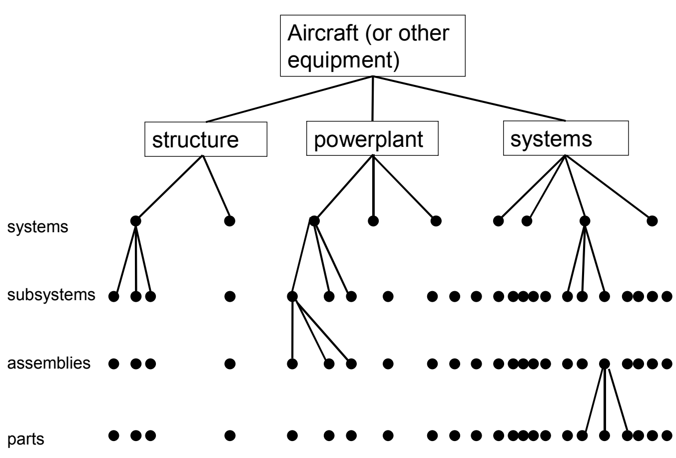



**Exhibit 4-1 Partitioning an aircraft for preliminary identification of significant items. The equipment is first partitioned to show all items in descending order of complexity. Those items whose failure clearly has no significant consequences at the equipment level are then pruned from the tree, leaving the set of items on which maintenance studies must be conducted. Each significant item will include as failure modes all the failure possibilities it contains.**

The objective, however, is to find the most convenient *level* of each system or assembly to classify as significant. The level must be **low enough to insure that no important failure possibilities are overlooked, but high enough for the loss of function to have an impact on the equipment itself**, since the consequences of a functional failure are significant only at the equipment level – that is, for the aircraft as a whole.

Once the optimum level of item has been selected for study in each case, we can prune the "tree" back to a set of several hundred potentially significant items with the assurance that any failure possibilities they include at lower levels will be taken into account as failure modes. As an example, consider the engine described in Section 3.1, in which failure of one or more individual tie bolts in a set of 24 was defined as a potential failure. Although this might be viewed as a functional failure of the tie bolt, the failure of a single bolt does not affect engine performance enough to be evident to the operating crew; consequently the tie bolt is not a significant item. It does, however, have a hidden function, and if enough tie bolts failed, the resulting multiple failure would indeed become evident. The inspection task selected to avoid such a multiple failure would still be the one described in Exhibit 3.2 – a check for broken tie bolts. However, viewed from the engine level this is an on-condition task, whereas at the parts level it would be considered a failure-finding task.

In other words, the level of item selected as significant is important only as a frame of reference. Whether we look up at a multiple failure or down and a failure mode, and analysis of all the failure possibilities will ultimately lead to exactly the same preventive task. The chief advantage of the partitioning process is that it allows us to focus intensive study on just a few hundred items instead of many thousands. In an aircraft these items will include some of the parts and assemblies, some subsystems, each of the systems, and each of the major divisions themselves. The parts selected as significant are usually those in which a critical failure mode originates. The structure division represents a special case, since the significant items are specific regions that require scheduled maintenance, rather than whole structural assemblies.

## Structurally significant items

The significant items in each of the major divisions of an aircraft have certain common characteristics which relate to their maintenance requirements. For example, the aircraft structure is a relatively static assembly of single-celled elements, and except for items such as control services, landing gear, or doors, the only structural movement is a deflection under applied loads. However, the structure is subjected to a great many such loads in the course of its operating life. As we saw in Chapter 2, single-celled parts of the mechanism frequently exhibit wear out characteristics. This is true of metallic structural elements, which are subject to metal fatigue—that is, to a reduction in failure resistance with increasing age.

Another physical process that can lead to the age-related failure of structural elements is corrosion, although the effects of corrosion are much less predictable than those of fatigue. Even minor pitting seriously reduces both static strength and fatigue life, since the loss of load-carrying material correspondingly increases the stress on the rest of the element. Accidental damage has a similar effect in preventing structural components from realizing their inherent fatigue resistance. Thus, although the aircraft structure is designed for a very long fatigue life, it is subject not only to age-related failure in general, but to physical processes that compound the decline in failure resistance with age. The failure of a major structural assembly which causes the loss of some basic structural function – such as enabling aerodynamic lifting forces to balance the weight of the airplane or providing flight-control surfaces for maneuvering capability – clearly has safety consequences. Moreover, any failures short of a critical failure – failures that do not result in a loss of function to the aircraft – will usually not be evident to the operating crew. The primary consideration in identifying significant structural members, therefore, is the effect that failure of that member has on the residual strength of the remaining assembly, although consideration is also given to susceptibility to corrosion and accidental damage.

The generic term *structurally significant item* (SSI) is used to denote each specific structural region that requires scheduled maintenance to guard against the fracture of a significant member. This region may be defined as a site that includes a number of structural elements, it may be defined as the significant member in itself, or it may be a particular region on the member that is the best indicator of its condition. Often such items are the point at which different structural elements are joined; for example, the wing-to-fuselage joint is always listed as a structurally significant item. Most aircraft structure is maintained by on-condition inspections of the regions identified as structurally significant items. These inspections are designed to identify and repair corrosion, fatigue, and other damage at the earliest possible stage, since the replacement of a failed structural element is both difficult and expensive.

## Functionally significant items

Unlike structural items, most systems are equipped with instrumentation to monitor the performance both of the system as a whole and of individual assemblies within it .As a result, the occurrence of any functional failure in the system is usually evident to the operating crew. Moreover, most systems are designed to be highly redundant, so that the failure of one unit often has no effect on operating capability. Unless a second unit fails, the aircraft is dispatched as usual, and the corrective maintenance is simply deferred to a convenient time and location. Thus although the system as a whole is a *functionally significant item* (FSI), the units that comprise it would be classified as non significant, since their individual failures have no consequences at the equipment level.

Systems items differ in two other ways from structural items. Most systems components are themselves multi-celled, or complex; hence their overall reliability shows little or no deterioration with age. Certain metal parts in mechanical systems are subject to fatigue and corrosion, but these are rarely responsible for a dominant failure mode. To meet space and weight requirements, systems components are usually designed with a narrow margin between initial failure resistance and stress. Since they are therefore subject to more frequent failure, the system is usually also designed to facilitate replacement of failed units. A further distinction between systems and structural items is that certain systems, such as electrical and electronic components, are characteristically unable to benefit from scheduled maintenance.

Although the power plant is itself a system, it warrants a category of its own because of its complexity, its high costs, and the critical nature of some of its failure modes. The shutdown of one engine in a multiengine aircraft has operational, but not safety, consequences. However, the failure of turbine or compressor disks – or any other failures that generate projectiles, cause fires, or leave the engine so that it cannot be shut down – can clearly affect safety. These failure modes are always given careful attention in a maintenance program.

The powerplant can be viewed as a functionally significant item in itself, but the failure characteristics of each of its modules, or major subassemblies, are often quite different from those of the engine as a whole. For example, the collective probabilities of all powerplant failures have little relation to operating age, whereas single important parts may be subject to directly age-related failures. Thus scheduled-maintenance tasks in the powerplant program may include safe-life limits for some items and scheduled to rework for others. In as many instances as possible, however, on-condition inspections are employed, both to avoid the consequences of functional failures and to reduce the costs associated with scheduled removals. The powerplant is unique from a maintenance standpoint in that it is designed to permit extensive inspection capability on the aircraft, it can be replaced in a fairly short time (although unscheduled replacements have operational consequences), and it is subject to extensive shop inspections as well.

In the case of new engines there may be some failure modes that cannot be effectively controlled except by redesign. The occurrence of an unanticipated type of failure in any engine prompts an immediate response on the part of maintenance. The failure consequences are quickly assessed and the engine is examined to determine the cause of the failure. Next, some method is usually devised for inspecting the rest of the engines in service (or the suspect group of engines) for early signs of the same kind of failure. These inspections forestall further failures while the part is being redesigned. The alternative, if the failure is critical and no preventive task can be found, is grounding the fleet until the problem can be solved.

Because items within the power plant are exposed to many different forms of deterioration, including all those that affect the structure and the various systems, they have no common failure characteristic. Unlike systems items, however all engine failures have operational consequences and some failure modes have safety consequences. For this reason significant items in the power plant are identified primarily on the basis of their failure in effects. The very complexity of the power plant results in one further characteristic. Engines are subject to so many failure possibilities that operating data accumulate rapidly, especially with use on multiengine commercial aircraft. This rapid feedback, along with the high cost of corrective maintenance on engines, favors the initial selection of intensive on-condition inspections for power plant items, since the applicability of age-limit tasks can be investigated before the point at which age-related failures would have any major economic impact.

## 4.2. The RCM decision process

The partitioning procedure gives us a conservative first approximation of the items that might benefit from scheduled maintenance. Each of these items must now be examined in detail to determine whether its failure consequences actually qualify it as significant—and if so, whether the item can in fact benefit from scheduled maintenance. Even when the significance of an item is confirmed, there may be no form of preventive maintenance that is applicable and effective. Such items cannot be eliminated from consideration, however, without a full analysis.

### Evaluation of failure consequences

The consequences of a functional failure depend on both the nature of the function and the nature of the failure. Hence it is necessary to begin the analysis with an accurate list of all the functions demanded of an item and a clear definition of the conditions that constitute a functional failure in each case. It is also necessary to know the failure modes involved in order to determine the possible effects of each failure. Once this information has been assembled for every item to be examined, we are in a position to evaluate the actual consequences of failure. As a result of the partitioning process certain items will have been identified that had hidden functions – that is, their failure will not necessarily be evident to the operating crew. The first matter to be ascertained in all cases, however, is whether we will know when a failure has occurred. The following question is necessary, therefore, to ensure that all hidden functions are accounted for:

**Is the occurrence of a failure evident to the operating crew during the performance of normal duties?**

This question must be asked, not for each item, but for each *function* of the item. The loss of an item's basic function may be evident, but in many cases the item will have secondary or other characteristic functions whose failure will not be evident to the operating crew.

Recall from our discussion in Chapter 2 that any functional failure which has a direct effect on operational capability – including critical failures – will always be evident to the operating crew. If the effects of a failure are not observable, the loss of function has no immediate impact. But by the same token, there is no assurance that the failure will be reported and corrected. Thus if the answer to this first question is no for any function, scheduled maintenance is required for that item. The purpose of the task is not necessarily to prevent failures of the hidden function, but to prevent exposure of the equipment to a multiple failure involving that item.

In the case of the failure that is evident to the operating crew, the consequences might be immediate; we therefore need to know how serious they are likely to be:

**Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?**

This question must be asked for each functional failure and for each *failure mode*. Modern design practices ensure that transport aircraft are exposed to very few critical losses of function. However, certain failure modes, especially in engines, do cause secondary damage that poses a safety hazard. Therefore a yes answer to either aspect of this question means that preventive maintenance is mandatory and can be considered effective only if it prevents **all** occurrences of this type of failure.

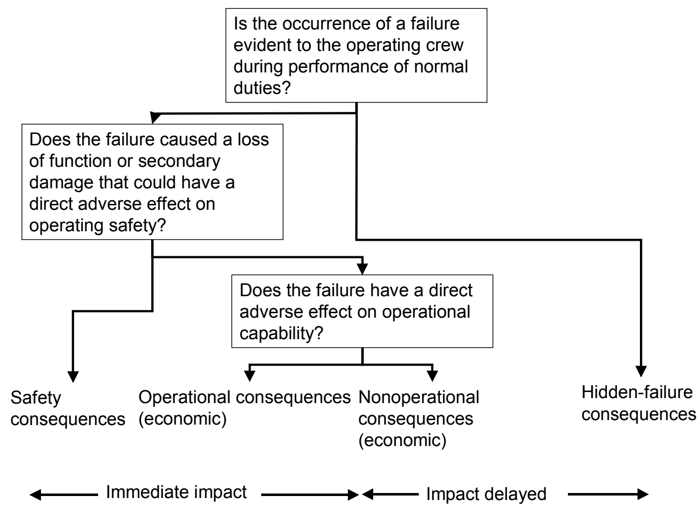



**Exhibit 4-2 Decision diagram to identify significant items and hidden functions on the basis of failure consequences. Failures that affect safety or operating capability have an immediate impact, since the aircraft cannot be dispatched until they have been corrected. The impact of nonoperational failures and hidden failures is delayed in the sense that correction can be deferred to a convenient time and location.**

If the answer to the safety question is no, our next concern is with the economic consequences:

**Does the failure have a direct adverse effect on operational capability?**

The consequences in this case include an immediate interruption of operations, reduced capability if the airplane continues in service, or the delay or cancellation of subsequent flights to make unscheduled repairs – all of which involve an economic loss beyond the cost of the repairs. In this case, although scheduled maintenance is not required for safety reasons, it may be desirable on economic grounds. Thus if the answer to this question is yes, any applicable preventive tasks must be investigated for cost effectiveness.

If the failure has no direct effect on operational capability, the economic consequences include only the cost of repair. However, certain functional failures may be far more expensive to repair than to prevent, especially in the case of the failure mode that causes extensive damage to surrounding items. Although scheduled maintenance is more likely to prove cost-effective when operational capability is a factor, there are certain failure modes for which it is often desirable to investigate the economic benefits of a preventive task. The relationship of these three questions and the decision outcomes in each case are illustrated in Exhibit 4.2. this simple decision-diagram approach provides us with the following basic information about each failure possibility:

- We know whether the failure will be evident, and therefore reported for correction.
- We know whether its consequences include a possible safety hazard for the equipment or its occupants.
- We know whether its consequences have a direct effect on operational capability.
- We know the objective of preventive maintenance in each case, and hence the criteria on for evaluating task effectiveness.

With this information we are now in a position to evaluate the maintenance possibilities for each item.

## Evaluating the proposed maintenance tasks

The first task to be considered for each anticipated failure mode of the item being study is an on-condition inspection:

**Is an on-condition task to detect potential failures both applicable and effective?**

If the answer is yes, an on-condition inspection task is put into the program for that failure mode. If we obtain yes answers for all the failure modes of an item, the analysis of that item is complete.

The applicability of an on-condition task can be determined by engineering specialists who are familiar with the design characteristics of the item, the materials used in it, and the inspection technology available. Thus this information will be on hand before the equipment goes into service. At the time an initial maintenance program is developed, however, there may not be enough information to determine whether the task will be effective. In this case we assume that it will be effective and establish the initial inspection intervals according to the seriousness of the failure consequences. Any applicable inspection task can be made effective in terms of failure prevention if the intervals are short enough, and if operating experience later shows was that it is not cost-effective, the task will be deleted from the program at the next review.

If an on-condition task is not applicable for certain failure modes, the next choice is a scheduled to rework task:

**Is a rework task to reduce the failure rate both applicable and effective?**

In this case the question of applicability as well and his effectiveness requires an analysis of operating data. Thus, unless the age-reliability characteristics of the items are known from prior experience with a similar item exposed to a similar operating environment, the assumption in an initial program is that an item will *not* benefit from scheduled to rework. In the absence of information, the answer to this question is no, and we wait for the necessary information to become available after the equipment goes into service.

A no answer to the rework question brings us to the question of a scheduled discard task:

**Is a discard task to avoid failures or reduce the failure rate both applicable and effective?**

In an initial maintenance program the only items selected for discard will be those for which the manufacturer has specified safe-life limits. The tasks associated with those items are put into the program, but in nearly all other cases the answer at this stage will be no.

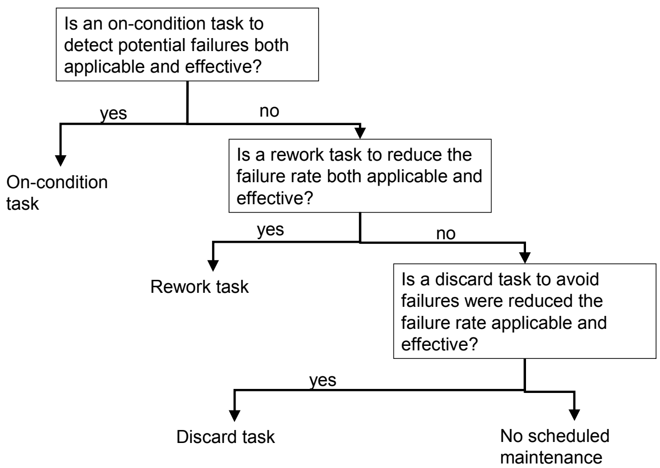



**Exhibit 4-3 Decision diagram to evaluate proposed scheduled-maintenance tasks. If none of the three directly preventive tasks meets the criteria for applicability and effectiveness, an item whose failures are evident cannot be considered to benefit from scheduled maintenance. If the item has a hidden function, the default action is a scheduled failure-finding task.**

# 4.3. Use of the RCM decision diagram

The small decision diagram in Exhibit 4.3 provides the essential mechanism for deciding which, if any, of the preventive-maintenance tasks are both applicable and effective for a particular item. To use this diagram, however, it is necessary to know the failure consequences that determine the effectiveness in each case and also dictate the default action to be taken at each decision level.

## The combined decision diagram

Exhibit 4.4, which brings together the decision questions in Exhibits 4.2 and 4.3, can be used to develop an RCM program either for new equipment or for equipment which is already in-service. As we will see in Chapter 5, it can also be used to modify the initial program as new information becomes available. The chapters in Part 2 discuss the application of RCM analysis to each of the three major divisions of the aircraft – systems, powerplant, and structures. For the time being, however, let's see how the failure consequences influence the process of task selection.

Consider an item which is subject to a critical failure. The answer to question 1 is yes, since any failure that has a direct adverse effect on operating safety will be evident to the operating crew. (This answer refers, of course, only to a loss of the particular function under consideration.) The answer to question 2 is also yes, since the failure has been stated as critical. All subsequent questions about this failure possibility therefore fall into safety branch of the diagram. This has two important implications for scheduled maintenance:

- Scheduled maintenance is *required* if an applicable preventive task can be found.
- A task can be considered effective only if it reduces the risk of critical failure to an acceptable level.

In the case of transport aircraft the risk must be at the level of extreme improbability to be acceptable, but in the general case an acceptable level does exist. For example, single-engine aircraft are utilized for various civilian and military applications.

Each failure mode that might result in this failure is now examined determine which of the proposed preventive tasks will accomplish the necessary objective. If an on-condition task is applicable for some failure mode, it can usually be made effective by assigning conservatively short inspection intervals (a yes answer to question 4). If there are failure modes for which on-condition inspection is not available, the question of scheduled rework is considered. However, in an initial program the failure data necessary to determine the applicability of such a task are rarely available, and no operating organization can afford the number of critical failures required to provide this information. Thus in the case of a critical-failure mode the answer to question 5 is no.

This brings us to the question of scheduled discard of the item or part in which the critical failure originates – that is, to a safe-life limit. In determining initial program requirements engineering advice may indicate that such a task is applicable. Its effectiveness cannot be evaluated, however, unless a safe-life limit has been established by developmental testing under simulated operating conditions. If a safe-life limit has been established, scheduled discard at this limit is required; if a life limit has not been established for this item, the answer to question 6 is no.

When some failure mode cannot be adequately controlled by any one of the preceding tasks we have one further recourse:

**7 Is a combination of preventive tasks both applicable and effective?**

There are occasional circumstances in which a combination of two or more preventive tasks will reduce the risk of critical failure to an acceptable level. In a single-engine aircraft, for example, any and all applicable tasks might be employed to reduce the likelihood of engine failure to the lowest level possible. In most instances, however, this is a stop-gap measure, pending redesign of the vulnerable part. If no combination of tasks can be found that will effectively avoid critical failures in the interim, it may be necessary to restrict operation of the equipment or even to remove it from service.

To return to the top of the decision diagram, suppose the failure of an item has no safety consequences (a no answer to question 2), but it does have operational consequences (a yes answer to question 3). In this event we are concerned only with the *economic* consequences of a functional failure:

- Scheduled maintenance is *desirable* if its cost is less than the combined costs of operational consequences and repair for those failures it prevents.
- The task can be considered effective only when it is cost-effective.

In scheduled airlines operational consequences can usually be measured in terms of the inability to deliver service to passengers in a timely fashion. In other operating contexts the cost of lost operational capability might be measured differently. However, a cost can always be imputed to any operational failure in terms of the *opportunity cost* of being unable to use the equipment has planned.

To determine whether a proposed maintenance task is economically desirable, it is necessary to know the imputed cost assigned to the expected operational consequences. In initial programs this will usually be an arbitrary figure based on the benefits anticipated at the time the equipment was purchased. In addition, it is necessary to have some idea of the likelihood of failure, the cost of the proposed task and the cost of corrective maintenance if the item is allowed to fail. Generally, if the expected failure rate is low and the operational consequences are not excessive, the decision will be to use no scheduled maintenance. As the total cost of failure increases, preventive maintenance becomes more attractive. In most cases it is possible to make a decision without a formal economic-trade-off study. (Later in the chapter we will examine a procedure for determining whether an economic-trade-off study is likely to be worthwhile.)

Where no applicable and cost-effective maintenance task can be found, we must either accept the operational consequences (no scheduled maintenance) or redesign the item to reduce the frequency of failures. This decision ordinarily depends on the seriousness of the operational consequences. If they represent a major economic loss, the default decision is redesign.

If the failure of an item has no operational consequences, the question of effectiveness is evaluated in direct economic terms:

- Scheduled maintenance is *desirable* if its cost is less than the cost of repair for those failures it prevents.
- A task can be considered effective only if it is cost-effective.

Task effectiveness in this case is a simple trade-off between the cost of prevention and the cost of cure. If both costs are of the same order of magnitude, the decision goes to no scheduled maintenance. The reason for this is that any preventive-maintenance task may disturb the steady-state conditions of the mechanism, and this risk should not be introduced without good cause. Thus a preventive task will be scheduled only where the cost of correcting failed items far outweighs the cost of preventing failures.

Note that many of the items designated for no scheduled maintenance through this decision process might well have been identified at the outset as those which cannot benefit from scheduled maintenance. This branch of the decision diagram, however, permits us to evaluate borderline items which might have benefited from a scheduled task if an applicable one could be found.

In the case of hidden-function items task effectiveness involves two criteria:

- Scheduled maintenance is *required* to avoid exposure to a possible multiple failure.
- A task can be considered effective only if it ensures adequate availability of the hidden function.

Some hidden functions are sufficiently important that their availability is protected by periodic checks by the operating crew – that is, they are made evident by defining the normal duties of the crew to cover them. In all other cases, however, scheduled inspections are necessary. Since hidden failures can have no direct effect on safety or operational capability, we can allow such items to fail, but we cannot afford the possible consequences of undetected failures. Thus in the absence of any directly preventive task that is applicable and effective, a specific failure-finding task must always be assigned.

## The role of the default strategy

The information to be channeled into RCM decisions requires analysis under **two different sets of conditions**. One is the development of an initial maintenance program on the basis of limited information. The other is modification of these initial requirements as information becomes available from operating experience. As information accumulates, it becomes increasingly easier to make robust decisions. In developing a prior-to-service program, however, there are many areas in which there is insufficient information for a clear-cut yes-or-no answer or the study group is unable to reach a consensus. To provide for a decision making under these circumstances it is necessary to have a backup default strategy which dictates the course of action in such cases.

The default strategy summarized in Exhibit 4.5 shows for each of the decision questions which answer must be chosen in case of uncertainty. In each case the default answer is based on protection of the equipment against serious consequences. For example, in the process of identifying significant items, if it can be demonstrated that the failure of an item has no effect on safety or operating capability, the item can be classified as nonsignificant and does not warrant further study to see if it can benefit from scheduled maintenance. **If there is any doubt**, however, it must be classified as significant and cannot be dismissed without further analysis. Similarly, if it is not certain that a loss of function will be evident to the operating crew, it is treated as hidden unless a failure mode involves critical secondary damage.

This default approach can conceivably lead to more preventive maintenance than is necessary. Some tasks will be included as protection against hazards that do not exist, and others may be scheduled far too frequently. The means of eliminating such excessive costs is provided by the age-exploration studies which begin as soon as the equipment goes into service. Through this process the information needed to refine the initial program (and make major revisions where necessary) is gathered systematically for evaluation. We will examine the techniques of age exploration and the nature of the information it provides in the next chapter.

Since an analysis of age-reliability characteristics requires failure data that will not become available until sometime after the equipment has been in-service, the default strategy will result in a no answer to nearly all questions concerning the applicability and effectiveness of scheduled rework and discard tasks. Consequently, any initial RCM program will consist essentially of on-condition tasks, a few safe-life discard tasks, and failure-finding tasks for hidden-function items, in addition to the usual servicing and lubrication tasks. Scheduled rework or economic-life discard tasks may be added at some later stage, after their applicability and effectiveness can be evaluated, but they rarely appear in an initial program.

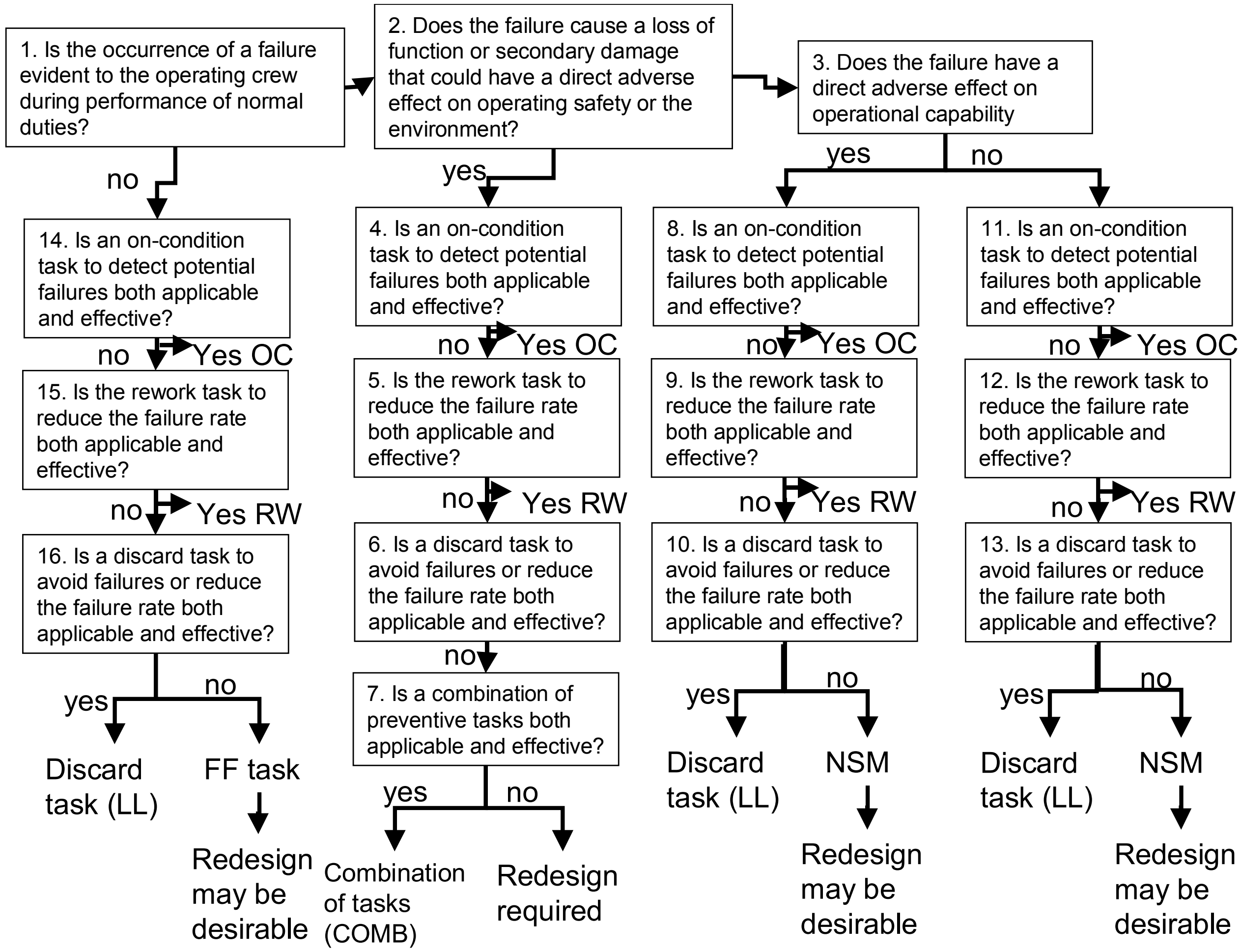



**Exhibit 4-4 The RCM decision diagram. These questions must be asked for each functional failure listed for the item. The first three questions determine the consequences of that failure, and hence the objective of preventive tasks. (F. S. Nowlan and H.F. Heap)**

**Exhibit 4-5 The default answer to be used in developing an initial scheduled-maintenance program in the absence of data from actual operating experience.**

| **Decision question** | **Default answer to be used in case of uncertainty** | **Stage at which question can be answered** | | **Possible adverse consequences of default condition** | **Default consequences eliminated with subsequent operating information** |
|---|---|---|---|---|---|
| | | Initial program (with default) | Ongoing program (operating data) | | |
| **IDENTIFICATION OF SIGNIFICANT ITEMS** | | | | | |
| Is the item clearly nonsignificant | No: classify item as significant | X. | X. | Unnecessary analysis | no |

| | | | | | |
|---|---|---|---|---|---|
| **EVALUATION OF FAILURE CONSEQUENCES** | | | | | |
| Is the occurrence of a failure evident to the operating crew during performance of normal duties? | No (except for critical secondary damage): classify function as hidden. | X. | X. | Unnecessary inspections that are not cost-effective | yes |
| Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety and the environment? | Yes: classify consequences as critical | X. | X. | Unnecessary redesign or scheduled maintenance that is not cost-effective | No for the redesign; yes for scheduled maintenance |
| Does the failure have a direct adverse effect on operational capability? | Yes: classify consequences as operational (production ) | X. | X. | Scheduled maintenance that is not cost-effective | yes |
| **EVALUATION OF PROPOSED TASKS** | | | | | |
| Is an on-condition task to detect potential failures technically feasible? | Yes: include on-condition task in the program. | X. | X. | Scheduled maintenance that is not cost-effective | yes |
| If an on-condition task is technically feasible (effective), is it worthwhile? | Yes: assigned inspection intervals short enough to make the task effective. | X. | X. | Scheduled maintenance that is not cost-effective | yes |
| Is a rework task to reduce the failure rate applicable? | No (unless there are real and applicable data): assign item to no scheduled maintenance. | -- | X. | Delay in exploiting opportunity to reduce costs | yes |
| If a reworked task is applicable, is it effective? | No (unless there are real and applicable data): assign item scheduled maintenance | -- | X. | Unnecessary redesign (safety) or delay in exploiting opportunity | No for redesign; yes for scheduled maintenance |
| Is a discard task to avoid failures or reduce the failure rate applicable? | No (except for safe-life items): assign item to know scheduled maintenance | X. (safe life only) | X. (economic life) | Delay in exploiting opportunity to reduce costs | Yes |
| If a discarded task is applicable, is it effective? | No (except for safe-life items): assign item to know scheduled maintenance | X. (safe life only) | X. (economic life) | Delay in exploiting opportunity to reduce costs | yes |

## 4.4. Determining cost effectiveness

Since a moderate amount of information gathering is necessary for calculations of cost-effectiveness, it is helpful to know whether the effort is likely to be fruitful. The decision-diagram approach is also useful in this area. Exhibit 4.6 illustrates one method for deciding whether a detailed assessment of an applicable task might be worthwhile.

Up to this point we have not been concerned about failure rates, since it is not a primary measure of consequences. In the case of critical failures it has no bearing; in fact, the sole objective is to avoid any failures on which to base a rate. Where the consequences are economic, however, the total cost depends on the frequency with which these consequences are likely to occur. The first question in evaluating the cost effectiveness of prevention, therefore, concerns the frequency of functional failures:

**Is the functional-failure rate high?**

Since it is seldom worthwhile to deal with rare types of noncritical failures, this question rules out items that fail so seldom that the cost of scheduled maintenance would probably be greater than the benefits to be derived from it. The term *high*, of course, is open to interpretation. In airline practice a failure rate > 1 per 1000 hours of flight time is usually considered high, where as a rate of less than 0.1 per 1000 hours is usually not considered important. This question is often easier to answer if the failure rate is described in terms of the number of failures per month.

If the failure rate is judged to be high, the next concern is the cost involved. Operational consequences are usually the major costs associated with a high failure rate:

**Does the failure involve operational consequences?**

Any failure that prevents continued dispatch of the equipment involves operational consequences. However, the extent of the economic loss depends largely on the intended use of the equipment. In a military context, for example, a much higher cost might be imputed to dispatch of an airplane with restrictions on its operating performance and would be the case in a commercial-airline context. If the failure does have operational consequences, the total cost of failure includes the combined cost of these consequences and the cost of repair.

Even when operational consequences are not involved, it may be advantageous to forestall a particularly expensive failure mode:

**Does any failure mode cause unusually high repair or operating costs?**

This question must be investigated separately, since such failure modes will usually be responsible for only a small fraction of the total number of failures.

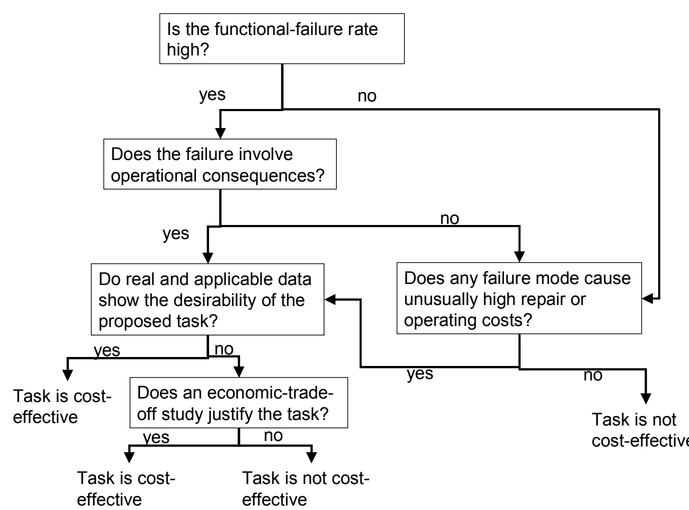



**Exhibit 4-6 Decision diagram for evaluating the probable cost effectiveness of a proposed task when scheduled maintenance is not required to protect operating safety or the availability of hidden functions. The purpose of the decision technique is to reduce the number of formal economic-trade-off studies that must be performed.**

A yes answer to either of the preceding two questions means that we need further information:

**Do real and able data show the desirability of the proposed task?**

It is possible to arrive at a yes answer to this question if there is substantial evidence that this task was cost-effective in the past for this or a similar item. If so, the task can be scheduled without a formal study.

**Exhibit 4-7 A pro forma for analyzing the support costs associated with scheduled removals for rework. At least four proposed rework intervals must be examined to determine whether a cost-effective interval does exist.**

| item | | |
|---|---|---|
| Annual volume of operation | | |
| Proposed interval | | |
| Number of failures per year[1] | X. | |
| Average base cost of repairing a failed unit[2] | $X | |
| Annual base cost of repairing failed units | | $X |
| Number of failures that have operational consequences[3] | X. | |
| Average cost of operational consequences after failure | $X | |
| Annual cost of operational consequences | | $X |
| Number of scheduled removals per year | X | |
| Average base cost for a time-expired unit[14] | $X | |
| Annual base cost for time-expired units | | $X |
| Number of spare units required to support workload | X. | |
| Cost of unit | $X | |
| Annual cost of spare units required | | $X |
| Total annual support costs[4] | | $X |

Otherwise the question of economic trade-off must be evaluated for each of the applicable maintenance tasks:

**Does an economic-trade-off study justify the task?**

An economic-trade-off study involves several steps:

- An estimate of the incremental effect of the task on the failure rate of the item for several different task intervals
- A translation of the reduced failure rate into cost reductions
- An estimate of the cost of performing the proposed task for each of the intervals considered
- Determination of the interval, if one exists, at which the cost benefit ratio is the most favorable

Exhibit 4.7 shows a pro forma for evaluating the cost effectiveness of a scheduled to rework task. As we saw in Chapter 3, the cost factors for on-condition tasks and scheduled rework tasks are quite different. Scheduled removals increase both the total shop volume and the number of spare units that are undergoing rework. Consequently, unless the frequency of a very expensive failure is materially reduced by an age limit, the total cost of this task will usually outweigh its economic benefits.

In contrast, the total number of potential failures removed as a result of on-condition inspections is not appreciably greater than it would be if each unit were allowed to fail. Moreover, the cost of repairing potential failures is usually less than the cost of repair after a functional failure. As a result, on-condition inspection tasks, when they are applicable, are relatively easy to justify.

The important role of cost effectiveness in RCM decision-making helps to clarify the nature of inherent reliability characteristics. The inherent reliability of an item is not the length of time it will survive with no failures; rather, it is the level of reliability the item will exhibit when it is protected by preventive maintenance and adequate servicing and lubrication. The degree of reliability that can be achieved, however, depends on certain characteristics that are a direct result of the design details of the equipment and the manufacturing

[1] It may be desirable to study a specific expensive failure mode separately.
[2] Includes cost of removing and installing at line station and of transporting it to and from the maintenance base
[3] The number of failures that have operational consequences may be different from the total of failures, since not every failure will have such consequences.

[4] If the change in volume of work at the maintenance base results in changes in facility requirements, the annual cost of such changes should be included in the support costs.

processes that produced it. These characteristics determine both the need for preventive maintenance and the effectiveness with which it can be provided. Thus from a maintenance standpoint inherent reliability characteristics are decision factors such as those listed in Exhibit 4.8. Notes that the answer to each of the questions in Exhibit 4.4 requires a knowledge of at least one of these characteristics.

| Inherent reliability characteristic | Impact on decision-making |
|---|---|
| Failure consequences | Determines significance of items for scheduled maintenance; establishes definition of task effectiveness; determines default strategy when no applicable and effective task can be found |
| Visibility of functional failure to operating crew | Determines the need for failure-finding task to ensure that failure is detected |
| Ability to measure reduced resistance to failure | Determines applicability of on-condition tasks |
| Rate at which failure resistance decreases with operating age | Determines interval for long-conditioned tasks |
| Age-reliability relationship | Determines applicability of rework and discard tasks |
| Cost of corrective maintenance | Helps establish task effectiveness, except for critical failures |
| Cost of preventive maintenance | Helps establish task effectiveness except for critical failures |
| Need for safe-life limits to prevent critical failures | Determines applicability and interval of safe-life discard tasks |
| Need for servicing and lubrication | Determines applicability and interval of servicing and lubrication tasks |

**Exhibit 4-8 examples of inherent reliability characteristics and their impact on decision-making. Each decision question in Exhibit 4.4 requires a knowledge of at least one of these characteristics. In the absence of this knowledge, a default answer must be employed in developing an initial scheduled-maintenance program.**

The test of cost effectiveness means that RCM program will not include some tasks that might reduce the likelihood of noncritical failures. However, when a failure has economic consequences the inclusion of the task that is not cost-effective would merely transfer these consequences from one cost category to another; it would not reduce them thus the cost factors on both sides must be considered inherent reliability characteristics, since they dictate the level of reliability that is feasible for an existing design. Within this framework, RCM analysis ensures all the operating reliability of which the equipment is capable. Moreover, it results in a selection of only those tasks which will accomplish this objective; hence it also provides the required maintenance protection and minimum cost.

Certain of the inherent reliability characteristics of new equipment are unknown at the time a prior-to-service maintenance program is developed. Consequently the initial program is somewhat more expensive than later refinements of it will be (although it is still a minimum-cost program in terms of the information available at the time). This situation is inevitable because of the default decisions necessary to protect the equipment in the absence of full information. It is not too serious a matter, however, because of the relatively slow rate at which fleets of new equipment grow. For example, the Boeing 727 fleet shown in Exhibit 4.9 took six years to reach its maximum size of 150 aircraft. Although the full fleet finally flew more than 400,000 total hours a year, the 20 planes in service by the end of the first year had flown a total of only 34,300 hours. Thus the maintenance costs stemming from these initial default decisions have little overall economic impact and will be materially reduced with the information available by the time the fleet reaches full-size.

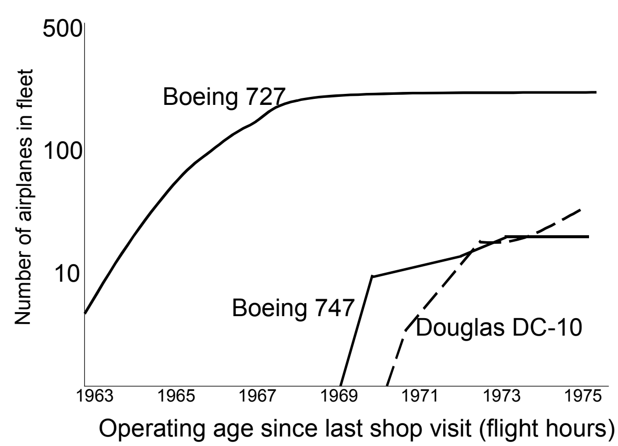



**Exhibit 4-9 Examples of fleet growth in a commercial airline. Each purchasing airline has a**

**maximum rate at which it can accept new airplanes, determined by training and staffing requirements. The rate at which new equipment can enter service is highest for large airlines. (United Airlines)**

## 4.5. Age exploration

One of the most important aspects of an initial RCM program is *age exploration* to determine the applicability of certain tasks and the most effective intervals for others. In the case of aircraft this process starts with the manufacture's certification test flights, during which some of the most frequent types of failures will be identified. If some of these failures have major consequences, product improvement will be initiated before any equipment is delivered to the purchaser. The information obtained during the certification period, however, identifies only those items which have failed – presumably those with a high probability of failure. The entire certification program for a new commercial transport plane requires a total of only 1500 to 2000 flight hours accumulated on the five or six planes assigned to the program. The flying time for any one test plane is usually no more than 400 or 500 hours. In contrast, once a plane is put into service, it may fly 300 or more hours a month. At this point we can begin to acquire information on the additional reliability characteristics of the equipment.

**As we saw in Section 3.1, applicability of an on-condition task depends on the ability to measure reduced failure resistance. Its effectiveness, however, depends on the interval between inspections. The same holds true for failure-finding tasks assigned to hidden-function items. For this reason all such tasks are assigned conservatively short intervals in an initial program, and all items whose failure could have safety or economic consequences are carefully monitored by frequent sample inspections to determine the exact effect of operating age on their condition. The simple part illustrated in** Exhibit 3-1**, for example, would initially be monitored at the intervals shown in Exhibit 4.10 to determine the exact point to be defined as a potential failure, the age at which inspections should start, and the most effective interval between inspections. Because on-condition inspections play a large role in the maintenance programs for turbine engines, some interesting practices have evolved to reduce the cost of obtaining this information. When an initial program is being developed, experience with earlier types of engines will suggest many parts that might benefit from on-condition tasks, as well as some that might benefit from scheduled rework. Consequently the sample inspections required for age exploration make up a large part of the initial maintenance program for any powerplant. Some of these inspections can be performed while the engine is installed, but others can be performed only at a major maintenance base after a certain amount of disassembly of the engine.**

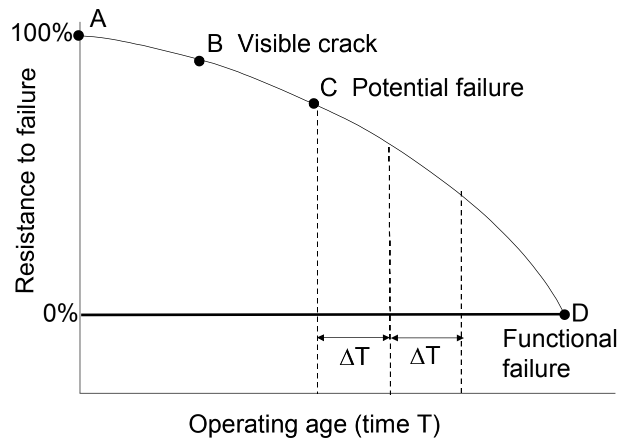



**Exhibit 4-10 Initial sampling intervals assigned to an age-exploration program to determine the rate at which failure resistance declines. Reduced resistance is not detectable until a visible crack appears; thereafter the rate of crack propagation is monitored to determine the exact point to be defined as a potential failure, the point at which it is necessary to begin on-condition inspections, and the most effective inspection interval to ensure that all failing units will be identified at the potential-failure stage.**

The "on-the-wing" inspections are handled by an initial requirement for early inspections of the items on all engines. However, if inspection of the first few engines to reach this limit discloses no unsatisfactory conditions, the limit for the remaining engines is extended. Thus very few engines are actually inspected at any fixed time limits until the point at which it becomes desirable to stop extending the limit.

For those parts that require engine disassembly for inspection, the practice is to define any limit at which inspection information is considered to be of value. The initial operating age of a part might be limited, for example, to 1500 hours without inspection, and the threshold age for valid sampling information might be set at 500 hours. This was done for the General Electric CF 6-6 in the Douglas DC-10. In that case the FAA required inspection of two sets of parts (equivalent to 2 engines) to justify an increase in the 1500-hour limit. The initial maintenance program stated that sampling information could be obtained either from one part aged 500 to 1000 hours and a second part aged 1000 to 1500 hours, or else from two parts that were both aged 1000 to 1500 hours. The two sets of part-inspection reports could be based on the inspection of parts in any number of engines.

The reason for this flexibility in scheduling is to take advantage of *opportunity samples*, samples taken from engines that have failed and have been sent back to the main base for repair. Any undamaged parts from these engines can be used to meet the sampling requirements. This procedure makes it unnecessary to schedule engine removals for disassembly solely for the purpose of inspecting parts. Such *forced removals* are necessary only when the required volume of sampling cannot be obtained from opportunity samples. Because new types of engines usually have high failure rates that create abundant opportunity samples, it is possible to make a careful evaluation of the condition of each part before any engines on the aircraft actually age to the initial maximum limit.

On-condition inspections also play the primary role in the maintenance programs for structures. However, unlike power plants, structure does not provide opportunity samples. The structure is designed as an integral unit, and corrective maintenance on any structural item removes the entire airplane from service. Moreover, because the failure of any major structural assembly is critical, all parts of the structure are designed to survive to very high ages. In the case of structure, therefore, the inspection program itself is the only vehicle for age exploration, and the inspection samples consist of individual airplanes, rather than samples of parts from different airplanes. The initial inspection interval for each structurally significant item is set at only a fraction of the age at which evidence of deterioration is expected to appear, not only to find and correct any conditions that may reduce the anticipated design life, but also to identify the age at which reduced failure resistance first becomes evident.

Whereas powerplant items are continually interchanged and replaced as part of the normal repair cycle, structural members are repaired, but are rarely replaced with new parts. Consequently the age of most parts of a given structure is the same as the total age of the airplane. This makes it possible to concentrate age-exploration activities on the highest total-time airplanes/ The first few airplanes to reach the initial limit established for major structural inspections are designated as *inspection samples*. All inspection findings for these airplanes are carefully documented, so that any changes in their condition with age can be identified before younger airplanes reach this age. If there are no signs of deterioration, the starting intervals in the initial program will usually be increased for the remaining airplanes in the fleet.

Age exploration of systems items is conducted on still another basis. Systems items are generally characterized by low reliability; hence they provide abundant opportunity samples. However, because systems failures are rarely critical and so many systems items cannot benefit from scheduled maintenance, extensive inspection of opportunity samples is usually not justified by the value of the information obtained. In this case the frequency of failures is likely to have greater economic impact than the consequences of individual failures. Thus for systems items age exploration is based primarily on the monitoring and analysis of failure data to determine the cost-effectiveness of proposed tasks. In the following chapter we will examine the many aspects of the age-exploration process.

## 4.6. Packaging the maintenance tasks

Once each maintenance task in the prior-to-service program has been assigned an appropriate initial interval, either for the purpose of age exploration or on the basis of conservative judgment, the RCM tasks are combined with other schedule tasks – the servicing and lubrication tasks specified by the manufacturer and the scheduled zonal-installation inspections. All the tasks with similar intervals are then grouped into a number of *maintenance packages*, each with its own interval. The principle is the same as that spelled out in new-car warranties, which specify a certain group of servicing and inspection tasks to be performed every 1000 miles, another to be performed every 5000 miles, and so on. For commercial aircraft these intervals range from between-flight checks at every station to major inspections at 8- to 10-year intervals at the maintenance base.

This grouping results in slightly more frequent performance of some tasks than is strictly necessary, but the additional cost is justified by the increase in maintenance efficiency. Those tasks that are most expensive, both in actual cost and in terms of downtime for out-of-service equipment, tend to shape the overall package. Thus if one task must be performed every 1000 miles and another can be done easily at the same time, they will both be scheduled for that interval. If the second task is required, say, every 2500 miles, it will be scheduled every other time the first task is done, and so on.

Airlines frequently give each of the major scheduled-maintenance packages an alphabetical designation; hence they are commonly known as *letter checks*. An A check might be performed every 125 hours of flight time, a B check every 900 hours, and so on. Exhibit 4.11 shows the sequence of letter checks as they would occur for an airplane over an operating period of 3600 hours. The content of the given letter checks will not necessarily be the same every time it is performed, since some tasks will come up only at every second or third occurrence of a check. However, the fact that the more expensive packages occur at longer intervals means that as the level of work increases, fewer stations need to be equipped to handle it.

| Age (flight hours) | Work package | Age (flight hours) | Work package |
|---|---|---|---|
| 125 | #1A Check | 1925 | #17A Check |
| 250 | #2A Check | 2050 | #18A Check |
| 375 | #3A Check | 2175 | #19A Check |
| 500 | #4A Check | 2375 | #20A Check |
| 625 | #5A Check | 2425 | #21A Check |
| 750 | #6A Check | 2550 | #22A Check |
| 875 | #7A Check | 2675 | #23A Check |
| 900 | #1B Check[1] | 2700 | #3B Check[2] |
| 1025 | #9A Check | 2852 | #25A Check |
| 1150 | #10A Check | 2950 | #26A Check |
| 1275 | #11A Check | 3075 | #27A Check |
| 1400 | #12A Check | 3200 | #28A Check |
| 1525 | #13A Check | 3325 | #29A Check |
| 1650 | #14A Check | 3450 | #30A Check |
| 1775 | #15A Check | 3575 | #31A Check |
| 1800 | #2B Check[3] | 3600 | #1C Check[4] |

**Exhibit 4-11 A sample schedule of maintenance packages. Each work package includes all scheduled tasks to be performed at that interval. The A check includes all tasks scheduled at 125-hour intervals; the B check consists of all tasks scheduled at 900-hour intervals, as well as the A check that would otherwise be performed at that interval; and the C check, scheduled for 3600-hour intervals, includes all the tasks scheduled for that interval, along with both the A and B checks that would ordinarily take place at that time. The A checks are performed at any of several line-maintenance stations. Planes are routed to a few large maintenance stations for B checks, and C checks are performed at the maintenance base.**

In addition to the letter checks, which package the expensive or time-consuming tasks, there are a number of smaller service packages. For example, a #1 service check might include those tasks scheduled for every stop at the line maintenance station, and a #2 service check might be scheduled for every stopover of more than five hours (unless a higher-level package is being performed), and so on.

The entire scheduled-maintenance program, packaged for actual implementation, must be completed before any new aircraft can enter service. Up to this point RCM analysis has provided us with a set of tasks based on those reliability characteristics that can be determined from a knowledge of the equipment and the operating context. Once the equipment enters service a whole new set of information will come to light, and from this point on the maintenance program will evolve on the basis of data from actual operating experience. This process will continue throughout the service life of the equipment, so that at every stage maintenance decisions are based, not on an estimate of what reliability is likely to be but on the specific reliability characteristics that can be determined at the time.

[1] Includes #8 A check.
[2] Includes #16 A check.
[3] Includes #24 A check.
[4] Includes #4 B check and #32 A check.

# 5. Chapter Five - Evolution of the RCM program

In the preceding chapters we have examined the framework of RCM analysis and the decision process that leads to the selection of tasks for an initial maintenance program. After the equipment enters service information becomes available about its actual interaction with the operating environment. This information almost certainly contains some surprises – unanticipated types of failures, unexpected failure consequences, unusually high failure rates, or even an absence of anticipated failures. Because the volume of operation is small at first, information is gained at that time about the failures that are likely to occur soonest and with the greatest frequency. As operating time accumulates, the less frequent types of failures are discovered, as well as those that tend to occur at higher operating ages. All this information is used for continuing evolution of the ongoing maintenance program.

Any complex equipment is a failure generator, and failure events will occur throughout its whole operating life. The response to these events depends on the failure consequences. If an unanticipated failure has serious implications for safety, the first occurrence sets in motion an immediate cycle of maintenance and design changes. In other cases waiting until several failures have occurred allows a better assessment of their frequency to determine the economic benefits of preventive tasks, or possibly redesign. Very often waiting until enough failures have occurred to permit an evaluation of each-reliability relationships provides the information necessary to modify the initial maintenance decisions.

Evolution of the scheduled-maintenance program does not consist solely of reactions to unanticipated failures. The information that becomes available – including the absence of failures – is also used for systematic evaluation of all tasks in the initial program. On the basis of factual data, the initial conservative intervals for on-condition inspections can be adjusted and the applicability of scheduled rework and economic-life tasks can be investigated. Actual operations will frequently confirm the a priori assessments of failure consequences, but occasionally the consequences will be found to be more serious or less serious than anticipated, or a failure thought to be evident to the operating crew is not, and vice versa. The process by which all this information is obtained is called *age exploration*, both because the amount of information is a direct function of the age of the equipment in service and because some of this information relates to the ages of the items themselves.

## 5.1. The uses of operating data

It is important to recognize, both in planning a prior-to-service program and at the age-exploration stage, that a fleet of equipment does not materialize overnight. In commercial aviation new planes are delivered to an airline at a rate of 1 to 4 a month, and as we saw in Exhibit 4.9, the number of aircraft in service and the associated volume of operations builds up slowly. This allows us to concentrate first on the most frequent failures (since those that occur early will continue to occur early after either delivery or repair) or on those failures with the most serious consequences. As the volume of operations increases, the less frequent failures come to light and can be dealt with later. In a military environment, where operating experience does not accumulate as rapidly, this latter information may be obtained by deliberate heavy use of the first few pieces of equipment – the fleet-leader concept—although the small size of the sample data presents a serious drawback.

The reliability information obtained from actual operating experience is quite varied. Although the failure rate plays a role, early in operation, in pinpointing design problems and evaluating task effectiveness, an age-exploration program is organized to provide the following kinds of information:

- The types of failures the equipment is actually exposed to as well as their frequencies
- The consequences of each failure, ranging from direct safety hazards through serious operational consequences, high repair costs, long out-of-service times for repair, to a deferred need to correct inexpensive functional failures
- Confirmation that functional failures classified as evident to the operating crew are in fact evident during normal performance of duties
- Identification of the circumstances of failure to determine whether the failure occurred during normal operation or was due to some external factor, such as a bird strike
- Confirmation that on-condition inspections are really measuring the reduction in resistance to a particular failure mode

**Refinements of initial maintenance program**
**Results of age exploration**

| Inspection tasks | Proposed age-limit tasks | Items assigned to no scheduled maintenance | Unanticipated failure modes or consequences | New or redesigned item | Changes in inspection technology |
|---|---|---|---|---|---|
| Confirm that reduction in failure resistance is visible. | Determine age-reliability relationship to determine that conditional probability of failure increases with age | Monitor and evaluate operational data to see whether some applicable and effective task can be developed | Develop on-condition tasks to prevent critical failures and to prevent or reduce frequency of expensive failures at low ages. | Conduct RCM analysis of item when it first enters service. | Evaluate applicability and effectiveness of new on-condition techniques. |
| Determine rate of reduction in failure resistance. | If failures are age-related, determine whether a cost effective age limit exists. | | Develop design changes necessary for permanent correction of problems | | |
| Confirm or modify defined potential-failure condition. | | | Develop failure-finding tasks for hidden functions not identified in initial program. | | |
| Adjust inspection interval and age for first inspection, if applicable. | If a cost-effective interval can be found, add task to program | | Develop on-condition or other tasks to control critical or inexpensive failures at high ages, where product improvement may not be economically justified. | | |

**Exhibit 5-1 Summary of the uses of new information in the continuing evolution of the scheduled-maintenance program. After the equipment enters service, age exploration and the evaluation of actual operating data continue throughout its entire service life.**

- The actual rates of reduction in failure resistance, to determine optimum inspection intervals
- The mechanism involved in certain failure modes, to identify new forms of on-condition inspection and parts that require design improvement
- Identification of tasks assigned as default actions in the initial program which do not prove applicable and effective
- Identification of maintenance packages that are generating few trouble reports
- Identification of items that are not generating trouble reports
- The ages at which failures occur, so that the applicability of scheduled rework and discard tasks can be determined by actuarial analysis

Exhibit 5.1 summarizes the uses of all this information in refining and revising the initial maintenance program. The refinements are useful, but their overall economic impact is usually quite small. The major revisions are associated with unanticipated failures, design modifications, and the exploitation of new inspection technology; in this area far greater economies are realized.

## 5.2. Reacting to serious failures

After new equipment enters service it may experience unanticipated types of failures and failure consequences. The most serious of these are usually in the powerplant and the basic structure. Although such failures can occur at any point in the life of the equipment, they are most likely to occur early in operation. The first failure may have such serious implications for operating safety or economics that all operating organizations and the manufacturer react immediately. Thus there is a structured pattern of events associated with unanticipated failures which results in a characteristic cycle of reliability improvement.

Suppose the unforeseen failure is a critical engine failure. As an immediate step, engineering investigations are undertaken to determine whether some on-condition inspection or other preventive task will be effective. This preventive measure may result in a substantial increase in maintenance costs. With a new engine a large number of engine removals, dictated either by the discovery of potential failures or by scheduled removal of all units, will also make it difficult to provide replacement engines. The next step is action to redesign the parts in which the failure mode originates. When the new parts are available, all the engines in service must then be modified to incorporate the change. Not all design changes are successful, and it may take several attempts over a period of two or three years to correct the problem. Once the problem has been eliminated, the scheduled-maintenance tasks instituted to control this type of failure are no longer necessary and can be discontinued.

Exhibit 5.2 illustrates this cycle. A year after this engine entered service two critical failures occurred during a three-month period. Both failures were found to be caused by notch wear in the third-stage turbine blades. Since this failure mode was also found to be detectable at the potential-failure stage, a line-maintenance on-condition inspection was specified to check for loose turbine blades. Frequent inspection intervals resulted in a large number of engine removals for this condition, but removal of these potential failures prevented any further functional failures. The turbine blade was redesigned, and halfway through the following year modification of the existing engines was started to incorporate the new "low-swirl" blades. The on-condition inspections were continued, but as more and more modified engines entered service, the number of premature removals (potential failures) dropped. Finally, about three years after the first two failures, the on-condition inspections were discontinued.

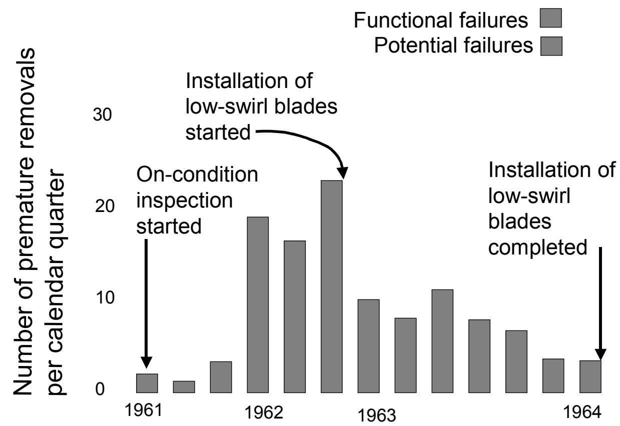



**Exhibit 5-2 The pattern of events associated with an unanticipated critical failure mode in the Pratt & Whitney JT4 engine. The data represents all engine removals for this failure mode, the first two as functional failures and the rest as potential failures found by an on-condition task developed after the first failure events. These premature removals prevented all further functional failures, and as modified engines entered service, the number of potential failures also decreased. When no further potential failures were found, the on-condition task was deleted from the program. (United Airlines)**

In new equipment the scheduled-maintenance tasks generated in response to early critical failures are nearly always on-condition inspections. Age-limit tasks are not likely to be feasible, since there are no data for actuarial analysis, and in the case of early failures, taking some fraction of the age at failure as a safe-life limit could easily be ineffective. Moreover, a short safe-life limit might effectively preclude continuing operations of the equipment, since it would be difficult to provide the labor and spare parts needed for such intensive maintenance. The definition of an applicable on-condition task, however, may require great ingenuity. The failure mode must be determined, and a specific part that shows physical evidence of reduced failure resistance must be identified. Then some means of inspecting the part while it is still installed must be devised.

Under the circumstances both the potential-failure point and the inspection interval will be established on a very conservative basis. As soon as the on-condition task is implemented, all the equipment in service is inspected. The first inspection of the fleet often leads to a large number of removals for the newly defined potential failure. The rate of removal after this first inspection will be much lower, of course. It may be low enough to justify increasing the initial conservative inspection interval, but the inspections themselves will be continued until experience has demonstrated that the problem no longer exists.

The cycle for early structural difficulties is similar. Once again, it is necessary to determine the failure mode and devise an on-condition inspection for potential failures. In this case the inspections may be scheduled as often as once every flight cycle or at intervals as long as 2000 or 3000 flight cycles. Again, even though the incidence of potential failures turns out to be relatively low after the first fleet inspection, the task itself is continued until the design can be modified.

Serious unanticipated failures to not necessarily occur early in the life of new equipment. At later ages, however such failures may not lead to design changes. The first response is still the same – the development of new scheduled-maintenance tasks. At this stage the imposition of safe-life limits may be both technically and economically feasible. On-condition tasks may also be applicable, but the inspections can be scheduled to begin at a relatively high age and may have longer intervals. Unless the failure mode is strongly related to age, in which case the life-limit task may be more appropriate, the number of potential failures found by on-condition inspections will be far lower than in relatively new equipment. Depending on the age of the equipment, the cost of redesign may not be warranted, since economic justification too depends on the remaining technologically useful life of the equipment.

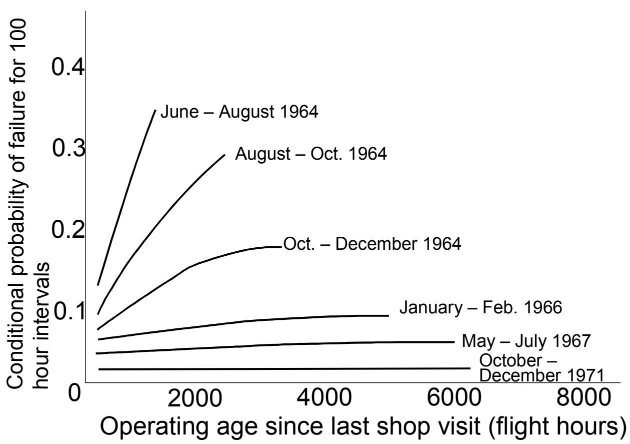



**Exhibit 5-3 Results of successive age-reliability and analysis of the Pratt & Whitney JT8D engine of the Boeing 727. As engineering improvements gradually overcame dominant failure modes, the conditional-probability curve continued to flatten until it eventually showed no relationship of engine reliability to operating age. (United Airlines)**

One further way of coping with failure is to restrict the operating procedures to put less stress on a vulnerable component until it can be redesigned. Sometimes the opposite strategy is also useful. When no specific potential-failure condition can be identified, it may be possible to preempt a serious failure by inducing it under other circumstances. In one such case failures of a compressor disk on a tail mounted turbine engine were occurring at very low ages, and on-condition inspections were feasible. It was possible to keep the plane in service, however, by requiring the pilots to brake at the end of the runway and apply takeoff thrust with the aircraft stationary. The peak stress on the disk occurred when takeoff thrust was first applied and decreased as the disk warmed up. Thus if the disk did not fail during warm-up, it was unlikely to do so during flight. This strategy resulted in several expensive failures, but they were not critical on the ground, whereas the secondary effects of the disk failure would have been critical in flight.

A new piece of complex equipment often experiences a high failure rate. Often, too, the majority of these failures result from a small number of failure modes. In the case of aircraft engines the conditional probability of such dominant failure modes will frequently increase rapidly with operating age. Exhibit 5.3 shows the results of successive analyses of engines that entered service in 1964. At that time its initial reliability was poor, the conditional probability of the failure was high, and this probability increased rapidly with age. However, the increase was linear and showed no identifiable wearout zone. Within a few months reliability of this engine was substantially improved by design modifications directed at the dominant failure modes. The initial high failure rate brought the unmodified engines into the shop very frequently, which facilitated fairly rapid incorporation of the modified parts. Consequently the conditional probability of failure continued to drop, and ultimately the reliability of this engine showed no relationship to operating age.

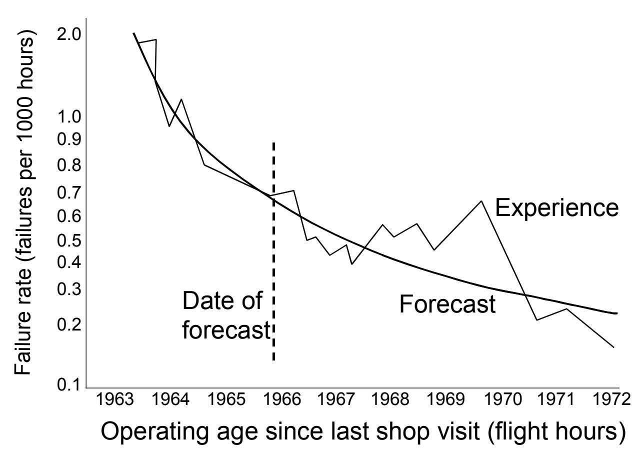



**Exhibit 5-4 Comparison of actual failure rates of the Pratt & Whitney JT8D engine with a forecast made in December 1965. During initial operation the failure rate based on small samples will show large variations in different calendar periods however, since reliability improvement is characteristically exponential, it is possible to predict the**

**expected reduction in failure rate over a longer calendar period. The temporary variation from the forecast level in this case was the result of a new dominant failure mode which took several years to resolve by redesign. (United Airlines)**

Once the early dominant failure modes in an engine are disposed of, it becomes increasingly difficult to make further improvements. Because of its complexity, the engine will always be subject to many different failure modes, and some needn't be dominant. However, the failure probability associated with any given mode is too low to justify further development of the engine. The difference between an item's initial and mature failure rate is its *improvable failure rate* – the portion that will be eliminated by product improvement. If a particular engine has a failure rate of two per 1000 hours when it first enters service and we anticipate that its failure rate will ultimately drop to 0.3, then the improvable failure rate is 1.7.

In many cases the improvable failure rate declines exponentially over calendar time – that is, the percentage of reduction remains constant, although the amount of reduction becomes smaller as the failure rate is reduced. This percentage has been as much as 40 percent a year for engines in a commercial-airline environment. Such a high degree of improvement is possible only when a large number of engines are in service to generate the failure data required both to direct product improvement and to lower its unit cost. The fact that improvement is characteristically exponential enables us to plot reliability growth in new equipment with a fair degree of success. Exhibit 5.4 shows a comparison of actual failure experience with a forecast that was made in 1965. The forecast was reasonably good until 1968, when a new failure mode became dominant. This problem took nearly three years to resolve, after which the failure rate dropped back to its forecast level.

## 5.3. Refining the maintenance program

The maintenance tasks added in response to unanticipated failures are only one aspect of the age-exploration process. At the time the initial program is developed certain reliability characteristics are unknown. For example, the ability to measure reduced failure resistance can be determined, but there is no information on the actual rate of reduction as various items age in service. Similarly, the information necessary to evaluate cost effectiveness and age-reliability relationships becomes available only after the equipment has been in service for some time. Once the maintenance program goes into effect, the results of the scheduled tasks provide the basis for adjusting the initial conservative task intervals, and as further operating data becomes available the default decisions made in the absence of information are gradually eliminated from the program.

### Adjusting task intervals

As part of the initial program many items are scheduled for frequent sample inspections to monitor their condition and performance, and other tasks are assigned conservatively short initial intervals. All these tasks are then packaged for implementation. If the first few units to reach this check limit show no unsatisfactory conditions, it is safe to assume that the task interval for the remaining units can be extended. Any equipment that has aged to the present check limit is designated a *time-extension sample*.

In many cases, as we saw in Chapter 4, the required number of samples is provided by opportunity samples, units that are available for inspection because they have failed for some reason related to only one failure mode. In the case of engines, for example, the availability of samples of a particular part depends on the number of shop visits occasioned by failures in the section of the engine containing that part. Since a new type of engine is far more likely to experience failures of components in the hot section than in the cold section, the engine data in Exhibit 5.5 show far more opportunity samples for the exit guide-vane assembly than for the compressor assembly. In both cases, however, opportunity sampling provided a means of inspecting these parts as they aged in-service. Since there was no great difference between the age of the highest-time installed part and the age of the highest-time sample inspected, it was possible to extend the check limits for both items until the age at which the sample units began to show signs of deterioration.

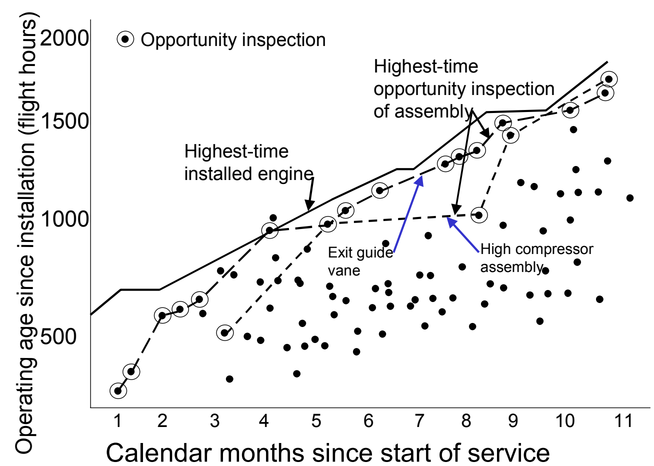



**Exhibit 5-5 The effectiveness of opportunity sampling of the Pratt & Whitney JT8D engine. Opportunity samples of the exit guide-vane assembly (black) were more abundant than samples of the high compressor assembly (red), but at every age the highest-time installed unit was only slightly older than the highest-time inspected sample. That is, any unsatisfactory condition detected in the**

**sample would be found before the remaining installed units had reached this age. (United Airlines)**

Task intervals for systems and structural items are ordinarily increased by increasing the interval of the letter-check package in which they have been included. However, if the inspection reports indicate that the interval for some particular task in this package should not be extended, the task must be moved to another package. A task originally assigned to the C check package for instance, might be reassigned to the package designated for every second B check. Conversely, there will be tasks whose original intervals now appear far too conservative. In this case the task interval might be increased, say from C2 to C4 at the same time that the C-check interval itself is being revised upward. The same result can be achieved, of course, by leaving the intervals of all packages fixed and moving all tasks from one package to another.

The management of maintenance packages requires careful planning. First, a schedule is needed for conducting the analysis necessary to support each interval extension. This schedule must allow time for the first few units that have entered service to age to the existing check limit, and also time for the analysis necessary to assess the desirability of extending the limit. The results of all inspections and corrective work determined on the sample units must be carefully analyzed so that the tasks for which intervals should not be extended can be moved to more compatible packages. Tasks producing marginal results may stay with the original package, that they should be noted for future attention. A hard-time directory is usually maintained to identify tasks for which the maximum interval appears likely. These tasks require closer study than the others, and maintenance planning is facilitated by advance knowledge that they may be moved to a different package in the near future.

## Uses of actuarial analysis in age exploration

Whereas serious unanticipated failures prompt an immediate response, action on infrequent failures or those with no major consequences is usually delayed until enough information has been gathered to make a full assessment of possible maintenance remedies. This is particularly true with regards to rework tasks, since these tasks are applicable only if the conditional-probability curve shows that an item has an identifiable wearout zone. Such curves are the result of an actuarial analysis in which the number of failures during various age intervals are measured in terms of the total exposure of the item (total operating time for all units) and the probability of survival to that age interval.

An actuarial analysis does not require hundreds of failure events. A survival curve can be constructed from the data on 20 functional failures, and if necessary, from a sample of 10. However, since it takes several thousand operating hours to accumulate this many occurrences of a given type of failure, there is sometimes concern about a surge of failures as a result of wearout after a certain age. If all the units in service were the same age this might be the case, but because of the slow buildup of a fleet of airplanes, the ages of the units in service are widely distributed. If the item is very reliable at lower ages, and the first failure does not occur until some time after the fleet has reached full strength, the age distribution of the in-service units at that time will be the same as that of the planes in the fleet. This means that there may be a difference of five years or more between the ages of the oldest unit and the newest one. If the item is not that reliable, there will be even fewer high-time units, since many of the units on the older airplanes will be replacements for units that have already failed.

It is this distribution in ages of in-service units of an item that makes it feasible to use actuarial analysis as a tool for age exploration. If it is found that there is a sharp increase in the likelihood of failure at higher ages, there is ample time to take preventive steps, since very few units are actually approaching the "cliff" when it is discovered. It follows that attention is concentrated on the failure behavior of the oldest units, so that in the event that there is a wearout zone, a rework task can be added to the maintenance program long before the other units reach this age.

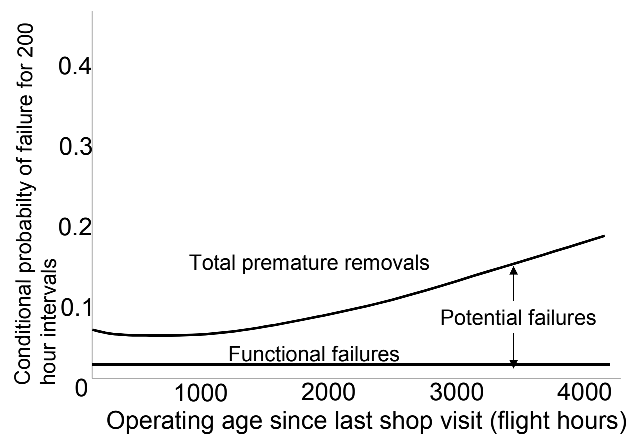



**Exhibit 5-6 Condition-probability curves for the General Electric CF6-6 engine of the Douglas DC-10. The upper curve shows the total number of premature removals for both functional and potential failures, and the lower curve shows the number of these units removed as functional failures. Although the rate of potential failures increases with operating age, as a result of effective on-condition inspections the functional-failure rate is kept in check and shows no increase with age. (United Airlines)**

Exhibit 5.6 shows the results of an actuarial analysis conducted to determine whether complete rework of a turbine engine would be an applicable task. The upper curve shows the total conditional probability for all units removed and sent to the shop for corrective work, and the lower curve shows the conditional probability of functional failures as reported by the operating crew. The distance between these two curves at any age represents the conditional probability of potential failures detected by on-condition inspections. It is functional failures that have safety or operational consequences, and the conditional probability of such failures in this case is constant since functional failures are independent of the time since engine installation (last shop visit), operating age is not a factor in the failure rate, and rework task is therefore not applicable.

The conditional-probability curve that includes potential failures does show an increase with increasing age. However, we do not want to reduce the incidence of potential failures except by redesign, since these inspections for potential failures are clearly effective in reducing the number of functional failures. As it is, each engine can remain in operation until a potential failure is detected, and under these conditions there is no increase in the functional-failure rate with age. Thus the on-condition task itself prevents a wearout zone for functional failures and at the same time permits each engine to realize almost all of its useful life.

The age-reliability relationship of verified and unverified failures can be examined in the same way to determine the effectiveness of troubleshooting methods. This information is of value to those concerned with stocking and allocating replacement units and spare parts, but it is also important in identifying the actual characteristics of verified failures, so that the failure mode can be pinpointed more exactly and a more accurate potential-failure condition can be defined.

Exhibit 5.7 shows the various age-reliability relationships that can be developed for an item subject to several different failure modes. The upper curve shows the conditional probability for all reported failures, and the curve below it shows the conditional probability of verified failures. The distance between these two curves represents the probability of unscheduled removals of units that are actually serviceable. Thus the first curve represents the apparent reliability of the item and the second curve represents its actual reliability.

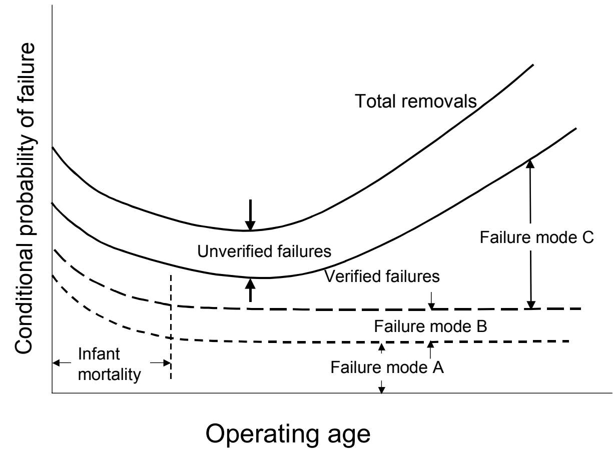



**Exhibit 5-7 Partitioning of a conditional-probability curve to show the number of unverified failures and the number of verified failures resulting from each of three failure modes. Note that the only high infant mortality occurs from failure mode A; this results in an upturn of the curves above it in a layered representation.**

To determine how we might improve the reliability of this item we must examine the contributions of each failure mode to the total verified failures. For example, failure modes A and B show no increase with increasing age; hence any attempt to reduce the adverse age relationship must be directed at failure mode C. There is also a fairly high conditional probability of failure immediately after a shop visit as a result of high infant mortality from failure mode A. The high incidence of early failures from this failure mode could be due to a problem in shop procedures. If so, the difficulty might be overcome by changing shop specifications either to improve quality control or to break in a repaired unit before it is returned to service. In the case of aircraft engines, for example, shop procedures in commercial airlines include a test-cell run at the end of the shop process, during which some engines are rejected and sent back for further work. These test-cell rejects to not appear in the failure count, since this count begins only after the engine is installed on the aircraft.

An actuarial analysis such as that in Exhibit 5.7 can direct improvements toward a great many different areas by indicating which factors are actually involved in the failure behavior of the item. An analysis of the Boeing 727 generator, for example, showed that the conditional probability of generator failure did not increase with age until bearing failures started at an age of 2000 hours. This failure mode usually results in destruction of the generator. Since a new generator costs about $2500, as opposed to $50 for a bearing replacement, a generator rework task during which the bearing was discarded was both applicable and cost effective at 4000-hour intervals.

# 5.4. Revisions in maintenance requirements

The maintenance tasks instituted in response to serious unanticipated failures are usually interim measures, intended to control the problem until it can be resolved by redesign. Two kinds of technological change, however, may lead to revision of the requirements for scheduled maintenance: the development of new diagnostic techniques and modification of the present equipment.

## New diagnostic techniques

Most on-condition inspections are diagnostic techniques, since they measure resistance to failure to identify specific problems. The earliest and simplest technique used for aircraft was visual examination, perhaps aided by a magnifying glass. This visual inspection was extended by development of the borescope. Numerous other techniques have been developed for detecting cracks in metallic items, such as eddy-current, magna flux, and zyglo inspections. Radiography is also widely employed, not only for detecting cracks, but also to check clearances and changes in configuration without the need to disassemble the item.

A useful diagnostic technique must be able to detect some specific condition that can confidently be defined as a potential failure. It should be sufficiently accurate to identify all units that have reached this condition without including a large number of units for which failure is remote. In other words, such techniques must provide a high power of discrimination. The demand for such discrimination depends in part on the consequences of failure. A technique with low resolving power might be of value for single-engine aircraft if it prevented even a small number of engine failures, despite the fact that it costs numerous unjustified removals. For multiengine aircraft the same technique would be unnecessary as a safety precaution and undesirable in economic terms.

Certain diagnostic techniques appear to have great potential but will require further development before they can be universally adopted. For example, spectrographic analysis is sometimes used to detect where in metal parts by measuring the concentration of metallic elements in lubricating oil. In many cases, however it has been difficult to define a failure condition related to the metal concentrations. Parts have failed without the expected warning, and warnings have not necessarily been associated with imminent failure. Even a change in the brand of oil may necessitate new criteria for interpreting the analysis. Nevertheless, if the failure is one with major consequences, even a low incidence of successful interpretations (and presented failures) may offset the cost of the inspections that produced no useful information.

Another recent technique is the use of computerized airborne integrated data systems (AIDS), which measure and record the performance characteristics of many items for later study. Some of these characteristics, especially in power plants, are also monitored by the normal flight instrumentation, but the data are not automatically recorded and integrated with other data. This procedure opens up the possibility of correlating performance trends with the likelihood of failures, or "establishing a signature" for the failure mode. By revealing a previously overlooked indication of reduced resistance to failure, AIDS may make it possible to prevent certain functional failures by on-condition maintenance. The new data systems have in fact assisted in troubleshooting, and they have indicated engine conditions that increase the stress on certain internal parts. However, their success in performing a true (and continuous) on-condition surveillance has so far been limited. Once again, this system may be worthwhile for some organizations if analysis convinces them that the value of its contribution outweighs its costs.

As we have seen, scheduled reworked tasks have limited applicability, and discard tasks apply only under rather special circumstances. Major improvements in maintenance effectiveness depends, therefore on expanded use of diagnostic techniques. The search for additional techniques continues, and the economic desirability of such new developments must be reevaluated from time to time.

## Design changes

The product-improvement process is also a factor in changing maintenance requirements, since design modifications may change the reliability characteristics of items either intentionally or otherwise. Hidden functions may be added or removed, critical-failure modes may be added or removed, dominant failure modes and/or age-reliability characteristics may be altered, and redesign may change the applicability of on-condition tasks.

Whenever an item is substantially modified, its maintenance requirements must be reviewed. It may also be necessary to repeat the age-exploration process for such items, both to find out whether the modifications have achieved their intended purpose and to determine how these modifications affect existing maintenance requirements for the item. Finally, entirely new items are added to most equipment during its service life. Initial requirements must be developed for each of these items, to be modified as necessary when operating data on them become available.

# 5.5. The product improvement process

In the course of evaluating the maintenance requirements of complex equipment many items will be found that cannot benefit from scheduled maintenance, either because there is no applicable preventive task or because the available forms of prevention cannot provide the level of reliability necessary. Because of the inherent conflict between performance requirements and reliability requirements, reliability problems identified and corrected during early operations are really a part of the normal development cycle of high-performance equipment.

The degree of reliability that can be achieved by preventive maintenance is limited by the equipment itself. Thus the product may be deemed unsatisfactory for any of the following reasons:

- Exposure to critical failures
- Exposure to failures that unduly reduce operational capability
- Unduly high maintenance costs
- A demonstrated need to make a hidden function visible

Failures may result from the stress and wear associated with normal operation of the item, or they may be caused by external factors such as lightning strikes, bird ingestion, corrosive environments, and so on. Product improvement to increase resistance to these external factors may be just as necessary as modifications to withstand the effects of the normal operating environment.

## Determining the need for product improvement

Product improvement directed toward better reliability may take a number of forms. An item may be modified to prevent critical failures, to eliminate a particularly expensive failure mode, or to reduce its overall failure rate. The equipment, or an item on it may be modified to facilitate replacement of the failed units, to make a hidden function visible, to incorporate features that make on-condition inspections feasible, or to add redundant features which alter the consequences of failure.

Product improvement is expensive. It involves the cost of redesign and the manufacture of new parts or whole new items. The operating organization also incurs the direct cost of modifying the existing equipment and perhaps the indirect cost of taking it out of service while such modifications are being incorporated. Further risks are always introduced when the design of a high-performance equipment is changed, and there is no assurance that the first attempt at improvements will eliminate or even alleviate the problem at which improvement is directed. For this reason it is important to distinguish between situations in which product improvement is necessary and those in which it is desirable. The decision diagram in Exhibit 5.8 is helpful in evaluating the necessity or desirability of initiating design changes. In this case the answers to the decision questions are all based on operating experience. As always, the first consideration is safety:

**Does the failure caused a loss of function or secondary damage that could have a direct adverse effect on operating safety?**

If the answer to this question is yes, the next concern is whether such failures can be controlled at the maintenance level:

**Are present preventive measures effectively avoiding such failures?**

If the answer is no, then the safety hazard has not been resolved. In this case the only recourse is to remove the equipment from service until the problem can be solved by redesign. Clearly, product improvement is required.

If the present preventive measures are effectively controlling critical failures, then product improvement is not necessary for safety reasons. However, the problem may seriously restrict operating capability or result in unduly expensive maintenance requirements. It is therefore necessary to investigate the possibility of reducing these costs:

**Its product improvement cost-effective?**

Here we are concerned solely with economics. As long as the safety hazard has been removed, the only issue now is the cost of the preventive measures employed. By the same token, if the answer to the first question was no – that is, the failure has no effect on safety – it may still have costly operational consequences. Thus a no answer to the safety question brings us directly to the question of cost effectiveness.

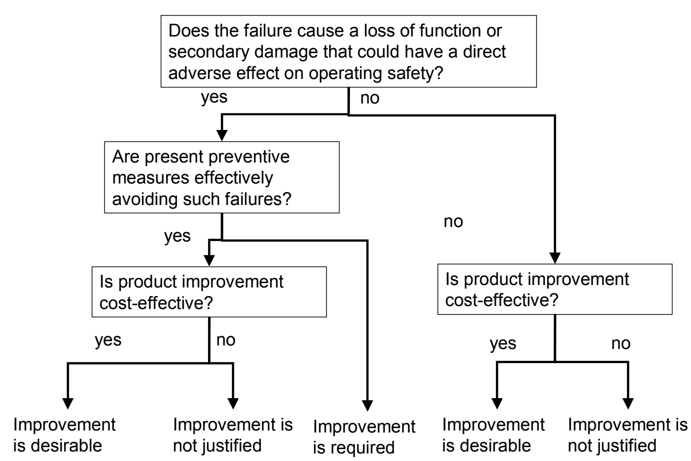



**Exhibit 5-8 Decision diagram to determine whether product improvement is required or merely desirable if it is cost-effective. Unless product improvement is required for safety reasons, its cost effectiveness must be assessed**

**(see Exhibit 5.9) to determine whether the improvement is in fact economically desirable.**

## Determining the desirability of product improvement

There is no hard-and-fast rule for determining when product improvement will be cost effective. The major variables can be identified, but the monetary values assigned in each case depend not only on direct maintenance costs, but on a variety of other shop and operating costs, as well as on the plans for continuing use of the equipment. All these factors must be weighed against the costs of product improvement.

An operating organization is always faced with a large number of apparently cost-effective improvement projects that are physically or economically feasible. The decision diagram in Exhibit 5.9 is helpful in ranking such projects and determining whether a proposed improvement is likely to produce discernible results within a reasonable length of time.

The first question in this case concerns the anticipated further use of the equipment:

**Is in the remaining technologically useful life of the equipment high?**

Any equipment, no matter how reliable, we'll eventually be outmoded by the new developments. Product improvement is not likely to result in major savings when the equipment is near the end of its technologically useful life, whereas the elimination of excess costs over a span of eight or ten years of continued service might represent a substantial saving.

Some organizations require, for budget approval, that the costs of product improvement be self-liquidating over a short period – say, two years. This is equivalent to setting the operational horizon of the equipment at two years. Such a policy reduces the number of projects initiated on the basis of projected cost benefits and ensures that only those projects with relatively high payback are approved. Thus if the answer to this first question is no, we can usually conclude that product improvement is not justified. If the economic consequences of failure are very large, it may be more economical to retire equipment early then to attempt to modify it.

The case for product improvement is obviously strengthened if an item that will remain in service for some time is also experiencing frequent failures:

**Is the functional-failure rate high?**

If the answer to this question is yes, we must consider the economic consequences of failure:

**Does the failure involve major operational consequences?**

Even when the failures have no operational consequences, there is another economic factor to be taken into account:

**Is the cost of scheduled and/or corrective maintenance high?**

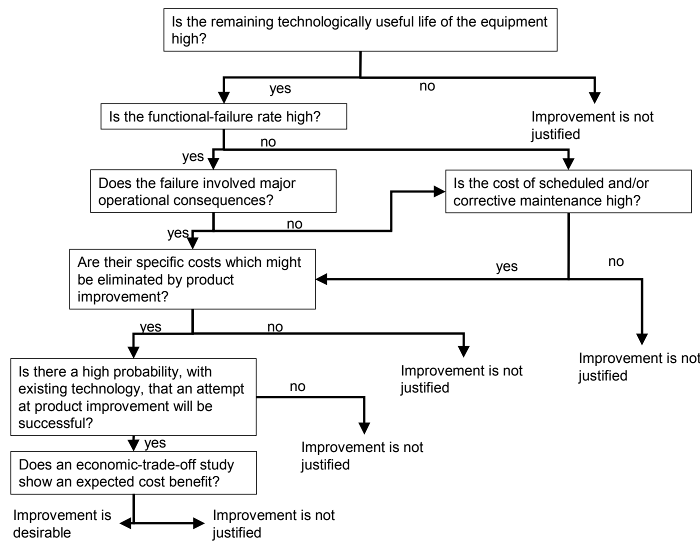



**Exhibit 5-9 Decision diagram to assess the probable cost effectiveness of product improvement. If a particular improvement appears to be economically desirable, it must be supported by a formal economic-trade-off study**

Note that this last question may be reached by more than one path. With a no answer to the failure-rate question, scheduled maintenance may be effectively preventing functional failures, but only at great cost. With a no answer to the question of operational consequences, functional failures may not be affecting operating capability, but the failure mode may be one that results in exceedingly high repair costs. Thus a yes answer to either of the two preceding questions brings us to the question of product improvement:

**Are their specific costs which might be eliminated by product improvement?**

This question concerns both the imputed costs of reduced operational capability and the more tangible costs associated with maintenance activities. Unless these costs are related to a specific design characteristic, however, it is unlikely that the problem will be eliminated by product improvement. Hence a no to this question means the economic consequences of this failure will probably have to be borne.

If the problem can be pinned down to a specific cost element, then the economic potential of product improvement is high. But is this effort likely to produce the desired results?

**Is there a high probability, with existing technology, that an attempt at product improvement will be successful?**

Although a particular improvement might be very desirable economically, it may not be feasible. And improvement directed at one failure mode may unmask another failure mode, requiring several attempts before the problem is solved. If informed technical opinion indicates that the probability of success is low, the proposed improvement is unlikely to be economically worthwhile.

If the improvement under consideration has survived the screening process thus far, it warrants formal economic-trade-off study:

**Does an economic trade-off study show an expected cost benefit?**

The trade-off study must compare the expected reduction in costs during the remaining useful life of the equipment with the costs of obtaining and incorporating the improved item. The expected benefit is then the projected saving if the first attempt at improvement is successful, multiplied by the probability of success at the first try. Alternatively, it might be considered that the improvement will always be successful, but only a portion of the potential savings will be realized.

There are some situations in which it may be necessary to proceed with an improvement even though it does not result in an actual cost benefit. In this case it is possible to work back through the set of decision questions and determine the values that would have to be ascribed for the project to brake even. Also, improvements in the form of increased redundancy can often be justified when the redesign of the offending item is not. This type of justification is not necessary, of course, when the in-service reliability characteristics of an item are specified by contractual warranties or when there is a need for improvement for reasons other than cost.

## Information requirements

No manufacturer has unlimited resources for product improvement. He needs to know which modifications to his product are necessary and which are sufficiently desirable for him to risk the cost of developing them. This information must come from the operating organizations, who are in the best position to determine the consequences and costs of the various types of failures, measure their frequency, and define the specific conditions that they consider unsatisfactory.

Opinions will differ from one organization to another about the desirability of specific improvements, both because of differences in failure experience and because of differing definitions of the failure. A failure with safety consequences in one operating context may have only operational consequences in another, and operational consequences that are major for one organization may not be significant for another. Similarly, the costs of scheduled and corrective maintenance will vary and will also have different economic impacts, depending on the resources of each organization. Nevertheless, the manufacturer must assess the aggregate experience of the various users and decide which improvements will be the greatest value to the entire group.

With any new type of equipment, therefore, the operating organization must start with the following assumptions:

- Certain items on the equipment will need improvement.
- Requests for improvement must be supported by reliability and cost data.
- Specific information on the failure mode must be provided as a basis for redesign.

Critical failures must be reported by a safety-alert system so that all operating organizations can take immediate action against identified safety hazards. Failure with other operational consequences are reported at short intervals so that the cost effectiveness of product improvement can be assessed as soon as possible. The airline industry imputes high costs to delay or canceled flights, and these events are usually reported on a daily basis. In military applications is important that operating data, especially peacetime exercise data, be examined carefully for its implications for operational readiness.

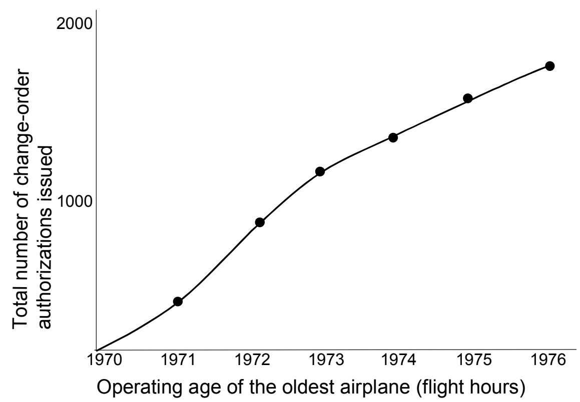
For items whose failure has no operational consequences, the only justification for product improvement is a substantial reduction in support costs. Many of these items will be ones for which there is no applicable and effective form of preventive maintenance. In this case statistical reliability reports at monthly or quarterly intervals are sufficient to permit an assessment of the desirability of product improvement. The economic benefits of redesign will usually not be as great under these circumstances. In general, the information requirements for product improvement are similar to those for management of the ongoing maintenance program. In one case the information is used to determine necessary or desirable design modifications and in the other it is used to determine necessary or desirable modifications in the maintenance program.

## The role of product improvement in equipment development

The role of the product improvement process in the development of new equipment is exemplified by the history of a fleet of Boeing 747's. The first planes in this fleet went into operation in 1970 and the last four planes were delivered in 1973. By April 1976 the airline had issued a total of 1781 change-order authorizations. Of this total, 85 of the design changes were required by regulatory agencies, 801 were the results of altered mission requirements by the airline, and 895 were required by unsatisfactory reliability characteristics. The cumulative number of these change orders over the first six years of operation is shown in Exhibit 5.10. Most of the change orders to meet regulatory requirements were issued in compliance with FAA airworthiness directives. Such directives mandate specific design changes or maintenance requirements to prevent critical failures. The cumulative number of the 41 directives issued (some entailed more than one change) is shown by the second curve in exhibit 5.10.

The 895 design changes required to improve reliability characteristics did not include those associated with critical failures. They consisted of the following types of product improvement:

- Those desirable to prevent or reduce the frequency of conditions causing delays, cancellations, or substitutions (495)
- Those desirable to improve structural fatigue life and reduced need for frequent inspection and repairs (184)
- Those desirable to prevent or reduce the frequency of conditions considered to compromise ground or flight safety (214)



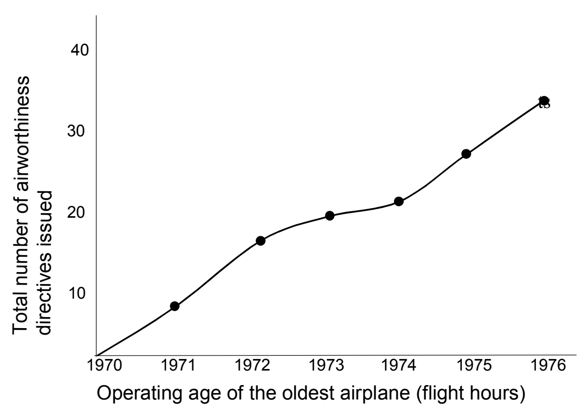




**Exhibit 5-10 History of change-order authorizations for design improvements in the Boeing 747 (top) and history of FAA airworthiness directives issued over the same time period (bottom). (United Airlines)**

All these changes were based on information gathered from actual operations after the equipment went into service. Such information is an essential part of the development cycle in all complex equipment.

## 5.6. RCM programs for in-service equipment

The decision process outlined in Chapter 4 was discussed in terms of new equipment. However, this procedure also extends to the development of an RCM program for equipment that is already in-service and is being supported by a scheduled-maintenance program developed on some other basis. In this case there will be much less need for default answers, since considerable information from operating experience is already available. For example, there will be at least some information about the total failure rate of each item, the actual economic consequences of various kinds of failures, what failure modes lead to the loss of function, which cause major secondary damage, and which are dominant. Many hidden functions will have been identified, and there may be information on the age-reliability characteristics of many items.

Preparation for the program will still require a review of the design characteristics of the equipment to define a set of significant functions and functional failures. The results will be that items currently treated individually can be grouped as a system or subsystem to be considered as one significant item in the new program. A set of proposed maintenance tasks will have to be established which includes all those existing tasks that satisfy the applicability criteria; additional tasks may then be introduced if they also meet these requirements. The tasks would then be analyzed for effectiveness in terms of failure consequences, as with a prior-to-service program.

The new RCM program should be developed with minimal reference to the existing program, and the two programs should not be compared until the proposal for the new one is complete. This is to avoid the influence of past biases and to allow for free exercise of the decision structure. When a decision is finally made, the new RCM program will generally have the following features:

- Many systems and subsystems will be classified as significant items.
- There will be a number of equipment items for which unique scheduled-maintenance tasks are specified.
- Most systems will no longer be subject to scheduled rework.

- Turbine engines and other complex items will be subjected to a few specific rework or discard tasks, rather than intensive scheduled overhaul.
- There will be age-exploration sampling of certain identified parts of the item, which is continued until the parts reach very high ages.
- There will be increased use of on-condition tasks.
- There will be some new tasks that are justified by critical-failure modes, operational consequences, or hidden functions.
- The intervals of higher-level maintenance packages will be greatly increased, whereas intervals of lower-level packages, which consist primarily of servicing tasks and deferrable corrective work, will remain about the same.
- The overall scheduled-maintenance workload will be reduced.

If the existing program assigns a large number of items to scheduled rework, there may be some concern that eliminating these tasks will result in a substantial increase in the failure rate. This question can be resolved by conducting actuarial analyses of the failure data for these items under the new program, to confirm that the change in maintenance policy has not adversely affected their overall reliability. If these analyses show that rework tasks are both applicable and effective for some items, they can be reinstated.

The new RCM program will not be as labor-intensive as the program it replaces, and this fact will have to be taken into account in adjusting staff requirements at maintenance facilities. It may be necessary to estimate the volume of work that has been eliminated in each maintenance package and make these adjustments when the new program is first implemented. Otherwise the anticipated reductions in man-hours and elapsed time for scheduled maintenance will often not be realized.

# Part Two
Applications

# 6. Chapter Six - applying RCM theory to aircraft

The reasoning behind RCM programs was described in detail in Part One. In the following chapters we will examine specific applications of these principles to actual equipment hardware. Although the examples discussed are drawn from commercial transport aircraft, they provide practical guidelines and easily extend to other operating contexts and to the development of scheduled-maintenance programs for other types of complex equipment. The principal distinction in the case aircraft has to do with design practices that are common to the aircraft industry.

In the case of commercial aircraft continuous evolution of the design requirements promulgated by airworthiness authorities and the feedback of hardware information to equipment designers by operating organizations have led to increasing capability of the equipment for safe and reliable operation. Thus most modern aircraft enter service with design features for certain items that allow easy identification of potential failures. Similarly, various parts of the airplane are designed for easy access when inspection is necessary or for easy removal and replacement of vulnerable items. A host of instruments and other indicators provide for monitoring of systems operation, and in nearly all cases essential functions are protected by some form of redundancy or by backup devices that reduce the consequences of failure to a less serious level.

Complex equipment that has not benefited from such design practices will have different – and less favorable – reliability characteristics, and therefore less capability for reliable operation. Since preventive maintenance is limited by the inherent characteristics of the equipment, in many cases RCM analysis can do little more than recommend the design changes that would make effective maintenance feasible. The principles of reliability-centered maintenance still apply, and the questions are the same. The answers to these questions, however, must reflect the design characteristics of the equipment itself and hence will be different for equipment designed to other standards.

In this chapter we will briefly review certain aspects of RCM analysis, examine the procedures for setting up a study team to develop a prior-to-service program, and consider some of the factors involved in monitoring the RCM program as it evolves after the equipment enters service.

## 6.1. A summary of RCM principles

The complexity of modern equipment makes it impossible to predict with any degree of accuracy when each part or each assembly is likely to fail. For this reason it is generally more productive to focus on those reliability characteristics that can determined from the available information than to attempt to estimate failure behavior that will not be known until the equipment enters service. In developing an initial program, therefore, only a modest attempt is made to anticipate the operating reliability of every item. Instead, the governing factor in RCM analysis is the impact of a functional failure at the equipment level, and tasks are directed at a very small number of *significant items*—those items whose failure might have safety or major economic consequences. These items, along with all hidden-function items, are subjected to intensive study, first to classify them according to their failure consequences and then to determine whether there is some form of maintenance protection against those consequences.

The first step in this process is to organize the problem by partitioning the equipment into object categories according to areas of engineering expertise. Within each of these areas the equipment is further partitioned in decreasing order of complexity to identify significant items (those whose failure may have serious consequences for the equipment as a whole), items with hidden functions (those whose failure will not be evident and might therefore go undetected), and non significant items (those whose failure has no impact on operating capability). As this last group encompasses many thousands of items on an aircraft, this procedure focuses the problem of analysis on those items whose functions must be protected to ensure safe and reliable operation.

The next step is a detailed analysis of the failure consequences in each case. Each function of the item under consideration is examined to determine whether its failure will be evident to the operating crew; if not, a scheduled-maintenance task is required to find and correct hidden failures. Each failure mode of the item is then examined to determine whether it has safety or other serious consequences. If safety is involved, scheduled maintenance is required to avoid the risk of a critical failure. If there is no direct threat to safety, but a second failure in a chain of events would have safety consequences, then the first failure must be corrected at once and therefore has operational consequences. In this case the consequences are economic, but they include the cost of lost operating capability as well as the cost of repair. Thus scheduled maintenance may be desirable on economic grounds, provided that its cost is less than the combined costs of failure. The consequences of a non operational failure are also economic, but they involve only the direct cost of repair.

This classification by failure consequences also establishes the framework for evaluating proposed maintenance tasks. In the case of critical failures – those with direct safety consequences – a task is considered effective only if it reduces the likelihood of a functional failure to an acceptable level of risk. Although hidden failures, by definition, have no direct impact on safety or operating capability, the criteria in this case is also risk; a task qualifies as effective only if it ensures adequate protection against the risk of a multiple failure. In the case of both operational and nonoperational failure task effectiveness is measured in economic terms. Thus a task may be applicable if it reduces the failure rate (and hence the frequency of the economic consequences), but it must also be cost-effective – that is, the total cost of scheduled maintenance must be less than the cost of the failures it prevents.

Whereas the criteria for task effectiveness depends on the failure consequences the task is intended to prevent, the applicability of each form of preventive maintenance depends on the failure characteristics of the item itself. For an *on-condition task* to be applicable there must be a definable potential-failure condition and a reasonably predictable age interval between the point of potential failure and the point of functional failure. For a scheduled *rework task* to be applicable, the reliability of the item must in fact be related to operating age; the age-reliability relationship must show an increase in the conditional probability of failure at some identifiable age (wear out) and most units of the item must survive to that age. The applicability of *discard tasks* also depends on the age-reliability relationship, except that for safe-life limits the life limit is set at some fraction of the average age at failure. *Failure-finding tasks* are applicable to all hidden-function items not covered by other tasks.

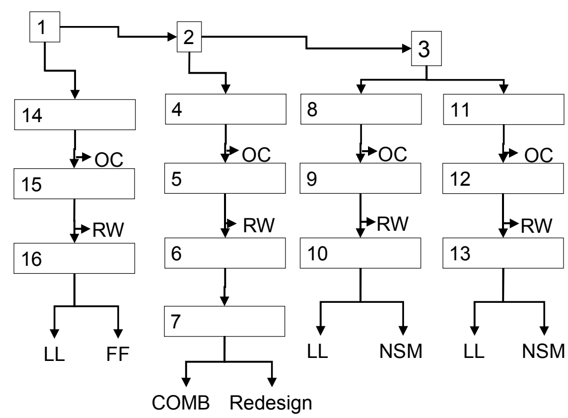



**Exhibit 6-1 Schematic representation of the RCM decision structure. The numbers represent the decision questions stated in full in Exhibit 4.4, and the abbreviations represent the task assigned or other action taken as an outcome of each decision question.**

The process of developing an RCM program consists of determining which of these scheduled tasks, if any, are both applicable and effective for a given item. The fact that failure consequences govern the entire decision process makes it possible to use a structured decision-diagram approach, both to establish maintenance requirements and to evaluate proposed tasks. The binary form of a decision diagram allows **a clear focus of engineering judgment** on each issue. It also provides the basic structure for a default strategy – the correct action to be taken if there is insufficient information to answer the question or if the study group is unable to reach a consensus. Thus if there is any uncertainty about whether a particular failure might have safety consequences, the default answer will be yes; similarly, if there is no basis for determining whether a proposed task will prove applicable, the default answer, at least in an initial maintenance program, will be **yes for on-condition tasks** and **no for rework tasks.**

It is important to realize that the decision structure itself is specifically designed for the need to make decisions even with minimal information. For example, if the default strategy demands redesign and this is not feasible in the given timetable, then one alternative is to seek out more information in order to resolve the problem. However, this is the exception rather than the rule. In most cases the default path leads to no scheduled maintenance, and the correction, if any, comes naturally as real and applicable data come into being as a results of actual use of the equipment in service.

The decision logic also plays the important role of specifying its own information requirements. The first three questions assure us that all failures will be detected and that any failures that might affect safety or operating capability will receive first priority. The remaining steps provide for the selection of all applicable and effective tasks, but only those tasks that meet these criteria are included. Again, real data from operating experience will provide the basis for adjusting default decisions made in the absence of information. Thus a prior-to-service program consists primarily of on-condition and sample inspections, failure-finding inspections for hidden-function items, and a few safe-life discard tasks. As information is gathered to evaluate age-reliability relationships and actual operating costs, rework and discard tasks are gradually added to the program where they are justified.

The net result of this careful bounding of the decision process is a scheduled-maintenance program which is based at every stage on the known reliability characteristics of the equipment in the operating context in which it is used. In short, reliability-centered maintenance is a well-tested answer to the **paradox of modern aircraft maintenance** – the problem of how to maintain the equipment in a safe and economical fashion until we have accumulated enough information to know how to do it.

## 6.2. Organization of the program-development team

In the airline industry the FAA convenes a maintenance review board (MRB) for each new type of airplane. This board is responsible for preparing and issuing a document that defines the initial scheduled-maintenance program for the new equipment. Although the initial program of each airline using the equipment is based on this document, the airlines very quickly begin to obtain approval for revisions on the basis of their individual experiences and operating requirements. Consequently the programs that ultimately come into effect may be quite different for users of the same equipment.

It is usual practice for the MRB to develop this document as a joint venture involving the aircraft and engine manufacturers, the purchasing airlines, and members of the FAA. The industry group – and manufacturers and airlines – ordinarily develop a complete program and submit it to the MRB as a proposal; the MRB then incorporates any necessary changes before final approval and release. On one hand, this procedure cannot be started until the design characteristics of the equipment are well established; on the other hand, the initial program must be completed and approved before the new plane can enter service. Thus there are certain time constraints involved.

While the initial maintenance program is being developed, other FAA personnel, manufacturing and airline engineers, and pilots of purchasing airlines compiled a *minimum-equipment list* (MEL) and a *configuration-deviation list* (CDL). These two lists give explicit recognition to the fact that the aircraft can be operated safely in a condition that is less than its original state. In fact, these lists help to define operational consequences, since they define the failures that must be corrected before further operation. The minimum-equipment list specifies the items that must be serviceable at the time a plane is dispatched and in some cases includes mandatory operating limitations if certain items are inoperative. The configuration-deviation list is concerned primarily with the external envelope of the aircraft and identifies certain parts, such as cover plates and small pieces of fairing, that are allowed to be missing.

The first draft of the RCM program is generally developed by an industry task force specially appointed for that purpose. Although there are no hard-and-fast rules about organization, the approach on airline programs has been a steering committee supported by a number of working groups. The steering committee consists of about 10 manufacturer and airline representatives and is responsible for managing all aspects of the program development; this committee also serves as the interface with the manufacturer and the various regulatory agencies. The first chore of the steering committee is to appoint working groups of 8 to 10 members to conduct the detailed study of the aircraft structure, powerplant, and systems. Seven such working groups were employed, for example, to develop the maintenance program for the Douglas DC-10. The steering committee sets the ground rules for each working group and selects a group chairman. Ordinarily the steering-committee member also sits in on each working-group meeting to audit the process and results problems.[1]

One other responsibility of the steering committee is to arrange for training. All members of the task force are given a one-week course to familiarize them with the features of the

[1] The role of the auditor in a program-development project is discussed in detail in Appendix A. This discussion also covers some of the common problems that arise during analysis and provides a useful review for those who may be working with RCM procedures for the first time.

new equipment. Members of the working groups, however, require additional training in RCM analysis (usually by the steering committee) and much more detailed training on the particular aspect of the equipment they are to analyze. The training in RCM procedures assures that all participants have a uniform understanding of the basic task criteria and the definitions of such key terms as *significant item, function, functional failure, failure mode, failure consequences,* and *cost effectiveness*. Working-group members must also be familiar with the decision logic used to sort and select tasks and with the default strategy to be employed when there is no information or the group is unable to reach a consensus.

The members of the task force should represent the best engineering and maintenance talent available. Ideally, the steering-committee should be headed by someone who has had previous experience with similar efforts and is completely familiar with RCM techniques (or employs someone who is familiar with them). All members of that committee should be generalists, rather specialists. Their duties require experience in management and analysis, whereas the working-group members need actual hardware experience. Thus the steering committee is often composed of reliability, engineering, and quality assurance manager's, whereas the working groups consist of working engineers.

The working groups are responsible for identifying and listing the significant and hidden-function items and evaluating the proposed scheduled tasks. Usually they will be able to start with preliminary worksheets prepared by the manufacturers. These worksheets are studied in detail, and in some cases the working group may examine an aircraft that is being assembled to confirm certain points. Each group recommends additions and/or deletions of significant items, essential functions, failure modes and anticipated failure consequences and selects appropriate scheduled tasks and task intervals for the portion of the equipment on which it is working. The results are then summarized in a way that allows the steering committee to evaluate the analysis and incorporate the scheduled tasks in the program.

## 6.3. Beginning the decision process

A new aircraft is never totally new. Rather the product of an era, although its design usually includes some recent technological developments to improve performance capabilities and reduce maintenance costs. The program-development team thus begins with a large body of knowledge gained from experience with other aircraft. In addition to this general context of expertise, there are specific test data on the vital portions of the aircraft. These are the manufacturer's tests, conducted during design and development of the equipment to establish the integrity of the structure, the reliability and performance characteristics of the powerplant, and other factors necessary to ensure that the various systems and components will in fact perform as intended. Finally, the new equipment will come to the RCM team with a list of manufacturer's recommendations for scheduled lubrication and service, and often more extensive maintenance suggestions as well.

In evaluating and selecting the scheduled-maintenance tasks for this new equipment, the analysis team will therefore have a fairly good idea, from the outset, of which functions, failures, and tasks are going to demand consideration. The first step in the procedure is to partition the aircraft into its major divisions so that these can be assigned to the various working groups. Usually one working group is established to study the structure, another to study the powerplant, and several more to study the various systems.

The *systems* division includes the various sets of items other than the engine which perform specific functions – the environmental control system, the communications system, the hydraulic system. It also includes the items that connect the assemblies; for example, the hydraulic system includes the lines of that connect the actuators to the pump. The *powerplant* includes only the basic engine. It does not include the ignition system or engine-driven accessories, such as the fuel control and the constant-speed drive, all of which are part of systems. Nor does it include the engine cowling and supports, which are part of the structure. *Structure* includes all the airframe structure, as well as the movable flight-control surfaces, hinges, hinged bearings, and landing gear. However, the actuator cables, gearboxes, and hydraulic components associated with these items are treated as part of the systems division.

Each working group partitions the portion of the equipment for which it is responsible in descending levels of complexity to identify nonsignificant items on the one hand and significant and hidden function items on the other. To help organize this process the items are usually characterized in some kind of order. For example, the engine is ordinarily partitioned according to the order in which it is assembled – by module, stage, and part – whereas the structure is partitioned according to geographic zones. Exhibit 6.2 shows some typical items included under each of the major divisions, as well as typical items covered by zonal-installation inspections. Although these general inspections are not established on the basis of RCM analysis, the tasks themselves, along with the necessary servicing and lubrication tasks, are included in the final list of scheduled tasks for packaging in the maintenance program.

| Systems | Powerplant | Structure | Zonal installations |
|---|---|---|---|
| **Flight-control system**<br>Actuators<br>Gearboxes | **Compressor section**<br>Stators<br>Spacers<br>Tie rods | **Wing and empennage**<br>Stringers<br>Spars<br>Skins | **Wing zones**<br>Hydraulics lines<br>Fuel lines<br>Wiring<br>Ducting |

| | | | |
|---|---|---|---|
| Cables<br>Linkages<br>Control valves<br>**Electric-power system**<br>Generators<br>Relays<br>Constant-speed drives<br>Bus-control unit<br>**Air-conditioning system**<br>Packs<br>Valves<br>Sensors<br>**Ignition system**<br>Igniter<br>Power supply | Blades<br>Air seal<br>Compressor hubs<br>Disks<br>**Combustion section**<br>Scavenge pumps<br>Exit guide vanes<br>Diffuser case<br>Inner case<br>Bearing assembly<br>Bearing carbon steel<br>Stator support<br>Combustion chambers<br>Rear support<br>Outlet ducts<br>Nozzle guide vanes | Control surfaces<br>Slats and flaps<br>Hinges<br>**Landing gear**<br>Shock struts<br>Pistons<br>**Fuselage**<br>Circumferentials<br>Longerons<br>Skins<br>Bulkheads | **Wheelwell**<br>Switches<br>Hydraulic lines<br>Wiring<br>**Fuselage zones**<br>Oxygen cylinders<br>Assembly housings<br>Waterlines<br>wiring |

**Exhibit 6-2 Typical hardware in each of the three major divisions of an aircraft. The level of items selected as significant in each case will depend on the consequences of a functional failure for the aircraft as a whole. These items will be subjected to intensive RCM analysis to determine how they might benefit from scheduled maintenance. The resulting program of RCM tasks is supplemented by a separate program of zonal inspections, which consists of scheduled general inspections of all the items and installations within the specified zone.**

The first sorting process to identify significant items is largely a matter of experience and judgment. Some items will be classified as significant because they have always been significant in the past; others may be included because there is some uncertainty about their impact on the system as a whole. In selecting the appropriate level of items for intensive study, two types of error are possible: partitioning too far down and unnecessarily increasing the workload, or else not partitioning down far enough and thus overlooking some failure mode that may later prove significant. The first inclination is to minimize this latter possibility in the interests of safety. However, with limited time and resources it is equally important to take some cutoff point that will not dilute the effort needed for truly significant items. The optimum cutoff point for each item thus lies in a fairly narrow range. The partitioning process organizes the problem, but it is also necessary to organize the information required to solve it. In addition to the manufacturer's designation of the item, a brief description is needed that indicates the basic function of the item and its location in the equipment. It is also necessary to make a complete and accurate list of all the other intended or characteristic functions of the item in order to define the functional failures to which it is subject. A *functional failure* is any condition that prevents the item from meeting its specified performance requirements; hence the evidence by which this condition can be recognized must be specified as well. The functional failure may have several *failure modes*, and the most likely one must be identified. For example, the list of functional failures for the main oil pump on a jet engine might include high-pressure, low-pressure, no pressure, contaminated oil, and leaks. However, the condition of no pressure may be caused by drive-gear failure, shaft failure, or a broken oil line.

To evaluate the consequences of each type of failure it is necessary to identify both the effects of a loss of function and the effects of any secondary damage resulting from a particular failure mode. For example, the loss of function for a generator might be described as no output; if the cause is bearing failure, however, the probable secondary damage is complete destruction of the generator, which is very expensive. Another important factor in evaluating failure consequences is the design of the equipment itself. All the redundancies, protective devices, and monitoring equipment must be listed, since these have a direct bearing on the seriousness of any single failure. If an essential function is available from more than one source, then a failure that might otherwise have a direct effect on safety or operating capability may have no significant consequences. Similarly, failure annunciators and other instrumentation mean that failures that would otherwise be hidden are in fact evident to the operating crew.

All these data elements are assembled for each item before the analysis begins. To keep track of the necessary information it is helpful to summarize the data for each item on a descriptive worksheet like that shown in Exhibit 6.3. The analysis itself consists of a systematic examination of each failure possibility and an evaluation of proposed maintenance tasks. Tasks are proposed by both the manufacturing members of the program-development team and by the members of the operating organization. The manufacturer has more specific knowledge of the equipment, it's intended design features, and the development and testing procedures that were employed. The operating organization has the more intimate knowledge of how the equipment will be used, what sorts of maintenance tasks are feasible, and which ones have proved most effective in the recent past.

**System information worksheet**

| | | | |
|---|---|---|---|
| Type of aircraft | | | |
| Item No. | | | |
| Item name | | | |
| Vendor part/model no. | | | |
| No. per aircraft | | | |
| system | | | |
| Zone(s) | | | |
| Prepared by | | Date | |
| Reviewed by | | Date | |
| Approved by | | Date | |
| Item description: | | | |
| | | | |
| | | | |
| **Redundancies and protective features:** | | | |
| | | | |
| | | | |
| **Built-in test equipment (describe):** | | | |
| | | | |
| | | | |
| **Can aircraft be dispatched with item inoperative? If so list any limitations which must be observed:** | | | |
| | | | |
| | | | |
| **Classification of item (check)** | | | |
| • Significant: ☐ | | | |
| • Hidden functions: ☐ | | | |
| • Nonsignificant: ☐ | | | |
| **Reliability data:** | | | |
| • Premature-removal rate (per 1000 unit hours) | | | |
| | | | |
| • Failure rate (per 1000 unit hours) | | | |
| • Source of data: | | | |
| | | | |
| **Functions** | **Functional failures** | **Failure modes** | **Failure effects** |
| | | | |
| | | | |
| | | | |
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| | | | |

**Exhibit 6-3 Item information worksheet. The data elements that pertain to each item are assembled and recorded on a descriptive worksheet before the analysis is begun. For convenience in documenting the decision process, it is helpful to use reference numbers and letters for the various functions, functional failures, and failure modes of each item.**

To ensure that the entire decision process is documented, the answer to each question in the decision diagram must be recorded. One convenient form is shown in Exhibit 6.4; the numbers across the top represent the decision questions, and the trail of answers shows the logic by which a particular decision was reached. Depending on the nature of the item, its failure characteristics, and the failure consequences that govern the evaluation, the outcome may be one or more scheduled tasks, redesign, or no scheduled maintenance. In each case, however, the reason for the decision will be clearly identifiable, both for auditing during analysis and for later review.

| **System decision worksheet** | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type of aircraft | | | | | | | | | | | | | | | | | | |
| Responses to decision-diagram questions | | | | | | | | | | | | | | | | | | |
| Ref. | | | Consequences | | | | | | | Task selection | | | | | | | | |
| F | FF | FM | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| | | | | | | | | | | | | | | | | | | |
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**Exhibit 6-4 Decision worksheet for systems and powerplant items. For each function (F), functional failure (FF), and failure mode (FM), the answers to the questions in the decision diagram are recorded to show the reasoning leading to the selection of a particular task. In the case of structural items the principal decision problem concerns the selection of task intervals; hence the worksheet form used for structures is somewhat different.**

The study up to this point represents a substantial effort. The analysis for the Douglas DC-10, which was based on similar principles, led to a set of reports approximately 10 inches high and represented about 10 man years of effort over and 18-month period. Nevertheless, given the complexity of modern aircraft, this effort is still modest in comparison to what might be envisioned if the several bounds on the process were relaxed. These bounds are established by the decision questions themselves, by the default strategy that provides for decision-making with minimal information, and also by the auditing process that goes on both during analysis and afterward.

## 6.4. The decision information flow in decision-making

The flow of information in RCM decision-making is a circular process that begins with the initial selection of items for intensive analysis and continues throughout the life of the equipment. The very selection of significant items requires not only substantial factual data, but considerable experience and judgment as inputs to a prior-to-service analysis. The outputs are a list of all the applicable and effective tasks to be included in the scheduled-maintenance program. These tasks are then assigned intervals and packaged for implementation, and from this point on the information from actual operating experience becomes the input data.

In most cases the transition from prior-to-service study to actual maintenance on in-service equipment takes place gradually. The first few planes delivered and put into service are inspected at relatively frequent intervals. This "excessive" maintenance is not expensive, since only a few planes are involved, and it serves both to work out the shortcomings in the maintenance program and to provide training opportunities for the personnel who will eventually handle the entire fleet.

During early operation the condition and performance of the aircraft are continually monitored through what the FAA terms an *analysis and surveillance program*. The maintenance department is prepared for unanticipated kinds of failures and is ready to react immediately to any critical events. Other failure experiences are reported systematically, and this information is used to review and revise the scheduled tasks and to provide the cost data necessary to initiate product improvement. The maintenance crew will also be able to confirm the reliability of many items; that is, they will see a great deal of non-failure, which is also reflected in the program as it evolves. For example, the inspection intervals for items that are performing satisfactorily will be extended, thus reducing the workload per plane at about the same rate that new planes are entering service.

By the time the fleet has reached full-size – about five years after the first planes enter service – the thrust of maintenance analysis turns to a more careful study of the items that may eventually show wearout characteristics and would therefore benefit from periodic rework or discard. As the potential-failure ages of longer-lived items are identified, some of these items may also be modified through redesign to increase their longevity, and there will be corresponding changes in their maintenance requirements, necessitating a further round of analysis and age exploration to determine their new reliability characteristics. Periodically the entire maintenance program is subjected to "purging" both to eliminate tasks that have crept in to take care of problems that have since been resolved and to omit borderline tasks that have not proved to be worthwhile.

As a result of continuous maintenance and product improvement, the aircraft also evolves throughout its operating life. Most commercial aircraft remain in operation for at least 20 years. At the end of this time, although the overall structure of any given plane will be essentially the structure it started with, the rest of the aircraft will have been substantially replaced or modified, and most of the replacement parts will have been changed many times. Thus the aircraft is not in fact 20 years old; only the basic structure is. This constant cycle of preventive and corrective maintenance ensures that an aircraft does not wear out with age. Instead, it remains in service until newer designs render it technologically obsolete.

To realize the inherent reliability of any aircraft it is necessary to keep track of its state, both individually and collectively, from the time the equipment enters service until the time it is finally retired. The information about failed items, potential failures, and the corresponding replacement of parts or components in each aircraft must be recorded and assembled in a form that allows for analysis of the performance of the aircraft as a whole, as well as the performance of individual items. At the earliest stages these information requirements concerned only individual failures and failure modes. Soon after, it becomes necessary to keep track of the accumulated operating time of the fleet in order to establish failure rates, and when they are sufficiently low, reduce inspection frequencies. It is sometimes helpful during the middle years of operation to make extensive studies of individual item histories (including actuarial analyses).

Given the hundreds of thousands of parts on a modern aircraft, these information requirements call for careful judgment. The notion that someone must be able to determine at any point how long the light bulb over seat 3F has been in operation would lead to staggering information costs. Just as it is crucial at the beginning to size the problem of analysis, so it is crucial to size the reporting system so that the information necessary to manage the ongoing maintenance program is not buried by an *information overload*. The various types of reporting systems and the specific kinds of information they provide are discussed in Chapter 11.

Whatever the equipment, as the maintenance program evolves each iteration of the decision process must be documented and audited by independent observers if the results are to be relied upon. This documentation is just as important for subsequent modifications of the initial program as it was in developing the initial program. The structure of the decision logic provides such documentation, since the list of yes/no answers to specific questions leaves a *clear audit trail* that can be checked both during and after the decision process. This audit trail, together with the information on which the initial decisions were made and modified during subsequent operation of the equipment, provides the starting point for the next round of design evolution. Given the transitory nature of the workforce in both government and commercial situations and the relatively long service life of complex equipment, this maintenance-system "memory" is a necessary factor in long-term technological improvement.

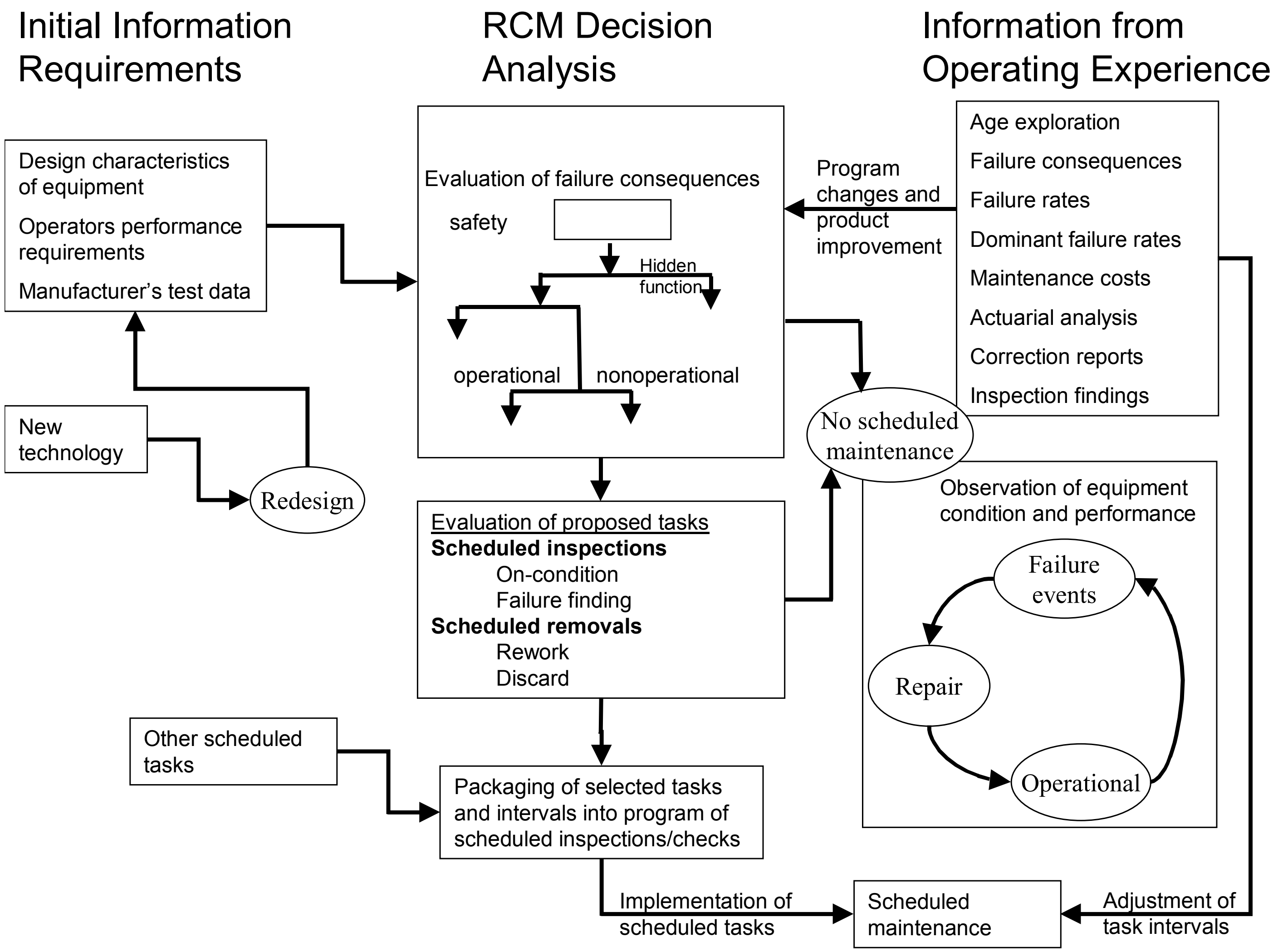



**Exhibit 6-5 The process of information flow and decision making in the development and evolution of an RCM program.**

# 7. Chapter Seven - RCM analysis of systems

The systems division includes all the systems required for operating the airplane except the powerplant itself. Most systems are composed of numerous separate assemblies, or components, linked by electrical or hydraulic lines or other connecting devices. Even in a new type of aircraft few of the systems components will be entirely new; most will have been used in previous designs. As a result, the reliability characteristics of many systems items are fairly well known and data are often available on the applicability and effectiveness of specific maintenance tasks. Maintenance experience has also shown that certain classes of items, such as electronic components, have the generic characteristic of being unable to benefit from scheduled maintenance.

A great many systems items do not require scheduled maintenance. While a number of systems do have hidden functions that must be protected by scheduled tasks, most aircraft systems have been designed to preclude critical failures and many have been designed to ensure that the aircraft will remain fully operational after the occurrence of a failure. An item whose failure is evident to the operating crew and has no safety or operational consequences would be classified as nonsignificant and would be assigned in an initial program to no scheduled maintenance. The system itself would be designed as significant, since its overall function is essential to the aircraft. In many cases, however, the units that actually perform this function are nonsignificant items, since a failure of any one of them has no consequences other than the cost of repair.

In general, the outcome of RCM analysis depends more on the design characteristics of the system than on the nature of the item. Nevertheless, certain results are typical for various classes of items. Mechanical items such as fuel pumps, gear boxes, and brake assemblies will often receive on-condition tasks, and on rare occasions a rework task, although frequently the assignment is to no scheduled maintenance. Hydraulic items are generally assigned on-condition tasks in which a gross-flow check of the entire system is followed by isolation checks to pinpoint the source of internal leaks. Electrical and electronic items, unless they have hidden functions that require failure-finding tasks, will nearly always be assigned to no scheduled maintenance.

# 7.1. Characteristics of systems items

Each type of system has a unique function in an aircraft – flight control, environmental control, fuel supply, high-frequency communication, and so on. Nevertheless, systems as a group have certain common characteristics that affect their maintenance requirements. Most systems are equipped with instrumentation which allows the operating crew to monitor the performance goals of the system as a whole and of many of its individual components. Thus as a general rule functional failures are evident to the crew. Also, such failures seldom affect operating safety. As a result of careful design, even unanticipated failure modes are unlikely to have safety consequences. The chief reason for this is the high degree of redundancy employed in systems design. All essential functions are available to the aircraft from more than one source, so that the system is *fail-safe*.

It is usual, in fact, for systems to include enough redundancy to permit completion of a day's flying after failure has occurred. Under the circumstances the airplane can be dispatched with one unit inoperative, and unless a second unit fails there is no need to interrupt scheduled operations for corrective maintenance. Thus, despite the frequency of systems failures, the majority of these failures have no operational consequences. Correction of the failure is simply deferred to a convenient time and location. In addition to the protection afforded by redundancy, some of the more exotic devices, such as the autoland system, employ a newer technique called *fail-operational*. In this case not only the aircraft, but the system itself remains fully operational after the occurrence of a failure.

Even though systems in commercial aircraft are designed to reduce failure consequences to the non operational level, once the equipment enters service the performance of all items, including those assigned to no scheduled maintenance, is carefully monitored during the early stages of operation. To meet the space and weight requirements of high-performance aircraft, systems components are generally designed with a low initial margin of failure resistance; hence their overall reliability tends to be low. To offset this problem components are usually designed for easy replacement in the field. Even so, the poor reliability of certain items may result in unacceptable repair or support costs, and the need to improve systems items by redesign is quite common in new aircraft.

Another characteristic of systems is that the assemblies that comprise them are themselves multi-celled and subject to numerous failure modes – that is, they are complex items. Since the overall reliability of a complex item generally shows little or no relationship to operating age, scheduled reworking is rarely applicable to systems components (see Section 3.2). Rework or discard tasks may be applicable, however, to relatively simple parts such as connecting lines or to items subject to mechanical wear or metal fatigue. Some assemblies may also include safe-life parts, such as the actuator endcaps in certain flight-control systems, for which redundancy is not feasible.

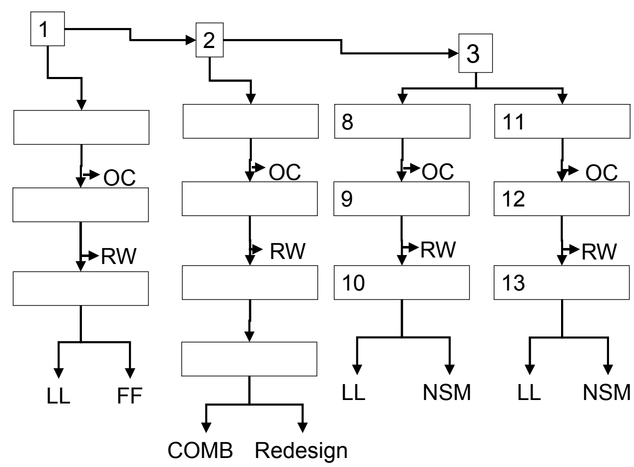



**Exhibit 7-1 The most common outcomes of RCM analysis in the systems division. Few systems failures fall in the safety branch; several, however, may fall in the hidden-function branch. The principal objective of analysis is to ensure that these exceptions are accurately identified.**

In terms of RCM analysis, then, systems items are characterized by evident failures which fall primarily in the economic branches of the decision diagram, where scheduled maintenance is desirable only if it is cost-effective (see Exhibit 7.1). For this reason, and because most failures are unrelated to operating age, the most frequent outcome of analysis is either an on-condition task or no scheduled maintenance. However, the exceptions to this general pattern may fall in any branch and lead to almost any of the possible outcomes. The principal focus in developing a prior-to-service program for systems is on proper identification of these exceptions.

## 7.2. Assembling the required information

The analysis of the system, subsystem, or assembly requires a knowledge both of the system itself and of the relationship of the system to the aircraft has a whole. To evaluate the consequences of a functional failure it is necessary to visualize the various failure possibilities in terms of the basic function of the entire system, rather than from the standpoint of its component units. For this reason particular attention must be paid to redundancies and other fail-safe features, since the amount of replication of a given function will determine the seriousness of the failure consequences. The failure in a nonredundant system might represent a critical loss of function for the aircraft, whereas the same failure in a highly redundant system may not affect operational capability.

| |
|---|
| **Identification of item** |
| Type of aircraft |
| Quantity per aircraft |
| System designation |
| Location(s) |
| Item name |
| Manufacturer's part number |
| |
| **Item information** |
| Item description (general function and major assemblies) |
| |
| Redundancies and protective features (including instrumentation) |
| |
| Built-in test equipment |
| |
| **Available reliability data** |
| Anticipated premature-removal rate |
| Anticipated verified failure rate |
| Source of data (test data or operating experience) |
| |
| **Operating restrictions** |
| Can aircraft to be dispatched with item inoperative? (from MEL) if so, do any limiting conditions apply? |
| |
| **RCM input** |
| Item functions |
| Functional failures (as defined for each function) |
| Predictable failure effects (for each failure mode) |
| Evidence of functional failure |
| Effects of loss of function on operating capability |
| Effects of failure beyond loss of function (including ultimate effects of possible secondary damage) |
| Nature of failure consequences |
| Evidence of reduced failure resistance that can be used to define potential-failure conditions |
| Experience with other equipment on which the same or similar item has been used |

**Exhibit 7-2 The data elements needed for analysis of systems items.**

Another design feature that affects the evaluation of failure consequences is the instrumentation or built-in test equipment for the system. This instrumentation is a major factor in determining whether functional failures will be evident or hidden from the operating crew. It is also necessary to know enough about the duties of the operating crew to judge whether functional failure will be evident during routine activities, either through use of the function or as result of standard crew checks of certain hidden-function items.

In the airline industry the minimum-equipment list and the configuration-deviation list, issued by the FAA, specify whether or not an aircraft can be dispatched with a given item inoperative. These lists help to determine whether a failure has operational consequences. They're not the sole determinant; a failure that can be corrected quickly may cause no delay in flight schedules, and highly unreliable items may involve occasional operational consequences as result of a multiple failure. However, any regulations that define acceptable flight configuration are an important part of the initial information requirements.

Exhibit 7.2 lists the data elements that must be collected and organized for each item to be studied. In the case of new aircraft much of this information is supplied by the manufacture in the various maintenance manuals and stores catalogs furnished with the equipment. For the wide-body Douglas DC-10, for example, the working groups were provided with worksheets, instruction manuals, and schematic diagrams showing nearly all the data available. Usually 200 to 300 of the most important systems, subsystems, and subassemblies will be classified either as functionally significant items or as items with hidden functions. If there is any doubt about whether an item is significant or has a hidden function, it is always classified on this basis initially and included in the list of items to receive further study.

Once the data elements for each item have been assembled, they are summarized on descriptive worksheets for convenient reference during analysis. Note in Exhibit 7.3 that the item description indicates the general function of the item, the level of items being considered, and the major assemblies and components it includes. The failure of any one of these components would represent a failure mode for the item itself. In listing the functions of the item it is important to describe both its basic function and each of its secondary functions clearly and accurately, since each of these functions must be analyzed separately. The functional failures should be worded to define the condition that constitutes a failure. Generally this is the condition or state that exists after a failure has occurred.

*Failure effects* refers to all the immediate results of the failure. For example, one effect of a locked wheel in a brake assembly is a tire blowout, with possible secondary damage to the airplane structure; another effect is noise and vibration, which will be apparent to the operating crew. The description of failure effects should always include any physical evidence by which the occurrence of the failure can be recognized. Very often this evidence is an instrument indication of a warning light that informs the pilot of a malfunction. In some cases the failure effects also include specific operating restrictions, such as the need to descend to a lower altitude. The failure effects must be described for each type of functional failure, since they help to determine the consequences of that failure for the equipment and its occupants.

All this information is examined, and the item is given a conservative initial classification of significant or nonsignificant on the basis of its failure consequences. Items in either category may have hidden functions; these must be identified whether the item is significant or not. Thus some items may have two classifications. An item classified as significant during the initial partitioning process may later be assigned to no scheduled maintenance, either because its failure consequences do not in fact qualify it is significant or because no maintenance task can be found that will improve its reliability. At this stage however, any borderline items would be included for analysis.

| **System information worksheet – type of aircraft: Douglas DC-10** | | | |
|---|---|---|---|
| Item No. | Number for aircraft: 3 | Prepared by: F.S. Nowlan | Date: 3/6/78 |
| Item name: air-conditioning pack | System: Air conditioning | Reviewed by: J.E. Kuhl | Date: 3/6/78 |
| Vendor part/model number: Airesearch 927370-4 | Zone(s): 110 | Approved by: | Date: |
| | | | |
| **Item description:**<br>Pack delivers temperature-controlled air to conditioned-air distribution ducts of airplane. Major assemblies are heat exchanger, air-cycle machine, anti-ice valve, water separator, and bulkhead check valve. | | **Redundancies and protective features (include instrumentation):**<br>The three packs are completely independent. Each pack has a check valve to prevent loss of cabin pressure in case of duct failure in unpressurized nose-wheel compartment. Flow to each pack is modulated by a flow-control valve which provides automatic over temperature protection back by an over temperature trip off. Full cockpit instrumentation for each pack includes indicators for pack flow, turbine inlet temperature, pack-temperature valve position, and pack discharge temperature. | |
| Reliability data: | | **Built-in test equipment (described):** none | |
| Premature-removal rate (per 1000 units hours): | | **Can aircraft be dispatched with item inoperative? If so list any limitations which must be observed:**<br>Yes. No operating restrictions with one pack inoperative. | |
| Failure rate (per 1000 units hours) | | Classification of item (check) | |
| Source of data: | | Significant | |
| | | Hidden function | X. |
| | | Nonsignificant | X. |
| | | | |
| **Functions** | **Functional failures** | **Failure modes** | **Failure effects** |
| 1 To supply air to conditioned air distribution ducts at the temperature called for by pack temperature controller | A conditioned air is not supplied at called-for temperature | 1 air-cycle machine seized | Reduced pack flow, anomalous readings on pack-flow indicator and other instruments |
| | | 2 blocked ram-air passages in heat exchanger | High turbine-inlet temperature and partial closure of slow-control valve by over-temperature protection, with resulting reduction in Pack airflow |
| | | 3 failure of anti-ice valve | If valve fails in open position, increasing impact discharge |

| | | | |
|---|---|---|---|
| | | | temperature; if valve fails in closed position, reduced pack airflow |
| | | 4 failure of water separator | Condensation (water drops, fog, or ice crystals) in cabin |
| 2 To prevent loss of cabin pressure by backflow if the duct is fails in unpressurized nose-wheel compartment | A No protection against backflow | 1 failure of bulkhead check valve | None (hidden function); if duct and or connectors fail in pack bay, loss of cabin pressure by backflow, and airplane must descend to lower altitude |

**Exhibit 7-3 And information worksheet for the air-conditioning pack in the Douglas DC-10.**

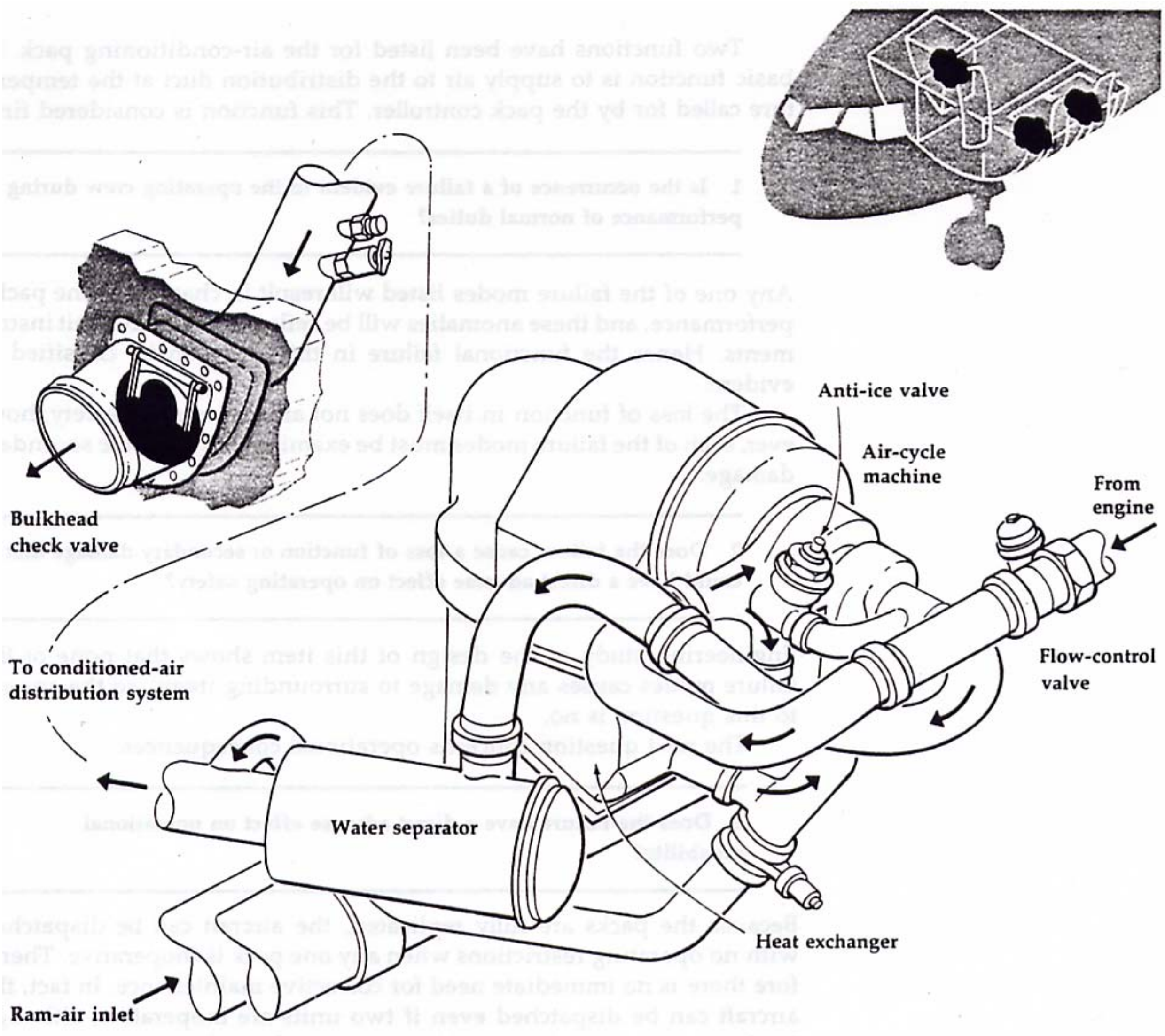



**Exhibit 7-4 The air-conditioning pack in the Douglas DC-10. the location of the three packs in the nose-wheel compartment is indicated at the upper right. (Based on Airesearch maintenance materials)**

# 7.3. Analysis of typical systems items

## Analysis of an air-conditioning pack

The air-conditioning pack described in Exhibit 7.3 is the cooling portion of the Douglas DC-10 air-conditioning system. This subsystem was classified as significant during the first review of the DC-10 systems because of its size, complexity, and cost. There are three independent installations of this system, located in the unpressurized nose-wheel side compartment of the airplane (see Exhibit 7.4). Hot high-pressure air, which has been bled from the compressor section of the engine, enters the pack through a flow-control valve and is cooled and dehumidified by a heat exchanger and the turbine of an air-cycle refrigeration machine. The cool air is then directed through a distribution duct to a manifold in the pressurized area of the airplane, where it is mixed with hot trim air and distributed to the various compartments. The performance of each pack is controlled by a pack temperature controller. Each pack is also monitored by cockpit instrumentation and can be controlled manually if there is trouble with the automatic control system.

The pack itself consists of the heat exchanger, the air cycle machine (which has air bearings), and an anti-ice valve, a water separator, and a check valve at the pressure bulkhead to prevent backflow and cabin depressurization if there is a duct failure in the unpressurized area. The duct is treated as part of the distribution system; similarly the flow-control valve through which air enters the pack is part of the pneumatic system. The pack temperature controller is part of a complex temperature-control system and is also not analyzed as part of the air-conditioning pack.

Two functions have been listed for the air-conditioning pack. It's basic function is to supply air to the distribution duct at the temperature called for by the pack controller. This function is considered first:

> **1 Is the occurrence of a failure evident to the operating crew during performance of normal duties?**

Anyone of the failure modes listed will result in changes in the pack's performance, and these anomalies will be reflected by the cockpit instruments. Hence the functional failure in this case can be classified as evident.

The loss of function in itself does not affect operating safety; however, each of the failure modes must be examined for possible secondary damage:

> **2 Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?**

Engineering study of the design of this item shows that none of the failure modes cause any damage to surrounding items, so the answer to this question is no.

The next question concerns operational consequences:

> **"3 Does the failure have a direct adverse effect on operational capability?"**

Because the packs are fully replicated, the aircraft can be dispatched with no operating restrictions when any one pack is inoperative. Therefore there is no immediate need for corrective maintenance. In fact, the aircraft can be dispatched even if two units are inoperative, although in this event operation would be restricted to altitudes of less than 25,000 feet.

On this basis we would reclassify the air-conditioning pack as a functionally nonsignificant item. Failure of any one of the three packs to perform its basic function will be evident, and therefore reported and corrected. A single failure has no effect on safety or operational capability, and since replacement of the failed unit can be deferred, there are no economic consequences other than the direct costs of corrective maintenance. Under these circumstances scheduled maintenance is unlikely to be cost-effective, and the costs cannot be assessed in any event until after the equipment enters service. Thus in developing a prior-to-service program there is no need to make an intensive search for scheduled tasks that might prevent this type of failure.

When we examine the second function of the air-conditioning pack, however, we find an element that does require scheduled maintenance. The bulkhead check valve, which prevents backflow in case of a duct failure, is of lightweight construction and flutters back and forth during normal operation. Eventually mechanical wear will cause the flapper to disengage from its hinge mount, and if the duct in the pressurized nose-wheel compartment should rupture, the valve will not seal the entrance to the pressurized cabin.

To analyze this second type of failure we start again with the first question in the decision diagram:

> **"1 Is the occurrence of a failure evident to the operating crew during performance of normal duties?"**

The crew will have no way of knowing whether the check valve has failed unless there is also a duct failure. Thus the valve has a hidden function, and scheduled maintenance is required to avoid the risk of multiple failure – failure of the check valve, followed at some later time by failure of the duct. Although the first failure would have no operational consequences, this multiple failure would necessitate descent to a lower altitude, and the airplane could not be dispatched after landing until repairs were made.

With a no answer to question 1 proposed tasks for the check valve fall in the hidden-function branch of the decision diagram:

> **"14 Is an on-condition task to detect potential failures both applicable and effective?"**

Engineering advice is that the duct can be disconnected and the valve checked for signs of wear. Hence an on-condition task is applicable. To be effective the inspections must be scheduled at short enough intervals to insure adequate availability of the hidden function. On the basis of experience with other fleets, an initial interval of 10,000 hours is specified, and the analysis of this function is complete.

<u>In this case inspecting the valve for wear costs no more than inspecting for failed valves and is preferable because of the economic consequences of a possible multiple failure. If a multiple failure had no operational consequences, scheduled inspections would still be necessary to protect the hidden function; however, they would probably have been scheduled at longer intervals as a failure-finding task.</u>

| System decision worksheet | | Prepared by: | Reviewed by: | |
|---|---|---|---|---|
| Type of aircraft | Douglas DC-10 | F.S. Nowlan | J.E. Kuhl | |
| Item name | Air-conditioning pack | | | |

| Responses to decision-diagram questions | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ref. | | | Consequences | | | | | | | | Task selection | | | | | | | | **Proposed task** | **Initial interval** |
| F | FF | FM | | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | |
| 1 | A | 1 | Y | N | N | | | | | | | | | | | | | | None. This functional failure has no significant consequences; reclassify as nonsignificant. | |
| 1 | A | 2 | Y | N | N | | | | | | | | | | | | | | | |
| 1 | A | 3 | Y | N | N | | | | | | | | | | | | | | | |
| 1 | A | 4 | Y | N | N | | | | | | | | | | | | | | | |
| 2 | A | 1 | N | - | - | - | - | - | - | - | | - | - | - | - | Y | | | Disconnect duct to manifold and examine check valve for wear, | Not to exceed 10,000 hours |

**Exhibit 7-5 A worksheet for showing the results of RCM analysis of the air-conditioning pack in the Douglas DC-10. the references in the first column are to the functions, functional failures, and failure modes listed in Exhibit 7.3.**

Exhibit 7.5 shows the results of the preceding analysis, including the response to each question in the decision diagram. Note that the basis for each answer to the first three questions is directly traceable to the information recorded on the descriptive worksheet in exhibit 7.3.

# Analysis of a nonredundant fuel pump

The fuel-pump assembly described in Exhibit 7.6 was classified as a significant item because the aircraft in which it is installed is a <u>single-engine attack plane</u>. This means that a complete loss of function will bring the airplane out of the sky. As indicated on the worksheet, the fuel pump is subject to four types of functional failures. The first of these is loss of fuel flow (and pressure), and the associated failure mode is stripped splines on the main drive shaft.

> **"1 Is the occurrence of a failure evident to the operating crew during performance of normal duties?"**

| System information worksheet – type of aircraft: Douglas A-4 | | | |
|---|---|---|---|
| Item No. | Number for aircraft: 1 | Prepared by: F.S. Nowlan | Date: 3/6/78 |
| Item name: fuel pump | System: fuel supply | Reviewed by: T.M. Edwards | Date: 3/6/78 |
| Vendor part/model number: | Zone(s): | Approved by: | Date: |
| | | | |
| **Item description:** Multistage engine fuel pump driven through splined shaft by engine-accessory gearbox. Delivers high-pressure fuel to fuel control and provides fuel-control governor with engine-speed information. Includes a fuel filter and filter bypass. | | **Redundancies and protective features (include instrumentation):** Fuel flow and fuel pressure are instrumented. Warning light indicates when fuel filter is bypassed; manual fuel-heat control can be used to clear filter of ice particles. Fuel-control unit includes fuel bypass with a constant-flow restrictor that automatically provides sufficient fuel for 80 percent $N_2$ engine speed if speed signal is lost. | |
| Reliability data: | | Built-in test equipment (describe): none | |

| | | | |
|---|---|---|---|
| **Premature-removal rate (per 1000 units hours):** | | **Can aircraft be dispatched with item in operative? If so list any limitations which must be observed:**<br>no | |
| Failure rate (per 1000 units hours) | | Classification of item (check) | |
| Source of data: | | Significant | X. |
| | | Hidden function | |
| | | Nonsignificant | . |
| | | | |
| **Functions** | **Functional failures** | **Failure modes** | **Failure effects** |
| 1 To pump fuel to engine through fuel-control unit | A No fuel flow (and pressure) | 1 Stripped splines on main drive shaft | Instruments show no fuel flow and pressure; engine flameout, requiring forced no-power landing |
| 2 To contain fuel, without external leakage | A External fuel leaks | 1 Worn or damaged main-shaft seals | Small loss of fuel through overboard drains |
| 3 To filter fuel | A Unable to filter fuel | 3 Filter clogged by ice or debris from wear | Warning light shows filter bypass, possible delivery of contaminated fuel to fuel control and engine; if fuel heater does not correct for ice particles (warning light goes out), airplane must land at nearest airport |
| 4 To provide engine-speed signal to fuel control | A Loss of engine-speed signal | 1 Stripped splines on fuel-control-governor drive shaft | Fuel control automatically provides fuel for 80 percent $N_2$ engine speed, no engine control except manual shutdown; landing hazardous |

**Exhibit 7-6 A worksheet showing the results of RCM analysis of the fuel pump in the Douglas A-4. The references in the first column are to the functions, functional failures, and failure modes listed in Exhibit 7.6.**

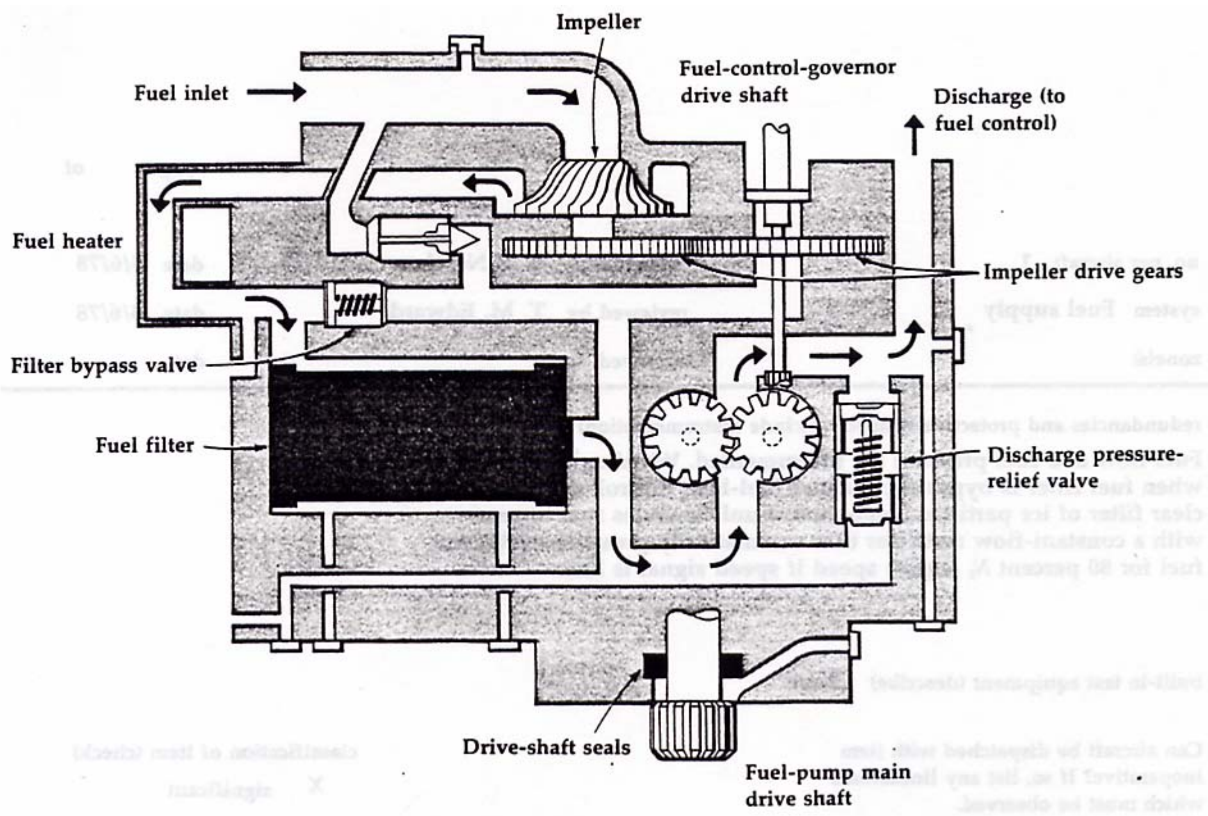



**Exhibit 7-7 Schematic diagram of the fuel-pump assembly in the Douglas A-4. The fuel-pump main drive shaft is powered by the airplane engine.**

Loss of fuel flow results in fuel starvation of the engine and an immediate and complete loss of thrust (flameout). The pilot will sense this loss of thrust by a reduction in engine noise and deceleration of the aircraft, but it will also be evidenced by many instruments – the fuel pressure indicator, and the altimeter. The answer to question 1 is therefore yes.

Since the failure is evident, the next concern is with its direct consequences:

> **"2 Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?**

In the event of a flameout, the pilot must either eject or make the best power-off landing he can, regardless of the landing conditions. In this case the loss of function itself has safety consequences, so it is unnecessary to consider whether either of the failure modes causes hazardous secondary damage. The yes answer to this question brings us to the safety branch of the decision diagram, where all applicable scheduled-maintenance tasks are required that are considered effective only if they reduce the risk of this failure to an acceptable level.

We must now evaluate possible preventive tasks directed at the failure mode, stripped drive-shaft splines:

| **System decision worksheet** | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type of aircraft | | | | | | Douglas DC-10 | | | | | | | | | | | Prepared by: F.S. Nowlan | Reviewed by: J.E. Kuhl | |
| Item name | | | | | | Air-conditioning pack | | | | | | | | | | | | | |
| Responses to decision-diagram questions | | | | | | | | | | | | | | | | | | | |
| Ref. | | | Consequences | | | | | | | Task selection | | | | | | | | **Proposed task** | **Initial interval** |
| F | FF | FM | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | |
| 1 | A | 1 | Y | Y | - | N | N | N | N | | | | | | | | | | None. Redesign is necessary to provide sufficient redundancy for operating safety. | - |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | If airplane must enter service before design is modified, the following responses would be appropriate, although there is no assurance that scheduled tasks will meet effectiveness criterion | | | | | | | | | | | | | | |
| 1 | A | 1 | Y | Y | - | Y | | | | | | | | | | | | | Inspect main fuel-pump drive shaft for spline wear | Not to exceed 1000 hours |
| 2 | A | 1 | N | - | - | - | - | - | - | - | - | - | - | - | - | N | N | N | Inspect for external leaks (failure finding) | During walkaround checks and overnight stops |
| 3 | A | 1 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Inspect filter for contamination | Not to exceed 60 hours |
| 4 | A | 1 | Y | Y | - | N | N | N | N | | | | | | | | | | Both come as for failure of main drive shaft, 1 A 1 | |

**Exhibit 7-8 A worksheet showing results of RCM analysis of the fuel pump in the Douglas A-4. the references in the first column hard to the functions, functional failures and failure modes listed in Exhibits 7.6.**

**"4 Is an on-condition task to detect potential failures both applicable and effective?"**

Periodic inspection of the drive shaft for spline wear will result in the removal of units from service at the potential-failure stage; hence an on-condition task is applicable. If this task reduced the risk of a functional failure to an acceptable level, it would also be considered effective, and the answer to the question would be yes. In an initial program however, the chief source of information concerning the effectiveness of an on-condition task is prior experience with a similar item. In this case such information is not available, and even though we know that task will be applicable, we have no means of determining that it will provide the degree of protection required. Under these circumstances we would be reluctant to consider this task as meeting the effectiveness criterion, and the answer to the on-condition question must therefore be no.

Since an effective on-condition task has not been identified we must investigate other types of tasks:

**"5 Is a rework task to reduce the failure rate both applicable and effective?"**

The fuel pump is a complex item, so we would not expect scheduled rework to make a difference in its overall reliability. Such a task might be applicable, however, for a specific failure mode involving a simple part, such as stripped drive-shaft splines. In this case scheduled rework what probably entail removing the pump from the aircraft and sending it to the maintenance base for machine work to restore the splines to "like new" condition. If analysis of the other failure possibilities identified additional parts that could benefit from rework, there might be quite extensive rework activity while the pump was at the base.

Scheduled rework might lead to an appreciable reduction in fuel-pump failures if the failure modes for which rework tasks were applicable represented a large portion of the failure possibilities for this item. However, this is an unusual situation for a complex item. Moreover, the information necessary to assess the value of a rework task is not available at the time an initial program is developed. At this stage, therefore, we cannot conclude that scheduled rework would provide any guarantee of operating safety and would have to answer this question no. A no answer to the rework question means that we must move on to the question of a discard task:

**"6 Is a discard task to avoid failures or reduce the failure rate both applicable and effective?"**

During the development of an initial program the answer to this question must be no unless the pump manufacturer has specified a safe-life limit for the drive shaft.

Since no single task has been identified thus far which will protect against loss of the basic fuel-pump function, there is one further recourse:

**"7 Is a combination of preventive tasks both applicable and effective?"**

The answer must again be no, since the only task that might possibly be of benefit is a on-condition inspection of the drive shaft. The outcome of the analysis, therefore, is that scheduled maintenance cannot prevent pump failures, and to avoid critical failures the design must be changed – in this case to provide redundant pumping capabilities in the fuel-supply system.

What can be done if the aircraft must enter service before the design can be modified? An on-condition inspection of the drive shaft for spline wear can be assigned because such a task is usually effective for a single mechanical part. We do not know whether it will prove effective in this case. A rework task would probably not be selected to re-machine splines; instead the shaft would be replaced if the splines were in bad condition. All such tasks, however, would entail scheduled removals, because the fuel pump must be disassembled to gain access to the shaft. The initial intervals would be very conservative, and we would still have to recognize that operating experience may show that these measures are not reducing the hazard to an acceptable level.

In addition to loss of fuel flow as a result of mechanical failure, the pump is also subject to external leaks. While a leak serious enough to affect fuel pressure would be evident to the operating crew, the fact that a leak has formed will not be evident from the cockpit instrumentation. The answer to the first decision question is therefore no, which takes us to the hidden-function branch of the diagram. As indicated by the answers recorded in Exhibit 7.8, there are no applicable and effective on-condition, rework, or discard tasks in this case. Therefore we arrive at the default alternative and must schedule a failure-finding task – and inspection during walkaround checks and overnight stops for any leaks that exceed a specified value.

A third type of functional failure results from clogging of the fuel filter. A warning light informs the pilot when this condition exists, so the failure is classified as evident. It does not present any safety problems, but it does have operational consequences, since a single-engine plane must land at the nearest airport and cannot be dispatched until the condition has been corrected. An on-condition inspection of the fuel filter for contamination is applicable. In this case the failure consequences are economic; hence the criterion of task effectiveness is cost. The cost of performing this task is so little that it would be judged as cost-effective in an initial program. As a result of experience with other fuel pumps, and initial interval of 60 hours is set for this check.

The fourth type of failure is inability to provide engine-speed information to the fuel control assembly, caused by failure of the governor drive shaft (see Exhibit 7.7). Since the analysis of this failure is similar to that for failure of the main drive shaft, the details are not repeated in Exhibit 7.8. If tasks were scheduled, they would be performed at the same time as those for the main drive shaft.

## Analysis of a landing-gear brake assembly

The brake assembly for the main landing gear of the Douglas DC-10 is classified as significant because the primary function of the braking system is to provide stopping capability after landing or during other ground operation. Since a complete loss of this function would clearly have safety consequences, it is necessary to consider how the brake assembly contributes to the overall system function. The full braking capacity is rarely used, and its effect is masked by concurrent use of reverse thrust from the engine. As a result, the pilot is not likely to notice the reduction in stopping capability caused by a failure in one brake assembly of a multi wheeled landing gear. This item therefore has hidden functions as well. Had there been a difference of opinion about the crews ability to detect this condition, the default strategy would also have required that these functions be classified as hidden.

A review of the design characteristics of the DC-10 shows that each truck on the main landing gear has four wheels, and each wheel has a multiple-disk brake assembly consisting of seven rotors and six stators (see Exhibit 7.9). The brakes are powered by eight pistons, four of which are driven by one hydraulic system and four by another. Without this inexpensive replication, especially of the wheels on each truck, reduced stopping capability in one brake assembly might be a critical failure. In this case the failure results only in slightly increased stopping distances. One of the failure effects, however, is a possible tire blowout, with secondary damage caused by rubber thrown from the damaged tire. Brake assemblies can be replaced in the field, but the time required will delays. The aircraft can also be dispatched with one assembly inoperative, but only at a great penalty in operating weight. Thus any observed failure of a brake assembly has operational consequences.

Note that in this case the primary function of the brake assembly is subject to two failure possibilities, no braking action and reduced braking action. Each of these functional failures must be considered separately the first type of failure is no braking action, caused by brake wear:

**"1 Is the occurrence of a failure evident to the operating crew during performance of normal duties?"**

If the brake pads are allowed to wear beyond a certain point, they come loose from the rotor and jam between the rotors and stators, causing the brake to seize. The wheel will therefore not rotate on landing, and the tire will skid and blow out, throwing pieces around the wheel well. The resulting noise and vibration would be evident to the flight crew; thus the answer to this question is yes.

With a yes answer to question 1 we must now consider the possible consequences of this failure:

**"2 Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?"**

The loss of braking function for one of the eight wheels is not in itself critical, so the answer to the first part of this question is no. The answer to the second part is also no, because this failure has been taken into account in the design of the wheelwell, so that secondary damage from occasional tired failures will not be critical.

Although the scheduled task is not required for safety reasons, the secondary damage does have serious operational consequences:

**"3 Does the failure have a direct adverse effect on operational capability?"**

In addition to the time required to exchange the brake assembly, this particular type of failure can result in extensive damage to hydraulic lines, flight control surfaces, and other fail-safe systems. Thus the secondary damage alone may prevent the airplane from being dispatched. Such a failure therefore has serious economic consequences, and we must consider the possible preventive tasks.

The first choice is an on-condition task directed at detecting brake wear:

**"8 Is an on-condition task to detect potential failures applicable and effective?"**

This brake assembly is equipped with wear indicators that show when the pad and disk have reached the wear level that calls for replacement. Since the where indicators make it possible to define a potential-failure condition, an on-condition task is applicable; it will also be effective as long as the inspection interval is short enough to ensure sufficient remaining pad to keep the brake from locking.

In an initial program inspection of the wear indicators might be assigned for every overnight layover at a maintenance station, since this would be a convenient time to change brake assemblies if a potential failure is found. The brake assembly will ordinarily be removed if the wear indicators shows that fewer than 20 more landings are possible. The wear indicators will also be checked on every preflight walk around, but the wear criterion will be less stringent. The objective is for the overnight mechanics to be the first to identify the need for a brake change, to reduce the number of delays incurred by the discovery of potential failures in the field.

The second type of functional failure, reduced braking action, is caused by a broken pressure line – the line from the fluid quantity limiter to the brake assembly itself. (These lines are treated as part of the brake assembly because the limiters and lines are independent for each system to each wheel.) Analysis of this failure possibility takes us again to the first question in the decision diagram:

**"1 Is the occurrence of a failure evident to the operating crew during performance of normal duties?"**

A broken pressure line will result in a loss of function for only half the actuating pistons in the affected assembly, as the limiter stops the flow of hydraulic fluid when the line brakes. Thus the other four pistons in the assembly will still provide normal braking action. There is sufficient braking margin that the slight reduction in braking capability would not come to the attention of the operating crew – that is, the failure would not be evident.

A no answer to the first question means a scheduled task is required to ensure that the failure will be found and corrected, and further analysis falls in the hidden-function branch of the decision diagram. In this case either one of the directly preventive tasks or a failure-finding task must be assigned to avoid the risk of a multiple failure. The choice depends on technical feasibility and relative cost.

**"14 Is an on-condition task to detect potential failures both applicable and effective?"**

On-condition inspections are not applicable for this failure mode because we cannot define a condition that will preclude functional failures. This brings us to the question of a rework task:

**"15 Is a rework task to reduce the failure rate both applicable and effective?"**

At the time the initial program is developed there is no information to indicate that a reworked task is applicable and will be cost-effective; hence the answer to this question is no.

**"16. Is a discard task to avoid failures or reduce the failure rate both applicable and effective?"**

Once again, there is no information to support the applicability of an economic-life limit, so the answer in an initial program is no. A failure-finding task is therefore required – and inspection during preflight walkarounds and overnight layovers to check for broken lines.

In addition to its primary function of providing stopping capability, the brake assembly has two further functions. It must be capable of releasing the brake, so that it does not drag, and it must contain the hydraulic fluid. Brake drag is caused by a malfunctioning automatic brake adjuster, and this subassembly is not visible unless the brake assembly is removed and disassembled. In most cases the only effect of this failure is increased brake where, which will show up on the brake where indicator. Thus the brake assembly will eventually be removed for repair as a result of the on-condition task already scheduled, and the automatic adjuster can then be checked and adjusted as necessary while the assembly is in the shop. In a few cases the failure effects may include overheating of the brake assembly, pulling of the brake on one side, a blowout of the tire-pressure plug, and possibly a landing on a flat tire – in short, the same ultimate effects as those caused by a locked brake. In this event the failure would be evident to the operating crew; however, the same additional task would apply in either case: a shop specification to inspect the automatic brake adjuster on all brake assemblies that come in for repair.

The last type of failure, hydraulic leaks cost by damaged or distorted seals, results in a slow loss of fluid from the hydraulic system. Like the broken pressure line, this failure possibility falls in the hidden function branch. If some leakage were permitted, so that slight could be defined as a potential failure, and on-condition task would be applicable in this case, however any leak is defined as a functional failure. Rework and discard tasks are not applicable for this failure mode, so the only choice by default is a failure finding task, and inspection during preflight walkarounds and overnight layovers for external leaks.

The results of this analysis are summarized in Exhibit 7.11. Note that we have discussed four types of functional failures, all of which could ultimately affect stopping capability of the airplane. <u>If we had treated reduced stopping capability</u> as a single functional failure, we would have considered exactly the same failure modes and identified exactly the same inspection tasks for inclusion in the program.

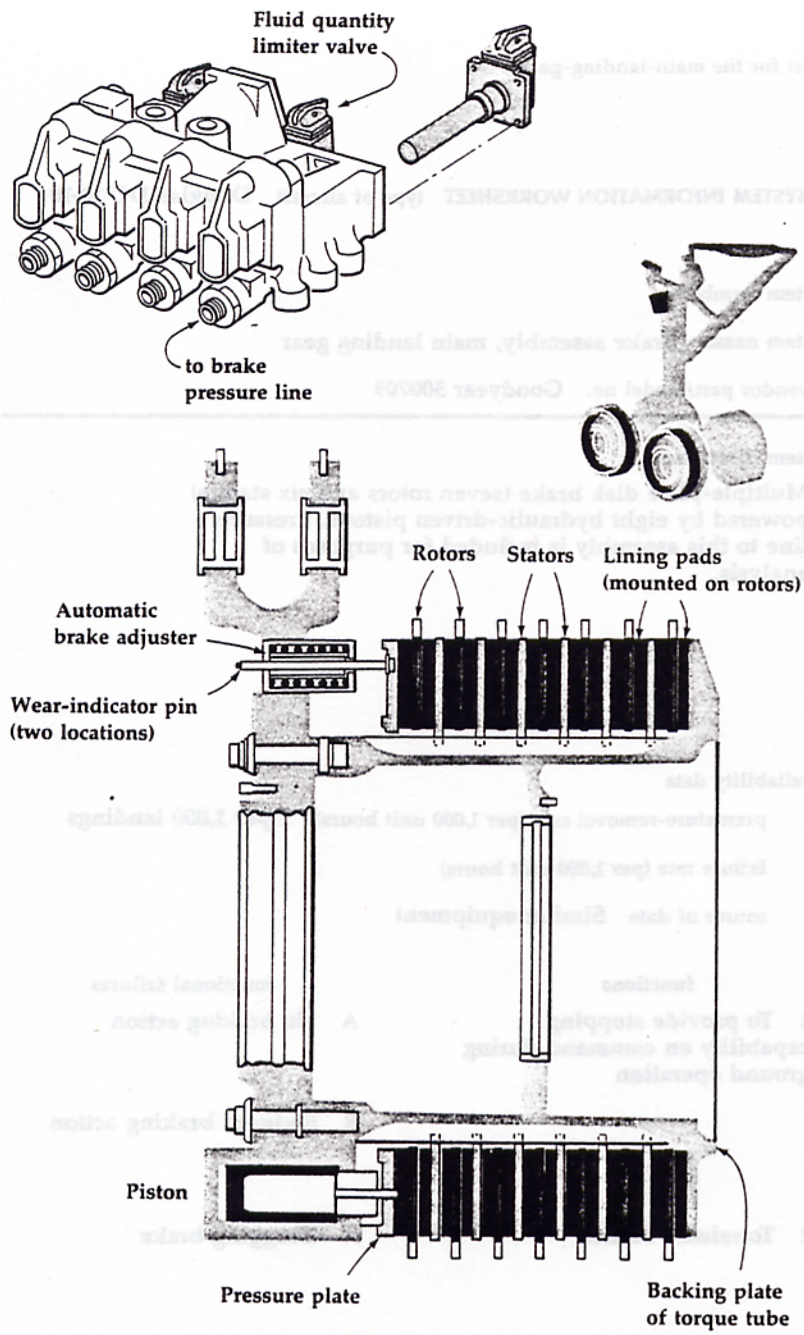



**Exhibit 7-9 The brake assembly on each wheel of the main landing gear of the Douglas DC-10. (Based on Goodyear maintenance materials)**

| System information worksheet – type of aircraft: Douglas DC-10 | | | |
|---|---|---|---|
| Item No. | Number for aircraft: 8 | Prepared by: F.S. Nowlan | Date: 3/6/78 |
| Item name: brake assembly, mean landing gear | System: landing gear | Reviewed by: T.M. Edwards | Date: 3/6/78 |
| Vendor part/model number: Goodyear 500709 | Zone(s): 733, 743 | Approved by: | Date: |
| | | | |

| | | | |
|---|---|---|---|
| **Item description:**<br>Multiple-plate disk brake (seven rotors and six stators) powered by 8 hydraulic-driven systems. Pressure line to this assembly is included for purposes of analysis. | | **Redundancies and protective features (include instrumentation):**<br>One brake assembly in each wheel (four) of each mean-landing-gear truck. Separate hydraulic systems power half the pistons in each brake; loss of brake fluid due to failed pressure line to wheel prevented by fluid quantity limiters in each hydraulic system. Engine thrust reverser provides another source of stopping capability. Wheelwell is designed to prevent critical secondary damage by debris from failure. | |
| Reliability data: | | **Built-in test equipment (described):** visual wear indicators | |
| Premature-removal rate (per 1000 units hours): one per 1000 landings | | **Can aircraft be dispatched with item in operative? If so list any limitations which must be observed:**<br>Yes. If one brake assembly inoperative, gross takeoff and landing weights must be reduced. | |
| Failure rate (per 1000 units hours) | | Classification of item (check) | |
| Source of data: similar equipment | | Significant | X. |
| | | Hidden function | X. |
| | | Nonsignificant | |
| | | | |
| **Functions** | **Functional failures** | **Failure modes** | **Failure effects** |
| 1 to provide stopping capability on command during ground operation | A no braking action | 1 brake wear to point of seizure | Wheel skid, causing tire blowout; audible noise and vibration, possible extensive secondary damage to systems within wheelwell; requires correction before dispatch |
| | B reduced braking action | 1 broken pressure line | No braking action from half the actuating pistons in one assembly, causing reduced braking capability and slightly increased minimum stopping distance |
| 2 to release brakes | A dragging brake | 1 malfunction of adjuster assembly | Increased wear of pad and disk; overheating of brake and tire may cause tire fuse plugs to blow, with landing on flat tire and secondary damage from the failure; requires correction before dispatch |
| 3 to contain hydraulic fluid | A external hydraulic leaks | 1 damaged or distorted piston seals | Slow loss of hydraulic fluid from one system |

**Exhibit 7-10 An information worksheet for the mean-landing-gear brake assembly of the Douglas DC-10.**

<table>
<tr><td colspan="19">System decision worksheet</td><td rowspan="4">Prepared by:<br>F.S. Nowlan</td><td rowspan="4">Reviewed by:<br>J.E. Kuhl</td><td rowspan="4"></td></tr>
<tr><td colspan="7">Type of aircraft</td><td colspan="12">Douglas DC-10</td></tr>
<tr><td colspan="7">Item name</td><td colspan="12">Brake assembly, main landing gear</td></tr>
<tr><td colspan="19">Responses to decision-diagram questions</td></tr>
<tr><td colspan="3">Ref.</td><td colspan="7">Consequences</td><td colspan="9">Task selection</td><td colspan="2" rowspan="2">Proposed task</td><td rowspan="2">Initial interval</td></tr>
<tr><td>F</td><td>FF</td><td>FM</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td></tr>
</table>

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | 1 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Inspect brake wear indicators | During walkaround checks and overnight stops |
| 1 | B | 1 | N | - | - | - | - | - | - | - | - | - | - | - | - | N | N | N | Inspect for broken lines (failure finding) | During walkaround checks and overnight stops |
| 2 | A | 1 | N | - | - | - | - | - | - | - | - | - | - | - | - | Y | | | Test automatic brake adjuster | Whenever brake assembly is in shop |
| 3 | A | 1 | N | - | - | - | - | - | - | - | - | - | - | - | - | Y | | | Inspect for external leaks (failure finding) | During walkaround checks and overnight stops |

**Exhibit 7-11 A worksheet showing the results of RCM analysis of the Douglas DC-10 brake assembly. References in the first column are to the functions, functional failures, and failure modes listed in Exhibit 7.10.**

## Analysis of a high-frequency communications subsystem

The information worksheet in Exhibit 7.12 describes the high-frequency to communications system used for voice communications on Boeing 747 aircraft operated on long over- water flights. This system consists of two identical subsystems which are completely independent of each other, right down to the antennas and the source of electrical power from the airplane's power supply system. Thus either subsystem provides the full system function. Additional sources of voice communication are provided by a separate very-high-frequency system. Each of the subsystems consists of numerous assemblies and components, all of which have specific functions. However, failure of any one of these components results in only three types of failure in terms of communications: inability to transmit, inability to receive, or inability to select the desired channel (frequency).

**"1 Is the occurrence of a failure evident to the operating crew curing performance of normal duties?"**

The failure effects described in Exhibit 7.12 show that any of these three basic types of failure will immediately be evident to the operating crew. Hence the answer to the first decision question is yes.

**"2 Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?"**

Because of system redundancy, none of the failures will result in the loss of the system function and will therefore not affect operating safety, so the answer to this question is no.

This brings us to the question of operational consequences:

**"3. Does the failure have a direct adverse effect on operational capability?"**

Most of the major assemblies in this item are plug-in/plug-out units and can be changed very quickly after failure has occurred. The time required to replace a failed unit may result in no delay if the failure is reported at a maintenance station, but it will cause a delay if the failure report is received at a non maintenance station. Since both subsystems must be operative before the plane can be dispatched, a failure is considered to have operational consequences. This means that the item must be classified as significant.

At this point we would ordinarily examine each failure mode to find preventive tasks that are both applicable and cost-effective. However, past experience with this type of system has shown that, although each major assembly is subject to many failure modes, current technology provides no means of

**System information worksheet – type of aircraft: Douglas DC-10**

| | | | |
|---|---|---|---|
| Item No. | Number for aircraft: 2 | Prepared by: F.S. Nowlan | Date: 3/6/78 |
| Item name: high-frequency communications subsystem | System: communications | Reviewed by: E.S. Wagner | Date: 3/6/78 |
| Vendor part/model number: all models | Zone(s): 733, 743 | Approved by: | Date: |
| | | | |
| **Item description:** Communications subsystem consisting of receiver, transmitter, power modulator, frequency-selector panel, antenna coupler, accessory unit, lightning arrestor, and boom antenna | | **Redundancies and protective features (include instrumentation):** System consists of two identical independent subsystems which can be used simultaneously for transmitting or receiving on any frequency. Backup systems include a very-high-frequency system for relay of messages and SELCAL (selective calling), which allows ground stations to ring bell in the cockpit to notify crew of call. | |
| Reliability data: | | **Built-in test equipment (describe):** fault-enunciator panel on accessory unit | |
| Premature-removal rate (per 1000 units hours): one per 1000 landings | | **Can aircraft be dispatched with item inoperative?** If so list any limitations which must be observed: no | |
| Failure rate (per 1000 units hours) | | Classification of item (check) | |
| Source of data: similar equipment | | Significant | X. |
| | | Hidden function | |
| | | Nonsignificant | |
| | | | |
| **Functions** | **Functional failures** | **Failure modes** | **Failure effects** |
| 1 to transmit voice signals | A no output | 1 many | No voice amplification, no response to transmission; loss of backup-frequency transmitting capability |
| 2 to receive voice signals | A no reception | 1 many | No background noise from receiver, no messages her; loss of backup-frequency monitoring capability |
| 3 to select desired channel | A failure to tune to selected channel | 1 failure of frequency selector | No response to transmission on expected frequencies; possible loss of backup-frequency monitoring capability |

**Exhibit 7-12 An information worksheet for the high-frequency communications subsystem in the Boeing 747.**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **System decision worksheet** | | | | | | | | | | | | | | | | | | | Prepared by: F.S. Nowlan | Reviewed by: E.S. Wagner |
| Type of aircraft | | | | | | | | | Douglas DC-10 | | | | | | | | | | | |
| Item name | | | | | | | | | High-frequency communications subsystem | | | | | | | | | | | |
| Responses to decision-diagram questions | | | | | | | | | | | | | | | | | | | | |
| Ref. | | | Consequences | | | | | | | Task selection | | | | | | | | | **Proposed task** | **Initial interval** |
| F | FF | FM | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | |
| 1 | A | 1 | Y | N | Y | - | - | - | - | N | N | N | | | | | | | None. There applicable and effective scheduled-maintenance tasks for this system. | |
| 2 | A | 1 | Y | N | Y | - | - | - | - | N | N | N | - | - | - | - | - | - | | |
| 3 | A | 1 | Y | N | Y | - | - | - | - | N | N | N | - | - | - | - | - | - | | |

**Exhibit 7-13 A worksheet showing the results of RCM analysis of the Boeing 747 high-frequency communications subsystem. The references are to the functions, functional failures, and failures listed in Exhibit 7.12.**

detecting reduced failure resistance. There are therefore no applicable forms of on-condition inspection. We would not expect scheduled rework to reduce the failure rate in a complex item, and in fact it does not. By the same token, discard tasks are not applicable. We must therefore conclude that this system cannot benefit from scheduled maintenance. If operating experience shows that its reliability is inadequate, especially as the result of the dominant failure of mode, design changes directed at the faulty component will be the only way of overcoming the problem. The results of this analysis are shown in exhibit 7.13.

## Analysis of other typical systems items

The failure of a hidden function cannot, by definition, have a direct effect on operating safety. In some cases, however, the consequences of a multiple failure involving the loss of this function can be critical. This situation is characteristic of emergency equipment, where the demand for a hidden function arises as the result of some other failure. Two examples are the powerplant fire warning system and ejection-seat pyrotechnic devices. All such items must be protected by some scheduled task to ensure that the function will be available if it is needed.

The powerplant fire-warning system is active whenever an airplane is in use, but it's function is hidden unless it senses a fire. Although some warning systems include fault indicators, certain failure modes can result in the loss of function that is not shown by the indicators; consequently this system is always classified as a hidden-function item. However, the required failure-finding task is not necessarily performed by the maintenance crew. In this case it is specified as part of the duties of the operating crew. The crew tests the system before each flight by means of a belt-in self-test circuit.

The pyrotechnic device in an ejection seat is also a hidden-function item that requires a high degree of the availability. Pyrotechnic materials deteriorate with age whether they are installed or not, so a discard task is applicable to this item. In an initial program the task interval is set either conservatively low or at a life limit based on previous experience with the same item in other aircraft. All units are tested when they are removed from service to see whether they would have worked, and the interval is adjusted as necessary on the basis of the test results. The cool-gas generator for the inflatable evacuation chute of passenger aircraft is accorded the same treatment.

Although systems items in commercial transport airplanes rarely fail in the safety branch of the decision diagram, not all systems components can be protected by redundancy. One example is the hydraulic landing-gear actuator, which powers the mechanism that raises and lowers the landing gear. If the actuator fails to retract the gear, the airplane must return to the point of takeoff. If it fails to extend the gear, the gear can still be extended by a free-fall feature. In either case the lost of function does not affect safety, but one of the failure modes does cause secondary damage.

One failure mode for these actuators involves cracking or separation of the end cap as a result of fatigue, perhaps accelerated by pitting corrosion. This type of failure may cause secondary damage to the aircraft structure, but only in the unlikely event of certain multiple failures. The structural damage in this case does not affect safety, but it does have major operational consequences, since any structural repairs take the entire aircraft out of service. Pitting corrosion, which will greatly shorten the fatigue life of the endcap, is visible when the actuator is disassembled in the shop. An on-condition inspection for corrosion is therefore applicable and would be scheduled as part of any shop visit of the landing-gear actuator. However, the primary failure process is fatigue, and it is not feasible to inspect the endcap often enough to detect fatigue cracks at the potential-failure stage. Scheduled reworking is not applicable for this failure mode. A discard task would take care of the fatigue problem, but this particular cap was designed for a fatigue life greater than the expected service life of the airplane; hence a life limit was considered unnecessary.

# 7.4. Establishing task intervals

At the time an initial maintenance program is developed there is usually enough information to determine the applicability of on-condition and failure-finding tasks. However, the information needed to determine optimum inspection intervals is ordinarily not available until after the equipment enters service. In many cases previous experience with the same or similar item serves as a guide, but in the absence of actual operating data it is necessary to set conservatively short intervals for all tasks and increase them on the basis of age exploration. Thus on a new aircraft tires and brake wear indicators are ordinarily checked once a day to determine the rate of reduction in failure resistance under actual operating conditions. Once this has been established, precise limits can be defined for potential failures and the inspection intervals can be adjusted as necessary.

Scheduled to rework tasks have proved to be ineffective for complex items in systems, and in any case, the information required to determine their applicability is rarely available until sufficient operating experience has accumulated for an actuarial analysis. Occasionally prior experience or concern about the economic impact of failures leads to the specification of rework tasks in an initial program. Seven items were specified for reworking in the Douglas DC-10 program and eight in the Boeing 747 program. The DC-10 generator control unit was scheduled for rework at an initial interval of 3000 hours , the DC-10 high-pressure bleed-control valve at an interval of 8000 hours, and the Boeing 747 generator at an interval of 5000 hours.

The intervals for safe-life items are known at the outset, since these are established by the manufacturer. Economic-life discard tasks for simple items such as hydraulic lines may be anticipated in an initial program, but they are rarely included at this stage. Like rework tasks, there is no basis for establishing a cost-effective interval until the equipment begins to age in service. The role of age exploration, especially in monitoring the performance of many systems assigned to no scheduled maintenance, is discussed in detail in Chapter 11.

# 8. Chapter Eight - RCM analysis of powerplants

The powerplant division of an airplane includes only the basic engine. Engines are complex, however, and are subject to numerous forms of failure, most of which are expensive and some of which are critical. Moreover, nearly all powerplant failures have operational consequences, since it is usually necessary to remove an engine and install a replacement after a failure has occurred. Thus the cost of failure includes both operational consequences and the support cost of very expensive replacement units, in addition to the high cost of corrective maintenance. For all these reasons there is a particularly strong incentive to find applicable and effective preventive tasks.

Powerplant is accompanied by a number of engine-driven accessories, such as the fuel pump and the fuel-control system. On some types of engines the thrust reverser is also an accessory, rather than an integral part of the engine. These accessories, as well as their connecting links to the engine, are treated as part of the systems division. However, some of failure possibilities to which they are exposed will influence the functioning of the engine itself; a fuel-pump failure, for example, may cause an engine flameout. It is therefore important for the study group working on the powerplant program to review the analyses of the essential engine accessories.

Because of its complexity a turbine engine is subject to a great many types of failures, most of which never reach the functional-failure stage. While potential failures may result in age-related removals, particularly if there are dominant failure modes, the residual failure rates – those seen by the operating crew – remains relatively constant at all ages because of the large number of failure modes involved. This fact has several implications for a scheduled-maintenance program. First of all, because those functional failures that cannot be prevented by on-condition tasks occur at widely disparate ages, scheduled overhaul of the entire engine and some particular age will do little or nothing to improve its reliability. However, engine removals for both potential and functional failures result in continual flow of engines to the shop throughout their operating lives, thus providing the opportunity for a more effective form of protection through on-condition tasks scheduled as part of the repair process. New engines in particular supply an abundance of such opportunity samples, and the assignment of internal engine parts to inspections for intensive age exploration is an important part of the initial powerplant program.

## 8.1. Characteristics of powerplant items

The operating gross weights of transport aircraft are not only restricted by structural considerations; they are also restricted flight by flight to ensure that a multiengine airplane will have a specified performance capability, measured in available rates of climb, after a complete loss of thrust from one engine (in some cases two engines). Hence the airplane is capable of safe operation with one engine inoperative as long as the remaining engines meet specified performance requirements. For this reason the basic function of an aircraft engine is defined as the capability of providing a specified amount of thrust, without vibration and at acceptable levels of other operating parameters. If an engine cannot perform this function, a functional failure has occurred. This failure may range from a complete loss of thrust (and engine shutdown) to insufficient thrust, cause, for example, by high exhaust-gas temperatures. In aircraft other than civilian transport airplanes the basic function of the engine can be stated in terms of specified thrust, but the consequences of a functional failure might be quite different. In a single engine aircraft, for instance, a significant loss of thrust would have a direct effect on operating safety, since there is only one source of power.

Cockpit instruments enable the operating crew to monitor most aspects of engine performance, such as compressor rotation speed, exhaust-gas temperature, fuel flow, oil pressure, oil-inlet temperature, and the engine pressure ratio. The engine pressure ratio is correlated with engine thrust, and power is set by advancing the throttle until a desired pressure ratio is reached. Ordinarily power will be obtained at an exhaust-gas temperature well below the maximum limit. However, when there is deterioration that reduces combustion efficiency or the efficiency of gas flow through the engine, more throttle movement, and hence more fuel consumption, is needed to obtain the same power. Consequently the exhaust-gas temperature is increased, and the engine may become temperature-limited even though no parts within it have failed. An engine failure of this kind always has operational consequences because, although a multiengine airplane can safely complete its flight with one engine inoperative, it cannot be dispatched in this condition.

In addition to failures resulting from inefficient engine performance, an aircraft engine is subject to numerous other failure modes, some of which cause secondary damage that presents a safety hazard. For both these reasons the engine as a whole must be classified as a significant item; a functional failure may have safety consequences and always has major economic consequences. If the engine is partitioned into smaller items, by module or by stage, many of its components will also be classified as significant items.

As an example, consider the Pratt & Whitney JT8D engine, which is used on such aircraft as the Boeing 737, the Douglas DC-9, and the Boeing 727. This turbine engine has five general sections, as illustrated in Exhibit 8.1. The compressor section consists of two axial-flow compressors, a front low-pressure compressor with six stages and a rear high-pressure compressor with seven stages. Each compressor is built up from individual disks for each stage. These disks rotate, and small blades attached to their peripheries compress the air as it flows by them. Air from the inlet section of the engine flows into the front compressor. The first two stages of this compressor are fan stages, and some of the air that flows through them bypasses the other compressor stages; the rest moves on to higher stages, with its pressure increased at each successive stage. The compressed air then enters the nine-can (can-annular) combustion chamber. Fuel is added to the air, the mixture is burned, and the expanding gases flow through a four-stage turbine and finally pickup speed as they are expanded out of the exhaust nozzle, thereby creating thrust.

Each stage of the turbine is a disk with blades on its periphery, somewhat like compressor stages. The forward stage of the turbine drives the high-pressure compressor and the other three stages drive the low-pressure compressor by means of concentric rotor shafts. Power is taken from the outer shaft by double gears and directed down a tower shaft to the main accessory case. Each accessory attached to this case is driven by spline-pinion connection to the main gear. Plenum rings and ports built into the engine case bleed off air from the sixth, eighth, and 13th stages of the compressor and direct it into ducting; this high-pressure air supplies the pneumatic system for cabin pressurization, air-conditioning, anti-icing, thrust-reverser actuation, and engine cross-starting capability. The thrust reverser is an accessory on the JT8D engine and would ordinarily be analyzed as a system's item. However, in some installations it is attached in such a way that it is removed along with the basic engine, and on other types of engines it is often part of the basic engine. For convenience, therefore, we will consider it as a powerplant item in this case. The thrust reverser is mounted behind the exhaust nozzle. It is of the mechanical-blockage type and moves two clamshell-shaped deflectors into the exhaust stream on the pilot's command. The deflected exhaust is then redirected forward by a panel of cascade vanes mounted on each side of the engine. Reverser is actuated pneumatically by a system of controls, valves, actuators, linkages, and plumbing.

When the engine is partitioned into modules (systems), sections (subsystems), and stages (assemblies), some of modules will be found to contain very few parts that are not significant. In a compressor, for example, the disks, hubs, and shafts are all significant items. Failures of most of the rotating parts and parts exposed to the gas path will be evident to the operating crew from the cockpit instruments; they will therefore have operational consequences. Failures of rotating, non gas-path parts, many of which form plenums (containing gases under pressure) or reservoirs (containing operating fluids such as oil) may not be evident and will require scheduled inspections for this reason. In short, there are very few parts of an engine that do not require some form of scheduled maintenance.

Because of the great number of failure modes to which aircraft engine is exposed, RCM analysis of powerplant items may follow in any of the four branches of the decision diagram. Many engine parts are subject to failures with critical secondary damage and will re be assigned safe-life discard tasks. In an initial powerplant program, however, the most frequent outcome in any consequence category is an on-condition task, with intensive inspection of certain items as part of the age-exploration plan. One reason for this is that corrective maintenance on engines is responsible for more than half the support costs for any airplane, and even when fractured parts do not cause hazardous damage, they may cause damage that is very expensive to repair. Another reason, of course, is to avoid the safety and operational consequences of a functional failure.

On-condition inspections of powerplant items are performed at two levels, depending on the accessibility of the item. Many items can be inspected visually or by borescope and radiography techniques while the engine is on the aircraft. Most internal engine parts cannot be inspected without a certain amount of disassembly. These parts are therefore assigned on-condition inspections in the shop when the engine is being disassembled for repair. When the combustion-chamber retaining lug is removed, for example, a plug gauge is fitted into the lug. If the fit meets specifications the combustion chamber can be reinstalled as is; otherwise it is routed to repair.

Whereas on-condition inspection on installed engines are performed at fixed intervals, the shop inspections of internal engine items are scheduled on the basis of *opportunity samples*, sometimes with a maximum age interval as a precaution. Opportunity samples take advantage of the fact that with a large fleet of multiengine airplanes there will be a sufficient flow of engines through the shop to provide continuing exposure of all the major parts. During the first few years of operation, when the fleet is small, the failure rate is usually also at its highest, which automatically brings a larger number of engines to the shop. These frequent shop visits not only provide information on the items that have failed, but also permit easy inspection of all the parts that must be removed to gain access to the failed item. Thus, in addition to the on-condition tasks that are known to be applicable, in an initial program many internal engine parts are assigned such inspections for the purpose of age exploration. Although some of these inspections may prove to have no real on-condition capability, they will be the only source of information on items that are not experiencing failures.

## 8.2. Assembling the required information

The analysis of significant items in an aircraft powerplant requires a broad knowledge of current maintenance practices, as well as a detailed understanding of the specific engine under consideration. The members of the powerplant working group will know from previous experience the areas of the engine that tend to be the most troublesome in new designs. They will also be familiar with the various forms of on-condition inspection and the uses of opportunity sampling in conducting age exploration. In addition to this background information, the engine manufacturer provides specific information about any new engine by reviewing the design characteristics of the production model with the entire working group. During this process similarities to and differences from in-service types of engines become apparent. The review also pinpoints areas in which new, or relatively new, technology has been incorporated in the design, either to reduce the weight of the engine or to increase its performance capabilities.

New aircraft engines are designed and developed over a period of years preceding certification of the aircraft in which they are installed. Extensive testing is conducted at each stage of development to ensure that a reliable product is being developed. Many different prototype engines are usually used during the certification test flights of the airplane itself, and experience with these engines gives the manufacturer an opportunity to identify and resolve any problems that come to light. In addition, once the engine design is stabilized, several are tested in endurance runs, either as part of the engine certification program or as an adjunct to it. Unfortunately this early experience may not be of great use during the development of an initial maintenance program, because the engine will usually have been modified to correct any known problems before the production engines are delivered. The development of an effective powerplant maintenance program thus depends heavily on the knowledge and experience of the working group.

Exhibit 8-2 lists the data elements that must be assembled before analysis begins. Much of this information comes from detailed review of the production model, supplemented by the manufacturer's instruction manuals and test data. The data elements for each item to be analyzed are recorded on the information worksheet like that used for systems items. In the case of power plant items the manufacture's identification is usually functionally descriptive in itself. However, the item description should include all major components and should reflect the level of item being considered (see Exhibit 8.3). Where the item is a module or stage, the description should list all the major assemblies it contains.

As with systems items, is important to list all redundancies and protective features. Bypasses and pressure-relief systems, as well as the extent of the cockpit instrumentation, are all factors in evaluating the consequences of a functional failure. If the engine case is designed to contain fractured parts, this information should be included, since it means that the secondary damage resulting from certain failures will not have safety consequences (although it may have major economic consequences). Ordinarily an aircraft cannot be dispatched with any major engine item inoperative (this information comes from the minimum-equipment list and pertains primarily to systems items). However, a yes answer for an individual part may mean that this item can be classified as nonsignificant, since the functional failure will have no operational consequences.

In listing the functions of an item is important to describe its basic function and all secondary or characteristic functions. Each function described should relate in some way to one of the overall engine functions. For example, the basic function of the nozzle guide vanes is to redirect the exhaust gases onto the first stage turbine blades; a second function is to create the proper nozzle area for efficient engine operation. The functional failures are the inability to perform these functions; note that in some cases there is more than one failure possibility for a given function. The failure modes are the specific ways each type of functional failure can occur. In addition to the failure modes listed for the nozzle guide vanes, rotating parts such as blades and disks are subject to fatigue. Combustion chambers may crack or burn through, or their locating pins may wear. Unless the failure modes are clearly identified, there is no way to determine what preventive tasks might be applicable.

The failure effects identify the immediate results of the failure. These effects include any secondary damage caused by the failure, as well as the impact of the loss of function both on the engine and on the aircraft.

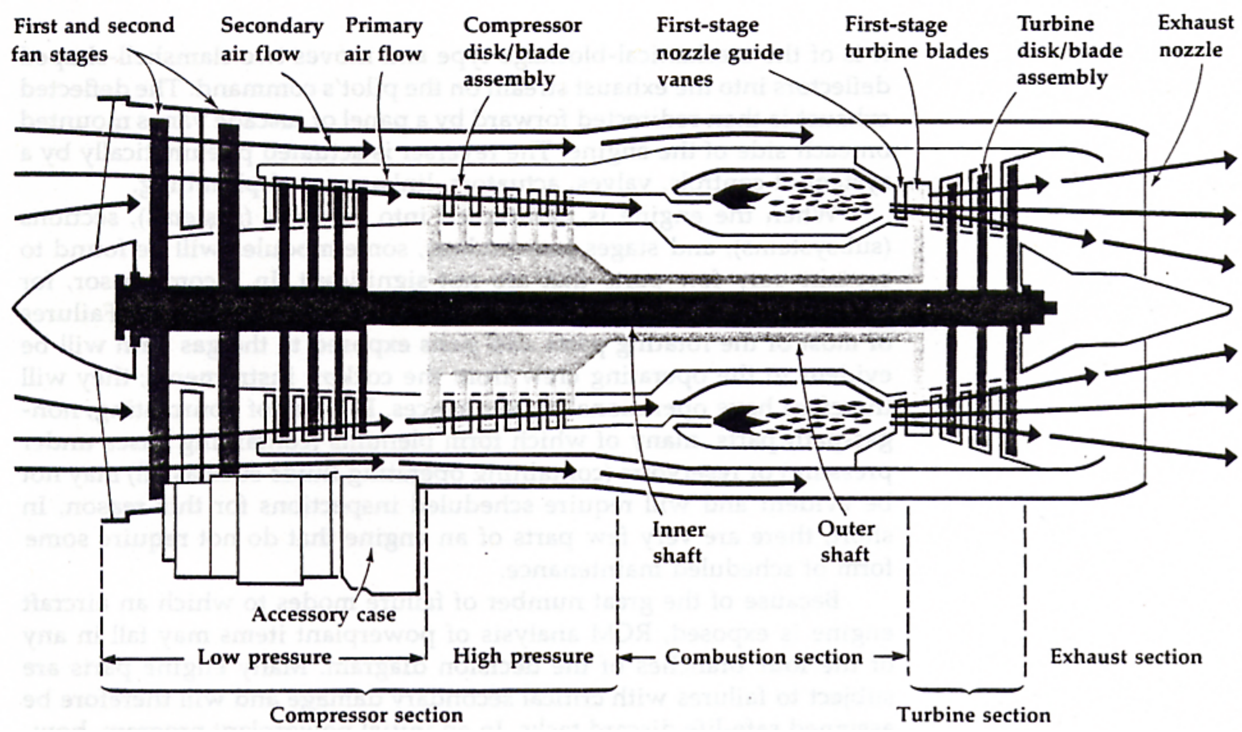



**Exhibit 8-1. Schematic diagram of the Pratt & Whitney JT8D turbine engine. The thrust reverser is not shown. (Based on Pratt & Whitney training materials)**

| **Identification of item** | **Quantity per engine** |
|---|---|
| Type of aircraft | |
| Item name | |
| Manufacturer's heart and model number | |
| **Item information** | |
| Item description (general function and major parts) | |
| Built in test equipment | |
| **Available reliability data** | |
| Anticipated premature-removal rate | |
| Anticipated verified failure rate | |
| Source of data (test data or operating experience) | |
| **RCM input** | |
| Item functions | |
| Functional failures (as defined for each function) | |
| Most probable failure modes | |
| Predictable failure effects (for each failure mode)<br>Evidence of functional failure<br>Effects of loss of function on operating capability<br>Effects of failure beyond loss of function (including ultimate effects of possible secondary damage) | |

| |
|---|
| Nature of failure consequences |
| Evidence of reduced failure resistance that can be used to define potential-failure conditions |
| Experience with other engines containing the same or similar item |

**Exhibit 8-2. The data elements needed for analysis of powerplant items.**

The description should also specify any physical evidence by which the occurrence of the failure can be recognized by the operating crew. In the case of most ancient failures this is an instrument indication, often the exhaust-gas temperature reading. The failure effects must be described for each failure possibility, since they help to determine the consequences of that failure, and hence the priority of maintenance requirements.

As an example, one of the failure modes listed in Exhibit 8.3 for the JT3D engine is bowing of the turbine nozzle guide vanes as a result of prolonged exposure to high temperatures. The effects in this case are progressive. Slight bowing will change the entry direction of the gases, reducing the efficiency of turbine-blade action and causing the exhaust-gas temperature to rise for a given thrust setting. If the temperature is already high because of other deterioration in the engine, the permissible temperature will be exceeded, and the pilot will report a functional failure. However, the exhaust-gas temperature measures the overall efficiency of the engine, and if the limit temperature is not reached, bowing may continue to the point at which stationary vanes come into contact with the rotating turbine blades. Either the blades or the vanes will fracture, and if the engine case cannot contain the fractured parts, the ultimate effect of bowed guide vanes in this engine design is critical secondary damage. The failure must be therefore classified as having safety consequences.

All the relevant information is examined for each engine item, and the item is then classified as significant or nonsignificant on the basis of its failure consequences. Items in either category may have one or more hidden functions; thus an item may be identified in this initial partitioning process as nonsignificant, but also has having a hidden function. Since all hidden functions must be protected by scheduled maintenance to ensure that failures will be found and corrected, both significant items and hidden-function items must be subjected to full RCM analysis.

| **System information worksheet<br>– type of aircraft: Douglas DC-8<br>– type of engine Pratt & Whitney JT3D** | | | |
|---|---|---|---|
| Item No. | Number for engine: 63 | Prepared by: T.M. Edwards | Date: 6/26/78 |
| Item name: | First-stage nozzle guide-vane assembly | Reviewed by: T.N. Mix | Date: 6/26/78 |
| Vendor part/model number: | 536751/JT3D | Approved by: | Date: |
| Section: | Turbine | Module | |
| **Item description:**<br>The 63 nozzle guide vanes form a set of airfoils located in the gas path immediately downstream of the combustion-chamber outlet duct. They accelerate and direct hot gases onto the first-stage turbine blades at the proper angle for aerodynamic efficiency. | | **Redundancies and protective features (include instrumentation):**<br>Vanes are made of small-grain alloy to resist heat deformation and receive protective coating to resist heat damage and erosion. Vanes are bolted in place to prevent fractured parts from slipping into air stream. | |
| Reliability data: | | **Built-in test equipment (describe):** None | |
| Premature-removal rate (per 1000 units hours): | | **Can aircraft be dispatched with item in operative? If so list any limitations which must be observed:**<br>no | |
| Failure rate (per 1000 units hours) | | Classification of item (check) | |
| Source of data: similar equipment | | Significant | X. |
| | | Hidden function | |
| | | Nonsignificant | |
| | | | |
| **Functions** | **Functional failures** | **Failure modes** | **Failure effects** |
| 1 To redirect gases at the proper velocity and angle | A Vanes form improper angle and nozzle area | 1 Bowing of nozzle guide vanes from heat deformation | Progressive loss in engine efficiency, increased fuel consumption and exhaust-gas temperature, and possible high-power stall resulting in engine shutdown; if vanes bow back into turbine-blade path, contact with rotating blades resulting in fracture and critical secondary damage from blade failure |
| | | 2 Erosion of nozzle guide vanes from direct exposure to exhaust-gas particles | Progressive loss in engine efficiency, leading to possible engine shut down as for 1 A 1 (no contact with turbine blades) |

**Exhibit 8-3. An information worksheet for the first-stage nozzle guide vanes of the Pratt & Whitney JT3D powerplant.**

The objective of the partitioning process outlined in chapter 4 is to select the most convenient level of item for analysis. Most powerplant analyses can be conducted conveniently at the module or section level. In this case the failure of any significant item included in the module or section under consideration would constitute a failure mode. For example, if the item selected for study were the turbine section, one of the failure modes would be a failure of the first-stage turbine nozzle guide vanes. However, the power plant itself can also be viewed as an item. While this is only one of several possible approaches, it has certain advantages in sorting the vast number of failure possibilities that must be considered into an organized pattern on the basis of their consequences. In the examples that follow, therefore we will consider the entire engine as a significant item.

The Pratt & Whitney JT3D engine used on the three-engine Boeing 727 is described by the information worksheet in Exhibit 8.4. Although this engine might be analyzed at the module or section level, at the engine level its functions can be defined as follows:

- To provide specified amounts of thrust without exceeding the acceptable levels of the engine operating parameters
- To drive engine-mounted accessories, such as the fuel pump, oil pump, fuel control unit, hydraulic pump, and constant-speed drive generator
- To provide high-pressure air to the pneumatic system for use by subsystems
- To provide reverse thrust to assist in braking the airplane (assumed as a function of this engine design)

At this point let us consider the first type of engine failure, a failure to provide specified thrust (including complete loss of thrust, or an engine shutdown):

**"1. Is the occurrence of the failure evident to the operating crew during normal performance of duties?"**

Any reduction in engine thrust will be evident, because the engine pressure ratio and other instrument readings are closely monitored by the operating crew. When the engine is in-flight, changes in engine output may also be signaled by throttle vibration or audible thumps. Hence the answer to this question is yes

The next step in RCM analysis would ordinarily be to examine each of the failure modes that might lead to dysfunctional failure. In identifying the probable failure modes, however, it will be found that some involve the fracture of a part that can cause critical secondary damage, whereas others involve a fracture without such damage, and still others involve general deterioration with no fractured parts. For convenience, then, we can group all significant assemblies and parts into these three classes and analyze each class of failure modes separately.

## Fractures with critical secondary damage

Compressor disks, turbine disks, and turbine blades are typical of the powerplant items whose fracture can cause critical secondary damage. It is apparent from the failure of disks described in Exhibit 8.4 that all such failures will immediately be evident to the operating crew. As for any failure of the basic engine function, therefore, the answer to the first decision-diagram question is yes.

**"2. Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?"**

Although the loss of thrust has no safety consequences, all items whose failure involves secondary damage fall into safety branch of the decision diagram (see Exhibit a 8.5).

Disks, for example, are subject to low-cycle fatigue failures, and when they fracture, any fragments that cannot be contained by the engine case can damage the nacelle, wing, or fuselage. Even if these projectiles do not damage the aircraft structure, there is the hazard of hot gases escaping through the tear in the engine case. Ejected turbine blades present the same hazards. Turbine-blade failures have sometimes occurred with no observable effect on thrust and no other evidence of failure (in this case failure-finding inspections are necessary). However, they have also been known to be ejected and cause critical secondary damage. There is no way of knowing whether this problem has been overcome in the present design, so in the interests of conservatism blades have been included in this class of items.

The next step is to evaluate proposed scheduled-maintenance tasks. A yes answer to the safety question means that no task can be considered effective unless it reduces risk of functional failure to an acceptable level. From this point on, however, we must examine each failure mode separately, because the applicability of a particular task will depend on the failure characteristics of the part. Our next question therefore concerns a possible maintenance task for the disk:

**"4. Is an on-condition task to detect potential failures both applicable and effective?"**

A low-cycle fatigue failure begins as a slip along crystallographic planes in the metal, which progresses under repeated load applications until a small crack becomes visible. After this point, however, the crack propagates very rapidly to the pointer fracture. Most of the disks are also inaccessible in the installed engine; thus even if it were possible to define the crack as a potential-failure condition, the engine would have to be removed and disassembled more frequently than is feasible. And on-condition task is therefore not applicable to the disk. A no answer to the on-condition question means we must look for other tasks:

**"5. Is a rework task to avoid failures or reduce the failure rate both applicable and effective?"**

| | | | |
|---|---|---|---|
| **Powerplant information worksheet – type of aircraft: Boeing 727 – type of engine Pratt & Whitney JT8D-7** | | | |
| Item No. | Number for aircraft: 3 | Prepared by: T.M. Edwards | Date: 2/14/78 |
| Item name: | Propulsion powerplant | Reviewed by: F.S. Nowlan | Date: 2/14/78 |
| Vendor part/model number: | JT8D-7 | Approved by: | Date: |
| Section: | Turbine | Module | |
| **Item description:** Axial-flow front-turbofan engine with a 13-stage split compressor (two spools), a 9-can (can-annular) combustion chamber, and a split four-stage turbine. | | **Redundancies and protective features (include instrumentation):** The airplane has three engines; operating weight is controlled for all flights so that airworthiness requirements can be met with one engine inoperative. Full instrumentation of all engine operating parameters; each engine protected by fire-warning and fire-extinguishing system. | |
| Reliability data: | | **Built-in test equipment (describe):** None | |
| Premature-removal rate (per 1000 units hours): | | **Can aircraft be dispatched with item in operative? If so list any limitations which must be observed:** no | |
| Failure rate (per 1000 units hours) | | Classification of item (check) | |
| Source of data: similar equipment | | Significant | X. |
| | | Hidden function | |
| | | Nonsignificant | |
| | | | |
| **Functions** | **Functional failures** | **Failure modes** | **Failure effects** |
| 1 To provide specified amounts of thrust without exceeding the acceptable values of engine operating parameters | A. Engine does not provide specified thrust (including case of no thrust) | 1. Failure of parts whose fracture can cause critical secondary damage:<br>a. failure of compressor or turbine disks<br>b. failure of turbine blades | Immediate loss of thrust or flameout, confirmed by instrument readings; possible critical secondary damage if engine case does not contain fractured parts; that it will abort takeoff if prior to takeoff-refusal speed, otherwise will land at nearest suitable airport; engine change required |
| | | 2. Failure of parts whose fracture does not cause critical secondary damage:<br>Tower shaft bearing or gear failure | Progressive loss in engine inefficiency, leading to possible engine shut down as for 1 A 1 (no contact with turbine blades) |
| | | 3. Failure resulting from general deterioration without the fracture of parts:<br>Deterioration of combustion chambers, nozzle guide vanes, compressor blades, etc. | Progressive loss of aging efficiency as shown by instrument readings; if desired thrust cannot be obtained without exceeding maximum exhaust-gas temperature, pilot will abort takeoff if prior to takeoff-refusal speed; if airborne may continue flight at reduced power or shut down |

| | | | |
|---|---|---|---|
| | | | engine and land at nearest suitable airport; engine change may be required |

**Exhibit 8-4. An information worksheet for analysis of the Pratt & Whitney JT8D-7 powerplant for the Boeing 727.**

The conditional probability of disk failure does increase at an identifiable operating age. However a rework task must restore the item's original resistance to failure. For a part subject to metal fatigue no rework method has been found that will eliminate the material's "memory" of repeated loads, so the answer to rework question is no.

**"6. Is a discard task to avoid failures or reduce the failure rate will applicable and effective?"**

Because on-condition inspections are not applicable, the manufacture has established a safe-life limit for the disk in each stage of the compressor and the turbine. One engine manufacture uses a computer model, based on material strength tests and stress calculations, that simulates the in-service aging of the disk. This model has been validated by the results of developmental spin testing of many different disks used in various engine designs. A safe-life limit determined by this technique is the operating age at which one disk per 1000 will develop a crack of 1/32 inch. The disks are designed to have safe lives ranging from 10,00 to 20,000 hours and these are intervals that will be used for the discard tasks.

The answer to the discard question is yes, and the analysis of this failure mode is complete. Each type of disk is assigned a discard task scheduled for the safe-life limit established for that disk. In this case an on-condition task <u>might also be assigned</u> – and inspection for any damage that might prevent attainment of the safe-life age, to be performed whenever the disks are accessible during the normal course of repair work on the engine.

The failure process in turbine blades is somewhat different from that in disks. The blades are in a hot-gas stream that exerts aerodynamic forces on them. The forces pulsate as the blades pass by the stationary guide vanes, with the result that the blades are also subject to fatigue failure. The propagation of fatigue cracks in blades, however, is much slower than in disks. In addition, the blades are subject to creep and oxidation caused by the high temperature of the gases and to erosion from solid particles in the gas. In this case on-condition inspection is more promising:

**"4. Is an on-condition task to detect potential failures both applicable and effective?"**

Potential failures can be defined for such conditions as oxidation, erosion, blade-root wear, and fatigue cracks; therefore an on-condition task is applicable. It will also be effective, since the blades can be inspected at short enough intervals to ensure that the potential failures will preempt functional failures. Thus the answer is yes, and analysis of this failure mode is complete.

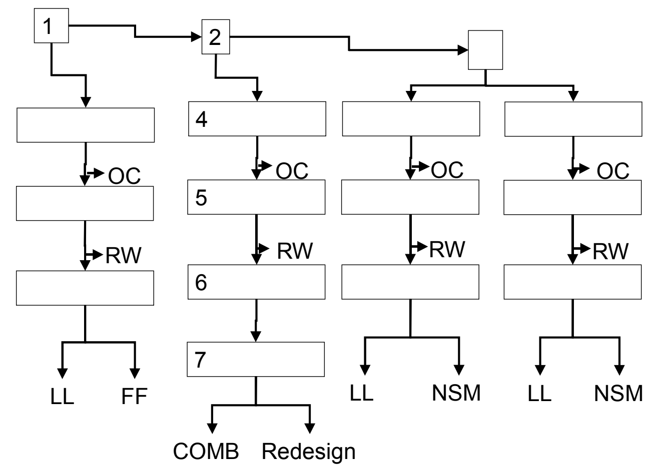



**Exhibit 8-5. The branch of the decision diagram used for analysis of engine failures involving critical secondary damage.**

On-condition tasks for the blades would probably be specified at two levels – on the aircraft and in the shop. For example, a borescope inspection of all turbine blades on installed engines might be assigned at an initial interval of 150 operating hours, with a "broomstick" check of the fourth-stage turbine blades for looseness scheduled at intervals of 300 to 400 hours. In addition, as part of the opportunity-sampling program, an inspection of the blades for creep, heat deterioration, cracks, and wear at the roots would probably be scheduled for every shop visit of the engine, with a threshold age of 500 hours.

Note that on some engines the first-stage turbine nozzle guide vanes would also fall into the class of items whose failure can cause critical secondary damage. The nozzle guide vanes on the JT3D engine, described in Exhibit 8.3,would therefore be analyzed through the safety branch of the decision diagram. This engine has a hollow shaft to which an isotope pill can be inserted to expose radiographic film placed on the engine case at the outer ends of the vanes. The exposed film shows the amount of bowing that has occurred, and also the remaining clearance between the vanes and the adjacent turbine blades. Thus an on-condition task is applicable, and it would be scheduled at intervals short enough to prevent all critical failures.

In the engine under consideration here the same task would apply. However, the JT8D engine has been designed so that bowing of the nozzle guide vanes will cause the exhaust-gas temperature to reach the limit before the vanes reach a state in which they can intersect the turbine plane. Thus the ultimate effect of this failure mode in the JT8D engine is a functional failure caused by engine inefficiency, rather than a failure with critical secondary damage.

## Fracture with no critical secondary damage

The second-class of powerplant items is subject to fractures that cannot cause critical secondary damage (although the secondary damage is often expensive). Typical items in this case are the towershaft bearing and the towershaft gears. Failure of either of these items will result in inability to drive the engine-mounted accessories, including the fuel pump, and the engine will flameout. We know, therefore, that the failure will be evident to the operating crew. Since the loss of thrust is not critical and this class of failure mode has no critical secondary effects, we also know that there are no safety consequences.

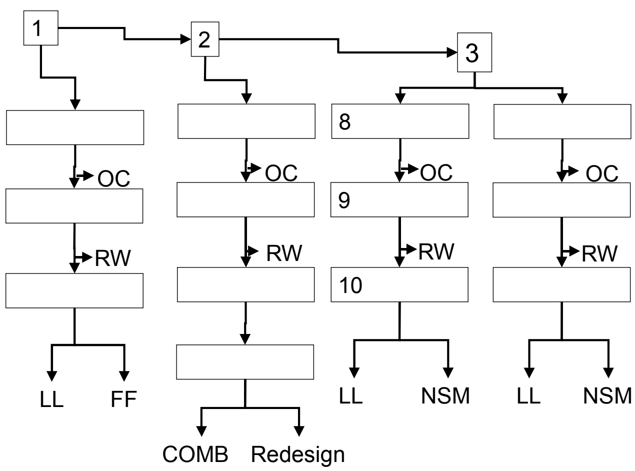



**Exhibit 8-6. The branch of the decision diagram used for analysis of engine failures that do not involved critical secondary damage.**

A no answer to the safety question brings us to the question of operational consequences:

**"3. Does the failure have a direct adverse effect on operational capability?"**

The answer to this question is yes, because any failure of the basic engine function has operational consequences. Since these consequences are economic, scheduled maintenance is desirable if it is cost-effective. Hence we must examine all applicable tasks on this basis (see Exhibit 8.6).

Bearing and gear failures are caused by fatigue, perhaps accelerated by inadequate or contaminated lubrication. The failure process begins with spalling and fine cracks on the bearings and wear and fine cracks in the gears. Eventually fragments of metal are chipped from the working surfaces, and when the integrity of the hard surface has been lost, complete disintegration proceeds rapidly.

**"8. Is an on-condition task to detect potential failures both applicable and effective?**"

In some cases fragments of shed metal can be detected by inspection of magnetic plugs and oil screens, and the existence of these metal particles can be defined as a potential failure. While such inspections are applicable, they miss a large number of potential failures. They are cost effective, however, because the discovery of even one potential failure more than offsets the cost of years of such inspections. Thus the answer is yes for these tasks, and they would be included in the program.

The real control of gear and bearing failures comes from on-condition inspections performed when the engine is in the shop. Visual inspection of the balls, rollers, races, and gear teeth for cracking, wear, or deformation, using 10- to 30-power magnification, has been found to identify most potential failures. The bearings and gears are put in the opportunity-sampling program to establish the optimum interval for shop inspections, and the analysis of these items is complete.

## Failures caused by deterioration

Whereas fractured parts can cause extensive secondary damage – with or without safety consequences – a large number of engine failures are the result of deterioration that does not involve the fracture of any part. When some part of the engine is not functioning efficiently, more and more throttle is required to attain the desired thrust. This increases the fuel flow, and thus the exhaust-gas temperature, which may further accelerate deterioration of the parts involved. Eventually one of the engine operating parameters, usually the exhaust-gas temperature, will be exceeded before the desired thrust is reached, and a functional failure of the engine will have occurred. Items involved in this class of failure modes are the air seals, compressor blades, combustion chambers, and, in this engine, turbine nozzle guide vanes.

The reduction in engine power is evident to the operating crew and has no safety consequences. Such failures will still have operational consequences, however, because the engine may be replaced after the airplane lands. Hence analysis of the items in this category also falls in the operational-consequences branch of the decision diagram, where scheduled maintenance is desirable if it is cost-effective.

Compressor blades are exposed to erosion and air seals to wear, causing losses in aerodynamic efficiency. Since the burner cans and the turbine nozzle guide vanes are in the gas path, they are also subject to heat deformation. All these deterioration processes occur slowly and at a relatively constant rate, a situation which favors on-condition inspections:

**"8. Is an on-condition task to detect potential failures both applicable and effective?"**

The answer is yes for most of these items, such as compressor blades, combustion chambers, and nozzle guide vanes. Their condition can be ascertained by borescope or radioisotope inspections while the engine is still installed, and the rate of deterioration is slow enough to identify it at the potential-failure stage.

| **Powerplant decision worksheet** | | | | | | | | | | | | | | | | | | | Prepared by: T.M. Edwards | Reviewed by: F.S. Nowlan |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Type of aircraft:** Boeing 727 | | | | | | | | | **Type of engine:** Pratt & Whitney JT8D-7 | | | | | | | | | | | |
| Item name | | | | | | | | | Propulsion powerplant | | | | | | | | | | | |
| Responses to decision-diagram questions | | | | | | | | | | | | | | | | | | | | |
| Ref. | | | Consequences | | | | | | | Task selection | | | | | | | | | **Proposed task** | **Initial interval** |
| F | FF | FM | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | |
| 1 | A | 1a | Y | Y | - | N | N | Y | | | | | | | | | | | Remove and discard all compressor and turbine disks at life limit | Manufacturer's safe-life limit for each type of disk |
| 1 | A | 1b | Y | Y | - | Y | | | | | | | | | | | | | Borescope inspection of all turbine blades | Fifty flight cycles or 150 hours whichever is first |
| | | | | | | | | | | | | | | | | | | | Broomstick check of fourth-stage turbine blades for looseness | 300 to 400 hours |
| | | | | | | | | | | | | | | | | | | | Inspect all turbine blades for wear, creep, and cracking | During engine shop visit; use opportunity sampling to establish best frequency, initial threshold 500 hours |
| 1 | A | 2 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Check magnetic plugs and screens for metallic particles | 300 to 400 hours |
| | | | | | | | | | | | | | | | | | | | Inspect all tower shaft and drive-train elements for wear, deformation, and cracking | During engine shop visit; use opportunity sampling to establish best frequency, initial threshold 500 hours |
| 1 | A | 3 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Borescope inspection of combustion chambers, nozzle guide vanes, liners, supports, and seals visible through hot-section access ports | 50 flight cycles or 150 hours, whichever is first |
| | | | | | | | | | | | | | | | | | | | Borescope inspection of seventh- to thirteenth-stage compressor blades, stators, spacers, and seals visible through compressor access ports | 150 flight cycles or 450 hours, whichever is first |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | Inspect all rotating parts, gas-path parts, hot-section parts, and main bearings for wear, deformation, and cracking | During assembly for engine repair; use opportunity sampling to establish best frequency, initial threshold 500 hours. |

**Exhibit 8-7. A worksheet showing the results of analysis for the primary engine function of the Pratt & WhitneyJT8D-7 powerplant. The references in the first column are to the failure modes listed for the primary engine functions in Exhibit 8.4.**

Since the hot section usually suffers the most rapid deterioration in a new engine, borescope inspections might be scheduled for the combustion-chamber outlets, nozzle guide vanes, and surrounding liners, supports, and seals at an initial interval of 50 flight cycles or 150 operating hours, whichever comes first.[1] Next to the hot section, the high-pressure compressor has the highest rate of deterioration. Thus borescope inspections of the seventh- to thirteenth-stage compressor blades might be scheduled for an initial interval of 150 to 200 flight cycles or 450 to 600 operating hours.

In addition to the scheduled inspections on installed engines, most of the rotating parts, gas-path parts, hot-section parts, and bearings would be assigned to shop inspection of opportunity samples, with an initial age threshold of perhaps 500 hours. During these inspections the dimensions and condition of each part are compared with the "acceptable for service" limits established by the manufacturer. Parts that have deteriorated beyond these limits are repaired or replaced and parts within the limits are returned to service.

Note that taking the engine out of service because the exhaust-gas temperature exceeds a defined limit is in itself a form of on-condition action, since this limit is established to prevent extensive damage to the combustors, turbine blades, vanes, and liners. One might wonder, therefore, why additional on-condition tasks are directed at these items. The reason is that increased exhaust-gas temperature measures the total efficiency of all gas-path parts. Thus the temperature might be within the limit if most parts were in good condition, even if one part – say, the nozzle guide vanes – had deteriorated beyond the point of economical repair. In the interests of economy, then, it is better to inspect the nozzle guide vanes and judge them by their individual condition than to wait for the temperature to reach the limit. This concept becomes increasingly important for in-service engines, which are composed of parts of diverse ages as a result of the normal repair cycle.

[1] These low initial intervals represent the practices followed in the mid-1960s

It is also important to bear in mind that this analysis is based on a redundant engine installation. The engine is one of three in a multiengine airplane. If this engine were installed in a single-engine aircraft, analysis of the same items would lead to completely different results, because in this case a loss of function might in itself constitutes a critical failure. The analysis of all failure modes involving a major loss of thrust would therefore fall in the safety branch, or any applicable tasks would be scheduled regardless of cost effectiveness. The criteria for task applicability would remain the same, however; thus scheduled the work would still be applicable only for those engine parts whose conditional-probability curves showboat and identifiable wear out age and a high probability of reaching that age without failure. Since an item subject to numerous failure modes rarely satisfies these conditions (see section 2.8), scheduled rework of the entire engine would be unlikely to make a significant difference in its operating safety.

## 8.3. Failures of secondary engine functions

In addition to the basic engine function of providing specified thrust, three secondary functions have been listed for the Pratt & Whitney JT8D-7 engine under consideration. These functions and their associated functional failures and failure modes are listed on the continuation worksheet shown in Exhibit 8.8. One of these functions, to drive the engine-mounted accessories, has two failure possibilities: inability to drive any of the accessories and the inability to drive a particular accessory. The failure modes that cause a total inability to drive any of the accessories are associated with bearing and gear failures in the towershaft drive train, discussed in the preceding section. The inability to drive individual accessories could be defined as a separate functional failure for each accessory. From the standpoint of the engine, however, we can consider this case as a single functional failure with several failure modes.

The first question, as before, is whether failure of the engine to drive some one of the accessories will be evident:

**"1. Is the occurrence of the failure evident to the operating crew during the performance of normal duties?"**

The performance of each engine accessory is monitored by means of cockpit instrumentation, and a malfunction of any accessory would be evident from the instruments readings (Exhibit 8.8). Thus the answer to this question is yes for all failure modes.

.

| **Continuation worksheet<br>– type of aircraft: Boeing 727<br>– type of engine Pratt & Whitney JT8D-7** | | | |
|---|---|---|---|
| Item No. | Number for aircraft: 3 | Prepared by: T.M. Edwards | Date: 2/14/78 |
| Item name: | Propulsion powerplant | Reviewed by: F.S. Nowlan | Date: 2/14/78 |
| Vendor part/model number: | JT8D-7 | Approved by: | Date: |
| Section: | Turbine | Module | |
| **Functions** | **Functional failures** | **Failure modes** | **Failure effects** |
| 2. To drive the engine-mounted accessories | A. Inability to drive any engine accessory | 1. Failure of main-gearbox drive | Instruments show no output from any accessory; engine flameout; pilot will abort takeoff if prior to takeoff-refusal speed, otherwise will land nearest suitable airport; engine change required |
| | B. Inability to drive one of the engine accessories | 1. Failure of constant-speed-drive generator splines | Instruments show no output from generator; crew will disconnect generator from constant-speed drive as a precaution; aircraft can be dispatched with one generator inoperative |
| | | 2. Failure of hydraulic-pump drive splines | Instruments show no pressure from one pump; crew will disconnect pump for completion of flight; gearbox or engine change required at destination |
| | | 3. Failure of fuel-pump drive splines or bearings | Instruments show no output from fuel pump; engine flameout, with operational effects as for 2 A 1; gearbox or engine change required |
| | | Failure of oil-pump drive bearings | Instruments show loss of oil pressure, requiring engine shut-down; operational effects as for 2 A 1; engine change required |
| 3. To provide high-pressure here to the pneumatic system | A. Does not provide sufficient bleed air (pneumatic pressure) | 1. Burst saddle duct | Loss of some pneumatic pressure, instruments show increased fuel flow, exhaust-gas temperature, and engine speed; heat damage to installation and hoses, with probable fire warning resulting in engine shutdown; operational effect as for 2 A 1; engine change required |

| | | | |
|---|---|---|---|
| 4. To provide reverse thrust for brakeing assistance | A. Inability to provide reverse thrust | 1. Burst pneumatic-actuator supply duct | Instruments show thrust reverser inoperative, loss of braking assistance from one engine; may require correction before further dispatch |
| | B. thrust reverser jam during reverse-thrust sequence of | 1. Binding view to wear of mechanical components | Instruments show thrust reverser active; correction required before further dispatch |

**Exhibit 8-8. Continuation information worksheet for the secondary functions of the Pratt & Whitney JT8D-7 powerplant.**

This brings us to the question of possible safety consequences:

**"2. Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety"**

Failure of certain of the accessory drives, such as those for the fuel pump and the oil pump, can lead to complete loss of thrust from the engine, but an engine shut down does not in itself affect safety. Recent engines including this one, have also been designed so that accessory-drive parts cannot penetrate the case. There is therefore no exposure to critical secondary damage from these failures, and the answer to this question is no.

**"3. Does the failure have a direct adverse effect on operational capability?"**

The airplane usually cannot be dispatched when one of the engine-driven accessories is inoperative (this information would appear on the information worksheets for the pertinent systems items). If the problem is caused by a failure of the internal accessory drive, however, it is necessary to repair or replace the engine before further dispatch. Thus any failure of the accessory drive train has operational consequences, and scheduled maintenance is desirable if it is cost-effective.

To evaluate proposed tasks we must consider the failure process:

**"8. Is an on-condition task to detect potential failures both applicable and effective?"**

Spline wear in each of the accessory drive trains is a major source of trouble, and we know that on-condition inspections to measure spline wear are applicable. Hence the answer to this question is yes. The accessory drive shafts, gear, and bearings are assigned to the shop opportunity-sampling program to determine the most effective inspection interval; in addition, the splines in the accessory gearbox are scheduled for inspection on the aircraft whenever an accessory is changed.

The third function of the engine is to provide high-pressure air for the pneumatic system and, and one failure mode is a burst bleed-air duct. In a powerplant analysis we would be concerned with the ducting that is part of the quick-engine-change assembly; this includes the sixth-, eighth-, and thirteenth-stage saddle ducts. Downstream ducting is analyzed either as part of the pneumatic system or as part of the system it serves. The burst saddle duct in any of these stages will be evident to the operating crew. Cockpit instrumentation shows the pressure in the duct to the cabin air-conditioning system, but hot air from the duct will also trigger a fire warning, and the free escape of bleed air will affect engine performance.

Because of the fire-warning system, this type of failure is not critical. Although hot thirteenth-stage bleed air may burn wiring insulation and char hoses, the most serious effect is the need to shut down an engine after fire warning. Such failure does have operational consequences, however, since the airplane cannot be dispatched until the burst duct is repaired. Thus once again we are concerned only with the cost-effectiveness of proposed maintenance tasks.

Examination of the failure process shows that stresses in the duct leads to the development of fine cracks, which can be detected by on condition inspections. Experience with earlier equipment has shown that such inspections will not identify all potential failures. However, this task can be performed on installed engines and can be scheduled for short intervals. An on-condition task is therefore both applicable and cost-effective. And our analysis of this to the failure is complete.

The fourth function of the engine is to provide reverse thrust to assist in braking the airplane, and this function is also subject to failure possibilities: either the reverser will not operate at all or it jams during the reversing sequence. The only predictable mode for the first-failure is bursting of the pneumatic supply duct to the actuator, whereas the second-failure can be caused by wear in many different parts of the mechanical linkages. The cockpit instruments include a light that indicates when the reverser has left its stowed position and is in transit to the reverse-thrust position. Inability of reverser to operate is therefore evident.

No credit is given to availability of reverse thrust in determining the runway lengths required for landing and takeoff, and it is permissible to dispatch an airplane with one reverser inoperative. Thus the failure of a reverser is not considered to have safety consequences. The reverser does have great value in certain situations, however, such as the need to avoid other aircraft on the runway or when braking action is reduced by water or snow. For certain destination conditions the operating crew may request that all reversers are operative at take off. A reverser failure is therefore classified as having operational consequences, although these consequences will not be involved under all circumstances. Inspection of the pneumatic supply ducts would be scheduled for the same work package as inspection of the engine pneumatic ducts, as shown in Exhibit 8.9.

The second type of failure, jamming of the reverser in the reverse-thrust position, is also evident, since there is a cockpit warning light that indicates when the reverser is in this position. In this case the failure clearly has operational consequences. Wear and binding in the thrust-reverser mechanism are signs of reduced resistance to failure. On-condition inspection is therefore applicable, and the various linkages, actuators, and tracks would be scheduled for inspection at the same time as the supply ducts.

| **Powerplant decision worksheet** | | | | | | | | | | | | | | | | | | | Prepared by: T.M. Edwards | Reviewed by: F.S. Nowlan |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Type of aircraft:** Boeing 727 | | | | | | | | | | **Type of engine:** Pratt & Whitney JT8D-7 | | | | | | | | | | |
| Item name | | | | | | | | | | Propulsion powerplant | | | | | | | | | | |
| Responses to decision-diagram questions | | | | | | | | | | | | | | | | | | | | |
| Ref. | | | Consequences | | | | | | | Task selection | | | | | | | | | **Proposed task** | **Initial interval** |
| F | FF | FM | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | | |
| 2 | A | 1 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Same tasks as 1 A 2 4 tower shaft drive-train elements | |
| 2 | B | 1 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Inspect all drive shafts for spline wear. | Whenever accessory unit is changed or is accessible during engine shop visit |
| 2 | B | 2 | Y | N | Y | - | - | - | - | Y | | | | | | | | | | |
| 2 | B | 3 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Inspect all accessory drive-train elements for wear and cracking | During engine shop visit; use opportunity sampling to establish best frequency, initial threshold 500 hours |
| 2 | B | 4 | Y | N | Y | - | - | - | - | Y | | | | | | | | | | |
| 3 | A | 1 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Inspect all engine pneumatic ducts for heat distress, cracking, and leaks | 100 to 200 hours |
| 4 | A | 1 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Inspect thrust-reverser pneumatic ducts for heat distress, cracking, and leaks | 100 to 200 hours |
| 4 | B | 1 | Y | N | Y | - | - | - | - | Y | | | | | | | | | Inspect thrust-reverser linkages, tracks, and actuator mechanism for wear or binding | 100 to 200 hours |
| | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | |

**Exhibit 8-9. A worksheet showing the results of analysis for the secondary engine functions of the Pratt & WhitneyJT8D-7 powerplant. The references in the first column are to the functions, functional failures, and failure modes listed in Exhibit 8.8.**

## The role of age exploration

The preceding analysis covers only a few of the tasks that would be included in an initial powerplant program. It is apparent from these examples, however, that when the engine itself is treated as a significant item, the parts that cause it to fail will generally be assigned only two types of tasks. Some parts whose failure could cause critical secondary damage will be assigned safe-life discard tasks, but most parts are assigned on-condition tasks, often as part of an opportunity-sampling age-exploration program.

The reason no failure-finding tasks were assigned has to do with the level of the analysis. The fracture of a single compressor blade or guide vane does not cause a perceptible reduction in engine thrust, and since it also may not result in any secondary damage, the failure of individual blades and vanes may not be evident to the operating crew. Viewed from the parts level, each of these failures would be classified as a hidden functional failure. Similarly, at the assembly level erosion of these parts beyond the acceptable limits would be defined as a hidden failure, since this condition would not necessarily be apparent from the overall exhaust-gas temperature. At the engine level, however, these conditions become potential failures for the engine itself, and in both cases on-condition tasks have been specified. The periodic inspections assigned to the compressor blades and nozzle guide vanes would reveal any fractured elements as well as other forms of deterioration.

Note that the initial program also contains no rework tasks for individual items. This is partly because there is no information at this stage to support their applicability and partly because on-condition tasks are applicable to so many engine parts. After the equipment enters service the abundance of opportunity samples results in a very rapid accumulation of operating data on engines. Thus the applicability and cost-effectiveness of rework for specific items can be established by the time the first few airplanes in the fleet reach the proposed rework age. Even when age exploration does show that certain items would benefit from scheduled rework, however, the intervals at which such tasks are cost-effective may vary widely for different items. Since there are no rework tasks that can be consolidated into a single work package to be performed at some specified operating age, complete rework (scheduled overhaul) of the entire engine is unlikely to be justified at any point in its operating life, let alone in an initial program.

An age-expiration program is required for all new aircraft engines. In most cases the requirement calls for the inspection of sets of parts equivalent to two or three complete engines before any installed engine exceeds a specified operating age, say, 1500 hours. The use of opportunity samples from engines that have aged to a specified lower limit – perhaps 500 or 1000 hours is permitted to satisfy this requirement. If there are not enough premature removals to provide the required samples, it may be necessary to remove and disassemble engines that have reached the 1500-hour limit for the sole purpose of inspecting their parts. After the condition of parts is evaluated, the upper limit for complete sets of parts may be extended, say, to 3000 hours.

The requirement for whole-engine sampling is usually dropped after two such inspections, but there will be continuing age exploration for certain selected items. The sampling in this case may also be based on the threshold limits for each item. The inspection information is useful in assessing the effects of age only if the item has aged to the lower limit. With this type of program any units of the item that aged to the upper threshold must be inspected even if additional disassembly of the engine is necessary to reach them. Such units are termed *forced samples* in contrast to the opportunity samples of parts available for inspection during the normal course of disassembly. Both threshold limits are ordinarily extended after two or three samples of an item have been inspected and found to be in satisfactory condition.

A newer and more economical variation of this procedure is an age-exploration plan based entirely on opportunity sampling. This concept involves a lower threshold limit and a sample size of one unit. The first opportunity sample whose age exceeds an initial lower limit is inspected, and if the inspection findings are satisfactory, the age of this sample unit becomes the new threshold limit. As a result, documented sample information increases steadily in small age increments, with the age of the oldest inspection sample roughly parallel at all times to the age of the oldest installed engine (see Exhibit 5.9 in chapter 5). It is preferable in this type of program that the inspection samples not be reworked before they are reinstalled unless their condition is judged unacceptable for continued service. In this way the time since rework is not zeroed out, and it is possible for sampling to proceed rapidly to units of higher ages. At some age the condition of the units inspected will show enough deterioration to identify the appropriate intervals for first-hand repeat inspections of all units of the item. In this case the condition defined as a potential failure would be based on an inspection interval equal to the interval between successive shop visits of the engine (the meantime between removals). As an alternative, the sampling threshold may be held at a fixed age limit to accumulate more information on the condition of parts at that particular age. If this additional information shows that a large proportion of the units are reaching the potential-failure point at a fairly well-defined age, a rework task might be assigned to the item – or, depending on the ratio of rework costs to replacement cost, a discard task might be specified for a slightly higher age.

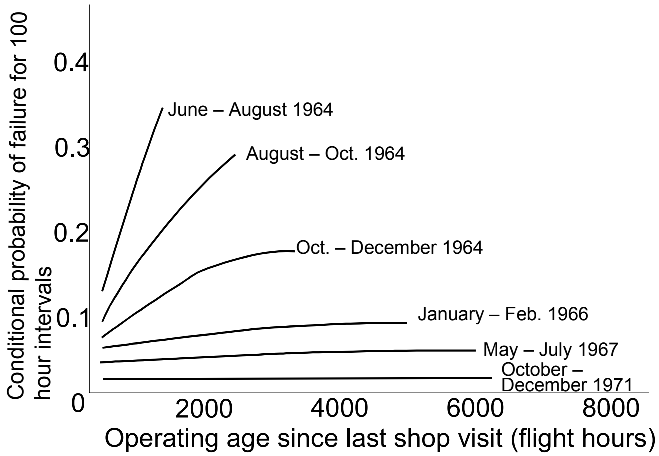



**Exhibit 8-10. the results of successive age-reliability analyses of the Pratt & Whitney JT8D-7 engine after (it entered service. (United Airlines)**

Exhibit 8.10 shows the results of successive age-reliability analyses conducted as part of the age-exploration activities after the Pratt & Whitney JT8D engine entered service. Each curve represents all premature removals, both those resulting from on condition inspections and those resulting from crew-reported malfunctions. While the first few curves show a very high conditional probability of failure, complete engine overhauls at an age low enough to effect the premature-removal rate would have grounded the fleet (engine overhauls take about 45 days). If the data had been partitioned to show the respective contributions of potential and functional failures to the total premature removals, it would also be apparent that the potential failures were much more age-related than the functional failures. In other words, on-condition inspections were effectively removing faulty units from service at a much earlier stage than would have been feasible with any rework age limit. In this case actuarial analysis of premature-removal data identified the dominant failure modes, which were in the hot section of the engine, and redesign of the parts most susceptible to rapid heat deterioration resulted in the ultimate reliability shown by the final curves. Apart from the fact that complete engine overhauls would have represented a needless expenditure on the other sections of the engine, which were in excellent condition, they would have impeded improvement of the engine itself. If all parts of the engine had been zero-timed at fixed intervals, there would have been no means of determining the actual potential-failure ages of individual items and improving the inherent reliability of the engine accordingly. In the powerplant division age exploration in fact plays a dual role. On the one hand, it provides a means of determining the actual maintenance requirements of each engine item, and on the other, it provides the information necessary to improve the overall safety and operating reliability of the engine. This latter role is an integral part of the development process for any new engine.

# 9. Chapter Nine - The RCM analysis of structures

The structure division consists of all the load-carrying elements of the airplane. These include not only the basic airframe – the fuselage, wings, and tail assembly – but a variety of other assemblies and components that are subjected to loads:

- The landing gear (except brakes, tires, and retraction mechanisms)
- Movable flight control surfaces and high-lift devices (except their associated actuators and gearboxes)
- Integral fuel tanks
- Powerplant pylons, supports, and cowlings
- The aircraft skin
- Doors, hatches, windshields, and cabin windows
- Internal partitions, decks, and braces
- Connecting elements such as brackets and clips

Airplane structures are subject to may types of loads during operation – gust loads, maneuvering loads, landing loads. The magnitude and frequency of these loads depend on the nature of the operating environment, although in general low loads will occur frequently and peak loads will be encountered very infrequently. The structure must therefore be designed in terms of all its load spectra and must be so strong that it is extremely unlikely to encounter any load it cannot withstand during its intended type of operation. The role of scheduled maintenance is to find and correct any deterioration that would impair this load-carrying ability.

Unlike systems and powerplant items, few failures short of a critical failure will be evident to the operating crew. The ultimate effects of most functional failures, however, have a direct impact on safety; hence RCM analysis of all structurally significant items falls in the safety branch of the decision diagram. In this case there are only two task outcomes: on-condition insepctions for all items, with the addition of a discard task for safe-life elements. The focus in developing a structure program, therefore, is not on a search for applicable and effective tasks. Rather, it is on determining an appropriate inspection interval for each item. All parts of the structure are exposed to the age-related processes of fatigue and corrosion, but these processes interact and are not entirely predictable. Thus even for an airplane that embodies well-known materials, design practices, and production processes, the intervals assigned in an initial program are only a small fraction of the age at which any evidence of deterioration is anticipated. In fact, the inspection plan itself merely delineates the start of structural age-exploration activities.

## 9.1. Characteristics of structural items

The structure of an airplane consists of numerous individual assemblies. As an integral unit, however, it performs a variety of functions, a few of which can be defined as follows:

- To enable aerodynamic lifting forces to balance the weight of the airplane
- To provide mounts for the powerplants that produce the thrust necessary to balance aerodynamic drag
- To provide movable flight-control surfaces for maneuvering the airplane
- To provide the means (landing gear) for making a transition from air to ground operation
- To provide volumes for carrying fuel
- To provide space and mounting points for the evarious systems required for oprating capability
- To provide space with a suitable environment (often pressurized) for the operating crew and the payload to be carried

Loads are imposed on the structure during the performance of these functions and if any major assembly cannot withstand them, the structure experiences a functional failure. Thus the basic function of individual assemblies or structural members is to withstand the loads imposed on them without collapsing or fracturing.

Many of the functions listed above are of such a nature that a functional failure would have an immediate effect on operatng safety; hence the design practices followed for the stucture ensure that failures are extremely unlikely. Whreas other parts of the aircraft are designed to facilitate reports of functional failures by the operating crew, the crew will rarely be in a postiion to report structural failures (although there are occasional crew reports of failed landing gear and high-lift devices).

It is also very difficult and expensive to replace parts of the structure. Systems and powerplant items are continually changed throughout the operating life of the aircraft; hence on any in-service airplane these items are likely to be of widely varying ages. In contrast, structural elements are repaired, often by the use of doublers, and they are also modified, but they are rarely replaced. Consequently, except for those parts added as repairs or modifications, nearly all parts of the structure on any given airplane will be of the same age. Since all structural elements are subject to a primary failure process that is directly related to total age, the structure as a whole is designed to a goal of failure ages far longer than the expected operating life of the airplane.

## Design Strength

Airplane structures are designed to withstand many different kinds of loads, such as those caused by air turbulence, flight maneuvers, landings, and takeoffs. For commercial transport airplanes manufactured in the United States, each of these load requirements is defined by FAA airworthiness regulations. For aircraft operating in other contexts, load requirements are specified either by the appropriate airworthiness authority in the case of civil aviation or by the purchasing organization in the case of military aviation. Individual design-load requirements are stringent enough to ensure that a more severe load situation would be extremely improbable in the operating environment for which the airplane is designed. For example, one of the load requirements for structures in the commercial-transport category is defined as follows:[*]

25.341 *Gust Loads*
*a. The airplane is assumed to be subjected to symmetrical vertical gusts in level flight. The resulting limit load factors must correspond to the conditions determined as follows:*
*1. Positive (up) and negative (down) rough air gusts of 66 fps at $V_B$ [the design speed for maximum gust intensity] must be considered at altitudes between sea level and 20,000 feet. The gust velocity may be reduced linearly from 66 fps at 20,000 feet to 38 fps at 50,000 feet.*
*2. Positive and negative gusts of 50 fps at $V_C$ [the design cruising speed] must be considered at altitudes between sea level and 20,000 feet. The gust velocity may be reduced linearly from 50 fps at 20,000 feet to 25 fps at 50,000 feet.*
*3. Positive and negative gusts of 25 fps at $V_D$ [the design dive speed] must be considered at altitudes between seal level and 20,000 feet. The gust velocity may be reduced linearly from 25 fps at 20,000 feet to 12.5 fps at 50,000 feet.*

During the development and certification of any new aircraft the manufacturer conducts numerous tests to confirm that each structural assembly can withstand the specified design loads without damage or permanent deformation. Design loads with this objective are called *limit loads*. There are also requirements that the structure be able to withstand at least 150 percent of the limit load without collapsing (experiencing a functional failure). When design loads are factored upward in this way they are called *ultimate loats*. The present airworthiness requirements for design strength have been effective in protecting against functional failures as long as the specified load-carrying capabilites of the structure are preserved.

[*] *Federal Aviation Regulations*, Airworthiness Standards: Transport Category Airplanes, sec 25.341, effective February 1, 1965.

After the airplane enters service the operating organization is responsible both for preserving the design strength of the structure and also for ensuring that theoperating gross weight of the airplance does not exceed the maximum weight at which the structure can satisfy the various load requirements.

## The Fatigue Process

All the loads to which an aircraft structure is subjected are repeated many times throughout the course of its operating life. Although any single load application may be only a fraction of the load-carrying capability of the elemetn, the stress imposed by each one reduces the remaining margin of failure resistance. Eventually, as a result of these cumulative reductions, a small crack will appear in the metal. Until the crack reaches the stage at which it is visible, there is little change in the strength of the affected element. Thereafter, as internal stresses cause the crack to propagate, the strength of the element is reduced at an ever-increasing rate.

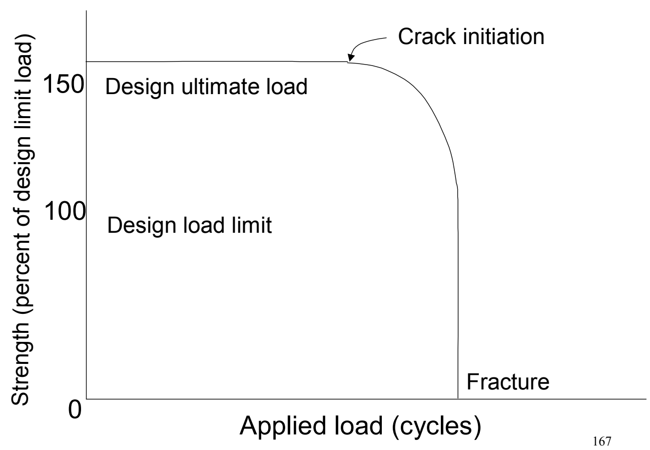



**Exhibit 9-1Model of the effect of fatigue on the strength of a single structural element exposed to cyclic loads**

The fatigue process thus has two aspects. Because the effects of repeated loads are cumulative, as the operating age increases, the age interval before a crack will appear decreases – that is, there is a reduction in the remaining time before crack initiation, the appearance of a visible crack. The operating age at which a fatigue crack first appers in a structural item is termed the *fatigue life* of the item.[*] The second aspect is the reduction of strength, or load-resisting capability, of the item associated with *crack propagation*. Both fatigue life and the rate of crack propagation vary not only with the material from which the item is made, but also with its size and shape and the manufacturing process by

[*] The term *fatigue life* is also used to denote the age at which a fracture occurs as a result of fatigue. In this discussion fatigue life always means the time to crack initiation.

which it was produced. For this reason fatigue tests must be conducted on actual structural elements and assemblies to determine their individual fatigue characteristics.

The fatigue process in a single structural element is illustrated in Exhibit 9-1. When the structure is new the element can withstand an ultimate load, or 150 percent of its design limit load. As the element ages in service its failure resistance (time to crack initiation) decreases with repeated load applications until a fatigue crack appears. Up to this point its load-resisting capability is relatively unchanged. Now, however, the crack will propagate, and the strength of the element will decrease accordingly. At some point the crack will reach a length at which the element can no longer withstand the limit load; it then becomes a *critical crack*. If this element is subjected to the limit load it will fracture immediately, but even when the continued loads are much lower than the limit load, the rate of crack growth will become so rapid tha ta fracture cannot be prevented by scheduled maintenance.

If the item that fractures is a monolithic element and is not part of a redundant assembly, this functional failure is usually critical. If the item is one element of a multiple-load-path assembly, the fracture reduces the load-carrying capability of the assembly but does not result in a complete loss of function. The resulting redistribution of the load to the remaining elements does, however, accelerate the fatigue processs in those elements. This situation is illustrated in

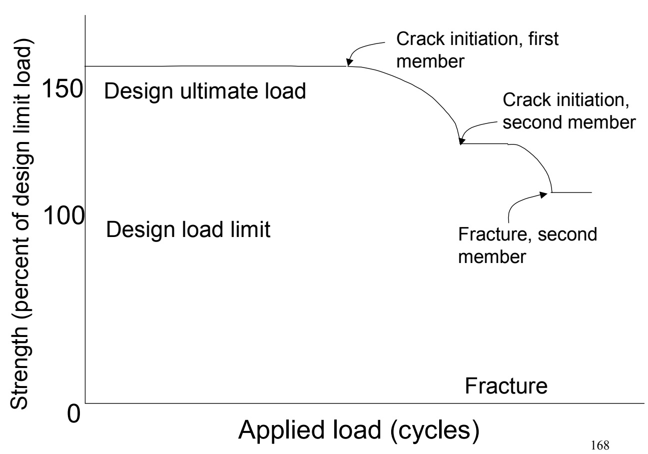



**Exhibit 9-2 Model of the effect of fatigue on the strength of a multiple-load-path (redundant) structural assembly exposed to cyclic loads**

Exhibit 9-2. The cracking or fracture of the first element reduces the residual strength of the assembly. After this the load-carrying capability will remain relatively constant until a crack initiates in a second element, which results in a transition to a still lower residual strength. The amount of reduction in each case will depend on the contribution of each element to the total strength of the assembly.

The difference between these two situations has lead to two basic structural-design practices to prevent critical failures. The older, and perhaps better-known, practice is *safe-life design*, which applies to structural elements with little or no redundancy. A newer practice is *damage-tolerant* (fail-safe) *design*. This term refers not only to redundant fail-safe structure, but also to monolithic portions of the structure characterized by easily detected cracks with slow propagation rates. <u>**A structural assembly** is said to be damage-tolarant if after the complete fracture of any one element it can still withstand the damage-tolarant loads specified by the appropriate airworthiness authority. **A monolithic item** is considered damage-tolerant if the rate of crack propagation is slow enough for at least two inspections to be feasible during the interval from crack initiation to a crack of critical length.</u>

Suppose, for example, that the specified damage-tolerant load is the design limit load treated as an ultimate load. This means that in its intact condition a structural assembly must be capable of withstanding the limit load without permanent deformation, whereas after the failure of one of its elements it must be able to withstand the same load without a functional failure. This specification is similar to the requirement that the engines on a transport airplane provide sufficient residual thrust for safe operation after a complete loss of thrust from one engine (or, in certain situations, from two engines). The residual strength after a single element fails is lower than desired for continuous operation. However, it is still so high that the airplane is unlikely to encounter dangerous loads during the time that will pass before the failed element is discovered and repaired. The concept of damage-tolerant design depends, of course, on an adequate inspection program.

It is rare for the failure of a single element to reduce residual strength to the damage-tolerant level. In fact, depending on the degree of redundancy (number  of load paths), the failure of some structural elements has little effect on the assembly. Moreover, the design strength of most elements is determined by the single hightest load requirement, such as that for landing loads, and their contribution to the strength of the assembly may be less under other loading conditions. The appearance of a fatigue crack in an element can therefore be defined as a potential-failure conditon, and since even the fracture of a single element is not critical, on-condition inspections will be effective at intervals short enough to ensure that not more than one element will fracture.

Most modern aircraft employ damage-tolerant design principles as widely as possible, but there are some parts of the structure, such as the landing gear, for which the criteria for damage tolerance cannot be met. Consequently it is necessary to impose safe-life limits on these elements. Since fatigue is directly related to total operating age, the limit is based on tests conducted to simulate operating loads in order to determine the fatigue life (time to crack initiation) for each element. Although a safe-life discard task based on such fatigue tests is applicable, it cannot be considered effective in the case of structural elements because they are exposed to other deterioration processes that may prevent safe-life limit from being achieved. Hence any safe-life structural items must be supported by a combination of tasks – on-condition inspections for corrosion and accidental damage and a safe-life discard task to ensure that the item is removed from service before a fatigue failure can occur.

The replacement of safe-life items and the repair of fatigue damage in other structural elements is both time-consuming and very expensive. Thus for economic reasons as well as safety reasons, the structure of an aircraft is designed for high safe-life limits, and also for a long fatigue life. The design goal for the Douglas DC-10, for example, was a mean fatigue life (to crack initiation) of 120,000 hours for the structure as a whole, with the expectation that any individual airplane would be free of any fatigue problems up to 60,000 hours.

## Factors that affect fatigue life

The primary deterioration process in structure is fatigue. However, the integrity of the structure is also threatened by manufacturing imperfections, accidental damage, overloads during operation, and corrosion. All these factors can have a direct effect on structural strength and can also accelerate the fatigue process itself. The age at which fatigue cracks first appear in a given structural item may therefore vary widely from one airplane to another, and the structural inspections must begin long before the age at which fatigue-test data indicate that a fatigue crack can be expected.

One well-recognized manufacturing problem is assembly-induced *preload*, a condition caused by design, fabrication, or assembly errors.

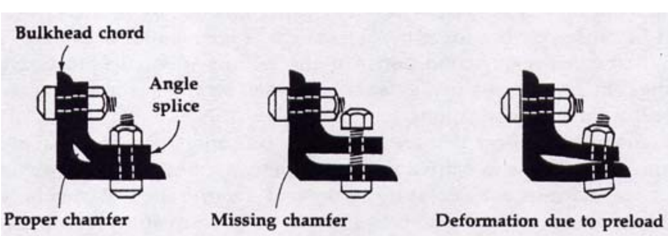



**Exhibit 9-3, Example of a preload condition. Although the discovery of this condition on one airplane prompted an immediate inspection of the entire fleet, only a few cases of preload were actually found.**

Exhibit 9-3 shows an example of a preload condition in an angle splice. In this case a missing chamfer allows the edge of the angle to dourge into the radius of the chord piece. When the horizontal joint is drilled and bolted without proper shimming, a further effect is deformation of the pieces. The result is either radial cracking at the joint or a splice with such high imposed loads that it is highly susceptible to any small additional loads. In either case the residual strength of the assembly containing this chord and splice will deteriorate in a fraction of its intended design life. Fortunately the existence of a preload condition is usually detected early in the age-exploration process, but its discovery necessitates immediate inspection of the entire fleet to locate all defective units.

In addition to localized problems, all parts of the structure are exposed to *corrosion*, the deterioration and ultimate destruction of a metal by its environment. There are many different forms of corrosion, ranging from simple oxidation to electrolytic reactions. Like fatigue, corrosion is age-related. It is not nearly so predictable, however, since metals corrode at rates that depend on a complex of environmental conditions and maintenance practices. Corrosion damage has a particularly adverse effect on structural strength. Unless it is detected at an early stage, the localized loss of material will reduce the load-carrying capability of the portion of the structure affected, and the resulting increase in stress levels will accelerate the fatigue process in the remaining metal.

Most types of corrosion are observable as surface deterioration which results in a measurable reduction in the cross section of the element. *Stress corrosion*, however, is more difficult to detect. This form of corrosion is caused by the combined effects of environment and sustained or cyclic tensile stress, and it can lead to the spontaneous collapse of the metal with no macroscopic signs of impending failure. Stress corrosion develops as fine intercrystalline or transcrystalline cracks in the metal itself. Since there may be no external evidence of deterioration, we must rely on such nondestructive techniques as eddy-current inspection to detect this condition. In a moist environment stress-corrosion cracking can occur under stresses much lower than the yield stress of the material. The problem is most common in high-strength aluminum alloys that have been strengthened by heat-treating. It can be caused by improper heat treatment, a poor choice of materials for a particular set of conditions, or the lack of adequate protective coatings. In some cases it may also be caused by the sustained stress created by preload conditions.

Generally the areas that are exposed to dirt, moisture, and heat are the most susceptible to corrosion, and properly applied and maintained protective coatings are necessary to prevent deterioration. Particularly short inspection intervals are required in such corrosion-prone areas as fuselage bilges, the areas under lavatories and galleys, and cargo pits to check for incipient corrosion and resore any deteriorated protective coatings.

## Structurally significant items

Nearly all parts of an airplane structure are inspected at one time or another, both to preserve the design strength of the structure and because deterioration detected in its early stages is relatively inexpensive to repair. Because of the cost and difficulty of replacing failed structural members, most such items might be viewed as significant on the basis of economic consequences. However, the primary consideration in determining structural significance is the effect that failure of an element has on the residual strength of the remaining assembly and on the functional capability of the overall structure. Thus safe-life elements and damage-tolerant monolithic elements are classified as significant because their failure would lead to a complete loss of function of a major assembly either immediately or in the near future. Many elemets of a damage-tolerant assembly will also be classified as significnat, depending on their contribution to the strength of the assembly and the significance of the assembly to the overall structure.

The generac term *structurally significant item (SSI)* is used to denote each specific structural region that requires scheduled maintenance as part of an RCM program to guard against the fracture of significant elements. Such an item may be defined as a site which includes several elements, it may be defined as the significant element itself, or it may be defined in terms of specific regions on the element which are the best indicators of its condition. In this sense a structurally significant item is selected in much the same way as a functionally significant item, which may be a system, a sybsystem, an assembly, or a significant part in an assembly.

During the selection of structurally singificant items consideration is also given to the susceptiblity of various parts of the structure to corrosion and accidental damage. Thus the relative ranking of significant items takes into account not only the effect of the item's failure but also how soon a particular item is likely to cause problems. Consequently, although significant items are often defined in terms of specific stress points, shuch as the joint between two structural members, an entire area that is exposed to moisture, and hence to corrosion problems, may also be classified as significant. In this case specific stress points within the area might be designated as separate items on the basis of fatigue factors. Sometimes different surfaces of the same structural element are designated as separate items, especially if different access routes are required to perform the inspections.

In the development of a prior-to-service program the manufacturer provides the initial designation of structurally significant items, since at that time he is the only one in a position to identify safe-life and damage-tolerant monolithic items, the effect of a failed element on the strength of damage-tolerant assemblies, and the expected fatigue life and crack-propagation characteristics of each structural element. Although the numbering schemes differ from one manufacturer to another, significant items are usually identified on the basis of a three-dimensional reference system that shows their exact physical location by section or station or within a designated zone.

All structurally significant items are subjected to *detailed inspections*. Many of these inspections are visual, but they must be performed at close range and require special attention to small areas, such as a check for corrosion in bolt holes. Others may entail the use of special equipment, such as x-ray or eddy-current devices. In addition to these detailed inspections, many items also receive frequent *general inspections*, visual checks for any obvious problems, which require no tools or disassembly other than the opening of quick-access doors. These latter inspections are performed as part of the preflight walkaround checks, the zonal prgram, and general external inspections, which include nonsignificant portions of the structure as well. Thus, although the RCM structural program includes only those items designated as structurally significant, evey aspect of the structure is examined at one time or another to ensure that any signs of fatigue, corrosion, or accidental damage will be detected in their early stages.

## 9.2. The structural inspection plan

The structure of an airplane is exposed to random damage from contact with loading or other ground equipment and from foreign objects such as stones or ice on runways and bird strikes during flight. It is also subject to occasional severe loads during operation as a result of air turbulence or hard landings. However, the chief causes of deterioration (a reduction of failure resistance) are fatigue and corrosion, both of which are age-related. Fatigue is related to the total operating age of the structure, and corrosion is a function of the time since corrosion damage was last repaired and anti-corrosion treatments were renewed. The objective of the structural inspection plan is to find and correct any deterioration of those items of greatest significance to the structural integrity of the airplane, and to collect information on the aging characteristics of less significant items by inspections of a sample of the fleet. The sampling information may, of course, lead to inspection of certain items on every airplane as evidence of these characteristics begin to appear.

Because deterioration in its early stages is relatively inexpensive to repair, it is cost-effective to inspect many structural items far more frequently than would be required solely to protect the airworthiness of the airplane. General inspections of the external structure, for example, are scheduled very frequently because they can be performed quickly and easily. *External structural items* are those portions of the structure that can be seen without removing any covering items or opening any access doors. These general inspections will detect not only accidental damage, but also any external signs of internal deterioration, such as discoloration, popped rivets, buckled skin, and fuel leaks. This external evidence is often a specific design feature in damage-tolerant structure, and the ease of external inspections makes it practical and safe to lengthen the inspection intervals for the internal items themselves.

Any part of the structure that is not visible extemally is termed an internal structural item. Intemal items are more difficult to inspect. Some require only the opening of quick-access doors, but others require the removal of floorboards, linings, and insulation or the disassembly of other parts of the structure or of the aircraft systems. Intemal significant items, like external ones, receive detailed inspections. However, whereas external inspections are performed on every airplane, some intemal inspections are performed on only a portion of the fleet. In the power-plant division age exploration of internal engine items is based on a continual flow of engines through the repair shop, but structure does not provide such opportunity samples - portions removed and sent to the shop while the airplane remains in service.Thus the inspection program itself is the only vehicle for age exploration.The intervals assigned in an initial program therefore represent only a fraction of the ages at which any signs of deterioration are expected and, in effect, merely de-fine the start of age exploration for each item.

The current practice in developing an initial structure program is based on a rating scheme that makes full use of the designer's information and the manufacturer's test data for the various structural elements. The first consideration is whether the portion of the structure in question is a structurally significant item. If so, it will be assigned a detailed inspection task, but the frequency of inspection will depend on further considerations. If the item is on the underside of the airplane, which is particularly susceptible to accidental damage, it will be inspected more often than one on the upper surface. The inspection intervals for damage-tolerant items will be longer in general than those for safe-life elements. In this case, however, the interval for internal items will depend on whether a damage-tolerant assembly has been designed to provide extemal evidence of internal damage. The general relationship of these considerations is diagrammed in Exhibit 9-4. The starting point for the development of a structure program is a list of structurally significant items. Not all these items will be of the same significance. The failure of some redundant elements, for example, will cause a much greater reduction in residual strength than the failure of others. Moreover, the test data on fatigue life, as well as differences in susceptibility to corrosion and accidental damage, will usually indicate that inspection of all items need not start at the same operating age. To determine an appropriate interval for each item, therefore, it is necessary to assess the following design characteristics:

- The effect of failure of the item on residual strength
- The anticipated crack-free life (fatigue life) of the item
- The crack-propagation characteristics of the item
- Susceptibility of the item to corrosion
- Susceptibility of the item to accidental damage

These five factors are used to develop inspection ratings for each item, and the ratings are then transformed into a class number that identifies the appropriate relative interval.

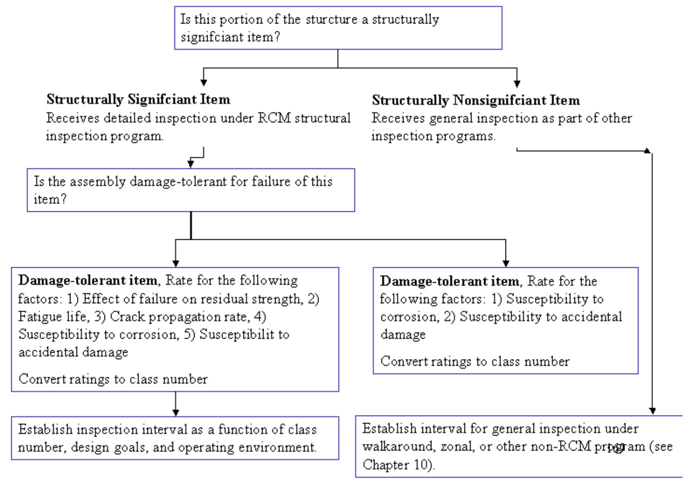



**Exhibit 9-4 A plan for inspection of the complete structure**

To illustrate, suppose the item is an internal structural element in a damage-tolerant assembly. The first step is to rate each of the five factors independently on a scale of 1 to 4, as outlined in Exhibit 9-5. This scale keeps the number of choices small, but also avoids a middle value, which would tend to be overused. Note that the ratings for fatigue life and crack propagation for an internal item may be increased by 1 if there is external evidence of the item's failure. This does not apply to corrosion ratings, however, since the objective is to inspect often enough to prevent corrosion damage from reaching the stage at which it would be evident externally. Nor does it apply to accidental damage. Thus this particular internal item might be rated as having very little effect on the residual strength of the assembly (4), moderate fatigue life (2 + 1 = 3), rapid crack growth (1+ 1= 2), moderate susceptibility to corrosion (2), and very little exposure to accidental damage (4).

The procedure for safe-life items is similar, except that these items are rated for only two factors: corrosion and exposure to accidental damage. A functional failure (fracture of the item) would reduce the residual strength to zero, and crack propagation is not a consideration because a safe-life item cannot be allowed to reach the point of crack initiation. If it were feasible to define a crack as a potential failure and depend solely on on-condition inspections to ensure removal of the item before the crack reached critical length, the item would have been classified as damage-tolerant instead of safe-life.

| Reduction in residual strength | Fatigue live | Crack propagation | Suscepibility to corrosion | Susc. to accidental damage | Rating |
|---|---|---|---|---|---|
| Large | Short | Rapid | High | High | 1 |
| Moderate | Medium | Moderate | Moderate | Moderate | 2 |
| Small | Long | Slow | Low | Low | 3 |
| Very small | Very long | Very slow | Very low | Very low | 4 |

**Exhibit 9-5 Rating scales for the five factors that determine structural inspection intervals. Each structurally significant item is ranked on a scale of 1 to 4 for each of the factors that apply. The lowest of these rankings represents the class number assigned to that item.**

While the ratings are clearly a matter of judgment, they make the best possible use of the information that is available at the time. For example, in assessing the reduction in residual strength caused by the fracture of a single element, consideration must be given not only to the role of the element in relation to the load-carrying capability of the assembly, but also to the role of the assembly itself in relation to the overall structure. From the standpoint of the assembly, one determining factor is the number of elements at the same site that can fail before damage-tolerant capability is lost. The reduction is rated as major if the failure of a second element would leave the assembly incapable of supporting the damage-tolerant load; it would be rated as moderate if the failure of two elements could be tolerated, and if the loads originally carried by the two elements were of the same order of magnitude. Alternatively, the ratings can be based on the percentage of loss in residual strength caused by the fracture of structural elements. For example, if the failure of two elements can be tolerated, a rating of 2 would be used if these failures reduce the margin between the ultimate and damage tolerant strength by 75 percent; a reduction of 50 percent would be rated as 3, and a reduction of 25 percent would warrant a rating of 4.

In assessing fatigue life and crack-propagation characteristics the working group would consider whether or not the item had undergone fatigue and crack-propagation tests (if not, all the ratings would be lower), whether the loads applied to the test items are representative of the expected operating loads, and the results of the test in relation to the fatigue-life goal for the airplane. In making corrosion ratings they would consider previous experience with the anticorrosion treatments used in manufacture, the type of environment in which the equipment will be operated, and any specific problems related to the location of the item in the equipment. Operation in a hot, humid environment close to salt water, for example, would affect corrosion ratings for the entire structure. In commercial aircraft those structural items adjacent to the cargo pits, galleys, hot-air ducts, and lavatories are particularly susceptible to corrosion. Susceptibility to corrosion is difficult to rate, since corrosion is a function of the operating environment, and for some types of equipment evidence of corrosion might be acceptable at much lower ages than it is for transport aircraft. Similarly, the susceptibility of an item to accidental damage will range from high for external items exposed to foreign objects on runways to low for internal areas subject to little traffic from maintenance personnel.

One way of rating the fatigue life and crack-propagation characteristics of an item is in terms of the fatigue-life design goal for the structure as a whole. The design goal for the Douglas DC-10, for example, was an average fatigue life of 120,000 hours to crack initiation (about 40 years of airline service, or two operating lifetimes). An individual item with an expected fatigue life of less than 120,000 hours would be rated 1 for fatigue life, an item with an expected fatigue life of 120,000 to 180,000 hours would be rated 2, and so on. The ratings for crack propagation would be based similarly on a ratio of the crack-propagation interval for the item to the overall fatigue-life design goal. Thus an item with an interval of less than 15,000 hours from the time of crack initiation to critical crack length (or in the case of a redundant element, to fracture of the element) would receive a rating of 1 for this factor.

| Crack-propagation rate | | Susceptibility to corrosion | | Susciептibility to accidental damage | |
|---|---|---|---|---|---|
| Ratio of interval to fatigue-life design goal | rating | Ratio of corrosion-free age to fatigue-life design goal | rating | Exposure as a result of location | rating |
| 1/8 | 1 | 1/8 | 1 | High | 1 |
| ¼ | 2 | ¼ | 2 | Moderate | 2 |
| 3/8 | 3 | 3/8 | 3 | Low | 3 |
| ½ | 4 | ½ | 4 | Very low | 4 |

**Exhibit 9-6 Factors used to develop ratings for damage-tolerant structurally significant items. In each case the item is rated for the effect of a single failure on the residual strength of the assembly. Tha fatigue life of each item represents the time to crack initiation in relation to the fatigue-life design goal for the structure as a whole.**

Corrosion ratings can be developed in the same way, by comparing the age at which corrosion is first expected to become evident with the fatigue-life design goal. The ratings for susceptibility to accidental damage cannot be expressed in terms of a reference age, but they are based on the item's resistance to damage, as well as the type and frequency of damage to which it is exposed.

Once the item under consideration has been rated for each of the factors that apply, the lowest rating for any individual factor is assigned as the class number for that item.[*] The damage-tolerant item described above has ratings of 4, 3, 2, 2, and 4; hence its class number is 2. A safelife item rated 4 for corrosion and 1 for susceptibility to accidental damage would have a class number of 1. The class number is the basis for the relative length of the initial inspection interval. The lower the rating, the lower the class number, and therefore the shorter the inspection interval.

For damage-tolerant items the design goal can also serve as a reference for converting class numbers to inspection intervals. The interval must be one that provides for at least two inspections during the crackpropagation interval; if the first inspection does not disclose a potential failure, the second one will. In addition, there should be 20 to 30 inspections before the expected appearance of a fatigue crack on the most significant items, although there may be as few as five for those of least significance. Such inspections not only protect the structure from the effects of incipient corrosion and accidental damage, but also make it possible to confirm that the design fatigue life has in fact been achieved.

[*] The lowest number must be used because there is no basis for tradeoffs between any of the individual rating factors.

There is no hard-and-fast rule for establishing initial inspection intervals, because the rating process itself must be based on cautious informed professional judgment. The scale outlined in Exhibit 9-7 does, however, reflect current practice for commercial swept-wing jet transport aircraft. This scale applies only to structural items that meet damage-tolerant design criteria. Safe-life items must also be inspected to find and correct any deterioration that could prevent attainment of the safe-life limit. The ratings for corrosion and susceptibility to accidental damage will provide rankings for the relative intensity of such inspections, but there is no accepted basis for converting the resulting class numbers to actual intervals. This is because of the wide variations both in susceptibility to such damage and in the value judgments applied to ratings in individual operating contexts. Consequently the initial intervals for safe-life elements are generally set at conservative values which reflect their relative class numbers and are extended, if possible, on the basis of the findings from these inspections after the equipment enters service.

| Class number assigned to item as a result of ratings | Initial inspection interval as a fraction of fatigue-life design goal |
|---|---|
| 1 | 1/24 |
| 2 | 1/12 |
| 3 | 1/8 |
| 4 | 1/6 |

Notes:

**1** An internal item whose class number has been raised because of external detectability will have an associated external SSI with the class number of the internal item without this increase

**2** Class 1 and class 2 items may be considered for higher initial intervals on later aircraft after a sufficient number of inspections on the original fleet have shown no signs of deterioration.

**3** Class 3 and class 4 items may be considered as candidates for total-time fleet-leader sampling after pertinent operating information becomes available.

**Exhibit 9-7 A suggested scale for converting class numbers to relative inspection intervals for significant items in damage-tolerant structure. In this case the initial interval is expressed as a fraction of the fatigue-life design goal for entire structure. A similar scale cannot be used for safe-life elements because the only two factors rated (susceptibility to corrosion and accidental damage) vary with the item and the intended use of the equipment.**

At this point let us examine some of the implications of Exhibits 9.6 and 9.7 and see how the starting and repeat intervals for structural items relate to the fatigue characteristics of the item. Consider a case in which the class number of an item results from its crack-propagation rating. The relationships would be as follows:

| *Class number* | *Ratio of crack-growth interval to fatigue-life design goal* | *Ratio of inspection interval to fatigue-life desing goal* |
|---|---|---|
| 1 | 1/8 | 1/24 |
| 2 | ¼ | 1/12 |
| 3 | 3/8 | 1/8 |
| 4 | ½ | 1/6 |

In each case the inspection interval ensures three inspections be- tween the time of crack initiation and time at which the crack will reach critical length. The intervals are therefore quite satisfactory for use as repeat intervals to detect potential failures before the item actually frac- tures. However, these intervals are also used in the initial program to define the ages at which inspections must be performed to begin the age-exploration process. The same interval will be used for the first, second, and subsequent inspections of the item until there is sufficient information to support a change. Such information will usually show an absence of deterioration at lower ages, and it will then be possible to start inspections on later-delivery airplanes at a higher age-that is, to eliminate the first few inspections in the sequence. Now suppose that the item in question has a class number of 1, and that the ratings for residual strength and crack propagation are both 1. The inspection interval of 1/24 of the fatigue-life design goal is suf- ficiently conservative to protect a very significant item in damage- tolerant structure. If both ratings are 2, the inspection interval will be increased to 1/12 of the design goal. However, if the item has been rated 1 for residual strength and 2 for crack propagation, the class number is 1 and the inspection interval remains at 1/24 of the fatigue-life design goal-a somewhat illogical but subjectively attractive increase in con- servatism, both for protection of the item and for the intensity of age exploration. Low ratings for fatigue life and exposure to corrosion or accidental damage can lead in the same way to increased conservatism. Although the intervals in Exhibit 9.7 are generally conservative, items with fairly rapid crack-propagation characteristics may be far off the scale and may require special treatment. This is frequently the case with serious unan- ticipated failures which occur after the airplane enters service, but then real information is available for use in establishing the appropriate intervals for first and repeat inspections. While the question of when each item should first be inspected is always believed to be of intrinsic importance in developing an initial inspection program, it is an interesting paradox that the methods actu- ally used to determine initial intervals can be explained only in terms of repeat intervals, with in-service age exploration to establish which multiple of these intervals should be used as the starting interval on later-delivery airplanes. There has been a gradual extension of initial inspection intervals as a result of satisfactory experience with in-service aircraft, and further experience may well support substantially longer initial intervals for designs incorporating familiar technology. It.is important to remember that the intervals suggested in Exhibit 9.7 are based on vast experience with various types of airplanes that have employed similar materials, design practices, and manufacturing processes. They can therefore be applied with confidence to new types of airplanes that represent an extrapolation of this experience. However, if the aircraft designer is less experienced in this field, or if new types of materials or new manufacturing or bonding processes are employed, or if the equipment is to be operated in an unfamiliar environment (such as supersonic transport), the initial intervals must be far more conservative and the age-exploration activity more intensive. It goes without saying that the effectiveness of an inspection program depends on the proper identification of structurally significant items. It is essen- tial, therefore, that all operating organizations report serious structural deterioration at any age to central coordinating agencies, usually the manufacturer and the regulatory agencies, who will evaluate them and define new significant items, adjust inspection intervals, call for spe- cial inspections, or even require that modifications be made to the structure.

## 9.3. Assembling the required information

Most of the information required to develop an initial structural pro- gram must be supplied by the manufacturer. In addition to the test data used to establish fatigue life and the effect of a failure on residual strength, the working group must know the flight profile assumed as ethe basis for fatigue-life design goals and the structural design philoso- phy that was followed. To determine appropriate inspection intervals, they must also know whether the design characteristics include external evidence of internal failures, what the accessibility of each item will be, the physical properties of each of the materials used, and the corrosion- prevention procedures and types of paint systems used. All this information is provided during the design reviews con- ducted by the manufacturer. As an example, the following design goals were discussed with the entire working group during early presenta- tions on the Douglas DC-10:

- The residual strength after the failure of any single structural item must be great enough to withstand the applied limit load considered as an ultimate load (the criterion for damage-tolerant structure).
- A part containing discontinuities must have a fatigue life equal to or greater than the same part without discontinuities.
- Joints must be stronger than their surrounding elements.
- The design goal for the airplane is a mean fatigue life of 120,000 flight hours, with a reasonable probability that any single airplane will be crack-free to 60,000 hours (approximately 20 years).

- Every effort must be made to ensure that areas most subject to fatigue damage are easy to inspect by detailed inspections in small localized areas.
- The outer-skin cracks which are evidence of fractures in adjacent internal elements must be detectable before they reach critical length.

Proper evaluation of this information, however, depends heavily on the experience and professional judgment that the working-group members bring to the decision process. From experience with other . recent designs, they will know the areas of the structure in which fa- tigue cracks are most likely to appear, the parts of the airplane subjected to the harshest environmental conditions (trapped water, condensation, spillage, damage from cargo), the durability and effectiveness of protective coatings in actual use, and the reaction of various structural materials under loads and environmental conditions similar to those to which the new aircraft will be subjected.

The data elements that must be assembled for each structural item to be analyzed are similar to those required for systems and powerplant items. Because the primary decision problem concerns the assignment of appropriate inspection intervals, however, the information is re- corded in a slightly different form (see Exhibit 9.8). In addition to the item name and number, which are usually based on the manufacturer's identification of parts for design reference, a brief description is needed to pinpoint the exact location of the item. The zone numbers are also included, since they are useful when the tasks are assembled into work packages. If an item appears on both sides of the aircraft, both zone numbers should be included. Similarly, if it is a skin panel or some other large area, all zone designators should be included.

It is important to specify the materials from which the item is manu- factured, since prior experience with various materials will have great bearing on the evaluation of their properties. The results of fatigue and static-load tests of the complete airplane or its major assemblies are usually not available at the time an initial program is developed, since the tests on most items will still be in progress. However, there are often test data on smaller assemblies, and in some cases relevant data may be available for a similar portion of the structure on in-service aircraft. Where tests on safe-life items are still in progress, the test data which are available must show a zero conditional probability of failure at the safe-life limit indicated.

In the case of all structural analyses it is necessary to indicate whether the item is a safe-life element or meets the criteria for damage- tolerant design. The worksheet should also show whether the item is an internal one or is visible externally. As with systems and powerplant items, the design redundancies that make an item damage-tolerant and the external detectability of internal problems help to determine the specific area (or areas) of the structure defined as structurally signifi- cant, as well as the ratings which establish the intensity of inspection required. The ratings themselves are recorded on the worksheet, along with the class number assigned to the item as a result of the controlling rating factor. Where individual ratings have been increased because of external detectability or decreased because of the absence of test data, these adjustment factors should be noted. The information on related structurally significant items is especially useful in evaluating later adjustments of the initial intervals as a result of age exploration.

Whereas the information worksheets for systems and powerplant items included a detailed list of functions, functional failures, failure modes, and failure effects, this information is rarely needed on struc- tures worksheets. (The reason for this will be explained in the next sec- tion.) Instead, the rest of the worksheet covers the nature of the pro- posed inspection tasks. Where both general and detailed inspections are required for the same item, each task is listed separately, with its appropriate interval. If the item is one that is likely to control the work package in which it is included, the initial interval should be stated in actual operating hours, spectrum hours, or flight cycles. Where a wide range of intervals can be assigned, it may be necessary only to state the letter-check package in which the task is to be included (see Section 4.6).

In assigning initial inspection intervals it is important to bear in mind that the structural inspection program will provide the framework for all the major scheduled-maintenance packages. Thus tasks must be considered not only in terms of their frequency, but also in terms of the length of time the aircraft will have to be out of service while they are performed. Inspections directed at those portions of the structure that are both easily accessible and the most susceptible to corrosion or acci- dental damage are called out in the more frequent lower-level packages, from the walkaround check on up. While the intervals must be short enough both to protect the equipment and to find damage at a stage when it is still inexpensive to repair, when damage is found, the repair itself may be scheduled for a later time.

| | |
|---|---|
| **Item Number**: 105 | **No. per aircraft:** 2 |
| **Item Name**: Wing-to-fuselage attach "tee" | **Major area:** Outer wing, upper skin panel |
| **Vendor part/model no**: 573.01.105/DC10/10 | **Zones:** 264/5, 161/2, 254/5, 274/5 |
| **Description/location details**: Attach tee is located under upper | **Design criterion:** |

| | |
|---|---|
| wing-root fairing and runs along upper chord from fornt to rear spar at wing station XW 118.2; SSI includes attach tee and skin 12 in. all sides of tea (both faces), accissible through doors 527FB, 627FB, 527GB, and 627GB. | Damage tolerant element:____<br>Safe-life element: _____<br>**Inspection access:**<br>Internal: ____<br>External: ____ |
| **Material (include manufacturer's trade name):** Titanium alloy 6AL-4V (Douglas specification 1650) | **Redundancy and external detectability:** Three pieces to prevent cracks from growing to entire length of tee; no external detectability |
| **Fatigue-test data**<br>**Expected fatigue life:** 240,000 hours<br>**Crack propagation:** 60,000 hours<br>**Established safe-life:** ------<br>**Design conversion ratio:** 1.5 operating hours/flight cycle | **Is element inspected via a related SSI? If so, list SSI no.:** No<br>**Classification of item (significant/nonsigniticant):** significant |

| Residual strength | Fatigue life | Crack growth | Corrosion | Accidental damage | Class no. | Controlling factor | Inspection (int./ext) | Proposed task | Initial interval |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 4 | 4 | 4 | 4 | 4 | ---- | Int. | Detailed visual inspection for corrosion and cracking | Not to exceed 20,000 hours (D check) |

**Exhibit 9-8 A worksheet for recording the relevant information, ratings, and task outcomes for structurally significant items**

The more extensive inspections-those that will take the airplane out of service for more than twenty-four hours-are usually consoli- dated in a work package performed at much longer intervals. Many of the internal inspections can be performed only at the major mainte- nance base, where the airplane can be disassembled as necessary to check parts of the structure for evidence of fatigue as well as corrosion damage. This comprehensive inspection, or "airplane overhaul," is usually referred to as aD check and includes all, or nearly all, the inspection tasks in the program. Depending on the complexity of the structure and the size of the maintenance crew, it may take the airplane out of service for a week to several months.

The first of these complete inspections is a very important part of the age-exploration program, since it includes many inspections that are being performed for the first time. The first airplane that ages to the initial interval becomes the inspection sample; the findings for each item are carefully evaluated, tasks and intervals for individual items are adjusted as necessary, and the conservative initial interval for the D-check package is extended. Consequently, although external inspec- tions are performed on every airplane, most internal items will be inspected at the initial interval only on the first one or first few air- planes to reach this age limit. They will, however, be inspected at suc- cessively higher ages as the equipment ages in service, often on a fleet-leader sampling basis.

## 9.4. RCM Analysis of structural items

As we saw in Chapters 7 and 8, RCM analysis of systems and power- plant items may fall in any branch of the decision diagram. In contrast, all structurally significant items fall in the safety branch, and the eval- uation of proposed tasks can have only one of two possible outcomes (see Exhibit 9.9). This is true no matter which of the structural functions we consider. As an example, one function of the aircraft structure is to permit lifting forces to balance the weight of the airplane. Although most of the lift is provided by the wing, its center of lift does not neces- sarily coincide with the airplane's center of gravity, and the horizontal stabilizer must provide a balancing load that brings the vertical forces into equilibrium. The portions of the structure associated with this function, therefore, are the wing, the fuselage, and the horizontal tail.

The first question is whether a loss of the balancing function will be evident:

**1 Is the occurrence of a failure evident to the operating crew during performance of normal duties?**

The answer is yes, of course, since a loss of this function as the result of a structural failure would be all too evident, not only to the crew, but to any other occupants of the airplane as well.

Next we would ordinarily examine the various failure modes that could cause such a failure. In the case of structural items, however, the failure modes all involve the fracture of a load-carrying member. Thus the following question relates to any of the failure possibilities:

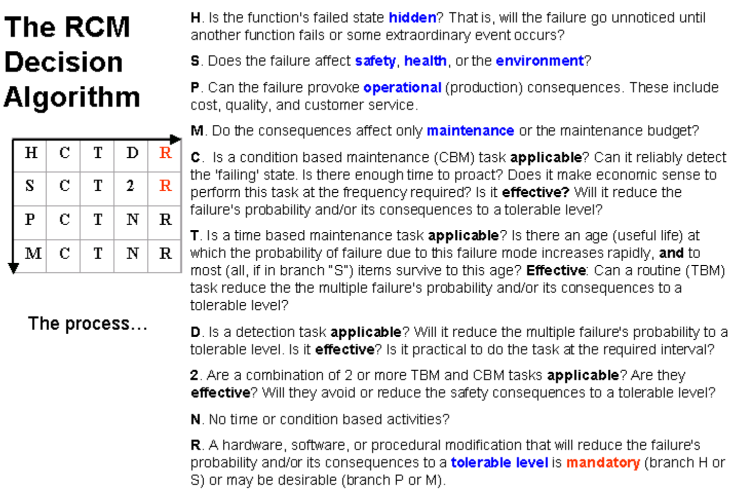



**Exhibit 9-9 The "S" branch of the decision diagram is used for RCM analysis of all functions of the aircraft structure. The only possible task outcomes for structurally significant items are on-condition inspection for elements of damage-tolerant structure and a combination of on-condition and discard tasks for safe-life elements.**

**2 Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?**

The fracture of a structural item may well cause critical secondary damage, but in this case the loss of function alone is sufficient to classify the failure as critical. The answer to this question is therefore yes regard- less of the failure mode involved, and further analysis falls in the safety branch of the decision diagram. This means that scheduled mainte- nance is required and that a task will be considered effective only if it reduces the risk of a functional failure to an acceptable level; in other words, it must result in substantial preservation of the load-carrying capability of the item. The first type of task we would consider is an on-condition inspection:

**4 Is an on-condition task to detect potetnial failures both applicable and effective?**

For items designed to damage-tolerance criteria the answer to this question is yes. The existence of a crack in a structural element can be defined as a potential failure, and in an assembly with redundant load paths even the fracture of one element will not reduce residual strength below the safety level. Hence an on-condition task is applicable, and if it is performed at short enough intervals to ensure that a second ele- ment does not fracture (or in the case of a monolithic member, that the crack does not propagate to critical length), the task is also effective. RCM analysis of a damage-tolerant element is therefore complete once this question has been answered, and all that remains is to assign appro- priate inspection intervals for each of the significant items. For safe-life items the answer to question 4 is no. Although the initiation of a fatigue crack can still be defined as a potential failure, unless its propagation characteristics meet damage-tolerant load re- quirements, we cannot rely on on-condition inspections to prevent fatigue failures. Such inspections are applicable to detect corrosion and accidental damage, which can greatly shorten fatigue life, but since they will not prevent all functional failures, we must look for other tasks:

**5 Is a rework task to reduce the failure rate both applicable and effective?**

Although the fatigue process is directly related to operating age, there is no form of remanufacture that will erase the cumulative effect of the loads the material has experienced up to that point (restore the original resistance to failure). A rework task can therefore have no effect on the time at which fatigue failures might occur. Since this task is not appli- cable, the answer to the rework question is no, and we must consider the next possibility, a safe-life discard task.

**6 Is a discard task to avoid failures or reduce the failure rate both applicable and effective?**

A safe-life limit is based on the fatigue life of the item, as established during developmental testing. However, since corrosion and damage can affect that life, these factors may prevent a structural element from reaching the safe-life age established on the basis of testing in a less hostile environment. Consequently we cannot conclude that a safe-life discard task alone will satisfy the criterion for effectiveness in pre- venting critical failures, and the answer to this question is no. A no answer to question 6 brings us to the final question in the safety branch:

**7 Is a combination of preventive tasks both applicable and effective?**

Both on-condition and discard tasks are applicable, and a combination of the two meets the effectiveness requirements. The on-condition inspections ensure that the item will reach its safe-life limit, and the discard task ensures that it will be removed from service before a fatigue failure occurs. The results of this analysis are shown on the decision worksheet in Exhibit 9.10. Note that an analysis of any one of the functions listed in Section 9.1 would follow the same path and lead to the same out- comes: on-condition inspections for damage-tolerant items and on- condition inspections plus discard at the safe-life limit for safe-life items. If the elements of a damage-tolerant assembly were analyzed individually, the fracture of a single element would be viewed at the assembly level as a hidden failure. The task itself, however, would be exactly the same-an inspection for cracks and corrosion scheduled at intervals short enough to avoid the risk of a multiple failure of such elements.

Once again, particular care must be given to the definition of func- tions and functional failures. For example, one of the functions of the structure is to provide movable flight-control surfaces for maneuvering the airplane. However, if the ailerons on each wing are duplicated, a failure of one of the two ailerons will not result in a loss of that function. Rather, from the standpoint of maneuvering capability, it will result in a potential failure. In this sense the failure of a single aileron is analogous to the fracture of a single element in a damage-tolerant assembly, and the maintenance task to prevent a loss of aileron function to the aircraft is an on-condition inspection scheduled at intervals short enough to prevent the failure of more than one aileron.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Loss of balancing function, all failure modes: | | | | | | | |
| Damage-tolerant assembly (failure mof multiple elements: | Y | Y | - | Y | | | |
| Safe-life element | Y | Y | - | N | N | N | Y |
| | | | | | | | |

| Proposed task | Initial inteval |
|---|---|
| On-condition inspection for cracks, corrosion, and accidental damage | As determined by class of item |
| On-condition inspection for cracks, corrosion, and accidental damage<br><br>Discard at safe-life limit | As determined by class of item<br><br>As determined by safe-life limit for item |

**Exhibit 9-10 The results of RCM analysis for structurally significant items. All functions of the aircraft structure depend on the ability of significant elements to withstand applied loads, and all failure modes lead ultimately to a fatigue failure resulting in the loss of this load-carrying capability. Thus the answers to the decision-diagram questions will be the same for any damage-tolerant item and for any safe-life item, regardless of the particular item under consideration.**

## 9.5. Establishing initial inspection intervals

The Douglas DC-10 is basically a damage-tolerant aircraft, the only safe-life items being the nonredundant parts of the landing gear. During the very early development of this design typical structural components were fatigue-tested, either individually or in assemblies or sections, to determine their contribution to the design goal of an average crack- free fatigue life of 120,000 hours, with 60,000 hours of crack-free opera- tion for any individual airplane. Although a fatigue test on the entire structure was conducted to the full 120,000 hours, and inspections were to be concentrated on this article as the test progressed, the final results were not available at the time the initial program for the DC-10 was developed. The following examples have been updated to reflect both the results of the fatigue test and the additional parameters used in RCM analysis.* However, the recommended intervals resulting from this analysis are similar to (although not identical with) those in the original prior-to-service program.

DAMAGE-TOLERANT STRUCTURAL ITEMS

The wing-to-fuselage attach tee, together with the structural area around it, is one of the damage-tolerant structurally significant items on the Douglas DC-10. This portion of the structure, identified as SSI 105, is located on the top surface of the wing and consists of the titanium-alloy tee at wing station XW 118.2 and the aluminum-alloy fuselage and upper wing skin within 12 inches of it. The tee, which is in three separate, sections, extends from the front to the rear spar and forms part of themating joint between the wing and the fuselage. It also forms part of the pressure vessel; thus it is subjected to pressurization loads as well as to flight loads. This structural item cannot be seen externally. The outer portion is under the wing-to-fuselage fairing and the inner portion is under the cabin flooring.

Exhibit 9.11 shows all the pertinent information for this significant item, a record of the ratings, and the resulting inspection interval. The rating for residual strength in this case is 4 because the tee plays a relatively minor role in transferring wing loads to the fuselage, and even the failure of two of the three sections of the tee results in only a small reduction in the

* The structural program for the DC-10, developed just before this aircraft was certified, was based on MSG-2 principles, which involved a similar comprehensive analysis. For a detailed discussion of the considerations behind the original program see M. E. Stone and H. F. Heap, Developing the DC-10 Structural Inspection Program, Seventh Annual FAA International Aviation Maintenance Symposium, Oklahoma City, Oklahoma, December 7-9, 1971, and M. E. Stone, Airworthiness Philosophy Developed from Full-scale Testing, Biannual Meeting of the International Committee on Aeronautical Fatigue, London, July 23-25, 1973.

load-carrying capability of the basic structure. The attach tee is made of an alloy that has excellent fatigue and corro- sion resistance, and this part of the structure is expected to survive to more than twice the 120,000-hour design goal; hence the fatigue-life rating is 4. The crack-propagation interval is more than half the design goal, so this rating is also 4. The area is well-protected and well drained, and these properties, in addition to the high corrosion resistance of the material itself, warrant a corrosion rating of 4. This is an internal structural item (either the inner flooring or the outer fairing must be removed for inspection), and since it is exposed to little mechanic traf- fic, the accidental-damage rating is also 4. The result of these ratings is a class number of 4. From the rating scale outlined in Exhibit 9.7 we see that this class number represents an initial inspection interval of 1/6 of the fatigue-life design goal, or 20,000 hours.

See Exhibit 9-9

**Exhibit 9-11Worksheet for analysis of the wing-to-fuselage attach tee on the Douglas DC-10**

Another significant structural element on the Douglas DC-10 is the wing rear spar, which is one of the main load-carrying members of the airplane. A failure of the aluminum-alloy lower cap of that spar would cause a large reduction in the residual strength of the wing, although it would still be able to carry the damage-tolerant load in the absence of failures of any other significant elements at the same site. The spar also forms the rear wall of the integral fuel tanks, and since the front tang of the spar cap is therefore difficult to inspect, it was designed for a lower stress level than the rear tang and will thus have a longer fatigue life. This means that inspection of the rear tang will provide the first evidence of fatigue in the spar cap, particularly if inspections are concentrated on regions of structural discontinuities, such as splices (the spar is made in four sections which are spliced together).

The area identified as SSI 079 in Exhibit 9.13 is the rear tang of the lower spar cap at a point where the spar is spliced and also changes direction. This point lies behind the wing-engine pylon and is in front of the aileron attach fitting. The spar cap and splice require internal inspection and are accessible through two doors in the lower wing skin behind the wing tank on each side of the aircraft. Internal problems are expected to show such external signs as fuel leaks, cracked skin, or popped rivets long before any extensive deterioration of the underlying structure occurs.

The information for this item is summarized on the worksheet in Exhibit 9.14. In this case a failure will have a large effect on residual strength. The rating for residual strength is therefore 1. The splice has an anticipated fatigue life 1 1/2 times the 120,000-hour design goal, and the crack-propagation interval is 1/8 of this time. Ordinarily this would mean a fatigue-life rating of 2 and a crack-propagation rating of 1. However, because of the excellent external indicators of deterioration, both ratings have been increased by 1. The corrosion rating is 2 because of the location of this item; it is exposed to dirt and moisture condensation. The rating for susceptibility to accidental damage is 4 because the item is internal and is exposed to very little mechanic traffic.

The controlling factor is the residual-strength rating. The class number is therefore 1, and this item is scheduled.for inspection at 1/24 of the overall fatigue life, or an interval of 5,000 hours. This is a starting interval for the initial program, and it may be extended for later-delivery airplanes on the basis of the inspection findings after the first airplanes have gone into service. In addition to this internal inspection, the ex- ternal area expected to show evidence of internal problems will also be designated a significant item, and this external area will be inspected at least as frequently.

The front tang of the spar cap, identified as SSI 077, is not expected to be the first indicator of fatigue damage. It must be inspected for corrosion, however, because it is in the fuel tank and is thus exposed to a different environment from the rear tang. Since the forward face of the spar is an interior surface of the fuel tank, it is necessary to drain and purge the tank in order to inspect it. The worksheet in Exhibit 9.15 shows no ratings for residual strength, fatigue life, or crack propagation because these factors are covered for the spar cap by SSI 079. Suscepti- bility to corrosion is rated as very low, 4, because the tank itself is com- pletely sealed and is protected from microbial action by inhibitors. The accidental-damage rating is also 4, because this face of the spar is exposed to even less possibility for damage than the opposite face.

The class number in this case is the lower of the two rating factors, or 4. Thus this item will be inspected initially at 1/6 of the fatigue-life design goal, or an interval of 20,000 hours. With a class number of 4, it will also be eligible for reduced inspection in the ongoing program if the results of early sampling confirm that the area is not prone to deterioration. This is an example of a situation in which two structurally significant items have been designated to identify specific regions of a single element that should be inspected to cater to different factors and environments. There are many additional such designations along the full length of the rear spar. The designer plays an important role in such cases in making the primary indicators of deterioration occur in easily inspectable areas.

SAFE-LIFE STRUCTURAL ITEMS

The shock-strut outer cylinder on the main landing gear of the Douglas DC-10 is one of the few safe-life structural items on this aircraft. The following analysis of this item shows the treatment of a safe-life item in an airline context. However, there is no universal approach to setting inspection intervals for safe-life items, and each case must be considered separately. This particular item is of interest because there are two different models, and the outer cylinder on each model has a different safe-life limit. Exhibits 9.17 and 9.18 are worksheets for the two models.

Since this is a safe-life item, it must be removed from service before a fatigue crack is expected to occur; hence it is not rated for residual strength, fatigue life, or crack-propagation characteristics. Both models are of the same material. However, the manufacturer's fatigue tests showed that model ARG 7002-501 had a safe-life limit of 23,2001andings, or 34,800 flight hours, whereas tests on a redesigned model, ARG 7002- 505, resulted in a safe-life limit of 46,800 landings, or 70,200 flight hours. The safe-life limits are effective only if nothing prevents the item from reaching them, and in the case of structural items there are two factors that introduce this possibility-corrosion and accidental damage. Both factors reduce the expected fatigue life from that for an undamaged part, and both apply equally to the two models of the shock-strut outer cylinder.

Experience has shown that landing-gear cylinders of this type are subject to two corrosion problems. First, the outer cylinder is suscep- tible to corrosion from moisture that enters the joints at which other components are attached; second, high-strength steels such as 4330 MOD are subject to stress corrosion in some of the same areas. Both models are therefore given a corrosion rating of 1, which results in a class number of 1.

The onset of corrosion is more predictable in a well-developed design than in a new one, and previous operation of a similar design in a similar environment has shown that severe corrosion is likely to develop by 15,000 to 20,000 hours (five to seven years of operation). It can be detected only by inspection of the internal joints after shop disassembly; hence this inspection will be performed only in conjunc- tion with scheduled inspections of the landing-gear assembly. This corrosion inspection is one of the controlling factors in establishing the shop-inspection interval. It is customary to start such inspections at a conservative interval and increase the interval at a rate determined by experience and the condition of the first units inspected. The initial requirement is therefore established as inspection of one sample be- tween 6,000 and 9,000 hours and one sample between 12,000 and 15,000 hours to establish the ongoing interval. During the shop Visits for these inspections any damage to the structural parts of the assembly are repaired as necessary and the systems parts of the assembly are usually reworked. Thus the combined process is often referred to as landing- gear rework.

In addition to the corrosion rating, both models of the shock-strut cylinder are rated for susceptibility to accidental damage. The cylinder is exposed to relatively infrequent damage from rocks and other debris thrown up by the wheels. The material is also hard enough to resist most such damage. Its susceptibility is therefore very low, and the rating is 4 in both cases. However, because the damage is random and cannot be predicted, a general check of the outer cylinder, along with the other landing-gear parts, is included in the walkaround inspections and the A check, with a detailed inspection of the outer cylinder sched- duled at the C-check interval. The same inspection program applies to both models, since they have the same susceptibility to corrosion and accidental damage. The only difference is in the interval for the safe- life discard task; this task is scheduled at the safe-life limit for each model.

Note that the outer cylinder has been treated in this case as a single structurally significant item. It could also have been designated as two items, with the interval for the internal surface controlled by the cor- rosion rating and that for the external surface controlled by a single rating for accidental damage. This treatment would, of course, have resulted in the same set of tasks and intervals.

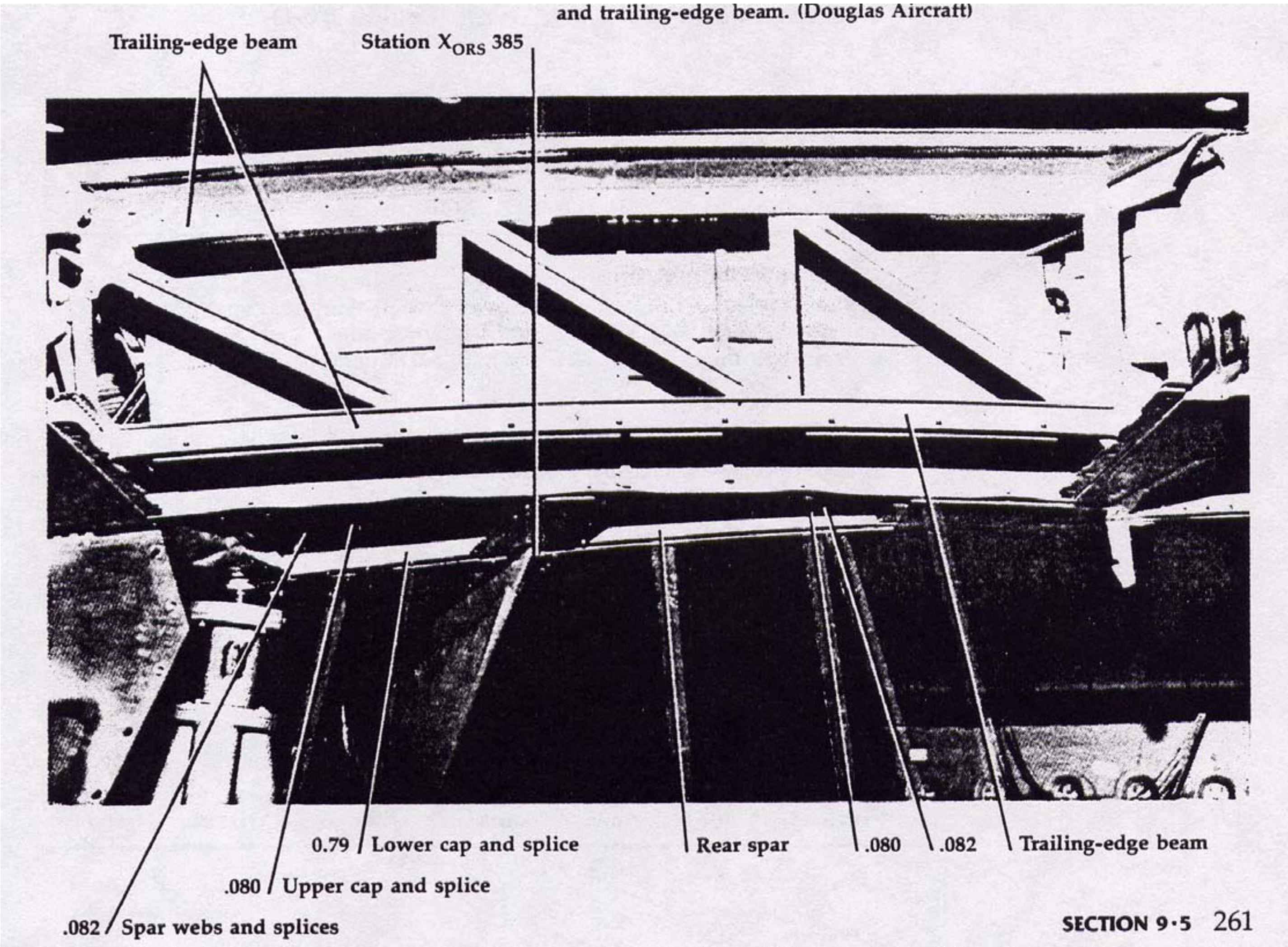



**Exhibit 9-12 A portion of th eDouglas DC-10 outer wing, showing the outer face of hte wing-to-fuselage attach tee (SSI 105). This view is from the left-hand wing, looking inboard at the fuselage (outer fairing removed). (Douglas Aircrafts)**

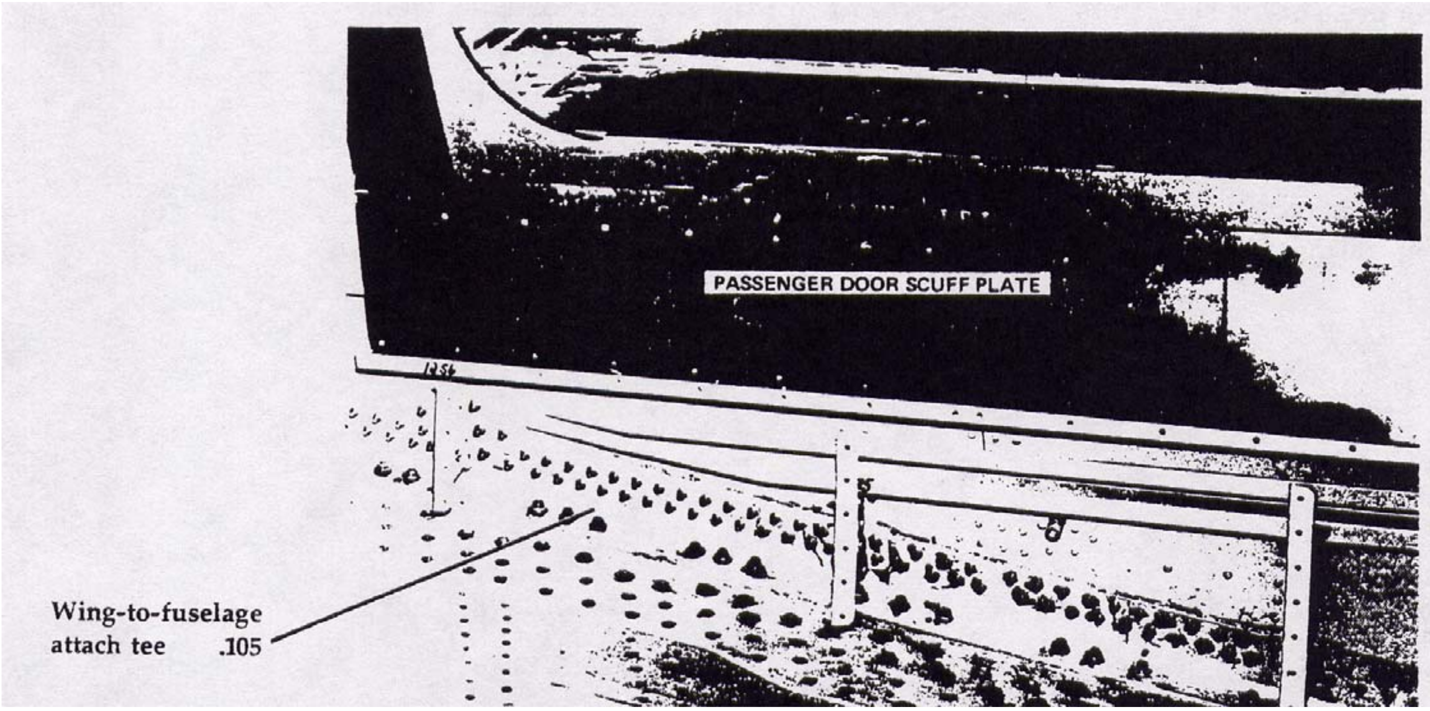



**Exhibit 9-13 A protion of the Douglas DC-10 wing rear spar, showing the lower spar cap and splice (SSI 079). This view is from aft of the left-hand sing, looking forward at the outer-wing rear spar and trailing-edge beam (Douglas Aircraft)**

| | |
|---|---|
| **Structures Worksheet:** type of Aircraft **Douglas DC-10-10** | |
| **Item Number**: 079 | **No. per aircraft:** 2 |
| **Item Name**: Lower spar cap and splice | **Major area:** wing |
| **Vendor part/model no**: 571.04.079/DC10-10 | **Zones:** 541, 641 |
| **Description/location details**: Cap and splice are located on aft lower face of wing rear spar at outer rear spar stations $X_{ORS}$372 to 480; SSI includes aft face of cap and splice, accessible through doors 541HB; 641HB, 541FB, and 641FB | **Design criterion:**<br>Damage tolerant element: Yes<br>Safe-life element: __<br>**Inspection access:**<br>Internal: Yes<br>External: __ |
| **Material (include manufacturer's trade name):** Aluminum alloy 7075-T651 | **Redundancy and external detectability:** Designed for rear tang of spar cap to show first evidence of fatigue; deterioration visible externally (fuel leaks, cracked skin, popped rivets, discoloration) |
| **Fatigue-test data**<br>**Expected fatigue life:** 120,000 hours<br>**Crack propagation:** 15,000 hours<br>**Established safe-life:** ------<br>**Design conversion ratio:** 1.5 operating hours/flight cycle | **Is element inspected via a related SSI? If so, list SSI no.:** Yes. SSI 077 (forward face) SSI 079 (external area)<br>**Classification of item (significant/nonsigniticant):** significant |

| Residual strength | Fatigue life | Crack growth | Corrosion | Accidental damage | Class no. | Controlling factor | Inspection (int./ext) | Proposed task | Initial interval |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3* | 2* | 2 | 4 | 1 | Residual strength | Int. | Detailed visual inspection for corrosion and cracking | Not to exceed 5,000 hours |

Adjustment factors *Increased by 1 for external detectability.

**Exhibit 9-14 Worksheet for the analysis of the lower spar cap and splice onthe wing rear spar of the Douglas DC-10.**

| | |
|---|---|
| **Structures Worksheet:** type of Aircraft **Douglas DC-10-10** | |
| **Item Number**: 077 | **No. per aircraft:** 2 |
| **Item Name**: Lower spar cap and splice | **Major area:** wing |
| **Vendor part/model no**: 571.04.077/DC10-10 | **Zones:** 541, 641 |
| **Description/location details**: Cap and splice are located on forward face of wing rear spar at outer rear spar stations $X_{ORS}$372 to 480; SSI includes forward face of cap and splice, accessible through doors 533 AT; and 633 AT | **Design criterion:**<br>Damage tolerant element: Yes<br>Safe-life element: __<br>**Inspection access:**<br>Internal: Yes<br>External: __ |
| **Material (include manufacturer's trade name):** Aluminum alloy 7075-T651 | **Redundancy and external detectability:**<br>As for SSI 079 |
| **Fatigue-test data**<br>**Expected fatigue life:** 120,000 hours<br>**Crack propagation:** 15,000 hours<br>**Established safe-life:** ------<br>**Design conversion ratio:** 1.5 operating hours/flight cycle | **Is element inspected via a related SSI? If so, list SSI no.:** Yes. SSI 079 (aft face) SSI 077 (external area)<br>**Classification of item (significant/nonsigniticant):** significant |

| Residual strength | Fatigue life | Crack growth | Corrosion | Accidental damage | Class no. | Controlling factor | Inspection (int./ext) | Proposed task | Initial interval |
|---|---|---|---|---|---|---|---|---|---|
| - | - | - | 4 | 4 | 4 | - | Int. | Detailed visual inspection for corrosion and cracking | Not to exceed 20,000 hours (D Check) |

Adjustment factors Ratings for residual stregnth, fatigue life, and crack growth not applicable, covered by SSI 079

**Exhibit 9-15 Worksheet for analysis of th elower spar cap and splice (forward face) on the wing rear spar of the Douglas DC-10.**

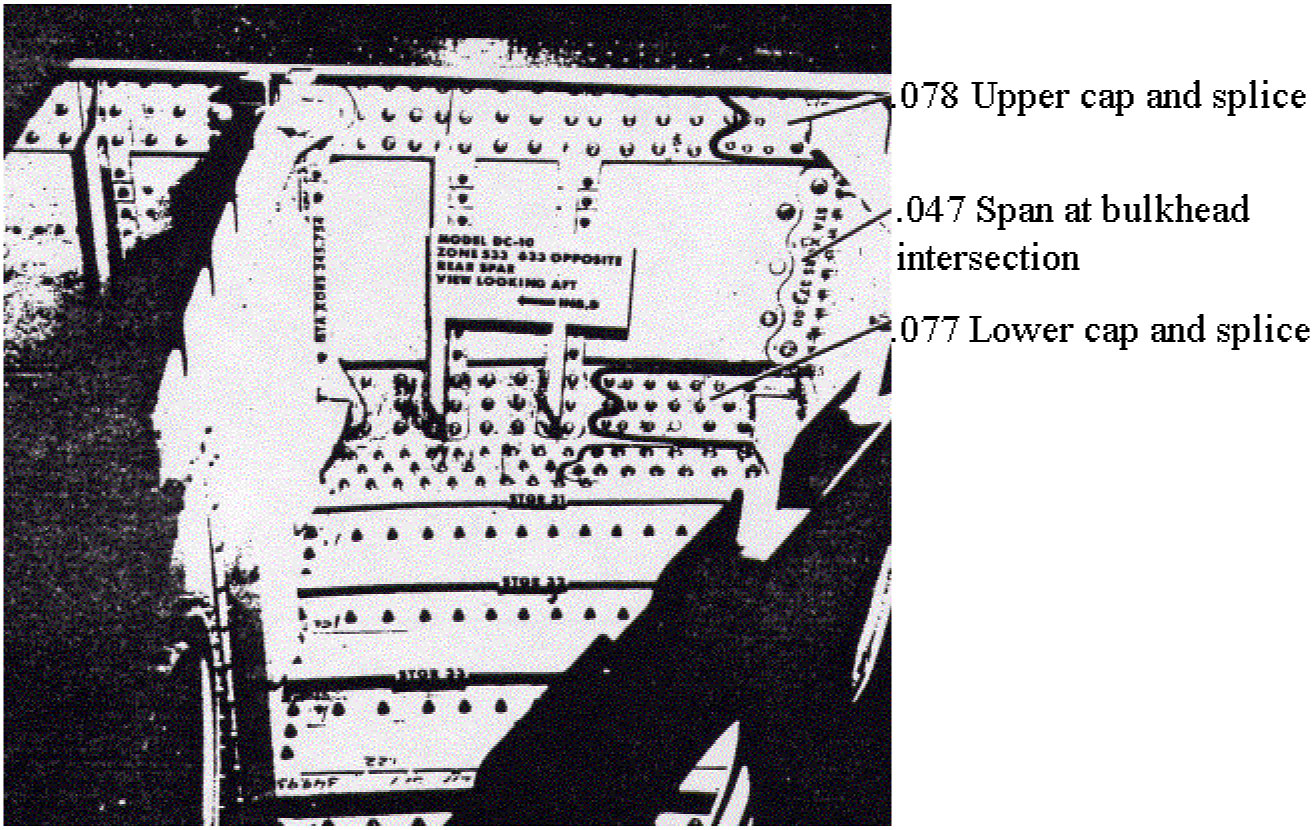



**Exhibit 9-16 A portion of hte Douglas DC-10 wing rear spar, showing the forward face of the lower spar cap and splice (SSI 077). This view is from forward of the left-hand wing, looking aft at the rear spar of the outer wing box (upper panel removed for clarity) (Douglas Aircraft)**

| | |
|---|---|
| **Structures Worksheet:** type of Aircraft **Douglas DC-10-10** | |
| **Item Number**: 101 | **No. per aircraft:** 2 |
| **Item Name**: Shock-strut outer cylinder | **Major area:** main landing gear |
| **Vendor part/model no**: PN ARG 7002-501 | **Zones:** 144, 145 |
| **Description/location details**:<br>Shock-strut assembly is located on main landing gera; SSI consists of outer cylinder (both faces) | **Design criterion:**<br>Damage tolerant element: __<br>Safe-life element: Yes<br>**Inspection access:**<br>Internal: Yes<br>External: Yes |
| **Material (include manufacturer's trade name):** Steel alloy 4330 MOD (Douglas TRICENT 300 M) | **Redundancy and external detectability:**<br>No redundancies; only one cylinder each landing gear, left and right wings. No external detectability of internal corrosion. |
| **Fatigue-test data**<br>**Expected fatigue life:**<br>**Crack propagation:**<br>**Established safe-life:** 23,200 landings 34,800 operating hours<br>**Design conversion ratio:** 1.5 operating hours/flight cycle | **Is element inspected via a related SSI? If so, list SSI no.:** No<br>**Classification of item (significant/nonsigniticant):** significant |

| Residual strength | Fatigue life | Crack growth | Corrosion | Accidental damage | Class no. | Controlling factor | Inspection (int./ext) | Proposed task | Initial interval |
|---|---|---|---|---|---|---|---|---|---|
| - | - | - | 1 | 4 | 1 | Corrosion | Internal | Magnetic-particle inspection for cracking and detailded visual inspection for corrosion | Sample at 6000 to 9000 hours and at 12000 to 15000 horus to establish best interval |
| | | | | | | | External | General inspection of outer surface | During preflight walkarounds and at A checks |
| | | | | | | | | Remove and discard at life limit | 34,800 hours |

Adjustment factors

**Exhibit 9-17 Worksheet for analysis of the outer cylinder o fthe shock-strut assembly, model ARG7002-501, on the Douglas DC-10.**

| | |
|---|---|
| **Structures Worksheet:** type of Aircraft **Douglas DC-10-10** | |
| **Item Number**: 101 | **No. per aircraft:** 2 |
| **Item Name**: Shock-strut outer cylinder | **Major area:** main landing gear |
| **Vendor part/model no**: PN ARG 7002-505 | **Zones:** 144, 145 |
| **Description/location details**:<br>Shock-strut assembly is located on main landing gera; SSI consists of outer cylinder (both faces) | **Design criterion:**<br>Damage tolerant element: __<br>Safe-life element: Yes<br><br>**Inspection access:**<br>Internal: Yes<br>External: Yes |
| **Material (include manufacturer's trade name):** Steel alloy 4330 MOD (Douglas TRICENT 300 M) | **Redundancy and external detectability:**<br>No redundancies; only one cylinder each landing gear, left and right wings. No external detectability of internal corrosion. |
| **Fatigue-test data**<br>**Expected fatigue life:**<br>**Crack propagation:**<br>**Established safe-life:** 46,800 landings 70,200 operating hours<br>**Design conversion ratio:** 1.5 operating hours/flight cycle | **Is element inspected via a related SSI? If so, list SSI no.:** No<br>**Classification of item (significant/nonsigniticant):** significant |

| Residual strength | Fatigue life | Crack growth | Corrosion | Accidental damage | Class no. | Controlling factor | Inspection (int./ext) | Proposed task | Initial interval |
|---|---|---|---|---|---|---|---|---|---|
| - | - | - | 1 | 4 | 1 | Corrosion | Internal | Magnetic-particle inspection for cracking and detailded visual inspection for corrosion | Sample at 6000 to 9000 hours and at 12000 to 15000 horus to establish best interval |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | External | General inspection of outer surface | During preflight walkarounds and at A checks |
| | | | | | | | | Detailed visual inspection for corrosion and cracking | Not to exceed 1,000 hours (C check) |
| | | | | | | | | Remove and discard at life limit | 34,800 hours |

**Exhibit 9-18 Worksheet for analysis of the otuer cylinder of the shock-strut assembly, model ARG 7002-505, on the Douglas DC-10.**

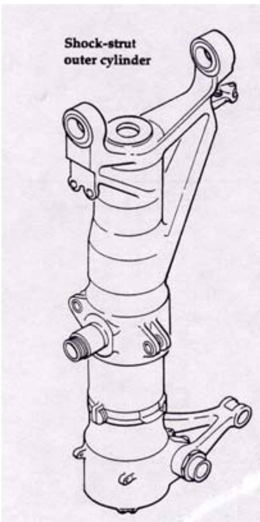



**Exhibit 9-19 The shock-strut assembly on the main landing gear of the Douglas DC-10. The outer cylinder is a structurally significant item; the rest of the assembly is treated as a systems item. (Based on Douglas DC-10 maintenance materials)**

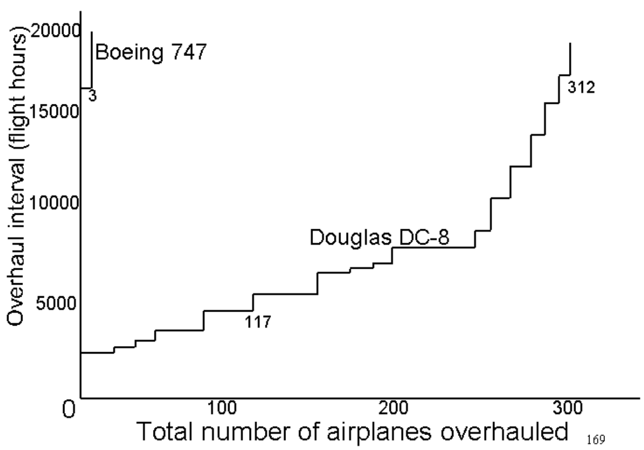



**Exhibit 9-20 The number of heavy structural inspections (overhauls) required to reach the same maximum interval under different maintenaance policies. The figures shown for the Douglas DC-8 indicate the total number of overhauls performed up to the time of an interval extension. The very initial interval for this airplane was extended slowly until a change in maintenance concepts occurred. The intial interval for the Boeing 747 was established after thsichange in concept, and only three heavy inspections were required to reach a 20,000-hour interval. (United Airlines)**

# 9.6. Structural Age Exploration

In the systems and powerplant divisions the consequences of many functional failures are economic and do not involve safety. Thus little attempt is made to predict those reliability characteristics that cannot be determined until after the equipment enters service. Instead, the default strategy is employed, and additional tasks are incorporated in the scheduled-maintenance program only after there is sufficient oper- ating information to assess their economic desirability. In the analysis of structural items, however, the determination of inspection intervals for damage-tolerant structure is based on an assessment of the effect of failures on residual strength, the relationship of fatigue-test results for individual items to the design goal for the overall structure, crack- propagation characteristics, and the anticipated rate of corrosion. All these assessments involve some degree of prediction. The results are therefore treated very conservatively, not only because they are extra- polations from test data, but also because manufacturing variations, differences in operating environments, and different loading histories may lead to wide variations in fatigue life from one airplane to another.

In all cases there will be differences between the manufacturer's test environment and the environment in which a given fleet of ir- planes is actually operated. If different airplanes in the fleet are to be assigned quite different types of missions or will be operating in dif- ferent types of environments, it may be advisable to develop a separate set of inspection intervals for each kind of operation and implement these tailored programs from the outset. Any initial structure program, however, merely specifies the start of age exploration for each item to determine its actual fatigue characteristics. The program includes all the inspection tasks necessary to protect the structure, but it is the results of these inspections after the equipment enters service that will determine the intervals to be used during continuing operation.

Until fairly recently structural inspection programs did not take into account the explicit role of the inspections themselves in the age- exploration process. The heavy structural inspections, the work package that includes all the inspection tasks in the program, were often the major part of what was called an "airplane overhaul"- an unfortunate term, since it implies that something can be done to restore the struc- ture to like-new condition. Although the repair of damage found during such inspections will restore the original load-carrying capability, there is no form of remanufacture that will zero-time the effects of fatigue. The so-called overhaul, therefore, could have no effect on the operating age at which fatigue cracks might appear.

Under older policies a fairly large proportion of the fleet was given a full structural inspection at a low age (2,500 hours in the case of the Douglas DC-8), the inspection findings were assessed, and the proce- dure was then repeated at a slightly longer interval. At all times, how- ever, the emphasis was on the time since the last inspection, not on the total operating age of the airplane. As a result, 117 such inspections were performed on one fleet of Douglas DC-8's before the overhaul interval was extended beyond 5,000 hours, and of the 32 overhauls performed at the 5,000-hour limit, 9 represented the fourth overhaul and 16 the third overhaul for individual airplanes (see Exhibit 9.20).

The density of inspections performed under this policy varied from item to item; some items were inspected at every overhaul, some at every second overhaul, and so on. This procedure was explicit recog- nition of the fact that some items were more significant than others and that the exposure to deterioration varied from item to item. The con- cept of sampling is still employed in the age exploration of internal structural items with a high class number. This and other aspects of structural age exploration are discussed in detail in Chapter 11.
Since the airplanes in any given fleet will have entered service over a period of years, the difference in operating age between the oldest and the youngest airplane may be as much as 30,000 hours. As it became clear that the oldest members of the fleet were more likely to provide new information about fatigue damage, inspection emphasis shifted to what is often termed the fleet-leader concept, concentration of heavy structural inspections of the airplanes with the highest total time. This approach not only provides the same amount of information in the shortest calendar time, but identifies the age at which fatigue damage is likely to appear before the younger aircraft reach this age limit. Thus it is possible to perform fleetwide inspections for damage while it is still in its early stages and also to develop design modifications that will extend the fatigue life of the structural areas involved. The result of this change in concept was much more rapid extension of overhaul intervals and fewer such overhauls performed on aircraft too young to provide the necessary information.

As the structure ages in service the intervals for many individual items will be adjusted to ensure that deterioration is found as early as possible, and some items that are unacceptably short-lived may have to be modified to increase their fatigue lives. In general, however, the state of the art is now such that the designer can often establish quite meaningful predictions of fatigue life, and as these predictions have been borne out by experience, there has been a tendency to begin age exploration at increasingly higher ages with each new design.

# 10. Chapter Ten - Completing the maintenance program

THUS FAR we have been concerned with scheduled-maintenance tasks generated by explicit consideration of failure consequences and the inherent reliability characteristics of each item. These tasks comprise the major portion of the total scheduled-maintenance program, but not all of it. The set of tasks identified by RCM analysis is supplemented by certain other scheduled tasks which are both so easy to perform and so obviously cost-effective that they require no major analytic effort. Five common categories of such additional tasks are zonal-installation inspections, preflight walkaround inspections, general inspections of external structure, routine servicing and lubrication, and regular testing of functions that are used only intermittently by the operating crew.

Zonal inspections, preflight walkarounds, and general inspections of external structure are not directed at any specific item and hence can- not in themselves be considered RCM tasks. However, they often serve as a vehicle for specific on-condition or failure-finding tasks. Servicing and lubrication tasks do in fact fit RCM decision logic, but their bene- fits are so obvious that the cost of analysis is not worthwhile. In con- trast, the testing of infrequently usedfunctions merely takes advantage of the scheduled-maintenance program to supplement the failure- reporting duties of the operating crew.

Once all the scheduled tasks have been assembled, we must turn our attention to the problem the maintenance organization faces in scheduling and controlling the accomplishment of the work. It is pos- sible, of course, to schedule each of the hundreds of different tasks at the optimum interval for each item. It may even be desirable to do so if the fleet is very small and the opportunities for scheduled mainte- nance are very frequent. In most cases, however, it is necessary to group the tasks into a fairly small number of work packages so that they can be consolidated at a few maintenance stations and do not interfere with scheduled use of the equipment. Although this procedure results in shorter intervals than necessary for a great many individual tasks, the additional cost is more than offset by the overall increase in efficiency. There is no single optimum way of packaging tasks, since the overall cost of the maintenance process depends on such factors as organiza- tional structure, maintenance resources and facilities, and operating requirements.

This chapter discusses the additional work, beyond RCM analysis, that is required to complete an initial scheduled-maintenance program.

## 10.1. Other scheduled-maintenance tasks

ZONAL-INSTALLATION INSPECTIONS

Zonal inspections are based on the three-dimensional reference system required to identify the physical location of any item on an airplane. The entire airplane is considered to be partitioned into discrete spaces, or zones, usually bounded by physical features such as floors, bulk- heads, and outer skins. The specific zones in each type of airplane are designated by the manufacturer, usually at the design stage, and are then carried through to all reference material on maintenance for that particular design. Exhibit 10.1 shows the zonal reference system used for the McDonnell F4J and Exhibit 10.2 shows a portion of the Boeing 747 zonal system.

The various assemblies and connecting lines (wiring, hoses, duct- ing, attach fittings) of the aircraft systems that are in each zone are re- ferred to as zonal installations. In some cases, such as the cockpit area, the whole zone is readily accessible. More often, however, a zone must be entered by some access door in the outer surface so that mechanics can inspect, repair, or replace the various installations. Consequently zonal installations are subject not only to the normal wear and tear of use, but also to accidental damage from the traffic of mechanics and other per- sonnel in the zones. In the interests of prudence, therefore, a separate zonal inspection program is needed to complement the program of RCM tasks.

Although zonal inspections are directed primarily at the installa- tions in each zone, they also include general inspections of those por- tions of the internal structure that can be seen with the installations in place. These inspections are relatively nonspecific checks on the secur- ity of installed items- to detect loose or missing parts or parts that may rub against each other-checks for any accidental damage, and a quick survey for obvious leaks. In some cases the number and location of the access doors govern the amount of a zone that is inspected. These inspections do not qualify as on-condition tasks, since they are not directed at a specific failure mode, except where leaks have been de- fined as a failure condition for a given item. However, they are very inexpensive to perform and provide an opportunity to spot early signs of problems developing in the systems. Thus they are cost-effective if they result in even a small reduction in repair costs or identify a poten- tial failure at a time that avoids operational consequences.

In current practice the intervals assigned to zonal inspections are judgmental, although they are based on a general consideration, zone by zone, of susceptibility and failure consequences. In this case suscep- tibility refers to the overall vulnerability of the installations within a zone to damage, loss of security, and leaks (which we can construe as the probability of failure for the zone), and failure consequences refers to the ultimate effect of not detecting and correcting the conditions that could be discovered by a zonal inspection. These effects include the consequences of a functional failure (even the absence of emergency equipment in the event of an emergency), a more advanced potential- failure stage, or a multiple failure that might have been avoided by the inspection.

The interval for some zones may be very short. The cockpit of an airplane, for example, contains many items of emergency equipment, and since it is subject to heavy traffic by members of the operating crew, the cabin crew, and the maintenance crew, these items are all susceptible to damage. The consequences of not having this equipment in position and serviceable if it is needed are also very serious. These considerations lead to intervals as short as 20 hours and never longer than 200 hours (the usual A-check interval) for zonal inspections of this area. These inspections are often complemented by additional inspections that are part of the crew duties. At the other end of the scale, zones that contain no system installations are inspected at D-check intervals (20,000 hours or more). These inspections are for the sole pur- pose of looking at the nonsignificant portions of the internal structure within these zones.

While the intervals for zonal inspections are based on general assessments, rather than a comprehensive analysis of specific data, it is sometimes helpful to rate each zone for susceptibility and conse- quences and then assign class numbers, much like the rating scheme used to establish intervals for structurally significant items (see Section 9.2). The considerations in rating a zone for susceptibility to trouble would include:

- The number and complexity of installed items in the zone
- The susceptibility of individual items to deterioration of one kind or another (damage due to corrosion, heat, or vibration, for example, will usually depend on the location of the zone)
- The traffic in the zone that might cause damage, including the relative frequency of access for on-condition tasks and the replacement or repair of failed items

As with structural items, a scale of 1 to 4 is used to rate susceptibility and consequences separately for the zone in question:

| susceptibility | consequences | rating |
|---|---|---|
| High | Serious | 1 |
| Moderate | Moderate | 2 |
| Low | Minor | 3 |
| None | None | 4 |

In this case none means that there are no system installations in the zone. Such zones are still given a rating, however, since the zonal inspection program is the vehicle that ensures general inspections of nonsignificant internal structural items. (Structurally significant items are covered by the basic structure program, as described in Chapter 9.) The ratings for both factors are, of necessity, a matter of experience and judgment. Although consequences are taken into account, the evalua- tion is a very broad one and is not based on detailed examination of the reliability characteristics of each item, as is the case in developing a set of RCM tasks.

The lower of the two ratings is the class number for the zone and determines the relative frequency of zonal inspections: the lower the class number, the shorter the inspection interval for that zone. The intervals themselves depend on further subjective considerations of de- sign characteristics, operating environment, and the flight hours logged during a given operating period.

The zonal inspection program is usually developed by a separate working group, and the results must be integrated with the scheduled tasks developed by the systems and structure groups to eliminate gaps and overlaps between the two programs.

WALKAROUND INSPECTIONS

Walkaround inspections are general visual inspections performed at the ground level to detect any obvious external damage. This may be accidental damage caused by contact with other aircraft, ground equip- ment, buildings, or debris thrown up from the runway, or it may be loose fittings or leaks from the various fluid lines. These checks are performed by the maintenance crew before each departure from a main- tenance station and often incorporate simple on-condition tasks, such as a check of the brake wear indicators and specific checks of the struc- tural areas expected to show external evidence of internal structural damage. There may also be independent preflight inspections by a member of the operating crew. In some military operations walkaround checks are performed both before and after each flight.

Walkaround inspections not only detect failures with minor con- sequences, but often provide the first indication of an impending en- gine or structural failure. A simple diagram like that in Exhibit 10.3 is usually included in the maintenance manual to identify the portions of the airplane where damage is most likely to be found.

GENERAL EXTERNAL INSPECTIONS

General inspections of the external structure are similar to the inspec- tions performed during walkarounds, except that they include those portions of the structure that cannot be seen from the ground. Inspec- tion of the vertical tail and the upper surfaces of the wings and fuselage requires the use of scaffolding that is part of the hangar dock. Conse- quently these inspections are performed at intervals corresponding to those of work packages that require hangar facilities.

SERVICING AND LUBRICATION TASKS
The scheduled-maintenance program also includes the periodic servic- ing and lubrication tasks assigned to various items on the airplane. Ser- vicing includes such tasks as checking fluid reservoirs and pressures and replenishing or adjusting them as necessary, replacing filters, adding nitrogen to tires and landing-gear struts, and so on. Each of these tasks could be generated by RCM analysis (see Section 3.6), and sometimes they are.More often, however, the tasks are simply scheduled as recommended by the aircraft, powerplant, or system manufacturer, since their cost is so low in relation to the obvious benefits that deeper analysis is not warranted.

All servicing and lubrication tasks tend to involve the replace- ment of consumables, where it is expected that the need will be time- related. Although such tasks are usually assigned conservatively short intervals, the tasks themselves are so inexpensive that effort is rarely spent on age exploration to find the moit economical interval.

TESTING OF RARELY USED FUNCTIONS
Much of the scheduled-maintenance program hinges on the fact that the operating crew will detect and report all evident functional failures. In some situations, however, an evident function may be utilized infre- quently or not used at all during certain deployment of the aircraft. Such functions are not hidden in the strict sense of the word, since a failure would be evident during the normal performance of crew duties. Rather, they are hidden only when they are not being used. Under these circumstances the scheduled-maintenance program is a convenient vehi- cle for periodic tests to ensure their continued availability.

This continued availability is especially important for multiple- role equipment subject to sudden changes in operational use. One obvious example is an airplane all of whose scheduled flights fall in the daylight hours. In this case it is necessary to include tests of the landing lights, cockpit lights, and other items used for nighttime operation in the maintenance program, since actual use of these functions by the operating crew will not constitute an adequate failure-reporting system. The inverse of this situation-the extension of crew duties to cover tests of certain hidden-function items-usually applies in any operating context; hence it is taken into account during RCM analysis (tests by the operating crew make the failure evident). However, the need for inspec- tion tasks to cover rarely used functions depends on the actual use of the equipment, and such tasks must ordinarily be added to the program on an individual basis by each operating organization. Where the air- planes in a fleet are used under different sets of operating conditions, these tasks may be required for some members of the fleet, but not for others.

EVENT-ORIENTED INSPECTIONS
There are special inspections that are not scheduled in the ordinary sense, but must be performed after the occurrence of certain unusual events. Typical examples are hard-landing and rough-air inspections of the structure and overtemperature and overspeed inspections of engines. These are all on-condition inspections of the specific sig- nificant items which are most likely to be damaged by the unusually severe loading conditions.

## 10.2. Packaging the maintenance workload

All the task intervals we have discussed so far have been based on the individual requirements of each item under consideration. The control of these individual tasks is greatly simplified by grouping the tasks into work packages that can be applied to the entire aircraft, to an installed engine, or to a removable assembly. In many cases the study groups developing each segment of the program will have anticipated the pack- aging procedure; thus individual tasks may be specified for an inter- val that corresponds to the preflight walkaround or to the A-check or D-check interval. In some cases a maximum interval is specified in hours or flight cycles as well, and the grouping of tasks must ensure that each task will be performed at some time within this limit.

Generally speaking, the tasks that have the shortest intervals are servicing tasks and simple inspections such as the walkaround checks, which do not require specialized training, equipment, or facilities. Thus the smaller maintenance packages are generally called service checks. A #1 service check may be a group of tasks that can be per- formed at every stop at a maintenance station, and a heavier #2 service check, amounting to 2 or 3 manhours of scheduled work, may be per-formed during every long layover if the airplane has flown more than 20 hours since the preceding #2 service. The major work packages, called letter checks, are performed at successively longer intervals (see Exhibit 4.11 in Chapter 4). Each letter check incorporates all the work covered by the preceding checks, plus the tasks assigned at that letter- check interval. Thus each one requires an increasing amount of man-power, technical skills, and specialized equipment.

Although the intervals for letter-check packages are customarily expressed in terms of operating hours, some organizations may prefer to convert them to calendar time based on average daily use of the equipment. Packages would then be designed to include tasks to be performed once a day, once a week, once a month, and so on. Similarly, the operator of a small fleet-say, two airplanes-may not want to be faced with a very heavy intermittent workload of two C checks a year, each requiring an expenditure of perhaps 2,000 manhours. He may prefer instead to distribute the C-check tasks among the more frequent checks, with a different group of C-check tasks performed at every A and B check. It is also possible to work out nightly packages with equal- ized work content by distributing the A and B packages as well. In this case, although the workload will be relatively constant, the actual tasks to be performed will vary greatly from night to night, making control of their accomplishment more difficult.

Even when the letter-check packages are not broken up in this way, their content will not necessarily be the same each time they are per- formed. For example, a task that has a long interval but is not time- consuming may be assigned to one of the more frequent letter checks but scheduled only for every second or every fourth such check. Con- versely, a group of tasks that are especially time-consuming may be distributed among successive letter checks of the same designation, or there may be items that are monitored independently and scheduled for the time of the nearest check regardless of its designation. Conse- quently the actual tasks performed will often differ greatly for the same letter check from one visit of the airplane to the next.

Usually the objective in packaging is to consolidate the work into as few check intervals as possible without unduly compromising the desired task intervals. Some maintenance organizations attempt to make the interval for each higher check a multiple of the lower checks. This has the advantage of simplicity, but the necessity of maintaining the geometric relationship penalizes workload scheduling. One method of relating each check to the next higher check is illustrated in Exhibit 10.4. In this case the intervals are arranged to overlap as follows:

- The#2 service check includes a #1 service check and therefore zero-times the #1 check.
- The A check inclu.des a #2 service check and zero-tirnes it.
- The B check includes the next A check due and zero-times all the A-check tasks performed.
- The C check includes the next B check due and zero-times all the B-check tasks performed.
- The D check includes the next C check due and zero-times all the C-check tasks performed.

Alternatively, the C check might be divided into four smaller pack- ages, with one of these packages assigned to each B check. The check that combines B- and C-check tasks is often called a phase check. Whereas a full C check would take the airplane out of service for 24 hours, it may be possible to accomplish a phase check in an elapsed time of 10 or 12 hours. When the C-check tasks are distributed in this way, the D-check includes the next phase check and zero times the tasks in that phase check.

The first step in assembling the tasks for each letter-check package is to establish the desired letter-check intervals. In an initial program these intervals, like the task intervals themselves, are highly conserva- tive. The next step is to adjust the intervals for individual tasks to cor- respond to the closest letter-check interval. Whenever possible, poor fits should be accommodated by adjusting the task interval upward; otherwise the task must be scheduled at the next lower check or multiple of that check. As an example, the initial interval assigned to a corrosion-control task for the internal fuselage lower skin of the Boeing 747 was 9,000 hours. The inspection is essential to protect the bilge areas of the plane from corrosion, but this interval would have necessitated a separate visit to the maintenance base for a single task. Since the inter- val represented a conservative value in the first place, some flexibility was considered allowable, and it was decided that the interval could safely be extended to 11,000 hours, which coincided with a group of tasks scheduled for a midperiod visit at half the D-check interval.
Exhibit 10.5 shows a partial list of the scheduled tasks included in each letter check for the Boeing 747. Note that this program employed phase checks in place of a C-check work package. When phase checks are used there is no real C check, in the sense of a group of tasks all of which are to be performed at the same time. It is helpful to refer to a phantom C check, however, to develop the content of the phase-check packages, and the tasks of the phantom C check have the desired inter- val if they are performed at every fourth phase check.

Exhibit 10.6 shows sample tasks from a somewhat different pack- aging scheme for the McDonnell F4J. This program was designed for a military context, but it includes several of the packaging features found in its commercial counterpart. For example, the work package designated as the maintenance check is actually spread out over six lower-level phase checks, much like the series of phase checks performed at the B-check interval on the Boeing 747.

Both the task intervals and the package intervals in an initial pro- gram are subject to age exploration. Usually the intervals for individual tasks are increased by extending the package intervals, as discussed in Section 4.6. When a maximum interval is identified for a specific task, the task will either be assigned to a different letter-check package or, if it is a task that controls the rest of the package, the check interval will be frozen.

# 11. Chapter Eleven - The use of operating information

Age exploration, the process of determining the reliability characteristics of the equipment under actual operating conditions, begins the day a new airplane enters service. This process includes monitoring the condition and performance of each item, analyzing failure data to identify problems and their consequences, evaluating inspection findings to adjust task intervals, and determining age-reliability relationships for various items. Since the decision process that led to the initial scheduled-maintenance program was based on prior-to-service information, the program will reflect a number of default decisions. As operating experience begins to produce real data on each item, the same decision logic can now be used to respond to unanticipated failures, assess the desirability of additional tasks, and eliminate the cost of unnecessary and over intensive maintenance resulting form the use of default answers.

In the preceding chapters we considered certain aspects of age exploration as they relate to task intervals and the intensive study of individual items in the systems, powerplant, and structures division. In a broad sense, however, age exploration encompasses all reliability information on the aircraft as it ages in service. Thus the heart of an ongoing maintenance program is the collection and analysis of this information, either by the engineering organization or by a separate group.

## 11.1. Typical Information Systems

Although intensive age exploration of individual items plays a direct role in assessing their maintenance requirements, this is only one of many sources of reliability information. In the case of airplanes it is also not the information of most immediate concern. In order to respond to unanticipated problems, an operating organization must have some means of identifying those that require first priority. On this basis the airline industry ranks the various types of reliability data according to the priority of failure consequences and is generally concerned with information in the following order:

1. Failures that could have a direct effect on **safety**
2. Failures that have a direct effect on **operational** capability, either by interrupting the flight or by restricting its continuation
3. The failure modes of units removed as a result of **functional** failures
4. The causes of potential failures found as a result of on-condition **inspections**
5. The general condition of **unfailed** parts in units that have failed

- The general condition of parts in units removed specifically for **sampling** purposes.

The order of importance is consistent with the priorities underlying the RCM distinctions between necessary and economically desirable scheduled-maintenance tasks.

The data needed to manage the ongoing maintenance program must usually be extracted from a number of information systems, some of which were established for purposes quite different from that of supplying data to maintenance analysis. As a result, it is sometimes a laborious process to assemble all the information elements needed for maintenance decision. Most information systems can be classified according to three basic characteristics.

- *Event-oriented systems* collect and record data whenever an undesirable event occurs. Such systems range from a plan for immediate telephone communications between designated executives in the event of any failure that involves safety considerations to a system for recording unsatisfactory conditions found during scheduled inspections.

- *Monitoring systems* summarize data about some aspect of the operation during a specified calendar period.. The data are extracted from event-oriented systems and are summarized in reports such as the monthly premature-removal report, the monthly delay-and-cancellation report, and so on. These reports are prepared regardless of the occurrence of any reportable events; thus they give positive information about the absence of problems as well as information on any problems that have occurred.

- *Analysis systems* not only collect, summarize, and report data, but also give the results of some special analysis of the information. This might be an actuarial analysis, a determination of the 20 items with the highest premature-removal rates, or some other specific analysis.

| S. Officer | S. Officer | JFK | | | | |
|---|---|---|---|---|---|---|
| | Flight crew make entries in white area | Indicate work accomplished | | | Maintenance release signatures | Station |
| | | Enter ✓ | Enter initial | Enter no. | | |

| Airplane Flight Log | K | Other | T&B | #15VC | #25VC | A | B | C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | LM | | | | | 1 | L. Mechanic | ORD |
| | | | | NT | | | | | 2 | N. Turner | DEN |
| | | | | | | | | | 3 | | |
| | | | | | | | | | 4 | | |
| | | | | | | | | | 5 | | |
| | | | | | | | | | 6 | | |
| | | | | | | | | | 7 | | |
| | | | | | | | | | 8 | | |

| Flt no & Date | Max | Act | Gallons Boarded | Block Dept | Bl arr | From | To | Max. cruise altitude | Off | On | Hrs | Min | Check whether or not service required |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28757 | 1.85 | 1.79 | 3969 | 43.2 | 20.6 | JFK | ORD | 39.0 | 1255 | 1445 | 1 | 50 | |
| 28757 | 1.90 | 1.79 | 4705 | 50.8 | 23.7 | ORD | DEN | 39.0 | 1557 | 1804 | 2 | 07 | |
| 28757 | | | 1810 | 34.9 | 22.8 | DEN | SLC | 39.0 | 1950 | 2050 | 1 | 00 | |
| TSO Start | 1705504 | | TSO End | | | 1706001 | | | Trip Time | | 4 | 57 | |

| Item no. | Discrepancy | Fault isolation code | Item no. | Station | Corrective Action | Def. no. new | Def. No. corr. |
|---|---|---|---|---|---|---|---|
| | | | | ORD | ----DOM----- | --- | ---- |
| 1 | Precautionary shutdown of #1 eng acct. fluctuating oil press., oil press light on, high oil temp. Windmilling time: 25 min. Shutdown oil press.: 10-20 psi. | | 1 | SLC | Pulled accy. case; oil strainer, scavenge oil screen, main oil screen found ok. Refilled oil tank. Ran engine. No leaks. Ok for service per SFOLM A. Controller | | |
| 2 | Had to use continuous ignition to start #2 Eng. | | | SLC | Recheck #1 Eng main oil screen in 50 hrs. by TSO 17110:01 per SFOLM A. Controller | 277 | |
| | | | 2 | SLC | OK to cont Def. per SFOLM A. Controller | 278 | |
| | | | 2 | SLC | Replaced exciter box – B. Mechanic DENMM | | 278 |

**Exhibit 11-1. Log sheet from an airplane flight log. The flight log shows any unsatisfactory conditions reported by the operating crew.**

One of the most important information systems is the airplane *flight log*. The primary purpose of this log is to record the operating and maintenance history of each airplane. Such information as the flight number, the names of the crew members, fuel on board at takeoff, oil on board at takeoff, takeoff time, landing time, and observed engine performance parameters and vibration levels are always recorded. In addition, any instances of unsatisfactory conditions observed during the flight are entered on the log sheet to alert the maintenance organization to the need for corrective maintenance (see Exhibit 11.1). The maintenance crew also uses the log to record the repairs made as a result of these reports, to record the performance of scheduled tasks, and by signing a maintenance release, to certify the airplane's airworthiness. Copies of recent log sheets are kept in the airplane for review by the operating crew, and the older sheets are sent to a permanent central file.

Another event-oriented system is the *aircraft maintenance information system* which keeps track of all the scheduled-maintenance tasks performed at each line station and the manhours required for each one, as well as the time spent on corrective work as a result of crew-reported failures or conditions discovered during performance of the scheduled tasks. Some of the larger airlines have computerized this system and enter the log-book failure reports into it as additional data. This allows a maintenance station to determine what deferred repairs are going to be necessary for an arriving airplane. However, this real-time on-line system is still in the early stages of development.

The *daily operations report* is both a monitoring and an event oriented system. Among other things, it provides a brief narrative description of any unusual flight incident, flight interruption, delayed departure, or cancelled flight that has occurred during the preceding 24-hour period.

Data associated with premature removals are reported by means of *identification and routing tags* another event-oriented system. A tag attached to the unit that is removed records the removal information and information on the replacement unit and then routes the removed unit back to a maintenance base (see Exhibit 11.2). The tag stays with the unit throughout the repair process and is then filed for future reference. When a major assembly, such as an engine or landing gear, reaches the shop for rework, additional tags are generated for any sub-assembly that is removed and routed to another shop.

Some of the event-oriented systems are complemented by monitoring systems. For example, data are extracted periodically from the identification and routing tags to show the premature-removal rates of significant items. Similarly, data extracted from the daily operations report for the monthly summary of delays and cancellations identify the associated failures on a periodic basis.

There are additional information systems designed to ensure that there will be a record of all adverse findings during every inspection performed, as well as a record of any corrective work done as a result of such findings. While this information is available on all items subject to scheduled tasks, the data may be difficult to retrieve. For this reason it is common practice to designate certain units as *time-extension samples* when an increase in task intervals is being considered and to pay particular attention to data gathering for these samples.

In many cases it is relatively easy to review the data and decide whether a change in the scheduled-maintenance program would be desirable. If it takes a long time to repair a certain type of failure, and scheduled flights must therefore be cancelled, the economic justification for a preventive task is apparent – particularly if the failure is one that occurs frequently. And if no preventive tasks are applicable to an item, there is no point in adding them, regardless of the operational consequences of the failures (there may, of course, be a point in redesigning the item). Sometimes, however, when a functional failure might or might not have operational consequences, depending on the circumstances, it may be necessary to retrieve information from a number of different sources to gain a clear picture of the problem.

Suppose, for example, that the daily operations report, or perhaps the monthly summary of delays and cancellations, indicates that failures of a particular system item are causing a fairly large percentage of delayed departures. Under these circumstances the maintenance organization would investigate to see whether these consequences can be alleviated. The first step is to review the delay-and-cancellation summaries for the past several months to obtain a broader[based statistic on the delays. It is then necessary to go back to the daily operations report to find out the actual length o f the delay and the assembly or assemblies involved in most of the failures.

| **Identification and Routing Tag** | |
|---|---|
| Plane no. | 7567 |
| Plane TSO | 13766 |
| Date | 1/22/75 |
| Station | SEA |
| Date servicable | 1/20/75 |
| Quantity | 1 |
| Why was unit removed? | Suspect. failure |
| Detailed reason for removal | No brightness |
| What caused failure? | Picture tube 86718 |
| Enter remarks about serviceable unit only in this area | |
| Enter remarks about repairable units in this area | Replace. DST acct. Bad |

**Exhibit 11-2. An identification and routing tag showing the unit removed from the airplane, the reason for removal,**

**verification of the problem, and disposition of the unit. (United Airlines)**

Once the dimensions of the delay problem have been established, the next step is to determine whether failures are evident to the operating crew, and if so, what is being reported in the flight log as evidence of failure. It is always possible that the definitions of satisfactory performance are so demanding that the cost is greater than the benefits. The log sheets may also supply some information on the assemblies that are failing, but the best source of this information is the aircraft maintenance information system. This system will show whether corrective maintenance involves replacing failed units, and if so, the frequency of replacement and the line-station cost of the work. The frequency of repairs may be much higher than the frequency of operational delays; for example, failures on airplanes inbound to overnight layovers would have no operational consequences.

| Top 20 premature removals | | | | | | |
|---|---|---|---|---|---|---|
| Type of aircraft | Boeing 727 | | | Period | April-June 1978 | |
| **Premature removal rank** | **Maintenance records No.** | **name** | **No. of premature removals** | **Premature removal rate (per 1000 unit hours)** | **No. of verified failures** | **Percent of verified failures** |
| 1 | 21392 | Control, cabin pressure | 56 | 3.28 | 18* | 32 |
| 2 | 43132 | Indicator, WX radar | 189 | 1.85 | 66* | 35 |
| 3 | 42210 | Receiver, VHV navigation | 71 | 1.68 | 5* | 7 |
| 4 | 25342 | Dispenser, coffeemaker | 368 | 1.59 | 171* | 46 |
| 5 | 43122 | Accessory unit, WX radar | 161 | 1.58 | 14* | 9 |
| 6 | 43112 | Transmitter/receiver, WX radar | 151 | 1.48 | 73 | 48 |
| 7 | 41701 | Indicator, standby attitude (SAI) | 13 | 1.28 | 4 | 31 |
| 8 | 23711 | Recorder, cockpit voice | 124 | 1.22 | 82 | 66 |
| 9 | 41134 | Computer, their data | 31 | 1.14 | 21 | 68 |
| 10 | 42252 | Receiver, VHF nav/glidescope | 22 | 1.08 | 1 0* | 45 |
| 11 | 31212 | Recorder, flight data | 104 | 1.02 | 40 | 38 |
| 12 | 33496 | + Light, anti-collision | 10 | .98 | 5* | 50 |
| | 33495 | - included with 33496 | | | | |
| 13 | 22113 | Channel-pitch control | 26 | .96 | 6 | 23 |
| 14 | 43511 | Transmitter/receiver, radio altimeter | 95 | .93 | 23 | 24 |
| 15 | 23311 | Amplifier, public address | 66 | .88 | 12* | 18 |
| 15 | 23501 | Accessory unit, audio | 15 | .88 | 1* | 7 |
| 16 | 22305 | Controller, pedestal | 64 | .86 | 23* | 36 |
| 17 | 41294 | Battery box, SAI system | 87 | .85 | 46* | 53 |
| 18 | 41135 | Altimeter, electric | 17 | .84 | 3* | 18 |
| 19 | 21329 | Controller, cabin pressure auto | 61 | .82 | 19* | 31 |
| 20 | 41193 | Computer, your data | 59 | .79 | 16* | 27 |

**Exhibit 11-3. Premature-removal "top-20" report. This information, extracted from the monthly premature-removal report, lists data on the 20 items with the highest premature-removal rates. Note that this report also shows the number of premature removals that were terrified as functional failures. (United Airlines)**

If the failures do involve the removal of units, the monthly premature-removal report will provide an overview of the frequency of premature removals. This report also shows the proportion of premature removals that are verified failures (see Exhibit 11.3). If there are numerous unverified failures, better troubleshooting methods are needed. A check of the present methods requires reference to the identification and routing tag system, shop records, and engineering records. A quick analysis of these records will also show whether one or more dominant failure modes account for a large proportion of the failures. In either case the shop cost records must be examined to determine the material and labor costs incurred in repairing failed units.

With this information, together with a figure for the imputed cost of delays, it is now possible to return to the RCM decision diagram to examine possible cost-effective tasks. If none can be found, were even if there are applicable and effective tasks, the desirability of design changes to improve the inherent reliability of the item should also be investigated. One supplementary bit of information will help substantiate the cost effectiveness of a design change – the reduction in spare replacement units that would result from a lower or premature-removal rate. This information requires a special analysis by the inventory-planning organization.

A complete analysis of this type has required reference to eight different information systems (see Exhibit 11.4). in time the integrated databases will make it easier to assemble the relevant data. Fortunately, however, not all maintenance decisions require this complete a study. Indeed, the need for a formal study can often determined fairly simply by means of the decision diagram discussed in section 4.4.

| **Information needed** | **Source of data** |
|---|---|
| Identification of system whose failures may be causing operational delays | Daily operations report or monthly summary of delays and cancellations |
| Frequency of delays | Monthly summary of delays and cancellations |
| The failure evidence that is apparent to operating crews | Flight-log sheets |
| Identification of assembly or part causing a large proportion of system failures | Daily operations report and aircraft maintenance information system |
| Determination of whether at line station requires replacement (premature removal) of unit | Aircraft maintenance information system |
| Frequency of unit replacement | Aircraft maintenance information system and monthly premature-removal of report |
| Cost of corrective maintenance (labor) at line station | Aircraft maintenance information system |
| Cost of corrective maintenance (labor and materials) at maintenance base | Shop cost records |
| Identification of failure modes and failure-mode dominance | Shop records, identification and routing tags, special analysis |
| Desirability of modifying scheduled-maintenance program | RCM analysis |
| Effect of failure rate on spare-unit requirements | Inventory-planning system |
| Desirability of design change (product improvement) | Special analysis |

**Exhibit 11-4. An example of the information systems that might be consulted to determine the desirability of introducing a change in the scheduled-maintenance program.**

## 11.2. Typical types of routine analysis

Many analyses are performed routinely as part of age exploration. The engine data recorded in the flight log, for example, are fed into a computer after each flight and are analyzed on a daily basis. This computer analysis reduces the observed data to "standard-day" reference conditions, compares performance of the engine with that of other engines on each airplane for a specific flight, and compares each engine with its prior history. The observed data are weighted so that small changes in recent information receive more attention than small changes between recent and older performance, and statistic-significance tests are used to identify engines whose performance parameters require further investigation.

This program of *flight-log monitoring* is useful in detecting minor variations and trends that would not be apparent to the operating crew. The process cannot pinpoint the exact cause of the variation, and the readings can be affected by instrument changes, since each instrument has different calibration errors. However, flight-log monitoring does prompt investigations that may lead to engine removals (usually less than five percent of the total premature-removal rate), and on this basis it might be considered a form of on-condition inspection.

Two other elements that are monitored by trend analysis are in-flight engine shutdowns and premature removals. Exhibit 11.5 shows a typical report generated by a shutdown and a summary report of all shutdowns for that type of engine during a given month. Exhibit 11.6 shows long-term trends in shutdown and premature-removal rates for the same engine. Premature-removal rates are summarized monthly for all significant items, usually with a supplementary report like that in Exhibit 11.3, listing the items with the highest removal rates. These summaries do not identify the failure consequences, but they do show which items are the least reliable.

Premature-removal data are used not only for actuarial analysis, but also to help identify chronic maintenance problems, failures that are deep in a system and are not corrected by replacing the items that seem to be causing the problem. Removal data are fed into a computer that retains a certain amount of recent history, usually covering a period of about a month. New data are compared with the stored history and an alert is given if an item has more than the expected number of removals during the period covered. This alert report identifies the airplanes that have had repeated removals and also notifies the maintenance organization that special troubleshooting effort is needed to locate the source of the problem. Other systems for identifying airplanes with chronic problems use the flight log as a database. All such reports are intended to aid in troubleshooting on airplanes with especially complex systems, but as the use of built-in test equipment (BITE) becomes more common, they may become unnecessary.

| | | | |
|---|---|---|---|
| Plane No. | 8042U | Station | SLC |
| Incident No. | 081400 | Unscheduled landing | |
| Delay | Delay time | Cancellation | Substitution |
| Flight in/date | | Flight out/date | |
| Plane No. dispatched | | In-flight stage | Cruise |
| Primary resp. station system | 79 | Engine in-flight shutdown | Yes |
| Problem and pair, parts replaced (include part numbers) | | | |
| **Log report:** precautionary shut down No. 1 engine acct fluct oil press, lite on, hi temp. windmilled twenty-five minutes, maintained 20 psi | | | |
| **Action:** SLC M refill the oil tank, ran 20 minutes, no oil loss. No external oil leakage found. Found oil quantity gauge stuck at 8.5. swapped gauges and oil quantity checked OK after filling oil tank. Accessory strainer, scavenge oil screen, main oil screen all checked OK. Deferred SFOMM. | | | |

| Type of aircraft: Douglas DC-8<br>Type of engine: Pratt & Whitney JT3D-1/3/3B | | | | | | Period: February 1976 |
|---|---|---|---|---|---|---|
| No. | Plane, eng | Date, station | Eng. age | Reason for shutdown | Line action | findings |
| 1 | 8042U<br>1 | 2/7<br>SLC | 20681 | High oil temperature | Engine change | Undetermined<br>Critical other X. |
| 2 | 8081U<br>2 | 2/11<br>ORD | 22303 | Engine oil temperature pegged, found rear bearing seal failed | Engine change | Gearbox full of oil; severe cavitation erosion in pressure-pump cylinder wall through which oil leaked<br>Critical other X. |
| 3 | 8044U<br>3 | 2/18<br>JFK | 16920 | Low oil pressure | Found oil leak at B nuts inlet and outlet of oil-scavenge screens; re-torqued B nuts, checked OK, returned plane to service | Loose B nuts at scavenge screen<br>Critical other X. |
| | | | | | | |

**Exhibit 11-5. Top, a typical in-flight shut down report showing the details for that event, and bottom, a monthly summary of the in-flight shut downs for that type of engine.**

From time to time it is desirable to explore the age-reliability relationship for a particular item to determine whether a scheduled rework task is applicable. In this case the premature-removal data are supplemented by other data for the several different analyses that might be made.[1] Exhibit 11.7 shows the history of a constant-speed-drive unit on the Boeing 727 over one calendar quarter. Note that this report identifies the types of functional failures, as well as the failure

[1] For a detailed discussion of the actuarial techniques employed in these analyses, see Appendix C.

modes. Exhibit 11.8 shows the results of an actuarial analysis of this history, and the curves in Exhibit 11.9 show a summary analysis of data over a period of several years. The constant-speed drive shows no evidence of a wear out age, indicating that removal of this item for rework at some arbitrary operating age will have little effect on its reliability.

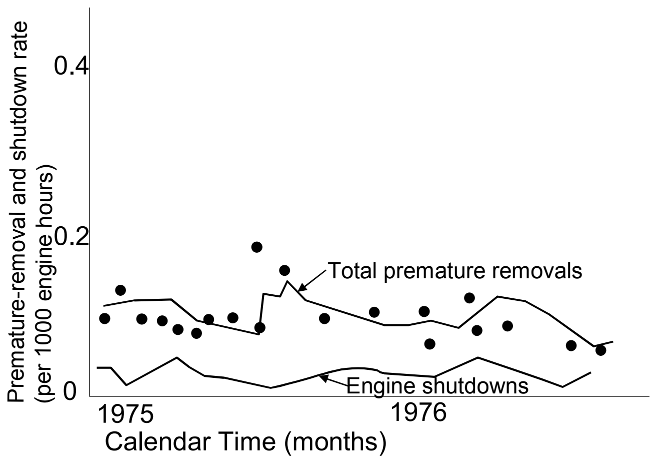



**Exhibit 11-6. Shutdown and premature-removal rates plotted over an 18-month period for the Pratt & Whitney JT3D-3 engine on the Douglas DC-8. (United Airlines)**

At the time the curves in Exhibit 11.8 and 11.9 were developed this constant-speed drive was subject to an overhaul age limit, although it was being rapidly extended as a result of actuarial analysis and the findings of teardown inspections of time-expired units. Evidence of deterioration will usually be found in serviceable units that are removed at some specified age limit, but it is generally beyond human capability to estimate from this evidence the rate at which the deterioration will progress. Consequently teardown inspections of time-expired units rarely provide the information in which we are most interested. The condition of parts in failed units, however, provides information on the general deterioration of these units, as well as on the specific failure modes to which they are subject. Moreover, since the failed units are available for inspection at far more frequent intervals then would be necessary (or feasible) for a reworking age limit, this information accumulates continuously without the need to remove the units from service at fixed intervals. Exhibit 11.10 shows how high-time inspection samples become available for age exploration with and without the imposition of a rework age limit.

Of course, the real criterion of applicability for scheduled rework is the existence of a well-defined wearout region in the conditional-probability curve. Thus unless enough failures have occurred to provide the necessary data for a conditional-probability curve, there is no basis on which a rework task can be scheduled – nor is there any basis for determining whether it would be cost-effective even if it proved to be applicable.

Whereas age exploration to support scheduled rework tasks relies on statistical analysis, the analyses directed at extension of the initial intervals in an RCM program are based on the results of the tasks themselves. Most of the tasks in an initial program are on-condition inspections, and when they are grouped into the various letter-check packages, it is with the expectation that the inspection findings on a small number of airplanes (time-extension samples) will support major extensions of these work-package intervals. During the period in which intervals are being extended, engineers and analysts participate in the inspections of the units designated as time-extension samples and make their own notes to supplement the information that will become available from other information systems.

**Item identification MR 24118 727 constant-speed drive study period January 1 – March 30, 1976**

| | | | **Reason for removal** | | | | | | **Shop findings** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **1** | **2** | **3** | **4** | **5** | **6** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | |
| Unit TSO in 500-hr intervals | Operating hours per interval | Number of premature removals per interval | Metal in sump | Faulty output | High oil temperature | Leaks, low oil level | Low oil pressure | miscellaneous | Housing leak | Seal leak | Hydraulic log failed | Gov. failed | Differential log failed | Spraggs failed | Idler gear failed | miscellaneous | No trouble | Other trouble | In process | No. units in interval at end of period |
| 0-499 | 11,239 | 2 | | | / | / | | | | / | | | | | | o | / | | | 26 |
| 500-999 | 3774 | 0 | | | | | | | | | | | | | | | | | | 14 |
| 1000-1499 | 4157 | 0 | | | | | | | | | | | | | | | | | | 7 |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1500-1999 | 6111 | 2 | // | | | | | | | / | / | | | O | | o | | | | 9 |
| 2000-2499/ | 6261 | 1 | | / | | | | | | | O | | | | | | | / | | 11 |
| 2500-2999 | 5885 | 1 | / | | | | | O | | | / | | | | | O | | | | 13 |
| 3000-3499 | 4743 | 1 | | | | | | / | | | | | | | | | / | | | 10 |
| 3500-3999 | 3524 | 0 | | | | | | | | | | | | | | | | | | 7 |
| 4000-4499 | 4989 | 1 | | O | | | / | | | | | | / | | | O | | | | 8 |
| 4500-4999 | 3606 | 0 | | | | | | | | | | | | | | | | | | 9 |
| 5000-5499 | 2706 | 0 | | | | | | | | | | | | | | O | | | | 6 |
| 9000-9499 | 5358 | 2 | | / | | / | | | | O | / | | / | | | | | | | 10 |
| 9500-9999 | 5067 | 0 | | | | | | | | | | | | | | | | | | 9 |
| 10,000-10499 | 5069 | 5 | / | | / | // | / | | | //o | //od | | | /ooo | | Oo | | | | 10 |
| 10,500-10 999 | 6071 | 3 | | // | | / | | | | | | / | | | | Oo | | / | / | 10 |
| 11,000-11,499 | 5897 | 2 | | | | / | | / | | / | / | | | | | O | | | | 12 |
| 11,500-11,999 | 9147 | 3 | | / | | // | | | | O | // | | | O | | Oo | | / | | 15 |
| 12,000-12,499 | 9550 | 2 | | | | // | | | | // | D | | O | O | | O | | | | 16 |
| 12,500-12,999 | 14,544 | 6 | // | | | // | | // | | // | //od | | O | | | /oo | / | | | 25 |
| 13,000-13,499 | 16,186 | 3 | / | / | | | | / | | O | / | | | | | O | | / | | 23 |
| 13,500-13,999 | 15,189 | 4 | / | | / | // | | | | // | / | | O | | | /o | | | | 35 |
| 14,000-14,499 | 14,925 | 5 | /// | | / | / | | | | /// | //o | | | | | D | | | | 22 |
| 14,500-14 999 | 16,373 | 4 | / | | | / | // | | | /od | //o | | | | | DD oo | | | | 31 |
| 15,000-15499 | 12,034 | 4 | / | | | // | | / | | /o | //o | | | O | | / | | | | 26 |
| 15,500-15,999 | 7530 | 2 | / | | | | | / | | | | | | | | | | | // | 18 |
| 16,000-16,499 | 3068 | 0 | | | | | | | | | | | | | | | | | | 8 |
| 16,500-16,999 | 2379 | 3 | / | | | / | | / | | / | | | | | | | / | | / | 2 |
| 17,000-17,499 | 1610 | 2 | | | | / | | / | | / | | | | O | | O | | | / | 6 |
| 17,500-17,999 | 745 | 0 | | | | | | | | | | | | | | | | | | 1 |
| 18,000-18,499 | 615 | 0 | | | | | | | | | | | | | | | | | | 1 |
| 18,500-18,999 | 855 | 1 | | | | / | | | | / | | | | O | | O | | | | 2 |
| 19,000-19,499 | | | | | | | | | | | | | | | | | | | | |
| Total | 236,212 | 63 | 15 | 7 | 4 | 21 | 5 | 11 | | 21 | 18 | 1 | To | 4 | | 3 | 4 | 5 | 5 | 450 |
| 3-month removal rate 0.27 | | | | | | | | | | | D = secondary trouble O = other trouble | | | | | | | | | |

**Exhibit 11-7. A history of operating experience over one calendar quarter with a constant-speed drive on the Boeing 727. The unit TSO refers to operating age since last shop visit. (United Airlines)**

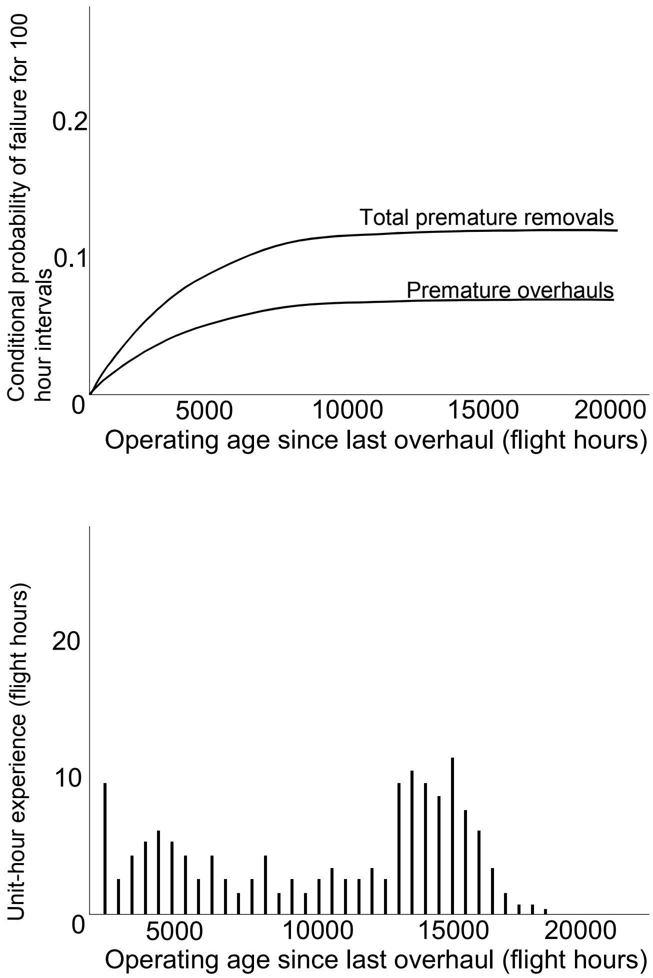



**Exhibit 11-8. The results of actuarial analysis of the operating history shown in Exhibit 11.7. Of the total of premature removals, some units were repaired and returned to service and others required sufficiently extensive work to zero-time their operating ages. (United Airlines)**

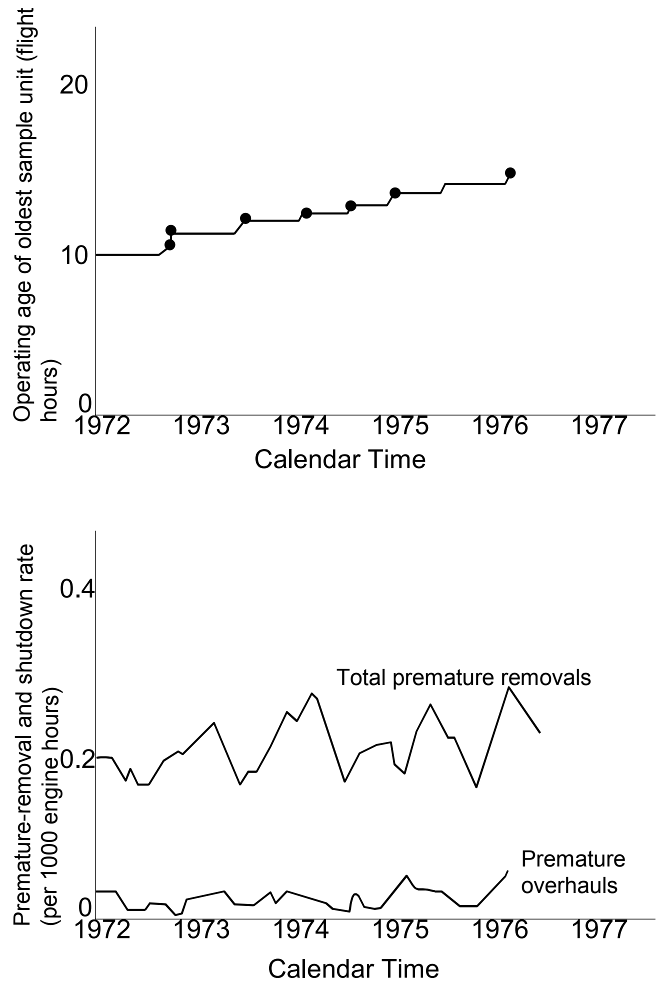



**Exhibit 11-9. The results of actuarial analysis of operating experience over a five-year period for the constant-speed drive of the Boeing 727 (United Airlines)**

## 11.3. Modifying the maintenance program

The nature of the items in the systems, power plant, and structures divisions leads to different patterns in their maintenance requirements, and hence in the n paths used to arrive at an initial set of scheduled tasks. For the same reason, age-exploration activities in each of the three major divisions tend to focus on different sources of reliability information. In some cases the study of individual items involves no specified age limits; in other cases it involves limits that are moved freely and rapidly on the basis of inspection findings. The essential factor in all cases is not the existence of an age limit, but knowing the age of each unit of the item examined.

# Age exploration of systems items

The systems division consists of a large number of readily replaceable complex items and their relatively simple fixed connecting lines. Usually and initial systems program includes few scheduled-maintenance tasks other than servicing and failure finding inspections, and there are rarely defined age exploration requirements, as in the powerplant and structure programs. The cost of corrective maintenance is fairly low for most systems items, and when operating data and do indicate that additional preventive tasks are justified, it is gy because of an unexpectedly high failure rate that involves operational consequences. In some cases the failure rate may be high enough to warrant the replacement of certain components with more reliable ones.

One aspect of operational consequences not discussed thus far is passenger reaction to failures that would not otherwise affect the operating capability of the airplane. A case in point is the problem that developed with toilets on the Boeing 747. The airplanes is equipped 11 laboratories; hence he system is protected by redundancy. The toilet units are of the recirculating type, in which the flushing water is pumped through filters, deodorized and eventually pumped back to the unit for reuse. One failure mode is a plugged line or flushing ring, so that the toilet can no longer be flushed. When this the laboratory is closed, and the failure is recorded in the flight along for repair when the airplane reaches its destination. However, with one or more laboratories closed, a long line forms at the operable units, and passengers often find the wait uncomfortable. Moreover, one of the failure effects that was overlooked was the fact that the deal arising action is ineffective on an inoperable toilet.

When passenger reaction indicated an extensive problem, especially during summer, when each trip has more passengers and more trips are full, the failure was treated as one that had serious operational consequences. In this c on-condition task was added to the program. A partially plugged line or ring is evidenced by incomplete flow from the ring. Thus it was possible to check the amount of the bowl wetted during the flushing operation and treat units with incompletely wetted bowls as potential failures (see Exhibit 11.11). This task was scheduled, of course, to coin with inspections of other problems.

Since the reliability of systems items on the whole tends tw, the principal age-exploration school in the systems division is actuarial analysis of failure data. Ordinarily the conditional probability of failure for a complex item is not expected to vary much with operating age. However, a newly designed system will sometimes show a dominant failure that is both age-related and expensive enough to make-limit task desirable. Exhibit 11.12 shows a conditional-probability curve derive from operating experience with the engine-driven generator of the Boeing 727. There is little change in the failure rates until about 2000 hours, when the bearing starts to fail; thereafter the conditional probability of failure increases with age as this failure mode becomes more dominant. The survival curve in Exhibit 11.12 shows the probability that a generator will not suffer a bearing failure.

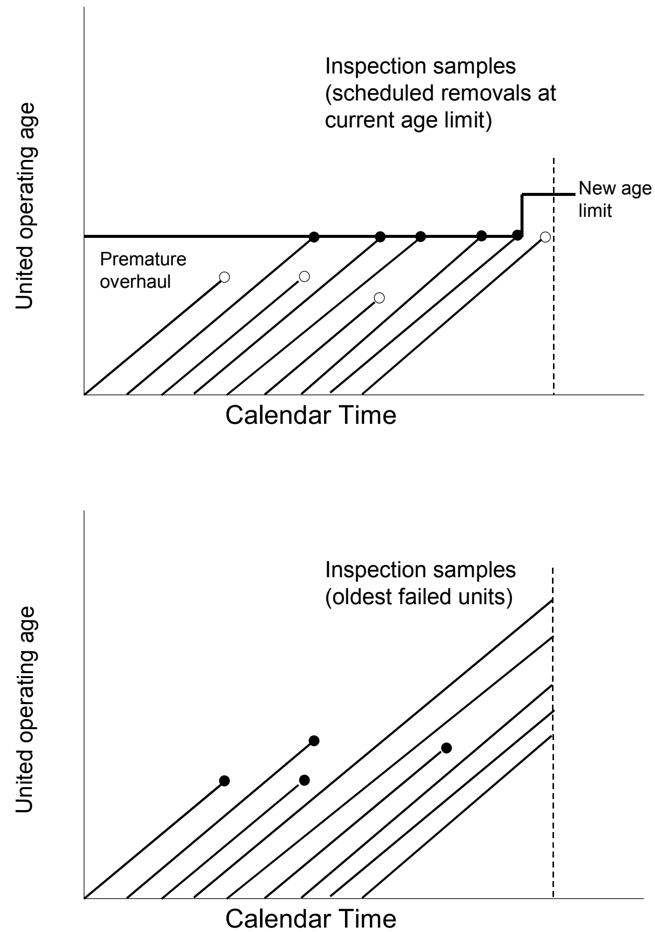
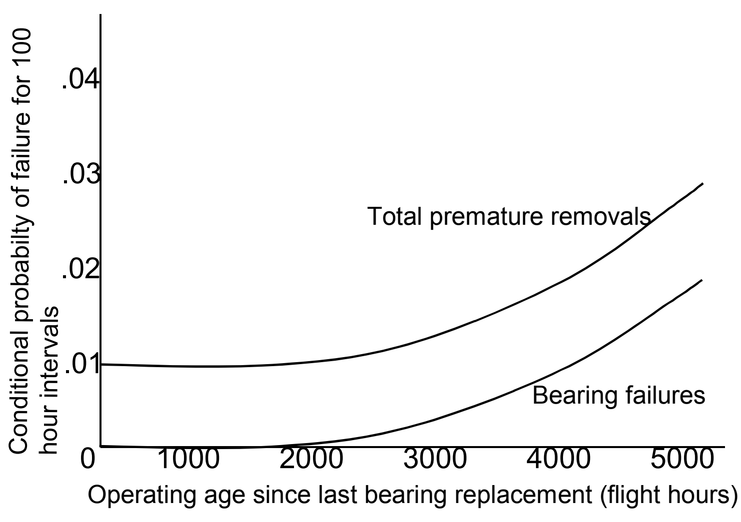



**Exhibit 11-10. The effect of an overhaul limit on age exploration. With time limit, units that fail shortly before they are due for scheduled removal are overhauled prematurely. This procedure zero-times many units, thus reducing the number that survive to the end of the interval and can be used as inspection samples to support extension of the current limit. With no fixed removal limit, the economic reasons for premature overhaul no longer exist, and inspection of the oldest opportunity samples provided by failures results in samples at increasing the ages instead of a number of samples all of the same age.**

| | Insp. | Accomp. by |
|---|---|---|
| | 09 | Clear flush-ring fluid outlet in bowl of residue and check flushing action. Caution: do not operate toilet flush pumps if waste tank is empty. A. with a long handled brush and system flushing fluid, remove obstruction from the Flushing-ring fluid outlets in bowl of toilets listed: |
| 2 | W | 1 Lav U1 |
| 2 | W | 2 Lav B |
| 2 | W | 3 Lav C |
| | | B. check toilet flushing action of each toilet listed below, as follows: 1. Push flushing button and allow completion of one full cycle; Wait 30 seconds (minimum) before starting test cycle. 2. push button for test cycle. The cycle should start immediately and continue for 12 plus or minus three seconds. There must be a vigorous flushing action in the bowl and the inside of the bowl shall be completely whetted. Make a write up to correct inadequate flush action. |
| 1 | I | A Lav U1 |
| 1 | I | B Lav B |
| 1 | I | C Lav C |

**Exhibit 11-11. The job instruction card added to the Boeing 747 maintenance program to prevent operational consequences. (United Airlines)**



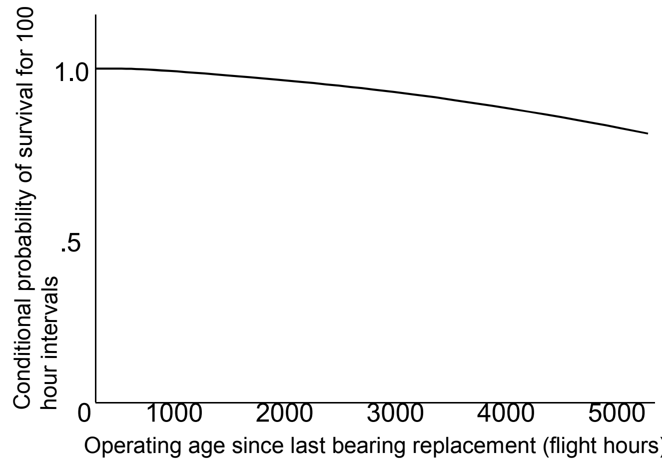




**Exhibit 11-12. The results of actuarial analysis of operating experience with the engine-driven generator of the Boeing 727. The data represent a total of 1,310,269 units hours from January 1, 1970 to January 31, 1971. (United Airlines)**

Bearing failures caused such extensive damage to a generator that the entire generator must be scrapped and replaced with a new one, and the cost of about $2500. The bearing itself costs only $50. In this case a cost analysis showed that it would be desirable to assign an economic-life discard task to the bearing at the interval of 4000 hours. Such a task could also be viewed as a scheduled reworked task for the generator, with the rework specification including discard and replacement of the bearing.

The generator and bus-tie relay on the Douglas D.C. 8 was assigned a scheduled rework task for a different reason. The relay is a complex mechanical system in the first type of aircraft to have three-phase 400-cycle AC power systems. It's basic functions are to convey the power from each generator to its own load bus and to convey ground power to the individual load buses. The failure of either of these functions will be reported to the operating crew and will result in removal of the faulty relay for repair. The relay also has a number of secondary functions, some of which are hidden. However, the maintenance program for this aircraft predated the use of RCM techniques, and at the same time no recognition was given to hidden functions.

When older units began coming into the shop for repair, many of the hidden functions were found to be in a failed state; in addition, many of the parts were so worn that the units could no longer be repaired. On this basis to relay was assigned a rework task – scheduled removal and a maximum age limit of 14,000 hours for shop disassembly to the extent necessary for repair. This task was intended primarily to protect the important hidden functions, but the saving in repairable units in this case more than offset the expense of scheduled removals. Although unanticipated failures in the systems division rarely involve safety, some failures to have serious enough consequences to be treated as if they were critical. One such case was a function of the landing-gear actuator endcap on the Douglas DC-10, discussed in section 7.3. The endcap was designed to have a fatigue life longer than the expected service life of the airplane, and since corrosion was not expected to be a problem with this item, the only task assigned in the initial program was an on-condition inspection of the cap whenever the actuator was in the shop for repair. The check for initial hydraulic leaks had also been discussed area but it was considered unnecessary for this type of actuator. Unfortunately this actuator is not removed as part of the landing gear, and it has a very low failure rate. Consequently no opportunity inspections had been performed.

The endcap actually experienced to failures in the industry, each with different airlines. These failures originated in the exposed internal portion of the endcap, where an O-ring is used to seal into the hydraulic fluid. The original design and assembly techniques have a lot of moisture to accumulate between the cap and body of the actuator on the air side of the O-ring, causing pitting corrosion. Wendy and Separates from the actuator, all the hydraulic fluid is lost from the number three hydraulic system. And the landing gear cannot be retracted. If this failure occurred during flight, the gear in the field position would rest on the doors, and when the pilot extended the landing gear, all three gear is with simply free-fall to the down and locked position. However, if the gear doors were also to fail, the fail to gear with free-fall through the opening, and in the extreme case at high speed, the door could separate and fall to the ground. This multiple failure would be considered critical.

While neither of the two endcap failures in themselves were classified as critical, the action taken with similar to that for an unanticipated critical failure. First, a safe-life limit was established for the endcap and a modified part with greater fatigue life was designed. This modified Is being installed at or before the existing caps reach the present life limit. Second, all actuators are being removed and sent to the shop for upgrading as fast as they can be handled. Each actuator is this assembles, the endcap is replaced with the new part, corrosion on other parts of the actuator is removed, and improved corrosion-protection materials are applied on reassembly. This procedure consists of applying fluid-resistant primer to the threads of both the end cap and the barrel, renewing the cadmium plating and painting, assembling the actuator with grease on all threads, and applying corrosion-inhibiting sealants on the last thread at all threaded joints. When all the shorter-life parts are removed from service and all the actuators have been assembled with this new procedure, it is expected that problem will be resolved.

Failure data are also the basis for adjusting task intervals for hidden functions in systems items. Many of the failure-finding tasks are based on opportunity samples, tests or inspections of hidden functions on units sent to the shop for other repairs. Results of these inspections are recorded and analyzed to find the inspection interval that will provide the required level of availability at the lowest inspection cost. The units tested in the shop are considered to be a random sampling of the units in the operating fleet. Thus the percentage of failures found in the shop tests can be taken as the percentage of failures that would be found throughout the fleet. Failure-finding inspections of items installed on the airplane are performed at scheduled intervals. In this case the percentage of failures found will represent approximately twice the percentage expected in the entire fleet, because the inspection occurs at the end of the assigned interval, rather than at random times since the preceding inspection.

## Age exploration of powerplant items

Age exploration is an integral part of any initial powerplant program. A completely new type of engine, often incorporating new technology, is usually quite unreliable when it first enter service. During the first few years of operation premature-removal rates are commonly as high as 2 per 1000 engine hours. This high removal rate makes it possible for the engine repair shop to obtain information not only on the parts involved in the failure, but on the condition of other parts of the engine as well.

Most new aircraft engines experienced unanticipated failures, some of which are serious. The first occurrence of any serious engine failure immediately set in motion for developmental cycle described in Section 5.2. The cause of the failure is identified, and an on-condition task is devised to control functional failures until the problem can be resolved at the design level. Modified parts are then incorporated in the operating fleet, and when continued inspections have shown that the modification is successful, the special task requirements are terminated.

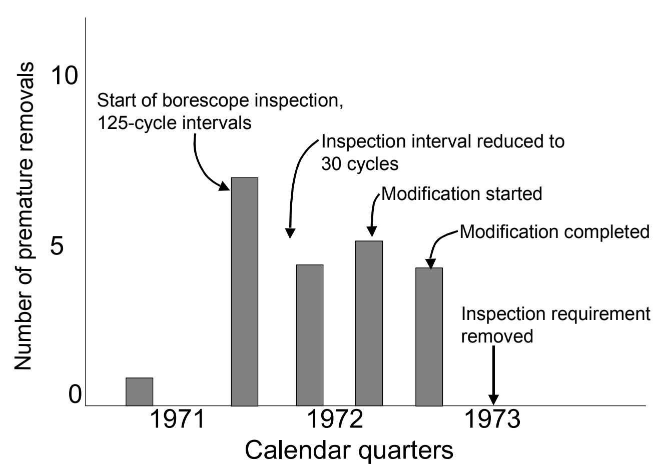


**Exhibit 11-13. History of the C-sump problem in the General Electric CF6-6 engine on the Douglas DC-10. The on-condition task instituted to control this problem had to be reduced to 30-cycle intervals in order to prevent all functional failures. The precise cause of this failure was never pinpointed; however, both the inspection task and the redesigned part covered both possibilities. Once modification of all in-service engines was complete no further potential failures were found, and the inspection requirement was eventually eliminated.**

The General Electric CF –6 engine on the Douglas DC-10 experienced several such unanticipated failures during early operation. The low-pressure turbine sections separated from the engine, and these separated rear sections fell off the airplane. Investigation determined that these failures were probably a result of oil fires in the engine case, caused by seepage due to a pressure imbalance in the oil scavenging system. Opponents However, and there was also a possibility that there had been a structural failure in the C sump, which supports two of the bearings. Thus on-condition borescope inspections of the C sump, which supports two of the bearings. Thus on-condition borescope inspections of the C sump or oil on its external surface. The initial interval for this inspection was 125 flight cycles, but the interval was lowered to 30 cycles after another functional failure occurred (see Exhibit 11.13). Inspections were continued at this short interval until the engines were modified.

Over the course of six or seven years, has failure information is used to improve the engine, the total premature-removal rate (for both potential and functional failures) usually drops to 0.3 or less per 1000 engine hours. There are many noncritical parts in the engine which are quite reliable, however, and which may not fail at all until much higher operating ages. The question is whether a rework or discarded age limit will prevent these failures from occurring. Until some unsatisfactory condition appears, there is no information from which to determine and each-reliability relationship. In this case all we can do is inspect unfilled parts at successive ages until some signs of deterioration appear. While such inspections do not always have on-condition capability, they are the only source of information on parts performing satisfactorily.

| Section and part name | Inspection limit | Inspection threshold |
|---|---|---|
| **Cold section** | | |
| No. 2 bearing assembly<br>Engine manual, 72–09-50 | -- | 21,000-24,000 |
| Intermediate case (Cadillac)<br>Engine manual, 72-34-1 | -- | 19,500-21,000 |
| Intermediate case (non-Cadillac)<br>Engine manual, 72-34-1 | -- | 17,000-19,000 |
| 13th-stage MFD<br>engine manual, 72-72-0<br>heavy maintenance, 72-72-0 | <br><br>Available | <br>16,000-18,000<br>-- |
| 8th-stage bleed MFD<br>engine manual, 72-72-0<br>heavy maintenance, 72-72-0 | <br>--<br>Available | --<br>14,000-16,000<br>-- |
| No. 4 ½ carbon seal, #728 981-600 assemblies only<br>Engine manual, 72-09-13<br>Engine manual, 72-09-10<br>Engine manual, 72-09-20<br>Heavy maintenance, 72 -53 | <br>--<br><br><br>Available | <br>9500-12,500<br><br><br>-- |
| No. 4 ½ carbon seal, other part number assemblies<br>Engine manual, 72-09-13<br>Engine manual, 72-09-10<br>Engine manual, 72-09-20<br>Heavy maintenance, 72-53 | <br>9500<br><br><br>Available | --<br>--<br><br><br>-- |

| | | |
|---|---|---|
| No. 6 carbon seal | | |
| Engine manual, 72-09-13<br>Engine manual, 72-09-10<br>Engine manual, 72-09-20 | 8600 | -- |
| Heavy maintenance, 72-53 | Available | -- |
| Accessory bearings, front accessory drive | | |
| Engine manual, 72-09-50 | -- | 9000-12,000 |
| Accessory bearings, gearbox drive tower shaft | | |
| Engine manual, 72-09-50 | -- | 8500-11,500 |

**Exhibit 11-14. A portion of the opportunity-sampling program for age exploration of the Pratt & Whitney JT8-7 engine. (United Airlines)**

As opportunity samples provide documented information on parts and increasingly higher ages, the maintenance organization gradually compiles a list of significant parts, their failure modes if they have failed, and aged which full inspection should be started for each item. This list identifies the part, refers to this section of the maintenance manual in which the task itself as defined, and states the threshold age limits at which the task is to be performed. The schedule falls within these age limits is treated as an opportunity sample if it becomes available for inspection while an engine is being disassembled for repair. If any engine has a part that his age beyond the upper limit, that part must be inspected even if further disassembly is required for this purpose alone. In either case, the inspection sample is measured against appropriate standards, and its condition is documented on a special sampling form.

Sampling requirements usually specify that the threshold limits for each item may be increased after two inspection samples have been examined and found to be in satisfactory condition, although engineers will often want to inspect far more than two samples before authorizing extensions of limits. To ensure that most of the samples will be opportunity samples, the two threshold limits are set as much as 3000 hours apart while the inspection intervals are still being extended. Consequently, when a maximum interval is identified, this “opportunity band” will already have removed a great many units before they reached the upper limit, leaving very few age-limited units in the field. This type of age-exploration program has been quite successful in extending limits without the need for engine removals solely to inspect parts.

If the item is one that has experienced functional failures, and an actuarial analysis has established that a rework or discard task will improve its reliability, the task is added to the program and the item is removed from the sampling schedule. In the event of the serious unanticipated failure of a high-time part, the status of the item will be reviewed in the entire fleet, and the engines with high-time parts will be inspected on the wing if this is possible; otherwise such engines will be removed and sent to the shop for disassembly. As a result of the continual process of repair and replacement of field parts and the incorporation of design modifications, the parts of any engine that has been in service for some time will be of widely disparate ages. The overall age identified with an engine is the age of its nameplate. The nameplate is useful in referring to individual engines, at any engines in operating fleet may consist of parts older or younger than its nameplate. For this reason it is necessary to keep track not just of the age of each engine, but of the ages of all the parts from which it is assembled.

## Age exploration of structural items

Whereas systems and powerplant names are designed to be interchangeable, there is no simple way of replacing most structural elements. Repairs and even detailed inspection of internal parts of the structure involves taking the entire airplane out of service, sometimes for an extended period. For this reason structural items are designed to survive too much higher ages and systems or powerplant components. Nevertheless, initial intervals in the structural inspection plan are only a fraction of this design like school, both because of the consequences of the structural failure and because of the factors that can affect the design fatigue life in individual airplanes. These include variations in the manufacturing process, overloads encountered by individual airplanes, loading spectrum that differ from the standards employed by the designer, environmental conditions causing corrosion, and accidental damage from foreign objects.

In the structure division inspection program itself is the vehicle for age exploration. Thus the initial intervals are intended not only to find and correct any deterioration that may have occurred, but also identify the age at which deterioration first becomes evident for each structural item. Exhibit 11.15 shows the form in which the findings of an A-check past are recorded, along with a record of any corrective action taken. The inspection findings and work performed at the line station are usually monitored by engineers, who log all the relevant findings on those airplanes designated as inspection samples in the form shown in exhibit 11.16. With this information there is a good basis in the ongoing program for revising the age at which inspections of structurally significant items should begin in later-delivery airplanes. In general interval to the first inspection in the initial program is the same as the interval for repeat inspections, and successive inspections are performed on each airplane at ages to identify the agent which deterioration first becomes evident. This procedure provides adequate information in interval is short in relation to the fatigue-life design goal. Inspection of an item at intervals of 5000 hours, for example, will result in documentation of its condition at total ages of 5000 hours, 10,000 hours, 15,000 hours, and so on. However, if an item is assigned an initial interval of 20,000 hours, subsequent inspections at total ages of 40,000 and 60,000 hours would leave great gaps in the flow of age-condition information to be useful. The items that are assigned such long intervals, of course, are those which not only have very little effect on residual strength, but also have a very low susceptibility to corrosion and other damage.

Because it takes several years for fleet airplanes to build up, is always hoped that the conservative start-of-inspection intervals in the initial program will apply only to the first few airplanes to reach these ages, and that inspection findings will support an increase in the ages at which the first inspections are performed on subsequent airplanes entering the fleet. This increase is usually accomplished by "forgiving" the first few inspections in the sequence, rather than by changing the intervals. Information obtained from the inspections is supplemented by data from the manufacturer's continuing fatigue tests, as well as by inspection information from other operating organizations. Once the first evidence of deterioration does appear, this new information may indicate that adjustments of the repeat interval itself would be desirable. When early deterioration appears in structural item, low start-of-inspection and repeat intervals must be defined and maintained until design changes have been incorporated that avoid the need for such early and frequent inspections.

| | TSO | | | Type of Check | | | | | | Source | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plane no. | Hours | Min | Station | Other | #15V | #25V | A | B | C | Log | Def | mech | Job no |
| | | | | | | | | | | | | | |
| Work area | | | | | Job type | | | System code | | | | | |
| T | L | H | O | A | E | O | S | | | | | | |
| | | X | | | | | | | | | | | |
| Replaced aft long rt floor panel in lower galley acct. soft<br>Replaced panel | | | | | | | | Deferred checklist | (details omitted)<br>Date and time: by:<br>4 – 21/0100 | | | | |

**Exhibit 11-15. A record of structural-inspection findings and corrective maintenance as reported during a number 2 A check. Omitted details include labor time, sign offs by the mechanic and in the inspector, and reference file Nos.. (United Airlines close)**

| On-aircraft inspection findings | |
|---|---|
| 1 | **On 9/2/71 at 285 hours**<br>Indications of material flowing out of center waste from in aft waste tank<br>103 rivets popped or lose, RH side of aft pylon fin |
| 2 | **On 9/28/71 at 571 hours**<br>No significant defects recorded |
| 3 | **On 11/3/71 at 181 hours**<br>No significant effects recorded |
| 4 | **On 12/12/71 at 1166 hours**<br>No significant defects recorded |

| | |
|---|---|
| 5 | **On 1/24/72 at 1475 hours**<br>A couple of write ups that could indicate a chronic condition. Numerous loose rivets on left and right wing tips; also loose rivets on No. 2 engine top aft fairing. |
| 6 | **On 3/21/72 at 1835 hours**<br>Repair fuselage damage under captain's window, left side of fuselage; scrape for feet long. Removed rivets, bumped out skin to contour, installed 2024 T3 tapered shims between skin and frame, reinstalled rivets. To be inspected, sta 330 frame, in approximately 3000 hours. Lower LH leading-age skin cracked. Installed patches, replaced door<br>Leading-aged door is found loose even though they had previously been taped; one door had broken through |

| | |
|---|---|
| | taped, was hanging down approximately ¾ in.<br>Aft, center, and forward cargo door hinges rusted. Cleaned and sprayed with oil<br>Evidence of working rivets above LH overwing entry door and splices, sta 1256 and 1305 and longeron 15. No action taken. |
| **7** | **On 5/8/72 at 2186 hours**<br>80 rivets loose and popped at vertical stabilizer fin above aft engine hot section. Replaced rivets.<br>No. 6 axle sleeve has migrated and rotated. Shop repaired.<br>Bracket cracked on No. 1 pylon cap area. Replaced bracket.<br>Right inboard spoiler upper skin cracked. Replaced spoiler.<br>Typical and chronic loose leading-age plates, topped rivets on wing-tip structure… |
| **8** | **On 6/16/72 at 2533 hours**<br>Possible corrosion source: drain in service center leaks to FFR. Blew out all drain lines, unable to find traceably.<br>Chronic – right and left wing leading-edge plates cracked, latches loose, etc.<br>Firewall cracked, No. 2 engine, PT 7 bulkhead fitting loose and bolt missing just aft of aft engine mounts. Stop-drilled cracks, installed double or under bulkhead fitting. |
| **9** | **On 8/7/72 at 2968 hours**<br>Rib flanges cracked and rivets sheared at forward end of tailfin above after end of No. 2 engine. 2d, 3d, 4th, and 5th form top on left side and 5th, 6, and seventh on right side, interior. OK to continue to special routes for COA.<br>Lowering leading-edge plate cracked, loose, etc. (typical).<br>Lower leading-edge skin area just forward of center accessory compartment has water. Stuccoed water (recorded as possible corrosion source).<br>LH No. 2 lead-inch slat retract cable frayed beyond limits (center track at wing leading edge). Replaced cable. Cost by contact…. |

**Exhibit 11-16. An example of the inspections findings recorded for a designated inspection sample of the Douglas DC-10 airplane. (United Airlines)**

In short, the initial structural inspection program defines starting points for an age-exploration program that will continue throughout the operating life of the airplane. At first all significant items are inspected on all airplanes, and as information is obtained, the starting intervals assigned in the prior-to-service program are lengthened. Scratch, if possible, to reduce the inspection workload on later-delivery airplanes. The major structural inspections, or D checks, usually entail inspection of all significant items and most nonsignificant ones, and this may be the only work package that requires inspection of class 4significant items.

The first D checks are performed on the highest total-time airplanes of the fleet – the fleet leaders, which are the first airplanes to reach the end of the starting interval. While the starting interval for this work package is being extended, the number of major structural inspections in anyone fleet is relatively small. Once a maximum limit is reached, however, the volume of major inspections increases markedly as individual airplanes each to this fixed limit. At this point it becomes necessary to examine possibilities for reducing maintenance costs which do not involve interval extension. It is common in the airline industry to divide the ongoing inspections program into two parts – *a 100 percent program* , which consists of those tasks to be performed on every airplane, and a *sampling program*, consisting of tasks to be performed only on a specified portion of the fleet.

The two parts of the ongoing inspection program take into account the wide range in the importance of individual structurally significant items which is exemplified by the rating process. Class 1 and class 2 items are identified by a joint consideration of the effect of their failure on residual strength and their susceptibility to deterioration. If either of these factors as large, that item must remain in the 100 percent program to minimize the likelihood of a functional failure. The 100 percent program thus ensures the integrity of those structural elements which are essential to the safety of airplane.

The concept of damage-tolerant design depends on the existence of this 100 percent inspection plan to reveal any failed structural member before the failure of the second member can cause an unacceptable reduction in residual strength. In practice the inspection intervals for such elements are intended to detect cracks and corrosion and a sufficiently early stage to prevent the first member from failing. This early detection of damage also lowers the cost of repairs; however, we do not differentiate between structural integrity and economic considerations in the 100 percent program.

In contrast, the failure of a class three or class 4 item, by definition, has only a small effect on residual strength, and such items also have little susceptibility to deterioration. Consequently we can permit economic considerations to play a large role in their scheduled-maintenance requirements. Detection of deterioration in its early stages will reduce the cost of repairs, but this saving must be balanced against the cost of inspections necessary to find the first evidence of deterioration in every airplane. A sampling plan is therefore used to determine the age characteristics of the fleet, with full knowledge that individual uninspected airplanes may require extensive repairs by the time to sample inspections identify a problem area. Since the issue in this case is not structural integrity, but the relative cost of repairs, the risk of occasional high repair costs is acceptable if the result is a marked reduction in inspection costs. This exposure would not be acceptable, of course, for class 1 and class 2 items, where failure would have a market effect on residual strength.

A relatively small number of sample inspections may be adequate for economic purposes. For example, suppose an item has a relatively short fatigue life of 60,000 hours. In a sample of ten airplanes all of the same total age, the probability of discovering this defect by 50,000 hours is .63, and the same defect would be expected to appear at this age in 10 percent of the uninspected airplanes.[1] In practice, however, sample inspections are performed on highest-age airplanes, and when the defect is discovered, its incidence in the lower-age airplanes in the rest of the fleet will be much less than 10 percent. In by going years, when a large number of airplanes were to be inspected at a fixed major-inspection interval it was common practice to inspect items of relatively low significance on a fraction of the fleet – say, every fifth airplanes – and this practice was referred to as *fractional sampling*.

Once the sampling inspections have identified the aged which an item begins to show signs of deterioration, some action must be taken. This may be an increase in the number of aircraft samples, perhaps to 100 percent, or it may be treatment or modification of the affected area to forestall deterioration in other airplanes. For example, doublers may be installed on all airplanes, or protective coatings may be applied to prevent corrosion. As the fleet ages, more and more of the sampling inspections will revert to 100 percent inspections unless such basic preventive measures are taken.

As the operating fleet of a specific type of airplane ages and service, from time to time it is necessary to conduct a thorough review of the structural meet its program in light of the information obtained from operating experience and later manufacturer's tests. In 1976 Douglas Aircraft conducted such a review for the D.C. 8, and special inspections for 27 items were added to the program for airplanes with age is greater than 50,000 hours. Similar reviews of its structural designs are being conducted by Boeing. The British Civil Aviation Authority now requires a Structural Integrity Product and Inspection document:[2]

"5 Structural Integrity Audit and Inspection document

5.1 The Constructor's Role. For each airplane type to which this Notice is applicable to necessary work is that the constructor should carry out a 'structural integrity audits' in which each area of the structure for which fail-safe characteristics are critical is considered, and the acceptable extent, rate of growth, and detectability of damage is assessed, together with the probability of damage being present in associated areas based on this Product, and Inspection Document should be drawn up and made available to operators.

5.1.1 The Inspection Document should include:
(a) A statement of (or reference to) all the inspections (and replacements, repairs or modifications) considered by the constructor to be necessary to ensure that is safe level of structural strength will be maintained.
(b) For each location, the thresholds (Time/flights, to first inspection) frequencies and height and method of inspections required and the extent of damage which is aimed to be able to find.
(c) Reference to the types of operations for which is considered valid. Notes: it's validity may, of course, the varied by reissue from time to time.

5.1.2 The Inspection Document would have to be prepared on the basis of a Structural Integrity Audit (or other process providing similar results) generally acceptable to the Authority, but would not require approval in detail. Guidance on the method of carrying out a Structural Integrity Audit and as to what should be included in the Inspection Document is given in CAA Information Leaflet, Continuing Integrity of Transport Airplanes.

While the manufacturer is formally responsible for conducting these structural reviews, their value depends on adequate information from the operating organizations.

Quite apart from problems associated with higher ages, there is always the possibility of an unanticipated failure of the structural item at more modest ages, just as there is for systems and powerplant items. One such example was the cracking of the Boeing 747 floor beams as a result of cyclic loading from cabin pressurization. This problem was first discovered when increased floor flexibility and lose seats were reported in an airplane that had accumulated approximately 8400 pressurization cycles. The discovery led to a Boeing service bulletin, followed within a week by a U.S. Department of Transportation airworthiness directive, detailing and on-condition inspection program for the floor beams and specifying a modification of the structure to eliminate the problem.[3] The airworthiness directive required that all

[1] M.E. Stone and H.F. Heap, Developing the DC-10 structural inspection program, seventh annual FAA International Maintenance Symposium, Oklahoma City, December 7-9, 1971

[2] Continuing Structural Integrity of Transport Air planes, civil aviation authority, airworthiness Notice 89, Aug. 23, 1978.

[3] Boeing Service Bulletin 747-53-2176, Feb. 10, 1978, and U.S. Department of transportation airworthiness directive 78-04-04, February 16, 1978.

airplanes with more than 6000 landings be inspected within the next 100 landings and that the inspections be repeated within the next 1200 landings if no cracks were found. If not more than one bean was found to be cracked, and if the crack in the beam wed was less than three inches long, the crack would be stop-drilled and inspected for evidence of further progression within the next 50 landings, subject to the provision that the crack be permanently repaired within 1200 landings. If you crack more than three inches long was found, repair was required before further flight.

Note that this directive embodies the concept of a long initial interval followed by short repeat intervals. In this case both of the intervals are firmly established by information derived from actual operating experience. The continuing age exploration of damage-tolerant structure will lead to the same results. Once the agent which fatigue damage becomes evident has been identified for each item, there will either be short inspection intervals starting at this age or else a design modification that extends the fatigue life of the item and makes the inspection task unnecessary.

The decision to modify an airplane structure depends on its remaining technologically useful life. When the airplane is likely to be outdated soon by new designs, is usually difficult to justify structural modifications on economic grounds, and it may be necessary to perform frequent inspections of items that have been identified as approaching their fatigue lives. In this case there is an increasing likelihood that the detection of the fatigue and will also take the airplane out of service to repair, and if the cost of repair cannot be justified, it may be necessary to retire the airplane. Whenever an active modification policy is not followed, the frequency of repair and the number of out-of-service incidence will be a direct function of the increasing age of the airplane.

It is frequently considered axiomatic that all structural inspections must be intensified within airplane reaches higher ages. However, this is not necessarily been the experience with transport aircraft because of the policy of modifying items as soon as they are identified as nearing their fatigue lives. Consequently in decisions concerning fleet retirement costs of maintaining structural integrity has been secondary to such factors as fuel consumption, speed, passenger acceptance, and payload/range capability.

When a safe-life structural item reaches its defined life limit there is usually no alternative to replacing it with anyone. Thus an airplane designed to safe-life structural criteria must have greater economic viability than one designed as damage-tolerant structure in order to justify the more expensive procedures that required for continued operation.

## 11.4. Intervals: an information problem

The difficulty of establishing "correct" intervals for maintenance tasks is essentially an information problem, and one that continues throughout the operating life of the equipment. With the techniques of RCM analysis is fairly simple to decide what tasks to include any scheduled-maintenance program, but the decision logic does not cover the intervals at which these tasks are to be performed. Since reworked and economic-life tasks are developed on the basis of age exploration, the intervals for these tasks cannot be determined until operating information becomes available. Safe-life intervals, which are based on the manufacturer's test data, are set prior to service with the expectation that operating information will never become available. The most effective preventive tool in the maintenance program, however is on-condition inspections, and in this case there is just not enough information to set fixed intervals, even after airplanes are in-service and each expiration is underway.

At the time and initial program is developed the available information is usually limited to prior experience with similar items, familiarity with the manufacturer's design practices, and the results of the developmental and fatigue tests for the new airplane. With this information is possible to arrive at a rough estimate of the ages at which signs of deterioration can be expected to appear. However, the initial intervals are then set at only a fraction of these ages. Indeed, the fraction may be very small one, to force intensive age exploration, if the manufacturer is relatively inexperienced, if the design contains the materials or processes, or if the airplane is to be operated in an unfamiliar environment. While there is some economic penalty in the use of short intervals, the overall impact is small because the intent is to increase intervals on the basis of actual operating data as a new fleet grows in size.

The basic concept underlying on-condition inspections is that the interval to the first inspection should be long enough for some physical evidence of the tear ration to be seen, and the interval for repeat inspections should be sure enough to insure that any unit that has reached the potential-failure stage will be removed from service before a functional failure can occur. In theory, then, it seems that the problem should merely be one of using age exploration to determine the appropriate intervals for first inspection and repeat inspections of each item, and that once this is done intervals can be fixed. However, matters are not quite that simple.

In most cases, particularly if the remaining service life of the airplane is high, once the potential-failure ages of significant items have been identified they will be judged undesirably low. Items will therefore be modified to increase their longevity, and there must be another eight-exploration cycle to determine the intervals appropriate to the improved item. Consequently any set of initial and repeat intervals may apply only from the time the original information becomes available until the time the modified item goes into service. While the dynamics of this process had to the age-exploration requirements, they also reduce the growth in the maintenance workload associated with short repeat intervals for more items as the airplane grows older.

# 11.5. Resolving differences of opinion

It isn't inevitable that there will be differences of opinion concerning the interpretation of operating information and the revisions that should be made to the scheduled-maintenance program. In most cases these differences can be resolved in reference to the principles underlying the development of an RCM program.

One common situation is that an item initially assigned to no scheduled maintenance which has experienced a high in-service failure rate. Although the failure rate is one that has no safety consequences, the engineer may assume that all mechanical items have a wearout age and that the high failure rate is in itself evidence of wear out. On this basis he might propose that the item be assigned a scheduled rework task to improve its reliability. The data required for an actuarial analysis are available in this case, since the failure rate is high; hence we can gain a fair picture of the items age-reliability characteristics. If the conditional-probability curve does show increased with age, then the failure rate that would result from the imposition of any given age limit can be computed as described in chapter 3.

So far there is no difference of opinion. However, scheduled removals will certainly increased the shop workload. The cost of the increased workload must therefore be compared with the saving that would result from a reduction in the failure rate. If these added costs outweigh the benefits, the task may be applicable, but it is not cost-effective. Even when the proposed task appears to be cost-effective, there may be other difficulties. Very often the items that show high failure rates in service were not expected to do so. Thus the spare-unit inventory is already inadequate as a result of these unexpected failures, and the same is true of parts and tools needed for repairs. Consequently a reworked task, though economically desirable on other grounds, maybe impractical, since acting scheduled removals to the current workload would increase in already serious logistics problem.[1]

There is usually no difficulty in reaching an agreement if it turns out that it is not practical to implement a scheduled reworked task. Suppose, however, that the conditional-probability curve shows that a reworked task is not applicable to the item in question. In this case the difference of opinion may be more difficult to resolve. The engineer may want to know why the actuarial curves cannot support is intuitive police that high failure rate is synonymous with whereof, and an analyst working with statistical data is often not equipped to explain why particular item does not show whereof characteristics. The situation may be further complicated when pared down inspections show the surviving units to be in for physical condition. They have been many instances in which highly qualified inspection teams have judged the parts of time-expired samples to be in such poor condition that they could not have survived to a proposed higher age limit. Nevertheless, when these items were allowed to continue in service with no age limit, subsequent analysis of their operating histories showed no actual increase in their failure rates. Under the circumstances the discrepancy is between two sets of physical facts, and while the differences of opinion may not be resolved, and understanding of principals discussed in chapters 2 3 lead these provide a basis for arriving at a decision.

Occasionally the problem is one that requires reference to the decision logic itself. The following situation is more complex, and fortunately far less common. The initial maintenance program for the Douglas D.C. 8 called for lubrication of the flight-controlled elevator bearings and every D. check. At this time half the bearings were to be removed and inspected; those in good condition were then reinstalled and the others were scrapped. This task specification had remained in the program without change for many years. During that time it had been major extensions of the D. check interval, and interval for the newer plans entering the fleet had reached 17,000 hours. When these later planes aged to the D. check interval, however, the inspections showed that many of the bearings were badly corroded. The inner race was difficult or impossible to turn by hand, and when it could turned, some of the bearings fell from. Obviously the interval between lubrications had become too long, and it was reduced accordingly to the C. check level. But the problem was what to do about the high-time bearings in the rest of the operating fleet. One group insisted that the situation was critical and that all high-time bearings would have to be removed from service immediately; this was tantamount to imposing a safe-life limit on the bearings. Another group felt that such drastic action was not warranted.

For a clear picture of the problem that is considered the bearing itself as a significant item. This item is a roller bearing housed in a fitting taxed to stabilizer. A hinged bowls on the elevator passes through the bearing deformity control-surface teams. The function of the bearing is to reduce friction and where (and consequent free play) in the rotating joint. Only two types of failure are important: where or mechanical damage, resulting in looseness or free play in the daring, and unacceptable operating friction, leading to seizure of the inner and odor bearing races. This latter failure mode is

[1] For a further discussion of this point see section C.5 in appendix C.

one of concern. The designer's description of the control system for this aircraft states in part:[1]

> Flight control surface hinges and pilot control system rotating joints were designed to be tolerant of inevitable deterioration and/or possible failure of bearings. Possible seizure of a bearing's inner and odor races is compensated for by ensuring that the bearing's function is transferred to the rotating joint's pin or shaft. Friction in the joint will increase considerably in this event, that would not prevent relative motion between components. Control surface moments about the hinge line are so great that bearing seizure cannot in Pete surface travel. Control surface hinges and other rotating joints that would be adversely affected by bearing free play are redundant such that deterioration or failure of the bearing in this mode will not create intolerable levels of looseness or structural loading of the connection and will not, therefore, affect the airworthiness of the airplane.

If we apply the decision logic to these characteristics, we see immediately a loss of function in this bearing will not be evident to the operating crew. When flight tests were conducted on equipment with high-time bearings, for handling characteristics of the airplane were normal even though subsequent inspections showed that the bearings were seriously deteriorated. However, while the bearing failure has no direct effect on safety, it's function is hidden. Therefore a schedule task for the bearing is required to avoid the risk of the multiple failure. The first possibility in the hidden-function sequence is an on-condition task, and we find that there is already such task in the program. Combined with more frequent lubrication, scheduled inspection of the bearings for where should ensure adequate availability (although the interval for this task might require adjustments as well).

The conclusion in this case was that the situation was not critical and it was no need to impose a safe-life limit on the bearing, however, those airplanes with high-time bearings that might already had been affected by inadequate lubrication were scheduled for bearing inspection prior to 20,000 hours as a failure-finding task.

# 11.6. Purging the program

One of the most important activities in the management of an ongoing maintenance program is periodic purging of the entire program, and organize review of *all* scheduled tasks to identify those that are no longer worth continuing. Often the conditions that originally supported the inclusion of a specific task the change, and the task can now be deleted from the program. Moreover, in the maintenance organizations concerned with complex equipment many different groups will be responsible for adding tasks to the program, and the additions are often made without enough attention to the totality of scheduled tasks. For this reason it is necessary to conduct a formal review every three to five years to purge the program of all tasks to become superfluous. The results can be impressive. In such a review of the Boeing 747 program after the airplane had been in service for six years, so many tasks were eliminated from the phase-check package (a combination of B and C checks) that the man-hours required to accomplish the scheduled work in this package were reduced by 21 percent.

The review should be conducted by special team, with representatives from each of the organizational groups concerned with the maintenance program. The people selected must be knowledgeable and objective and fully prepared to challenge the continued requirements for any scheduled task. Once the group has been assembled, it will ordinarily be responsible for developing review standards and procedures, collecting and summarizing data, and assembling review packages consisting of task job cards, a sample of typical inspection findings, and a list of the review procedures. The review packages are then processed through the various departments involved, including production (maintenance shops), production planning, reliability analysis, and engineering, after which they returned to the review team for resolution of any disagreements. The review team then obtains approval for the changes and repackages the tasks for implementation.

Certain findings are typical in such a review:

- Scheduled tasks that do not meet the criteria for applicability and effectiveness; these can be deleted from the program.
- Tasks that originally met these criteria that are no longer effective as of subsequent modifications to the equipment; these can be deleted from the program.
- The absence of tasks that do meet the criteria; these can be added.
- Tasks that are duplicated; the duplication can be eliminated.
- Task intervals that are either too long were too short; these intervals can be adjusted.
- Job cards that either do not clearly defined the requirements of the task and procedures to be followed with do not reflect the intent of the engineering department; these can be revised.

The final results of the review will be a more effective program as well as a less costly one.

[1] R.N. Frankel, Douglas Aircraft Company, letter to R.M. Casterline, United Airlines, Sept. 25, 1974.

# 12. Chapter Twelve -The role of scheduled maintenance

This chapter is a reprise. It brings together the concepts discussed in preceding chapters to expand in several areas on the role of scheduled maintenance. One of these areas is the relationship of safety, reliability, and scheduled maintenance as it pertains to the modern air-transport industry. In particular, we will examine the current safety level of transport airplanes, the manner in which this basic safety level is affected by various types of functional failures, and the proposed requirement that the likelihood of certain failures not exceed one in one billion flights. We will also considered the design-maintenance partnership and the type of relationship necessary both to realize the inherent safety and reliability of the equipment and to identify specific design modifications that will improve it.

In the preceding chapters we have discussed the development and evolution of RCM programs for new equipment. Because operating data are already available for in-service fleets, it is a simple matter to extend RCM analysis to the many types of airplanes that are currently being supported by maintenance programs developed along other lines. However, the same principles extend to any complex equipment that requires a maintenance support programs. Although older designs may have more limited capability for on-conditioned inspections to protect functional reliability, RCM analysis will pinpoint their specific maintenance requirements, and thus permit elimination of costs tasks which are not applicable and effective.

## 12.1. Safety, reliability, and scheduled maintenance

As we have seen throughout this volume, the failure process is a phenomenon that cannot be avoided by any form of preventive maintenance. However, by focusing on this process in each item whose function is essential to the aircraft, RCM programs ensured that the maximum capabilities of preventive maintenance are used to prevent those functional failures which impair safety or operating capability. The nature and extent of the impairment – the consequences of a particular failure – as well as the feasibility of protecting against it, depend on the design of the equipment itself. It is possible to design equipment in such a way that individual failures do not affect operating safety, or else with specific provisions for controlling such failures by scheduled maintenance. These design characteristics determine the inherent safety level of the equipment.

There is no really satisfactory analytic determination of the inherent safety level associated with current airworthiness requirements for transport airplanes. There have been instances in which modern swept-wing jet aircraft have not had the structural or performance capability to survive the conditions they encountered even when their structures worry intact to all engines were functioning normally. The number of these accidents is too small to provide meaningful statistics, but in rough terms we might say the safety level of modern transport aircraft whose capabilities have not been reduced by any functional failures is somewhere on the order of $10^{-7}$, or one accident per 10 million flights. Let us therefore examine the way in which safety levels are reduced by functional failures and the role of scheduled maintenance in preventing this reduction.

### Systems failures

A complete loss of certain system functions would have critical consequences for the aircraft; for example, a loss of all electrical power in weather that requires instrument procedures would clearly jeopardize the equipment and its occupants. Other system functions, such as pressurization and air-conditioning, are more forgiving; pilots can compensate for the loss by changing the conduct of the flight and, if necessary, by making an unscheduled landing. In this case the loss of function affects operational capability, feet is not critical. There are many other functions whose loss has only minor operational consequences or not at all. However, the designer of an aircraft system can always ensure that the complete loss of a particular function will be extremely unlikely simply by replicating the items that provide that function.

The availability of a system function is usually a go/no-go situation: even function is available to the airplane or it is not. When the source of a function is duplicated the probability of its becoming unavailable during a given flight is very small. If a failure of one source does occur, the function is still available. Thus, although there may be many flights during which one source of the function fails, the risk level associated with any flight is the probability of a joint event – a failure of one source, followed during the same flight by an independent failure of the remaining source. After the first failure, however, the overall exposure per flight hour during the remainder of the flight becomes considerably higher, (see Section 2.4). Consequently the actual risk level may vary not only during the course of the flight, depending upon the occurrence or nonoccurrence of a first failure, but also from one flight to another, depending on the duration of the flight. The risk level also varies, of course, with the inherent reliability of the item and the degree to which the function in question is essential to the aircraft.

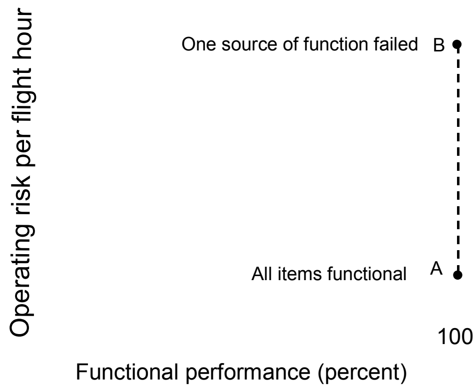



**Exhibit 12-1. The effect on the safety of functional failures in the systems division.**

This situation is illustrated in Exhibit 12.1. In a system with two independent sources, point A represents normal performance when all the items associated with both sources are serviceable. The functional performance at the airplane level will still be normal after a failure of one of the sources, but the risk per flight hour of a the laws of function is now much higher during the remainder of the flight. Except for servicing and lubrication, scheduled maintenance usually can do very little to reduce the failure frequencies of individual complex items in the systems division. Failure-finding tasks will ensure the repair of items that have already failed, but if the failure rate proves unacceptably high, the only way to improve the reliability of such items is by design changes. The information derived from operating experience will indicate very clearly the areas in which such action is needed.

## Powerplant failures

A complete loss of all proposal of power in aircraft is always critical. Once again, however, the likelihood of such a loss is made extremely remote by replication of the basic engine function on multiengine transport airplanes. In some cases this protection is also supported by certain operating restrictions. For example, the length of over water flights for twin-engine airplanes in commercial service is restricted to ensure that the airplane will not have to fly more than one hour if an engine becomes inoperative. Similarly, transport aircraft operating on transoceanic flights are restricted in weight to ensure that with two engines inoperative the remaining engines will still provide the specified rate of climb.

Although the design goal is assurance of adequate power to overcome any conditions that the airplane may encounter, there is still the remote possibility of extreme turbulence or wind shear that it cannot survive even with all engines operative. When one or more engines are inoperative, even though the remaining engines provide the required minimum thrust, the airplane's performance capabilities are reduced. Thus there is an increased risk during the remainder of the flight that it will encounter conditions that cannot be handled. This risk may vary during the course of the flight, since it is higher after an engine shutdown than it is when all engines can develop full power. The safety level may also vary from flight to flight, since airplanes fly at different weights below the maximum permissible ones, and airport conditions, en route terrain, and atmospheric conditions all vary from one flight to another.

The general effect of hand in-flight engine shutdown onto the level of operating risk is illustrated in Exhibit 12.2. The performance capability of the airplane, and hence the risk level, can be measured in terms of available rate of climb. The risk is lowest when all the engines can generate full power and increases as the airplane has less reserve power to draw upon. Unlike most systems functions, however, the situation is not limited to the two cases defined by points A and B. Since an engine failure is defined as the inability to develop a specified amount of thrust, there are many functional failures in which power is reduced but not entirely lost. Thus the risk level may fall at various points between A and B.

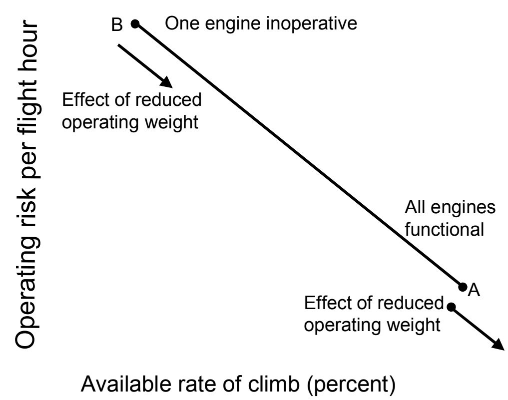



**Exhibit 12-2. The effect on operating safety of functional failures in the powerplant division.**

In multiengine aircraft primary control in maintaining a safe level of available performance is flight-by-flight control of the operating weight of the airplane. Whenever the actual operating weight is less than the maximum performance-limited weight, the available rate of climb is increased accordingly. The effect of this weight reduction on the risk level is shown in Exhibit 12.2. Scheduled maintenance does play a secondary role, however, since it reduces the frequency of engine failures, and hence the frequency with which the risk level approaches point B. In the case of single-engine aircraft, of course, scheduled maintenance is the primary control, since there is only one source of power regardless of the operating weight.

Scheduled maintenance can accomplish much more for engines and it can for some of the systems items. Because modern aircraft engines are designed to facilitate the use of advanced inspection technology, many parts of the engine can be inspected without removing them from the airplane. Thus on-condition tasks can be employed to protect individual engines against many types of functional failures, and safe-life tasks usually prevent the few types of failures that can cause critical secondary damage. While the inherent level of risk depends on the degree of engine replication and the design features of individual engines, the overall effect of scheduled maintenance for a multiengine airplane is, in fact, equivalent to the effect that could be achieved by a reduction in operating weight.

## Structural failures

The consequences of a structural failure depend on the design characteristics of the structure, but the functional failure of any major assembly is usually critical. With the exception of the landing gear, it is rarely possible to replicate major structural assemblies; hence scheduled maintenance is the only technique available to control the likelihood of functional failures. Although it usually includes some safe-life tasks, the maintenance program consists from the most part of on-conditioning inspections directed at specific structural sites. It is possible to rely on on-conditioning tasks, not only because they are applicable in all cases, but also because most modern aircraft structures are designed to be damage-tolerant – that is, they are designed to ensure that the residual strength of a structural assembly needs specified standards after the fracture of an individual element. Although the objective of the inspections is to prevent the fracture of single elements, the practice of damage-tolerant design insures that a structural assembly will still be capable of withstanding the defined damage-tolerant load in the event that fracture does occur.

As in the case of the power plant, there is always the remote possibility that an aircraft structure will encounter loading conditions it cannot withstand even though there has been no reduction of its original strength. Again, the risk level can also vary during a single flight and from one flight to another. If a structural element fractures in the course of life, the residual strength will be slightly lower during the remainder of the flight. Similarly, since the fractured elements may not be discovered and repaired until the next inspection, the risk level can vary from flight to flight, depending on whether a fracture has occurred and the effect on residual strength of the particular element that fractures. In addition, the operating weights of individual airplanes may be much less than the required structural limits, and there is a wide variation – sometimes from one moment to the next – in atmospheric conditions.

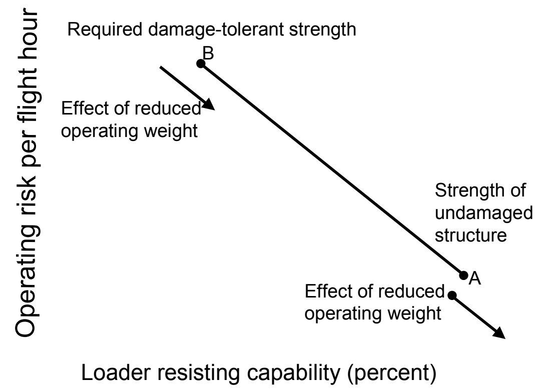



**Exhibit 12-3. The effect on operating safety of functional failures in the structure division.**

Exhibit 12.3 illustrates the general effect that functional failures (fractures) of individual structural elements have on the risk level associated with damage-tolerant assemblies. The assembly itself will suffer a critical loss of function if it can not withstand any load to which the airplane is exposed. The risk of such an event is lowest when the structure is intact, at point A. The operating weight of the airplane is restricted to ensure that the structure can withstand certain defined loading conditions in its undamaged state; it must also be able to withstand the defined damage-tolerant load at the same weight. After a failure occurs, the risk level increases to point B and remains at this level until the damages found and corrected. As in the powerplant division, however, the actual operating risk can assume any value between A and B, and the risk under any specific set of conditions is reduced when the operating weight is less than the maximum permissible structural weight.

The primary control of the safety level for structures, then, it is provided by damage-tolerant design practices and the control of operating weights. The role of scheduled maintenance in this case is to prevent the fracture of individual elements by detecting fatigue cracks in these elements soon after they occur. When the program is effective, the operating risk rarely rises above the level represented by point A. Once again, the overall effect of scheduled maintenance is equivalent to be affected that would be achieved by a reduction in operating weight.

# 12.2. Air-transport safety levels

## The problem of risk evaluation

As we have seen, there is a remote but undetermined risk level associated with an airplane before its resistance to failure is reduced by any of the forms of impairment to which it is exposed. This inherent level is increased by functional failures, but the amount of increase depends on such design features as the replication of the essential functions and the use of multiple load paths in damage-tolerant structures. Scheduled maintenance merely reduces the frequency with which functional failures occur, and hence the frequency with which the basic risk levels are exceeded. Unfortunately, however, we have no precise means of assessing either the inherent level of risk or the increased risks that do result from failures.

At first glance the assessment of risks in the systems division might seem to be a simple matter of computing flight hours and failure rates that individual items. The problem is not this straightforward, however, because the results of these considerations must be modified by a probability distribution representing the degree to which each function is essential for the safety of any individual flight. Another important variable, and one that is least amenable to analytic treatment, is the ability of the pilot to respond to and compensate for many types of systems failures.

Risk evaluation in the power plant and structure divisions is even more difficult. Airplane performance and structural-strength requirements have slowly increased over the years as a result of the few accidents that have occurred, until they have become stringent enough to produce the current safety record. Thus both performance and strength requirements are based on incurable data associated with the rear-events end of a probability distribution describing the conditions that airplanes must be able to withstand. The problem of assessing the basic risk level for any individual airplane is further complicated by operating weights which are usually much less than the airworthiness limits and flight procedures which may differ markedly from those assumed for airworthiness purposes. Consequently, even if the effect of each reduction in failure resistance could be evaluated satisfactorily, we have no means of determining the actual level from which the increase should be measured.

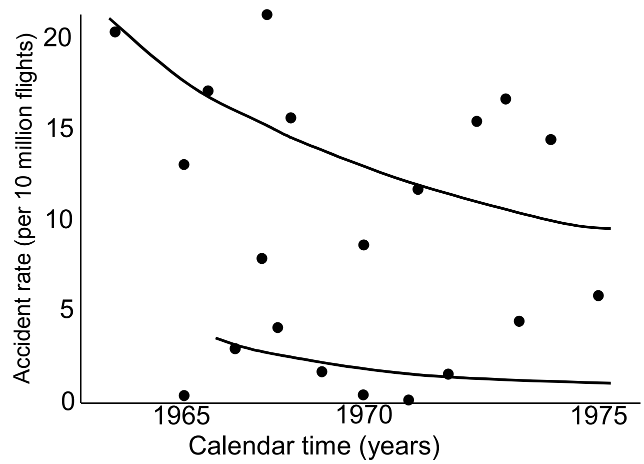



**Exhibit 12-4. Fatal accident rates for all United States air carriers over and 11 year period. the lower curve represents the accidents that involves a mechanical failure. (Based on National Transport Safety Board statistics, 1965-1975)**

Although accident statistics do not provide enough data to establish meaningful safety levels, a review of the National Transportation Safety Board statistics for the 11-year period of 1965 to 1975 shows the general trends plotted in Exhibit 12.4. The data represents all fatal accidents on domestic and international operations of United States air carriers (excluding training, ferry, and military flights) over a period representing approximately 54 million flights. During these 11 years there was a total of 523 accidents from all causes, both fatal and nonfatal, and of the 73 fatal accidents, 11 were either caused by or involves a mechanical failure and 54 were landing accidents.

The causes of these 11 accidents were classified as shown in Exhibit 12.5 to identify the ones that scheduled maintenance might have been able to prevent. Even with the benefit of hindsight, it is unlikely that additional or more effectively perform maintenance could have reduced the rate by more than half. The residual accident rate, which includes some failures of apparently sound structure in extreme turbulence, appears to be one for 10 million flights. Scheduled maintenance probably never will be pressed into enough to prevent the first occurrence of certain completely unanticipated types of failure, even though recurrence is can be prevented. Thus it will be very difficult to reduce the rate of such accidents to less than one in 10 million flights.

## The dynamite of extreme improbability

The current airworthiness regulations for transport airplanes cover many aspects of aircraft design – structural strength, powerplant characteristics, airplane performance characteristics, flight handling qualities, and systems characteristics. These regulations are directed not only at reducing the likelihood of various types of failure, but also at mitigating the consequences of those failures that will inevitably occur. Thus there are detailed requirements for damage-tolerant structure and for the residual performance capabilities of the airplane after one (or more than 1) engine has lost power. In addition, there are many requirements to ensure that the operating crew will be capable of handling the airplane safety after a failure has occurred. These airworthiness regulations have resulted in a commendable safety record for transport aircraft.

| Cause of accident | No. of accidents | Preventable by scheduled maintenance |
|---|---|---|
| Failure of apparently undamaged structure in turbulence | 2 | No |
| Failure of the damaged structure: | | |
| Airplane | 1 | Yes |
| Helicopter | 2 | ? |
| Failure of flight-control system | 1 | Yes |
| Secondary damage associated with functional failures: | | |
| Auxiliary-power unit | 1 | ? |
| Propulsion system | 1 | Yes |
| Propeller | 1 | ? |
| Obscure (functional failures involved, but role in sequence of events leading to accident cannot be identified) | 2 | ? |
| | ∑= 11 | 3 yes<br>2 no<br>6 ? |

**Exhibit 12-5. Classification of fatal air-carrier accidents involving mechanical failures.**

The regulations include a certification process to verify that the design requirements have in fact been met, and it then becomes the responsibility of the operating organization to maintain the equipment in such a way that the design characteristics are preserved. The operator must also ensure that the flight crews are trained in the procedures necessary to cope with various types of failures. A unique problem is now being encountered, however, with certain systems whose functions cannot be duplicated by the human flight crew. This situation introduces the possibility that at some time a relatively unlikely sequence of failures, some of them perhaps hidden, might result in the loss of one or more functions that are essential to operating safety.

The design objective, of course, is to ensure that such critical failures are extremely improbable, and AFA has suggested that *extremely improbable* be defined as an expected failure rate of no more than one per billion flights (or operating hours, as applicable). Even when an analysis based on assumed failure rates does indicate that the requirements will be met, the validity of the assumed rate cannot be determined in the limited amount of flying done during certification tests. A further proposal, therefore, is that the maintenance intervals be reduced if actual failure rates are higher than those assumed for the calculations. A reliability-stress analysis based on assumed failure rates may be quite involve even for a simple system. For example, the Boeing 727 automatic-takeoff trust control is a nonredundant system whose failure can because by the failure of any one of approximately 100 different items, some of which have hidden functions. The items considered to be the least reliable in this system was a fuel-control unit that had an estimated meantime between failures of 167,000 hours. To meet the extreme improbability requirements, however, the availability of this unit would have to be protected by a failure-finding interval of only 125 hours.[1]

The question, of course, is whether such intensive maintenance to meet this probability requirement is necessary or can possibly achieve the desired result. One in one billion, or $10^{-9}$, is a very, very small number. They're probably have not been one billion airplane flights since the Wright brothers took to the air. To put it another way, one billion flights represents 200 years of operation at the current activity level of the United States air carrier industry. A risk level of $10^{-9}$ he is one percent of the current residual accident rate that cannot be reduced by scheduled maintenance, and it is one-fifth of one percent of the current landing-accident rate. On this basis the proposed requirement seems unrealistic. In fact, it may even be counterproductive, since it is likely to prevent the development of systems that would improve safety even delay cannot satisfy the extreme-probability criterion. The real issue, however, is whether it is possible to develop an analytic model for evaluating new systems that is in itself accurate to anything approaching this order of magnitude.

Under the circumstances, although reliability-stress analysis is a valuable tool for comparing alternative design approaches, its application to actual operating and maintenance requirements would be difficult to justify. Further work is

[1] For a discussion of this analysis see J.J. Treacy, The use of Probability Analysis in Aircraft Certification and It's Effects on Maintenance and Equipment Maintenance, AIAA Aircraft Systems and Technology Meeting, Seattle, WA, Aug. 22-24, 1977.

clearly necessary to develop a more viable approach to the problem

## 12.3. The design-maintenance partnership

The interrelationship between design and maintenance is always most apparent in the case of aircraft. On one hand, the design of the equipment determines its inherent reliability characteristics, including the consequences of functional failures; on the other hand, scheduled maintenance attempts to preserve all the safety and operating reliability of which the equipment is capable. Realization of the school, however, requires a joint effort which has not always been recognized. Designers have not always understood the capabilities of scheduled maintenance and the practical limits on these capabilities. By the same token, maintenance organizations have not always had a clear grasp of the design goals for the equipment may maintain. They need for a cooperative effort has always existed, but the comprehensive analysis required by RCM techniques makes this need far more apparent.

During the development of a prior-to-service program the identification of significant items and hidden functions depends on the designer's information on failure effects as well as the operator's knowledge of their consequences. At this stage the information on anticipated failure modes and their associated mechanisms must also come from the designer. While the maintenance members of the study group will be able to draw on prior experience with similar materials, design practices, and manufacturing techniques, this information should be complemented by the designer's advice concerning the ages at which various forms of deterioration are likely to become evident.

At a more fundamental level, it is important for the designer to bear in mind some of the practical aspects of scheduled maintenance. In general, on-conditioned inspections are the most effective weapon against functional failures. However, it must be possible to use them, preferably without removing items from their installed positions on the airplane. Thus the designer must not only help to identify the items for which such inspections are applicable, but must also make sure that there is some means of access to the area to be inspected. An equally important factor is the use of materials and design features such as damage tolerance which result in a relatively slow deterioration of items intended for on-conditioned inspections.

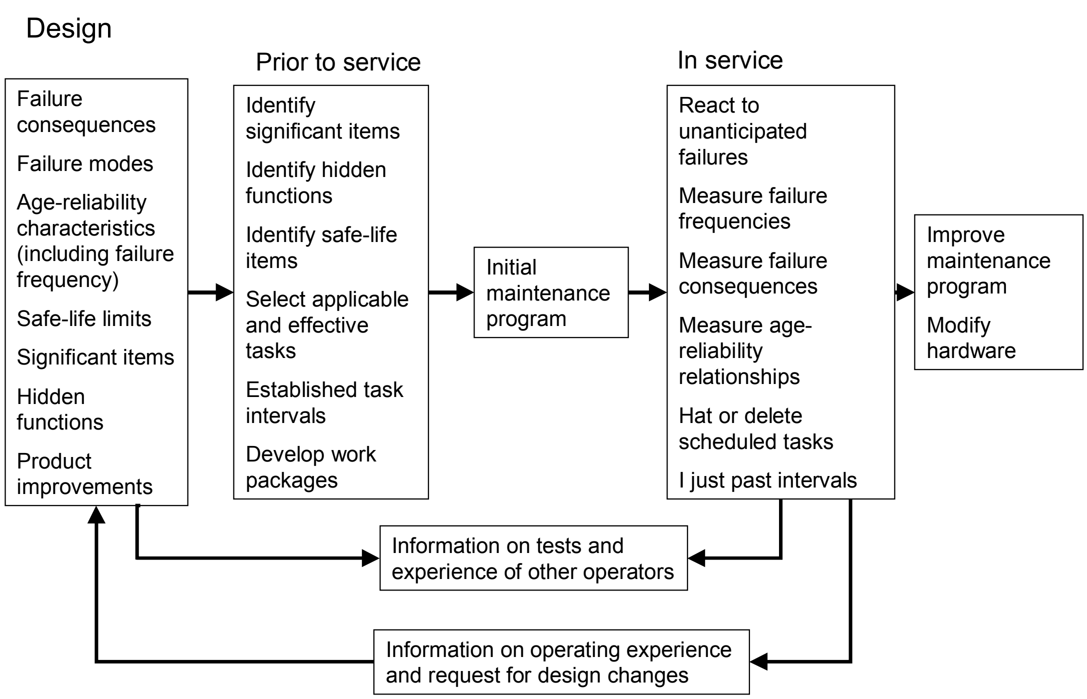



**Exhibit 12-6. The design-maintenance partnership**

Once the new airplane goes into service, they will be continuous refinement and improvement of the basic maintenance program as a result of age exploration. There will also be unanticipated failures, some of which require immediate action. In these cases the designer's help is crucial in developing new interim scheduled tasks that will control the problem until design changes can be developed and incorporated in the operating fleet. Both the design and maintenance organizations must work together to identify the failure mechanism, because this information is needed for product improvement as well as to develop the interim tasks. The product-improvement process and its role in the development of all complex equipment was discussed in detail in Section 5.5. However, it entails a two-we flow of information: the operating organization must identify the need for an improvement, and the manufacturer must advise the operator of the results of his continuing test programs and the experience is that other users of the equipment have encountered. The development of airplanes that can be more effectively maintained and achieve still higher levels of reliability and safety depends on a continuing close partnership, with both design and maintenance organizations familiar with and sympathetic to each other's problems and the goals.

## 12.4. RCM programs for in-service fleets

# 13. Appendix A Auditing the RCM program development

And RCM analysis is conducted by experienced maintenance people, and their professional expertise is one of their most valuable assets. This specialized experience has a corresponding penalty, in that it tends to create to certain biases which make objective judgment difficult. The decision-making process therefore requires an independent review by someone who is not directly involved in the analysis – an auditor, who can test the logic of the decision against the prescribed criteria and procedures and check for any flaws in the reasoning. Although the auditor's own judgments may not be completely free of bias or error, the fact that he is independent of the detailed analysis provides him with a different perspective. Thus the audit serves as a practical tool for identifying some of the common errors in the use of the decision logic, and frequently some of the more subtle errors as well.

In the air-transport industry the auditing function is performed by members of the steering committee, which also has overall responsibility for the program-development project (see Section 6.2). Thus the auditors assigned to individual working groups will be aware of the scope of the project, the overlap of work among the various groups, and the specific level of effort needed to coordinate their activities. Because the problems and focus of the analysis will differ from one group to another, it is difficult to offer any universal guidelines. However, working groups tend to stray from the objective of developing a set of applicable and effective schedule tasks, and it is important for the auditor to be able to detect this and help keep the project on the track. In many organizational contexts the work of the steering committee and the overall management of the project are themselves subject to audit, to ensure that the work will proceed efficiently and will result in the intended product. Once the program has been developed and packaged for implementation, a group within the operating organization will be responsible for collecting and analyzing reliability data needed to assess its effectiveness and evaluate the desirability of new tasks. The auditing functions in these two areas often require a different set of skills and experience from those needed to review the detailed analysis of the equipment. In all cases, however, both the auditor and the program-development team will require a clear understanding of basic concepts outlined in this volume.

## 13.1. A-1 Auditing the program development project data

The first draft of an RCM program is generally prepared by a special task force consisting of a steering committee and several working groups. The project may be organized and managed in several ways, and the auditor's first concern is whether the organization, staffing, and working procedures are adequate to carry out to project.

### Scope of the project

To ensure that the finished maintenance program will be accurate and complete, both the auditor and all participants in the project must have a clear understanding of its exact scope. In some cases the project will encompass certain portions of the equipment, rather than the entire aircraft. In either case is important to know whether the program is to cover all levels of maintenance, from servicing tasks and walkaround checks to the major-inspection level. It is difficult to design a complete maintenance program for only a few of the levels of maintenance, even if the program is just for one portion of the equipment. If the project does include only portions of the aircraft, there must also be clear provisions for handling items that interface with the portions that are not included. Otherwise the resulting confusion will lead almost inevitably to gaps and overlaps in the total program. The auditor should make sure he understands the scope of the project and should check periodically to see that it is not expanding beyond its intended bounds.

### Definition of the final product

The completed scheduled-maintenance program consists of all of the scheduled tasks and their intervals, but the exact form of this program must also be specified. Both the auditor and the program-development team must know whether the final product is to be simply a list of the RCM tasks and intervals, with a brief description for the use of production planners, or whether it consists of a complete set of work packages, like the letter-check packages assembled in airline practice. In either case, the definition of the final product should specify the level of task detail and the amount of descriptive material to be included. Will the procedures writers be able to translate the results of the analysis into job instructions that accurately reflect the purpose of each task? For whom is the final report intended? Are detailed explanatory write-ups of the program needed as part of the package? The final product will have to be checked against these requirements before it is submitted, and a clear understanding of them at the outset will facilitate the work of the analyst and the auditor alike.

### Timetable for the project

The timetable developed for completion of various aspects of the project is also subject to audit. Is it realistic in terms of the amount of work to be accomplished, the number of analysts assigned and their previous experience with RCM analysis? Are the milestones at logical points for adequate control of the schedule – or perhaps over specified, so that the crucial target dates are likely to suffer? Do they take into account the fact that analysis of the first few items will proceed much more slowly as part of the learning process? It is apparent from these questions that the timetable must be reasonably tight, but also flexible and realistic

The auditor must accomplish his own work within this timetable. In most cases progress reviews will be conducted when the overall plan is drafted, when the program-development team has been organized and trained, when each working group has agreed on the list of significant items and analysis of the first few items has been completed, when each major portion of the program has been completed, and when the final product has been assembled and is ready for approval. Additional audits will be needed between these checkpoints to review progress and clear up any questions or misconceptions in the analysis itself. Where subsequent work depends on the results of the auditor's review, is the review timed to ensure that it will not impede other aspects of the analyst's work?

### The program-development team

In addition to those factors that relate to the project itself, the auditor must also consider the organization of the program-development team and the skills of people who comprising it. Whereas the analysts will be working engineers with extensive hardware experience, the task force should be headed by someone with managerial experience, and preferably someone who has had experience on similar products. Is the manager himself knowledgeable about RCM principals, or is he assisted by someone who is? Is he an organizational person that will facilitate completion and implementation of the project? To what extent is the project supported by top management?

The adequacy of the staffing, the working arrangements among the team members, and the availability of outside resources all require careful study. Are there are enough people to do the work in the time allotted – and not too many to work closely as a team? Are the analysts in each working group experts in the portion of the equipment they will be analyzing? Are all engineering and reliability disciplines represented or available for consultation? How is the task force organized? Does the organization provide for direct interaction among members of the group, or are their organizational obstacles that may impede communication? Is each analyst responsible for a complete analysis, or are various aspects of the job (researching information, completing worksheets, etc.) assigned in a way that makes work difficult to integrate? What arrangements have been made for the analysts to obtain help from outside resources or more details about the operation and construction of the equipment? Is the designer available to answer questions about specific failure modes and effects? Is there someone available to each working group who has an extensive knowledge of RCM techniques? The auditor should not only check the availability of these resources, but also determine how frequently they are being used.

### Standards and procedures

One important function of the steering committee (or manager of the task force) is to arrange for training of all participants. This includes general familiarization with the design features of the new equipment, as well as training in RCM procedures and the standards to be used for this particular project. If this is a large project, some members will require more training that others. Has each member of the task force received adequate training in RCM methods, and is the RCM text available for easy reference? Other standards that apply to the project should also be available in written form. Does each analyst have a copy of the cost-trade-off models to be used, including the costs imputed by this organization to various types of operational failures? What failure rates or repair expenses are considered high enough to qualify an item for analysis? Alll written standards and procedures should be checked carefully for any ambiguity or lack of clarity. They should also be checked for any fundamental conflicts with basic RCM concepts.

Each working group will require additional detailed trading on the portion of the equipment to be analyzed. Have all analysts been furnished with written materials, schematics, and full descriptions of the hardware and its relationship to other aspects of the airplane? Are reliability data available for similar items, either from developmental testing or from service experience? Is there access to an actual production model of the equipment if further questions arise?

## 13.2. A-2 Auditing the decision process

### The selection of items for analysis

Once the program-development team has been assembled, organized, and trained, the focus of auditing shifts to the analysis process itself. Ordinarily this phase of auditing is carried out by a member of the steering committee, but the chief prerequisite is a clear understanding of RCM principals. As a preliminary step the working group will screen out all obviously nonsignificant items and complete descriptive work-sheets for those items selected for analysis. Thus the first problem may be in arriving at a common definition of *significant item*. There is often a tendency to identify items as significant on the basis of their cost and complexity, rather than on the basis of their failure consequences. It is important that all members of the group understand that failure consequences refers to the direct impact of a particular loss of function on the safety and operating capability of the equipment, not to the number of failure possibilities for the item or the effect of these failures on the item itself.

Another area that may require clarification is the definition of operational consequences. If the minimum-equipment list or other regulations stipulate that the equipment cannot be dispatched with an item inoperative, the item is always classified initially as one whose failure will have operational consequences. However, the actual economic impact will vary from one of operating context to another and even from organization to organization, depending on the scheduled use of the equipment, maintenance facilities, the ease of replacing field units, and a variety of other considerations. For this reason it is necessary to have a clear definition of the circumstances that constitute operational consequences and the relative costs imputed to those consequences by the organization for which the program is being prepared. Without this information there is no clear basis for determining whether a given type of failure would have major economic consequences for this particular organization.

## Reviewing the information worksheets

Several problems may come to light when the completed worksheet forms are examined. One of these is the design of the worksheets themselves. Each organization will have its own preferences about forms, but the worksheets must cover all the points to be considered in the analysis. Whenever worksheets are redesigned there is always the danger of overlooking some of the basic elements or a introducing "improvements" that reflect misconceptions. In general the forms should be as simple as possible and still provide an adequate record of the decision process. The chief criterion is that each task be completely traceable. At any time, either during or after the analysis, it must be possible to start with any function and trace through to the task assigned to protect it or to backtrack from a given task to examine the reasoning that led to it. Obvious omissions can often be spotted from an examination of the blank forms, but more subtle difficulties may not come to light until the first few worksheets are completed.

Another problem – and perhaps the single most important error for the auditor to detect – is improper definition of the functions of an item. Is the basic function stated precisely for the level of item in question? Does it relate directly to some higher-level function that is essential to operating capability? If not, there may be some confusion about the level of item under discussion. Have all secondary or characteristic functions being listed, and is each in fact a separate function from the standpoint of the operating crew or the system as a whole? Does the list include all hidden functions (again, stated in terms of the system as a whole)? If there are failure possibilities with no related function, this is a clue that the functions themselves require further thought. For example, the basic function of the fuel pump is to pump fuel; however, if this item is also subject to leaks, one additional function must be to contain the fuel (be free of leaks).

It is important to bear in mind that the level of item being analyzed will affect the way the functions are described. At the parts level each part has a function with respect to the assembly in which it is contained, but the description of these functions leads to an analysis of failures only from the standpoint of the assembly, not from the standpoint of the system or aircraft as a whole. At to high a level the number of functions and failure possibilities may be too great for efficient analysis. One test is to select a few items and try combining them or dividing them further to see whether this changes the list of functions. If so, that makes the analysis most efficient but still includes all the functions that can clearly be visualized from the aircraft level.

The statement of functional failures should be examined carefully for any confusion between functional failures and failure modes. This statement must describe the *condition* defined as a functional failure (a loss of the stated function), not the manner in which this failure occurs. There is often a tendency to describe a failure such as external leaks as "leaking oil seal," with the result that other failure modes that lead to external leaks may be overlooked, or else erroneously attributed to some other function. This problem is often a source of the difficulty in defining the item's functions. The statement describing the loss of a hidden function requires particular care to ensure that it does not refer to a multiple failure. For example, if the function of a check valve is to prevent backflow in case of a duct failure, the functional failure in this case is not backflow, but no *protection* against backflow. Errors in this area can be quite subtle and difficult to spot, but they frequently lead to confusion about the failure consequences.

The identification of failure modes is another problem area. Do the worksheets list failure modes that have never actually occurred? Are the failure modes reasonable in light of experience with similar equipment? Have any important failure modes been overlooked? In this area the auditor will have to rely on his own general engineering background to identify points on which further consultation with the designer or other specialists is advisable. One problem to watch for his superficiality – failure modes that are not the basic cause of the failure. Another is the tendency to list all possible failure modes, regardless of their likelihood. This results in a great deal of unnecessary analysis and the possible inclusion of unnecessary tasks in the initial program.

Just as failure modes may slide back into the description of functional failures, they also tend to slide into the description of failure affects. Thus one point to watch for is a description of failure effects that relates to the cause of the failure, rather than to its immediate results. Again, the failure modes "leaking oil seal" will sometimes be stated as a failure effect (perhaps with "oil-seal failure" given as the failure mode). This is a subtle error, but it obscures the effect of the functional failure in question on the equipment and its occupants.

The description of failure effects must include all the information necessary to support the analyst's evaluation of the failure consequences. Does the statement include the physical evidence by which the operating crew will recognize that a failure has occurred – or if there is none (a hidden failure), is this fact mentioned? Are the effects of secondary damage stated, as well as the effects of a loss of function, and is it clear from the description whether or not secondary damage is critical? Is the description stated in terms of the ultimate effects of the failure with no preventive maintenance? In the case of hidden functions the ultimate effects will usually represent the combined effects of possible multiple failure. This information helps to establish the intensity of maintenance required to protect the hidden function; however, it must be clear from the description that these effects are not the immediate results of the single failure under consideration.

The failure effects should be examined to ensure that they do not represent overreaction by inexperienced analysts. At the other extreme, there is a possibility that serious effects may have been overlooked where the equipment cannot be shown to be damage-tolerant for certain types of failures. In either case the effects stated – including secondary damage – must be a direct result of the single failure in question, and not effects that will occur only in conjunction with some other failure or as a result of possible pilot error. As with hidden-function items, protection against multiple failures is provided for in the decision logic by independent analysis of each single failure possibility.

## Classification of failure consequences

The first three questions in the decision logic identify the consequences of each type of failure, and hence the branch of the decision diagram in which proposed tasks are to be evaluated. The answers to these questions therefore warrant special attention during auditing to ensure that tasks have been measured against the correct effectiveness criterion. The basis for each answer should be clearly traceable to the information recorded on the descriptive worksheet.

There are several common problems in identifying hidden functions. The first matter to be ascertained concerns the use of the decision diagram itself. Has the evident-failure question been asked, not for the item, but for each of its functions? If not, the answer may be true only for the basic function, and other functions will be analyzed according to the wrong criteria. And if the basic function of the item happens to be evident, hidden functions that require scheduled tasks may be overlooked. Another common error is the tendency to overlook cockpit instrumentation as a means of notifying the operating a crew of malfunctions that would otherwise not be evident. An error that is more difficult to spot is the identification of a replicated function in an active system as evident when a failure would in fact not become evident until both units failed.

Have the functions of emergency items, such as ejection-seat pyrotechnics and stored oxygen, been overlooked? Hidden-function items with built-in test equipment may be improperly identified as having evident functions because failure-finding tasks are performed by the operating crew. Similarly, items whose loss of function is evident during normal use may be mistakenly classified as hidden-function items simply because they are not used during every flight. (In this case the failure-reporting system may have to be supplemented by maintenance checks to ensure continued availability, but the analysis of this function does not fall in the hidden-function branch.)

Answers to the safety questions may reflect some misconceptions about the definition of a critical failure. Has a failure been identified as critical (or for that matter, as evident) on the basis of multiple-failure consequences, rather than the consequences of a single failure? Has it been identified as critical because it requires immediate corrective maintenance – that is, it has operational (but not safety) consequences? Has the analyst taken into account redundancy and fail-safe protection that prevents a functional failure from being critical? One problem that requires special attention is the failure to identify secondary damage as critical when the aircraft cannot be shown to be damage-tolerant in this respect.

Answers to the operational-consequences question should be checked for any inconsistencies with the minimum-equipment list (MEL) and the configuration-deviation list (CDL). The auditor should watch for tendencies to interpret failures that are expensive to repair as having operational consequences, or to describe operational consequences to failures that inconvenience the operating crew but do not limit the operating capability of the equipment in any way. In some cases operating restrictions associated with continued operation after the occurrence of a failure may be overlooked as operational consequences. If they have also been overlooked in the statement of failure effects, they should be added to the information worksheet.

A no answer to question 3 means that the failure in question has only non operational consequences, and that function need not be protected by scheduled tasks in an initial program. If the item is subject to a particularly expensive failure mode, it will ordinarily be assigned to intensive age exploration to determine whether scheduled maintenance will be cost-effective. At this stage, however, any task analysis that falls in the third branch of the decision diagram is subject to challenge by the auditor and must be supported by a cost-trade-off study based on operating data for the same or a similar item.

All answers to the first three decision questions should be examined in detail, at least for the first few items completed by each analyst. Even experienced analysts will have to refer to the RCM procedures to refresh their memories on certain points, and the auditor's review of this aspect of the decision logic is essential not only to correct errors, but to ensure that the analyst fully understands the nature of the questions. Misconceptions in this area are often evidenced by attempts to revise the decision diagram to overcome some apparent shortcoming. So far. such revisions have proved to stem from an incomplete understanding of RCM concepts. Rather than from deficiencies in the diagram. The auditor should therefore be alert to this tendency and make sure that the decision diagram has not been altered.

## Task selection: applicability criteria

The answers to the remaining decision-diagram questions represent the evaluation of proposed tasks. The most important point for the auditor to determine here is that the analyst understands the relative resolving power of the four basic types of task and specific conditions under which each type of task is applicable. One frequent error in evaluating an on-conditioned task is the failure to recognize all the applicability criteria. If the task is merely an inspection of the general condition of the item and is not directed any specific failure mode, it does not constitute an on-conditioned task. The failure mode must also be one for which is possible to define a potential-failure stage, with an adequate and fairly predictable interval for inspection. Another error is extending the task to include the detection of functional failures (as defined for the level of item being analyzed); the objective of an on-condition task is to remove units from service before the functional failure point.

It is important to a evaluate proposed on-condition tasks in terms of their technical feasibility. The failure mode may be one for which on-condition inspection is applicable, but is the item accessible for inspection? Is the task one that is feasible within the maintenance framework of the organization? Working groups often suggest inspection techniques that are still in the developmental state or recommend methods that are feasible in theory but have not been tested. In the case of critical failure modes this may be necessary, but it is equally likely that redesign will eliminate the need for the task, and both alternatives should be investigated. Does each inspection task include the specific evidence the mechanic is to look for? If not the procedures writers may have difficulty converting the task to the proper job instruction, especially when the task is a visual inspection.

If a rework task has been specified, have the age-reliability characteristics of the item being established by actuarial analysis? Does the conditional-probability curve show wearout characteristics at an identifiable age *and* a high probability of survival to that age? Is the failure mode one for which rework will in fact restore the original resistance to failure? The auditor should be prepared to question assumptions that the item under study will prove to have the same reliability characteristics has a similar item that was shown to benefit from scheduled rework. If there is a reason to believe that scheduled removals for rework will be of value, is there a cost-effective interval for this task? Has the item been assigned to age exploration to obtain necessary information?

The only discard tasks that should appear in an initial program are for items that have been assigned life limits by the manufacturer. However, there is sometimes confusion about the difference between safe-life limits and other age limits. Does the safe-life limit represent a zero conditional probability of failure after that age? Is the limit supported by manufacturer's test data? If the task interval instead represents the average age and failure, it is incorrect. Safe-life tasks are applicable only two items subject to critical failures; hence they should appear only in the safety branch of the decision diagram. The life items assigned to hidden-function emergency items – which are not in themselves subject to critical failures – are adjusted on the basis of failure-finding tests and in the strict sense are not safe-life limits. The auditor should question any safe-life discard tasks that are not supported by on-condition inspections (where possible) to ensure that the safe-life will be achieved.

There are several pitfalls to watch for in auditing failure-finding tasks. One is the failure to recognize that these tasks are the result of default – that is, they are the outcome of all no answers in the hidden-function branch of the decision diagram. Another problem is failure to recognize that these tasks are limited to the detection of functional failures, not potential failures. The intervals for such tasks should be examined for mistaken assumptions concerning the required level of availability. Does the level of availability properly reflect the consequences of a possible multiple failure? Has the analyst overlooked the fact that the interval is based only on the required availability of the hidden function itself? Have failure-finding tasks covered by routine crew checks been accounted for on the decision worksheets?

## Task selection: effectiveness criteria

It is important to remember that the applicability criteria for tasks pertain only to the type of task and are true for that task regardless of the nature of the failure consequences. The effectiveness criteria, however, depend on the objective of the task – the category of failure consequences it is intended to prevent – regardless of the nature of the task. Thus the expected resolving power of a particular task can be measured only in terms of the effectiveness criterion for the branch of the decision diagram in which the failure is being analyzed.

Some practical problems come up in interpreting the effectiveness criterion of the safety branch. Do the tasks and intervals selected have a reasonable chance of preventing all critical failures? If not, what is the basis for judging that the remaining risk level is acceptable? It is important in this connection to bear in mind the resolving power of the different types of tasks. On-condition tasks provide control of individual units and therefore have a good chance of preventing all functional failures if the inspection interval is short enough; in contrast, age-limit tasks (scheduled removals) merely control overall failure rate for the item. The auditor should therefore question the decision outcome of scheduled rework in the safety branch, because a reduction in the failure rate is unlikely to reduce the risk of failure to an acceptable level. What is the policy or procedure for items for which no applicable and effective tasks can be found? Is there an established procedure for referring them back for design? Is there provision for a review with the designer prior to any such referrals?

For tasks in the operational-consequences branch the only criterion for effectiveness is cost-effectiveness. Does the analysis show the basis for determining that the task will be cost-effective? What costs are imputed to the operational consequences, and what is the source of these costs? Is the number of operational interruptions shown in the analysis realistic? Is the expected reduction in this number as a result of the proposed task based on real data, or at least real data for a similar item?

Cost effectiveness is far more difficult to justify in the nonoperational-consequences branch. If a task has been assigned, what is the basis for the cost-trade-off analysis? Does the analysis erroneously attribute imputed costs of operational interruptions to these failures? If it includes any savings beyond the cost of correcting the failure and its resulting secondary damage, the cost analysis is incorrect.

In the hidden-function branch the proposed task must ensure the level of availability necessary to reduce the risk of a multiple failure to an acceptable level. Is there a policy concerning this risk level that can be used to interpret adequate availability? Does the policy differentiate between items on the basis of the consequences of the multiple failure?

### Use of the default strategy

In any initial program the decision paths will reflect default answers. Thus the analyst's use of the default strategy should also be audited. Have the failures which may or may not be evident to the operating crew always been classified has hidden? Where it cannot be demonstrated that any anticipated secondary damage will not be critical, has the failure been assigned to the safety branch? Have any opportunities been overlooked to assign on-condition inspections that may be partially effective in preempting functional failures? Have all items for which the necessary information was unavailable been assigned to age exploration? In checking the analyst's understanding of the default strategy, the auditor may encounter some instances of overuse. Are default answers being used when real and applicable data for the item are in fact available as the basis for a firm decision?

### General use of the decision logic

After examining individual aspects of the decision logic, the auditor must review the results of the analysis in larger perspective. Has every task being assigned through direct application of the decision logic? One major problem is the tendency to select a familiar maintenance task and then work back through the decision logic to justify it. This handicaps the analysis in two ways: on one hand, more of the tasks tend to stay justified, and on the other, the possibilities of new tasks are not explored. Some analysts may have a strong preference for rework tasks and will specify them whether they are applicable or not. Others will favor chronic condition inspections under any and all circumstances.

The auditor should look for signs of individual bias during the progress-review meetings, and by actually counting the numbers of each type of task selected by the various analysts. If there are more than a dozen rework tasks for the entire systems division of a new type of airplane, the results of the analysis should be questioned. It is also important to check the disposition of items that have no scheduled tasks. Is the number disproportionately high or low? Have items whose failures have neither safety nor operational consequences been reclassified as nonsignificant?

The worksheets and all supporting information should be assembled for each item, usually with a cover sheet summarizing all the tasks and intervals. After this material has been audited for accuracy and completeness, and revised or corrected as necessary, the auditor should sign or initial the list of tasks as final approval.

## 13.3. A-3 Auditing analysis of the equipment

The auditing principles discussed thus far apply to all divisions of the equipment. However, each of the major divisions – systems, power plant, and structure – has certain features that pose specific problems during the analysis.

### Analysis of systems items

The chief difficulty in analyzing systems items is confusion about the appropriate level of analysis and the functions of the specific item under consideration. Does the list of significant items consist of systems and subsystems, perhaps with a few of the more important complex assemblies? If more than 500 systems have been classified as significant at the aircraft level, the list is probably too long, and if there are fewer than 200, it may be too short. If any subsystem includes more than half a dozen functionally significant items, their classification should be re-examined.

Another problem is finding the dividing line between one system and another. Have the working groups agreed on the list of significant items and specific hardware each analysis will cover? Does the procedure allow for later revisions as each group gets into the details? Working groups will occasionally overlook a significant item or a hidden function. The auditors should check for this by scanning the list of items classified as nonsignificant and questioning any that are doubtful.

Several questions will come up in examining the list of functions for each item. Is the basic function correctly stated for the system level represented by the worksheet? (*Is* the system level clearly identified on the worksheet?) how does the analyst know that all the functions have been listed? Does each functional failure have at least one failure mode, and are the failure modes all the real and possible? Do the failure effects reflect the complete impact of each type of failure on the rest of the equipment? It pays to play "what if" with the analyst for a sample of failure possibilities to determine whether he is analyzed the item in sufficient depth.

In auditing the tasks assigned to the item the auditor should check to see that on-condition inspections are generally limited to installed items. There is a tendency to specify shop inspections for systems items simply because they will be in the shop often, which may unnecessarily increase workload. Any rework tasks must be substantiated by actuarial analysis. Does this analysis showed that scheduled rework will in fact improve the reliability of the item? Rework is not cost-effective for many systems items even when their failures are age-related. If a rework task is applicable, has a cost-effective interval been found?

Are discard tasks specified only for the few items to which the manufacturer has assigned life limits? Are safe-life limits supported, where possible, by shop inspections of opportunity samples for corrosion or other damage? Do failure-finding tasks scheduled for installed systems items duplicate either shop inspections or routine crew checks? Where such tasks are added to crew duties, what consideration has been given to the present workload of the operating crew? What provisions have been made for evident functions that the analyst knows will not be used regularly in the intended operating context?

## Analysis of powerplant items

In auditing a powerplant program is important to know exactly what the powerplant includes. In some cases the analysis covers only the basic engine; in others it includes all the quick-engine-change parts. If this has not been determined, some key items may escape analysis. Certain problems will be a matter of coordination. Was the systems analysis of the central engine accessories far enough along to be taken into account by the powerplant analysis? Did they have access to the structural analyses of the engine mounts and cowling? How do the failure possibilities for these items affect the basic engine?

The engine itself is subject to a number of failure modes that involve secondary damage. Whether or not this damage is critical, however depends on both the model of engine and the type of airplane. Does the working group have a complete understanding of the specific design characteristics of this engine? The failure effects require particularly careful auditing. Has the analyst considered the ultimate effects in the absence of any preventive maintenance, or does the description presuppose that progressive failure modes will be halted before they reach the critical stage? Will a failure mode that would otherwise be critical in fact be preempted by non critical loss of function? Where the failure evidence depends on cockpit instrumentation, what instrumentation indications are evidence of this particular type of failure?

Unless the engine is installed in a single-engine plane, an engine failure that does not involve critical secondary damage does not have safety consequences. Have evident failures being properly placed in the operational-consequences branch of the decision diagram?

Safe-life limits must be covered by discard tasks, but most of the tasks in an initial powerplant program will be on-condition inspections. Have these tasks been assigned two installed engines whenever possible, to avoid the need for engine removals? Are they limited to non problem areas, with the remaining on-aircraft inspection capability reserved for troubleshooting and later scheduled tasks if necessary? The intervals for inspections on installed engines should be specified in operating hours or flight cycles, whereas shop inspections of internal engine items should be scheduled to take advantage of opportunity samples. Have any shop inspections been specified in a way that will require scheduled removals or unnecessary disassembly to reach a single part?

The entire age-exploration program for the powerplant should be reviewed. Does it include procedures for increasing task intervals on the basis of inspection findings? Does it provide for inspection of the oldest parts available on an opportunity basis, without special disassembly for age-exploration purposes? Does it include threshold limits, or a similar plan, to allow the removal of most units from service at or before the upper limit without special engine removals? If any of these features are missing, that aspect of the age-exploration plan should be questioned.

## Analysis of the structure

Auditing of the structure program consists of a review of the ratings and class numbers used to establish the initial inspection interval for each structurally significant item. Both the auditor and the analysts must have a clear understanding of the difference between damage-tolerant and safe-life structure, the rating factors that apply in each case, the basis for rating each factor, and the basis for converting the final class number into an inspection interval. Some members of the working group may have more difficulty than others in grasping the distinction between resistance to failure and residual strength. Are all members of the working group using the same definition of fatigue life, and are the manufacturer's data expressed in these terms? Was the conversion of test data into safe-life limits based on an adequate scatter factor?

The definition of a structurally significant item is one of the most important aspects of the analysis. Is the basis for this definition clearly understood by the working group? Are the significant items generally confined to primary structure, or is needless effort being devoted to evaluation of much of the secondary structure as well? Has adequate consideration been given to the possibility of multiple failures at the same site? If the designations are correct, most of the significant items will represent small localized areas, rather than whole structural members; otherwise each item will require much more inspection time in the continuing program. Has the manufacturer's engineering department participated in the identification of significant items? No one else is in a position to identify the structural elements most susceptible to fatigue failure and the effect of such failures on the strength of the assembly.

If the structure includes any new material or manufacturing processes or is to be operated under any new conditions, the inspection intervals will be far more conservative. Even with familiar materials and conditions, however, the test data must the data for this production model. Is a fatigue test being conducted for the whole structure, and will preliminary results the available in time for use in developing the initial program? Will inspection findings and any failure data from the flight-test program be available? The fatigue data should be examined to determine whether the flight-load profile is realistic. The usual test method is flight cycles; is the conversion to operating hours realistic for the intended to operating environment?

While structural strength and fatigue life are the manufacturer's responsibility, the operating organization is concerned in these matters as well. The working-group members must therefore have enough information about the design and the test results to be able to evaluate and question the manufacture's maintenance recommendations. One point the auditor should check at an early stage is whether there is adequate interaction between the manufacturer's and the operator's representatives to provide for full participation by all members. Before work begins there must the general agreement on the basis for the selection of significant items and the basis on which each factor will be rated. A sample of structurally significant items and their ratings should be audited to make sure they correspond to this agreement before significant items are selected for the whole structure. Do the ratings give proper recognition to areas prone to corrosion as a result of their location? Has external detectability been properly considered? What was the basis for converting class numbers to intervals? Are the intervals similar to those in current use for other aircraft?

The number of structurally significant items on an airplane will depend on the size of the airplane, the size of the area designated as significant, and in some cases on the number of ways it can be accessed. Has the exact location of each significant item been clearly designated? Have photographs been provided which show the designated items? The working group should verify the entire list of significant items by inspection of an airplane in its fully assembled configuration. Some items assigned visual inspection may in fact be hidden beneath other structural elements or behind installations. In this case x-ray inspection may have to be specified, or some other approach to the area may have to be employed for this significant item. The tasks themselves should be audited to ensure that the inspection plan as a whole does not include unnecessarily expensive or sophisticated techniques. Is x-ray inspection, for example, limited to areas in which it is known to be useful, or are all items covered in the hope that it will be useful?

The basic inspection plan covers only structurally significant items. However, it will be supplemented by general inspections of nonsignificant structure as part of the zonal program, preflight walkaround inspections, and general inspections of the external structure. The structure program should therefore be reviewed in connection with these other programs, both for any obvious conflicts and to ensure that all nonsignificant portions of the structure have been accounted for. Has external structure that is not visible from the ground been taken into account? Do the inspections assigned to structural elements in systems and power plants take into account the other inspection requirements of powerplants

## Non-RCM program elements

The zonal inspection program should be audited to ensure that all zones in the airplane are included. If the rating scheme has been used to establish relative inspection intervals, is it consistent with RCM principles? Do the relative intervals for each zone correspond to the rating scheme? How do these intervals correspond to those for detailed inspection of internal structurally significant items? If there are conflicts can the zonal inspection intervals be adjusted? Zonal inspections are general visual inspections; do the tasks clearly describe the elements in the zone to be inspected?

The servicing and lubrication tasks should be audited for completeness, and any deviations from the manufacturer's recommendations should be substantiated. The specifications for walkarounds and other damage inspections should be audited to make sure that all the important areas are clearly indicated – especially those most likely to incur damage from ground operation and from mechanic traffic itself.

## The completed program

After each working group has completed its analysis and results have been audited separately, additional questions may arise when the program is examined as a whole. Some apply to the accuracy and completeness of the worksheets when they are summarized for each major portion of the airplane; others apply to packaging questions that arise when all the tasks are grouped for implementation.

Do the tasks for each portion of the airplane cover all levels of maintenance? Have all of them been transcribed accurately? Do they still make sense when they are viewed together? One problem that may come up at this stage is a discrepancy in the level of task detail and amount of explanatory material for different items. All the tasks should be reviewed to see that they meet the original definition of the final product. Are there any gaps or overlaps? If the final product is simply a list of the tasks and their intervals, have those intervals that are flexible been indicated, to facilitate packaging decisions?

Packaging presents special auditing problems, since the standards to be applied depend on the organization, it's routing practices, the fleet size, the number and location of maintenance facilities, and a variety of other factors. High of these been taken into account? Are the most frequent tasks the kind that can be accomplished at small stations with limited staff and facilities? Auditing the packaging of the tasks is primarily a matter of determining whether the tasks have been scheduled as efficiently as possible for a given set of circumstances.

The impact of the maintenance program on the intended use of the equipment should not be overlooked in the audit. Will the proposed maintenance schedule permit each aircraft to carry out the longest series of scheduled flights without interruption? If not, can either the operating schedule or the maintenance schedule the revised? Does the program allow for all the operating environments that will be encountered, including a possible change from one set of operating conditions to another for the same aircraft. Does it provide for RCM analysis of any new systems or tasks that may be added as a result of age exploration?

# 13.4. A-4 Auditing the ongoing program

Once the initial RCM program has been completed and packaged for implementation, a group within the organization will also be needed to monitor failure data and results of age exploration and revise the prior-to-service program accordingly. The plans for these activities and overall management of the ongoing program are also subject to auditing. Certain information systems must be established before the aircraft goes into service:

- A system for recording failures, their frequency, and their consequences.
- An age-exploration system for continual evaluation of age-condition information, with procedures for extending task intervals as rapidly as data permit
- A system for controlling the addition of new scheduled tasks to ensure that they meet RCM criteria before they are accepted
- A system for periodic re-evaluation of all tasks in the program to eliminate those that are no longer needed
- A system for reviewing the content of the work packages as the size of the fleet grows
- A system for evaluating unanticipated problems and determining the appropriate action

Are the present information systems adequate to meet all these requirements? Are they adequate for the size and age of the fleet? How familiar are the key personnel with basic RCM concepts, and how are differences of opinion resolved?

Auditing an ongoing maintenance program may require different skills and experience from those needed to audit program development. The auditor's questions during program development are chiefly at the procedural level. At this stage, however, the auditor may often find himself in an adversary situation, where much of his work is with people having differing viewpoints about what should or should not be done. Thus he will have to be both inquisitive and objective to discern the overall pattern of reliability information from various sources and interpret its impact on the maintenance program.

## A-5 Auditing new programs for in-service fleets

The auditing principles in Sections A-2 and A-3 also apply to the new RCM programs for in-service aircraft, but there are some additional factors to bear in mind. Older aircraft may not be as sophisticated or complex as those currently being developed, and there are often fewer fail-safe or damage-tolerant features. Consequently both the pattern of analysis and the resulting tasks may differ somewhat from those for a new airplane. Another reason for the difference, however, is that much of the age-exploration information is already available; thus the tasks that would ordinarily be added later to a prior-to-service program will appear from the outset in a new program for in-service equipment.

It is especially important for the auditor to determine that the new RCM program has not been developed by an analysis of the existing tasks, but represents a completely independent analysis of the equipment. The set of tasks resulting from this analysis should then be compared with the existing program to determine the differences. At this time the current tasks that were not included in the new program should be reviewed, but only to ensure that nothing has been missed.

In developing a program for a new type of airplane, reliability data on similar items, even when it is available, may or may not apply to the item under study. In this case however, the necessary information is available from actual operating experience. Thus one of the major differences in auditing the analysis itself is to determine that the data were in fact used and were used correctly. The auditor should make sure the rework tasks, for example, have not been selected without an actuarial analysis of the data on this item. A sample of the actuarial analyses themselves should be reviewed to see that they conform to the general methods outlined in Appendix C.

The number of tasks in the program will ordinarily be somewhat greater for and in-service airplane, and in many cases their will be quite a few rework tasks for systems items. These should be reviewed thoroughly to make sure they are necessary; however, an older airplane may require more rework tasks than the new one for several reasons. First, the results of age exploration will show that a few rework tasks are economically desirable and should be included in the program. Second, the older designs may actually have more assemblies that show a wearout pattern. There may also be a larger number of scheduled tasks for hidden functions because of older design practices, and the number of on-condition tasks may be slightly higher because ways of exploiting these relatively inexpensive inspections will have been found for a number of items.

In comparing the completed RCM program with the existing program the auditor will have to take differences in terminology into account. Many older programs call some tasks on-condition that do not meet the criteria for this type of task. They may be inspections of the general condition of the item, or they may be inspections to find functional failures rather than potential failures. Similarly, the designation condition of monitoring will actually include failure-finding tasks for some items. In case of doubt the auditor (or the analyst) may have to refer to the job-instruction card for the present task to determine its actual nature.

As with any program-development project, the results should be reviewed to ensure that they are in accord with the definition of the final product. In the case of the program for in-service equipment the final product may consist only of the new RCM program, or it may include a full cost comparison of the two programs and perhaps a list of recommendations.

# 14. Appendix C actuarial analysis

The applicability criteria for both scheduled rework tasks and economic-life tasks include two conditions which require the use of conditional-probability and survival curves derived from operating data:

- There must be an identifiable age at which the item shows a rapid increase in the conditional probability of failure.
- A large proportion of the units must survive to that age.

Both conditions, of course, relate to the question of what good an age limit might do. In this appendix we will consider the problems and methods involved in determining whether the failure behavior of an item satisfies these conditions. Although much of the computation is amenable to computer applications, the discussion here is confined to manual methods, both to illustrate the computational details and to indicate the areas in which certain graphical procedures have distinct advantages over most available computer methods.

The development of an age-reliability relationship, as expressed by a curve representing the conditional probability of failure, requires a considerable amount of data. When the failure is one that has serious consequences, this body of data will not exist, since preventive measures must, of necessity, be taken after the first or the first few failures. Thus actuarial analysis cannot be used to establish the age limits of greatest concern – those necessary to protect operating safety. In these cases we must rely instead on safe-life limits established on the basis of the manufacturer’s test data. Fortunately safe-life items are single parts, and the ages at failure are grouped fairly closely about the average. However, the test data for long-lived parts are so scanty that we usually cannot associate them with any of the well-developed probability distributions. Thus a safe-life limit is established by dividing the test results by some conservatively large arbitrary factor, rather than by the tools of actuarial analysis.

The same limitation applies to failures that have serious operational consequences. The first occurrence of such a failure frequently requires an immediate decision about protective action, without waiting for the additional data necessary for an actuarial analysis. At the other end of the scale, there will usually be a large body of data available for those items whose failure has only minor consequences. Thus there is ample material for an actuarial analysis to determine whether an age limit would be applicable, but far less likelihood that it will meet the conditions for cost effectiveness. The chief use of actuarial analysis is for studying reliability problems in the middle range – those failures which, taken singly, have no overwhelming consequences, but whose cumulative effect can be an important cost consideration.

## 14.1. C-1 analysis of life-test data

Actuarial analysis is simplest when it is based on data obtained from a life test. In a life test a group of units of a given item begin operation simultaneously under identical operating conditions. Each unit is then permitted to operate until it either fails or reaches the age set as the termination age for the test. A life-test analysis conducted on the set of 50 newly installed engines will illustrate both the utility and limitations of this approach. The test period in this case was 2000 operating hours, and of the 50 units that started, 29 survived to the test-termination age, accumulating a total of 58,000 hours of operating experience. At various times during the test period, 21 units failed, and the failed units accumulated 18,076 hours of operating experience. The ages at failure are listed in Exhibit C. 1 in order of increasing age and failure. It is important to note that each of the 50 engines had an *opportunity* to survive to 2000 hours. Some did survive, whereas others failed at ages less than 2000 hours.

Exhibit 14-1 also shows the proportion of units surviving after each engine failure. The first engine failed at an age of 4 hours. The other 49 survived beyond that age. Thus 49/50, or 0.98, of the engines survived to an age greater than 4 hours. Similarly, 48/50, or 0.96, of the engines survived to an age greater than 33 hours. When the proportions surviving after the age of each failure are plotted on a graph, as shown in Exhibit 14-2, a smooth curve drawn through the points provides a smooth estimate of the proportion that would survive – the probability of survival – at any interim age. This smooth curve can also be used to estimate the probability of survival in the population of engines from which the sample of 50 was selected.

While this freehand process is likely to result in slight differences in the smooth curves drawn by different analysts, the curve is always constrained by the fact that the proportion of surviving (and hence the probability of survival) cannot increase, so that by definition the first derivative must be negative. This condition is generally sufficient to force a high degree of conformity, at least in the curves drawn by experienced analysts.

Number of units in test 50
Number of units surviving to 2000 hours 29
Number of units failed before 2000 hours 21

| Failure age of units that failed (hours) | Proportion surviving beyond failure age | Failure age of units that failed (hours) | Proportion surviving beyond failure age |
|---|---|---|---|
| 4 | 0.98 | 792 | 0.76 |
| 33 | 0.96 | 827 | 0.74 |
| 112 | 0.94 | A86 | 0.72 |
| 154 | 0.92 | 1136 | 0.70 |
| 309 | 0.90 | 1638 | 0.68 |
| 337 | 0.88 | 1657 | 0.66 |
| 359 | 0.86 | 1664 | 0.64 |
| 403 | 0.84 | 1807 | 0.62 |
| 694 | 0.82 | 1818 | 0.60 |
| 724 | 0.80 | 1986 | 0.58 |
| 736 | 0.78 | ∑ = 18,076 | |

Operating experience of 29 surviving units = 58,000 hours
Operating experience of 21 failed to units = 18,076 hours
Total operating experience of all units = 76,076 hours
Failure rates = 21/76076 = 0.276 for 1000 hours
Meantime between failures = 76076/21 = 3623 hours
Average age of failure 18,076/21 = 861 hours

**Exhibit 14-1. Life-test experience to 2000 hours with 15 newly installed Pratt & Whitney JT8D-7 engines. (United Airlines)**

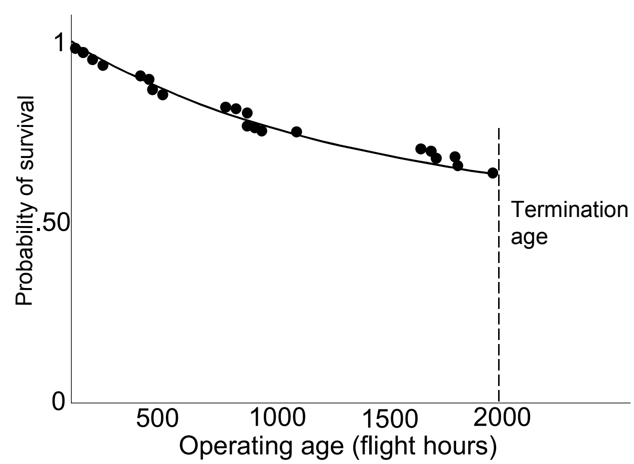



**Exhibit 14-2. Life-test experience to 2000 hours with 50 newly installed Pratt & Whitney JT8D-7 engines. (United Airlines)**

In looking at life-test data there is sometimes a temptation to concentrate on the ages of the units that failed, instead of balancing the failure experience against the survival experience. For example the test data in Exhibit 14-1 show a mean time between failure of 3623 operating hours, although the average age of the failed engines was only 861 hours. This large difference results from the test-termination age of 2000 hours. If the test had run instead to termination age of 3000 hours, additional failures would have occurred at ages greater than 2000 hours, making the average age at failure much higher; in contrast, the mean time between failures would not be much different. If the life test were permitted to continue until all 50 of the units failed, the average age of failure and the mean time between failures would of course, be the same.

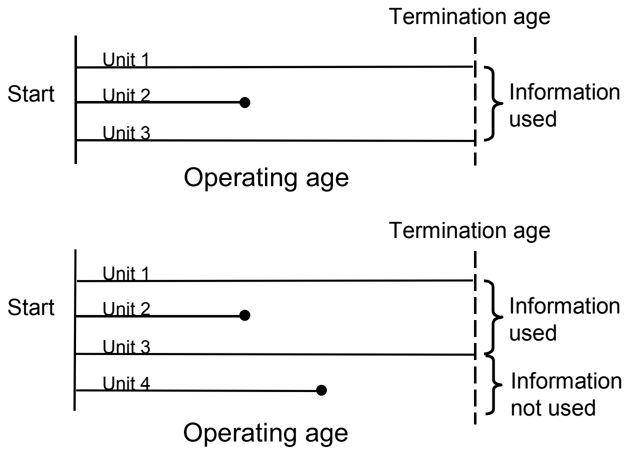



**Exhibit 14-3. An example of the information excluded by life-test data. Although information is available on unit 4, which replaced failed unit 2, this unit will not have aged to 2000 hours by the termination age, and hence cannot be taken into account.**

Caution must be exercised in using life-test failure rates as estimates of what might happen in the future. If maintenance practice required the replacement of all engines with new ones at the end of 2000 hours, and if the units in the life tests represented a random sample of the process that would supply the replacement units, then the failure rate of 0.276 per 1000 operating hours would be an accurate prediction for the engine in Exhibit 14-1. However, it is far more likely that the expensive complex items will receive an extensive corrective maintenance, and the repaired unit may not exhibit precisely the same failure rate as a new one. Moreover, as dominant failure modes are identified and corrected, the overall failure rate would be expected to drop. There would also be little point in removing the units that survived the life tests from service unless there were strong evidence that removal at that age would result in some overall gain, such as a lower failure rate. Thus the failure rate for a life test tells us little more than the simple fact that there were X. failures for the number of hours and experience covered by the test.

The life-test approach has certain advantages in an operational setting. Usually it is not possible to select the test units as a random sample of the population, since the objective of the test is to obtain information as soon as possible. This means that the study will ordinarily be based on the first units to enter service. Also it cannot be terminated until each of the selected units has reached the specified age – that is, until the last unit installed has reached the test-termination age. The analysis can be advanced, of course, either by reducing the number of units in the study or by reducing the length of the test. Reducing the number of units covered increases the likelihood of being misled by sampling effects. Reducing the termination age for the test, results in disregarding part of the available information – the actual experience at ages greater than the test-termination age.

Exhibit 14-3 illustrates another reason that certain available information cannot be used if operating data are used to simulate a life test. Suppose units 1 and 3 survive to the test-termination age, and unit 2 fails. In actual operations this field unit will be replaced by unit 4, which will age in-service but will not have reached 2000 hours by the time units 1 and 3 reach the termination age. Thus, although the experience of unit 4 is available, it cannot be considered in a life-test format. The fact that this type of analysis does not permit us to use all the available information is sufficient reason in itself to consider other methods of analysis that do not have this shortcoming.

Life-task analysis has one further shortcoming from the standpoint of an operating organization. If there are reliability problems, the operator will initiate product-improvement programs and is interested in determining as quickly as possible whether such programs are successful. This interest may be as great as the interest in age-reliability relationships as such. For this reason procedures for analysis have been developed which use operating data derived from experience over a relatively short calendar period.

## 14.2. C-2 Analysis of data from a defined calendar period

The first step in analyzing operating data over a defined calendar period is to define the length of the period. The choice of an appropriate study period is always a compromise between two factors. On the one hand, a short period is desirable to expedite decision making and to minimize the effects of changes in the character of the units and the external environment. On the other hand, a short period limits the amount of operating experience and failure data that can be considered. The relative magnitude of sampling effects is a function of the number of failures and increases as the number of failures decreases. Experience suggests that the calendar period selected for any item should be long enough to include at least 20 failure events.

Once the period has been defined, the following data must be obtained:

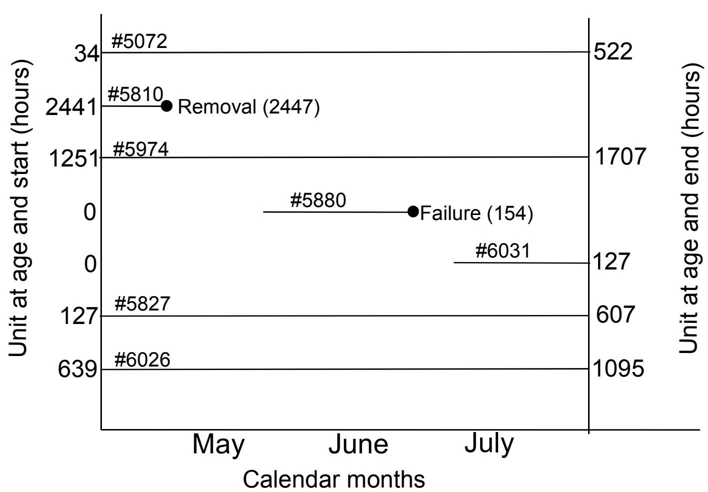
- The age and identity of each unit of an item that was in operation at the beginning of the calendar period
- The age and identity of each unit of an item that was still in operation at the end of the calendar period
- The age and identity of each unit that was removed from operation during the calendar period and the reason for removal (failure of this unit or removal for some other reason)

- The age and identity at each replacement unit that was installed during the calendar period.

Notice the emphasis on unit identification. Reliability analysis is greatly facilitated by giving each unit a unique serial number. Exhibit 14-4 describes the operating history of seven such units over a three-month calendar period. The same information is displayed in Exhibit 14-5. Each horizontal line in the first graph represents a unit's operating position on a piece of equipment. If the history for all units were plotted, an installation would follow the removal of unit 5810 on May 4. Similarly, the removal would precede the installation of unit 5880 on May 27 – unless that line represented equipment that first entered service on that date. Lack of continuity on any line is an indication that unit life histories are missing. The second graph shows the relationship between events and the operating ages of the units.

| Serial number | Date on | Date off | Reason off | Age, 5/1/74 | Age on | Age off | Age, 7/31/74 |
|---|---|---|---|---|---|---|---|
| 5072 | 4/23/74 | -- | -- | 34 | -- | -- | 522 |
| 5810 | 12/17/72 | 5/4/74 | NF[1] | 2441 | -- | 2447 | -- |
| 5974 | 8/19/73 | -- | -- | 1251 | -- | -- | 1707 |
| 5880 | 5/27/74 | 6/29/74 | F[2] | -- | 0 | 154 | -- |
| 6031 | 7/7/74 | -- | -- | -- | 0 | -- | 127 |
| 5827 | 3/18/74 | -- | -- | 167 | -- | -- | 607 |
| 6026 | 12/15/73 | -- | -- | 639 | -- | -- | 1095 |

**Exhibit 14-4. Operating history of seven units from May 1 to July 31, 1974. (United Airlines)**



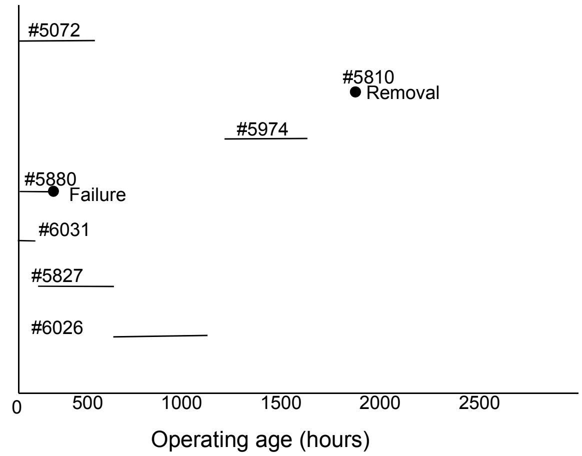




**Exhibit 14-5. Operating history of the seven units in Exhibit C-4 shown as a function of calendar time (top) and as a function of operating age (bottom). (United Airlines)**

Briefly, then, what happens during a fixed calendar period is this: a certain number of units, of varying ages, enter the study period in service; these units build up time, with some continuing operations over the entire period and others being withdrawn from service, either because they have failed or for some other reason. New units enter service to replace the ones that have been removed, and these new units also accumulate operating experience during that time; some of these may also be removed before the end of the calendar period and replaced, in turn, by other new units. From this picture we want to determine what proportion of the units failed prior to a given age and what proportion survived.

The first step in an actuarial analysis is to break the total lifetime of the oldest unit down into age intervals. These may be age intervals of any length, but a reasonable rule of thumb is to have fewer age intervals than there are failures (otherwise many of the intervals will have zero failures). In this situation described in Exhibit 14-6, for example, the oldest engine in the study was less than 5400 hours old, and there were 30 verified failures during the three-month study period; hence we can use 200-hour age intervals. The total age range can then be viewed as a series of discrete intervals – 0-200 hours, 201-400 hours, 401-600 hours, and so on – and the aging process consists of a series of trials to traverse each successive interval. Thus the first trial for a newly installed unit is to traverse the 0-200-hour interval. If the unit fails prior to 200 hours, the trial is unsuccessful. If the unit survives this interval, its next trial is to traverse the 201-400-hour interval. There are only two possible outcomes for a trial: a successful traverse or failure.

[1] Removal for reasons not associated with a failure.
[2] Removal because of a failure.

| Age interval | No. which entered interval | No. in interval on May 1 | No. in interval on July 31 | Total removed | No. failed | Cumulative failures | No. of trials | Experience in interval | Cumulative experience |
|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 0-200 | 42 | 19 | 16 | 4 | 4 | 4 | 43.5 | 8300 | 8300 |
| 201-400 | 41 | 16 | 18 | 3 | 3 | 7 | 40.0 | 7700 | 16,000 |
| 401-600 | 36 | 20 | 18 | 2 | 1 | 8 | 36.5 | 7200 | 23,200 |
| 601-800 | 36 | 14 | 16 | 4 | 4 | 12 | 35.0 | 6600 | 29,800 |
| 801-1000 | 30 | 4 | 14 | 2 | 2 | 14 | 25.0 | 4800 | 34,600 |
| 1001-1200 | 18 | 7 | 9 | 1 | 1 | 15 | 17.0 | 3300 | 37,900 |
| 1201-1400 | 15 | 8 | 9 | 1 | 0 | 15 | 14 | 2800 | 40,700 |
| 1401-1600 | 13 | 6 | 3 | 1 | 0 | 15 | 14.0 | 2800 | 43,500 |
| 1601-1800 | 15 | 8 | 7 | 3 | 3 | 18 | 15.5 | 2800 | 46,300 |
| 1801-2000 | 13 | 3 | 2 | 6 | 3 | 21 | 12.0 | 2100 | 48,400 |
| 2001-2200 | 8 | 5 | 5 | 1 | 1 | 22 | 8.0 | 1500 | 49,900 |
| 2201-2400 | 7 | 7 | 1 | 1 | 1 | 23 | 10.0 | 1900 | 51,800 |
| 2401-2600 | 12 | 5 | 2 | 5 | 2 | 25 | 12.0 | 2200 | 54,000 |
| 2601-2800 | 10 | 2 | 4 | 3 | 1 | 26 | 8.0 | 1500 | 55,500 |
| 2801-3000 | 5 | 3 | 4 | 1 | 0 | 26 | 4.0 | 800 | 56,300 |
| 3001-3200 | 3 | 0 | 0 | 1 | 1 | 27 | 3.0 | 500 | 56,800 |
| 3201-3400 | 2 | 3 | 2 | 1 | 1 | 28 | 2.5 | 400 | 57,200 |
| 3401-3600 | 2 | 0 | 0 | 1 | 1 | 29 | 2.0 | 300 | 57,500 |
| 3601-3800 | 1 | 1 | 0 | 0 | 0 | 29 | 1.5 | 300 | 57,800 |
| 3801-4000 | 2 | 0 | 1 | 0 | 0 | 29 | 1.5 | 300 | 58,100 |
| 4001-4200 | 1 | 0 | 1 | 0 | 0 | 29 | 0.5 | 100 | 58,200 |
| 4201-4400 | 0 | 0 | 0 | 0 | 0 | 29 | 0.0 | 000 | 58,200 |
| 4401-4600 | 0 | 0 | 0 | 0 | 0 | 29 | 0.0 | 000 | 58,200 |
| 4601-4800 | 0 | 0 | 0 | 0 | 0 | 29 | 0.0 | 000 | 58,200 |
| 4801-5000 | 0 | 1 | 0 | 0 | 0 | 29 | 0.5 | 100 | 58,300 |
| 5001-5200 | 1 | 0 | 0 | 1 | 1 | 30 | 1.0 | 100 | 58,400 |
| 5201-5400 | 0 | 0 | 0 | 0 | 0 | 30 | 0.0 | 000 | 58,400 |
| | | | | $\sum = 42$ | $\sum = 30$ | | | | |

**Exhibit 14-6 C6. Procedure followed in an actuarial analysis of operating experience with the Pratt & Whitney JT8D-7 engine on the Boeing 737 from anyone to July 31, 1974. (United Airlines)**

The ratio of failures during an interval to the number of trials at the interval is the *conditional probability of failure* during that age interval – that is, it is the probability of failure, given the condition that a unit enters the interval. The ratio of successful traverses across the interval to the number of trials at the interval is the conditional probability of survival across the age interval.

A trial is counted as a whole trial under three circumstances:

- A unit enters an interval and makes a successful traverse.
- A unit enters an interval and fails in the interval.
- A unit starts in interval and fails in the interval.

A trial is counted as a fractional trial win:

- A unit enters an interval and is removed during the interval without failure.
- A unit starts in an interval and either makes a successful traverse or is removed during the interval with a failure.

Each fractional trial is counted as half of a whole trial – which it is, on the average.

Considered the 0-200-hour age interval. Some of the units that were in that age interval on May 1 and some of the units that entered it after May 1 failed. Others made a successful traverse and survived to enter the next interval, with 201-400 hours. The number that entered into this next interval is the number that were either in the 0-200-hour interval on May 1 or entered it after that date, less the number of removals and the number of units which were still in the interval on July 31. in other words, referring to the column numbers in Exhibit C.6, the number of units that leaves any age interval to enter the next higher age interval is computed as

$$\left(col2 + col3 - col4 - col5\right)$$

Note that whenever any unit is removed, the replacement unit, which has just come out of the shop, enters the 0-200-hour interval at age of 0 hours. There were 42 units removed from service during the study period, 30 caused by failures and 12 for other reasons. This means that 42 units entered the 0-200-hour interval as new units. The number entering each of the other intervals must be calculated from the equation above.

Now we must calculate the trials associated with each age interval. The number of traverses of the upper boundary of interval is greater than the number of successes during the calendar., because those units that were already in that interval on May 1 had, on the average, each completed half a trial. The number of trials associated with the successful traverses is therefore

$$\left(col2+col3-col4-col5\right)-\frac{col3}{2}=col2+\frac{col3}{2}-col4-col5$$

Each engine failure counts as a full trial. The engine removals that were not associated with failures and the units that were still in the age interval on July 31 are counted as fractional trials. The total number of trials associated with age interval is

$$col2+\frac{col3}{2}-col4-col5+col6+\frac{col5-col6}{2}+\frac{col4}{2}$$
$$=col2+\frac{col3}{2}-\frac{col4}{2}-\frac{col5}{2}+\frac{col6}{2}$$

Each trial associated with a successful traverse represented 200 hours of operating experience. Each engine removal and each unit still in the interval on July 31 therefore represents an average of 100 hours of operating experience. Consequently the operating experience represented by an age interval is computed as

$$200\times\left[\left(col2+\frac{col3}{2}-col4-col5\right)+\left(\frac{col5}{2}+\frac{col4}{2}\right)\right]$$
$$=200\times\left[col2+\frac{col3}{2}-\frac{col4}{2}-\frac{col5}{2}\right]$$

The next step is calculation of the proportion of the trials that end in successful traverses of each age interval and the proportion that result in failure in each interval. The results of these calculations are shown in Exhibit C. 7. The proportion of units surviving or failing in a given age interval are considered to be estimates of the respective probabilities. The cumulative probability of survival to the end of any interval is the product of the survival probabilities for all preceding intervals and the probability of survival across the interval in question. Similarly, the cumulative failure number for the end of any age interval is the sum of the probabilities of failure in all preceding intervals and the probability of failure in this interval. The cumulative failure number is not a probability. It can be considered to represent the average number of failures which would occur if single trials were made to traverse the selected interval and each of the earlier intervals.

| Age interval | Number of trials | Number of failures | Proportion surviving | Cumulative probability | Proportion failing | Cumulative failure number |
|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| 0-200 | 43.5 | 4 | 0.908 | 0.908 | 0.092 | 0.092 |
| 201-400 | 40.0 | 3 | 0.925 | 0.840 | 0.075 | 0.167 |
| 401-600 | 36.5 | 1 | 0.973 | 0.817 | 0.027 | 0.194 |
| 601-800 | 35.0 | 4 | 0.886 | 0.724 | 0.114 | 0.308 |
| 801-1000 | 25.0 | 2 | 0.920 | 0.666 | 0.080 | 0.388 |
| 1001-1200 | 17.0 | 1 | 0.941 | 0.627 | 0.059 | 0.447 |
| 1201-1400 | 14.0 | 0 | 1.000 | 0.627 | 0.000 | 0.447 |
| 1401-1600 | 14.0 | 0 | 1.000 | 0.627 | 0.000 | 0.447 |
| 1601-1800 | 15.5 | 3 | 0.806 | 0.505 | 0.194 | 0.641 |
| 18 01-2000 | 12.0 | 3 | 0.750 | 0.379 | 0.250 | 0.891 |
| 2001-2200 | 8.0 | 1 | 0.875 | 0.332 | 0.125 | 1.016 |
| 2201-2400 | 10.0 | 1 | 0.900 | 0.298 | 0.100 | 1.116 |
| 2401-2600 | 12.0 | 2 | 0.833 | 0.249 | 0.167 | 1.283 |
| 2601-2800 | 8.0 | 1 | 0.875 | 0.217 | 0.125 | 1.408 |
| 2801-3000 | 4.0 | 0 | 1.000 | 0.217 | 0.000 | 1.408 |
| 3001-3200 | 3.0 | 1 | 0.667 | 0.145 | 0.333 | 1.741 |
| 3201-3400 | 2.5 | 1 | 0.600 | 0.087 | 0.400 | 2.141 |
| 3401-3600 | 2.0 | 1 | 0.500 | 0.044 | 0.500 | 2.641 |
| 3601-3800 | 1.5 | 0 | 1.000 | 0.044 | 0.000 | 2.641 |
| 3801-4000 | 1.5 | 0 | 1.000 | 0.044 | 0.000 | 2.641 |
| 4001-4200 | 0.5 | 0 | 1.000 | 0.044 | 0.000 | 2.641 |
| 4201-4400 | 0.0 | 0 | -- | -- | -- | -- |
| 4401-4600 | 0.0 | 0 | -- | -- | -- | -- |
| 4601-4800 | 0.0 | 0 | -- | -- | -- | -- |
| 4801-5000 | 0.5 | 0 | 1.000 | 0.044 | 0.000 | 2.641 |
| 5001-5200 | 1.0 | 1 | 0.000 | 0.000 | 1.000 | 3.641 |
| 5201-5400 | 0.0 | 0 | 0.000 | 0.000 | 0.000 | 3.641 |

**Exhibit 14-7 C6. for the survival characteristics of the Pratt & Whitney JT8D-7 engine on the Boeing 737 during the period May 1 to July 31, 1974. (United Airlines)**

The occurrence of a failure in any interval is a random event. Thus it is possible to have a number of failures in one age interval, none in the next, and a few again in the next. Our concern with the age-reliability relationship is the possibility that the failure rate may increase significantly with age, and if it does, we may wish to evaluate the utility of an age limit for the item in question. (Infant mortality is also of concern, but this is a different and much simpler problem, since it occurs quickly, if at all, and there is an abundance of data available for study.) The thus local variations in the failure rate are of little interest. This implies that we will have to smooth the data to reduce the effect of the random time occurrences of the failures.

## 14.3. C-3 the smoothing problem

The conditional probability of failure is simply the ratio of the number of failures in a given age interval to the number of units that attempt that interval. In an actuarial study this represents the proportion of the units entering each age interval that failed during that interval, as shown in column 6 of Exhibit C. 7. The proportions very from 0 to 1, and as expected, the variation tends to increase as the number of units in the interval decreases.

The data for the engine under study suggests a relatively high failure rate at low ages (infant mortality), a lower rate at the middle ages, and a higher rate at the higher ages. This latest possibility is of particular interest because of its implications for scheduled to rework and economic-life-limit tasks. There are several ways of analyzing the data to try to clarify the picture:

- We can smooth the data through some standard smoothing procedure, such as moving average or exponential smoothing.
- We can increase the length of the age intervals, which would increase the number of failures for interval, and thus reduce the variability of the failure rate.
- We can construct cumulative graphs of the data in any of several ways and simply draw a smooth curve through the data points.

The first of these procedures will not be discussed here, since it is well-covered by the literature. The second smoothing procedure – increasing the age interval in such a way that each interval has approximately the same amount of unit experience – is somewhat more common. One such grouping, for example, yields the following results:

| Age interval | Failures | Experience | Failure rate (per 100 hours) |
|---|---|---|---|
| 0-400 | 7 | 16,000 | 0.044 |
| 400-800 | 5 | 13,800 | 0.036 |
| 800-1600 | 3 | 13,700 | 0.022 |
| 1600-5200 | 15 | 14,900 | 0.101 |

This grouping of the data suggests a linearly decreasing failure rate for the first 1600 hours, followed by a very sharp increase immediately after this age. Intervals might also be adjusted as follows

| Age interval | Failures | Experience | Failure rate (per 100 hours) |
|---|---|---|---|
| 0-400 | 7 | 16,000 | 0.044 |
| 400-1200 | 8 | 21,900 | 0.037 |
| 1200-5200 | 15 | 20,500 | 0.073 |

In this case the data suggest a more moderate initial decrease in failure rate, followed by a more moderate increase starting at 1200 hours (rather than 1600 hours). Other choices would lead to still other variations of this sort. Age grouping is simple and statistical interpretation is straightforward. However, it is obvious from the examples above that the interpretation is highly dependent on the grouping process.

The chief problem in representing failure data is to reduce the apparent variations so that different analysts will come to similar conclusions. A common engineering procedure to accomplish this is to cumulate the data and then the graph the cumulative values. There are three methods in general use, although all three have the limitation that they do not explicitly take into account the varying amounts of unit experience in different age intervals. For example, the engine data in Exhibit 14-6 show much more experience in the earlier age intervals than in the later ones – and this will necessarily be the case whenever field units are automatically replaced by units with zero age. Thus the trial counts in Exhibit 14-7 ranges from 43.5 to 35 trials in the first four age intervals, whereas in the later intervals the number of trials was as small as 4 or 2, or even 0. This kind of variation in unit experience makes it more difficult to assess the validity of the pattern suggested by a smooth curve.

One method of cumulating the data is to multiply the proportions surviving successive age intervals to obtain the cumulative probability of survival for each interval (column 5 in the Exhibit 14-7), draw a smooth survival curve through the points (as shown in Exhibit 14-2), and then compute the conditional probability of failure for each interval from the simple formula

$$\text{Conditional probability of failure in interval} = \frac{\left(\text{Probability of entering interval}\right) - \left(\text{Probability of surviving interval}\right)}{\text{Probability of entering interval}}$$

This procedure breaks down, of course, when we reached an interval in which all the units fail (because of the proportion surviving a 0). However, the likelihood that all the units in an interval will fail is small unless the number of units in an interval is itself small. With the engine described in Exhibit 14-6 and Exhibit 14-7 this happens for the first time in the 5000-5200-hour interval, which contains only one unit. If, as sometimes happens, we had had failure data beyond this age interval, a smoothing procedure that relies on multiplication would not have permitted us to use it.

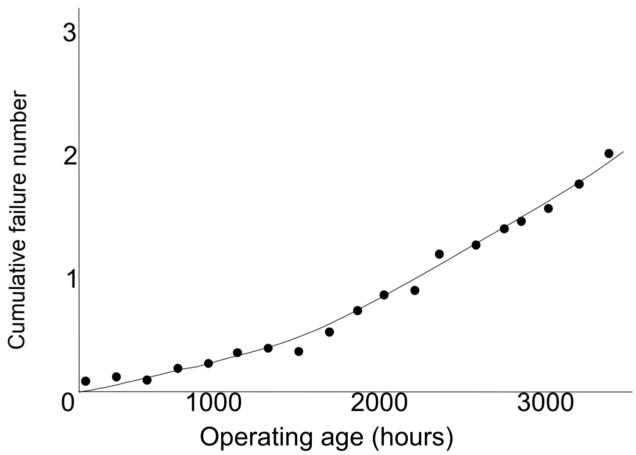



**Exhibit 14-8. C8. The cumulative failure number for the Pratt & WhitneyJT8D-7 engine on the Boeing 737. (United Airlines)**

Another method makes use of the cumulative failure number (column 7 of Exhibit 14-7). This number, at the end of the given interval, is the sum of the probabilities of failure in all preceding intervals and the probability of failure in the interval in question. Remember that the cumulative failure number is not itself a probability; it represents the average number of failures that would occur if single trials were made to traverse the selected interval and each of the earlier intervals. Exhibit 14-8 shows the cumulative failure numbers at the end of each age interval plotted as a function of operating age, with a smooth curve drawn through the points. The conditional probability of failure in an interval is the difference between the cumulative failure numbers at the end and the beginning of the interval. For example, from Exhibit 14-8, the smooth cumulative failure number at the end of 1000 hours is 0.395 and at the end of 100 hours it is 0.310. Thus the conditional probability of failure in the 801-1000-hour interval is .395 - .310 = .085, or at 9:00 (mid-interval), .08 5/2 = .042 per 100 hours.

The procedure differs from the previous one in terms of the quantity that is being smoothed. The precise difference cannot be pinned down if the grafting is done manually, since there is no way to tell with either method precisely how the experienced analyst is weighting the two factors when he draws the smooth curve. The procedure is primarily additive, however, so that there is no difficulty in treating intervals in which all units fail.

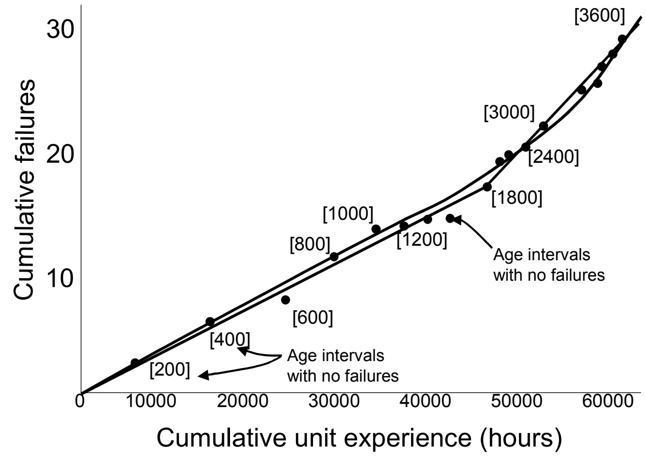



**Exhibit 14-9. A simple method for determining the age-reliability relationship of the Pratt & Whitney JT8D-7 engine. The slope of the smooth curve at any operating ages is a measure of the conditional probability of failure at that age. (United Airlines)**

A third method is to plot the cumulative number of failures by the end of each interval against the cumulative experience by the end of that interval. The values for both of these variables are listed in Exhibit 14-6, and the resulting plot is shown in Exhibit 14-9. The slope of the smooth curve at any age is the conditional probability of failure associated with that age. There is a temptation in this case to represent the plot points by three straight line segments – one from 0 to 200 hours, another from 200 to 1800 hours, and the third from 1800 to 5200 hours. Such straight line segments would lead to the following conditional probabilities of failure:

| Operating age (hours) | Conditional probability of failure (per 100 hours) |
|---|---|
| 0-200 | .048 |
| 200-1800 | .037 |
| 1800-5200 | .100 |

This construction suggests abrupt changes in the conditional probability of failure at 200 hours and they can at 1800 hours. While it is conceivable that dominant failure modes might be dispersed about these average ages, it is highly unlikely that there are actual discontinuities in the conditional probability of failure.

The discontinuities can be avoided simply by drawing a smooth curve instead of straight line segments through the plot points (the black curve in Exhibit 14-9). Conditional probabilities can then be obtained from the smooth curve by drawing tangents to it at various operating ages. Typical results are as follows:

| Operating age (hours) | Conditional probability of |
|---|---|

| | failure (per 100 hours) |
|---|---|
| 0 | .050 |
| 200 | .042 |
| 400 | .038 |
| 600 | .036 |
| … | … |
| 1600 | .049 |

The conditional-probability curve obtained by plotting the conditional probability of failure as a function of operating age is shown in Exhibit 14-10.

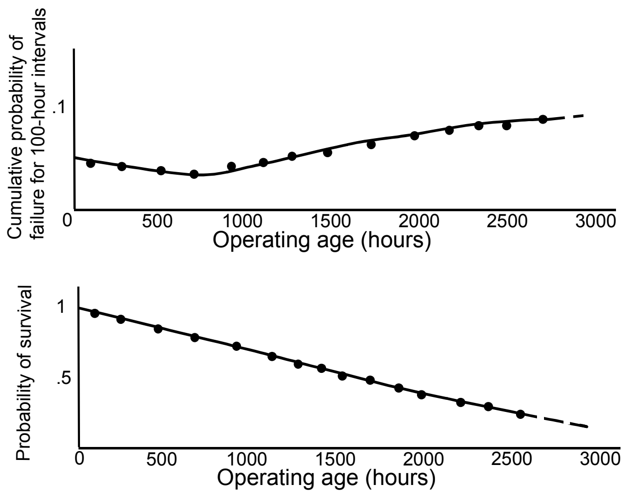



**Exhibit 14-10. C10. Conditional-probability and survival curves derived from the smooth curve in Exhibit C. 9.**

The average conditional probability of failure in the interval from 0 to 200 hours is .046 (at the midpoint of this interval); hence the probability that an engine will not survive to 200 hours is 2 x .046 = .092, and the probability that it will survive is 1 – (2 x .040) = .908. Similarly, the probability that an engine that has survived to 200 hours will continue to survive to 400 hours is 1 – (2 x .040) = .920. The probability that an engine will survive both the 0-200 and the 201-400-hour age intervals is the product of both these probabilities, or .908 x .920 = .835. A plot of the survival curve for this extended example is also shown in Exhibit 14-10. Both the conditional-probability curve and the survival curve are broken and ages above 2600 hours as a warning that the levels of the curves are not well-established beyond that age. (The choice of 2600 hours as a caution point is arbitrary.)

This third procedure for computing conditional and survival probabilities allows the analyst to assess the varying numbers of failures and trials, and hence to judge reasonably well what portion of the data is well-defined and what portion is more questionable. Smoothing that does occur, while still subject to the variations of freehand construction, will usually lead to nearly identical results for the same data.

Exhibit 14-11 shows conditional-probability curves obtained by all three methods, as an indication of the consistency of the curve that will result, regardless of the procedure followed. The histogram below this graft is a convenient way of displaying the experience on which the analysis was based. The vertical bars show the volume of operation in each age interval, and number above each bar is the number of failures that occurred in that interval. These failure rates are shown as data points on the conditional-probability graph, but it would be difficult to fair a curve through them and define a trend. The actuarial procedures we have discussed over, this difficulty.

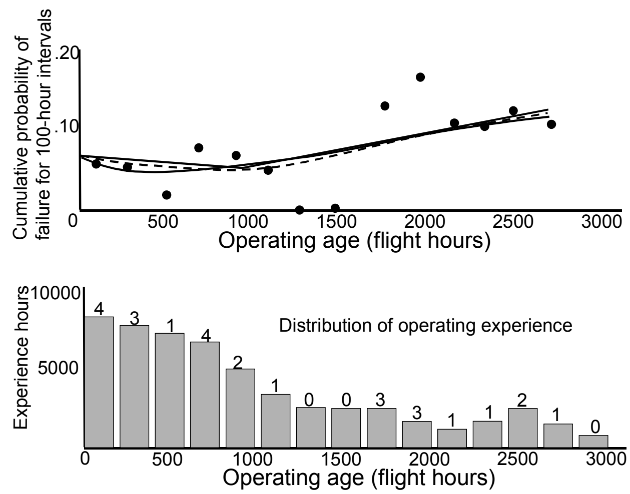



**Exhibit 14-11 C11. A comparison of conditional-probability curves derived by three different methods. The bar chart shows the distribution of operating experience on which all three analyses were based.**

## 14.4. C-4 analysis of a mixed population

The data used in the preceding analyses pertain to an engine that is not subject to scheduled removals. Each engine remains in service until an unsatisfactory condition is detected, either by the maintenance crew or by the operating crew. At that time the engine is removed and sent to the shop for corrective maintenance. Since extensive work may be done on the engine while it is in the shop, this repair process is considered to zero-time the engine. It's operating age is thus measured as engine time since the last shop visit – that is, as the time since the last repair – and all engines are treated as members of a single population.

When engine is subject to a limit on maximum permissible operating age, it is assumed that complete overhaul of the unit that was operating satisfactorily will also re-establish its age at zero. In the text discussion concerning the effect for each limit (Section 2.7), it was further assumed that both repaired and reworked engines have the same age-reliability characteristics.

This assumption is equivalent to saying that both are members of the same population. Suppose we want to test the validity of this assumption. In that case our analytic techniques must allow for the possibility that the two shop processes may result in different age-reliability characteristics. This can be done by treating the total population of engines as a *mixed population*.

At one time it was believed that overhaul of the turbine engine prior to a specified operating age played a major role in controlling reliability. On this basis a complete overhaul was the only process considered to zero-time the engine, and operating age was measured as the time since overhaul (TSO). Under this policy and engine removed prematurely for corrective maintenance was repaired and returned to service, but was considered to have experienced no change in its operating age. Two factors, however, might result in *premature overhauls* – overhauls before scheduled removal age:

- The occurrence of a failure in the last 20 to 25 percent of the permissible operating age, in which case a complete overhaul during this shop visit would avoid the need for a scheduled removal soon after the repaired engine was reinstalled
- A failure requiring such extensive repairs that it would be economically desirable to do the additional work needed for a complete overhaul, regardless of the age of the engine

Under these circumstances the results of an actuarial analysis of a mixed population would have to show survival curves, probability-density curves, and conditional-probability curves for three variables – failures, repairs, and overhauls.

The analysis of a mixed population requires very little change from the method discussed in Section 14-3 (page 178). It is necessary only to plot the cumulative number of repairs and the cumulative number of overhauls for each age interval as a function of the cumulative experience for that interval. Exhibit 14-12 shows the results for a hypothetical analysis of a mixed population subject to an overhaul age limit of 2500 hours. The conditional-probability curves show the probability of failure and all ages up to the 2500-hour limit and the probability of premature overhaul of the units that fail. Below 2000 hours most of the field units are repaired and returned to service without overhaul; after 2000 hours all failures become premature overhauls. The survival curves show that the probability of survival without overhaul decreases slowly up to 2000 hours; therefore it decreases at exactly the same rate as the probability of survival without failure. The probability of survival without repair is higher than the probability of survival without failure, since some failures will result in premature overhauls before 2000 hours; after 2000 hours the probability the probability of survival without repair remains constant, since all failed units after that age are overhauled.

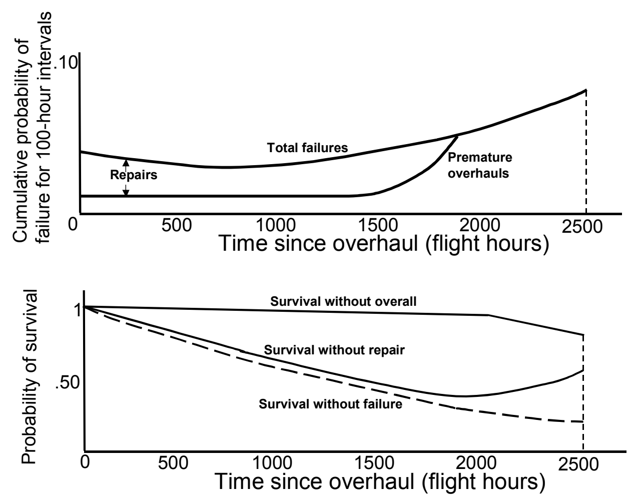



**Exhibit 14-12 C12. Hypothetical or results of an actuarial analysis of a mixed population subject to a scheduled to rework task.**

Actuarial analysis of a mixed population requires a number of detailed but simple changes in the format outlined in Exhibits C6 and C7. The following adjustments are necessary in Exhibit C. 6:

- Column 2, which shows the number of units entering an age interval, must take into account reinstallation of a repaired unit, as well as entry of a unit from the preceding interval.
- The failure count in column 6 must be partitioned into the number of failed units that are repaired and the number of failed units that are overhauled.
- The trial count in column 8 must be adjusted to account for the experience of repaired units that are reinstalled during the study period. The failure of the repaired unit during the interval in which it was installed counts as a whole trial; if the unit survives to leave this interval, this experience counts as a fractional trial.

Similar changes are necessary in the details of Exhibit C7:

- The failure number must be partitioned into failed units that are repaired and failed units that are overhauled.
- The possibilities of survival, both for each interval and cumulative, must be partitioned into survival without overhaul, survival without repair, and survival without failure.
- The calculations to determine the probability of failure in each interval must be repeated to obtain the probability of a repair in each interval.
- A cumulative repair number, like the cumulative failure number, must be calculated for the end of each age interval. This number will be less than the cumulative

failure number. The difference between these two numbers is the probability of an overhaul and the complement of the cumulative probability of survival without overhaul for the corresponding interval.

## 14.5. C-5 useful probability distributions

At certain stages of an actuarial analysis curves are faired through sets of data or calculated points, and subsequent calculations are intended based on numerical values ridden from these curves. This curve-fitting technique is not mathematically precise, and one feels somewhat uncomfortable using extrapolations from such curves. In many cases it is possible to model age-reliability relationships by the mathematical functions which represent certain probability distributions. Special graph papers are available for some of the more common distributions which have the property that a survival curve appears on them as a straight line.

It is known that certain failure processes and the characteristics of certain items result in age-reliability relationships that can be approximated by specific probability distributions. Much information on the physical processes that produce this capability is available in the literature, and this knowledge is the best guide in evaluating the adequacy of a given probability distribution to represent the results of an actuarial analysis. Another more empirical guide is the shape of the conditional-probability or probability-density curve that resulted from the initial analysis. If there is reason to believe that the age-reliability characteristics of an item to follow a particular probability distribution, it is usually more accurate to fit a straight line through survival points on graph paper that is unique to that distribution than it is to draw a curve through the corresponding points plotted on Cartesian coordinates.

Many probability distributions had developed and can be used for reliability analysis. The three which have the widest application are the exponential distribution, the normal distribution, and the Weibull distribution. Exhibit C13 shows the relationship of the conditional probability of failure, the probability density of failure, and the probability of survival for the *exponential distribution*. The conditional probability of failure associated with an exponential distribution is constant at all ages – that is, but probability of failure is the same at any age to which a given the unit may survive. This is sometimes expressed by saying that an item with exponential characteristics has no memory. This conditional-probability relationship, described by curve E in Exhibit 2.13, is characteristic of complex items with no dominant failure modes, and also of electronic items, particularly at ages beyond the infant-mortality period.

The failure-density curve shows that the incidence of failures for items characterized by an exponential distribution is highest at low ages, starting at installation. This, of course, is it because low ages represent the greatest amount of unit experience, and since the conditional probability of failure is constant, the more units there are in an age interval, the more failures there will be. The survival curve of the exponential distribution has a shape similar to that of the density curve. The exponential distribution is a single-parameter distribution. This parameter is the failure rate. It is a scaling parameter, since it determines the magnitude of the conditional probability of failure, the initial value and rate of decrease of the density curve, and the rate of decrease of the survival curve.

Exhibit C. 14 shows the corresponding relationships for the *normal distribution*. The conditional probability of failure associated with a normal distribution is relatively small at lower ages and increases monotonically with increasing age. This distribution is therefore a candidate for consideration when an item exhibits increasing signs of wearout after relatively low probabilities of failure at earlier ages. The failure-density curve for the normal distribution has clearly defined maximum value. This occurs at the average age at failure if all units are permitted to continue in operation until they fail. Note that the density curve is symmetrically disposed about this average age. This is an important characteristic of a normal distribution. The survival curve passes through a probability of .50 at the average age at failure and has twofold symmetry with respect to this probability point.

The statement that an item has the "life of x hours" is usually based on supposition that it has age-reliability characteristics which can be represented by a normal distribution. In other words, such statement assumes the following characteristics:

- The probability of failure at low wages is very small.
- The probability of failure increases as operating age increases.
- There is an age at which the density of failure has a relatively well-defined maximum value.
- The density of failure at lower or higher ages is symmetrically disposed about the maximum value.

The normal distribution frequently does represent the age-reliability characteristics of simple items (those subject to only one or a very few failure modes).

The normal distribution is a two-parameter distribution. One parameter is a location parameter; it defines the age at which the maximum failure density occurs. The other parameter is a scaling parameter and is determined by the degree of dispersion of the failure densities about the peak value. The scaling parameter thus establishes the curvature of the survival curve, the magnitude of the conditional probabilities, and the magnitude of the maximum failure density and of other densities about the maximum value.

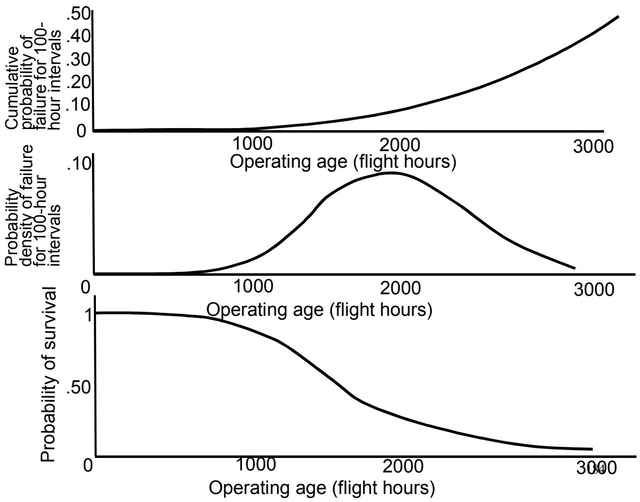



**Exhibit 14-13 C-13. The relationship of conditional probability, probability density, and probability of survival for an exponential distribution within mean time between failures of 2000 hours.**

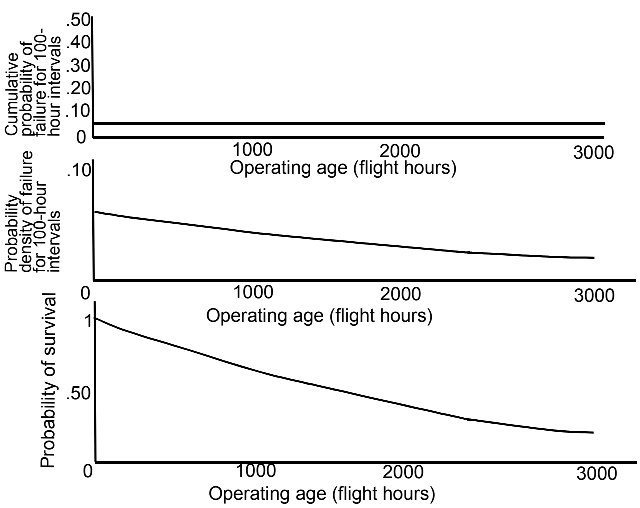



**Exhibit 14-14. C-14. The relationship of conditional probability, probability density, and probability of survival for a normal distribution with a mean time between failures of 2000 hours and a standard deviation in failure age of 500 hours.**

Exhibit C. 15 shows the characteristics of a *Weibull distribution*. In this particular example conditional-probability curve resembles that for the normal distribution, in that the conditional probability of failure increases monotonically with age. It is dissimilar, however, with respect to the conditional probability at low wages, which is shown as being relatively high. The Weibull distribution is a candidate for representing items that have a moderately high probability of failure at low wages and demonstrate monotonically increasing (or decreasing) failure probabilities thereafter.

This discussion takes considerable liberty with the Weibull distribution. The Weibull distribution is a very versatile one with wide applicability. It can in fact be used to represent items with high or low conditional probabilities at low ages, and age relationships in which the probability of failure either increases or decreases with increasing age. The exponential and normal distributions are both special cases of the Weibull distribution.

The Weibull distribution in Exhibit C. 15 has a failure-density curve that is not too different from that for the normal distribution shown in Exhibit C. 14. There is an age at which the density function has a well-defined maximum value. Unlike the normal distribution, however, the densities in a Weibull distribution are not necessarily symmetrically disposed about this peak value. They can be, but they usually are not.

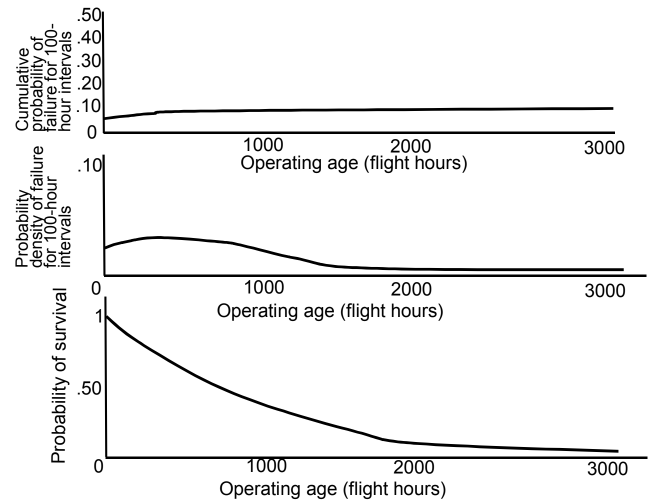



**Exhibit 14-15 C-15. Relationship of conditional probability, probability density, and probability of survival for a Weibull distribution with a meantime between failures of 1013 hours, scaling parameter a = 33.15, and shaping parameter Beta = 1.45.**

By the same token, the survival curve for Weibull distribution does not necessarily passed through the point to .50 point at the age corresponding to the maximum failure density, nor does it have the symmetry of the normal curve.

The Weibull distribution described here is a three-parameter distribution. One parameter is a location parameter which, in effect, defines a negative age at which the conditional probability of failure is zero. The other parameters are scaling and shape parameters.

Each of the probability distributions enables us to express the additional probability of failure, the probability density of failure, and the probability of survival without failure as a function of operating age and certain parameters. These parameters make it possible to develop a large family of different relationships for each probability distribution. In practical work we are ordinarily not concerned with inhuman rating parameters that apply to a specific analysis or writing the equations that describe the age-reliability relationship. The purpose of an actuarial analysis is to determine whether the reliability of the item deteriorates with operating age, and if it does, to assess the desirability of imposing a limit on operating age. Thus any interest in probability distributions is entirely pragmatic and centers on the possibility of using the specialized craft papers for such distributions to simplify the task of faring occurs through the survival data. Experience has shown that none of these three probability distributions provide a satisfactory model for the results of turbine-engine analysis, and in that case representation still depends on subjective curve fitting by the analyst.

## 14.6. C-6 a special use of the exponential distribution

Spare units for each item are purchased and kept on hand to support new equipment when it enters service. The provisioning is based on an anticipated failure rate for each item. It is not uncommon, however, for an item on newly designed equipment to experience a failure rate much higher than was anticipated. This results in an unexpected increase in the shop workload, and also in depletion of the supply of serviceable spare units needed to support the equipment. This means that pieces of equipment may have to be removed from service because there are no replacement units of the unreliable item. A problem of this kind can persist for some time, since the process of proving that specific design changes to do in fact improve reliability is a slow one. Moreover, not only does it take time to manufacture additional spare parts, but there is also a reluctance to invest in additional units of a designed that has proved unsatisfactory.

Invariably the question arises as to whether a limit on the maximum operating agent such an item is desirable to alleviate the spare-unit problem caused by a high failure rate. The exponential distribution can give useful information that permits a quick answer to this question. Exhibit C. 16 shows the probability of survival of an item with exponential reliability characteristics, with the operating age expressed as a multiple of the mean time between failures. The exponential distribution represents a constant conditional probability of failure at all ages, as described by curve E in Exhibit 2.13. Obviously an item whose failure behavior corresponds to curve A, C, or F in this family of curves would have smaller survival probabilities at all ages than one with exponential characteristics. Items with characteristics described by curve B have survival possibilities which are about the same as those for a class E item at low wages and deteriorate at high ages. The relatively few items whose conditional-probability curves correspond to curves D path survival probabilities which are actually somewhat better than exponential at higher ages. For the purposes of this question. However, it is reasonable to assume that the troublesome item can be represented by the exponential survival curve in Exhibit C. 16.

Suppose this item has a failure rate of one per 1000 hours. The meantime between failures is, of course, 1000/1 = 1000 hours. An age limit of 1500 hours has been proposed for this item. If we extrapolate values from the exponential survival curve, we find that an age limit which represents 1.5 times the mean time between failures, 22.3 percent of the units can be expected to survive to that limit and becomes scheduled removals:

| Ratio of age limit to mean time between failures | Probability of survival to age limit |
|---|---|
| 0.1 | .905 |
| 0.2 | .819 |
| 0.4 | .670 |
| 0.6 | .549 |
| 0.8 | .449 |
| 1.0 | .368 |
| 1.5 | .223 |
| 2.0 | .135 |
| 2.5 | .082 |
| 3.0 | .050 |
| 3.5 | .030 |
| 4.0 | .018 |
| 5.0 | .007 |

The scheduled removals will further increase the demand for spare units, and hence will aggravate the present inventory problem instead of alleviating it. Any additional operating life that can be realized by this 22.3 percent of the units represent a saving over the number of spare units that would be needed with an age limit.

**Exhibit 14-16 C16. A nondimensional form of the exponential survival curve that can be used to determine the probability of survival to any multiple of the mean time between failures.**

If there are major economic consequences associated with the failures – and if the national probability of failure in fact increases rapidly after 1500 hours – and an age limit may be desirable to reduce the failure rate regardless of the increase in the inventory problem. This, however, is a solution to a different problem from the one that has been posed. There are many situations in which the assumption of a simple exponential distribution service as a useful tool in helping to define the actual problem.

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