RELIABILITY CENTERED MAINTENANCE

1. Introduction. A large percentage of defense spending is devoted to maintaining equipment. Consequently, when more efficient maintenance concepts are developed, these concepts are incorporated into developmental and fielded equipment whenever possible.

a. "One of the underlying assumptions of maintenance theory has always been that there is a cause-and-effect relationship between scheduled maintenance and operating reliability. 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 ensure reliable operation. Over the years, however, it was found that many types of failures could not be prevented no matter how intensive the maintenance activities."[1]

b. Consequently, by the late 1950s, the airline industry had begun conducting studies of maintenance in order to discover a means of reducing costs. These studies of actual operating data began to contradict certain basic assumptions of traditional maintenance practice. One assumption is the belief that reliability is directly related to the intervals between scheduled overhaul. These maintenance studies indicated that for many items, a maintenance policy based exclusively on some maximum operating age would, no matter what the age limit, have little or no effect on the failure rate.

c. As a result of these early studies, a task force was formed in 1960 to investigate the capabilities of scheduled maintenance. The results produced by this task force were used to develop a maintenance program for Boeing's 747 jet. This program was successful and has been further refined and applied to several other aircraft projects (Lockheed 1011, DC-10, F4, P-3, Airbus Industrie A-300, and the Concorde). The name of this maintenance program is now called Reliability Centered Maintenance (RCM).

2. Definition. RCM is a scheduled maintenance program designed to realize the inherent reliability potential of equipment. The objective of RCM is to develop a scheduled maintenance program that ensures the equipment's maximum safety and reliability and meets this requirement at the lowest cost. RCM is based upon the premise that maintenance cannot improve upon the safety or reliability inherent in the design of the hardware. Good maintenance can only preserve those characteristics. The RCM concept uses a decision logic to evaluate and construct maintenance tasks which are based on the equipment functions and failure modes.[2] Because of industry's success with the RCM concept, in 1979, the Army directed that RCM be extended to all commodities.

3. A Discussion of Failure. To better understand maintenance and, subsequently, RCM, a knowledge of failure is required.

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[1] Nowlan, F. Stanley and Heap, Howard F., Reliability Centered Maintenance, Dolby, Access Press, 1978, page 1.
[2] Guide to Reliability Centered Maintenance, (RCM) for the Fielded Equipment, DA Pam 750-40, February 1980.

a. A failure is an unsatisfactory condition. Any identifiable deviation from the original condition which is unsatisfactory to a particular user is a failure. The exact division between satisfactory and unsatisfactory conditions depends upon the function of the item, the nature of the equipment in which the item is installed, and the operating context in which the equipment is used. This determination of failure will vary from one operating organization to another. However, within each operating organization, unsatisfactory conditions must be clearly defined.

b. Because 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, failures must be further classified as either functional failures or potential failures.

(1) A functional failure is the inability of an item (or the equipment containing it) to meet a specified performance standard. This definition requires that you specify a performance standard, thus generating an identifiable and measurable condition for functional failures. In order to define a functional failure for an item, you must have a clear understanding of all the functions of the item.

(2) A potential failure is an identifiable physical condition which indicates a functional failure is imminent. This ability to identify a potential failure permits the maximum use of an item without suffering the consequences associated with a functional failure. Items are removed or repaired at the potential failure stage, so that potential failures pre-empt functional failures. Figure 1 illustrates these relationships.

4. Data Requirements. Data used to perform an RCM analysis consists of:

a. An operational mode summary. "A description of the anticipated mix of ways the equipment will be used in carrying out its operational role. Includes expected percentage of use in each role and percentage of time it will be exposed to each type of environmental condition during the system life."[3] These data are used to establish the reliability and maintainability (R&M) characteristics of the equipment. In other words, it gives us a baseline to which our maintenance program must support. Figure 2 illustrates a typical operational mode summary and mission profile.

b. Hardware breakdown. Prior to performing an RCM analysis, the individual components comprising the system must be identified. Since there are so many possible failures a system can experience, it may be necessary to subdivide the system into manageable segments (components) in order to identify all possible failures. This process is known as a work breakdown structure (WBS). Figure 3 illustrates a sample hardware WBS. When performing an RCM analysis on a fielded system, we can use a Maintenance Allocation Chart (MAC) in lieu of generating a separate WBS (see Appendix A).

c. The next data required for an RCM analysis are a Failure Mode, Effects, and Criticality Analysis (FMECA). This term is a combination of three separate efforts:

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[3]AR 702-3.

(1) Failure mode--the manner by which a failure is observed. It generally describes the way the failure occurs and its impact on equipment operation. Each component has one or more failure modes and a separate analysis must be performed on each failure mode.

(2) Failure effect--the consequence(s) a failure mode has on the operation, function, or status of the specific item being analyzed. Failure effects are classified as local effect, next higher level, and end effect.

(3) Criticality analysis--a procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence. The criticality analysis is probably most valuable for maintenance and logistics support oriented analyses since failure modes which have a probability of occurrence (high criticality numbers) require investigation to identify changes which will reduce the potential impact on the maintenance and logistics support requirements for the system. Since the criticality numbers are established based upon subjective judgments, they should only be used as indicators of relative priorities. Figure 4 illustrates a partial failure mode, effects, and criticality analysis.

(a) Severity is classified as:

1 Category I--Catastrophic. A failure which may cause death or weapon system loss; e.g., disintegration of the rotor blades on a helicopter, a ruptured artillery tube, or premature detonation of a missile warhead.

2 Category II--Critical. A failure which may cause severe injury, major property damage, or major system damage which will result in mission loss; e.g., a blown truck engine, a seized breechblock, loss of brakes, or stripped transmission gears.

3 Category III--Marginal. A failure which may cause minor injury, minor property damage, or minor system damage which will result in delay or loss of availability or mission degradation; e.g., cracked windshield, loss of hydraulic turret drive on a tank, loss of four-wheel drive capability, or loss of blackout lights.

4 Category IV--Minor. A failure not serious enough to cause injury, property damage, or system damage, but which will result in unscheduled maintenance or repair; e.g., turn signal on a jeep, bent towing shackle, dent in a fender, blown fuse, or frayed canvas tiedown rope.

(b) Probability of Failure Occurrence: Failure modes identified in the failure mode and effect analyses are assessed in terms of probability of occurrence when specific parts configuration or failure rates are not available. Individual failure mode probabilities of occurrence should be grouped into distinct, logically defined levels. They are:

1 Level A--Frequent. A high probability of occurrence during the item operating time interval. High probability may be defined as a single failure mode probability greater than 0.20 of the overall probability of failure during the item operating time interval.

2 Level B--Reasonably Probable. A moderate probability of occurrence during the item operating time interval. Reasonably probable is a single failure mode probability of occurrence which is more than 0.10 but less than or equal to 0.20 of the overall probability of failure during the item operating time.

3 Level C--Occasional. A single failure mode probability of occurrence which is more than 0.01 but less than or equal to 0.1 of the overall probability of failure during the item operating time.

4 Level D--Remote. An unlikely probability of occurrence of a single failure mode which is more than 0.001 but less than 0.01 of the overall probability of failure during the item operating time.

5 Level E--Extremely unlikely. A failure whose probability of occurrence is essentially zero during item operating time interval (less than 0.001 of the overall probability of failure).

(c) By combining the severity of the failure and the probability of occurrence, a matrix can be constructed which will indicate a priority of failure modes. During research and development, those failure modes possessing the highest priority should be redesigned if possible. The criticality matrix is contained in Figure 5.

d. Mean-time-between-failure (MTBF) is another data element needed for the RCM analysis. This number is derived by:

$$\frac{\text{Total Operating Time}}{\text{Sample Size (N)}} = MTBF$$

For example, suppose we have a sample of five parts and we test them to failure. Our test data may show:

PART	*OPERATING HOURS*
1	*26*
2	*15*
3	*17*
4	*13*
5	*20*

After totaling the operating hours (91), we divide by the sample size (5) and obtain an MTBF of 18.2 hours. Additionally, we can divide 1 by the MTBF and derive the failure rate (e.g., $\frac{1}{18.2} = .0549$).

The value of MTBF and the failure rate will give us an idea of the reliability of the part. More specifically, we can: (1) calculate the failure rate of each failure mode and decide whether a design review is desired on a developmental item, and (2) decide when the part should be replaced if scheduled replacement is required. NOTE: Failure rates are frequently expressed as the number of failures per million hours of operation; i.e., 10^{-6}.

e. Failure dispersion around the mean must be considered when deciding whether to replace or inspect the component at fixed intervals. This will be discussed further in paragraph 6.

5. The RCM Decision Logic. In order to achieve a consistent approach to maintenance planning, several decision logics have been developed. The Maintenance Steering Group (MSG) 2 developed a logic which the Army has been using; a new logic based on some of the refinements was developed by MSG 3. Appendix B contains the new RCM logic, an explanation of each block, and a flow chart for economic analyses.

6. Determining the Task Interval.

a. Scheduling maintenance tasks is a two step process. The first step is determining the task interval. The task interval is the period of time or operation that occurs between the task's performance. The task interval is calculated by considering component failure characteristics, cost effectiveness, or convenience. The maintenance planner's experience with similar systems will be important in some decisions.

b. Different maintenance tasks require different types of failure information to determine the appropriate task interval. Determining an inspection interval will be discussed first.

c. An inspection interval is based upon the time from potential failure to functional failure. A curve is developed showing the time occurring from the onset of failure to functional failure. This time period is known as time from onset (T_{OS}). Figure 6 provides an example. The point on the slope at which a physical symptom (potential failure) appears is the beginning of T_{OS}. The maximum inspection interval is T_{OS}. To assure that an inspection to detect impending failure will occur between the appearance of the potential failure and functional failure, inspection intervals must be shorter than T_{OS}. Inspection intervals are set at no more than 1/2 to 1/3 of T_{OS}. This assures that if an inspection failed to spot the symptom, there would be at least one more inspection before functional failure occurred. For structural items, the inspection interval may be 1/12 to 1/24 the T_{OS}.

d. Scheduling a replacement or overhaul task is based upon a curve indicating the cumulative probability of failure of a component at different ages. Figure 6 shows the cumulative probability of failure as a component's age increases. The task interval is selected to provide an acceptable probability of failure. In this case, the decision for replacement of the component occurs at 3,000 operating hours where the probability of failure exceeds .15.

e. The Mean Time Between Failure (MTBF) can be used to schedule maintenance intervals. The MTBF is the average time or usage occurring between failures. This method is used when there is data available from the actual use of equipment. Figure 7 shows a curve representing a normal failure distribution. This means the failures are evenly distributed around the mean. When the failures occur in a narrow range, this method of task scheduling is appropriate. Remember, a mean is an average. If the average number of hours of operation between failures is 500, that could mean the first failure occurred after 10 hours of operation and the last failure was recorded after 1,000 hours of operation. If the failures were evenly distributed in this range, this situation would not lend itself to the use of MTBF for scheduling maintenance tasks.

f. Figure 8 uses failure data based on hours of operation and standard deviations to illustrate how to determine a maintenance task interval. Failure data indicates that the Mean Time Between Failures of a component is 52. Using a formula to determine the variance of the failures around the mean and the standard deviation of the variance, it is determined that 68% of the failures occur within 3.5 hours (+ or -) of the mean (one standard deviation); 95% of the failures occur within a range of 45 to 59 hours (two standard deviations); and 99.7% of the failures occur within a range of 41.5 to 62.5 hours. Therefore, if a removal and replacement of this component were made after 41.5 hours of use, a failure rate of less than 1% could be expected.

7. The Final Step. Whatever maintenance action evolves from the decision logic, the process is not completed.

a. For a fielded system, technical writers must change the existing technical manuals in order to accommodate the results of the RCM analysis. Detailed maintenance procedures (inspections, replacements, etc.) will be written and these changes will be published and distributed. Approved design changes will be implemented through Product Improvement Proposals (PIPs).

b. For a developmental item, RCM analysts will identify components which require a design review. If the contractor is performing the RCM analysis, a list of components requiring design review should be given to the Government RCM analyst. Further, the contractor can be tasked to give the Government RCM analyst a report of the disposition of those components requiring a design review. The purpose of this procedure is to give the Government RCM analyst a quality assurance tool which can be used to ensure critical parts having a high failure rate are made more reliable. After the developmental system has matured, the results of the RCM analyses are given to the technical writers. These maintenance tasks then form the basis of the system's technical manuals.

c. Additionally, the Depot Maintenance Work Requirements (DMWR) must be written to include the application of RCM principles. These RCM principles being applied to DMWRs are:

(1) Preshop analyses. These analyses consist of inspecting components of the end item prior to disassembly in order to ascertain their serviceability. If the component functions to a

desired specification, no maintenance is performed on it. Should the component fail the preshop analysis, overhaul of the component will be undertaken.

(2) Elimination of cosmetic maintenance. Any maintenance action which does not improve the component's reliability or safety is being eliminated. Initiatives such as spot painting vehicles are being preferred over the traditional sand blast, prime, and paint methodology.

8. Summary.

a. RCM is not a maintenance "cure-all." In order for any maintenance program to work, two conditions must exist: (1) operators and mechanics will know their job; and (2) maintenance will be properly supervised.

b. RCM analyses should be performed by maintenance engineers and those equipment specialists having field experience with that particular system (or a similar system). Technical writers should also be included on the RCM analysis team. Figure 9 shows where RCM is conducted in the development life cycle of an item. It should be noted that RCM does not stop after materiel fielding.

c. The principal benefits of RCM are to eliminate unnecessary scheduled maintenance and ensure proper maintenance is performed on all components having critical safety and mission failure potentials.

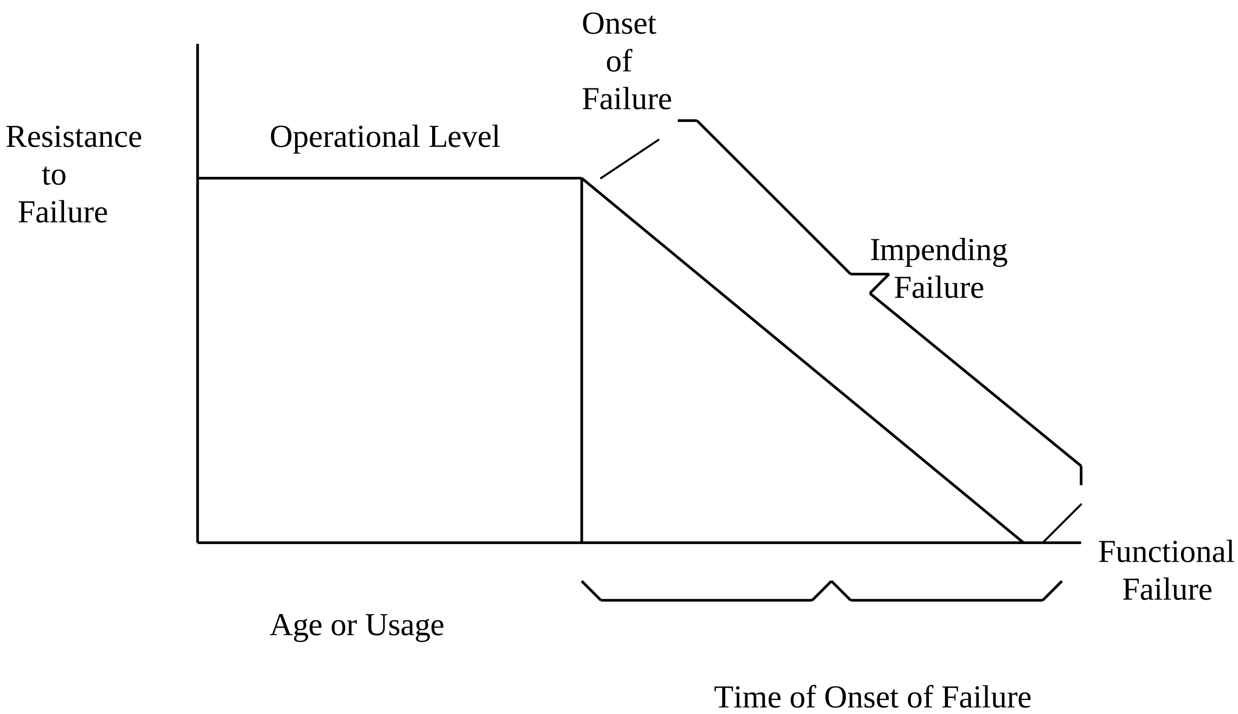


Figure 1

ANALYSIS OF FAILURE

With Age/Usage, the Resistance to Failure Decreases

Extract from: TRADOC/DARCOM Pam 70-11

Table 1-1. OMS/MP Example

A. MISSION PROFILES

1. Wartime Conditions

MISSION ESSENTIAL FUNCTION	MISSION PROFILE			ANNUAL USAGE
	STATIC	DYNAMIC	GROUND SUPPORT	
Fire Control	14 Hrs	24 Hrs	0	3,060 Hrs
Shoot	240 Rds	160 Rds	360 Rds	46,000 Rds
Mobility	12 Miles	30 Miles	30 Miles	3,300 Miles
Expected Percentage	75	20	5	N/A

2. Peacetime Conditions

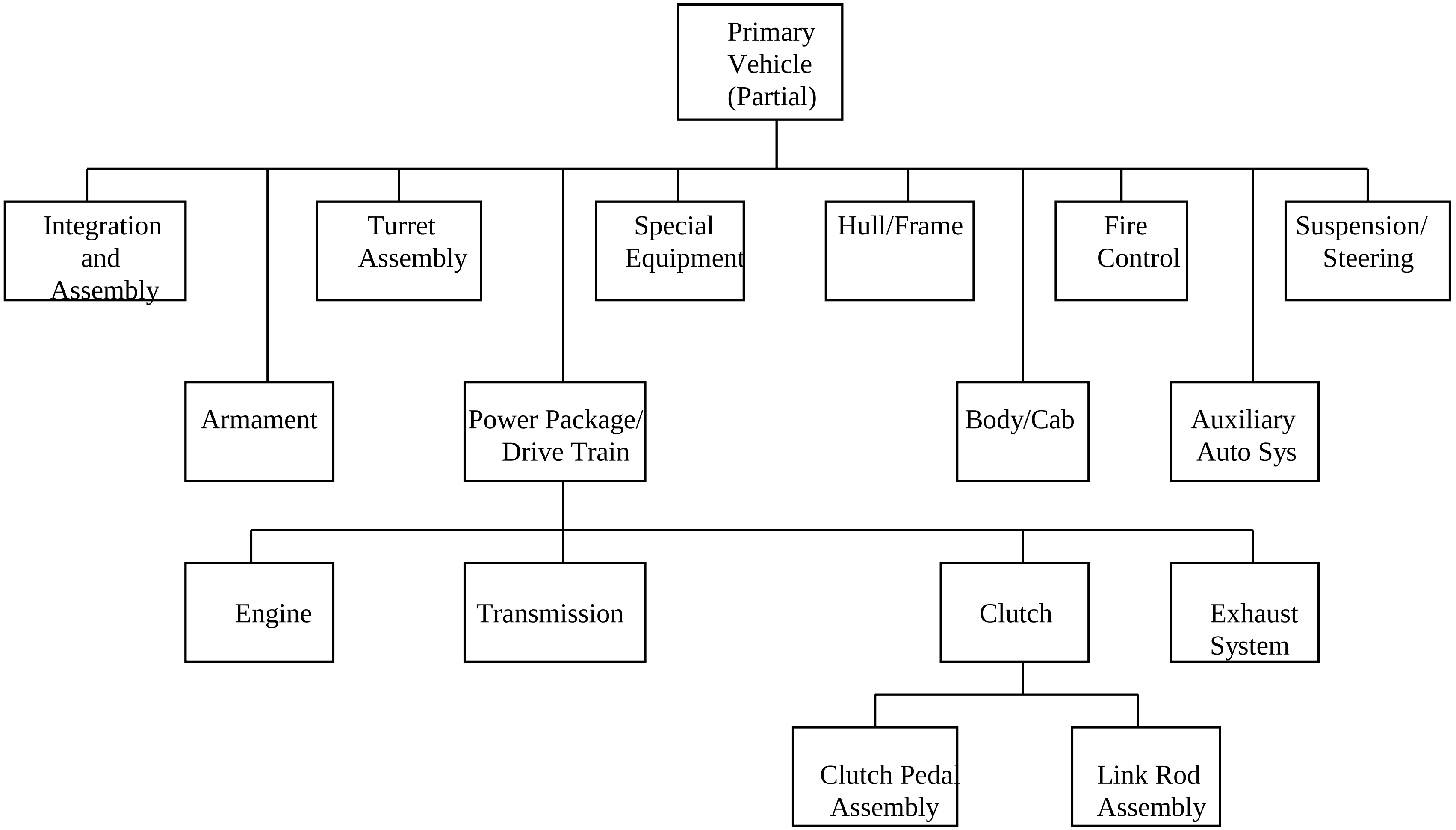
MISSION ESSENTIAL FUNCTION	MISSION PROFILE			ANNUAL USAGE
	STATIC	DYNAMIC	GROUND SUPPORT	
Fire Control	8 Hrs	14 Hrs	0	468 Hrs
Shoot	20 Rds	20 Rds	20 Rds	1,200 Rds
Mobility	12 Miles	20 Miles	20 Miles	816 Miles
Expected Percentage	80	10	10	N/A

B. ENVIRONMENT FOR BOTH WARTIME AND PEACETIME CONDITIONS

CLIMATIC DESIGN TYPES (AR 70-38)	% FLEET
Hot	20
Basic	60
Cold	15
Severe	5

MOVEMENT TERRAIN
10% Primary Road
35% Secondary Road
55% Cross-Country

Figure 2
RAM
Mixed Ways Equipment will be Used



WORK BREAKDOWN STRUCTURE

Figure 3

Identification and Drawing Reference	Failure Mode	Failure Class	Possible Safety Hazard	Independent Failure Causing Failure Mode	Casual Environment	Failure Prob
Tail Gear Box (70358-06300-041)	Seal leakage	III	None	None	Age	D
	Bearing Failure	II	None	None	None	B
	Gear Failure	II	None	None	None	B
	Corrosion	IV	None	None	None	D
	Housing Mount Crack	III	None	None	None	C
	Mounting bolt failure (breakage or loss of torque)	IV	None	None	None	C
	Drive flange cracking	II	None	None	None	C
	Rotor flange cracking	II	None	None	None	C
	Locking assembly fails on input gear locknut	III	None	None	None	B

Figure 4
FMECA

CRITICALITY ANALYSIS

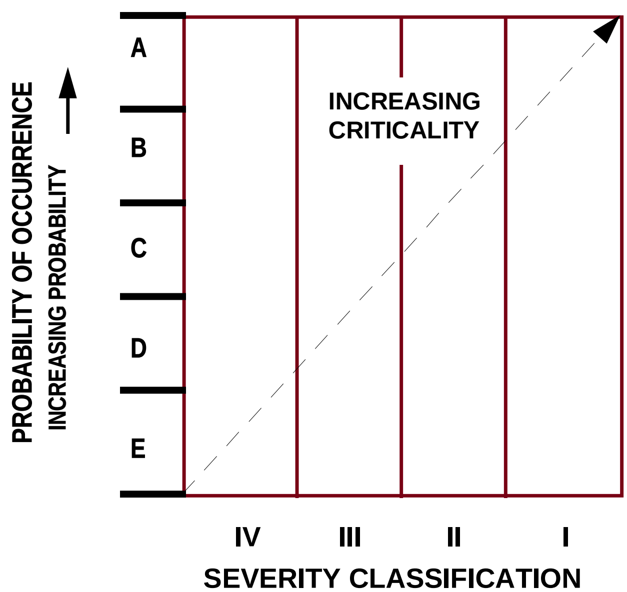


Figure 5

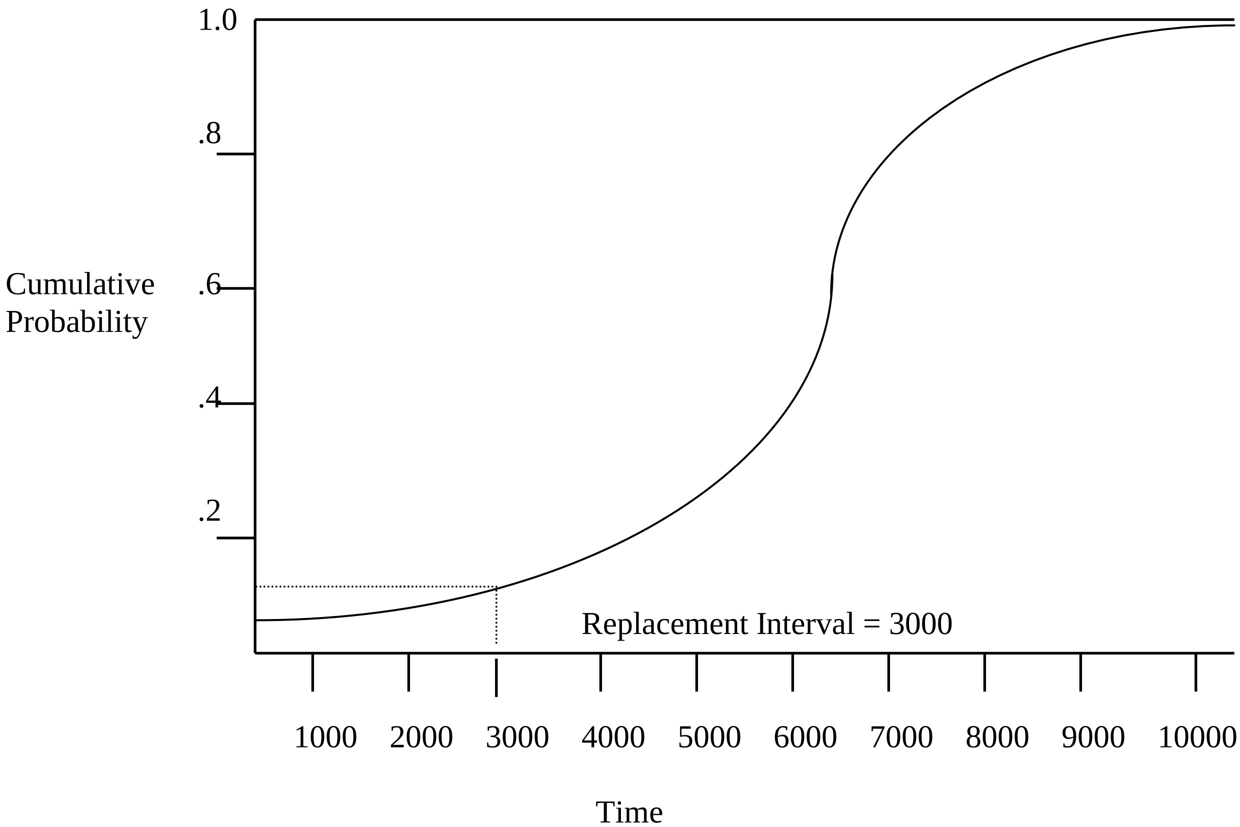


Figure 6

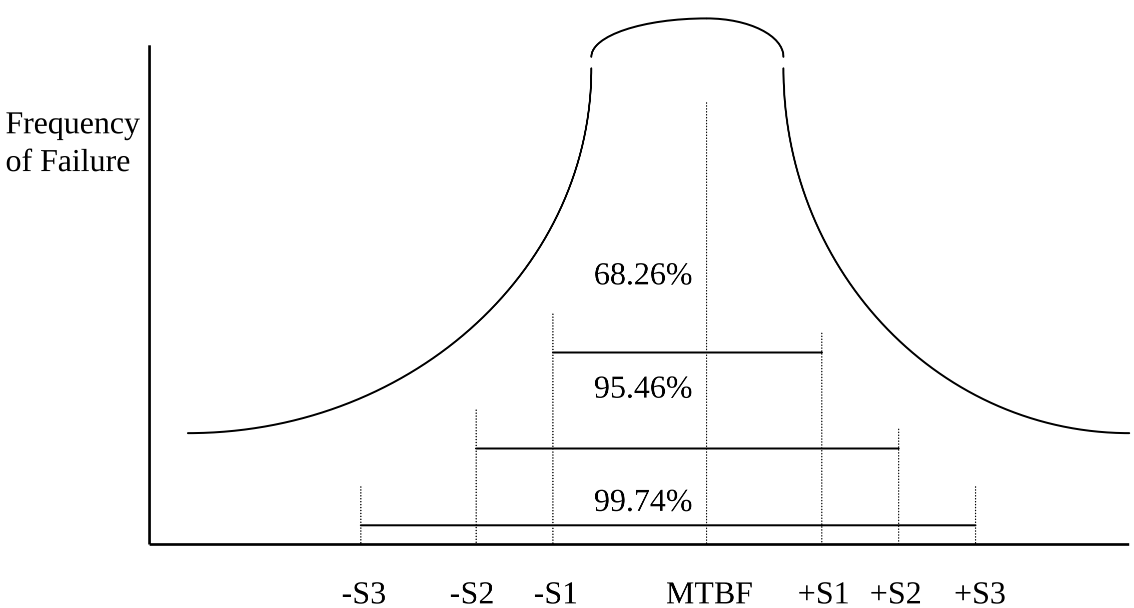


Figure 7

SCHEDULING A
REPLACEMENT INTERVAL

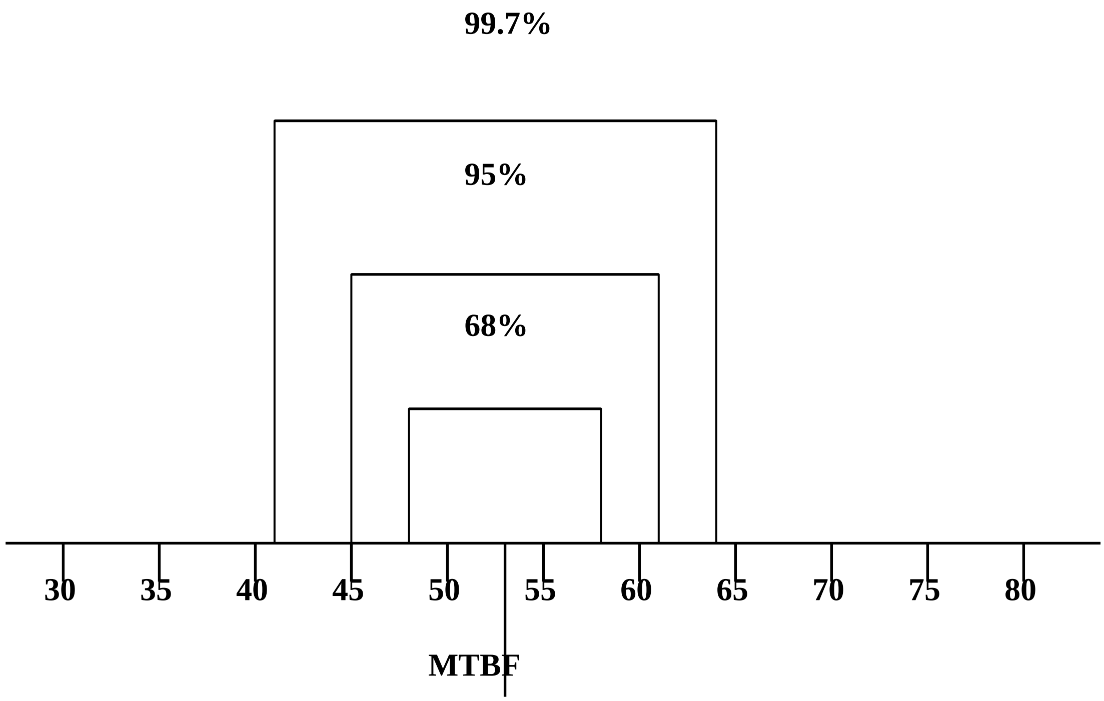


Figure 8

CONCEPT EXPLORATION	PROGRAM DEFINITION & RISK REDUCTION	ENGINEERING & MANUFACTURING DEVELOPMENT	PRODUCTION, FIELDING, DEPLOYMENT & OPERATIONS SUPPORT

DEVELOPMENTAL SYSTEMS

Emphasis on design influence

FIELDED SYSTEMS

Emphasis on verifying PMCS

Figure 9

APPENDIX A

TM 5-6115-590-12

//MAINTENANCE ALLOCATION CHART EXTRACT//

(1) Group Number	(2) Component/Assembly	(3) Maintenance Functions	Maintenance Category C	O	F	H	D
19	ENGINE AND SKID ASSEMBLY						
1901	Assembly	Inspect		0.5			
		Service		1.5			
		Replace			4.0		
		Repair		10.0			
		Overhaul					25.0
1902	Pump, Fuel Boost	Inspect	0.3				
		Test		0.5			
		Service		0.5			
		Replace		1.5			
		Repair			2.5		
		Overhaul					3.0
		Rebuild					3.5
1903	Tank Assembly, Fuel Float and Vent Valve	Inspect	0.3				
		Test		0.5			
		Replace		1.0			
		Repair			1.0		
1904	Tank, Oil	Inspect	0.3				
		Service	0.1				
		Replace		1.0			
		Repair			1.0		
1905	Tank, Fuel	Inspect	0.3				
		Service	0.6				
		Replace		1.5			
		Repair			2.5		
1906	Chassis Assembly, Upper Electrical Power	Inspect		0.5			
		Test		1.0			
		Replace			3.0		
		Repair		4.0			
1907	Harness, Electrical	Inspect	0.3				
		Test		0.8			
		Replace		2.0			
		Repair			2.5		
		Rebuild					4.0
1908	Battery Charger Assembly	Inspect	0.3				
		Test		0.5			
		Adjust		0.5			
		Replace		0.8			
		Repair					3.0
		Overhaul					3.5
		Rebuild					4.0
1909	Printed Circuit Board	Inspect					0.3
		Test					0.5
		Replace					0.5
		Repair					1.5
		Rebuild					2.5

APPENDIX A (CONTINUED)

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Table 3-1. Operator/Crew Preventive Maintenance Checks and Services

B--Before Operation D--During Operation A--After Operation

Item No.	Interval B	D	A	Item to be Inspected	Procedures	Equipment Will Be Reported Not Ready (RED) if:
1	•			Power plant, utility	Walk around unit, look for loose connections, foreign material in makeup air doors, leaks, damage, and general condition (Fig. 2-10).	
				a. Grounding connection	Look for loose or missing grounding cable (Fig. 2-9).	
				b. Fire extinguisher	Check availability of extinguisher and proper pressure (Fig. 2-9).	
				c. Extenal filter/separator	Drain water before float ball reaches indicator mark (Fig. 4-18)	
				d. Fuel and water	Ensure that supply is adequate for anticipated length of operation. (Max. consumption, fuel 35 GPH, water 540 GPH).	
2		•		Control panel		
				a. Ammeter DC	Shall indicate between 0–30 amps on positive side of meter (Fig. 2-1)	Not indicating a charging current.
				b. Exhaust temperature	Shall not exceed 1225°F (663°C) during steady state operation (Fig. 2-1)	Temp exceeds 1260°F (682°C).
				c. Frequency meter (400 Hz)	Shall indicate 400± Hz (Fig. 2-8).	Above or below 400 ± 12 Hz.
				d. Ammeter AC (400 Hz)	Shall indicate applied current, not to exceed 100% (Fig. 2-8)	
				e.Voltmeter AC (400 Hz)	Shall indicate 120 ± 3 volts (Fig. 2-8).	Above or below 120 ± 3 volts.
				f.Frequency meter(60 Hz)	Shall indicate 60 ± 2 Hz (Fig. 2-7).	
				g. Ammeter AC (60 Hz)	Shall indicate applied current, not to exceed 100% (Fig. 2-7).	

APPENDIX B

RCM LOGIC

1. RCM Logic - General.

a. The RCM logic presented in Figure B-1 is designed to accomplish the following--

(1) Using data from the system safety and reliability programs, identify components in the system/equipment which are critical in terms of mission or operating safety.

(2) Provide a logical analysis process to determine the feasibility and desirability of scheduled maintenance task alternatives.

(3) Highlight maintenance problem areas for design review consideration.

(4) Provide the supporting justification for scheduled maintenance task requirements.

b. The RCM logic provides a more rational procedure for task definition and a more straightforward and linear progression through the decision logic. It takes a "from the top down" or consequence of failure approach. At the outset, the functional failure is assessed for consequence of failure and is processed for one of four basic categories--

(1) Catastrophic.

(2) Critical.

(3) Marginal.

(4) Minor.

The four categories are identified as Safety Hazard Severity Codes (SHSCs) 1 - 4. With the consequence category established, only those task selection questions pertinent to the category need be asked. This eliminates unnecessary assessments and expedites the analysis. A definite applicability and effectiveness criteria has been developed to provide a more rigorous selection of tasks. In addition, this approach helps to eliminate items from the analytical procedure whose failures have no significant consequence.

c. The logic process is based upon the following-

(1) Scheduled maintenance tasks should be performed for noncritical (categories 3 and 4) components only when performance of the scheduled task will reduce the life-cycle cost of the equipment/ system.

(2) Scheduled maintenance tasks should be performed on critical components (categories 1 and 2) when such tasks will prevent a decrease in reliability or deterioration of safety to unacceptable levels, or when the tasks will reduce the life cycle of ownership of the system/equipment.

d. The RCM logic is intended for application once a component's failure modes, effects, and criticality have been identified. As with other supportability analysis tasks, the logic process will be reapplied as available data moves from a predicted state to measured values with a higher degree of certainty, and as design changes are made. In addition, once all components have been subjected to the logic process, an overall system analysis is required to arrive at the overall maintenance plan. This system analysis merges individual component requirements into a system maintenance plan by optimizing the frequency of scheduled maintenance requirements and the sequence of performance of individual scheduled tasks.

e. The RCM logic will be applied to each reparable item in the system/equipment. The maintenance task requirements will be identified against the reparable components; however, individual failure modes must be addressed during the application of the RCM logic. Thus, for a given component, different scheduled tasks could be arrived at due to the different failure modes and their characteristics. As an example, a given component might undergo crew monitoring during normal operations to detect the majority of predicted failure modes for the component, while still having a scheduled inspection requirement due to a failure mode that is not detected during routine operator/crew monitoring.

f. In addition to the scheduled maintenance task requirements identified during application of the RCM logic, any scheduled tasks that were assumed in establishing the reliability characteristics of the system/equipment under the reliability program must be included in the maintenance plan. Inherent failure rates and failure modes and effects may need adjusting if an assumed scheduled maintenance action is omitted from the maintenance plan after application of the RCM logic. For example, the reliability data provided for an internal combustion engine and its internal components may be based on a 6,000-mile scheduled oil and oil filter changes. If this schedule is changed because of Army oil analysis in developing the detailed maintenance plan for the engine, the resulting effect on the reliability parameters must be determined.

g. When determining if a failure is critical for mission considerations, the mission of an individual piece of equipment will be the governing factor. Thus, for a missile component, the individual missile is addressed, not the complete missile system composed of many launchers and missiles.

h. Task determination questions are arranged in a sequence so that the most preferred task, most easily accomplished, is considered first. Potential tasks are considered in sequence down to and including possible redesign.

i. The logic is maintenance-task-oriented and not maintenance-process-oriented. By using the task-oriented concept, one will be able to see the entire maintenance program reflected for a given item (e.g., an item may show a before operation inspection, a lubrication task at a monthly interval, and an align on a quarterly basis). Servicing/lubrication is included as part of the logic diagram since this ensures that an important task category is considered each time an item is analyzed.

j. The selection of maintenance tasks as output from the decision logic has been enhanced by a clearer and more specific delineation of the task possibilities contained in the logic.

k. Treatment of hidden functional failures is more thorough as the logic provides a distinct separation between tasks applicable to either hidden or evident functional failures.

l. The effect of concurrent or multiple failure is considered. Sequential failure concepts are used as part of the hidden functional failure assessment and multiple failure is considered in structural evaluation.

m. There is a clear separation between tasks that are economically desirable and those that are required for safe operation.

2. RCM Logic - Abbreviated.

a. The RCM logic displayed in Figure B-1 is an abbreviated version of the one used to determine if a component should have a scheduled (preventive) maintenance requirement, and if so, what scheduled maintenance tasks should be performed. Each decision point is numbered and detailed instructions for each are provided below.

b. The following is a detailed set of instructions for application of the logic in Figure B-1.

(1) Decision 1. Is functional component failure critical for safety or mission? This question will be asked for each failure mode identified for the component under analysis. The answer to this question will be based on the Failure Modes and Effects Analysis. A "yes" answer indicates that this failure mode exists and has been identified as critical or catastrophic which corresponds to a safety hazard severity code (SHSC) of 1 or 2 and will result in a safety hazard or possible serious mission impact. Components and failure modes for which a "yes" answer is obtained will be referred to as critical. These critical items will be analyzed further to determine if a scheduled maintenance task will help prevent deterioration of reliability or safety levels, thus minimizing the risk of a possible serious mission impact or safety hazard. A "no" answer indicates that the component is classified with a SHSC of 3 or 4 and further exploration is required to determine if scheduled maintenance is required for secondary failures which are critical, have hidden failures, or have economical impact.

(2) Decision 2. Does failure cause secondary failure that is critical for safety or mission? The instructions for this decision point are the same as for decision 1, but this question refers to secondary failures that are caused by the primary failure modes considered in decision 1. A "yes" answer identifies a noncritical failure mode which causes a secondary failure classified as critical and results in either a safety hazard or a mission abort. The failure mode will be analyzed further to determine what scheduled maintenance tasks can be performed that will prevent or decrease

the likelihood that reliability or safety will deteriorate below acceptable levels. A "no" answer to each question in decisions 1 and 2 indicates that the failure mode for the component is noncritical and may be operated to failure without incurring a safety hazard or a mission abort.

(3) Decision 3. Does economic analysis indicate scheduled maintenance?

(a) Decision point 3 identifies scheduled tasks which can be performed and that will decrease the cost of ownership of the end item. To address this decision point, it must first be determined whether a scheduled task can be done. This can be determined by applying the questions in decision points 4 through 14, which identify the specific tasks that are judged to be effective. Keep in mind that the questions are being addressed for noncritical failure modes. If economic analysis does not indicate scheduled maintenance, operate to failure. This completes the decisionmaking process for this failure mode.

(b) In determining if a scheduled maintenance task is economically justified, the difference in ownership cost for the end item must be calculated. It is not intended that a complete life-cycle cost be calculated for each alternative, but rather those cost factors which would be different between the alternatives should be determined. Consideration must also be given to any manpower, downtime, or availability constraints on the end item if an additional scheduled task is included in the maintenance plan for a noncritical component. If a substantial cost savings could be realized through some scheduled maintenance action which impacts one or more system constraints, then a trade-off analysis shall be performed.

(c) This decision point should not be addressed until the RCM logic has been applied to the critical components of the system/equipment under analysis, because the results of the critical component analysis could affect the cost of feasible scheduled tasks on noncritical components. For example, a noncritical inspection may not be economically justifiable by itself if it requires excess time and cost, but if the time and cost are determined to be required for a critical component inspection, then the noncritical inspection may be economically justifiable. For this reason, the economic aspects of noncritical tasks should only be addressed after the scheduled maintenance requirements for critical components are determined.

RCM LOGIC - ABBREVIATED

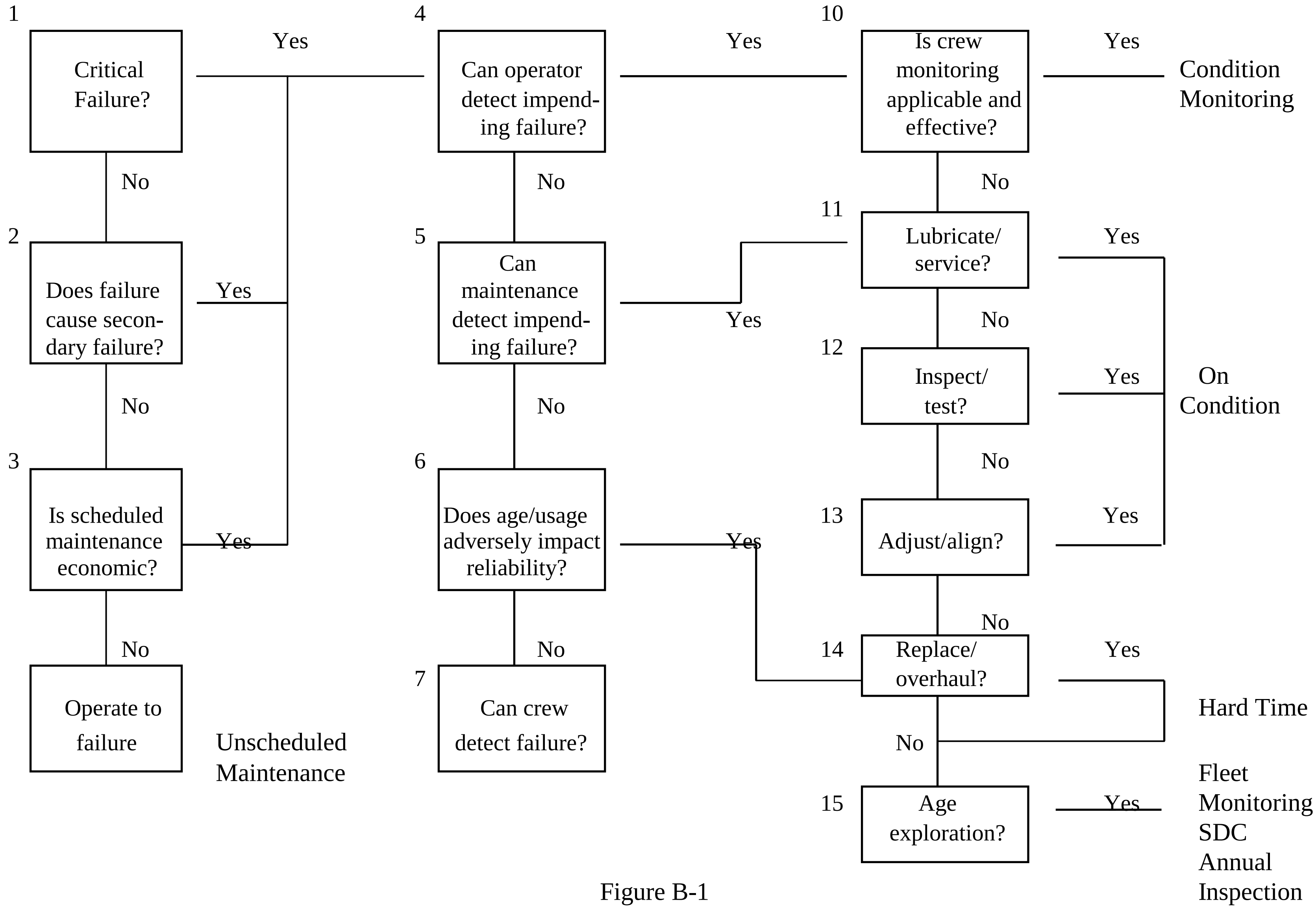


Figure B-1

RCM LOGIC - ABBREVIATED

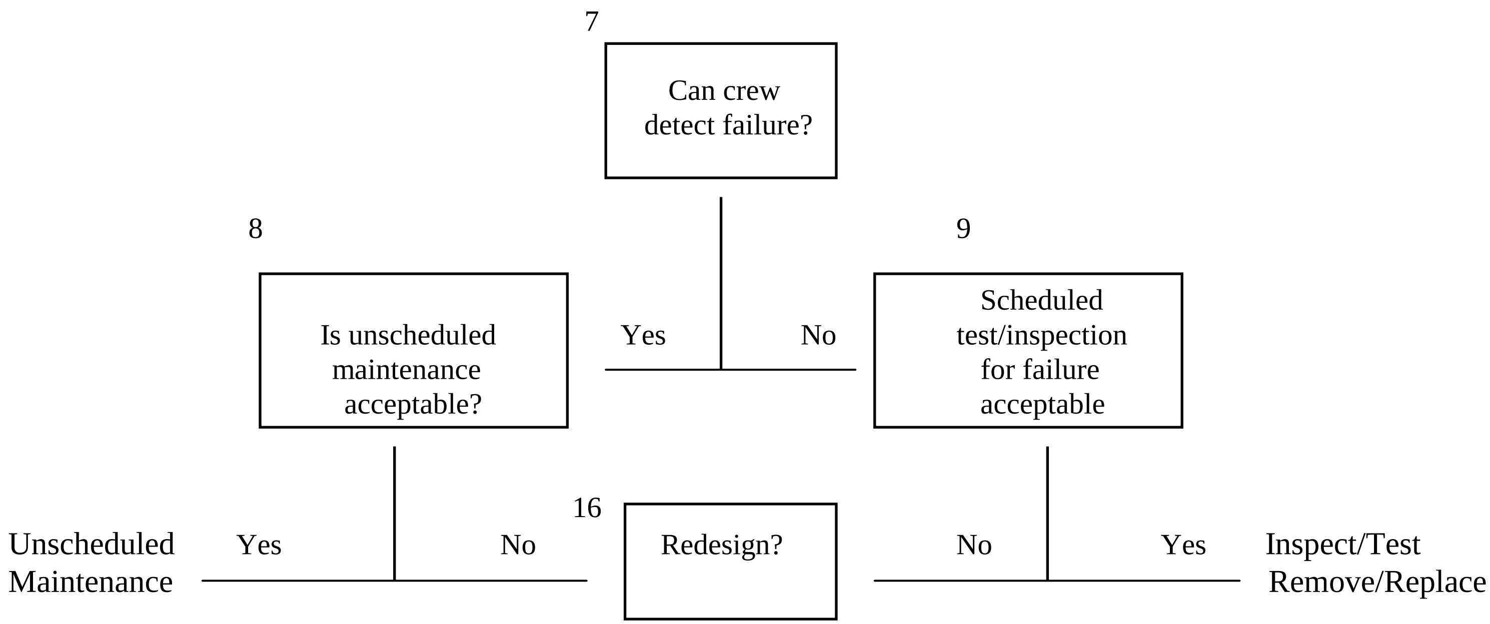


Figure B-1(cont'd)

(d) If the analysis shows that scheduled maintenance tasks on the noncritical component reduces the cost of ownership of the system/equipment, then this task(s) would be included in the overall maintenance plan, and the decision recorded. If a scheduled task is not feasible or is not economically justified for the noncritical component under analysis, then the component would be operated to failure and only unscheduled maintenance would be performed.

(4) Decision 4. Can operator detect impending failure?

(a) This is the first of four decision points (4 through 7) that will determine if scheduled maintenance tasks are applicable and effective.

(b) The question at this decision point is intended to identify those critical failure modes which can be detected through routine operator/crew monitoring with sufficient leadtime to prevent a mission abort or safety hazard. If there is a high probability that the failure mode under analysis can be detected with sufficient leadtime before it will actually occur to prevent a mission abort or incurrence of a safety hazard, then the question will be answered "yes." This will be the case for failure modes which have a sufficient time difference between onset of initial degradation and actual failure, and a means of detecting the onset. The detection means can be in the form of instrumentation (gauges, warning lights, etc.) or operational characteristics (vibration, sound, etc.). The question will be answered "no" if the operator/crew cannot detect an impending failure, or if the time difference between onset and actual failure is not long enough to prevent a mission abort or safety hazard.

(5) Decision 5. Can maintenance detect impending failure?

(a) The question at this decision point is addressed to identify the potential efficiency of a scheduled maintenance task on the component under analysis and must be considered in two parts. First, the impending failure must be physically detectable either by visual inspection or through use of test or measurement equipment. To be detectable, measurable physical properties of the component must change with the onset of degradation to allow identification of impending failure through comparison with normal properties.

(b) The second consideration is the probability that the scheduled maintenance task will coincide with the time between onset of degradation and the occurrence of failure so that the impending failure will be detected and corrected before it occurs. As an example, a component which fails within seconds after the onset of any measurable degradation would not be a good candidate for a scheduled task. The probability that any reasonable inspection interval would result in the inspection occurring within the time between onset and failure is very small in this case; consequently, the payoff would be extremely small. On the other hand, if the time between measurable failure onset and actual failure occurrence was measured in days or months, then an inspection interval could be established which would result in a high probability of detecting the failure under analysis before it occurs. In answering this consideration, the failure distributions from the Reliability Program, data from a historical data review, and applicable test results must be analyzed.

(c) If the impending failure is measurable, and a reasonable maintenance task interval which results in an acceptable probability of detection can be established, then the question in Decision Point 5 would be answered "yes." If one of these considerations is not met, then Decision Point 5 would be answered "no."

(6) Decision 6. Is there an adverse relationship between age or usage and reliability? (See paragraph 5 of this appendix for a discussion of age/usage and reliability.)

(a) The question at this decision point is to identify wearout type components and to determine the feasibility of scheduling replacement of the component under analysis. This question would be answered "yes" if the probability of component failure increases as calendar time or usage indicators (operating hours, miles, rounds, cycles) increase. For these items, a scheduled removal could be identified at a point in time or after a specified amount of usage when the probability of failure increases to an unacceptable level. Removal and replacement with a new item will return the probability of failure to its original level. This question will be answered "no" if the probability of failure is independent of either calendar time or usage. This is the case for components which exhibit an exponential failure rate.

(b) In answering the question of this decision point "yes," it should be noted that a means of measuring the interval between the scheduled replacements of the component be provided. If the component cannot be economically maintained, then the question at this decision point must be answered "no."

(7) Decision 7. Can failure be detected by crew?

(a) The question at this decision point is addressed to identify hidden functions where occurrence of the failure under analysis may go undetected until the function is required. If the operator/crew cannot detect that a failure has occurred, maintenance inspections or tests may be required to ensure that a failure has not occurred and that there is a high probability the hidden function will be available when required.

(b) A "yes" indicates that the failure under analysis can be detected by the operator/crew and a "no" indicates that the maintenance task is required to detect the failure.

(8) Decision 8. Is unscheduled maintenance acceptable?

(a) This begins the part of the analysis which determines whether maintenance should be scheduled and whether the design of the item is adequate to meet the requirements for maintenance. If the question is answered "no," continue to decision point 16.

(b) This decision point identifies components which have critical hidden failure modes with no means of detecting impending failure or reducing the probability of a failure. Actual failures are detectable by the operator/crew either at the time of occurrence or after occurrence so that unscheduled maintenance can be accomplished in the event of failure. The answer to this decision point is based upon the probability of failure, failure detection, rate, predictability, and criticality. If the failure or effects of the failure can be tolerated, the corrective maintenance task, identified as a result of the FMECA, is recorded. A "no" for this decision point indicates that the risks of incurring a mission abort or safety hazard or hidden failure would be unacceptable and that the only alternative is to redesign the component or interfacing components to eliminate the critical or hidden failure modes or to provide a means of detecting the impending failure. In some cases, the required redesign may involve the addition of a test point or a measurement device, while in other cases, the cost of incorporating the redesign may be prohibitive or the redesign may not be technically feasible.

(9) Decision 9. Is scheduled inspect/test for failure acceptable? This decision point identifies components which have critical failure modes with no means of detecting impending failures, no wearout characteristics, and no means for the operator/crew to detect failures that have occurred. For components that fall into this category, a scheduled maintenance task must be indicated in the maintenance plan to detect failures that have occurred and to ensure that there is a high probability of the hidden function being available when required. The corrective action for this decision will be prescribed.

c. Decision Points 10-14. The maintenance tasks listed decision points 10-14 are listed in a priority sequence for correcting a failure. During the RCM analysis, these scheduled maintenance tasks are evaluated to determine if they are applicable and effective for identifying and correcting a failure mode. It may be necessary to perform more than one maintenance task within a decision block or a combination of decision blocks in order to maintain the inherent reliability of an item. The objective of this process is to optimize the maintenance program while minimizing the maintenance resource requirements. If any of the tasks listed are determined to be effective and applicable, then a scheduled (preventive) maintenance action is selected. If no preventive maintenance task is effective or applicable for the failure mode being analyzed, the analysis resumes at decision point 7, 8, 9, and 16 after considering decision point 15.

d. Decision 15. Is age exploration applicable? This decision point addresses age exploration and the identification of critical or hidden failure modes that require monitoring and updating of the maintenance plan.

This decision point is used during the initial analysis and for any update of the RCM as data becomes available through test, analysis, and actual field use. If any category 1 or 2 failure mode that is addressed through this logic is found to require continued monitoring or testing after development, and the current maintenance plan does not satisfy the safety and mission requirements, then this decision point will be answered "yes," identifying the item as a candidate for an age exploration effort.

e. Decision 16. Is redesign applicable?

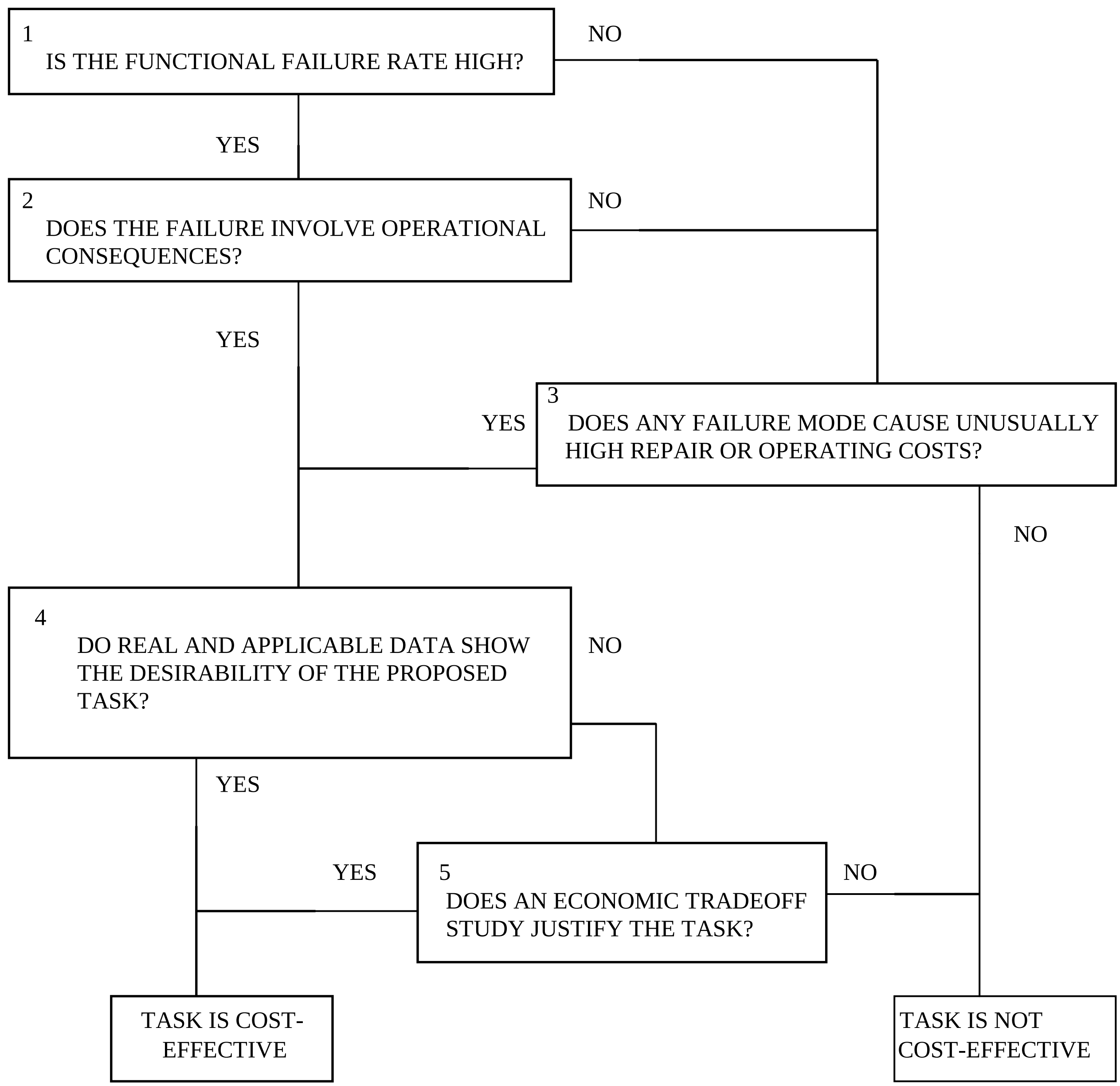
(1) This decision point allows the analyst to review the maintenance program for each failure to ensure that will meet the required mission and safety levels. A task analysis will be performed to select the best task or combination of tasks that will meet these requirements. If this analysis indicates that the maintenance tasks will not meet the requirements, redesign should

be considered. The cost and feasibility of a redesign must be considered along with the potential benefits derived from the redesign. In some cases, the required redesign may involve the addition of a test point or measurement device, while in others, the cost redesign may be prohibitive or the incorporation of a redesign may not be technically feasible.

(2) Since RCM is a reiterative process as the design matures and data becomes available, the redesign decision point will be used less and less. If redesign is not applicable, reenter logic chart at decision point 1. Evaluate all previous decisions considering that redesign is not applicable and that an alternative solution must be chosen.

3. RCM Task Selection. Upon completion of each failure mode through the RCM logic, analysis of preferred task is performed to select the most applicable and effective maintenance task or combination of maintenance tasks that will meet the required mission and safety requirements. The scheduled maintenance tasks selected must meet the criteria of applicability and effectiveness. Figure B-2 summarizes the applicability and effectiveness criteria for most cases. It is important to understand that the applicability of a task depends on the failure characteristics of an item, and the effectiveness of a task depends on the failure consequences for each case. Therefore, an applicable task must satisfy the requirements of the characteristics of failure. These requirements are different for scheduled maintenance overhaul and remove/replace tasks as shown in Figure B-2. The applicability criteria is dependent solely on the type of task, regardless of failure consequence. Once a task is chosen which is applicable, the effectiveness of that task in preventing the failure consequences must be determined. Note that in Figure B-2, the effectiveness criteria varies by failure consequences. Therefore, each type of task must meet the same effectiveness criteria under the same consequence of failure. The specific applicability criteria will be discussed in detail as the individual tasks are presented.

Effectiveness criteria for safety and hidden failure consequences. The evaluation of the effectiveness criterion is the same for each failure consequence, regardless of the type of task. The effectiveness criteria for each failure consequence are discussed separately. For safety consequences, the effectiveness criteria require that the task reduce the risk of critical failure to an acceptable level. To assess the risk of failure, an iterative process must be followed. After a task is proven to be applicable, an initial task interval is assigned. Using this interval, the probability of failure must be low enough to ensure that failures are very unlikely.



DECISION DIAGRAM FOR EVALUATING THE PROBABLE COST-EFFECTIVENESS OF A PROPOSED TASK WHEN PREVENTIVE MAINTENANCE IS NOT REQUIRED TO PROTECT OPERATING SAFETY OR THE AVAILABILITY OF HIDDEN FUNCTIONS. THE PURPOSE OF THE DECISION TECHNIQUES IS TO REDUCE THE NUMBER OF FORMAL ECONOMIC TRADEOFF STUDIES THAT MUST BE PERFORMED.

Figure B-2 Decision Diagram for Cost-Effectiveness

4. Age-Reliability Characteristics.

a. 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, the numerous conditional-probability curves for aircraft components were developed to ensure that the higher overhaul times were not reducing overall reliability. It was found that the conditional-probability curves fell into the six basic patterns shown in Figure B-3. Pattern A is often referred to in reliability literature as the bathtub curve. This type of curve has three identifiable regions--

(1) An infant-mortality region, the period immediately after manufacture or overhaul in which there is a relatively high probability of failure.

(2) A region of constant and relatively low failure probability.

(3) A wearout region, in which the probability of failure begins to increase rapidly with age.

b. 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.

c. The presence of a well defined wearout region is far from universal. Indeed, of the six curves in Figure B-3, only A and B show wearout characteristics. It happens, however, that these curves are associated with a great many single-celled or simple items. 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.

d. 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.

e. 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 right after installation is fairly high. Also, the conditional-probability curve usually 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, imposing 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.

f. 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.

g. It is apparent from the discussion thus far, that most statements about our "life" of equipment tell us little about its age-reliability characteristics. For example, the statement that an aircraft engine has a life of 2,000 operating hours might mean any of the following--

(1) No engines fail before reaching 2,000 hours.

(2) No critical engine failures occur before 2,000 hours.

(3) Half the engines fail before 2,000 hours.

(4) The average age of failed engines is 2,000 hours.

(5) The conditional probability of failure is constant below 2,000 hours.

Age-reliability patterns. In each case, the vertical axis represents the conditional probability of failure and the horizontal axis represents operating age since manufacture, overhaul, or repair. These six curves are derived from reliability analyses conducted over a number of years, during which all the 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).

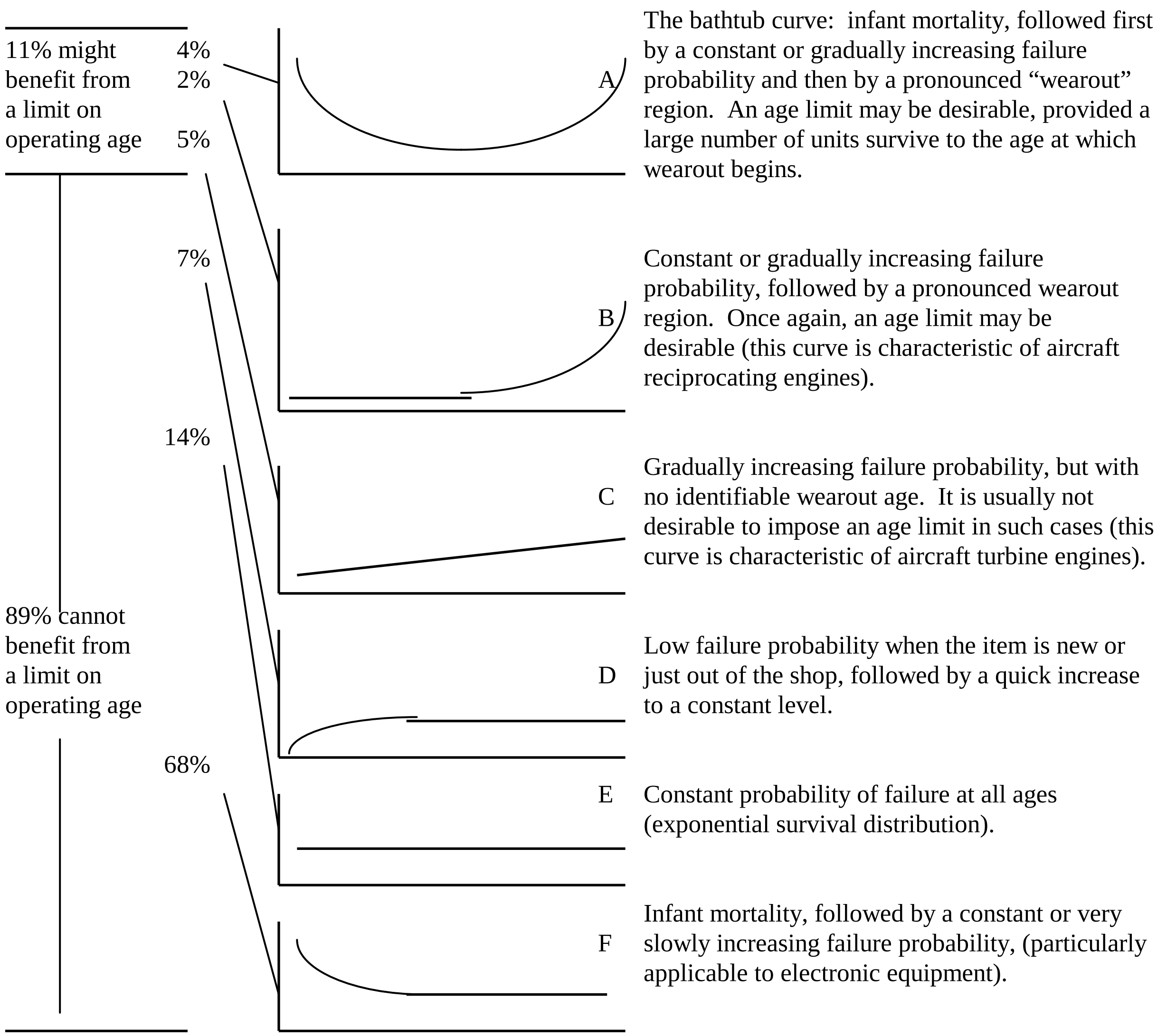


Figure B-3. Age-Reliability Characteristics