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HELICOPTER RELIABILITY AND MAINTAINABILITY TRENDS DURING DEVELOPMENT AND PRODUCTION

Norman J. Asher
Lee L. Douglas
Ray H. Jakobovits

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July 1981

Prepared for

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This study updates and extends IDA Study S-451, "Changes in Helicopter Reliability/Maintainability Characteristics over Time," dated March 1975. This study presents more recent data and, based on the combined data of both studies, summarizes the observed helicopter R&M trends. Trends observed during the development phase are compared with those of the production phase.

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PREFACE

This study was prepared by the Institute for Defense Analyses for the Office of the Assistant Secretary of Defense (MRA&L) under Contract MDA903-79-C-0320, Phase I of Task Order No. 80-I-1, dated 3 March 1980. The study was under the technical direction of Messrs. Russell R. Shorey and Martin A. Meth of the Office of the Special Assistant for Weapon Support Improvement.

The purpose of this Phase I study was to update and extend a 1975 IDA study of changes in helicopter reliability/maintainability (R&M) characteristics over time [1]. In this study more recent data have been collected; based on the combined data of both studies, the observed helicopter R&M trends are summarized.

The submission of this paper is in fulfillment of the contract.

ABBREVIATIONS AND GLOSSARY

α	If reliability growth can be shown as a straight line on log-log paper, then α is the slope.
AAH	Advanced Attack Helicopter
Abort Rate	Number of aborting failures per flight hour
Aborting Failures	Failures serious enough to cause abort of a mission
Achieved Availability	In the UTTAS and AAH programs, 100 percent less the percent of maintenance downtime; it assumes no loss in availability due to NORS or administrative delay.
AFCS	Automatic Flight Control System
AMSAA	Army Materiel Systems Analysis Activity
APU	Auxiliary Power Unit
AVIM	Aviation Intermediate Maintenance
AVUM	Aviation Unit Maintenance
BED	Basic Engineering Development Phase; that phase of the UTTAS and AAH programs during which competitive prototypes were developed, built, and tested (through DT II/OT II).
Bench Test	Testing of components in laboratory test equipment
BIS	Board of Inspection and Survey (Navy)
Burn-in	The operation of an item to induce infant mortality failures before field use in order to stabilize its operational characteristics upon commissioning to those expected for the useful life period.
Component	A basic assembly or part which performs a function

CONUS	Continental United States
C.O.P.	Company Owned Prototype
CRIM	Component Report for Intensive Management System
Customer's Risk	The risk, or probability, that a product will be accepted by a reliability test when it should properly be rejected.
Design Review	Multipurpose design verification procedure and project management tool used to evaluate the R&M, life cycle cost, performance, and various other characteristics of an equipment at major design and testing milestones.
DODI	Department of Defense Instruction
Duane	An engineer at General Electric who found that reliability growth often can be depicted as a straight line on log-log paper when cumulative failure rate is plotted against cumulative test hours (hence, the "Duane curve").
DSARC	Defense Systems Acquisition Review Council
DT II	Development Testing - Two
Failure	The inability of an item to perform within previously specified limits. There are many ways of counting failures: "system failures" generally include all failures; "mission failures" include only those failures serious enough to cause abort of a mission; "primary failures" are those attributable to the inherent design characteristics of the component (as opposed to "non-primary failures" which are attributable to faulty maintenance, improper handling, etc.); "chargeable failures" are defined to differentiate failures chargeable to a contractor from failures occurring in GFE; "independent failures" refer to initial failures which may in turn induce other "dependent failures," etc. These many categories of failures, often ill-defined, may introduce distortions in comparing different programs and reporting systems (and sometimes result in inconsistencies even within a given program and reporting system when ground rules for counting failures are changed).

Failure Mode	A particular way in which failures occur; the condition or state which is the end result of a particular failure mechanism.
FDTE	Force Development Test and Experimentation
FFAR	Folding Fin Aircraft Rocket
FH	Flight Hours
FIP	Fleet Introduction Program (Navy).
Flight Safety Reliability	In the UTTAS and AAH programs, the probability of completing a one-hour mission without failure or malfunction which results in a forced landing or mishap.
GCT	Government Competitive Testing
GFE	Government-Furnished Equipment
GSE	Ground Support Equipment
GTV	Ground Test Vehicle
Helicopter System	The helicopter, consisting of all its systems.
HLH	Heavy Lift Helicopter
HMMS	*HELLFIRE* Modular Missile System
HSR	Hardware System Reliability failure. Any fault in any equipment that results in the inability of the item to perform its required function and requires unscheduled removal of that item. (Term used in CH-47D program).
IOC	Initial Operational Capability
JC	Justification Code (Used in Army PIPs)
LCC	Life Cycle Cost
LMI	Logistics Management Institute
LRU	Line Replaceable Unit
Maintenance Action	An action necessary for retaining an item in or restoring it to a specified condition. Maintenance actions may be differentiated with respect to scheduled versus unscheduled actions and level of maintenance activity performing the action.
Maintenance Downtime	The sum of all clock time for preventive and corrective (on-aircraft) maintenance.

Maturity	The phase of an aircraft program life cycle when little or no further improvement in R&M characteristics takes place--generally after roughly 20,000 to 100,000 flight hours.
Maturity Phase	That phase of the UTTAS and AAH programs following selection of the winner after the competitive fly-off and before the delivery of production aircraft.'
MFHBF	Mean Flight Hours between Failures. (Same as MTBF)
MFHBMA	Mean Flight Hours between Maintenance Actions. (Same as MTBMA)
Mishap	A malfunction or failure which is potentially injurious to or results in injury to flight crew, ground crew or passengers, or damage to the aircraft.
Mission Reliability	The probability that the helicopter will fly for a specified time without incurring a failure causing abort of a mission.
MMH/FH	Maintenance Man-Hours per Flight Hour
MQT	Military Qualification Test
MTBF	Mean Time Between Failures
MTBM	Mean Time Between (Unscheduled) Maintenance (Actions)
MTBMA	Mean Time Between Maintenance Actions
MTBR	Mean Time Between Removals
MTTR	Mean Time to Repair
Navy 3-M	The Navy Maintenance Material Management reporting system
NSC	Naval Safety Center
O&M	Operation and Maintenance
Off-board MTBF	For helicopters, the first flight is the time that the design is considered off-board.
Operational Availability	The probability that a requested aircraft is not down for maintenance or spare parts.

Operational Failures	In the UTTAS and AAH programs, all system failures plus dependent failures, operator and maintenance errors, foreign object damage, and GSE induced malfunctions.
OT II	Operational Testing - Two
PEP	Procurement Engineering and Planning
PIP	Product Improvement Program
Producer's Risk	The risk, or probability, that a product will be rejected by a reliability test when it should properly be accepted.
PVT-G	Production Verification Testing - Government
RAM	Reliability, Availability, Maintainability
RAM-D	RAM-Durability (selected aircraft, in the Black Hawk program)
RAM/LOG	Reliability, Availability, Maintainability, Logistics Sample Data System
RDT&E	Research, Development, Test and Evaluation
Removal Rate	The number of removals of a component per unit time
RFP	Request for Proposal
RFQ	Request for Quotation
RIW	Reliability Improvement Warranty
RPM	Reliability Planning and Management
R&M or R/M	Reliability and Maintainability
SDC	Sample Data Collection System
SOR	System Operational Reliability. As used in the CH-47D program, a system failure is called an SOR failure. It includes all Primary and Non-Primary, Independent and Dependent Failures.
STA	Static Test Article
System Reliability	The probability that the helicopter will fly for a specified time without incurring a failure.
TADS/PNVS	Target Acquisition Designation Sight/ Pilot Night Vision Sensor

TAMMS	The Army Maintenance Management System
TBO	Time Between Overhaul. This is the maximum number of flight hours that a component is scheduled to operate between overhauls. The actual time between overhauls may be less.
TSARCOM	Troop Support and Aviation Materiel Readiness Command
UMSDC	Unscheduled Maintenance Sample Data Collection System
USASC	U.S. Army Safety Center
UTTAS	Utility Tactical Transport Aircraft System
WUC	Work Unit Code
66-1	Air Force Maintenance Management System (name derived from the Air Force manual that sets out maintenance policy.)

SUMMARY

This study was conducted in response to Phase I of Task Order No. 80-I-1, "Helicopter Reliability and Maintainability Characteristics." It updates and extends a 1975 IDA study of changes in helicopter reliability/maintainability (R&M) characteristics over time [1]. In this study we have collected more recent data and, based on the combined data of both studies, have summarized the observed helicopter R&M trends. We have compared the trends observed during the development phase with those of the production phase. In general, the data obtained in this study for the more recent programs are compatible with the data presented in the 1975 study for the earlier programs.

The study relates R&M characteristics to test and operational flight hours and calendar time. We were not able to estimate the associated dollar expenditures for R&M improvement because current cost accounting systems do not clearly separate expenditures for R&M improvement from expenditures for the many other aspects of helicopter development and production programs. The combined effects of initial "off-board" reliability and subsequent rate of reliability improvement in achieving reliability goals is analyzed.

A. CONCLUSIONS

Tables S-1 and S-2 summarize data on helicopter reliability and maintainability (R&M) trends during the development and production phases of helicopter programs, respectively. Our 1975 study contained all the R&M trend data that we were able to assemble at that time on helicopter programs up to the early

Table S-1. HELICOPTER R&M GROWTH - DEVELOPMENT PHASE

Program / Measure	System Failure Rate	Abort Rate	Achieved Availability	Maintenance Manhours per Flight Hour	Component Removal Rate
YUH-60A	Improved during BED (α=0.13); worsened during Maturity (p. 68)	Improved during BED (α=0.47); worsened during Maturity (p. 78)	Improved during BED; worsened during Maturity (p. 81)	Improved during BED; worsened during Maturity (p. 84)	
YUH-61A	Improved during BED (p. 99)				Improved during BED (p. 99)
YAH-64	Improved during BED (α=0.09) (p. 107)		Improved during BED (p. 106)	Improved during BED (p. 106)	
CH-53E	Improved (p. 121)	Improved (α=0.23) (p. 120)		Improved (p. 121)	
CH-47D	Improved during BED (α=0.14) (p. 117)				Constant during BED (p. 117)
AH-56A	Improved (α=0.16) (p. 148)	Improved (p. 143)			
OH-6A	Improved (α=0.11 for first 5,000 flight hours) (p. 236)				Improved (α=0.19 for first 5,000 flight hours) (p. 238)
T-700 Engine	Slight improvement during first 16 months of ground testing. α = 0.03 or 0.09 (p. S-4)				
CH-53A		Improved from ~0.25 at 100 FH to ~0.07 at 5,000 FH (α=0.3-0.4) (p. S-4)			
UH-1D, AH-1G, OH-58A	MTBF at 100 FH was 20-30 percent of MTBF of mature production aircraft (p. S-4)				

Table S-2. HELICOPTER R&M GROWTH - PRODUCTION PHASE

Program \ Measure	System Failure Rate	Abort Rate	Achieved Availability	Maintenance Manhours per Flight Hour	Component Removal Rate	Component Time Between Overhaul	Operational Availability	Accident Rate	Mishap Rate	Mean Time Between Maintenance Actions
UH-60A	Improved from 1st to 2nd Year Production A/C (α=0.29)(p. 75)	Improved from 1st to 2nd Year Production A/C (α=0.12)(p. 78)	Improved from 1st to 2nd Year Production A/C (p. 81)	Improved from 1st to 2nd Year Production A/C (p. 84)						Improved from 1st to 2nd Year Production A/C (p. 84)
Army UH-1, AH-1, CH 47, CH-54, OH-6, OH-58							Operationally ready rates generally remain constant over time (p. 208)	Accidents (both those involving materiel and total) improved (p. 188)	Mishaps (both those involving materiel and total) worsened (p. 188)	
Navy H-1, H-2, H-3, H-46, H-53 (3-M Data)	Worsened for every major component group for every basic helicopter type from 1968 to 1978 (p. 176)			Worsened for every major component group for every basic helicopter type from 1968 to 1978 (p. 176)				Accidents (both those involving materiel and total) improved (p. 199)	Mishaps (both those involving materiel and total) worsened (p. 199)	Worsened for every major component group for every basic helicopter type from 1968 to 1978 (p. 176)
USAF H-1, H-3, H-53				Worsened in 6 cases; constant in 2 cases; improved in 2 cases (p. 182)						Worsened for 4 A/C; constant for 1 A/C (p.182)
OH-6A	Improved (α=0.35 from 5,000 to 27,000 flight hours)(p. 236)				Improved (α=0.26 from 5,000 to 27,000 flight hours)(p. 238)					
CH-53A/D		Improved from about 0.06 to 0.04 (p. 256)			13 components improved, 1 worsened. Average α = 0.23 for 14 components (p. 261)					
H-13 and UH-1A						Improved by several hundred flight hours (p. 240)				
CH-47	Total aircraft experienced low growth (α=0.06). 9 systems improved while 2 worsened (p. 218)			Total aircraft improved (α=0.17) All systems improved (p. 218)	4 transmissions improved. 8 other components generally constant (5 improved while 3 worsened) (p. 221)	4 transmissions improved. 3 other components improved while 1 was indeterminate (p. 221)				
CH-46	Total aircraft improved from 2.0 malfunctions per flight hour in 1962 to 0.64 in 1970, then worsened to 0.93 in 1972 (α=0.22) (p. 219)			Total aircraft worsened slightly (α=0.01). 8 systems improved while 15 worsened (p. 220)	5 components worsened slightly on average (2 improved while 3 worsened) (p. S-7)					

(continued)

Table S-2. (concluded)

Measure / Program	System Failure Rate	Abort Rate	Achieved Availability	Maintenance Manhours per Flight Hour	Component Removal Rate	Component Time Between Overhaul	Operational Availability	Accident Rate	Mishap Rate	Mean Time Between Maintenance Actions
CH-54A/CH-54B	CH-54A and B both improved from first to second quarter, then worsened. CH-54B worse than A (p. 246)	CH-54A improved. CH-54B improved slightly, and was slightly worse than A (p. 247)		CH-54A worsened during first year, then constant. CH-54B constant but worse than CH-54A (p. 243)	CH-54A: 4 components constant, 5 worsened. CH-54B: 3 improved, 1 worsened. CH-54B vs 54A: 7 improved; 1 worsened. Overall: generally improved (p. 251)	CH-54A. 3 improved, 3 constant, 1 worsened. CH-54B. 2 improved, 1 constant; 2 worsened. CH-54B vs 54A. 3 improved; 1 constant; 2 worsened. Overall: generally improved (p. 251)	CH-54A and B both improved initially, then constant at about same level (p. 246)			
UH-1D	Worsened (p. 34)			Improved over first 3 years of Army service (p. S-10)			Improved over first 3 years of Army service (p. S-9)			
T-53 Engine	Improved in successive models (p. S-4)			Improved in successive models (p. S-10)	Improved in successive models (p. S-6)					
OH-58A	Worsened during first 3 months of 15-month R/M demonstration; then constant (p. S-3)				Approximately constant (p. S-6)					Worsened somewhat during first 2 years of service (p. S-3)
AH-1G				Improved during first half-year of service, then approximately constant (p. S-10)	Generally worsened (p. S-6)		Improved during first half-year of service; then approximately constant (p. S-9)			
Several Engines					Definite improvement (p. S-6)					
T-5-L-7/7B/7C					Approximately constant (p. S-7)					
All Army helicopters				Most tended to remain constant; for those that changed, more worsened than improved (p. S-10)						
All USAF helicopters				Tended to worsen (p. S-10)						

1970s. Those data are included below the double horizontal lines of Tables S-1 and S-2; page references are given in parentheses. Data obtained in the current study are summarized above the double lines. Principal conclusions based on the combined data of both studies are:

- Substantial R&M growth occurs during development
- Failure rates generally show worsening trends for production systems
- On limited evidence (UH-60) a specifically funded maturation phase can result in modest improvement in production over development results
- On limited data (CH-47D) major modification programs of fielded systems can improve R&M but are expensive
- Accident rates generally show major improvement after fielding (while maintenance demands worsen)
- On average Component Improvement Programs (CIPs) for dynamic components result in some improvement, but performance modifications may result in worsening failure trends
- On a limited sample, recent commercial aircraft programs either have achieved high initial reliability or complete intensive growth in the first two years of production

R&M trends during each program phase are discussed below. It should be noted that this study only shows R&M trends for helicopters. Thus, they are largely representative of complex mechanical type systems but are not necessarily representative of complex avionics subsystems such as those presently being developed for the AH-64A and LAMPS Mark III programs.

B. DEVELOPMENT PHASE

Data were obtained on five R&M characteristics: (1) system failure rate, (2) abort rate, (3) achieved availability, (4) maintenance manhours per flight hour, and (5) component removal rate. In every case, R&M characteristics improved during the development phase. However, after improvement during the Basic Engineering Development phase, the YUH-60A exhibited a degradation in R&M characteristics during the Maturity phase. Some possible reasons for this worsening are discussed in Chapter II, Section I.

Aborting failure rates seem to improve more rapidly than system failures; this is probably due to the fact that aborting failures (being more serious in nature) receive more corrective attention than failures in general. For system and aborting failures, the data obtained in the current study (above the double line) basically corroborate the data from the 1975 study (below the double line).

The results of Table S-1 indicate quite strongly that all helicopter R&M measures improve during the development phase.

In a number of cases, the R&M data have been presented in the "Duane" format, and the "α's" presented in Table S-1 refer to the Duane equation. Duane [2] found that for some equipments, cumulative failure rate versus cumulative operating hours resulted in a straight line when the data points were plotted on log-log paper. He expressed these "Duane curves" by the equation

$$CFR = \lambda t^{-\alpha} ,$$

where

CFR = cumulative failure rate
λ = initial failure rate (intersection at t=1 hour)
t = cumulative operating hours
α = exponent.

$-\alpha$ denotes the slope of the cumulative failure-rate line: when α is positive, there is a decreasing failure rate; when it is negative, there is an increasing failure rate. If cumulative failure rate versus cumulative operating hours falls on a straight line (the "Duane curve"), then instantaneous failure rate will also fall on a straight line with the equation:

$$IFR = (1-\alpha)\lambda t^{-\alpha} .$$

The Duane paper presented data for five equipments whose α's fell in the range of 0.4 to 0.5. Because of the scarcity of reliability-growth data, the Duane data (α's of about 0.5) have been used in predicting reliability growth for many other equipment programs, including helicopters. However, the helicopter data presented herein indicate that α's for various measures of helicopter reliability tend to be much lower.

The helicopter R&M data indicate somewhat erratic trends of failure rate improvement during helicopter development programs. However, in at least a very approximate way, the programs tend to be characterized by the Duane growth process. Based upon the UH-60A Black Hawk system reliability data, let us hypothesize a "typical" helicopter development program characterized by α = 0.13 and a cumulative failure rate at 100 flight hours = 0.7. These two values permit us to calculate λ = 1.274. The cumulative and instantaneous failure rates for the "typical" helicopter are shown in Figure S-1. Note that the basic characteristic of the Duane curves is that the failure rate is reduced by the same proportion for each order of magnitude increase in cumulative flight hours. In the case of Figure S-1, the failure rate at 100 flight hours is about 74 percent of that at 10 flight hours; at 1,000 flight hours it is 74 percent of that at 100 flight hours, etc. The nature of the relationship becomes much more dramatic visually when the instantaneous failure rate is replotted on a linear grid (see Figure S-2). On Figure S-2 we have added a dashed line (α=0.4) representing the fastest rate of improvement we are aware of for any helicopter development program (the CH-53 abort rate). For comparison with the "typical" helicopter (α=0.13), we have assumed the same cumulative failure rate at 100 flight hours of 0.7.

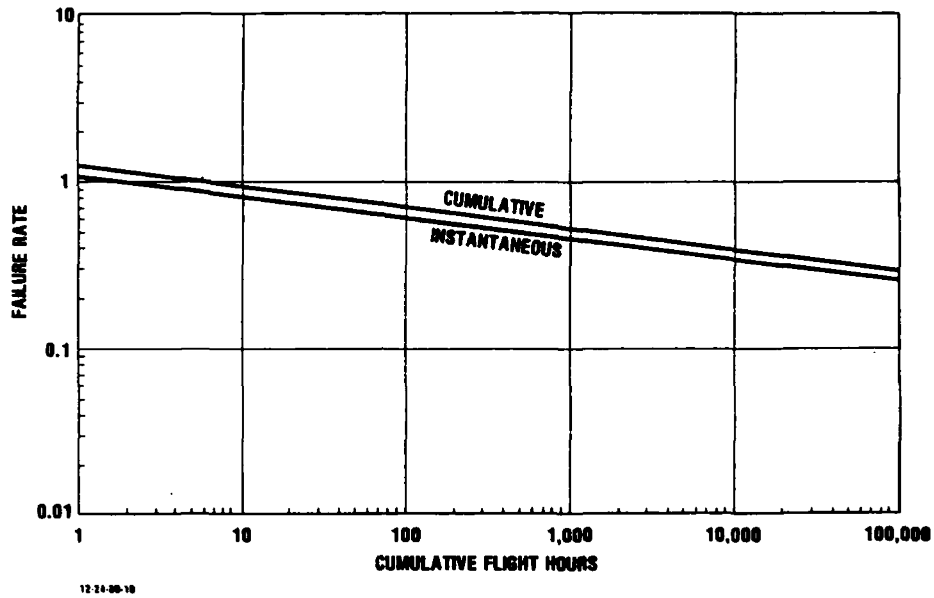


Figure S-1. FAILURE RATE VERSUS FLIGHT HOURS FOR "TYPICAL" HELICOPTER DEVELOPMENT PROGRAM

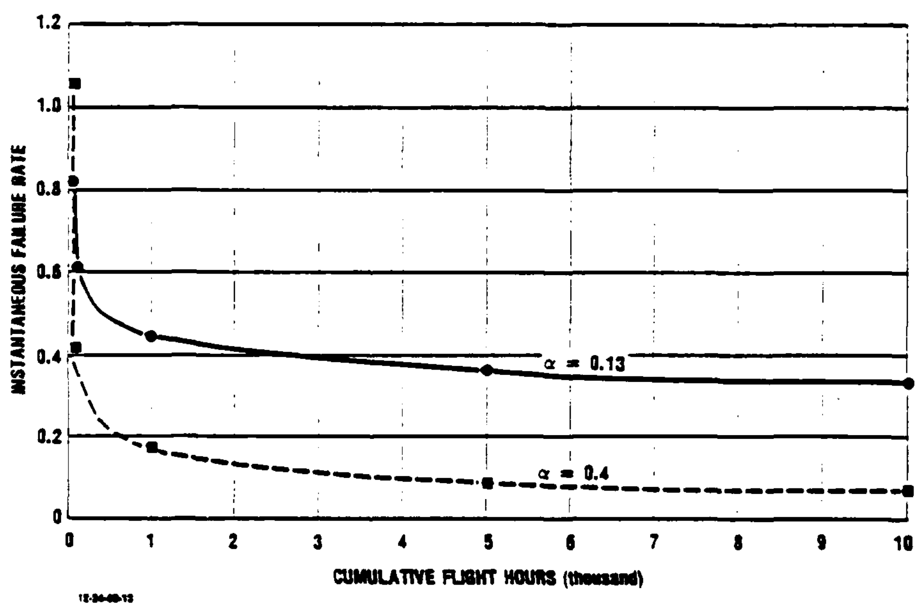


Figure S-2. INSTANTANEOUS FAILURE RATE VERSUS FLIGHT HOURS

The failure rate is driven down during the development phase by a continuous cycle of "fail and fix" consisting of the following basic steps:

1. Test hours accumulated:
   a. bench test
      (1) transmission test stand
      (2) rotor blade fatigue tests
      (3) flight control fatigue tests
      (4) miscellaneous component fatigue tests
      (5) failure data collected
   b. rotor whirl tower test
   c. ground test vehicle
   d. flight test.
2. Failures analyzed:
   a. failure mode identified
      (1) design deficiency
      (2) quality control
      (3) unanticipated environmental conditions
   b. corrective action established.
3. Redesign/rework to eliminate cause of failure.
4. Test redesigned reworked component to verify adequacy of corrective action.
5. Replace old part by new part in the system (test aircraft, spares, etc.).

As can be seen, the reliability growth process involves many interrelated elements. The convent al way of analyzing changes in helicopter R&M characteristics ov   time is to plot their values as a function of cumulative flight hours. When using such data, one must realize that the flying per se is only one element in the R&M growth process.

The Duane equation indicates that failure rate as a given number of flight hours is a function of both initial failure rate (λ) and the rate of improvement (α). Figure S-3 shows for various α's the cumulative MTBF at 100 flight hours, in

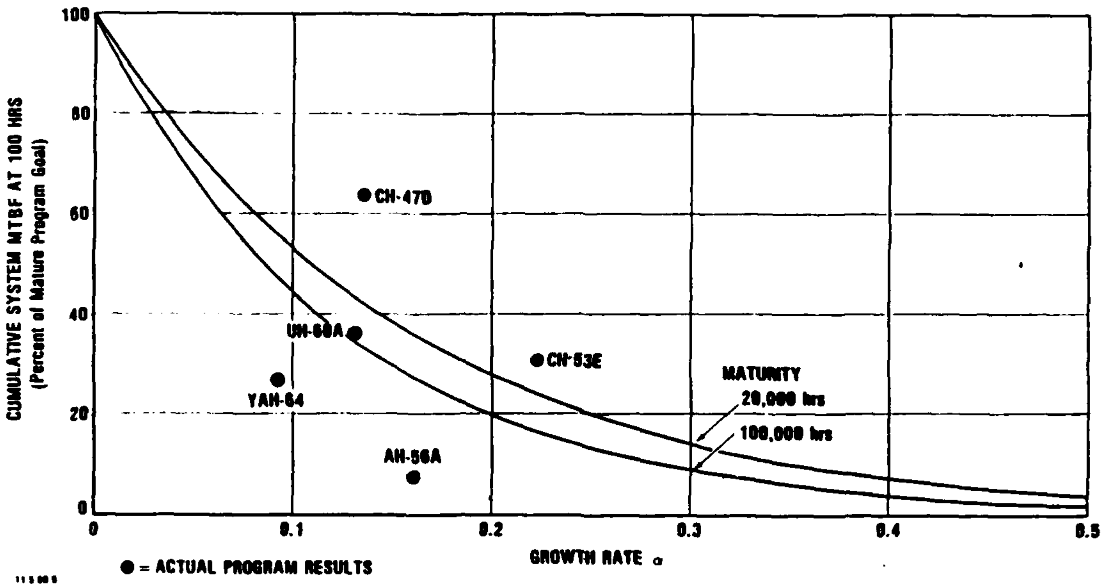


Figure S-3. CUMULATIVE SYSTEM MEAN TIME BETWEEN FAILURES (MTBF) AT 100 HOURS VERSUS GROWTH RATE REQUIRED TO ACHIEVE MATURE PROGRAM GOALS

percent of mature program goal, required to achieve the mature program goal. A program is generally considered to have reached maturity after 20,000 to 100,000 flight hours, and Figure S-3 shows the relationships for both values. For example, if failure rate improves at the rate α = 0.2, the goal at 100,000 flight hours will be achieved if the cumulative MTBF at 100 flight hours is 20 percent of the mature program goal.

On Figure S-3 are plotted the values for the following helicopters for which goals were established and for which we were able to obtain Duane curves:

	Mature Program MTBF Goal	Cumulative System MTBF at 100 Hours	Growth Rate (α)
AH-56A	10.60	0.59	0.16
UH-60A	4.00	1.40	0.13
YAH-64	3.25	0.87	0.09
CH-53E	0.92	0.28	0.22
CH-47D	1.40	0.90	0.14

Note that most of the α's lie in the 0.1 to 0.2 range. If that rate of growth can be maintained to 20,000 or 100,000 flight hours, then the cumulative MTBF at 100 flight hours must be approximately one-third of the mature goal in order for the helicopter to meet its mature program goal.

The UH-60A, CH-47D and CH-53E all appear to be capable of meeting their mature program goals. The two major modification programs (the CH-47D and CH-53E) appear much more likely to meet their failure rate objectives than the completely new helicopter programs. The AH-56A was unlikely to meet its mature program goal (which was much more ambitious than those of the other programs). Since its cumulative MTBF at 100 hours was only 5.6 percent of its mature goal, its α would have had to increase from 0.16 to approximately 0.4 in order to achieve its mature goal. In fact, the AH-56A program was terminated after 1,426 flight hours of developmental testing. The AH-64 may have difficulty in meeting its goal; its α will have to increase from the 0.09 experienced to date to approximately 0.17 in order to meet its goal by 100,000 flight hours.

C. PRODUCTION PHASE

Data were obtained on ten R&M characteristics: (1) system failure rate, (2) abort rate, (3) achieved availability, (4) maintenance manhours per flight hours, (5) component removal rate, (6) component time between overhaul, (7) operational availability, (8) accident rate, (9) mishap rate, and (10) mean time between maintenance actions. Table S-2 indicates a mixture of improvement, degradation, or approximately no change for different R&M measures for the different helicopter programs. Trends of these characteristics are discussed in their order of listing at the top of Table S-2.

1. System Failure Rate

The only engine entry (The T-53) showed improvement in successive models. Some of the helicopters showed improvement early in their production phase (YUH-60A, OH-6A, CH-46, CH-54A/CH-54B). However, many of them showed a long term degradation (CH-46, CH-54A/CH-54B, UH-1D), and the 3-M data for the Navy H-1, H-2, H-3, H-46 and H-53 showed a uniformly worsening trend for every major component group for every basic helicopter type from 1968 to 1978. The general picture emerging from these data is that there appears to be some early improvement during the production phase, but that the longer term trend shows degradation.

2. Abort Rate

Abort rate improved in all cases. As was hypothesized in the discussion of the development phase above, this is probably due to the fact that aborting failures receive more corrective attention than failures in general. (However, see 9. Mishap Rate, below).

3. Achieved Availability

The only entry for this measure shows improvement.

4. Maintenance Manhours per Flight Hour (MMH/FH)

The only engine entry (the T-53) showed improvement in successive models. For helicopters, we have mixed results: some improved (YUH-60A, CH-47, UH-1D, AH-1G); some worsened (Navy H-1, H-2, H-3, H-46, H-53 (3-M data), CH-46 and "All USAF Helicopters"); and some were approximately constant ("All Army Helicopters"). We believe the Navy 3-M data are the most reliable long term trend data. They indicate that MMH/FH worsened for every major component group and every basic helicopter type from 1968 to 1978.

5. Component Removal Rate

Of the three engine entries, two (the T-53 and "Several Engines") showed improvement, while the other (the T-55) was approximately constant. Again some of the helicopters improved (the OH-6A, CH-53A/D, CH-47 transmissions, CH-53B), some worsened (CH-46, CH-54A, AH-1G), and some were approximately constant (CH-47 "other components," OH-58A). In general, engines and transmissions (the most expensive components to overhaul) appear to definitely improve, while all other components improve less markedly or tend to remain approximately constant.

6. Component Time Between Overhaul

In most cases, time between overhaul (TBO) improved. A TBO establishes the maximum time that a component can be flown. However, components may fail before reaching their TBOs and hence the removal rate (5. above) is a more significant measure of component quality.

7. Operational Availability

The three entries for this measure from our 1975 report indicated a general improvement during the early production phase followed by an approximately constant availability. More recent data indicate that on average Army operationally ready rates generally remain constant over time.

8. Accident Rate

Both Army and Navy data indicate that accident rates (both those involving materiel and total) improved for all helicopter types. As was hypothesized in the discussion of system and abort failure rates, it appears that the more serious types of failures (those causing accidents) tend to be corrected, while minor problems are let go.

9. Mishap Rate

Both Army and Navy data indicate that mishap rates (both those involving materiel and total) worsened for all helicopter types. We are puzzled by this finding because mishaps lie between aborting failures and accidents in degree of seriousness, and both abort rates and accident rates seem to improve over time. Perhaps more warning indicators have been added to the helicopters over time, and they have resulted in more precautionary landings (one type of mishap) but fewer accidents. Final determination of the reason for increasing mishap rates would require detailed analysis of their causes.

10. Mean Time Between Maintenance Actions

Both entries indicate a worsening in this measure. Again, the 3-M data are believed to be reliable and (as in the case of system failure rate and MMH/FH) they show a worsening trend for every major component group for every basic helicopter type from 1963 to 1978.

The overall pattern shown by these data can be summarized as follows. It appears that the more serious failure modes (those causing aborts and accidents) tend to be corrected and therefore show an improvement trend, while the less important failure modes (those making up the bulk of mishaps and system failures) are not corrected and therefore show a worsening trend as the fleet ages. Similarly, the most important components (the engines and transmissions) tend to be improved and therefore show improved removal rates while the lesser components show a more constant removal rate trend.

D. CHANGES IN COMMERCIAL AIRCRAFT RELIABILITY/MAINTAINABILITY CHARACTERISTICS OVER TIME

Over 80 percent of the Free World's commercial airliners are produced in the U.S. and are widely acknowledged to be the best in the world. Accordingly, their R&M characteristics are probably close to optimum and may provide insights useful in formulating R&M policies for military aircraft.

R&M data for first (B-707, DC-8), second (DC-9, B-727, B-737) and third (B-747, DC-10, L-1011) generation commercial jet transports were obtained from the manufacturers. The trends in maintenance costs, maintenance manhours, and mechanical schedule reliability are summarized in Table S-3. First generation commercial jets were the only ones to show long term (i.e., greater than three year) improvement trends. Second generation jets showed little improvement in any R&M measure after introduction into service; they were basically good when introduced. Third generation jets experienced some reliability problems with their high by-pass ratio engines, but R&M characteristics stabilized after two or three years.

It appears that the commercial aircraft manufacturers strive to develop their aircraft to a mature level of R&M characteristics prior to introduction of the aircraft into service.

Table S-3. SUMMARY OF TRENDS IN COMMERCIAL AIRCRAFT RELIABILITY/MAINTAINABILITY CHARACTERISTICS

Jet Transport Generation	Direct Maintenance Costs in Constant Dollars	Maintenance Manhours per Flying Hour	Mechanical Schedule Reliability
First Generation (Four Engine Jets)	Decreased about 35% over first 17 years.	Decreased about 50% over first 17 years.	B-707-100 and DC-8 required about five years to maturity; later B-707 models required two or three years.
Second Generation (Twin and Tri Jets)	Approximately constant	Slight reduction	B-727 and 737 and DC-9 all had high initial reliability; DC-9 grew to a slightly higher level during first three years of service.
Third Generation (Wide Body Jets)			
B-747 & L-1011	Approximately constant	Approximately constant	Required two to three years to maturity
DC-10	Some increase due to engines		

When problems have developed in the last two generations of jets, they have been corrected within two or three years following introduction into service; thereafter, R&M characteristics have remained quite constant.

E. CONSIDERATIONS IN THE ALLOCATION OF RESOURCES FOR R&M GROWTH DURING THE DEVELOPMENT PHASE VERSUS DURING THE PRODUCTION PHASE

There are a number of factors that should be considered in deciding whether to allocate resources for R&M growth during the development phase or during the production phase of a helicopter program. Factors that favor allocation of resources during each phase are summarized in Table S-4 and are discussed below.

Table S-4. FACTORS THAT FAVOR ALLOCATION OF RESOURCES FOR R&M GROWTH DURING THE DEVELOPME PHASE AND DURING THE PRODUCTION PHASE

Development Phase	Production Phase
1. Should achieve a greater improvement in R&M per unit cost and time because of Duane curve characteristics.	1. Development phase costs less (but production phase will cost more if R&M growth is deferred to it).
2. R&M growth program should be more cost-effective because of controlled management and operating environment.	2. Development phase may take less time, resulting in possible earlier IOC date.
3. Improvements do not have to be retrofitted on delivered aircraft.	3. Earlier discovery of those failure modes induced by field environment.
4. Improved R&M characteristics available over entire life of aircraft.	

1. Factors Favoring R&M Growth During Development Phase

The discussion which follows is tied to Table S-4 in its listing of factors during the two phases of a helicopter program.

1. As discussed above, helicopter development programs, in a very rough way, tend to follow the Duane growth process. This process is characterized by a continual reduction in the degree of R&M improvement per unit of cost or time required to

achieve the improvement (see Figures S-2 and S-3). Since fewer flight hours have been accumulated in the development phase than in the production phase, it should be possible to achieve a greater degree of R&M improvement per unit of cost or time in the development phase. Further, while virtually all programs exhibit R&M improvement during the development phase, there is no clear-cut evidence that R&M characteristics in general improve during the production phase. Indeed, some data indicate that they worsen (see 3-M data of Chapter III, Section I).

2. R&M growth programs during the development phase would be conducted at the manufacturer's plant or at a service test facility in CONUS where manufacturer's personnel could be stationed. Accordingly, the operating environment is such that information on failures can be quickly collected and fixes developed, thus facilitating the R&M growth process. On the other hand, once a helicopter is in production and operating in the field (perhaps overseas), the collection and transmittal of failure data is much less complete and fast, and the time required to incorporate fixes into aircraft in the field is much greater. Further, in order to incorporate changes in a production program it is necessary to change production drawings/processes/tooling and in general interfere with the smooth functioning of the production process. Hence R&M growth programs should be considerably more cost-effective during the development phase because of the more favorable management and operating environment. One quantitative survey concluded that production phase changes are ten times as costly as development phase changes [3].

3. If design changes to achieve R&M growth are incorporated in the development phase, then later production aircraft will have the improved designs incorporated in them when they are built. However, if changes are made during the production phase, then the changes must be retrofitted into those aircraft which have already been produced. This retrofitting is more

expensive than incorporating changes in the initial construction of the aircraft. Further, retrofitting aircraft in the field degrades the mission operational readiness of the units to which they are assigned.

4. If R&M-related changes are incorporated during the development phase, the benefits of these changes are available over the entire life of the aircraft. If changes are made during the production phase, then the benefits are not realized in the already-produced aircraft until they are retrofitted.

2. Factors Favoring R&M Growth During Production Phase

1. and 2. The principal advantage of deferring R&M growth resources from the development phase to the production phase is that the cost and schedule time required for development may be reduced. As a result, an earlier IOC date can be achieved. This could be a very important consideration in some programs, depending on the military threat situation.

3. Some R&M problems only become apparent when an aircraft is operating in its normal field environment. These problems will be discovered earlier because of the earlier IOC date, but a special process involving data collection, engineering follow-up and production modification is required for timely incorporation of fixes (as in the Black Hawk program).

Chapter I

RESOURCES INVESTED IN RELIABILITY VERSUS RELIABILITY ACHIEVED: A SURVEY OF THE LITERATURE

A. INTRODUCTION

The costs of ownership typically account for over half of the total life cycle costs of major weapon systems. Consequently, reduction of the cost of ownership has become a matter of increasing concern for defense policy makers. Recently published Department of Defense Directive 5000.4 [4] deals with the setting, monitoring, and enforcement of reliability and maintainability (R&M) goals, long recognized as having a significant impact on total support costs of weapon systems.

Implicit in the policies set forth in [4] is the assumption that the impact of alternative R&M goals on both the acquisition and ownership costs of a new system can be evaluated early in the development cycle of that system. In contrast to that assumption, a recent Air Command and Staff College research study [5] concluded that "little has been written on how to establish an effective reliability growth program or the tools and resources required to implement such a program." The purpose of this chapter is to provide a summary of selected studies that have appeared in the literature dealing with the latter issue--the relationship between resources invested in reliability and reliability achieved.

Figure 1 depicts the issue schematically. Subject to state-of-the-art technological constraints, R&M program objectives, in theory, can be varied in order to adjust the relative contributions to total system life cycle cost of the development, procurement, and ownership phases of the program. In order to understand the linkage between R&M program goals and life cycle costs, however, it is necessary to understand--

(1) what resource levels are required during development in order to achieve the development R&M objectives;

(2) how those objectives demonstrated during development translate into field R&M attributes of the system;

(3) how those field attributes affect the cost of ownership of the system; and

(4) whether or not, and at what cost, R&M values can be improved once the system has been fielded.

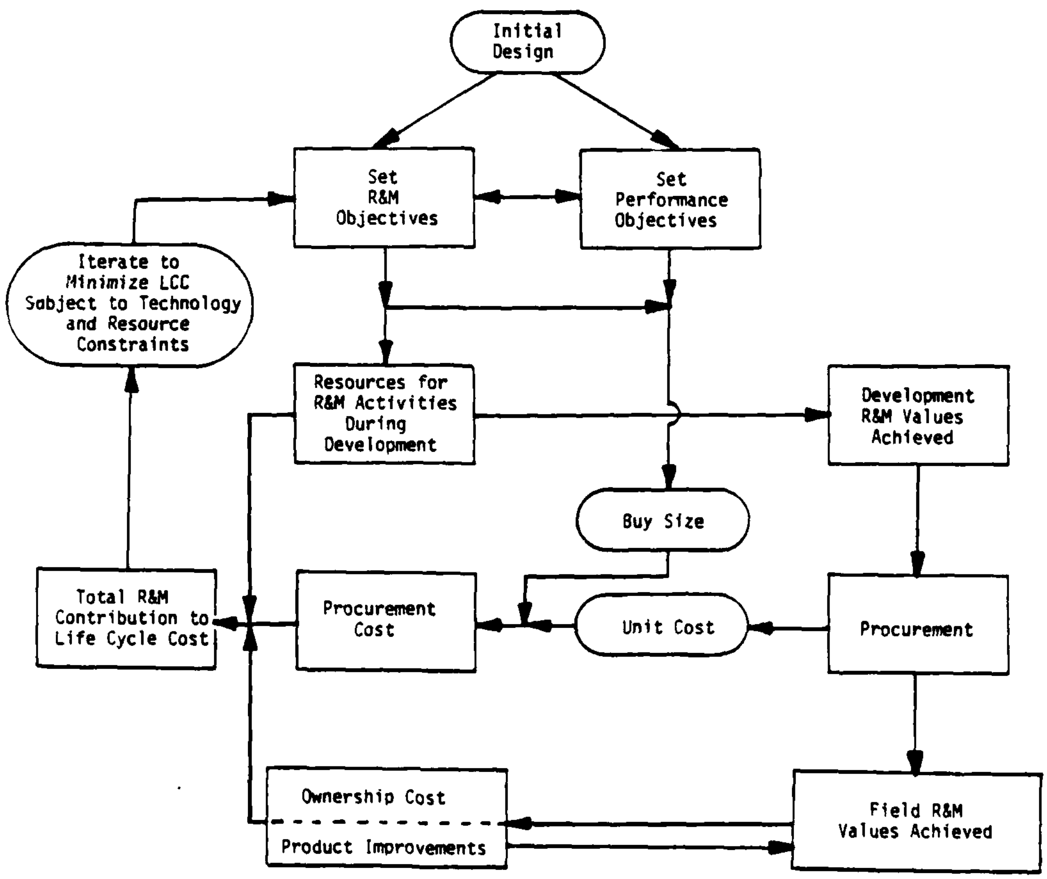


Figure 1. IDEALIZED R&M PLANNING PROCESS

In addition, if the relationship between reliability objectives, performance objectives, and mission requirements is included in the planning loop, then R&M can exert significant leverage on the procurement cost by influencing the size of the total buy.

In this chapter we concentrate on (1) and (2) above. Question (3) can be reasonably well quantified through the use of models designed for that purpose employing deterministic and/or probabilistic cost equations or Monte Carlo simulation methods (see, for example, [6], [7], [8]), but will not be discussed below. Little attention appears to have been devoted in the literature to question (4), apart from proposed methods for evaluating the cost-effectiveness of individual product improvements ([9], [10]), and one survey [3] which concluded that the cost of effecting a change to a system after it is fielded is roughly ten times the cost of making that change prior to production. The inclusion of buy size as a decision variable in the R&M planning loop has been incorporated into one model of the R&M process [11] which will be discussed in Section D.4 below.

In the context of this report, the primary focus of this chapter is on helicopters. Historically, however, the majority of published reliability growth efforts have been concerned with electronics equipment, and a brief survey of relevant studies from that segment of the literature is included as well. The narration is necessarily disjointed. The literature is relatively sparse, and differences in both definitions and focus among the various publications leave large gaps in the existing body of knowledge.

B. MODELS OF RELIABILITY GROWTH

In 1970, Selby and Miller [12] proposed the methodology for planning and monitoring reliability programs--known as Reliability Planning and Management (RPM)--which was based on the 1964 empirical observation of J.T. Duane [2] that a predictable relationship exists between test time and reliability achieved for complex systems. Since that time reliability growth modeling has been viewed as a useful means for structuring and monitoring the progress of development programs. While a large number of alternative growth models have been proposed (three conceptually different types are discussed below), the "Duane Model" has continued to dominate the literature.

1. The Duane Model

The Duane model assumes a linear relationship between cumulative failure rate and test hours when plotted on a log-log grid. Mathematically,

$$c(t) = \lambda t^{-\alpha}$$

when $c(t)$ denotes the cumulative failure rate of the system after t hours of testing, α is a constant, usually nonnegative, referred to as the "growth rate," and λ is the cumulative failure rate at $t = 1$ hour. Letting $n(t)$ denote the cumulative number of failures up to time t, and letting $i(t)$ denote the instantaneous failure rate at time t, by definition

$$c(t) = \frac{n(t)}{t}$$

$$i(t) = \frac{dn(t)}{dt} ,$$

and it is easily seen that

$$i(t) = (1-\alpha)\lambda t^{-\alpha} = (1-\alpha)c(t) .$$

Thus, the instantaneous failure rate is proportional to the cumulative failure rate.

In practice, the constants α and $\log \lambda$ are usually estimated from reliability data plotted on a log-log grid using standard linear least squares theory. Alternative estimators have been derived by Crow [13], Donelson [14], and others under the assumption that the stochastic process underlying the data is a nonhomogeneous Poisson process. Using the latter approach to analyze reliability data from 270 electronics equipment development programs, a study by Hughes Aircraft [15] found that in comparing the Duane model to five other reliability growth models, the Duane model nearly always fit the data (according to goodness of fit criteria proposed by the investigators) and was the best model overall, although in many specific cases one of the other models provided a better fit.

In using the Duane model for program planning and management, Selby and Miller proposed several rules of thumb. First, establish a program goal (reliability prediction) which is at least 125 percent of the program requirement. Second, take as the starting (100 hour) point for reliability growth a cumulative failure rate which is 10 percent (based upon empirical evidence from past programs) of the goal. And finally, assume a growth rate $\alpha = 0.5$ (based upon Duane's empirical observations) for an intense reliability effort. The result is an estimate of test hours required and a growth path which can be used as a yardstick for evaluating program progress. In a recent application of RPM to an avionics equipment development program, Clarke and Cougan [16] concluded that RPM was a useful approach for initial test duration planning purposes and for tracking reliability growth during the middle portion of the development program. During the early stages of development, they found that the cumulative failure rate was too sensitive to individual times between failure to enable quantification of the growth rate; during the final stages of the development program, the cumulative rate incorporated too much history and did not react quickly enough to what were perceived as effective corrective actions for failure sources uncovered during the program.

A common procedure for programs in which several different types of testing or phases are scheduled is to assume, at least for initial planning purposes, that the Duane model will be applicable, but that the growth rates will be different for the different phases. The growth path is then piecewise linear on a log-log grid, specified by an initial cumulative failure rate together with the sequence of growth rates and durations of the various phases. Letting t_j denote the test time at the end of phase j, $c(t_j)$ denote the cumulative failure rate at the end of phase j and α_j the assumed growth rate throughout phase j, it can be shown that

$$\frac{c(t_j)}{c(t_{j-1})} = \left(\frac{t_j}{t_{j-1}}\right)^{-\alpha_j} \qquad j=1,2,\ldots$$

where $c(t_0)$ and t_0 are specified as the initial cumulative failure rate and the initial time at which growth rate α_1 begins, respectively. Given $c(t_0), t_0, t_1, \ldots$, and the growth rates $\alpha_1, \alpha_2, \ldots$, the cumulative failure rates $c(t_1), c(t_2), \ldots$, and hence the growth path, can be determined.

2. The IBM Model

One shortcoming of the Duane model is the implication that reliability growth can continue at a constant rate until, in the limit, the failure rate goes to zero. By adding a third unknown parameter, a model proposed by Rosner [17] removes this deficiency while still treating test time as the variable controlling reliability growth. Rosner assumes that the system to be tested has both an inherent (unknown) failure rate λ and an (unknown) number N of "nonrandom" failure modes due to design faults, manufacturing errors, workmanship defects, etc. The removal of the nonrandom failure modes is the purpose of the development test program. Letting $k(t)$ denote the number of such modes remaining at time t, Rosner assumes that the rate of change of $k(t)$ is proportional to $k(t)$, that is

$$\frac{dk(t)}{dt} = -K \cdot k(t) ,$$

where K is an unknown constant of proportionality. Using the fact that $k(0) = N$, the solution to the above equation is

$$k(t) = Ne^{-Kt} .$$

Thus, assuming that each nonrandom failure mode only occurs once before being corrected, the expected number $F(t)$ of failures occurring by time t is given by

$$F(t) = \lambda t + N - k(t) = \lambda t + N(1-e^{-Kt}) .$$

The latter expression can be fit to the cumulative failure data using a nonlinear estimation algorithm, yielding estimates of λ, N, and K.

The Hughes study [15] mentioned above termed this model the "IBM Model" and found that it outperformed Duane and every other model tested when applied to reliability growth data of airborne electronics equipment.

3. The LRU-Age Growth Model

In analyzing failure rate data of electronic line-replaceable units (LRUs), Bezat, et al. [18] found that the mean age of the units was a key variable. Program data concerning a Digital Air Data computer system developed by Honeywell for use in the Douglas Aircraft Company's DC-10 aircraft were found to be well described by the model

$$\lambda_i = K \cdot H^{-\alpha} + \lambda_R$$

where

λ_i ≡ instantaneous equipment failure rate
K ≡ constant

$H \equiv$ mean age of equipment population

$\alpha \equiv$ growth rate

$\lambda_R \equiv$ limiting ("endless burn-in") failure rate .

The model extends the concept of infant mortality throughout the life cycle of the equipment population--each time a unit whose age is less than that of the population average fails, the reliability of the remaining population increases. The authors propose using the model as a management tool by estimating the model parameters in the following approximate fashion. First, obtain estimates for K and α by fitting a line to a log-log plot of failure rate versus mean equipment age. Second, assume that the initial (e.g., parts count) reliability prediction, say λ_i^*, holds at a mean equipment age of 1,500 hours. Then the difference between the failure rate predicted by the fitted line at 1,500 hours and λ_i^* yields an estimate of λ_R.

No relationship between resources invested and reliability achieved is captured by the model. Furthermore, one possible problem with using the model for program planning is the implication that for a fixed number of test hours, the greatest reliability improvement is achieved with the fewest number of test specimens.

4. Limitations of Reliability Growth Models

Reliability growth models are typically simple to apply, require minimal data at an aggregated level, and enable future prediction of what is, at best, a poorly understood quantity. However, the fact that all of the above models fit certain sets of data reasonably well underscores the most obvious limitation of such models--they are based upon empirical observations and do not explain why the data behave as they do. Historical evidence from similar programs provides the only clue as to which model should be chosen, if any, when a new program is begun. A second limitation concerns the time frame over which such models are applied. Typically, reliability growth cannot be modeled until end product testing has begun. If, from that point on, the growth rate is slow, then it is the starting reliability ("off-the-board") which may well dominate the mature reliability of the equipment. In fact, the starting value is itself the end product of a large investment of resources, yet growth models can only estimate that starting value after the fact, too late to make those early resource allocations which, most authorities agree, have the most leverage over reliability achieved. In the electronics equipment area, several investigations have been published regarding the effects on equipment reliability of alternative resource allocations early in the development phase. Those studies are discussed next.

C. STUDIES OF ELECTRONICS EQUIPMENT RELIABILITY

1. Defining the Costs of Reliability Programs

In order to be able to derive a functional relationship between reliability growth and program costs, it is necessary to be able to define the latter quantity. That is not an easy task. A large number of development program activities impact reliability, but few are devoted exclusively to reliability. Even when a specific reliability program is not part of the development, a certain level of these activities, such as testing, will be included. Reliability *growth*, therefore, is related to a cost increment above what the same program would cost in the absence of a formal reliability effort. In the studies described below, each author has a different definition of reliability program cost, depending upon the objectives of his study and the limitations of the accounting systems from which his data are derived. A paradigm of many cost models and one of the more extensive frameworks for defining reliability program cost (for electronics equipment) appears in a paper by Coppola [19]. The cost is divided into three elements--materials, labor (excluding test activity), and test costs (including labor and failure analysis)--which are in turn factored into a large number of subelements and overhead charges. Material cost is primarily the cost of parts screening. Labor excluding test activities includes engineering costs (for example, including design, parts programs, design reviews, etc.) as well as quality control costs. Test costs are divided into the various types of testing, including burn-in. The problem with the model from our perspective is that the inputs involve a circularity. In order to specify costs of failure analysis, for example, the equipment and subassembly field reliabilities as well as ratios of development reliabilities to field reliabilities are required as inputs. The latter values, however, would seem to depend upon the investment in reliability which is the output of the model.

2. Reliability as a Function of Program Cost

One of the earliest attempts to relate reliability achieved to costs of development activities is reported by Hevesch [20]. Interested in effecting marginal improvements to "standard" programs in which no special reliability program existed, Hevesch viewed reliability testing and failure analysis as necessary activities, but not "primary" reliability improvement methods. The latter were divided into three categories:

(1) Reliability-Oriented Design Review Activities (circuitry simplification, stress reduction through derating, etc.)

(2) "Ultra-Reliable" Parts Programs

(3) Introduction of Redundancy into Critical Functions.

In terms of total engineering research and development cost, Hevesch found that total reliability program costs comprised between two percent and eight percent of the average. Reliability improvement activities constituted 54 percent of the total reliability program costs.

Working with data from four system development programs, Hevesch found that the costs for each of the above activities increased linearly in proportion to the ratio θ/θ_0, where θ is the MTBF achieved with the improved design and θ_0 is the MTBF of the "standard" design. That is, treating each of the activities as an independent contributor to reliability improvement of the system, the cost increment resulting from application of the i^{th} activity, ΔC_i, is given by

$$\Delta C_i = K_i(\frac{\theta}{\theta_0} - 1)$$

for some constants K_i, $i=1,2,3$. Estimates of $\{K_i\}$ and associated incremental improvements to θ_0 resulting from each activity led to the conclusion that the second activity, ultra-reliable parts program, was the most cost-effective improvement method, followed by redundancy. Within the limits of extrapolation imposed by the data, the author estimated that a five percent cost increment over the engineering development cost of a "standard" development program would result in a 10 to 12 percent increase in MTBF. A suggested percentage allocation of reliability improvement funds to the three activities is also given. One limitation of the study, recognized by the author, is that the computed costs of the reliability improvement methods do not look beyond engineering development. For example, increased unit production costs resulting from the use of ultra-reliable parts or added redundancy are not considered.

Similar in scope to the Hevesch study (but going one step further, in that testing is also considered a legitimate reliability improvement parameter) is a study by Mercurio and Skaggs of General Electric [21]. The objectives of this study were to relate equipment reliability achieved to total reliability program element costs, and to quantify the incremental improvements to equipment reliability accruing from investments in various reliability program elements. Reliability program elements defined by the authors, slightly different from the definitions of Hevesch, are (in chronological order of occurrence):

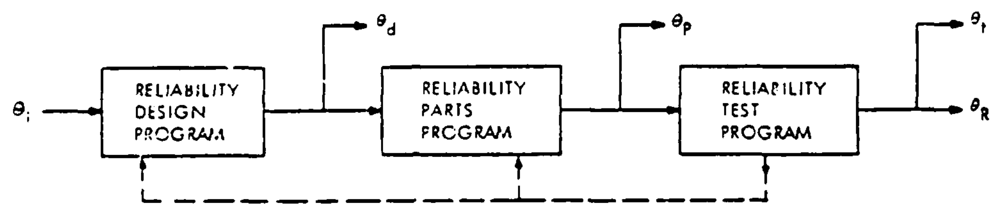
- Design Program (including reliability predictions, failure modes and effects analyses, design reviews)
- Parts Program (screening, standardization, vendor control)
- Testing (evaluation, environmental screening, demonstration).

Using data from the development program of 10 electronics equipments, the authors were able to obtain cost data, expressed in mandays, for each of the above elements, as shown in Table 1.

Table 1. RELIABILITY ELEMENT COST DATA (EXPRESSED IN MANDAYS) FROM GE STUDY [21]

Reliability Element	Equipment Letter Code									
	A	B	C	D	E	F	G	H	J	K
Design Program	6, 330	1, 496	1, 087	658	893	1, 427	713	2, 670	675	707
Reliability Prediction	3, 165	1, 036	761	452	487	649	549	207	527	544
Reliability Design Review	634	460	326	206	203	131	165	594	148	163
Reliability FMEA	2, 531	---	---	---	203	650	---	---	---	---
Parts Program	12, 026	4, 027	2, 174	986	2, 467	2, 467	1, 098	5, 934	1, 042	1, 142
Test Program	5, 094	4, 741	4, 458	1, 332	1, 989	1, 989	834	3, 343	815	946
Total R Program	23, 449	10, 264	7, 719	2, 976	5, 883	5, 883	2, 645	11, 947	2, 532	2, 795

Using a combination of available data and engineering judgment, the authors were also able to obtain values for system mean time between failures for each of the equipments after each element of the reliability program was completed. The relevant quantities are defined in Figure 2, taken from the study.



θ_i = EFFECTIVE ACHIEVED MTBF WITHOUT RELIABILITY PROGRAM

θ_d = EFFECTIVE ACHIEVED MTBF RESULTING FROM RELIABILITY DESIGN PROGRAM

θ_p = EFFECTIVE ACHIEVED MTBF RESULTING FROM DESIGN PLUS PARTS PROGRAM

$\theta_t = \theta_R$ MTBF RESULTING FROM DESIGN PLUS PARTS PLUS TEST PROGRAM

-----CORRECTIVE ACTION FEEDBACK LOOPS

Figure 2. RELIABILITY PARAMETERS ESTIMATED IN [21]

The value of θ_t was taken to be the value computed at the completion of demonstration testing. Working backwards, θ_p was computed by evaluating all the failure modes occurring during testing. By comparing the part failure rates actually experienced with known rates for similar parts procured with no particular attention given to the achievement of high reliability, the contribution of the parts program, and hence θ_d, was computed. Finally, θ_i was computed for each equipment by comparing initial designs with those which evolved from the reliability design program effort. The computed values for those parameters are shown in Table 2.

Table 2. INCREMENTAL EQUIPMENT RELIABILITY DATA FROM [21]

Equipment Letter Code	Off-the Board MTBF θ_i	Initial + Design MTBF θ_d	Design + Parts MTBF θ_p	Design + Parts + Test MTBF * θ_t	Design Gain $G_d = \frac{\theta_d}{\theta_i}$	Parts Gain $G_p = \frac{\theta_p}{\theta_d}$	Test Gain $G_t = \frac{\theta_t}{\theta_p}$	Resultant Equipment MTBF * θ_R
A	7.0	20.0	95.0	1350.0	2.9	4.8	14.2	1350.0
B	2.0	3.0	11.0	225.0	1.5	3.7	20.5	225.0
C	3.0	5.0	16.0	188.0	1.7	3.2	11.8	188.0
D	5.0	8.0	26.0	225.0	1.6	3.3	8.7	225.0
E	1.0	1.5	4.0	141.0	1.5	2.7	35.3	141.0
F	11.0	15.0	67.0	501.0	1.4	4.5	7.5	501.0
G	5.0	8.0	20.0	46.0	1.6	2.5	2.3	46.0
H	2.0	5.0	15.0	287.0	2.5	3.0	19.1	287.0
J	3.5	7.0	25.0	133.0	2.0	3.6	5.3	133.0
K	15.0	22.0	60.0	209.0	1.5	2.7	3.5	209.0

*60% LCL

Multiple regressions were run for both the MTBF data and Gain data of Table 2 versus the costs of Table 1 and the parts counts, N_{PK}, for each equipment. The MTBF equations tended to explain the data better. The resulting equations are as follows:

$$\theta_i = (1.061 \times 10^4)/N_{PK}^{0.921}$$

$$\theta_d = 0.211(\theta_i^{0.956})(C_d^{0.300})$$

$$\theta_p = 0.585(\theta_d^{1.134})(C_p^{0.185})$$

$$\theta_t = 0.094(\theta_p^{0.683})(C_t^{0.741})$$

$$G_d = 0.302(C_d^{0.247})$$

$$G_p = 1.145(C_p^{0.137})$$

$$G_t = 0.0064(C_t^{0.952}) \ .$$

Thus, above some threshold, testing yielded the greatest reliability gain per unit cost, followed by design activities and finally, parts programs. (This is just the opposite finding from Hevesch regarding the last two elements.) In contrast to the findings, the average actual resource allocations from the test sample were approximately 22 percent for design, 40 percent for parts programs, and 38 percent for testing. No total test hours or percentages of total engineering development costs allocated for reliability are given, so a comparison of the overall reliability efforts involved in the data sample programs cannot be made with those programs used to provide data for other studies. One final remark concerns the equation for θ_t given above. This equation is of the same form as the Duane model, except that the parameter is test cost instead of test hours. Only if C_t is proportional to $t^{(\alpha/0.74)}$ for some value of α would the two models agree.

Virtually the identical methodology was used in a study [22] by Schafer, et al. at Hughes Aircraft two years later. Whereas Mercurio and Skaggs focused on airborne equipment, the latter study focused on ground electronics equipment. Again, the authors defined three reliability program elements--design, parts, and testing (referred to as "evaluation" in their study)--obtained costs in mandays, and estimated incremental reliability gains for the three program phases. The cost and gain data, the latter shown only for those equipments used to derive the functional equations, are given in Table 3. In comparing Tables 1 and 3, note that the Hughes design costs (reliability-related only) are much smaller; the parts costs are about the same in both studies, and the test costs are also somewhat lower in the Hughes study.

The incremental reliability values shown in Table 3.B were obtained by working backwards, as in [21]. However, both θ_E and θ_P were obtained by fitting "Duane" lines to the failures versus test hour data. The final instantaneous values so obtained are the θ_E's (except in two cases where demonstrated values were used) and the initial computed values are the θ_P's. The θ_D values were found as in [21]. The estimates of θ_I were obtained from θ_D by assuming that the design gains were equivalent to the ratios of contractually specified MTBF's (demonstrated by all but one of the equipments) to initial reliability predictions (made prior to any reliability design effort).

Schafer, et al., analyzed the data by running five different types of regression models on 124 different variable combinations including those shown in Table 3 plus reliability specifications, predictions, and equipment parts counts. The results, which include equations estimating program element costs as a function of the latter three variables as well as equations expressing reliability gains as a function of resources, can obviously not be presented here. However, to compare the results with those of [21], the equations for incremental reliability improvements which best fit the data are:

$$\theta_D = 4.94(\theta_I^{1.19})(C_D^{-0.26})$$

$$\theta_P = 0.19(\theta_D^{1.15})(C_P^{0.26})$$

$$\theta_E = 18.64(\theta_P^{0.014} C_E^{0.29})$$

$$G_D = 0.27(C_D^{0.34})$$

$$G_P = 0.19(C_P^{0.29})$$

$$G_E = 0.000029(C_E^{1.61}) .$$

Table 3. RELIABILITY PROGRAM PHASE COST AND INCREMENTAL RELIABILITY DATA FROM HUGHES STUDY [22]

A. Reliability Program Phase Costs (Expressed in Mandays)

Reliability Program Phase	Equipment Number									
	1	2	3	4	5	6	7	8	9	10
Design Phase (C_D)	214	244	202	207	237	204	170	119	272	148
Parts Phase (C_P)	4,962	5,301	4,093	4,467	3,580	7,233	1,612	3,396	1,252	1,449
Evaluation Phase (C_E)	2,498	2,196	2,249	2,464	1,348	9,262	530	1,452	928	2,110
Total (C_T)	7,674	7,741	6,544	7,138	5,165	16,699	2,312	4,967	2,452	3,707

B. Incremental Reliability Data for Selected Equipment Used in Analyses

System Number	MTBF Initial θ_I	MTBF Post Design θ_D	MTBF Post Parts θ_P	MTBF Post Evaluation θ_E	Design Gain $G_D = \theta_D/\theta_I$	Parts Gain $G_P = \theta_P/\theta_D$	Test Gain $G_E = \theta_E/\theta_P$	Total Gain $G_T = \theta_E/\theta_I$
1	10.60	18.44	47.20	179.53	1.74	2.56	3.80	16.94
2	7.70	18.01	49.36	178.15	2.34	2.74	3.61	23.14
4	9.03	13.46	33.66	206.09	1.49	2.50	6.12	22.82
6	1.46	1.62	3.27	266.00	1.10	2.02	81.34	182.19
10	1.97	3.44	5.16	173.00	1.74	1.50	33.53	87.82

With the exception of the anomalous equation for θ_D, apparently driven by equipment number 10, and the weak dependence of θ_E on θ_P, apparently driven by equipment number 6, the equations are quite similar in cost exponent magnitude to those of [21] given above. In a section dealing with optimal allocation of a fixed budget of development program resources, Schafer, et al. concluded that within the bounds defined by the data set, essentially as much as possible (60 percent) should be spent on testing, only slightly above the lower bound on parts programs (39 percent), and as little as possible on reliability design (1 percent). Note that this order of priority agrees with the Hevesch results.

Going beyond the above studies to incorporate post-production activities is a model proposed by Butler [23]. Working at a much more aggregated level, his model is of the form

$$\text{System MTBF} = \text{MTBF}_p\ (R_g)(R_m)(R_f)$$

where MTBF_p is the initial reliability prediction (θ_1 in the notation of [21], R_g is a factor representing the total effect on reliability of the development program (i.e., collapsing all of the reliability elements discussed above), R_m represents the manufacturing influence (process control, vendor control, burn-in testing), and R_f represents the combined effect of the field environment, operator skill level, logistics support, etc. (R_f is included by Butler for completeness but not quantified). Butler's objectives in proposing the model are to be able to (a) maximize system reliability for a fixed production cost, or (b) minimize production cost for a fixed reliability constraint, and in conjunction with the model, he presents a framework for computing the unit production cost in terms of the reliability parameters. That is, much like the cost framework proposed by Coppola [19], Butler assumes that a one-to-one correspondence exists between the vector (MTBF_p, R_g, and R_m)

and unit production cost, and the latter value is easily determined. Before describing his model, Butler's paper contains a qualitative discussion of the most notable aspects of the reliability portions of 14 electronics equipment development programs. Data are not extrapolated from those programs in a format suitable for exercising his proposed model, although hypothetical examples are given.

Also dealing with aggregated data from both development and field environments is the study by Hughes Aircraft [15]. One section of this study providing a comparison of several reliability growth models was discussed briefly in Section B above. A second focus of the study was an attempt to compare the dollars invested in reliability engineering to the measured reliability growth of the 270 equipments comprising the data sample.

All programs were classified as belonging to one of three categories of reliability "aggressiveness," as determined by their levels of expenditures in reliability engineering. The categories were defined as follows:

"Aggressiveness" Category	Definition	No. of Programs in Category
R1	No program acquisition costs expended on reliability.	143
R2	Less than 1 percent but more than 0 percent of total program acquisition costs expended on reliability.	60
R3	More than 1 percent of total program acquisition costs expended on reliability.	67

It should be noted that not all of the 270 programs were Hughes-developed equipment and, in classifying those programs into the above categories, a specific reliability engineering budget item was required. If none was found, the program was put into category R1. Thus it is possible that many of the elements of a reliability program (as distinguished from a "standard" program with no reliability emphasis) may have been included in some of the R1 programs provided their costs were allocated to nonreliability budget items. The authors do indicate, however, that they are reasonably confident the above classification reflects the relative emphasis placed on reliability during the various programs. Also note that the overall levels of expenditures are somewhat lower than the levels (two to eight percent) reported by Hevesch [20].

In addition to being categorized by aggressiveness, programs were also categorized as either ground equipment or airborne equipment. Both development test and field data were carefully filtered to remove secondary failures that were caused by other relevant failures.

The Duane reliability growth model was used in all cases, having been previously determined that the model fit all the program data reasonably well. Reliability growth was expressed as both a rate and a "gain." The rate is the shape α of the Duane curve. The gain is defined in two ways--

$$RG_1 = \frac{\text{Observed Final Cumulative MTBF}}{\text{Calculated Initial Cumulative MTBF}}$$

$$RG_2 = \frac{\text{Calculated Final Cumulative MTBF}}{\text{Calculated Initial Cumulative MTBF}}$$

and represents the factor by which the "off-the-board" reliability as calculated from the Duane curve (initial estimates were felt to be too arbitrary to be used directly) had been improved through reliability growth.

Table 4 summarizes the study findings. As one might expect, the higher the level of reliability expenditures, the greater the growth rate. However, the reliability gains were larger in all cases for level of expenditures R2. This somewhat surprising finding is explained by the authors as follows:

The larger expenditures concentrated more funds in the design phase (as against testing) and the system/equipment was probably better (less design/workmanship faults) when testing started so there was less gain to be had to achieve the limiting cumulative MTBF.

Table 4. RELIABILITY GROWTH VERSUS RELIABILITY ENGINEERING COST FROM HUGHES AIRCRAFT STUDY [22]

Reliability Engineering Cost Category	Average Reliability Growth Rate[a]	Average Reliability Gain			
		Ground Equipment		Airborne Equipment	
		RG_1	RG_2	RG_1	RG_2
R1	0.30	3.88	5.42	3.09	5.03
R2	0.37	5.79	9.98	5.17	7.65
R3	0.45	4.02	7.10	2.17	3.57

[a]Combined Ground and Airborne Equipment

Also, many of the data sets were borderline between categories R2 and R3. Nevertheless, the formulas for RG_1 and RG_2 create a clear linkage between operating hours, growth rate, and gain; implicit in the findings shown in Table 4 is that the R3 programs, on the average, had fewer operating (test) hours than the R2 programs.

The consistent discrepancies between RG_1 and RG_2 in the Table are not explained by the authors, but would indicate that the Duane Curves, which yielded the numerator of RG_2 and denominators of both RG_1 and RG_2, were consistently overestimating reliability in the later stages of the measurement periods for the various equipments. The smaller gains for airborne equipment versus ground equipment were attributed to the fact that the former equipment undergoes more environmental and screening tests prior to final assembly, and, therefore, has a higher off-the-board MTBF, with less growth potential.

Finally, not evident in the Table was an additional finding concerning development versus field reliability growth. "Gains" during development were found to be approximately twice as large as gains on fielded equipment, and the development reliability growth rate was found to be approximately 30 percent higher ($\alpha = 0.36$ versus $\alpha = 0.28$) than that for fielded equipment.

3. Designing R&M Programs to Minimize Life Cycle Cost--the FAA Approach

The above studies were basically concerned with making marginal improvements to equipment reliability through resource investments in selected program activities. A much more comprehensive objective appears in a paper by Lakner, et al. [24], detailing a proposed methodology to be used by the Airways Facilities Service of the Federal Aviation Administration in procuring National Airspace System equipment. The objective is to establish and then achieve the R&M goals which minimize equipment life cycle cost, taking into account the contribution to acquisition costs of the R&M improvement program. The reliability improvement contribution stems from six distinct program elements:

- Parts Selection
- Derating
- Reliability Growth Testing
- Assembly Screening
- Vendor Surveillance
- Reliability Program.

The first three elements have appeared in studies mentioned above. The fourth and fifth elements represent the recognition that a decrease in reliability generally occurs during the transition from development to production. Screening tests (e.g., stress testing) eliminate incipient failures from the manufacturing process, and vendor surveillance is a quality assurance activity. Finally, the sixth element aggregates the overall level of reliability effort and program emphasis on a qualitative measurement scale. An example will be presented below.

As described in the article, the authors propose a three-stage R&M planning process which appears to be aimed at striking a compromise between a true optimization approach and an approach which is implementable. The goal of the first stage is to obtain a functional relationship between R&M improvement activities and acquisition costs. The process is illustrated in Figure 3, apparently from an actual case study by the authors though presented in abstract form in the article. Discrete levels of each program element are first defined. Next, selected combinations of those levels are used to define alternative reliability programs, varying from all elements at the lowest level (the "standard" program in our previous terminology) to all elements at the highest level (the "state-of-the-art"). Implicit in Figure 3.B is the assumption that the costs and reliability improvement corresponding to each of these levels can be quantified. The authors suggest simulation, Duane growth models, etc., as tools for obtaining the required values. (Our survey of previous studies above suggests that the necessary data and methodology may, in fact, exist.) Finally, plotting the values so obtained allows the required curve to be estimated. Similarly, a curve of maintainability improvement (measured in terms of mean time to repair) can be obtained, after adding modularity and diagnostics (e.g., built-in test/fault isolation test) to the list of program elements with associated discrete levels of activity.

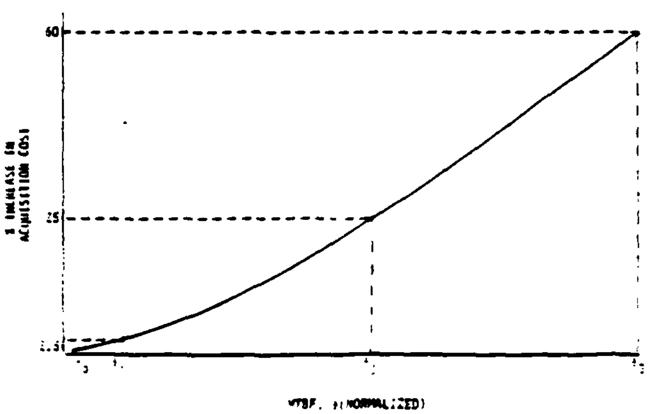
The second stage of the planning process uses the R&M acquisition cost versus effectiveness curves to minimize the total R&M contribution to life cycle (acquisition plus O&M) costs over the range of possible R&M parameter values. The O&M cost contribution can be obtained from standard models

ATTRIBUTES	APPLICATION LEVEL		
	A	B	C
Part Selection			
Microcircuits	Class A	Class B, B1, B2	Class C, Commercial
Semiconductors	JAN TXV	JANTX	JAN, Commercial
Resistors	S	R	P,M
Capacitors	T,S	R	P,M,L
Derating	Most Acceptable	Acceptable	Minimally Acceptable
Assembly Screening	Applied	Not Applied	- - - - - -
Vendor Surveillance	Performed	Not Performed	- - - - - -
R Growth Testing	Extensive	Moderate	None
R Program	Full MIL-STD-785	Modified MIL-STD-785	MIL-STD-785 Not Req'd

A. Reliability Improvement Program Elements and Application Levels

RELIABILITY ATTRIBUTE	ATTRIBUTE LEVEL FOR A GIVEN STATE			
	θ_0	θ_1	θ_2	θ_3
PART SELECTION	C	B	B	A
DERATING	C	B	B	A
ASSEMBLY SCREENING	B	B	A	A
VENDOR SURVEILLANCE	B	B	A	A
R GROWTH TESTING	C	C	B	A
R PROGRAM	C	B	A	A
NORMALIZED INCREASE IN ACQUISITION COST	0	2.5%	25%	60%
RELATIVE CHANGE IN MTBF LEVEL (WITH RESPECT TO θ_0)	1:1	4:1	18:1	30:1

B. Computed Increases in Costs and Reliability from Selected Combinations of Reliability Program Elements



C. Reliability Improvement Cost Versus Effectiveness Curve

Figure 3. EXAMPLE OF FAA METHODOLOGY FOR ESTIMATING THE COST OF RELIABILITY IMPROVEMENT PROGRAMS, FROM [24]

of the costs of corrective maintenance (including spares), preventive maintenance, and maintenance training as a function of the R&M parameter values. In principle, once this minimization is complete, the optimal values of MTBF and MTTR are determined, and the program yielding those values can be implemented. However, since there are only a discrete number of such programs, none of which may correspond to the optimal parameter values, a third stage is needed.

The third stage is the actual test planning process. As described by the authors, the second stage above is used to merely ascertain how close the "optimal" parameter values lie to the state-of-the-art limits (e.g., θ_3 in Figure 3). Based on their proximity, the authors suggest how tradeoffs should be made between growth, demonstration, screening and acceptance testing.

Thus, the proposed methodology falls short of the "idealized" planning loop of Figure 1, but is much more ambitious than previously published efforts. One notable omission from the approach is the possible discrepancy between reliability measured during development and reliability measured in the field (apart from infant mortality or quality control causes).

4. Demonstrated Versus Field Reliability

A number of studies have recognized and attempted to quantify the disparity between reliability (MTBF) measured in the field and reliability demonstrated or predicted during development. The consensus to date, however, appears to be that a general functional relationship does not exist, and the most accurate means of predicting field reliability for individual systems is to obtain field data for similar systems in similar operational and maintenance environments.

One common method of transforming development reliability to field reliability is the "K-factor" approach, wherein the demonstrated/predicted reliability is multiplied by a number of adjustment ("K") factors to account for definitional, operational, and environmental differences between the two measures. Shelley and Stovall [25], for example, define 15 such factors. Using data on 35 equipments from the C-5A program, those authors selected four of the K-factors--(1) ratio of unscheduled removals to verified failures, (2) ratio of equipment operating hours to flight hours, (3) operating environment differences (temperature, vibration levels, humidity, etc.) based on intuitive engineering judgment, and (4) ratio of total laboratory failures to "chargeable" (back to the contractor)/"relevant" failures--to quantify in order to attempt to fit equations to the data. The results were unsatisfactory. While it was concluded that the definitional differences (factor (4) above) played an important role in explaining the discrepancies between the development and field reliabilities, the *adjusted* field MTBFs averaged only 47 percent of the demonstrated MTBFs. The authors did not obtain useful predictive equations, and, in addition, the ranges of values of the K-factors over the 35 equipments (1.0-1.58, 0.05-2.63, 0.5-2.0, and 1.0-6.0 for factors (1) through (4), respectively) imply that this approach cannot be generalized beyond the individual equipment levels.

A study reported by Kern [26] concentrated on similar factors. Working with historical data for 16 avionics equipments, the raw field data were first adjusted for definitional factors (equipment operating hours, failure countability criteria) after which a new field MTBF was computed. The application of this definitional adjustment brought the average ratio of development MTBF to field MTBF down from 6:1 to approximately 2.4:1. Kern explained the remaining discrepancy in terms of operational factors (maintenance handling, utilization rates, mission durations, etc.) and environmental factors, with about half of the discrepancy explained by each. However, as in [24], the range of field to development ratios was large (0.07-1.27), and the author was not able to obtain a good statistical fit to the data. One interesting finding of this study, however, which may help in part to explain the difference in adjusted field versus development MTBFs in [25], was that a large percentage (39 percent) of the field maintenance actions were caused by equipment interfaces.

Finally, a study by Boeing [27] on 112 avionics equipments comparing raw Air Force and Navy field data to demonstrated/predicted MTBFs, also found that definitional factors, equipment operating hours versus flight hours in particular, were primary contributors to the discrepancies between the two measures. However, over a wide range of alternative functional forms, a statistical model explaining the observed discrepancies could not be found.

Clearly, if field reliability cannot be predicted from development reliability with any accuracy, then functional relationships between resources invested in reliability during development and development reliability achieved cannot be linked to more global measures of cost-effectiveness such as life cycle cost minimization. Also, if the interface problem is of the magnitude implied by the Kern results, then it may not make sense to separately analyze individual equipments when they are components of a more complex system. Nevertheless, prediction of field reliability from development reliability should not be an intractable problem, and more analysis is warranted in this area.

D. STUDIES OF RELIABILITY GROWTH DURING HELICOPTER DEVELOPMENT PROGRAMS

The investigations into reliability growth of electronics equipments discussed above were primarily comparative analyses of historical data with the objective of making marginal improvements to a methodology for developing equipment which is apparently well understood, at least at an intuitive engineering level. Helicopters, on the other hand, pose a more complex, less understood problem for several reasons. First, historical data are much more scarce. Only a few programs have included formal reliability efforts during development, and those are too recent to have generated studies of the.type discussed above. Second, helicopters are composed of a varied collection of complex subsystems that are themselves the subject of an intertwined collection of development programs. The problem of reliability apportionment--setting intermediate goals for all of the subsystem reliabilities such that the total system goal is equaled or exceeded--must be addressed. And finally, there is an extensive menu of alternative test activities from which to choose, each testing some subset of the set of subsystems at a given operating rate and cost.

The studies described below tend to focus on historical data from a single helicopter type in order to derive a methodology for planning future programs. Also, while life cycle cost minimization is not always the stated objective, the reliability parameter of interest tends to be mean time between removals (MTBR), historically the primary driver of the reliability contribution to ownership costs of fielded systems.

1. Reliability Growth Studies by Boeing Vertol

The most widely quoted study concerning the tradeoff between resources involved in reliability and reliability achieved for helicopters is a study by Rummel [28], with accompanying volumes by Aronson [29] and Jines [30]. The objective of this study was to develop a methodology for formulating cost-effective reliability test programs for future helicopters, given the contractual numerical reliability requirements. Undertaken in advance of the UTTAS (Black Hawk) program, discussed in Chapter II below, the focus of the study was on helicopters in the 15,000 lb. gross weight class, similar to the Black Hawk. Helicopters in the 90,000 lb. class were also treated, in anticipation of a possible HLH (Heavy Lift Helicopter) program, although the latter helicopter was the subject of a follow-on reliability growth study to be discussed below.

The Rummel study approach was to first use historical failure rate (MTBR) data from the CH-47 program to develop a list of "off-the-board" failure modes, with associated failure rates, predicted for the future helicopter. Second, the abilities of different types of testing to uncover the various failure modes were estimated. Finally, various combinations of those tests were compared with respect to both cost and required development program duration in order to achieve the overall reliability goal. Demonstration requirements (objective, duration, consumer risk, producer risk) were treated parametrically.

Rummel divided the various kinds of reliability tests into five general types.

(Type I) General Design Development Tests - Those tests (stress, fatigue, etc.) which support the design by aiding material and configuration selection and component sizing. Considerable flight testing, such as structural demonstrations as well as testing to establish aircraft load, stability, and performance characteristics, falls into this category. These tests have very specialized objectives and are not typically reliability-oriented.

(Type II) Reliability Problem Identification Tests - These tests (also termed "endurance," "qualification," or "service" tests) are designed to determine the existence, rate, and cause of reliability problems and whether corrective action is necessary and/or effective. Examples of these tests are transmission bench endurance, rotor whirl tower, tiedown, and dynamic system tests. Flight testing to identify reliability problems also falls within this category.

(Type III) Reliability Problem Investigation Tests - Designed to understand field-identified reliability problems, these tests may occur during either the development or the production phase of a program. They are specifically designed to reproduce certain failure modes, but may be a source of future Type II tests.

(Type IV) Reliability Demonstration Tests - The objective of these tests is to prove to the customer that contractual reliability requirements have been met. Usually they are performed by flight vehicles in the field once the design configuration has stabilized. Specifications for these tests are in the form of a reliability goal, a confidence level (level of customer risk) at which that goal is to be demonstrated, and a duration for the test. Given his level of risk of failing the demonstration, the producer can determine his own reliability goal for the system development program.

(Type V) Production Quality Assurance Tests - These tests determine if the reliability level has been maintained in the transition from development to production hardware.

Rummel was not concerned with Type I tests above. He considered the costs of such tests to be fixed and (optimistically) removed all failure modes from the "off-the-board" list which he felt would be uncovered during such testing. Thus, "off-the-board" defines the state of the hardware following such tests. Type IV and V tests were also not considered. Other assumptions underlying Rummel's approach are as follows:

(a) 1,500 Type I flight test hours are included in all candidate development programs;

(b) lead times and operating rates of the various test techniques are fixed;

(c) alternative overall test program durations of three, four, and six years are examined with the duration determining the number of test rigs and test articles;

(d) if a test technique is capable of detecting a failure mode, that mode will occur within a period of testing equal to twice the associated MTBF;

(e) corrective action for detected failure modes is immediate;

(f) all components have the same MTBR goal, chosen such that the overall system MTBR goal (which is varied parametrically) is achieved; and

(g) in specifying the individual test durations, the test lengths are sized to the lowest component MTBR output (i.e., some component MTBR levels may exceed their goals in order that the lowest component MTBR just meets the goal).

The costs of the various test techniques, assumed operating rates and lead times are shown in Table 5, extracted from the study. The costs as shown do include test equipment but do not include the cost of test articles (including flight test vehicles). Also not included are the costs of corrective actions resulting from failure mode detections. Rummel did estimate, however, that on the average 700 manhours are expended per failure mode for corrective action. The high cost per flight hour for Type I flight testing ($13,500 for the 15,000 lb. helicopter) is due primarily to engineering and manufacturing support labor costs.

It is impossible to reproduce all the test program results of the study, but some representative findings are displayed in Figure 4. In the Figure, "Demo-In" and "Demo-Out" refer to having the reliability demonstration during development or after development, respectively. In the former case, the time interval for problem identification testing is shorter (one year less) than in the latter case, and the cost per hour of demonstration testing is assumed to be higher (see Table 5); however, the results of the demonstration are known prior to production.

Table 5. RUMMEL STUDY TEST COST, OPERATING RATE SUMMARY

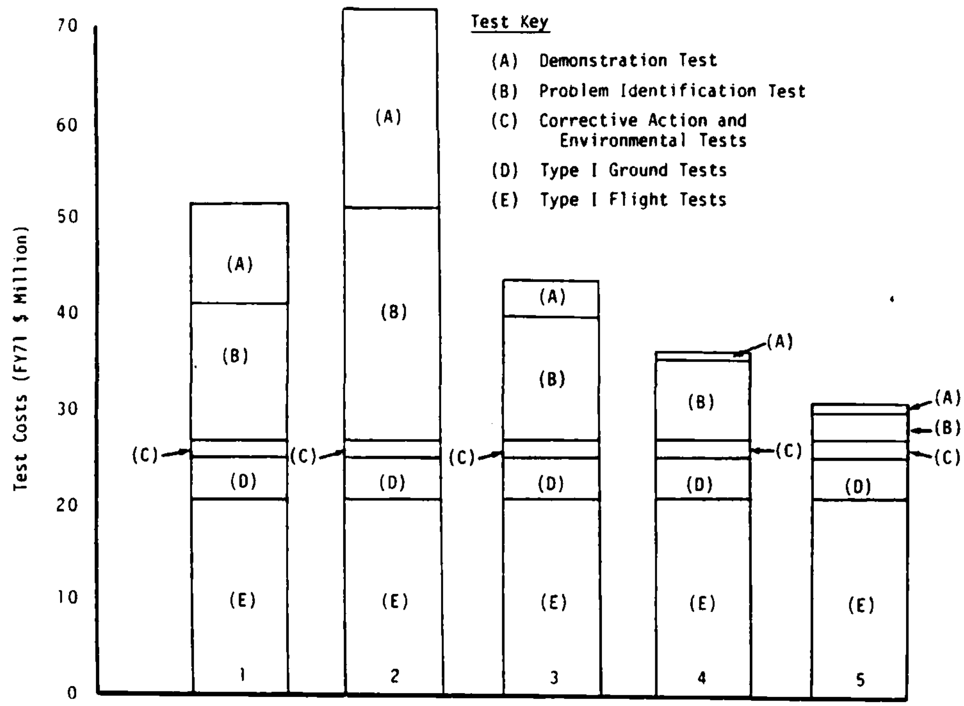
Technique	Costs (FY71 $)						Schedules					
	CH-47		Helicopter "A"[a]		Helicopter "B"[b]		CH-47		Helicopter "A"		Helicopter "B"	
							Lead Time (mo.)	Oper Rate (hr./mo.)	Lead Time (mo.)	Oper Rate (hr./mo.)	Lead Time (mo.)	Oper Rate (hr./mo.)
Type I	($ million)		($ million)		($ million)							
Fatigue Rotor Components	3.46	6.12	3.06	5.45	4.19	9.16	(Detailed schedules are not required to derive Type I ground test costs.)					
Fatigue Control Components	0.76		0.67		0.93							
Fatigue Drive Components	1.56		1.10		3.10							
Static Load	0.34		0.31		0.46							
Miscellaneous (Gear Resonance, etc.)	0.35		0.31		0.48							
Flight	26.40		20.30		39.00		26	8	24	20	26	20
	(1,700 flight hours)		(1,500 flight hours)		(1,500 flight hours)							
Type II	Non-recurring ($1,000)	Recurring ($/hr.)	Non-recurring ($1,000)	Recurring ($/hr.)	Non-recurring ($1,000)	Recurring ($/hr.)						
Controls Bench Back-to-Back	44	37	94	41	211	51	6	500	6	500	6	500
Controls Bench Single Specimen	44	37	74	37	166	46	-	500	6	500	6	500
Tiedown	4,190	2,200	2,300	1,700	-	-	24	165	24	165	-	-
Dynamic Systems Test	N/A	N/A	2,020	580	-	-	N/A	N/A	20	200	-	-
Whirl Tower	3,430	650	2,580	220	6,187	326	16	350	20	350	22	350
Hub Bearing	24	16	N/A	N/A	144	49	6	500	N/A	N/A	9	400
Transmission Open Loop	-	-	2,284	354	-	-	-	-	21	350	-	-
Tail Rotor Whirl Tower	N/A	N/A	330	110	N/A	N/A	N/A	N/A	16	400	N/A	N/A
Flight	N/A	N/A	-	2,500	-	4,630	N/A	N/A	24	70	26	70
Type IV												
Flight (Development Phase)	-	-	-	2,500	-	-	-	-	N/A	50	-	40
Flight (Operational Phase)	-	-	-	200	-	200	-	-	N/A	50		40

[a] 15,000 lb. gross weight single rotor

[b] 90,000 lb. gross weight tandem rotor

MTBR* denotes the reliability goal to be demonstrated at the indicated confidence (customer risk) level. The producer risk is always taken to be 80 percent. Note from the Figure that the Type I test costs (assumed fixed) always exceed the problem identification test costs, even at the most demanding demonstration level. Other conclusions of the study include:

- Of the cost variables studied, the demonstration approach (demo-in or demo-out) and the reliability levels to be demonstrated have a greater cost impact than the mix of techniques used in the program or the elapsed time of the program.



Demonstration Approach	Demo-In	Demo-In	Demo-Out	Demo-Out	Demo-Out
MTBR* (Hours)/Confidence (%)	1,000/90	1,500/90	1,500/90	1,500/30	500/30
Elapsed Time (Years)	4	4	4	4	6
Required MTBR Achieved (Hours)	3,000	4,750	3,000	1,900	590
Demonstration Duration (Hours)	5,500	9,000	25,000	2,400	1,500

Figure 4. RUMMEL STUDY [28] SAMPLE RESULTS

- Once the length of the program is fixed, the program cost is relatively insensitive to the mix or operating rates (varied as an excursion) of the various test techniques.
- Broader consideration of design effort, reliability apportionment, acquisition costs and O&M costs in the context of life cycle cost minimization would be desirable in future studies of this kind.

Concerning the study assumptions listed above, assumptions (d) and (e) are particularly critical in driving the study results, in drawing comparisons between this study and other helicopter studies to be discussed below, and in comparing pre-production versus post-production reliability programs. For example, one additional finding of the Rummel study is that there is a direct relationship between a percentage change in test program cost and a percentage change in the number of off-the-board failure modes present. That is, if, for example, the off-the-board MTBR is doubled by doubling the number of failure modes (keeping the *distribution* fixed), then the test costs will double. To compare this finding, with, say, the Duane reliability growth model, the latter requires a $2^{(1/\alpha)}$ increase in test time for each doubling of the initial failure rate. For a Duane growth rate $\alpha = 0.5$, a fourfold increase in test time is thus implied; for a growth rate $\alpha = 0.20$, similar to those measured for recent helicopter development programs discussed in Chapter II below, a 32-fold increase is implied. Assumptions (d) and (e) also imply that more attention than might be justifiable should be paid to low frequency (high MTBR) failure modes since those drive the test size/duration requirements, and that shorter calendar time development programs are less costly relative to longer calendar time development programs than they might be if failures were not detected and corrected so quickly. In [30], sensitivity analyses to (d) and (e) confirm this fact, indicating as shown in Table 6 that program cost also increases in proportion to corrective action efficiency. (Thus a Duane α of 0.5 corresponds to a 4 x MTBR corrective action efficiency in the Rummel study.) Finally, assumptions (f) and (g) indicate that the reliability apportionment problem--optimal allocation of component MTBR goals to minimize the cost of achieving the overall system goal--was not considered. For that reason, and because only a small, heuristically determined subset of possible test programs was evaluated, neither the methodology nor the results are "optimal" in a formal sense.

A follow-on study dealing with the HLH by Burden [31] carried the Rummel approach one step further by incorporating O&M costs into the analysis. The objectives of the Burden study were to (a) determine the relationship between

Table 6. RUMMEL STUDY [28] FOUR-YEAR TEST PROGRAM SENSITIVITY TO CORRECTIVE ACTION EFFICIENCY

Corrective Action Efficiency	System MTBR Required	Test Technique: Type I Flight Test (hrs.)	Type II Flight Test (hrs.)	Closed Loop Main Transmission Test Stand (hrs./No. of Stands)	Whirl Tower (hrs./No. of Stands)	Controls Bench Test Stand (hrs./No. of Stands)	Tail Rotor Test Stand (hrs./No. of Stands)	Total Test Program Cost (FY71 $ Millions)
2 x MTBR to Fix (Base Case)	600	1,500	0	2,500/1	0/0	850/1	0/0	2.1
	3,000	1,500	2,200	12,000/1	3,400/1	7,200/1	2,800/1	12.5
	5,200	1,500	4,500	22,600/2	4,200/1	2,150/1	1,900/1	22.1
4 x MTBR to Fix	600	1,500	500	7,800/1	0/0	3,900/1	800/1	5.4
	3,000	1,500	5,500	20,800/2	7,700/1	21,000/1	8,100/1	26.5
	5,200	1,500	11,500	36,000/3	8,700/1	4,000/1	5,100/1	46.4
8 x MTBR to Fix	600	1,500	3,600	11,700/1	0/0	5,800/1	0/1	14.0
	3,000	1,500	10,500	51,500/5	16,800/2	74,000/4	17,800/2	57.9
	5,200	1,500	22,700	71,500/6	18,300/2	13,000/1	11,800/1	91.0

reliability and life cycle cost, (b) design a test program to minimize development plus O&M costs, and (c) identify the most cost-effective reliability requirement for the HLH. Burden considers 27 separate HLH components; the parameter of interest is MTBR.

The distribution of failure modes, the off-the-board MTBRs, the effectiveness of the various test techniques, test costs and operating rates are all taken or extrapolated from the Rummel study. Test programs are proposed which achieve various alternate levels of initial production aircraft reliability. The fleet life cycle is simulated using a Monte Carlo model. Fleet sizes of 50, 100, and 200 aircraft with utilization rates of 30 hours per month and 60 hours per month are evaluated. Additional study assumptions include the following:

(a) An extensive component development (Type I test) program including the fabrication of one flying prototype and 100 hours of flight testing are assumed to have occurred prior to this study. The costs of this program are considered sunk.

(b) No calendar constraints are placed on the development program (keeping the number of test rigs/articles to a minimum).

(c) Corrective action efficiency during development is 2 x (component MTBR) to detect and fix each failure mode.

(d) The production rate is two aircraft per month. The fleet life is 10 years following the last production aircraft.

(e) Reliability growth continues throughout the useful life of the fleet. Corrective actions on fielded systems (ECPs) are assumed to be initiated after 15 occurrences of each failure mode and then require three years to be implemented.

(f) No discounting is used in computing O&M costs.

Findings and conclusions of the study include the following:

- "Optimal" development test program costs are approximately equal to the fleet 10-year O&M costs, as shown in the following sample results spanning the range of alternatives investigated:

Fleet Size	Utilization	Test Program Cost (FY73 $ Millions)	Fleet 10-Year O&M Cost (FY73 $ Millions)
50	30 hrs./month	33.5	34.5
200	60 hrs./month	69.0	53.0

- The test program costs break down into

  Flight Tests 25% - 30%
  Other Tests 25% - 35%
  Corrective Actions 35% - 50%

- The "optimal" reliability requirement is quite sensitive (the ratio of the lowest to highest value is about 2.5) to fleet size and utilization, driven primarily by the spares component of the O&M cost.
- Life cycle costs, however, are *not* sensitive (within a range of say ±50 percent) to achievement of the optimal reliability requirement. The assumption of reliability growth in the field mitigates the increase in O&M costs resulting from poorer initial reliability.
- Under the assumption of *no* reliability growth in the field, the optimal reliability requirement, as well as the minimum life cycle costs and corresponding development and O&M costs, all increase by about 30 percent. Also, the sensitivity of life cycle cost to reliability requirements increases substantially.

2. Reliability Growth Studies by Sikorsky

In parallel with the Rummel study, three authors at Sikorsky Aircraft were also investigating the relationship between reliability objectives and development program costs for helicopters of approximately 15,000 lb. The Sikorsky study [32] is more qualitative than the Rummel study and more closely tied to historical data, perhaps because the H-3 helicopter program from which those data were taken involved a 17,000 lb. single rotor helicopter, very similar to the hypothetical helicopter of interest.

The Sikorsky study consists of several loosely related sections. One section compared the relative frequencies of failure mode occurrences for H-3 rotor systems and transmission systems during development versus in-field use. The investigation found large discrepancies between those frequency distributions. For example, bearing failures accounted for approximately 50 percent of the main gearbox development failures but only 13 percent of the field failures. On the other hand, almost half of the field failures could only be categorized as "miscellaneous," versus only seven percent of the development failures. Leaking seals accounted for a high percentage of the field failures of both the intermediate and tail gearboxes, and both the main and tail rotor heads; such leaks were a minor source of failures during development. Absolute differences between failure *rates* during development and in the field were not compared. The authors' purpose in comparing relative frequencies was to ascertain whether changes to the H-3 development test program were warranted in designing a program for the new helicopter. While many of the observed discrepancies in the frequencies can be attributed to corrective actions made during development, the authors did conclude that more environmental conditions needed to be simulated during the qualification segment of the test program.

A second section of the study deals with accelerated (overload) testing. A qualitative discussion of the philosophy of employing accelerated loads and the potential calendar time reductions in the development program is presented.

The main section of the study deals with the test cost versus reliability achieved issue. The authors propose a five-year development test program (including the reliability demonstration), chosen from four variations of the H-3 development program and incorporating the environmental testing discussed above (but no accelerated loads). The reliability parameter of interest is again MTBR, although the focus, for demonstration purposes, appears to be only on the combined MTBR of the transmission system and rotor system components. Three such MTBR values--500, 1,000, 1,500 hours--and three demonstrated levels of confidence (customer's risk)--30, 60, 90 percent--are examined. The study does not trade off different mixes of tests in the manner that Rummel did. Instead, one duration is chosen for each MTBR and confidence level demonstration, which implies an MTBR to be developed (to satisfy the producer's risk criteria), which in turn implies a certain amount of component testing. Since the mix of testing is fixed, the five-year calendar time constraint together with test operating rates force a certain number of test specimens, and the test cost can be determined.

The costs and operating rates of testing are quite similar to those given in [28] and are reproduced here in Table 7 for possible future reference. Unlike Rummel's study, however, the effectiveness of testing is presented in a manner that is *component oriented* rather than test oriented. That is, Rummel estimated the capabilities of each testing technique for detecting failure modes exhibited by all components of the helicopter. The Burroughs, et al. study estimates the rapidity with which the failure rate of each component will be improved as it undergoes the given mix of tests. One interesting finding of the latter study is that after the first 3,000 test hours have elapsed, during which time little improvement in component failure rate occurs, the rate of such improvement, expressed as a percent of the off-the-board failure rate is *linear* in test hours. (However, this finding, while not explained in detail in the study, appears to be based on the comparison of H-3 failure modes detected during *development* testing with the duration of that testing. The contribution of failure modes detected subsequently on fielded aircraft to the test-effectiveness graphs presented in the paper is not clear.) The conclusions of the study are presented graphically, as development cost versus time curves for each demonstration requirement. In all cases, costs tend to increase rapidly for the first one and one-half years until all test facilities are complete, and then at a

Table 7. TEST COSTS (FY71 $) AND OPERATING RATES USED IN BURROUGHS, ET AL. STUDY [32]

Test (5)	Average Hours/Month: Development	Average Hours/Month: Demonstration	Facility Costs (1)	Unit Cost of Test (1) (4): Development	Unit Cost of Test (1) (4): Demonstration
Main Rotor Head and Shaft	140	200	$280,000	$60,000 per specimen	$45,000 per specimen
Tail Rotor Head and Shaft	140	200	$120,000	$30,000 per specimen	$22,000 per specimen
Rotor Structural Components (7)	N/A	N/A	$650,000	$ 5,000 per test hour	-
Main Rotor Whirl Tests (2)	10	N/A	$170,000	$ 400 per test hour	-
Tail Rotor Whirl Tests (2)	12	N/A	$120,000	$ 300 per test hour	-
Gear Endurance Regenerative Bench Test	100	N/A	$800,000	$ 200 per test hour	-
Gearbox Mode of Failure Regenerative Bench Test	50	N/A	- (3)	$ 500 per test hour	-
Propulsion System Test Bed	50	100	$700,000	$ 1,400 per test hour	$700 per test hour
Tiedown Test (6)	50	100	$200,000	-	$800 per test hour
Flight Test (6)	18	N/A	N/A	$10,000 per test hour	

(1) All costs are approximate and are based on 1971 dollars. These are planning figures only and are not be be used for quotation purposes.

(2) Facility already exists. Costs are only for setup (including adaptation of test component) and instrumentation.

(3) The mode of failure testing, no-load lubrication, gear development, and endurance all use the same ($800,000) regenerative bench test facility.

(4) Excludes cost of components to be tested.

(5) Design selection tests, experimental stress analysis, and bearing and seal tests are usually selective small test programs and have comparatively little effect on overall dynamic component reliability development program costs, and have not been included in these data.

(6) Aircraft for the Tiedown Test and Flight Test are bailed aircraft, and engines for the Power System Test Bed are GFAE equipment; their costs are not included in these data.

(7) The design requirements for fatigue are not specified as an MTBR but as a service life based on conservative fatigue allowables which give us a structure reliability order of magnitude greater than any MTBR considered in this report.

decreasing rate until the demonstration requirements have been met. The final program costs are summarized in Table 8.

Table 8. BURROUGHS, ET AL. [32] DEVELOPMENT TEST COSTS VERSUS DEMONSTRATION REQUIREMENTS (EXPRESSED IN FY71 $ MILLIONS)

Demonstration Requirement (MTBR)	CONFIDENCE LEVEL TO BE DEMONSTRATED (%)					
	30		60		90	
	Test Cost[a]	Test Cost Plus Demo Cost	Test Cost	Test Cost Plus Demo Cost	Test Cost	Test Cost Plus Demo Cost
500 hrs.	5.2	5.7	5.6	6.3	5.9	7.8
1000 hrs.	6.0	6.8	8.9	10.0	10.9	13.2
1500 hrs.	9.4	11.5	11.7	13.9	14.5	17.4

[a]Costs in this Table do not include flight testing or costs of aircraft parts except for tiedown vehicle(s) at one million per vehicle.

Note that a tripling of the MTBR requirement results in roughly only a doubling of the total development test costs (and even a smaller multiplier if flight testing costs are incorporated into the test program at a constant level for all demonstration requirements). In view of our discussion above concerning the effects of corrective action assumptions on the Rummel study results, this would appear to be a very optimistic finding. It may be related to the fact that the demonstration requirement appears to be restricted to the transmission and rotor system, and is certainly related to the linearity in test hours of test effectiveness as noted above. Detailed comparisons between the Rummel and Burroughs findings are impossible for a number of reasons:

(1) In [32] no distinction is drawn between Type I and Type II testing. All such testing appears to be a

legitimate variable in designing a test plan to meet a reliability goal, and the costs of all such testing were included in the results shown in Table 8. This reemphasizes a point made in discussing electronics studies above--it is very hard to determine what costs are attributable to an R&M program; not only do different programs put forth different definitions of how reliability should be measured, as will become apparent in subsequent chapters of this paper, but different contractors, both philosophically and in an accounting sense, have different definitions of what constitutes reliability cost.

(2) While [28] includes the reliability improvement (but not the cost) accruing from 1,500 hours of flight tests in each proposed development program plus both the cost and effect of additional flight testing, [32] viewed flight testing as being related only to performance and, hence, none was included.

(3) In [32], all demonstrations are assumed to be accomplished in ground tests, while flight testing is used in [28]. As a result, in the latter study both the magnitude and relative sensitivity of test costs to demonstration requirements are much greater.

While both [32] and [28] were completed just prior to and in anticipation of the development program for the Utility Tactical Transport Aircraft System (UTTAS--later the Black Hawk), a second Sikorsky study [33] was published shortly before the ...letion of that development program. Although much more ... in scope, concentrating on detailed helicopter drive ... design considerations, the latter study is of interest ...ext of this chapter for several reasons. First, ...xcellent guide to applying the Rummel approach ...--referred to here as "Generalized Test Plan- ..., that method is essentially repudiated on the grounds that (a) too many poorly understood quantitative assumptions are required, and (b) it may not be easily adapted to new test techniques or advances in technology, such as new types of structural materials, which may eliminate whole classes of failure modes, but also introduce new ones. Advocated instead, at least for helicopters like the Black Hawk, are programs patterned on the UTTAS drive system development tests, presumably arrived at through more heuristic application of engineering experience, on the grounds that the latter program was highly successful. Second, going back early in the design phase of a new system, one objective of [33] was to attempt to relate numerical reliability requirements to engineering design parameters such as stresses or bearing lives. The attempt was unsuccessful, because sufficient data did not exist for establishing failure rates over time (hazard functions) for individual failure modes of components, and because techniques of engineering analysis were not sufficiently evolved to enable determination of those engineering parameters acting on the component at any given time. Thus, while such indicators as parts counts appear to lead to reasonable reliability predictions for electronics equipment, the authors of [33] concluded that accurate reliability predictions for helicopter transmissions (and presumably for other complicated systems) are impossible, and high reliability of such systems should be a by-product of "currently accepted design practices" rather than the explicit output of specific reliability design activities. Finally, turning to the timing of reliability demonstrations, the authors felt that they must be done in the field. Development testing cannot reveal many field failure modes; quality control problems introduce a large number of failure modes into production units; and the costs to fabricate a statistically meaningful sample of demonstration test specimens are prohibitive. Quantitative resource considerations or comparisons of development versus field failures were beyond the scope of the study.

3. Reliability Growth Study by Bell Helicopter

Historical data from early production years of the UH-1D and AH-1G programs were used in a reliability growth study by Conway [34]. The objective was to determine those relationships between reliability growth characteristics and program parameters which might be useful in planning future development programs. Although neither the UH-1D nor the AH-1G had formal reliability programs during development (the author originally attempted to track reliability growth versus development test hours but concluded it was impossible), both helicopters underwent "M&R" programs early in their production phases during which extensive reliability and corrective action data were collected. Data were available on five fiscal year configurations of the UH-1D (FY62 through FY66) monitored during the M&R program, plus three additional configurations (FY67 through FY69) on which the effectiveness of corrective actions initiated during the M&R program could be assessed. For the AH-1G, three fiscal year configurations were monitored during the M&R program (FY66 through FY68), plus additional data, which were available on FY69 and FY70 models. The durations of the two M&R programs and total flight hours monitored were 39 calendar months and 50,000 flight hours for the UH-1D, and 29 calendar months and 66,000 flight hours for the AH-1G. Some aircraft were dropped from the data sample due to missing or suspect data. Also, although both the UH-1D and AH-1G evolved from the same parent aircraft--the UH-1A--differences were minimized by deleting data on systems not critical to flight, such as communication, navigation, and weapons.

The methodology used by the author for both helicopter types began with the construction of a baseline system failure rate, composed of the failure rates (computed from the data) for all those failure modes observed in the data base for which reliability improvements (corrective actions) were not experienced. The remaining failure modes each had two failure rates associated with them--a failure rate λ_0 prior to implementation of corrective action and a failure rate λ_1 following implementation. In all cases λ_1 was less than λ_0, and in those cases where no failures were observed between corrective action implementation and termination of the data collection period, λ_1 was (optimistically) taken to be zero. Finally, an annual system failure rate for each helicopter type was constructed by adding to the baseline failure rate either λ_0 or λ_1, for each corrected failure mode, depending upon whether or not corrective action had been implemented prior to the start of that fiscal year.

During the M&R programs, seven occurrences of a failure mode were required for corrective action initiation (except for failures affecting safety of flight).

The author compares failure rate growth for both calendar time and cumulative M&R program flight hours. Conclusions of the study, and some comparisons with other studies discussed above, include the following:

(1) The relationship of reliability growth to cumulative flight hours is shown in Figure 5 taken from the study. The data are plotted on a log-log grid in order to compare the results with Duane/RPM methodology. From the Figure, the author concluded that the time lag in implementing corrective actions on production aircraft caused the piecewise linearity of the growth curves, although once that time lag was overcome, straight lines appeared to fit the remaining data points well. The author found the "off-the-board" mean times between failure to be between 20 and 35 percent of the estimated mature program values--much higher than the RPM "10 percent" rule-of-thumb,--a fact which he attributed to the "flight-quality" hardware with which the helicopter programs began.

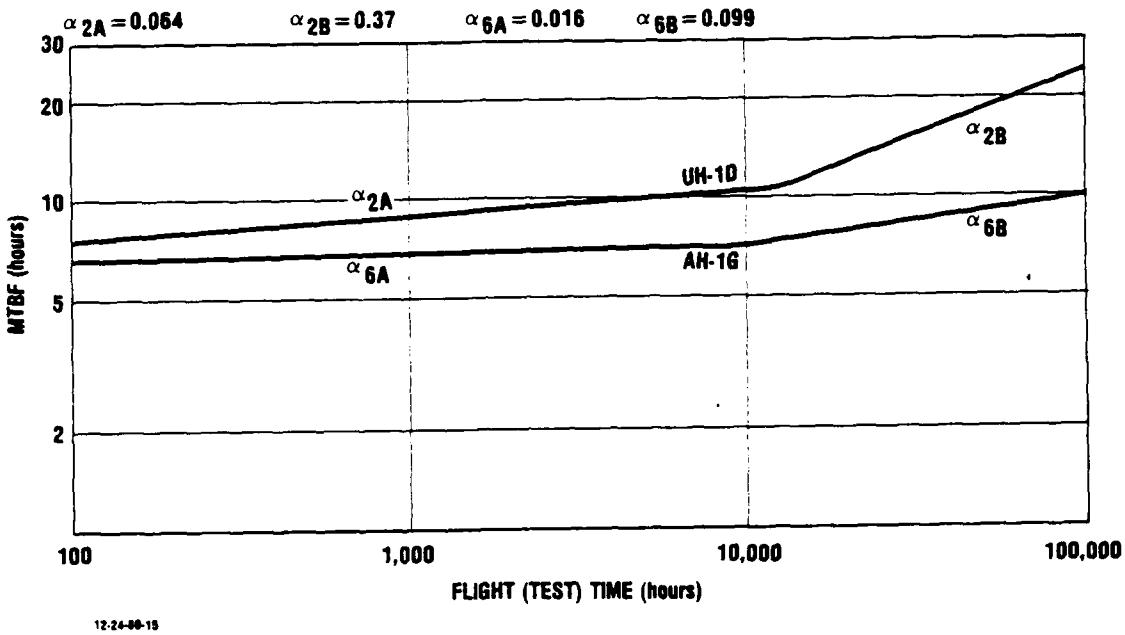


Figure 5. BELL STUDY [34] UH-1D AND AH-1G RELIABILITY GROWTH VERSUS CUMULATIVE FLIGHT HOURS

The reliability growth rates in Figure 5 are also lower than the Duane/RPM 0.5 value.

(2) In order to explain the difference in apparent growth rates between the UH-1D and the AH-1G, the author hypothesized that a calendar time constraint exists on the rapidity with which helicopter reliability growth can occur. No matter how quickly flight hours are run up, there is a practical limit to how quickly failure modes can be analyzed, design improvements made, approved, and implemented. While the intensity of the AH-1G program was higher than the UH-1D program, the rate of failure rate improvement when measured against calendar time was approximately equal for both programs and constant throughout the data collection period, as shown in Figure 6. The author assumed that the intensities of both helicopter

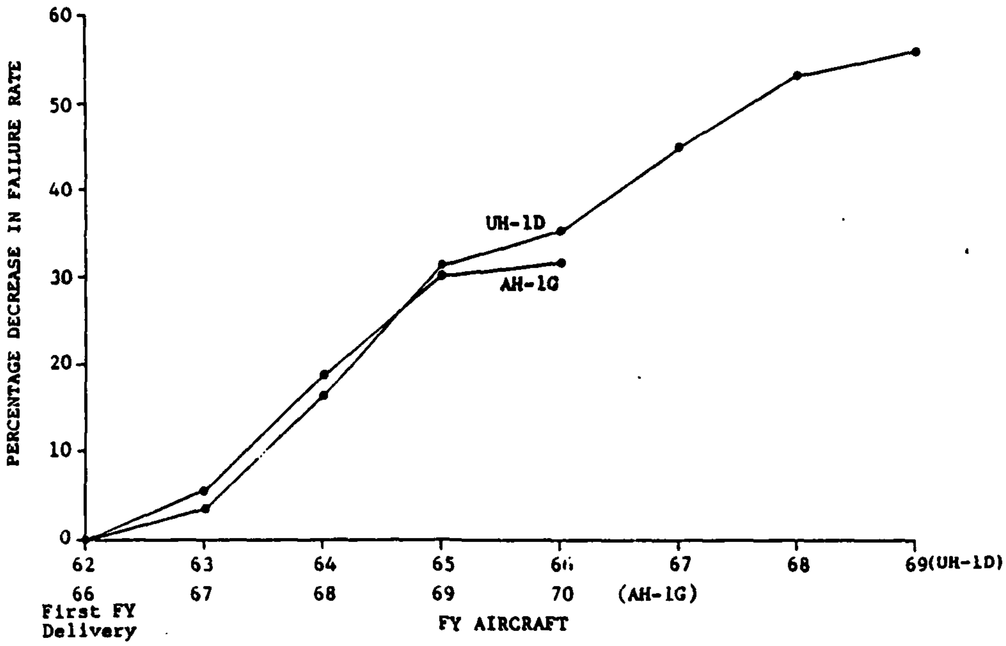


Figure 6. BELL STUDY [34] PERCENTAGE DECREASE IN FAILURE RATE VERSUS FY AH-1G AND UH-1D AIRCRAFT

M&R programs exceeded the calendar time to flight-hour threshold (estimated to be approximately 1,200 flight hours per month), and the upper bound on growth rate versus calendar time--computed from Figure 6 to be 8.6 percent per year--was reached in both programs.

(3) Aware of the Rummel study [28], Conway devoted a section of [34] to a discussion of the differences between his results and those of Rummel. All of the failure modes detected and counted during the M&R programs had associated mean times between failure (λ_0^{-1} in the notation used above) of 5,000 hours or less. Thus Rummel's approach would imply that a test program of 10,000 hours (2 times MTBF) would be sufficient to achieve the same level of growth

as the 50,000-hour M&R program. Conway lists a number of reasonable explanations why the Rummel approach is overly optimistic:

- Many failure modes are calendar-time-dependent and may not arise in a relatively short calendar period test program.
- Many failure modes are environment-dependent and will not be exposed in a test program on prototype aircraft.
- Corrective actions initiated for failure modes discovered during prototype tests may not be incorporated until the production aircraft. Thus, many development tests may be prematurely terminated by failure modes for which corrective actions already exist.
- A corrective action efficiency of seven failures to fix is more reasonable in a field environment, versus the single occurrence assumed by Rummel for a laboratory environment.

(We remark that the last reason itself may be sufficient to explain the fivefold increase in estimated test time. Assuming the usual exponential distribution for times between failure occurrences, it can be shown from tables of the Poisson distribution that

$$P\left\{\begin{array}{c}\text{failure mode}\\ \text{occurs at least}\\ \text{once in time period}\\ \text{of length } 2 \times \text{MTBF}\end{array}\right\} \cong P\left\{\begin{array}{c}\text{failure mode}\\ \text{occurs at least}\\ \text{7 times in time period}\\ \text{of length } 10 \times \text{MTBF}\end{array}\right\} \cong 0.87.\ )$$

(4) Conway made several qualitative recommendations for future helicopter programs based upon his study results, including:

- In view of the observed constraints on field reliability growth, intensive reliability engineering effort should be devoted during the design phase to improving the off-the-board failure rate.
- A reliability program of field failure monitoring on a controlled sample of production helicopters should be included.

While Conway indicated that the Rummel approach may not be valid for field reliability growth efforts, Conway's approach may require additional explanatory variables (perhaps additional time lags) before extrapolation from a controlled sample of helicopters to a fielded fleet is valid. In IDA Study S-451 [1], published UH-1D fleet reliability data (Figure 9, p. 34 of that study) indicate that during the period July 1964 through July 1965 (corresponding to flight hours 5,500 through 25,000 of the M&R program) the fleet reliability was, in fact, declining.

4. Other Related Studies

An extensive taxonomy of reliability activities comprising helicopter reliability development programs is presented in reference [35]. Using the Rummel study as a basis for inferring that reliability development costs can be related to helicopter reliability achieved, the report also proposes (in general terms) a methodology for planning helicopter reliability development programs to minimize development plus O&M costs which is virtually identical to the FAA approach [24] summarized above.

Focusing on the flight testing phase of a hypothetical (though patterned on the Black Hawk) helicopter development program, Pollack and Nulk [36] propose a method for determining the number of prototypes to be fabricated in order to also minimize the reliability contributions to development plus O&M costs. Reliability growth during development is assumed to adhere to the Duane model; the "starting point" and growth rate are taken to be the Selby and Miller values--10 percent of final cumulative MTBF and 0.5, respectively. (While the actual values chosen do not invalidate the approach, both the Bell study findings discussed above and the additional results presented in Chapter II below suggest that those values are not appropriate for helicopters. The starting point is too low, and the growth rate too high.) Given the reliability goal, the growth curve yields the number of flight hours required during development. As the number of prototypes is varied, the duration, in calendar time, of the development program also varies. The authors assume that the cost of that program is a convex function of the number of prototypes, with a minimum near the midpoint of the range of possible prototype values. The O&M cost is also taken to be a convex (decreasing) function of the number of prototypes in that a more rapid development program leads to more rapid replacement of the existing fleet by the newly developed aircraft, which are assumed to be less expensive to operate and maintain. Adding the two functions, the minimizing number of prototypes can be determined.

Finally, a paper by the Logistics Management Institute [11] proposes a methodology for setting reliability requirements which is clearly applicable to helicopter programs although it is applied primarily to fixed-wing aircraft in case studies described in the paper. The objective is to determine optimal *subsystem* reliability goals such that life cycle costs are minimized. In particular, the cost objective function comprises three components: (1) the Cost of Achieving Reliability, including design costs, prototype costs, testing costs, and costs of corrective actions, (2) the Cost of Downtime, which is the cost of procuring and operating additional systems to overcome mission reliability and operational availability constraints and enable performance of a given mission, and (3) the (recoverable) Cost of Maintenance, which is the cost of all the unscheduled maintenance events.

In computing values for the above cost components, the Duane reliability growth model is assumed to hold during development at the system level. The subsystem development reliabilities are assumed to carry over to field use (after definitional adjustments have been made for equipment operating versus system flight hours), and given the "failure criticalities" of each of the subsystems with respect to the mission objective for the total system, a heuristic iterative procedure for "optimizing" the allocation of the total system failure rate to the subsystems is proposed. The development reliabilities achieved translate into system mission reliability and operational availability and thereby influence the size of the total buy, also a decision variable, through the downtime cost component.

The LMI approach has a number of obvious shortcomings. For example, more decision variables governing the reliability activities during development could be included. Only a single type of testing (at the system level) is considered, and the apportionment of system reliability to the various subsystem does not consider the *development* resource costs of achieving alternate subsystem reliabilities, consideration of which certainly might have an effect on the final apportionment since some subsystems are considerably less expensive to test in dollars and calendar time than others. Also, the cost of downtime does not include, for example, attrition due to hostile action, cannabalization, or alternative types of missions, all of which may be important in determining the size of the total system buy. Furthermore, from our summary of electronics reliability literature, we know that the translation of development to field reliability involves more than just the one definitional conversion used in [11].

However, the overall framework proposed in the paper would appear to be expandable to a useful quantitative approach to the problem posed by the flowchart in Figure 1. Apart from purely theoretical treatments such as the one appearing in [37], it is the only model we know of which addresses the reliability apportionment issue, as well as being the only model to incorporate buy size as a decision variable. In case studies of various aircraft programs to which the modeling approach was applied, the authors concluded that intensive reliability improvement programs during system development could have resulted in significant cost-effectiveness benefits, even with buy size (fixed at the actual levels of procurement) deleted from the set of decision variables.

E. SUMMARY

Our survey of the literature indicates that the relationship between resources invested in reliability and reliability achieved is not well understood. No single study has addressed all of the issues raised in Section A above. The studies of electronics equipment reliability growth imply that sufficient understanding of the processes involved in improving reliability exists for useful data to be generated. Thus far, however, analytical attention in using those data has been focused on making marginal changes to existing development strategies. The broader objectives of setting reliability goals and of overall program planning to minimize ownership or development plus ownership costs have only been addressed in the abstract. Obstacles yet to be overcome include the definition of a "standard" taxonomy of reliability improvement activities, the definition of what constitutes cost of reliability improvements as distinct from other development costs, and determination of a means for translating measured development reliability into measured field reliability.

In the helicopter area, data from past programs have been much more scarce, particularly on the subsystem level during development testing, a level on which it would appear necessary to work in order to develop analytical models for setting reliability goals or planning and evaluating (in advance) development programs. Additional problems exist, such as reliability apportionment, which have yet to be incorporated into studies of historical data. The parameter of interest in tracking reliability improvement in published studies has usually been Mean Time Between Removals. The relationship (if any) between this parameter and the parameter Mean Time Between Failures, currently used as a yardstick for monitoring reliability growth in helicopters such as the Black Hawk discussed in Chapter II below, needs to be determined. A common thread linking the analyses performed to date comparing reliability improvement achieved during development with that achieved in the field is the concept of corrective action efficiency--the number of occurrences of a failure mode which are required before that mode is recognized as a candidate for corrective action.

Reliability growth models, particularly the Duane model, are used throughout the literature and appear to fit reliability data reasonably well. For monitoring reliability growth trends of electronics programs or of helicopter programs at the system level, they appear to be useful. For planning future programs, given more detailed cost data covering additional resource variables besides the independent variable used to develop a growth model, however, other functional relationships may be more appropriate, as was found to be the case in the studies by GE [21] and Hughes [22].

Chapter II

DEVELOPMENT PHASE R&M DATA

Section I

Black Hawk (UH-60A) Reliability, Availability, and Maintainability Trends

A. INTRODUCTION

This section presents a summary of reliability, availability and maintainability (RAM) trends experienced by the Black Hawk program throughout the development phase and the first two years of the production phase. The information has been derived from published sources and additional Army RAM/LOG (Reliability, Availability, Maintainability, Logistics Sample Data Systems) and UMSDC (Unscheduled Maintenance Special Data Collection System) data furnished IDA by the US Army Troop Support and Aviation Materiel Readiness Command, and is primarily descriptive. Lack of comparable historical data precludes any extensive comparisons with past development programs. Those inferences which can be drawn from comparisons of the identified Black Hawk RAM trends with those of past helicopter programs are deferred until Section VII below.

This section briefly describes the chronology of the Black Hawk program and the definition of the RAM parameters of interest and the associated program goals; it then presents the data and subsequent analyses; finally there is a summary of findings.

B. BACKGROUND

1. Black Hawk Program History

Originally known as the Utility Tactical Transport Aircraft System (UTTAS), the Black Hawk was developed as a replacement for the UH-1 series helicopters for air assault, air cavalry, and medical evacuation missions. Approval for full-scale development occurred in June 1971; in July 1971 a request for quotation (RFQ) for development of an advanced technology turboshaft engine was released to industry. In January 1972 a Request for Proposal (RFP) was issued to industry for the airframe development. General Electric was awarded the engine development contract in March 1972 and in August 1972 Boeing Vertol and Sikorsky were awarded competitive airframe development contracts.

Each airframe contractor constructed three flying prototypes (reduced by Congress from six each called for in initial Army plans), one ground test vehicle (GTV) and one static test article (STA). Each company also built a fourth flight article with company funds. Prototype qualification testing commenced in October 1974 and was completed in December 1976. Approximately 2,900 flight test and 2,750 ground vehicle test hours were accumulated by the two contractors during that period. Government Competitive Testing (GCT) (DT II/OT II) began in March 1976 and continued through September 1976. Approximately 550 flight hours on two prototypes from each contractor were logged during the latter period. DSARC III was held in November 1976. Selection of Sikorsky as the airframe contractor was announced along with the initial production contract award in December 1976.

Between February 1977 and February 1979, the three prototypes underwent additional testing, modifications, and system updates during the "Maturity Phase" of the program. In May

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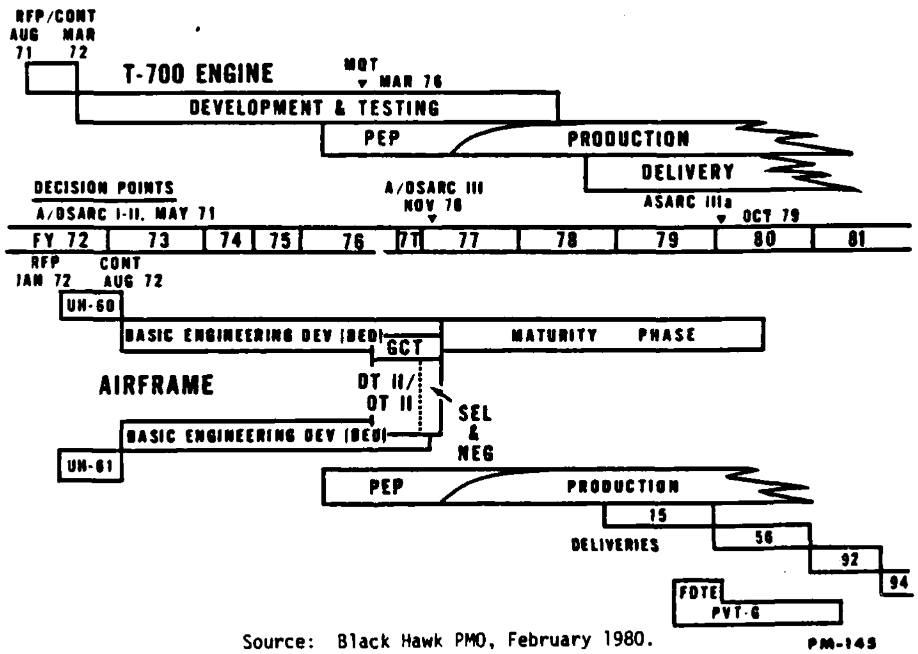
1978, one of the three prototypes crashed, leaving two prototypes to complete that phase of the program.

Production aircraft deliveries began in October 1978. Between June and October of 1979, initial operational testing (the Force Development Test and Experimentation (FDTE) program) was conducted utilizing eight first-year production aircraft in an aviation company at Fort Campbell. The FDTE program was designed to (a) evaluate flight characteristics and measure performance capabilities, (b) assess operational reliability, availability and maintainability of the Black Hawk, and (c) address additional logistics issues. Figure 7 summarizes the program schedule.



Source: Black Hawk PMO, February 1980. PM-145

Figure 7. BLACK HAWK PROGRAM SCHEDULE

2. RAM Definitions, Goals and Measurement Procedures

Black Hawk program goals were established for several RAM measures, as follows:

(1) System Reliability. The parameter receiving greatest management attention throughout the development phase of the program appears to have been System Mean Time Between Failures (MTBF). System MTBF is defined in terms of chargeable (to the contractor), independent failures. A comprehensive data collection system and detailed scoring criteria were established prior to GCT in order to accurately measure this and other RAM characteristics. In order to compute System MTBF, time is defined as flight hours measured from lift-off until touchdown. An item is considered to have failed any time corrective maintenance manhours must be expended on the item regardless of when the failure occurs or is discovered prior to lift-off, during flight or after touchdown. The Black Hawk goal is a System MTBF of 4.0 (or, alternatively, a system failure rate[1] of 0.25). During the FDTE program and in data collection on subsequent production aircraft, the system failure definition was expanded to include false malfunction indications resulting in mission aborts. At the same time, "Operational Failures" were defined to include all system failures plus dependent failures, operator and maintenance errors, foreign object damage, and GSE-induced malfunctions. No contractual goal has been established for the latter parameter, although 2.7 flight hours is cited (Reference [38] as the minimum acceptable value on the basis that at that value the maintenance burden for the UH-60A will equal the maintenance burden for the current utility helicopter.

(2) Mission Reliability. Mission reliability is defined as the probability of completing a one-hour mission without a malfunction which results in a mission abort. Flying time is

[1]In the analyses below, we use System Failure Rate, rather than its reciprocal System MTBF, to present the Black Hawk data.

one hour, but the mission includes events from the start of the flight crew's preflight inspection through engine shutdown following completion of the last mission leg. In addition to unintended landings or discontinuance of the mission, failures/malfunctions detected during preflight inspection that require more than 30 minutes of clock time to correct, or total accumulated delays of more than 30 minutes experienced during the course of the mission as a result of failures/malfunctions are chargeable as mission aborts. The mission reliability goal for the Black Hawk is .987.[1] In order that a Combat Support Aviation company be able to lift the assault elements of one rifle company, a minimum acceptable value of .982 has been established [38].

(3) Flight Safety Reliability. This is defined as the probability of completing a one-hour mission without failure or malfunction which results in a forced landing or mishap. A mishap is defined as an equipment malfunction/failure which is potentially injurious to or results in injury to flight crew, ground crew or passengers, or damage to the aircraft. The flight safety reliability goal is 0.9997. The evaluation of this parameter will not occur until 165,000 flight hours have been logged.

(4) Operational Availability. This is the probability that a randomly requested aircraft is not down for maintenance or spare parts. Maintenance downtime is the sum of all clock

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[1]In the analyses below, mission reliability data are presented using the Mission Abort Rate. Mission Reliability is determined by

$$\text{Mission Reliability} = 1 - e^{-(\text{Abort Rate})\cdot(\text{Mission Time})} .$$

For one-hour mission with mission reliability close to 1, we have

$$\text{Abort Rate} \approx 1 - (\text{Mission Reliability}) .$$

Thus, the mission reliability goal expressed in terms of Abort Rate is 0.013.

time for preventive and corrective (on-aircraft) maintenance. The Operational Availability goal is 0.82, based on a utilization rate of 69 flight hours per month. A minimum acceptable value of 0.80 corresponds to the 0.982 mission reliability for the assault mission discussed above. In order to assess this parameter, "Achieved Availability" is first computed. Dividing maintenance downtime by flight hours actually flown yields the factor hours downtime per flight hour. Multiplying this value by 69 yields a downtime total for a 69 flight hour month. Achieved Availability is computed using this total. Subtracting 0.10 (assuming an 8 percent Not Operationally Ready Supply (NORS) rate and a 2 percent administrative delay rate) from Achieved Availability yields Operational Availability.

(5) Corrective Maintenance Manhours per Flight Hour. Actions at the aviation unit (AVUM) and intermediate unit (AVIM) levels comprise the maintenance manhour component of this parameter. Modification work orders and configuration changes, cannibalization, and unwarranted actions are excluded. In addition, avionics and weapons system actions are excluded. The program goal is 2.8 manhours per flight hour. For assessment after October 1979 to determine if maintainability improvements are required, the Black Hawk project manager's office has accepted 3.8 manhours per flight hour, including preventive as well as total corrective maintenance, as the goal.

Finally, various Mean Time Between Removals (MTBR) goals have been contractually established for the dynamic components of the Black Hawk. These are to be demonstrated after 25,000 flight hours of data have been collected.

C. DATA AND ANALYSES

1. Army Data Systems

Several Army data systems provide data for monitoring RAM characteristics of the Black Hawk aircraft. The most comprehensive of these is the RAM/LOG system. Under RAM/LOG, detailed data on most aspects of reliability, availability and maintainability are recorded by specially trained, dedicated data collectors. An extensive computer software system has been created to process, edit, and provide access to data so collected.

The primary purpose of the RAM/LOG system is to determine compliance with program milestones and contractual requirements. During the Black Hawk program, data were collected throughout the development phase of all three prototypes, and then on early flight hours or selected aircraft from each of the first two production years. In the case of the second year production aircraft, the intensity (and cost) of the data collection effort was reduced by eliminating the monitoring of the detailed maintenance subtasks and thereby reducing the number of dedicated data collectors. "Modified RAM/LOG" is the phrase used to refer to the latter data. Table 9 summarizes the RAM/LOG data collected as of March 1980.

The RAM/LOG data system does not provide cross-sectional fleet data on fielded systems; this information is beginning to be provided by the Unscheduled Maintenance Sample Data Collection (UMSDC) System. Tested in late 1978 and implemented early in 1979, this system is intended to supply less extensive but far more reliable data than were collected under the old TAMMS system. A subset of the aviation field units is selected for data collection. At each selected unit, UMSDC forms (modified TAMMS 2407 forms) are completed by that unit's mechanics, and reviewed for accuracy and consistency by a

Table 9. BLACK HAWK PROGRAM RAM/LOG DATA COLLECTED AS OF MARCH 1980

Jun. 76 - Sept. 76	Complete RAM/LOG data during competitive flyoff at Ft. Campbell. Tail numbers S50, S52 for the Sikorsky UH-60A; V56, V57 for the Boeing Vertol YUH-61A.
Sept. 76 - Feb. 77	No flight hours logged.
Feb. 77 - Feb. 79	Maturity Phase. Total RAM/LOG data on the three UH-60A prototypes - S50, S51, S52--plus early flight hours logged on all production aircraft at Stratford, CT.
May 78	Total loss of S50.
Nov. 78 - Mar. 80	Complete RAM/LOG on RAM Durability (RAM-D) aircraft (one UH-60A) at Ft. Rucker.
Jun. 79 - Oct. 79	FDTE Program, Ft. Campbell. Complete RAM/LOG data (using new data collection formulas) on eight aircraft (some with few flight hours as a consequence of entering FDTE near the end of the program).
Nov. 79 - Mar. 80	Complete modified RAM/LOG data collected at Ft. Campbell on a unit of fifteen production aircraft (different from the FDTE aircraft above).

dedicated UMSDC on-site field monitor before being submitted to the UMSDC data base. As of June 1980 approximately 4300 Black Hawk flight hours had been so collected.

Two other Army data systems should be noted in connection with the Black Hawk program. The Component Report for Intensive Management (CRIM) system tracks the dynamic components of the Black Hawk in support of the reliability warranties in effect. Mean Time Between Removals data, provided by CRIM, are not readily extracted from either the RAM/LOG or UMSDC data systems, nor are they complete since those systems only monitor selected aircraft. Finally, the Operational Readiness (1352) Reporting system provides data on operational availability of fielded aircraft.

2. Data Analysis Methodology and Limitations

a. Data Furnished IDA

The Black Hawk data (Reference [39]) analyzed below come primarily from the RAM/LOG data base. Additional UMSDC data also were furnished IDA, but the latter do not appear compatible with RAM/LOG data for analytical purposes. A discussion of the apparent differences in the two data bases as well as an analysis of the UMSDC data is deferred until Section C.3.e below.

The RAM/LOG data have been aggregated into contiguous 90-day time intervals. The aircraft on which data were collected and the number of flight hours flown are listed in Table 10. Figure 8 relates this RAM/LOG data sample to the total program flight hours. During development, the RAM/LOG data are essentially total, although the approximately 600 flight hours logged on the prototypes before the Army took possession are not included in either curve shown in the Figure.

In some instances, minor contradictions were observed between the IDA data and published sources (References [38], [40], [41], and [42]). For example, larger numbers of system failures for the FDTE aircraft appeared in the computer listings provided IDA than were cited in Reference [38]. In another case, Reference [42] indicated that no flight hours were logged on a prototype for which the computer listing showed 45 flight hours and 40 system failures. (In the former example, the discrepancy, as explained in conversations with TSARCOM personnel, was caused by deferred maintenance items discovered in a post-FDTE inspection of the aircraft involved and entered into the RAM/LOG data base after [38] was generated; in the latter example, the discrepancy was never explained, but the total flight hours and system failure counts derived from either Reference [39] or Reference [42]

Table 10. BLACK HAWK RAM/LOG DATA FURNISHED IDA

Program	Time Period	Aircraft Flown (Tail Nos.)	Flight Hours	Cumulative Flight Hours
Prototypes	5156-5245	S50, S52	2.6	2.6
	5246-5335	S50, S51, S52	98.0	100.6
	5336-6060	-	0.0	100.6
	6061-6150	S50, S52	282.6	383.2
	6151-6240	S50, S52	273.0	656.2
	6241-6330	S50, S52	3.7	659.9
	6331-7054	-	0.0	659.9
	7055-7144	S50, S51, S52	155.9	815.8
	7145-7234	S51, S52	67.9	883.7
	7235-7324	S50, S51, S52	148.4	1032.1
	7325-8049	S50, S51, S52	136.6	1168.7
	8050-8139	S50, S52	75.6	1244.3
	8140-8229	S51	3.2	1247.5
	8230-8319	S51, S52	184.7	1432.2
	8320-9044	S51, S52	86.1	1518.3
	9045-9134	S51	3.0	1521.3
FDTE (First Year Production)	9134-9223	S21, S22, S23, S60	154.4	154.4
	9224-9313	S21-S25, S27, S28, S60	585.6	740.0
RAM-D (First Year Production)	8318-9043	S15	12.6	12.6
	9044-9133	S15	82.2	94.8
	9134-9223	S15	124.4	219.2
	9224-9313	S15	100.4	319.6
Test (First Year Production) Aircraft at Contractor Site	8318-9043	S14, S17	34.5	34.5
	9044-9133	S14, S17, S18	85.8	120.3
Second Year Production Aircraft	9314-0038	S73-S75, S77-S85	372.1	372.1
	0039-0128	S73-S75 S77-S85 S88, S89, S92	987.6	1359.7

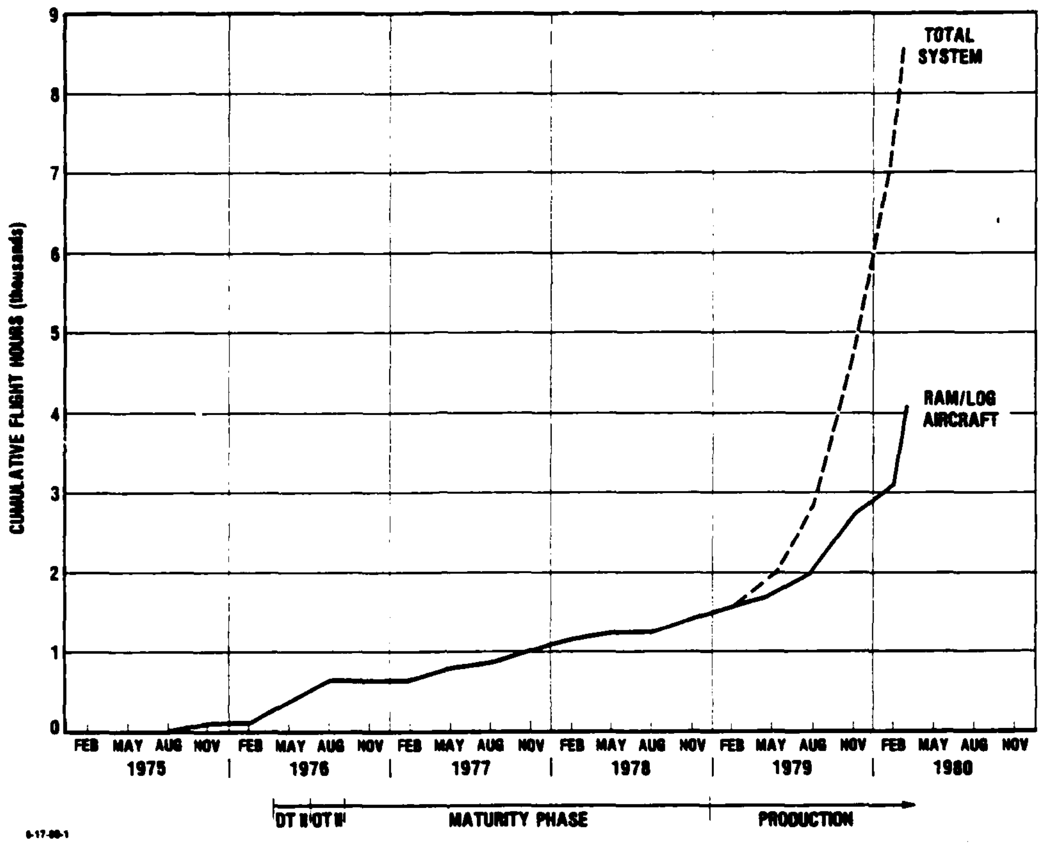

Figure 8. RAM/LOG AND TOTAL BLACK HAWK SYSTEM FLIGHT HOURS AS OF MARCH 1980

are very close.) In the analyses presented below, the computer listings are used as the data source in all cases. Published sources were checked for consistency, and no major discrepancies were discovered.

b. <u>Methodology and Limitations</u>

In aggregating and displaying the RAM/LOG data below, a number of implicit assumptions were made which require explanation.

First, in plotting the data chronologically, the three sources of first-year production aircraft data are aggregated. While different test environments, mission profiles, utilization rates, etc., characterize each of these sources, the resulting curves have the effect of smoothing the differences in RAM parameter values exhibited by the groups of aircraft at the three sites. In some cases, therefore, additional displays highlighting those differences are presented. However, in any reliability growth study, different articles simultaneously undergo different test environments. The justification for plotting the reliability with time (test hours, flight hours) as the sole independent variable lies in the fact that failure mode information from the various tests has been combined. By aggregating reliability data, we are making the same implicit assumption--that failure mode and corrective action information are communicated from site to site; in other words, that the aggregated reliability curve somehow represents the actual status of the total program at each point in time.

Second, in conforming to standard reliability growth literature, data are plotted in terms of cumulative rates. Ideally, in monitoring a development or production program, one would like to know the instantaneous rate for each RAM parameter at each point in time. However, while the cumulative rate is available directly from the data, the instantaneous rate is not. The instantaneous rates are readily derived whenever the cumulative rates plotted vs time are linear on rectangular, semi-log, or log-log (the "Duane" curve) grids.[1] In other cases, one must fit a curve to the cumulative number of failures vs time plot and differentiate it to obtain the

---

[1]Let $c(t)$ = cumulative failure rate
$n(t)$ = cumulative number of failures
$i(t)$ = instantaneous failure rate.

Then

$$c(t) = \frac{n(t)}{t},\ i(t) = \frac{dn(t)}{dt},$$

(continued on next page)

instantaneous rate curve (see, for example, reference [17]). Using the apparent linearity of both cumulative system failure rate and cumulative mission failure rate plots during various phases of the Black Hawk program, we have tentatively also obtained instantaneous rate curves for those parameters. The derivations are discussed in some detail in Section C.3.a. AMSAA (Reference [43]) has taken a slightly different approach to reliability growth tracking of the UH-60A. They develop failure rate point estimates based on small, approximately equal, flight-hour intervals and display those rates directly. Our results are also compared to theirs in Section C.3.a below.

Finally, in extending the RAM/LOG data to the total Black Hawk fleet, we assume that the production aircraft data are representative of the entire fleet and we linearly extrapolate from the sample data to obtain failure rates for the fleet. This procedure is illustrated in the next section, but it is important to note that this may be a serious shortcoming of the analysis. If the failure process were truly exponential, a valid statistical argument could be made for the foregoing procedure. However, since different configurations of each production-year aircraft are usually fielded at the same time (retrofitting changes takes time), and there is some evidence that many helicopter components have increasing failure rates over time (see, for example, [33]), it is likely that the above procedure, based on low flight-hour aircraft, biases the results by indicating faster *fleet* reliability growth than is actually achieved. Analysis of UMSDC cross-sectional fleet data in Section C.3.e below indicates that second-year aircraft

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(contd) and, letting λ = "initial" failure rate and α = "growth rate," we have

Relationship	c(t)	i(t)
linear	$\lambda-\alpha t$	$\lambda-2\alpha t$
log-linear	$\lambda-\alpha \cdot \log t$	$\lambda-\alpha(\log t + \log e)$
log-log	$\lambda t^{-\alpha}$	$(1-\alpha)\lambda t^{-\alpha}$

do, in fact, appear to be more reliable than first-year aircraft, so that the fleet as a whole has lower average reliability than the second-year aircraft alone. On the other hand, if one is interested in progress related to successive years of *new production* aircraft, such growth is accurately (subject to sampling errors) measured.

3. Results

a. System Reliability

The changes in Black Hawk system failure rate over time are shown in Figure 9. Referring to the Figure, the program appears to have experienced a moderate rate of reliability growth through Government Competitive Testing. By the end of GCT, the system failure rate was approximately .33 failures per flight hour (MTBF = 3 hours). During the maturity phase, the failure rate appears to have remained more or less constant at 1 per hour. Finally, very rapid reliability growth is apparent throughout the first two model years of production aircraft. Approximately 10 months and 3,500 flight hours into the production phase, the program returned to the system failure rate level measured during GCT. As of March 1980, the program appears to have equaled or exceeded the 0.25 failures per flight hour goal. The remainder of this subsection is devoted to a more detailed explanation and derivation of Figure 9.

Figure 10 presents a cumulative failure rate plot of the raw RAM/LOG data plotted against the total system flight hours. Table 11 contains the data comprising the Figure. Note in Table 11 that the RAM/LOG system failure count was linearly extrapolated during the post-production phase to yield a failure count for the fleet. Also note that while Figure 10 appears to show a worsening failure rate during the maturity phase (approximately 650 to 1,550 flight hours), Figure 9 indicates that the instantaneous rate actually jumped to a higher, but relatively constant, level.

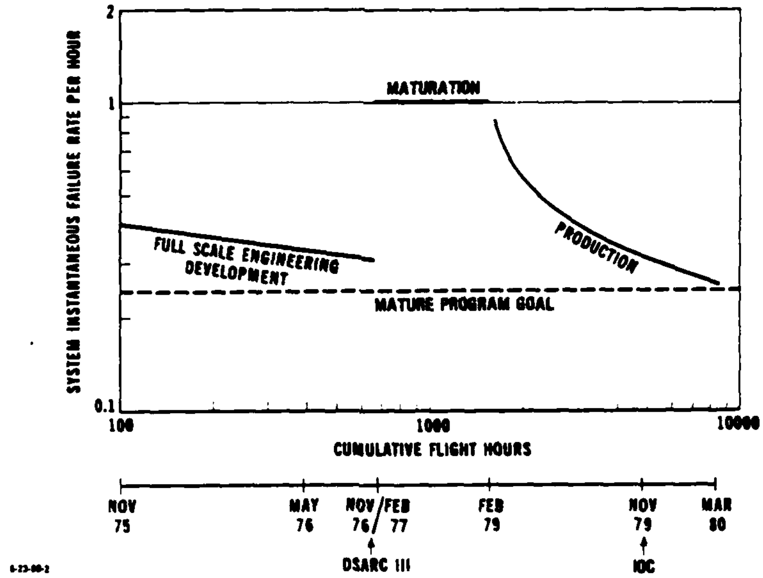


Figure 9. INSTANTANEOUS SYSTEM FAILURE RATE TRENDS OVER TIME FOR THE BLACK HAWK

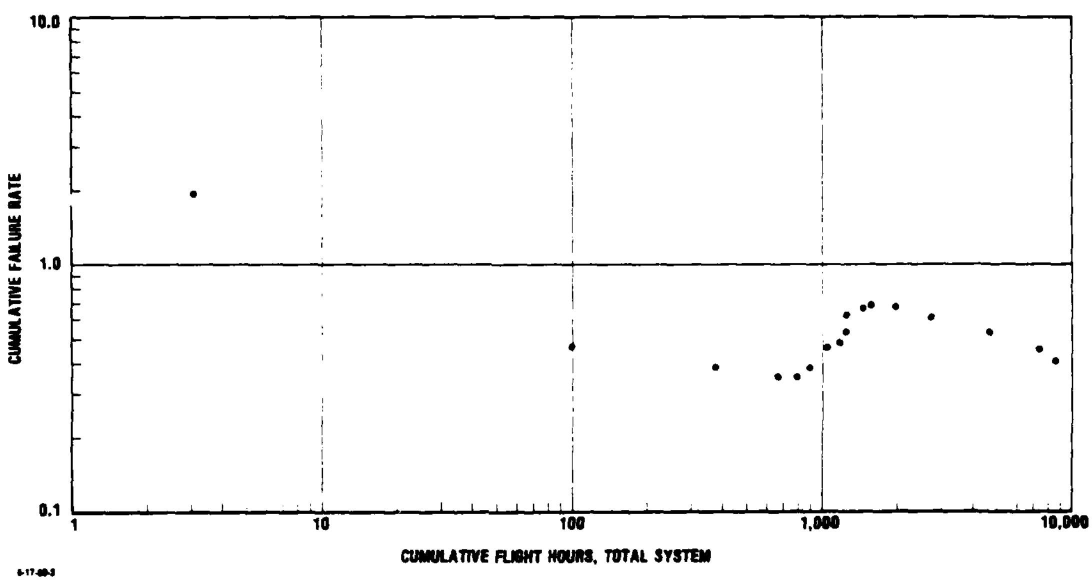


Figure 10. CUMULATIVE SYSTEM FAILURE RATE TRENDS OVER TIME FOR THE BLACK HAWK

Table 11. BLACK HAWK CUMULATIVE FAILURE RATES, TOTAL SYSTEM

	Flight Hours				System Failures				
	RAM/LOG		Total Fleet		RAM/LOG		Total Fleet		
Time Period	No.	Cum.	No.	Cum.	No.	Cum.	No.	Cum.	Cum. Rate
Jun 75 - Aug 75	2.6	3	2.6	3	5	5	5.0	5.0	1.92
Sep 75 - Nov 75	98.0	101	98.0	101	42	47	42.0	47.0	.47
Dec 75 - Feb 76	0.0	101	0.0	101	0	47	0.0	47.0	.47
Mar 76 - May 76	282.6	383	282.6	383	103	150	103.0	150.0	.39
Jun 76 - Aug 76	273.0	656	273.0	656	88	238	88.0	238.0	.36
Sep 76 - Nov 76	3.7	660	3.7	660	1	239	1.0	239.0	.36
Dec 76 - Feb 77	0.0	660	0.0	660	0	239	0.0	239.0	.36
Mar 77 - May 77	155.9	816	155.9	816	56	295	56.0	295.0	.36
Jun 77 - Aug 77	67.9	884	67.9	884	50	345	50.0	345.0	.39
Sep 77 - Nov 77	148.4	1032	148.4	1032	129	474	129.0	474.0	.46
Dec 77 - Feb 78	136.6	1169	136.6	1169	92	566	92.0	566.0	.48
Mar 78 - May 78	75.6	1244	75.6	1244	105	671	105.0	671.0	.54
Jun 78 - Aug 78	3.2	1248	3.2	1248	101	772	101.0	772.0	.62
Sep 78 - Nov 78	184.7	1432	184.7	1432	165	937	165.0	937.0	.65
Dec 78 - Feb 79	133.2	1565	133.2	1565	113	1050	113.0	1050.0	.67
Mar 79 - May 79	171.0	1736	376.0	1941	119	1169	263.0*	1313.0	.68
Jun 79 - Aug 79	278.8	2015	828.0	2769	131	1300	389.1*	1702.0	.61
Sep 79 - Nov 79	686.0	2701	1909.0	4678	289	1589	804.2*	2506.3	.54
Dec 79 - Feb 80	372.1	3073	2611.0	7289	106	1695	743.8*	3250.1	.45
Mar 80	987.6	4061	1302.0	8591	189	1884	249.2*	3499.2	.41

*Extrapolated from RAM/LOG data.

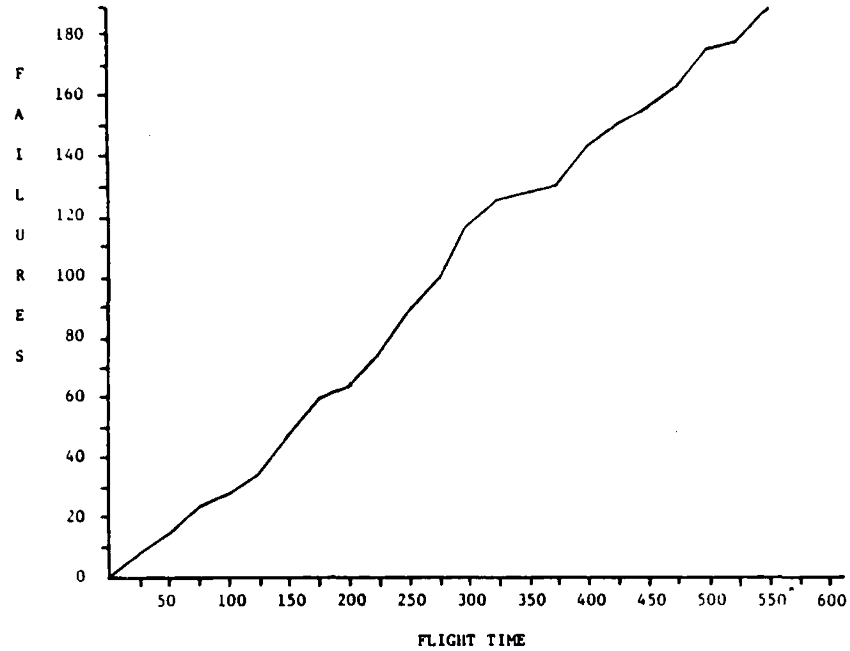
(1) Basic Engineering Development (BED) Phase

The first segment of the instantaneous system failure rate curve in Figure 9 was obtained by first fitting a line[1] to the BED cumulative failure rate values (deleting the 2.6 flight-hour point) and then using the slope (growth rate) of that line to

[1]Here and for the production phase data to follow, least-square regressions were used to fit lines to the data. Under the assumption that the failure counting process giving rise to the data is a Non-Homogeneous Poisson Process (NHPP), maximum likelihood estimators for the slopes and intercepts of such lines have been derived which differ slightly from those yielded by least-square regressions (see, e.g., [14]). However, the corrective action time lags and block changes which characterize helicopter programs tend to invalidate (see, e.g., [34]) the continuous-growth or immediate-improvement-following-failure assumptions underlying the NHPP approach.

generate the instantaneous rate curve as discussed above. The computed growth rate is 0.13. This is not rapid growth according to R&M folklore when compared to the "Duane" standard for a "high intensity" development program of 0.5. Also, while the contractors did incorporate improvements during testing, other reasons have been put forth which may further reduce the apparent growth rate. In particular, [44] states that during testing the failure criteria were changed, with certain maintenance actions being reclassified as preventive maintenance and therefore not chargeable. And in discussions [43] with AMSAA personnel, it was indicated that the test environment during OT II, the second phase of GCT, may have been less severe, with more nap-of-the-earth, low-speed (lower vibration) missions, than during DT II, the first phase of GCT. Furthermore, neglecting approximately the first 110 flight hours of RAM/LOG data which occurred prior to GCT, very little growth is apparent during GCT itself as is evident in Figure 11, taken from Reference [41].

On the other hand, the "off-the-board" system MTBF was quite high (compared to the "10 percent of final MTBF" rule of thumb), and the short duration of the competition may have been a limiting factor in initiating corrective action for observed failures. Also we should reiterate that the data given in Table 11 and plotted in Figure 10 do not include the approximately 600 initial contractor flight hours. If the plotted data were shifted by 600 flight hours (that is, if the instantaneous failure rates shown in Figure 9 were translated by 600 flight hours on the horizontal axis), the computed growth rate would increase somewhat. It is interesting to note, however, that extrapolation of the 0.13 growth rate over the entire program to date yields a system reliability value very close to that currently measured for production aircraft (see Figure 9).



Source: Reference [41]

Figure 11. CUMULATIVE FAILURES VERSUS FLIGHT TIME FOR BLACK HAWK DURING GCT

(2) Maturity Phase

During the maturity phase, a large number of components underwent design changes, both to reduce weight because there was a large weight-reduction incentive award and to enhance producibility. A number of failures were the result of minor parts wearing out due to removals and modifications of such components. For example, a large number of failures of the hydraulic quick disconnects were prematurely induced by coupling and uncoupling them as modifications were made to the hydraulic flight control system. Overstress testing induced further failures, such as many broken lights during testing with the vibration absorbers removed.

The system failure rate jumped significantly between GCT and this program phase. The constant failure rate shown in Figure 9 is derived from Figure 12. Referring to the latter Figure, failures appear to have occurred approximately linearly with flight hours. The big jump at approximately 1,240 flight hours (101 failures in 3.2 flight hours) was a result of a thorough inspection immediately following the crash of prototype S50. Many of the failures uncovered should be credited to earlier flight hours. For that reason the failure rate appears to be approximately constant, even though a Chi-square or other goodness-of-fit test of the raw data in Table 11 would not support that hypothesis. At the very end of the maturity phase, the reliability may have improved as noted by the dotted line in Figure 12. On the whole, however, any improvements resulting from corrective action seem to have been counterbalanced by failures resulting from further design changes or induced by the test environment. AMSAA personnel indicated that most fixes were deferred until production rather than being incorporated into the prototypes.

(3) Production Phase

Aggregated cumulative failure data for production aircraft only versus production fleet flight hours are plotted in Figure 13. As in Figure 10, failure counts for the total fleet are linearly extrapolated from the RAM/LOG data. Table 12 summarizes the data and computations.

For the production aircraft, operational as well as system failures are monitored. The ratio of operational to system failures (approximately 1.3 operational failures per system failure) provides some indication of the relationship between reliability in the field and reliability as measured during development.

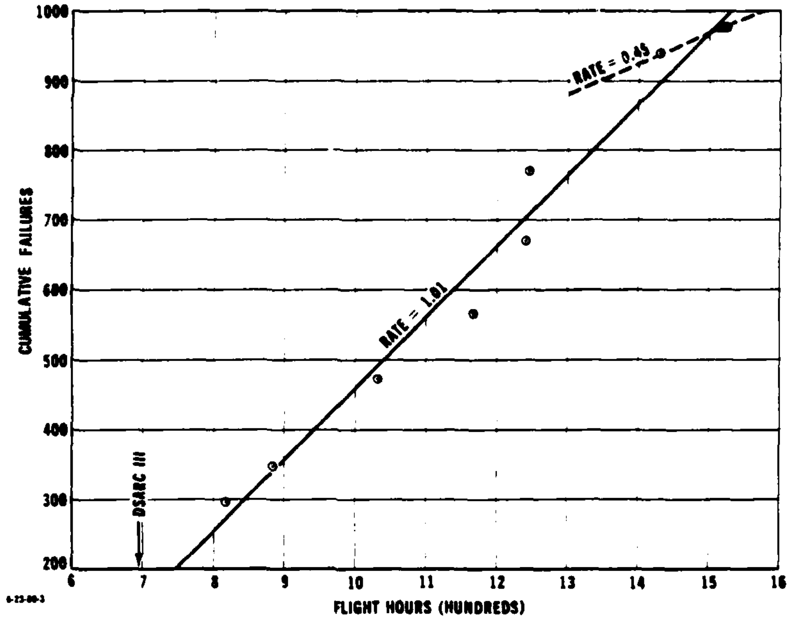


Figure 12. CUMULATIVE FAILURES VERSUS FLIGHT HOURS DURING THE MATURITY PHASE OF THE BLACK HAWK PROGRAM

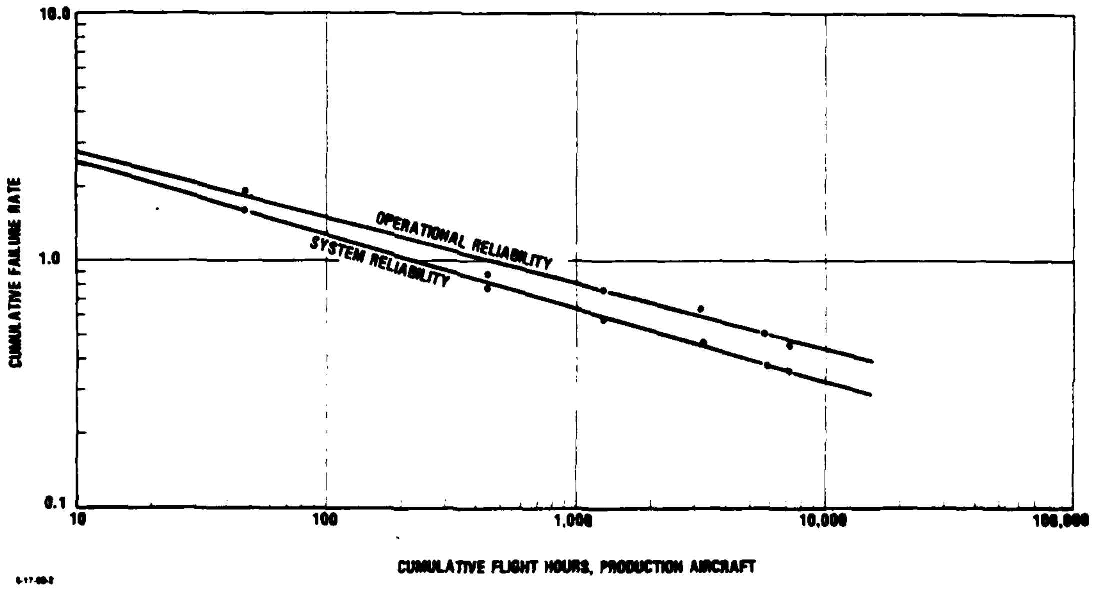


Figure 13. CUMULATIVE FAILURE RATES VERSUS FLIGHT HOURS FOR PRODUCTION BLACK HAWK

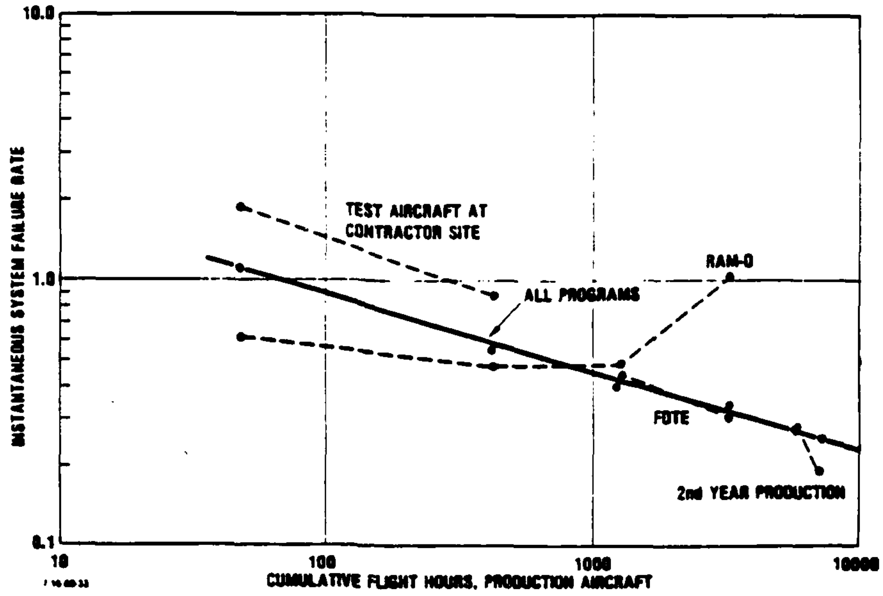
Table 12. BLACK HAWK CUMULATIVE FAILURE RATES, PRODUCTION AIRCRAFT

	Flight Hours				System Failures					Operational Failures				
	RAM/LOG		Total Fleet		RAM/LOG		Total Fleet			RAM/LOG		Total Fleet		
Time Period	No.	Cum.	No.	Cum.	No.	Cum.	No.	Cum.	Cum. Rate	No.	Cum.	No.	Cum.	Cum. Rate
Dec 78 - Feb 79	47	47	47	47	74	74	74.0	74.0	1.57	91	91	91.0	91.0	1.93
Mar 79 - May 79	168	215	373	420	118	192	262.0*	336.0	.80	137	228	304.2	395.2	.94
Jun 79 - Aug 79	279	494	828	1248	131	323	389.1*	725.1	.58	199	427	591.0	986.2	.79
Sep 79 - Nov 79	686	1180	1909	3157	289	612	804.2*	1529.3	.48	410	837	1141.0	2127.2	.67
Dec 79 - Feb 80	372	1552	2611	5768	106	718	743.8*	2273.1	.39	126	963	884.1	3011.3	.52
Mar 80	988	2540	1302	7070	189	907	249.2*	2522.2	.36	235	1198	309.8	3321.1	.47

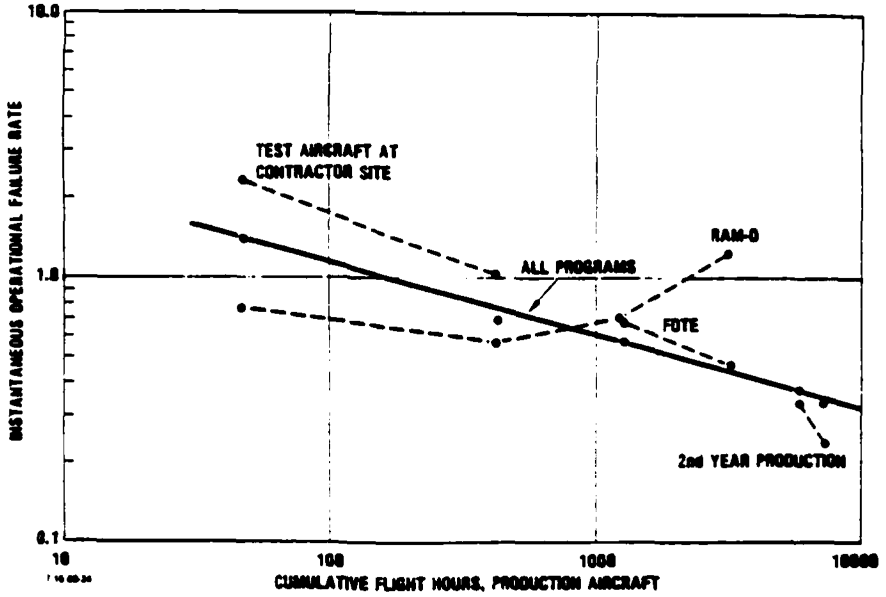
*Extrapolated from RAM/LOG data.

The reliability growth rates implied by Figure 13 (0.29 for system failures, 0.27 for operational failures) are about twice the pre-GCT rate. Because of the linearity, instantaneous rate curves are also linear, lying parallel to and below the cumulative rate curves shown in the Figure. The instantaneous system failure rate curve is shown in Figure 9 (although the linearity disappears when the curve is translated to account for the prototype flight hours).

The instantaneous failure rate curves also appear in Figure 14, which also shows the contributions of the individual groups of production aircraft comprising the data sample. Note that the first few production aircraft, with the exception of the one RAM-D aircraft, were worse than the trend line would indicate, with a system failure rate of more than 1 per hour. Also note that the early flight hours on the second-year production aircraft revealed a system failure rate close to 0.2 per hour (MTBF = 5 hours), whereas the aggregate trend passes through about 0.25 system failures per hour at the same flight-hour level. Finally it should be noted that the high failure rate of the RAM-D aircraft in the June 1979 to September 1979 time frame is a result of environmentally induced failures in desert testing at Yuma Proving Ground, Arizona.



A. System Failures



B. Operational Failures

Figure 14. COMPARISON OF ESTIMATED INSTANTANEOUS FAILURE RATE TRENDS WITH MEASURED VALUES FOR BLACK HAWK PRODUCTION AIRCRAFT GROUPS

(4) Comparison with AMSAA Analysis

The system reliability growth history as measured by AMSAA [43] is shown in Figure 15. Their approach has been to compute failure rates over approximately equal blocks of flight hours. In the Figure, flight hours shown are only those actually sampled, and "SDC" corresponds to what we have referred to as "modified RAM/LOG" in Section C.1 above. Comparing their computed values with ours, the conclusions are quite similar. During the maturity phase, Figure 15 shows a worsening trend, whereas the failure rate appeared constant to us; the final maturity phase and initial production phase values are approximately the same in both analyses. During the production phase, AMSAA shows a higher MTBF at the conclusion of the FDTE program; our analysis shows more rapid reliability growth since then.

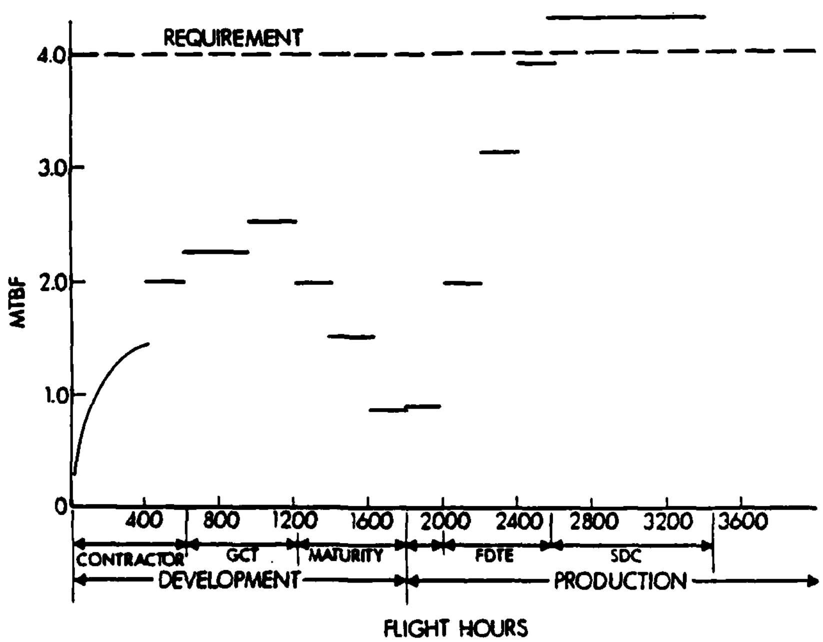


Figure 15. AMSAA MEASUREMENTS OF BLACK HAWK SYSTEM RELIABILITY GROWTH HISTORY

b. Mission Reliability

The Black Hawk instantaneous abort rate history is shown in Figure 16. As was the case with the system failure rate, the abort rate improves through GCT (growth rate = 0.47), jumps to a higher and relatively constant level for the maturity phase, and then again shows improvement during the production phase. Unlike system reliability, however, it does not appear that the program goal (abort rate = 0.013) will be achieved if the present rate of growth continues.

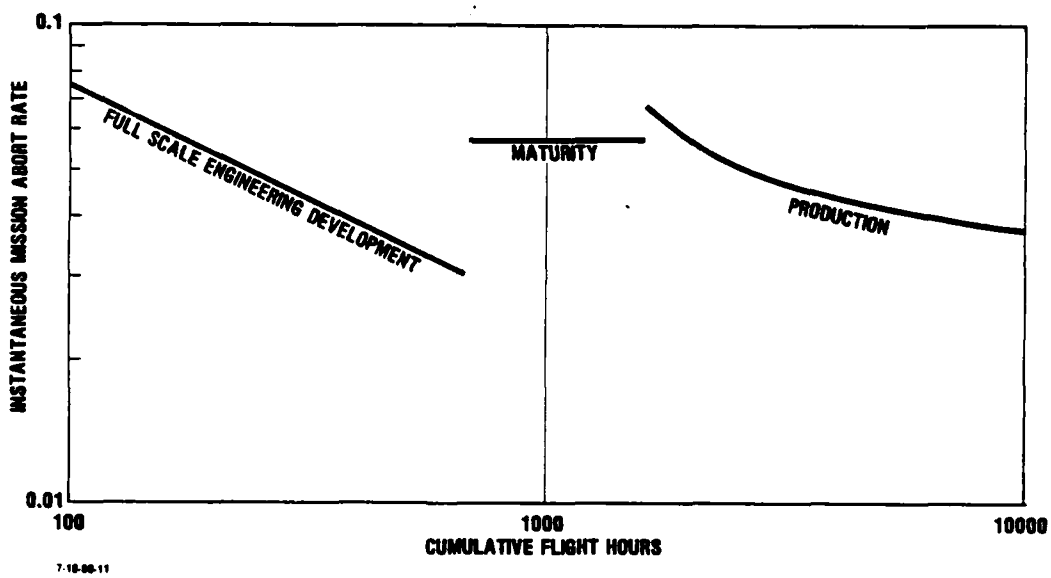


Figure 16. INSTANTANEOUS ABORT RATE TRENDS OVER TIME FOR THE BLACK HAWK

Figure 17 presents the cumulative abort rate plot of the RAM/LOG data superimposed on the fleet flight-hour history. Figure 18 focuses just on the abort rate data versus flight hours for the production aircraft. As with system reliability, the trend is approximately linear (slope = 0.12). The data displayed in Figures 17 and 18 are shown in Table 13.

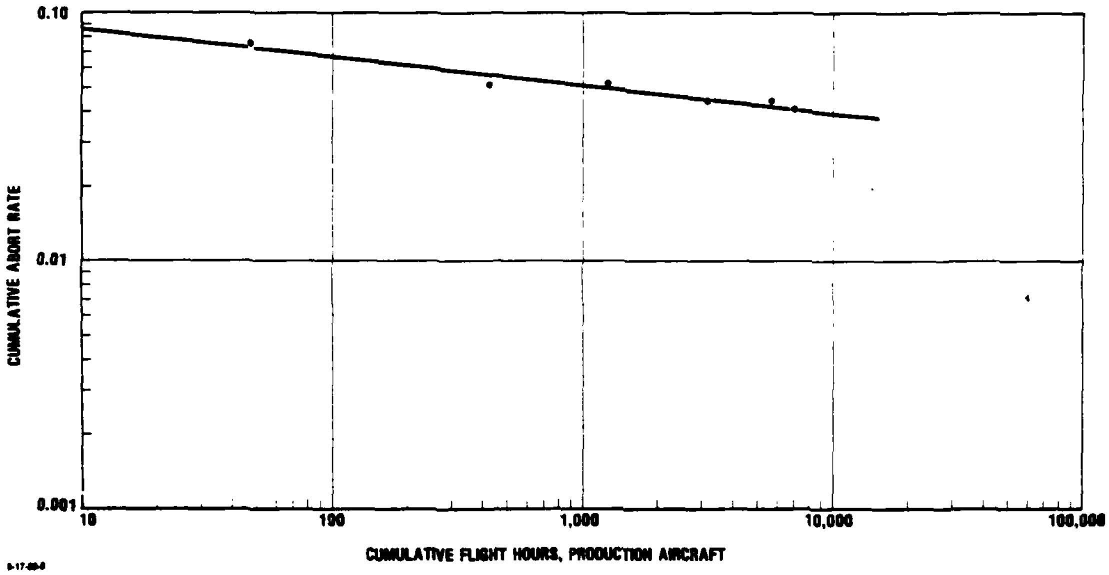


Figure 17. CUMULATIVE ABORT RATE TRENDS OVER TIME FOR THE BLACK HAWK

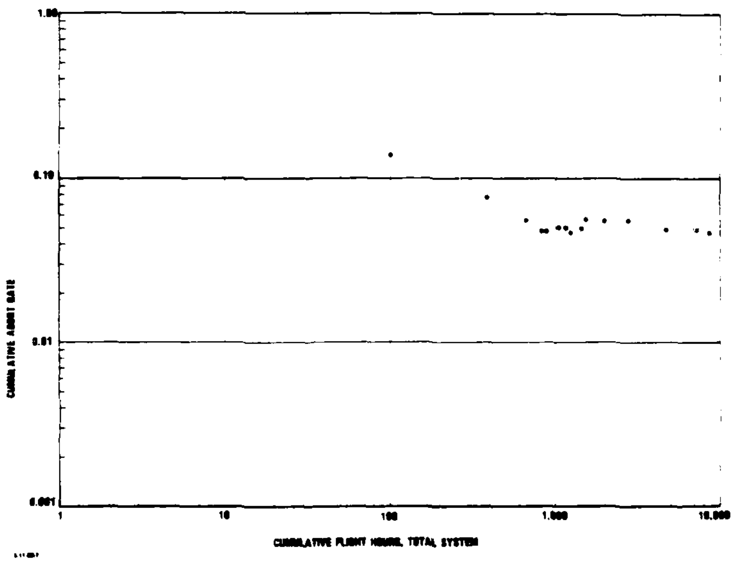


Figure 18. CUMULATIVE ABORT RATE VERSUS FLIGHT HOURS FOR PRODUCTION BLACK HAWK

Table 13. BLACK HAWK CUMULATIVE ABORT RATES, TOTAL SYSTEM AND PRODUCTION AIRCRAFT

Time Period	Flight Hours				Mission Aborts			Cumulative Abort Rate
	RAM/LOG		Total Fleet		RAM/LOG	Total Fleet		
	No.	Cum.	No.	Cum.	No.	No.	Cum.	Total Fleet
Total System								
Jun 75 - Aug 75	3	3	3	3	1	1.0	1.0	.385**
Sep 75 - Nov 75	98	101	98	101	13	13.0	14.0	.139
Dec 75 - Feb 76	0	101	0	101	0	0.0	14.0	.139
Mar 76 - May 76	283	383	283	383	16	16.0	30.0	.078
Jun 76 - Aug 76	273	656	273	656	7	7.0	37.0	.056
Sep 76 - Nov 76	4	660	4	660	0	0.0	37.0	.056
Dec 76 - Feb 77	0	660	0	660	0	0.0	37.0	.056
Mar 77 - May 77	156	816	156	816	3	3.0	40.0	.049
Jun 77 - Aug 77	68	884	68	884	3	3.0	43.0	.049
Sep 77 - Nov 77	148	1032	148	1032	10	10.0	53.0	.051
Dec 77 - Feb 78	137	1169	137	1169	5	5.0	58.0	.050
Mar 78 - May 78	76	1244	76	1244	0	0.0	58.0	.047
Jun 78 - Aug 78	3	1248	3	1248	1	1.0	59.0	.047
Sep 78 - Nov 78	185	1432	185	1432	13	13.0	72.0	.050
Dec 78 - Feb 79	133	1565	133	1565	15	15.0	87.0	.056
Mar 79 - May 79	171	1736	376	1941	9	20.0*	107.0	.055
Jun 79 - Aug 79	279	2015	828	2769	16	47.5*	154.5	.056
Sep 79 - Nov 79	686	2701	1909	4678	29	80.7*	235.2	.050
Dec 79 - Feb 80	372	3073	2611	7289	18	126.3*	361.5	.050
Mar 80	988	4061	1302	8591	36	47.5*	409.0	.048
Production Aircraft Only								
Dec 78 - Feb 79	47	47	47	47	4	4.0	4.0	.085
Mar 79 - May 79	168	215	373	420	9	20.0*	24.0	.057
Jun 79 - Aug 79	279	494	828	1248	16	47.5*	71.5	.057
Sep 79 - Nov 79	686	1180	1909	3157	29	80.7*	152.2	.048
Dec 79 - Feb 80	372	1552	2611	5768	18	126.3*	278.5	.048
Mar 80	988	2540	1302	7070	36	47.5*	326.0	.046

*Extrapolated from RAM/LOG data.

**Flight hour totals are rounded to the nearest integer for presentation in this Table. Cumulative abort rates were computed using cumulative flight hour totals expressed to one decimal place (e.g., cumulative abort rate of .385 is computed based on 2.6 flight hours).

Finally, Figure 19 displays the instantaneous abort rate curve corresponding to the cumulative graph in Figure 18 along with the individual contributions of the programs comprising the data sample.

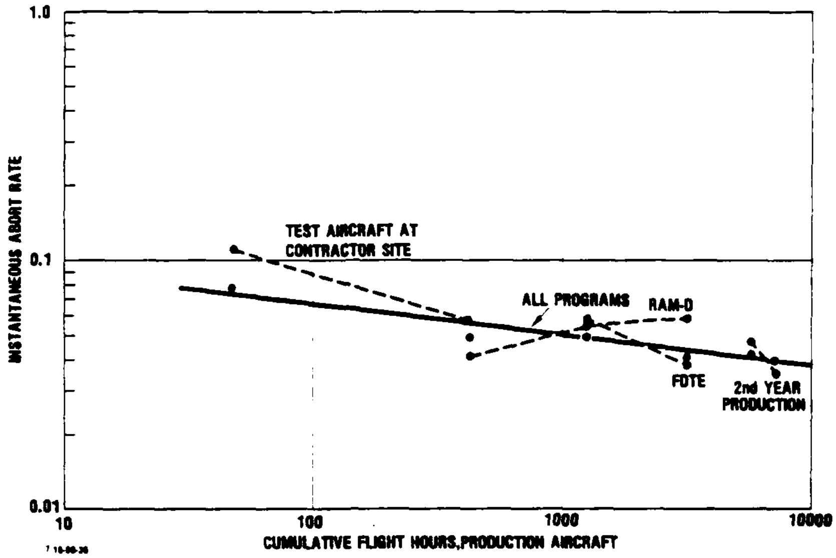


Figure 19. COMPARISON OF ESTIMATED INSTANTANEOUS ABORT RATE TREND WITH MEASURED VALUES FOR BLACK HAWK PRODUCTION AIRCRAFT GROUPS

c. Availability

Cumulative achieved availability vs flight hours is plotted in Figure 20. The same characteristics exhibited by the two reliability parameters above are exhibited by this parameter as well--growth through GCT, deterioration during maturity, and growth again during production. The production aircraft only data are shown in Figure 21. The data plotted in Figures 20 and 21 are given in Table 14. Referring to that Table, of the 965 flight hours and 905.7 maintenance hours recorded during the period June 1979 through November 1979, 740 flight hours and 583.5 maintenance hours were contributed by the FDTE aircraft. The latter values equate to an achieved availability of 0.925. Thus, the threshold of 0.92, as defined in Section 3.2, was crossed at the end of the FDTE program. The 0.92 goal corresponds to approximately 0.85 hours of (on-aircraft) maintenance downtime per flight hour; the FDTE program cumulative

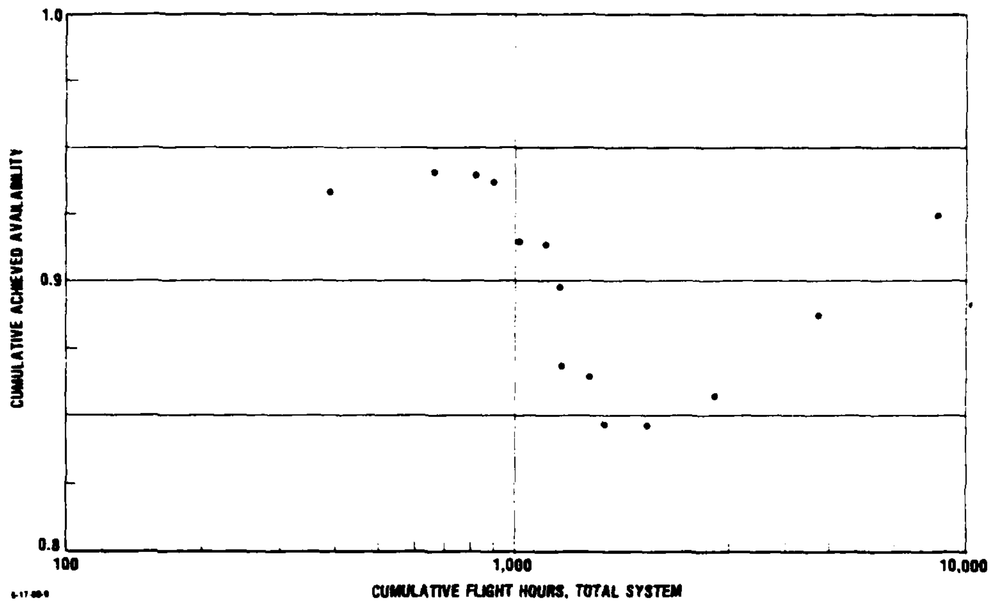


Figure 20. CUMULATIVE ACHIEVED AVAILABILITY TRENDS OVER TIME FOR THE BLACK HAWK

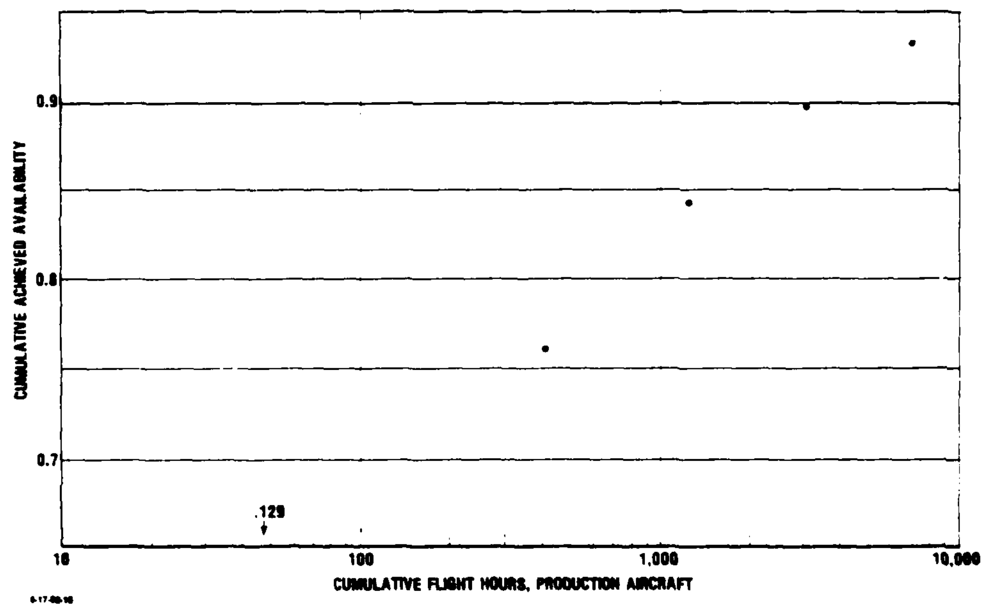


Figure 21. CUMULATIVE ACHIEVED AVAILABILITY VERSUS FLIGHT HOURS FOR PRODUCTION BLACK HAWK

Table 14. BLACK HAWK CUMULATIVE ACHIEVED AVAILABILITIES, TOTAL SYSTEM AND PRODUCTION AIRCRAFT

Time Period	Flight Hours RAM/LOG No.	Flight Hours RAM/LOG Cum.	Flight Hours Total Fleet No.	Flight Hours Total Fleet Cum.	Maintenance Hours RAM/LOG No.	Maintenance Hours Total Fleet No.	Maintenance Hours Total Fleet Cum.	Cumulative Achieved Availability Total Fleet
Total System								
Jun 75 - Aug 75	3	3	3	3	14.7	14.7	14.7	.47**
Sep 75 - Nov 75	98	101	98	101	135.9	135.9	150.6	.86
Dec 75 - Feb 76	0	101	0	101	0.0	0.0	150.6	.86
Mar 76 - May 76	283	383	283	383	119.4	119.4	270.0	.93
Jun 76 - Aug 76	273	656	273	656	146.2	146.2	416.2	.94
Sep 76 - Nov 76	4	660	4	660	2.6	2.6	418.8	.94
Dec 76 - Feb 77	0	660	0	660	0.0	0.0	418.8	.94
Mar 77 - May 77	156	816	156	816	104.9	104.9	523.7	.94
Jun 77 - Aug 77	68	884	68	884	74.2	74.2	597.9	.94
Sep 77 - Nov 77	148	1032	148	1032	331.3	331.3	929.2	.92
Dec 77 - Feb 78	137	1169	137	1169	148.5	148.5	1077.7	.91
Mar 78 - May 78	76	1245	76	1245	280.4	280.4	1358.1	.90
Jun 78 - Aug 78	3	1248	3	1248	367.2	367.2	1725.3	.87
Sep 78 - Nov 78	185	1432	185	1432	315.1	315.1	2040.4	.87
Dec 78 - Feb 79	133	1565	133	1565	517.1	517.1	2557.5	.86
Mar 79 - May 79	171	1736	376	1941	277.5	610.9*	3168.4	.85
Jun 79 - Aug 79	279	2015	828	2769	350.4	1040.6*	4209.0	.86
Sep 79 - Nov 79	686	2701	1909	4678	555.3	1539.4*	5748.5	.88
Dec 79 - Mar 80	1360	4061	3913	8591	462.3	1330.4*	7078.9	.92
Production Aircraft Only								
Dec 78 - Feb 79	47	47	47	47	434.0	434.0	434.0	.13
Mar 79 - May 79	168	215	373	420	273.2	606.6*	1036.6	.77
Jun 79 - Aug 79	279	494	828	1248	350.4	1040.6*	2077.2	.84
Sep 79 - Nov 79	686	1180	1909	3157	555.3	1539.4*	3616.6	.89
Dec 79 - Mar 80	1360	2540	3913	7070	462.3	1330.4*	4947.0	.93

*Extrapolated from RAM/LOG data.

**Flight hour totals are rounded to the nearest integer for presentation in this Table. Cumulative achieved availabilities were computed using cumulative flight hour totals expressed to one decimal place.

average was 0.80 hours per flight hour. The data shown in Table 14 for the period December 1979 through March 1980 were recorded for the group of second-year production aircraft. Those data show a ratio of maintenance downtime to flight hours of 0.34, with a corresponding achieved availability of 0.97. Finally, referring again to Figure 21, the low (0.129) initial value plotted in the Figure comes from the early flight hours of the single RAM-D aircraft; after twelve months of the RAM-D program; however, that aircraft was achieving availability of 0.9 (696.6 maintenance hours for 320 flight hours).

d. Maintainability

(1) Unscheduled Maintenance Events

Unscheduled maintenance events are all those events resulting in corrective maintenance manhours, as defined in Section B.2 above. The cumulative rates of such events are plotted versus flight hours in Figure 22. The production aircraft data only are shown in Figure 23. The data used to generate those figures are given in Table 15. As is the case with the other RAM parameters, growth through GCT, deterioration during maturity, and growth again during production characterize this parameter. However, in comparing the improvement of the unscheduled maintenance action rate with that of the system failure rate through GCT and again during the production phase, it is interesting to note that the former parameter had about twice the growth rate through GCT as the latter parameter (0.24 versus 0.13), but a slower growth rate (0.25 versus 0.29) during production. The ratio of cumulative unscheduled maintenance actions to cumulative system failures decreased during GCT from approximately 3.9 at the beginning to 3.2 at the end. During production, the ratio has increased from approximately 2.0 to 2.5 at the 8,500 flight-hour point.

(2) Maintenance Manhours

The cumulative unscheduled maintenance manhours per flight hour data versus flight hours are shown in Figure 24. The same characteristics exhibited by the previous RAM parameters are evident in this Figure as well, although the improvement in this parameter during the production phase appears quite dramatic. The RAM/LOG data for production aircraft only are displayed in Figure 25. The data comprising Figures 24 and 25 are given in Table 16.

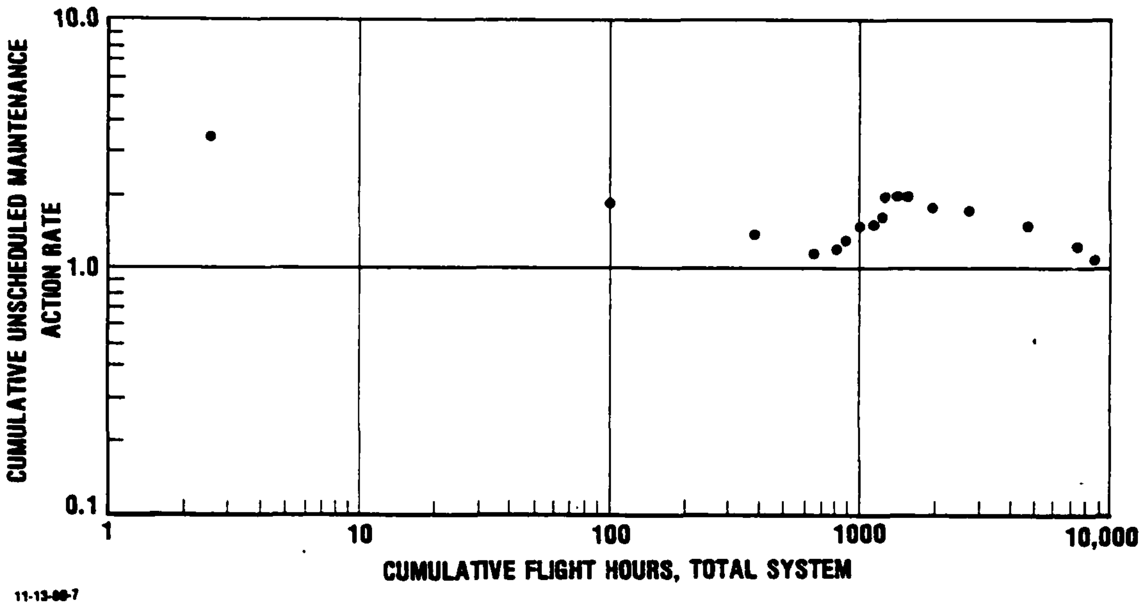


Figure 22. CUMULATIVE UNSCHEDULED MAINTENANCE ACTIONS PER FLIGHT HOUR VERSUS FLIGHT HOURS FOR THE BLACK HAWK PROGRAM

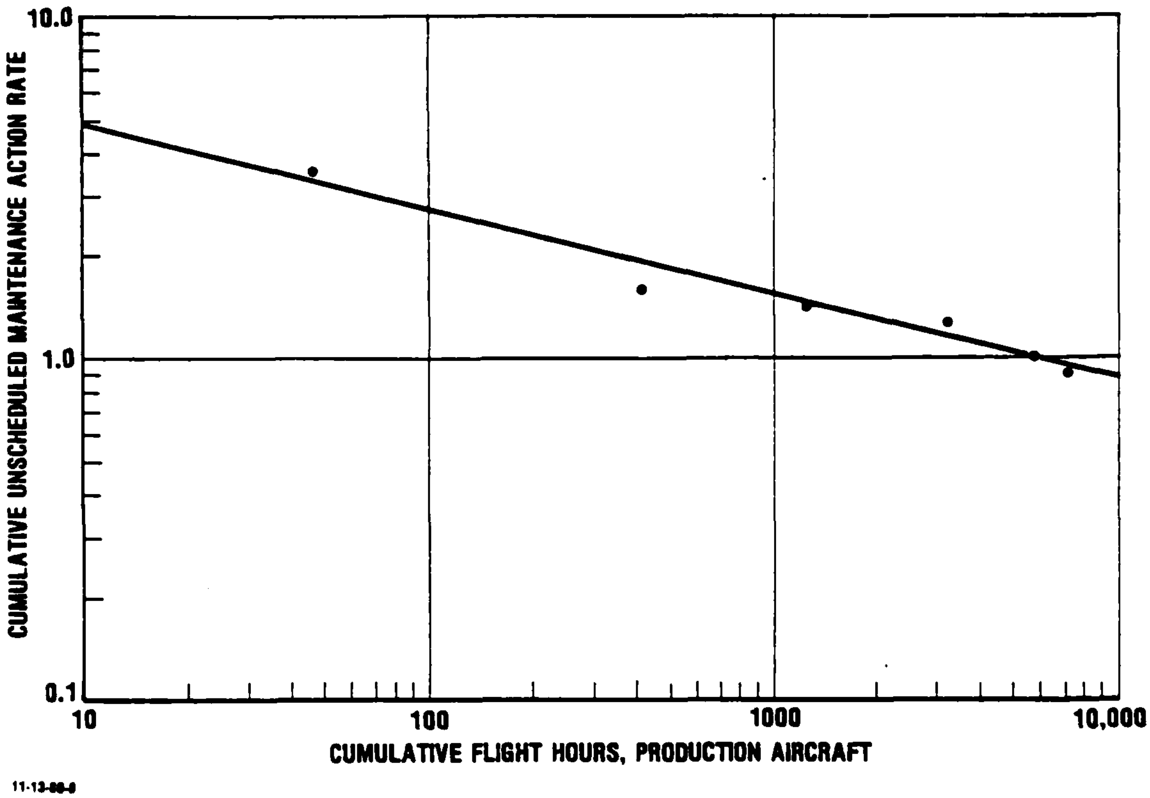


Figure 23. CUMULATIVE UNSCHEDULED MAINTENANCE ACTIONS PER FLIGHT HOUR FOR PRODUCTION BLACK HAWK

Table 15. BLACK HAWK CUMULATIVE UNSCHEDULED MAINTENANCE ACTION RATES, TOTAL SYSTEM AND PRODUCTION AIRCRAFT

Time Period	Flight Hours				Unscheduled Maintenance Actions			Cumulative Unscheduled Maintenance Action Rate
	RAM/LOG		Total Fleet		RAM/LOG	Total Fleet		
	No.	Cum.	No.	Cum.	No.	No.	Cum.	Total Fleet
Total System								
Jun 75 - Aug 75	3	3	3	3	9	9	9	3.46**
Sep 75 - Nov 75	98	101	98	101	173	173	182	1.81
Dec 75 - Feb 76	0	101	0	101	0	0	182	1.81
Mar 76 - May 76	283	383	283	383	339	339	521	1.36
Jun 76 - Aug 76	273	656	273	656	231	231	752	1.15
Sep 76 - Nov 76	4	660	4	660	0	0	752	1.14
Dec 76 - Feb 77	0	660	0	660	0	0	752	1.14
Mar 77 - May 77	156	816	156	816	214	214	966	1.18
Jun 77 - Aug 77	68	884	68	884	150	150	1116	1.26
Sep 77 - Nov 77	148	1032	148	1032	374	374	1490	1.44
Dec 77 - Feb 78	137	1169	137	1169	240	240	1730	1.48
Mar 78 - May 78	76	1244	76	1244	273	273	2003	1.61
Jun 78 - Aug 78	3	1248	3	1248	358	358	2361	1.89
Sep 78 - Nov 78	185	1432	185	1432	356	356	2717	1.90
Dec 78 - Feb 79	133	1565	133	1565	235	235	2952	1.89
Mar 79 - May 79	171	1736	376	1941	234	513.4*	3465.4	1.79
Jun 79 - Aug 79	279	2015	828	2769	413	1226.6*	4692.0	1.69
Sep 79 - Nov 79	686	2701	1909	4678	747	2078.8*	6770.7	1.45
Dec 79 - Feb 80	372	3073	2611	7289	249	1747.2*	8518.0	1.17
Mar 80	988	4061	1302	8591	406	535.3*	9053.2	1.05
Production Aircraft Only								
Dec 78 - Feb 79	47	47	47	47	164	164	164	3.49
Mar 79 - May 79	168	215	373	420	229	508.4*	672.4	1.60
Jun 79 - Aug 79	279	494	828	1248	413	1226.6*	1899.0	1.52
Sep 79 - Nov 79	686	1180	1909	3157	747	2078.8*	3977.8	1.26
Dec 79 - Feb 80	372	1552	2611	5768	249	1747.2*	5725.0	0.99
Mar 80	988	2540	1302	7070	406	535.3*	6260.3	0.89

*Extrapolated from RAM/LOG data.

**Flight hour totals are rounded to the nearest integer for presentation in this Table. Cumulative unscheduled maintenance action rates were computed using cumulative flight hour totals expressed to one decimal place.

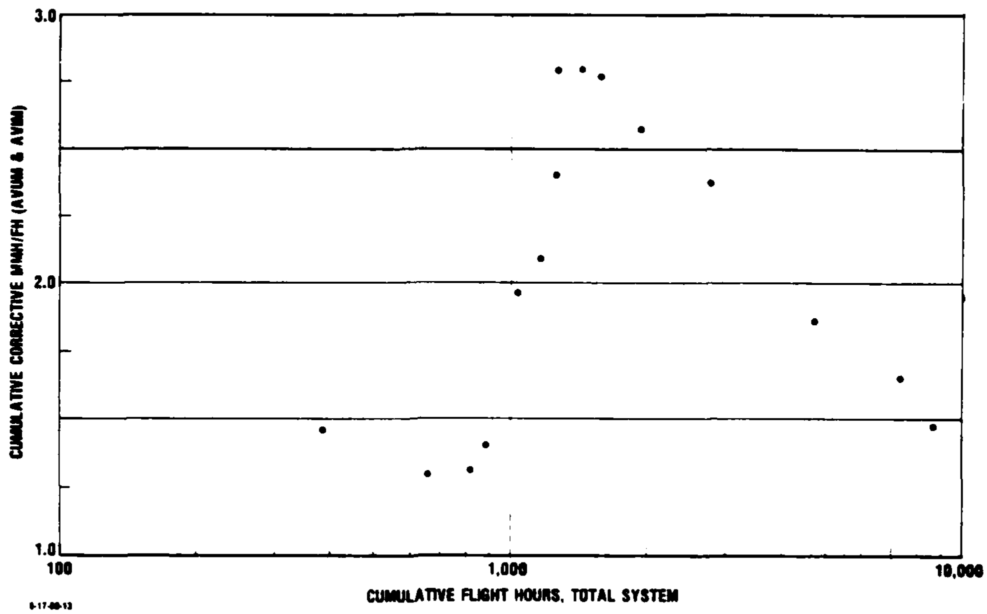


Figure 24. CUMULATIVE CORRECTIVE MAINTENANCE MANHOURS PER FLIGHT HOUR VERSUS FLIGHT HOURS FOR THE BLACK HAWK PROGRAM

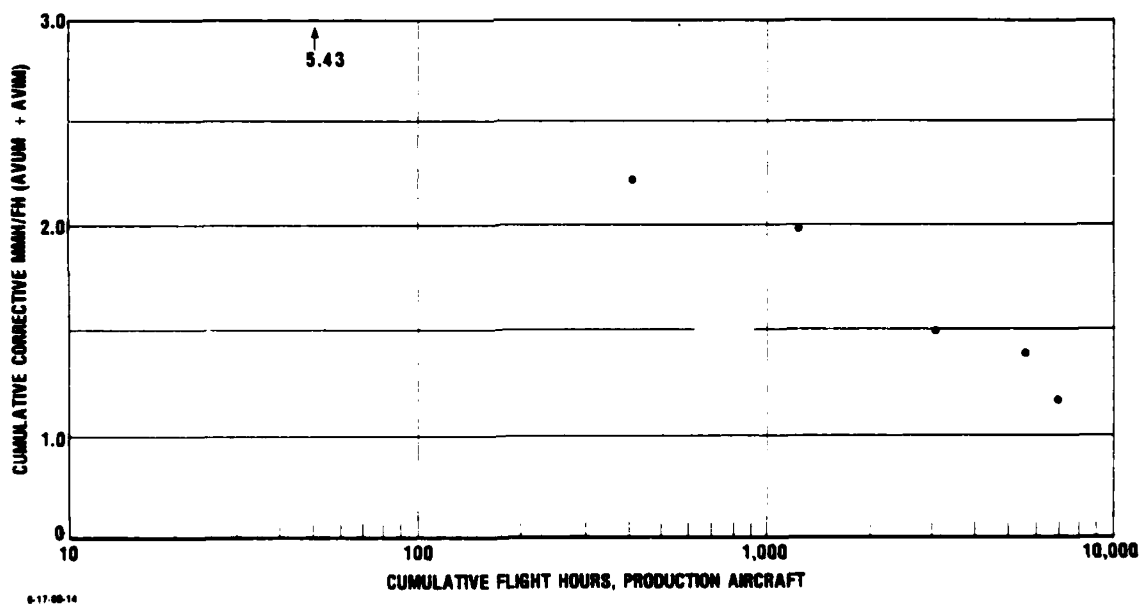


Figure 25. CUMULATIVE CORRECTIVE MAINTENANCE MANHOURS PER FLIGHT HOUR VERSUS FLIGHT HOURS FOR PRODUCTION BLACK HAWK

Table 16. CUMULATIVE CORRECTIVE MAINTENANCE MANHOURS PER FLIGHT HOUR, TOTAL SYSTEM AND PRODUCTION AIRCRAFT

Time Period	Flight Hours				Corrective Maintenance Manhours (AVUM + AVIM)			Cumulative MMH/FH
	RAM/LOG		Total Fleet		RAM/LOG	Total Fleet		
	No.	Cum.	No.	Cum.	No.	No.	Cum.	Total Fleet
Total System								
Jun 75 - Aug 75	3	3	3	3	9.8	9.8	9.8	3.78**
Sep 75 - Nov 75	98	101	98	101	215.6	215.6	225.4	2.24
Dec 75 - Feb 76	0	101	0	101	0.0	0.0	225.4	2.24
Mar 76 - May 76	283	383	283	383	330.8	330.8	556.2	1.45
Jun 76 - Aug 76	273	656	273	656	290.7	290.7	846.9	1.29
Sep 76 - Nov 76	4	660	4	660	11.8	11.8	858.7	1.30
Dec 76 - Feb 77	0	660	0	660	0.0	0.0	858.7	1.30
Mar 77 - May 77	156	816	156	816	214.9	214.9	1073.6	1.32
Jun 77 - Aug 77	68	884	68	884	165.7	165.7	1239.3	1.40
Sep 77 - Nov 77	148	1032	148	1032	795.9	795.9	2035.2	1.97
Dec 77 - Feb 78	137	1169	137	1169	404.2	404.2	2439.4	2.09
Mar 78 - May 78	76	1244	76	1244	547.1	547.1	2986.5	2.40
Jun 78 - Aug 78	3	1248	3	1248	496.4	496.4	3482.9	2.79
Sep 78 - Nov 78	185	1432	185	1432	534.3	534.3	4017.2	2.80
Dec 78 - Feb 79	133	1565	133	1565	301.5	301.5	4318.7	2.76
Mar 79 - May 79	171	1736	376	1941	308.8	681.5*	5000.2	2.58
Jun 79 - Aug 79	279	2015	828	2769	516.2	1533.1*	6533.2	2.36
Sep 79 - Nov 79	686	2701	1909	4678	813.9	2264.1*	8798.1	1.88
Dec 79 - Feb 80	372	3073	2611	7289	457.0	3206.7*	12004.9	1.65
Mar 80	988	4061	1302	8591	597.2	787.3*	12792.2	1.49
Production Aircraft Only								
Dec 78 - Feb 79	47	47	47	47	255.7	255.7	255.7	5.43
Mar 79 - May 79	168	215	37[illegible]	420	305.4	678.1*	933.8	2.22
Jun 79 - Aug 79	279	494	828	1248	516.2	1533.1*	2466.8	1.98
Sep 79 - Nov 79	686	1180	1909	3157	813.9	2264.1*	4731.7	1.50
Dec 79 - Feb 80	372	1552	2611	5768	457.0	3206.7*	7938.5	1.38
Mar 80	988	2540	1302	7070	597.2	787.3*	8725.8	1.23

*Extrapolated from RAM/LOG data.

**Flight hour totals are rounded to the nearest integer for presentation in this Table. Cumulative MMH/FH values were computed using cumulative flight hour totals expressed to one decimal place.

In order to compare the improvement in system failure rate during production (Figure 13) and the improvement in unscheduled maintenance events during production (Figure 23) with the MMH/FH improvement shown in Figure 25, let t denote flight hours, and define

$M(t) \equiv$ cumulative maintenance manhours

$N_1(t) \equiv$ cumulative failures

$N_2(t) \equiv$ cumulative unscheduled maintenance events.

From Figures 13 and 23,

$$\frac{N_i(t)}{t} \approx \lambda_i t^{-\alpha_i}, \qquad i=1,2 ,$$

and from Figure 25,

$$\frac{M(t)}{t} \approx a - b \cdot \log t ,$$

where (λ_1,α_1), (λ_2,α_2) and (a,b) are estimated by (4.7, 0.29), (8.6, 0.25), and (4.4, 0.82) respectively. Finally, let

$Y_c(t) \equiv$ cumulative maintenance manhours per failure

$Y_{in}(t) \equiv$ instantaneous maintenance manhours per failure,

so that

$$Y_c(t) = \frac{M(t)}{N_1(t)} ,$$

and

$$Y_{in}(t) = \frac{\frac{dM(t)}{dt}}{\frac{dN_1(t)}{dt}}$$

$$\approx \frac{a - b \cdot (\log t + \log e)}{(1-\alpha_1)\lambda_1 t^{-\alpha_1}} ,$$

with analogous formulas holding for maintenance manhours per unscheduled maintenance event. Using the parameter estimates given above, $Y_c(t)$ and $Y_{in}(t)$ are plotted over the sample flight-hour range in Figure 26. From the Figure we see that maintenance manhours expended per failure has remained relatively constant throughout the first 7,000 production flight hours, rising slightly for the first 3,000 and declining slightly for the last 4,000. The same behavior but with even less variability can be observed for maintenance manhours per maintenance event. In either case, one can conclude that if learning resulting in more efficient maintenance practices has occurred, it has been counterbalanced by failures requiring more maintenance manhours to fix. The findings of Figure 26 are supported by the mean time to repair production data, as shown in Figure 27. Over the sample period, the MTTR has remained approximately constant.

On the other hand, the MMH/FH values have remained well below the program goal of 2.8. During GCT, reference [44] offered some possible reasons for the low demonstrated value (1.56 corrective MMH/FH), including deferred maintenance of some items because of pending design changes, contractor-performed maintenance which was not counted, and low numbers of flight hours on the prototypes at the time. Whether any of those reasons remain valid, particularly low flight hours on individual production aircraft and deferred maintenance time, cannot be determined until more data have been collected. The first periodic inspection on each Black Hawk aircraft does not occur until 500 flight hours have been logged.

e. Analysis of UMSDC Data

The UMSDC data system is designed to collect, process, and analyze logistics management, equipment performance, and maintenance performance data on specified percentages of

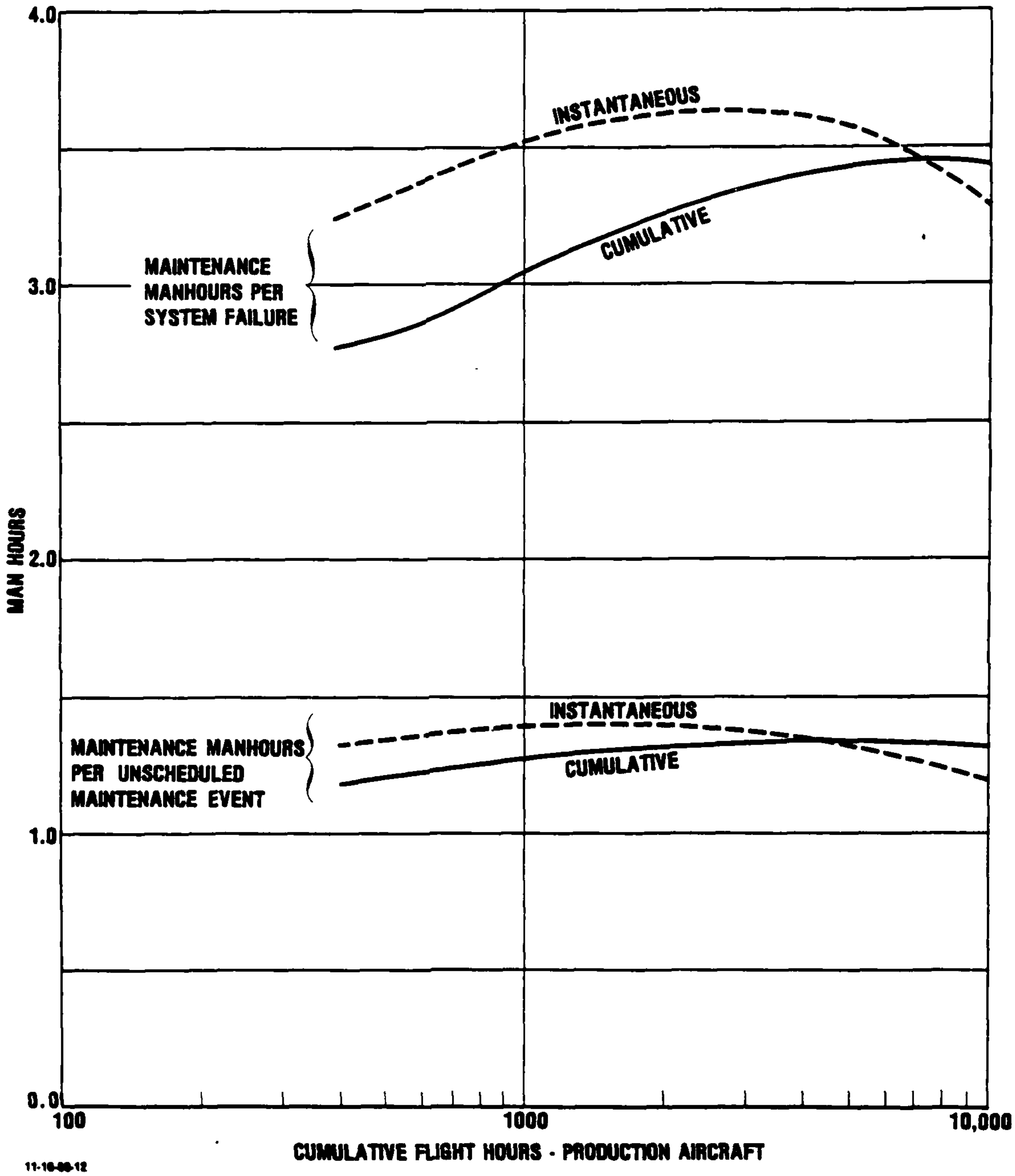


Figure 26. MAINTENANCE MANHOURS PER FAILURE AND MAINTENANCE MANHOURS PER UNSCHEDULED MAINTENANCE EVENT TRENDS DERIVED FROM PRODUCTION BLACK HAWK RAM/LOG DATA

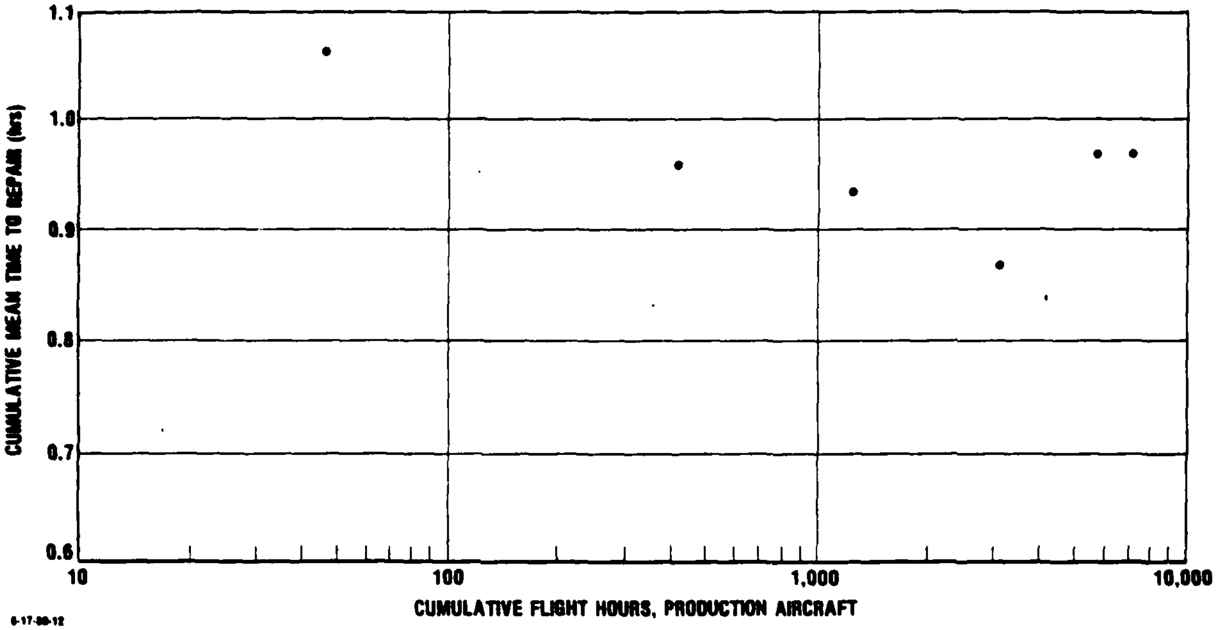


Figure 27. CUMULATIVE MEAN TIME TO REPAIR VERSUS FLIGHT HOURS FOR PRODUCTION BLACK HAWK

fielded fleet populations. A large fraction of the Black Hawk fleet is currently being monitored under this data system. The data furnished IDA are summarized in Table 17.

Note that while unscheduled maintenance events, mission aborts, and unscheduled maintenance manhours are tracked by the UMSDC system, the primary parameter receiving management attention during the development phase--system reliability--is not (or if it is, current system software is not designed to extract it from the data base). Furthermore, a comparison of UMSDC data with RAM/LOG data suggests that at least the first two parameters noted above are not measured under the two systems in a consistent manner. In particular, the eight FDTE aircraft (the first eight aircraft listed in Table 17) were monitored for consecutive and approximately equal flight-hour time periods by the two systems. The data appear in Table 18 below.

Table 17. BLACK HAWK UMSDC DATA AS OF JUNE 1980

Aircraft	Flight Hours	Unscheduled Maintenance Events	Mission Aborts	Unscheduled Maintenance Manhours
First-Year Aircraft				
7722721	191	92	2	243.7
7722722	203	106	5	362.2
7722723	237	127	2	212.1
7722724	90	56	3	118.4
7722725	160	101	2	209.1
7722727	162	79	3	192.9
7722728	260	108	2	208.2
Second-Year Aircraft				
7822960	254	95	4	210.4
7822961	366	96	1	126.5
7822962	156	75	4	154.8
7822966	256	136	6	373.5
7822967	154	102	2	295.4
7822968	190	91	1	183.6
7822969	220	123	1	191.4
7822970	177	98	3	206.7
7822984	62	10	0	11.8
7822986	104	36	0	91.6
7822989	51	0	0	0.0
7822990	125	45	2	143.1
7822991	96	69	2	165.2
7822993	126	53	1	131.0
7822995	130	44	0	66.6
7822996	64	41	1	102.6
7822997	14	18	0	24.2
7822998	161	33	0	61.5
7822999	66	41	5	83.9
7823000	89	41	1	103.1
7823001	82	26	1	39.1
7823002	60	18	0	50.4
7823003	22	2	0	3.3

Table 18. COMPARISON OF RAM/LOG AND UMSDC DATA COLLECTED ON FDTE AIRCRAFT

Time Period	Data System	Flight Hours	System Failures	Unscheduled Maintenance Events	Mission Aborts	Maintenance Manhours
May 79 - Sep 79	RAM/LOG	740	255	736	32	833.7
Oct 79 - Mar 80	UMSDC	742	--	404	7	911.3
Apr 80 - Jun 80	UMSDC	815	--	360	16	845.7

The apparent discrepancy in unscheduled maintenance event reporting evident in Table 18 stems from two possible causes. First, mechanics themselves are responsible for reporting maintenance events under UMSDC data collection, and it is likely that many minor events (e.g., tightening a loose screw) go unreported due to the paperwork involved. Second, other less critical repairs may be deferred until the phased inspections, the first of which does not occur until 500 flight hours. The discrepancy in mission abort reporting was explained by TSARCOM personnel as a definitional problem. Under RAM/LOG, a large number of mission aborts were precautionary landings caused by chip detector lights. Under UMSDC, if such a landing is made, the chip detectors are often removed, checked, cleaned off, and replaced, and the mission resumed with no abort charged if the resulting delay is less than 30 minutes. (As of this writing, the UMSDC data are being changed to label such events aborts as under RAM/LOG.) Finally, although not apparent in Table 18, TSARCOM personnel felt that more maintenance manhours would be reported for comparable tasks under UMSDC than under RAM/LOG because hands-on time would not be as carefully monitored under the former system. (For example, if a mechanic stops to smoke a cigarette while performing a maintenance action, RAM/LOG data collectors will stop recording maintenance time, but the mechanic, in reporting under UMSDC, is likely to include such short breaks in his labor total for the maintenance event.)

For the above reasons, we used the UMSDC data only to compare the first-year aircraft with second-year aircraft. The data of Table 17 are summarized in aggregated form in Table 19.

Table 19. COMPARISON OF FIRST-YEAR AND SECOND-YEAR BLACK HAWK USING UMSDC DATA

Aircraft	Flight Hours	Unscheduled Maintenance Events per Flight Hour	Aborts per Flight Hour	Unscheduled Maintenance Manhours per Flight Hour
First-Year	1303	0.513	0.0146	1.19
Second-Year	3026	0.427	0.0116	0.93
Total	4329	0.453	0.0125	1.01

The difference between unscheduled maintenance event rates and first- and second-year aircraft has rather high statistical significance, while the difference in abort rates is of slightly lower significance.[1] As in Section C.d.2 above, the improvement in MMH/FH due to the improvement in unscheduled maintenance events per flight hour can be determined by computing the quantity maintenance manhours per unscheduled maintenance event. For the first-year and second-year aircraft the values of the latter quantity are

[1]Based on a Wilcoxon Rank Sum Test [45, p. 68] of the ordered system maintenance event rates as computed from Table 17. If all the aircraft in Table 17 are used, the hypothesis of equal first-year and second-year unscheduled maintenance action rates is rejected at the 0.06 level. (That is, if the computed value of the Wilcoxon Rank Sum Test statistic is used as the rejection level for the test and if the equality hypothesis is, in fact, true, then the probability of a false conclusion is 0.06.) Using the same procedure applied to abort rates, the rejection level for the hypothesis of equal abort rates is 0.11.

2.31 and 2.18, respectively. Under reasonable assumptions, the difference in these two values is of rather low statistical significance.[1]

Thus, the UMSDC data confirm the finding of Figure 26 that maintainability, as measured by maintenance manhours per unscheduled maintenance event, seems not to have improved as second-year aircraft entered the fleet.

D. SUMMARY

Through analysis of the RAM/LOG and the UMSDC data, a general pattern of reliability, availability, and maintainability growth can be observed. RAM appears to gradually improve through GCT (approximately 700 contractor plus 650 Army flight hours), remain constant throughout the Maturity Phase of the program (approximately 1,550 cumulative Army flight hours), although at a substantially reduced level from that measured during GCT, and then appears to rapidly improve during the Production Phase. The lack of growth (or negative growth according to [43] during the Maturity Phase apparently did not imply lack of growth, or even slow growth, during the Production Phase. Regarding the specific RAM parameters:

(1) <u>The System Reliability</u> goal of 4.0 hours MTBF seems to have been achieved with the second-year production aircraft. However, the second-year production aircraft appear to be more reliable than the first-year production aircraft, so that the Black Hawk fleet as a whole will have lower reliability than Figure 9 would indicate.

---

[1]Assuming that the number of manhours recorded during each maintenance event for each aircraft is normally distributed with mean depending upon the production year of that aircraft, and variance common to all such recorded events, standard theory of linear models [46] can be used to derive a t-test for equality of the first-year and second-year means. That hypothesis would be rejected at only the 0.30 level.

(2) The growth rate must improve if the Mission Reliability goal is to be met. Either the system reliability and mission reliability goals are inconsistent, or the managerial emphasis placed on achieving the system reliability goal caused the rate of growth in mission reliability (e.g., through prioritization of corrective actions) to be reduced.

(3) The Operational Availability goal as defined for the program appears to have been met by the production aircraft. However, regarding the definition itself, linearly extrapolating from peacetime data used in this analysis based on utilization rates of 20-25 flying hours per month to wartime utilization rates of 69 flying hours per month would seem to be an overly simplistic method for defining operational capability, and an area worthy of more detailed study.

(4) Maintenance Manhours per Flight Hour has improved at a rate equivalent to the rate of growth in System Reliability. Mean Time to Repair does not appear to have improved during the Production Phase of the program. However, measured MMH/FH has remained well below the program goal of 2.8.

Section II

Boeing Vertol YUH-61A Reliability

The YUH-61A was the competitor of the Sikorsky YUH-60A for the Army UTTAS program. Four prototypes of each competing design were built--three under Army contract and one with company funding. The YUH-61A accumulated 1,690 flight hours through the OT II competitive fly-off. Following OT II, the Sikorsky YUH-60A was selected and the YUH-61A program ended.

Figure 28, taken directly from a Vertol report, shows MTBF for the three Army-owned aircraft and the company-owned prototype (COP). It indicates an improvement in MTBF for the individual aircraft from less than one hour during the early flight program to about 2.6 hours prior to start of GCT. According to Boeing Vertol personnel, the MTBF achieved during GCT was 3.0, which was right on the Boeing Vertol MTBF prediction, which was based on a modified Duane approach.

Figure 29, taken directly from a Vertol report, shows the cumulative number of removals versus flight hours for the YUH-61A dynamic components. These data conform closely to the Duane equation

$$c(t) = 0.295(t)^{-0.36} .$$

According to Boeing Vertol personnel, the MTBR demonstrated during GCT was in fact 2,500 hours as predicted from BED results.

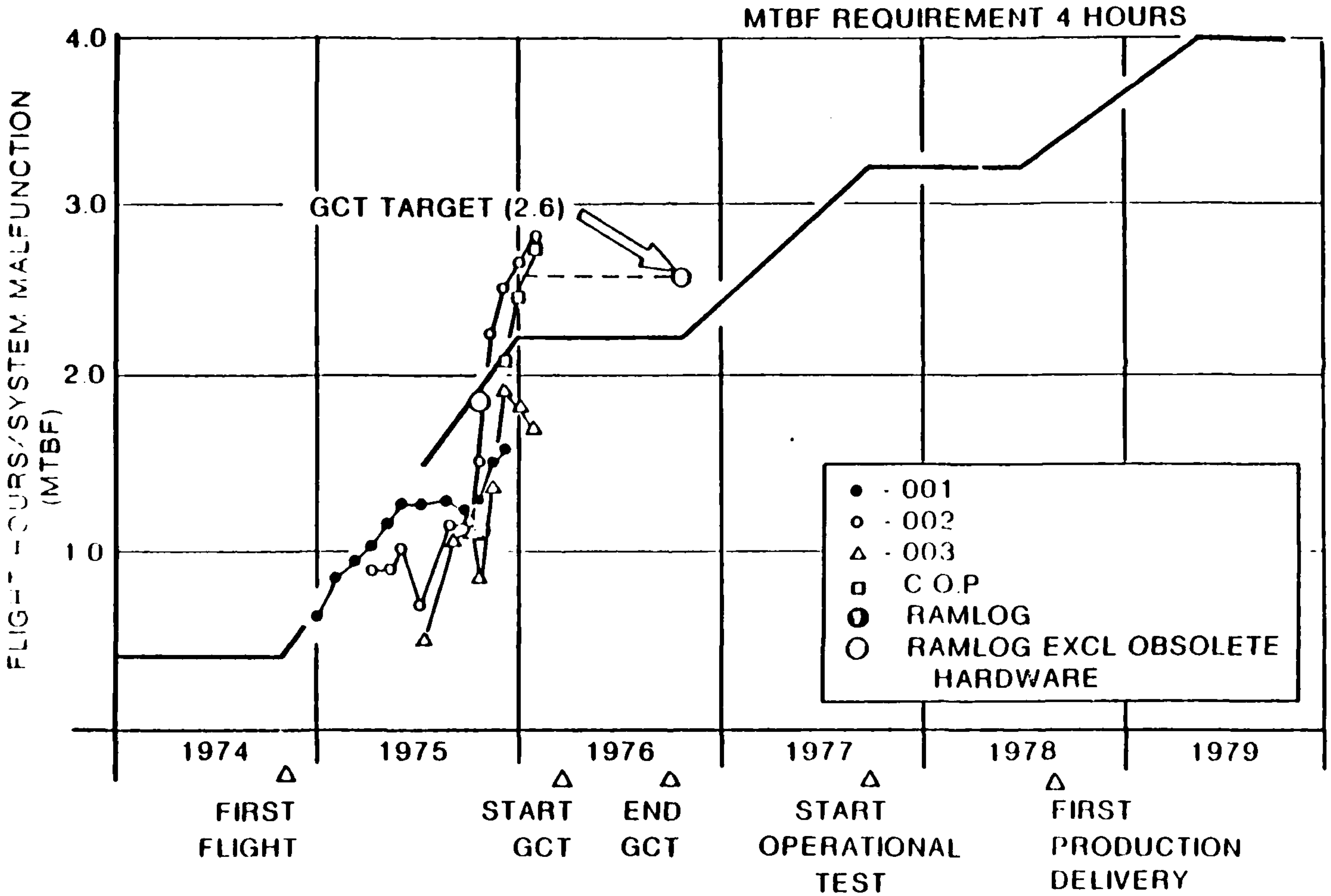


Figure 28. YUH-61A RELIABILITY GROWTH STATUS

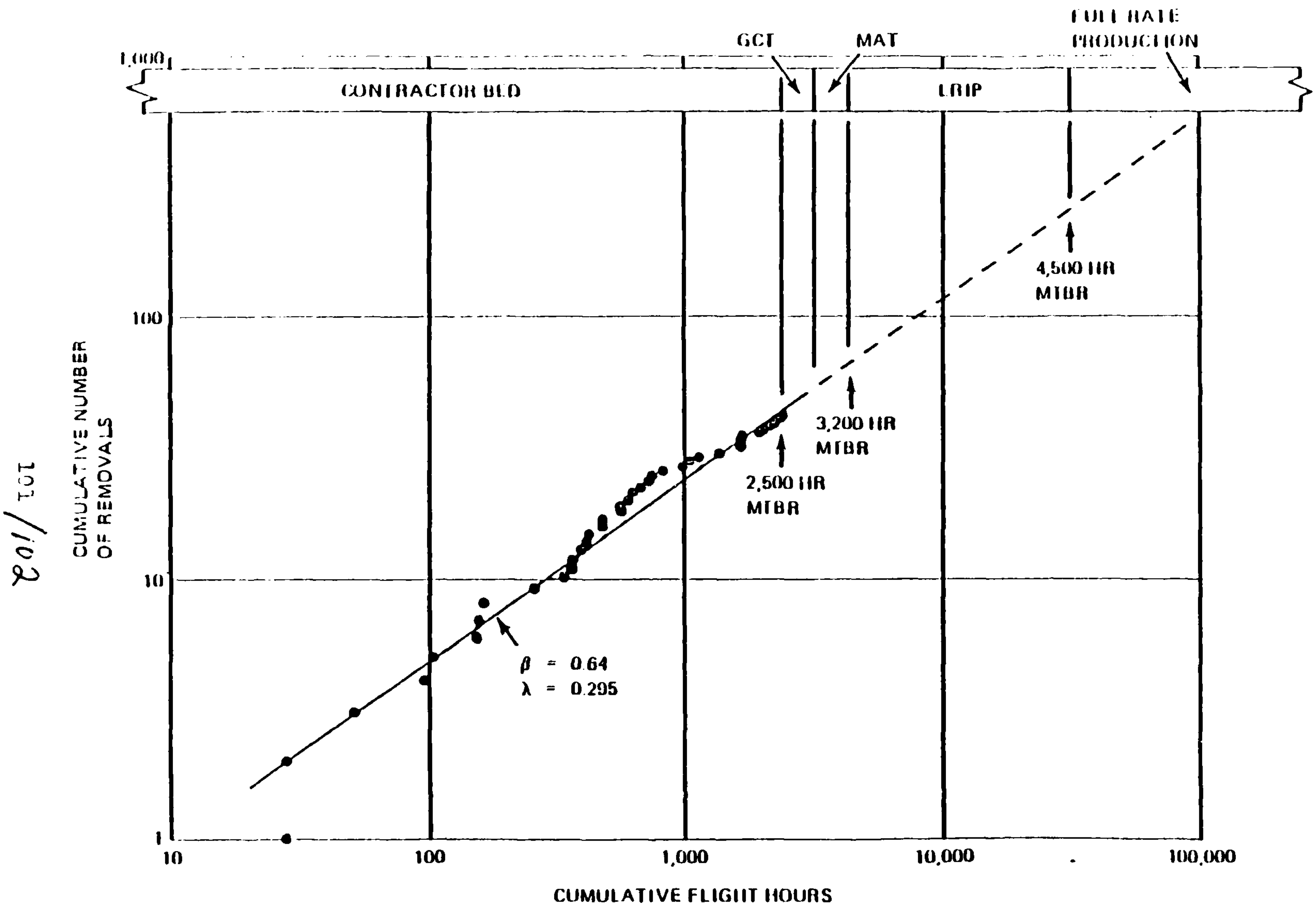


Figure 29. PROJECTION OF AVERAGE MTBR FOR UH-61A DYNAMIC COMPONENTS

Section III

Advanced Attack Helicopter Reliability and Maintainability Characteristics

In September 1972, in response to the report of a special Army Task Force, the Advanced Attack Helicopter (AAH) program was initiated. The Task Force had been formed to evaluate both the high prospective production and support costs of the AH-56A (Cheyenne) weapon system under development for the previous six years, and the knowledge gained from more recent field experiments and combat operations concerning the increased severity of the enemy anti-aircraft threat and new tactics envisioned to cope with that threat. The result was the AAH mission need, calling for an aircraft with greater agility and hover performance than the Cheyenne, but with lower speed, payload, firing range, navigation and gun system accuracy requirements, and also an aircraft which was smaller, less complex, and cheaper to operate and maintain.

In June 1973, competitive Phase 1 Engineering Development contracts were awarded to Bell Helicopter Textron and Hughes Helicopter. Each contractor was to design and fabricate a static test article, a ground test vehicle, and two flying prototypes. The competitive fly-off was held between June and September 1976, during which time each contractor's prototypes were flown for approximately 150 flight hours. In December 1976, Hughes was selected as the winner and awarded a Phase 2 Full-Scale Engineering Development contract.

The Hughes design, designated the YAH-64, is a tandem-seat (pilot aft), four-bladed aircraft with a three-point conventional wheel landing gear. It is powered by twin General Electric T-700 engines designed and developed under separate contract as Government Furnished Equipment (GFE).

Under the Phase 2 contract, Hughes was to modify the two Phase 1 prototypes, fabricate three additional air vehicles, and design and develop and/or test and integrate the mission subsystems, including the 2.75-inch Folding Fin Aerial Rocket (FFAR), the HELLFIRE Modular Missile System (HMMS), and the Target Acquisition Designation Sight/Pilot Night Vision Sensor (TADS/PNVS). Phase 2 flight testing began in November 1978 and is planned to continue through August 1981. The total Phase 2 effort is planned to be approximately 2,600 flight hours and 1,200 ground test hours. When this Phase 2 effort is added to that which was accomplished during Phase 1, the totals will be approximately 3,100 flight hours and 1,500 ground test hours [47]. Between January and March 1980, a competitive TADS/PNVS fly-off was held, with Martin Marietta Corporation being selected the winner over Northrop Corporation. DSARC III is anticipated in December 1981. If production is approved, the first production aircraft will be completed in November 1983.

Reliability, availability and maintainability objectives have been established for the AAH program as follows [48, 49, 47]:

(1) Mission Reliability - probability of 0.95 of completing a one-hour mission. Mission start is defined as the beginning of preflight and completion is defined as a successful landing at a predetermined point. Failures detected during preflight that require less than five minutes to fix are not considered mission failures, nor are failures of expendable ordnance (area weapon subsystem, FFAR rocket, HMMS missile).

(2) System Reliability - probability of 0.735 of completing a one-hour mission without a system failure. A system failure is any fault in any of the subsystems (except for expendable ordnance) which requires unscheduled maintenance. The corresponding system failure rate and system MTBF are 0.31 and 3.25, respectively.

(3) Flight Safety Reliability - 20,800 hours mean time between catastrophic failures.

(4) Maintenance Manhours per Flight Hour - 8.0 to 13.0 AVUM plus AVIM direct productive maintenance manhours (scheduled plus unscheduled) including all subsystems.

(5) Mean Time to Repair - 0.90 hours of AVUM plus AVIM on-aircraft corrective maintenance for all chargeable independent and resulting dependent failures.

(6) Achieved Availability - 0.88 based on a utilization rate of 110 hours per month.

In addition, RAM objectives have been established for the area weapon system and the TADS and PNVS systems which will not be listed here.

Flight test data have been collected under the Army's RAM/LOG Data System (described in Section I of this chapter) during the competitive fly-off in 1976 and throughout the Phase 2 program. The RAM/LOG data derived from published sources and furnished IDA by TSARCOM are summarized in Table 20. The data from the three time periods given in the Table are taken from references [49], [50], and [51], respectively. Notable omissions from Table 20 are mission reliability data and achieved availability data from the 1976 time period. The former data have not been collected to date since it is felt that the profiles being flown are not representative of AAH-type missions. Achieved availability was not measured during GCT because maintenance procedures were not fully developed at the time, nor were the aircraft sufficiently configured as attack helicopters to provide useful data [49]. Also not included in the Table are data from approximately 340 contractor test flight hours [52] flown prior to the 1976 competitive fly-off. With the exception of mean time to repair, the data are summarized in cumulative form. We were not able to obtain the data which comprise MTTR--unscheduled maintenance event counts and clock times for those events--to enable reconstruction of the cumulative MTTR trend over the three time periods.

Table 20. SUMMARY OF YAH-64 ADVANCED ATTACK HELICOPTER RAM/LOG DATA

Time Period	Aircraft Flown (Tail Nos.)	Flight Hours		System Failures			Maintenance Manhours			Mean Time to Repair	Achieved Availability		
											Maintenance Hours		Cum. Achieved Availability
		No.	Cum.	No.	Cum.	Cum. Rate	No.	Cum.	Cum. MMH/FH		No.	Cum.	
Jun 76 - Sep 76	H48	78.5		90			--			--	--		
	H49	69.6		55			--			--	--		
	Combined	148.1	148.1	145	145	0.98	823.0	823.0	5.56	1.20	--	--	--
Nov 78 - Feb 79	H48	41.7		42			151.0			1.66	155.6		
	H49	19.6		16			56.0			.99	57.0		
	Combined	61.3	209.4	58	203	0.97	207.0[a]	1,030.0	4.92	1.47	212.6	212.6	0.48[c]
Mar 79 - Jul 80	H48	424.0		344			1,176.9			1.51[b]	443.6		
	H49	272.1		253			534.1			1.07[b]	135.4		
	H57	85.3		43			108.5			1.00[b]	72.9		
	H58	76.3		34			87.5			1.23[b]	40.7		
	H59	3.7		0			2.1			--	0.0		
	Combined	861.4	1,070.8	674	877	0.82	1,909.1	2,939.1	2.74	1.32[b]	692.6	905.2	0.85[c]

[a] This value does not include the 1.8 indirect maintenance multiplicative factor used in the "RAM System Measures" section of Reference [6].

[b] These values are cumulative for the period Nov 78 - Jul 80.

[c] Cumulative values do not include data from the Jun 76 - Sep 76 time period.

To allow comparison with other helicopter development programs, the cumulative YAH-64 system failure rate is plotted on a log-log grid in Figure 30 below. The computed Duane growth rate is 0.094. However, it has been pointed out by the AAH program office, the TSARCOM Directorate for Product Assurance, and the Army Materiel Systems Analysis Activity that the YAH-64 has undergone a large number of system modifications to date and caution should be exercised in extrapolating beyond the time periods over which the data were collected. Also, as discussed in Section I of this chapter, if the fact that the contractor initially flew the prototypes for 340 hours were incorporated into the data plotted in the Figure, the computed growth rate would be somewhat larger.

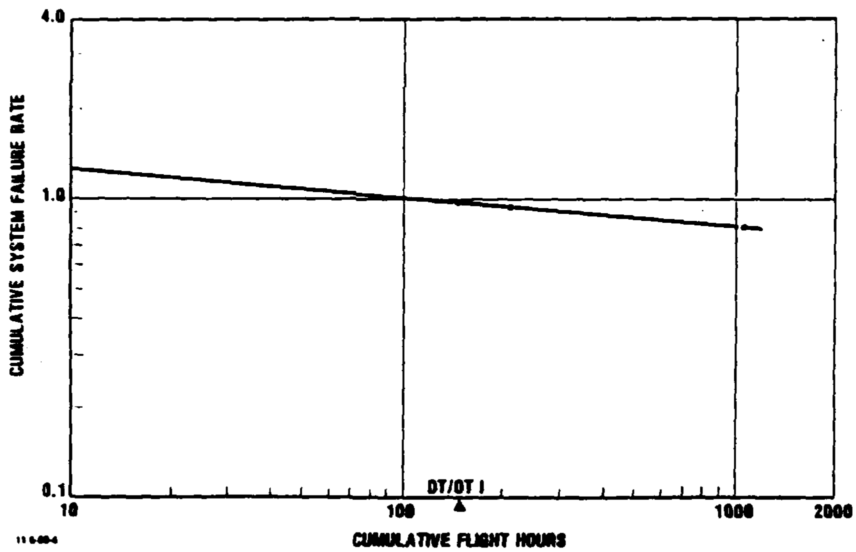


Figure 30. CUMULATIVE SYSTEM FAILURE RATE TREND OVER TIME FOR THE YAH-64 ADVANCED ATTACK HELICOPTER

Subject to the above caveat regarding the Table 20 data, it can be seen that (a) MMH/FH has improved and lies well below the program goal, (b) mean time to repair has not shown noticeable improvement, and (c) achieved availability has improved considerably.

Section IV

RAM Costs for the Army Utility Tactical Transport Aircraft System (UTTAS) and the Advanced Attack Helicopter (AAH)

The Army Utility Tactical Transport Aircraft System (UTTAS) and the Advanced Attack Helicopter (AAH) are the two most recent completely new helicopters developed by the U.S. military services. RAM was emphasized from the beginning in both programs.

It is very difficult to determine the true cost of RAM in these programs. If one defines RAM as a recent innovation in aircraft development designed to improve R&M characteristics above some basic level, then the costs involved are relatively small. However, if RAM is defined as including qualification of basic airworthiness, then the costs are a large portion of total development costs.

A. RESTRICTED DEFINITION OF RAM

If we restrict the definition of RAM to the effort required to improve R&M characteristics above some basic level, the identifiable contractor costs will be largely those of the Product Assurance Group and subsystem and flight tests including subsequent failure mode analysis over and above that required for Mil Spec qualification for airworthiness.

In the early 1970s the engineering departments expanded their organizations to include product assurance technical specialists who wrote detail specifications, test requirements, and failure mode analysis procedures related to R&M. They also signed off drawings for compliance with R&M specs to assure meeting "off-the-board" reliability goals.

The organization for product assurance varied considerably among manufacturers, and hence cost comparisons are difficult to obtain for identical tasks related to the R&M activity. From discussions with contractor personnel it appears that during the UTTAS and AAH development programs, the manufacturers organized their RAM efforts as follows:

> Boeing Vertol - Product Assurance reports to Engineering and includes reliability, maintainability, safety engineering, human factors, and survivability.
>
> Sikorsky - Reliability and Maintainability as a group reports to Systems Engineering (also called Attributes Group) which includes other engineering technical disciplines.
>
> Bell - Reliability and Maintainability, Safety, and Human Factors were separate groups in Engineering. A Product Assurance group reported to Manufacturing for the job of assuring currency of engineering changes.
>
> Hughes - Reliability and Maintainability reported to Engineering. Safety and Human Factors groups reported directly to the Program Manager.

The Product Assurance groups, like other technical disciplines, are involved in the engineering design trade-off cycle in which the optimization process considers all the requirements. Accordingly, there is a cost impact over and above the costs of the product assurance engineers.

The direct costs of the Product Assurance groups in the four recent Army helicopter development programs are shown in Table 21. The additional costs imposed on other contractor activities by the Product Assurance Groups cannot be obtained from any current accounting system. They can only be estimated by a costly audit of contractor records augmented by judgment. Our rough judgmental estimate is that they could double or triple the direct costs indicated in Table 21. In the Table it is indicated that direct RAM costs (Product Assurance group costs) range from about one to three percent of total contractor costs. If we include the other contractor

Table 21. UTTAS AND AAH PRODUCT ASSURANCE AND TOTAL CONTRACTOR COSTS

(Thousand Dollars)

	UTTAS		AAH[b]	
	Sikorsky YUH-60A	Boeing Vertol YUH-61A[a]	Bell YAH-63A	Hughes YAH-64A
Phase I				
Product Assurance (R&M only)	1,859[c]	3,306	1,210	1,303
Total	86,900	117,000	75,554	97,865
Phase II				
Product Assurance	623[d]	-	-	6,275
Total	62,300	-	-	373,919

Sources:

a. Boeing Vertol.

b. AAH Project Manager's Office.

c. Sikorsky Program Manager (8 engineers for 3.5 years).

d. Tony Tornatore, TSARCOM, Memorandum, "Black Hawk Contract Cost Data," no date. RAM program cost estimated at one percent of total contract cost.

costs discussed above, total RAM costs would probably fall somewhere in the range of two to nine percent of total contractor costs.

Note in Table 21 that Boeing Vertol spent much more in the UTTAS Phase I competition on Product Assurance than Sikorsky. Table 22 indicates that the R&M results achieved by the competing aircraft were very similar. This would indicate that the higher expenditures by Boeing Vertol were not effective. However, the accounting system definitions may have been different. Further, the YUH-61A was Boeing Vertol's first single rotor helicopter development and may have required extra resources to attain competitive R&M characteristics with the Sikorsky YUH-60A because of Sikorsky's much greater experience in single rotor helicopter development.

Table 22. SIKORSKY VERSUS BOEING VERTOL RAM VALUES DURING DT/OT II

UTTAS Program	Flight Hours	System Failure Rate	Mission Reliability	AVUM/AVIM Corrective MMH/FH	MTTR	MTBM	Achieved Availability
Boeing/Vertol							
DT II	304.9	.391	.9614	2,156	.650	.476	.942
OT II	259.5	.239	.9809	.864	.473	.784	.963
Combined	564.4	.321	.9703	1.562	.592	.581	.952
Sikorsky							
DT II	298.9	.388	.9479	1.189	.607	.566	.954
OT II	254.3	.287	.9728	.945	.582	.831	.958
Combined	553.2	.342	.9592	1.077	.598	.663	.956

Sources: [41] and [53].

In addition to the contractor costs discussed above, there are Army costs involved in setting up and administering the RAM program. Each Program Manager's Office has a Product Assurance and Test Management Division. Further, the Army maintains extensive R&M data reporting systems to support the R&M improvement program. RAM/LOG (Reliability, Availability, Maintainability/Logistics) is the R&M data system used during the aircraft test phase. Dedicated personnel collect very detailed R&M data on all aircraft. Once an aircraft is fielded, RAM/LOG is replaced by SDC (Sample Data Collection). Detailed (but less extensive than RAM/LOG) data are collected on a selected sample of aircraft. Maintenance personnel fill out modified TAMMS forms. An on-site dedicated field monitor completes the operational information and is responsible for the correctness of the maintenance data. CRIM (Component Record for Intensive Management) tracks individual components (by serial number) of all production aircraft. This system was set up primarily for warranty administration, but was subsequently used on non-warranty components as well. Approximately 170 components on each aircraft are tracked by CRIM, which records all removal, repair, and installation events.

We have not been able to quantify the substantial costs to the Army of these reporting systems which involve a number of personnel to record, computer process, and analyze large quantities of data.

B. EXPANDED DEFINITION OF RAM

If we expand the definition of RAM to include development and qualification of basic airworthiness (a safety requirement), we can identify much larger costs. Activities involved in this process, in addition to those of the "Restricted Definition of RAM" discussed above, would include the materials and process laboratory, subsystem tests, static test vehicle, ground test vehicle, and structural flight test vehicle. In addition to the costs of the different units of test equipment themselves, there would be the costs of conducting qualification testing and the associated "break and fix" cycle involved in correcting deficiencies. The costs of these activities make up a large part of the total development cost of a helicopter.

Section V

Comparison of CH-47C and CH-47D Reliability

The Army is planning to modernize all of its CH-47A, CH-47B and CH-47C helicopters to CH-47Ds. The CH-47D will have uprated engines and transmissions, a new APU, an advanced flight control system, fiberglass rotor blades, and a number of other improvements. The first CH-47D, converted from an A-model, began flight testing in May 1979 [54].

The D model will have essentially the same performance characteristics as the C model (15,000 pounds payload/4,000 feet/95°F); performance of the A and B models will be upgraded to that level. Two of the major modifications--the fiberglass rotor blades and the T55-L-712 engines--were approved as PIPs to the C model and would continue even if the D program were cancelled. In addition to the performance improvement, the goals of the program are to extend the life of the fleet; improve RAM, vulnerability/survivability, and safety; and provide enhanced terrain and night flying capability.

During the period April 1978 to December 1979, three CH-47Cs were flown for a total of 2,137 hours. During this period reliability data were collected under the RAM/LOG reporting system to establish a data baseline for comparison with the CH-47D. The CH-47D was flown for 342 hours in DT II and 125 hours in OT II. The OT II was flown side-by-side with the CH-47C, which flew 123 hours in OT II.

The cumulative results of these flight programs as of August 1980 (2,260 hours for the CH-47C and 467 hours for the CH-47D) are shown in Table 23.

Table 23. COMPARISON OF CH-47C AND CH-47D FAILURE RATES PER THOUSAND FLIGHT HOURS

Subsystem	Hardware System Reliability Failure Rate		System Operational Reliability Failure Rate	
	CH-47C	CH-47D	CH-47C	CH-47D
Airframe	61	49	311	315
Comm/Nav	38	45	46	60
Drive	36	34	64	68
Electrical	19	15	97	58
Equipment	46	21	103	79
Flight Controls	30	26	61	68
Hydraulics	21	4	54	15
Indicating	44	32	76	43
Landing Gear	14	26	26	34
Power Plant	99	26	283	88
(Engine)	(40)	(6)	(87)	(6)
Rotor	71	41	100	75
Total	479	319	1,220	903

A Hardware System Reliability (HSR) failure is any fault in any equipment that results in the inability of the item to perform its required function and requires unscheduled removal of that item. The unscheduled removal rate is used to determine HSR including only Primary and Independent Failures. HSR is a measure of the spares support requirement for the aircraft. A System Operational Reliability (SOR) failure is one which results in the inability of any component to satisfactorily perform its function within specifications and requires unscheduled maintenance for correction. The total malfunction rate is used to determine SOR including all Primary and Non-Primary and Independent and Dependent Failures. SOR is a measure of the total unscheduled maintenance requirements of the aircraft.

Table 23 indicates that the rate of occurrence of both types of failures is significantly less for the CH-47D than for the CH-47C. However, it should be noted that the failure rates for some of the subsystems are higher in the CH-47D than in the CH-47C.

Using RAM/LOG data provided by the CH-47D program office as of 152 flight hours together with the data as of 467 flight hours given in Table 23 above, reliability growth trends for the CH-47D can be computed, as shown in Table 24. While no growth can be observed for Hardware System Reliability, it should be noted that the cumulative rates cited above are already better than the mature program goal of .333 failures per flight hour. The growth rate of 0.136 for System Operational Reliability is consistent with growth rates of other helicopter development programs discussed in this paper. Using this growth rate and extrapolating back to the 100 flight hour point yields a cumulative System Operational failure rate of 1.11. The corresponding cumulative MTBF of 0.90 hours is 64 percent of the mature program goal of 1.4 hours MTBF, quite a high percent at 100 flight hours relative to other programs.

Table 24. RELIABILITY GROWTH TRENDS FOR THE CH-47D

Parameter	Cumulative Failure Rates		Growth Rate (α)
	152 Flight Hours	467 Flight Hours	
Hardware System Reliability	0.316	0.319	0
System Operational Reliability	1.050	0.903	0.14

Section VI

CH-53E Reliability and Maintainability Characteristics

The three-engine Sikorsky CH-53E has been developed from the two-engine CH-53D. Changes to increase performance include installation of a new seven-blade main rotor of increased diameter, with blades of titanium/fiberglass construction, a canted tail with increased diameter rotor, and an uprated transmission of 13,140 shp capacity [54]. A General Accounting Office study [55] concluded that planned parts commonality has been reduced to the point where the CH-53E more nearly resembles a new aircraft rather than a growth version of the CH-53D.

Under Phase I of the program, two YCH-53Es were built. First flight was 1 March 1974. One of these aircraft was lost in an accident in 1974. Phase II covered the construction of a static test vehicle and two production prototypes, the first of which flew on 8 December 1975. In February 1978, Sikorsky was awarded a contract to begin full-scale production, with initial approval for six aircraft [54]. First flight of the first production aircraft was in December 1980.

Figure 31, reproduced directly from a Sikorsky report [56], shows cumulative and instantaneous abort rates versus cumulative flight hours for the two production prototype helicopters. Note that these data fit the Duane model quite well. The trend shows a cumulative abort rate at 500 flight hours of 0.0805, a Duane slope of 0.23 and a derived current instantaneous abort rate of 0.0620. The trend reflects data for the total aircraft excluding GFE and the prototype expanded automatic flight control system (AFCS).

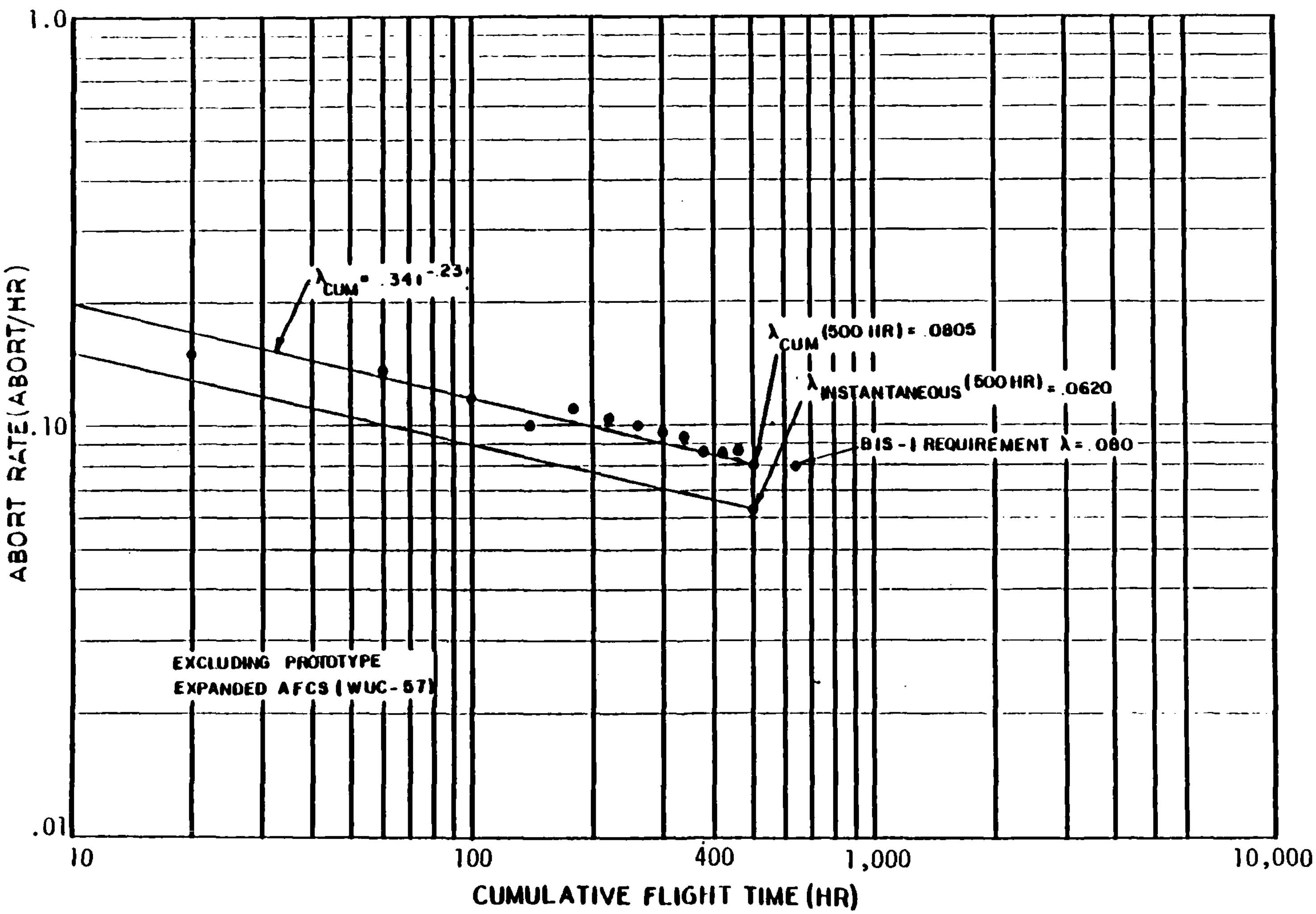


Figure 31. CH-53E MISSION RELIABILITY GROWTH TREND

Table 25 presents instantaneous mission reliability, system reliability, and maintenance manhours per flight hour versus calendar time and cumulative flight hours. All three of these R&M measures showed considerable improvement over the period reported. The mission reliability figures of Table 25 are somewhat lower than those implied by the abort rates of Figure 31 because Table 25 includes the AFCS whereas Figure 31 does not.

Table 25. CH-53E OBSERVED RELIABILITY AND MAINTAINABILITY CHARACTERISTICS (with GFE and Expanded AFCS)

Date	Cumulative Flight Hours	Mission Reliability (1 hour)	System Reliability (MFHBF)	Maintenance Manhours per Flight Hour
30 Apr 76	428	0.89	0.62	19.47
30 May 76	474	0.89	0.62	19.47
26 Jun 76	490	0.90	0.62	19.45
30 Aug 76	569	0.90	0.62	19.45
13 Jun 77	968	0.92	0.65	14.75
9 May 79	1,412	0.96	0.84	14.20

Source: Sikorsky Report SER-13242, Revisions 0 through 4.

The values in the table are point estimates (instantaneous values) computed over flight hour intervals ending at the dates given in the table. For example, the mission reliability of 0.96 reported for 9 May 1979 is based on four mission aborts occurring during the 101 flight hours between cumulative flight hour 1311 and cumulative flight hour 1412. Converting the mission reliability values in the table to instantaneous mission abort rates and computing a mission reliability growth rate yields a value of $\alpha = 0.79$. The system reliability growth rate as computed from Table 25 is $\alpha = 0.22$. The mission Reliability growth rate is extremely high relative to other helicopter development programs. The system reliability growth rate is also relatively high. Using the system reliability growth rate to extrapolate a starting (100 flight hour) *cumulative* MFHBF yields a value of 0.28 MFHBF, 30 percent of the mature program goal of 0.92. The reasons the data in Table 25 deviate from the expected Duane slope values are as follows:

(1) Duane slope calculations assume that changes are incorporated throughout the development program as problems are encountered and solved. In the case of the CH-53E, the changes were incorporated in a block toward the end of the development program, which resulted in sharp increases in the Duane slopes for Mission Reliability and System Reliability toward the end of the program.

(2) Calculation of the Duane slope requires that the failure data be cumulative as well as the flight hours. The failure data used to derive the Mission and System Reliabilities were computed over flight hour intervals ending at the dates in Table 25 corresponding to the cumulative flight hours. This resulted in the Duane slopes showing higher growth (because the earlier failure rate data were excluded) than was actually the case.

The *conclusion* to be drawn is that when block changes are incorporated into a helicopter, including design oriented (non-R&M) improvements, the reliability growth data do not correspond closely to the Duane curve formulation.

Section VII

Cost and Time Required to "Grow" R&M in the Development Phase

Duane [2] found that for some equipments cumulative failure rate versus cumulative operating hours resulted in a straight line when the data points were plotted on log-log paper. He expressed these "Duane curves" by the equation

$$CFR = \lambda t^{-\alpha} ,$$

where

CFR = cumulative failure rate
λ = initial failure rate (intersection at t=1 hour)
t = cumulative operating hours
α = exponent.

$-\alpha$ denotes the slope of the cumulative failure rate line: when α is positive, there is a decreasing failure rate; when it is negative, there is an increasing failure rate. If cumulative failure rate versus cumulative operating hours falls on a straight line (the "Duane curve"), then instantaneous failure rate will also fall on a straight line with the equation:

$$IFR = (1-\alpha)\lambda t^{-\alpha} .$$

The 1975 IDA Study [1] included data on R&M growth during the development phases of the AH-56A, OH-6A, and CH-53A helicopters. For convenience, four figures from the 1975 Study are reproduced here as Figures 32 through 35. Figure 32 shows that the AH-56A failure rate data fit a Duane curve quite well. This program was cancelled after 1,426 flight hours of developmental testing. Figure 33 for the OH-6A covers both development

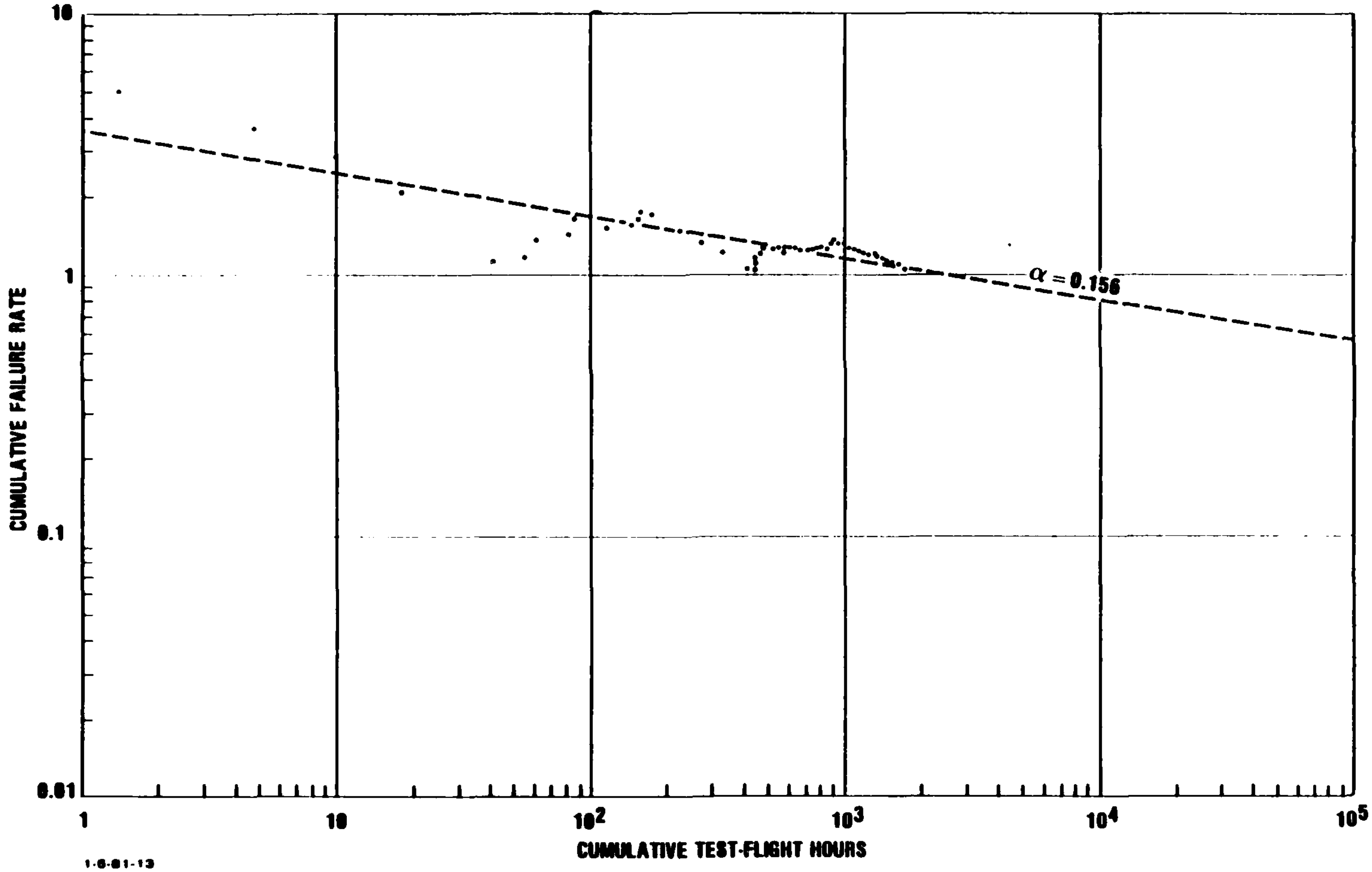


Figure 32. AH-56A RELIABILITY GROWTH CURVE FOR TOTAL SYSTEM

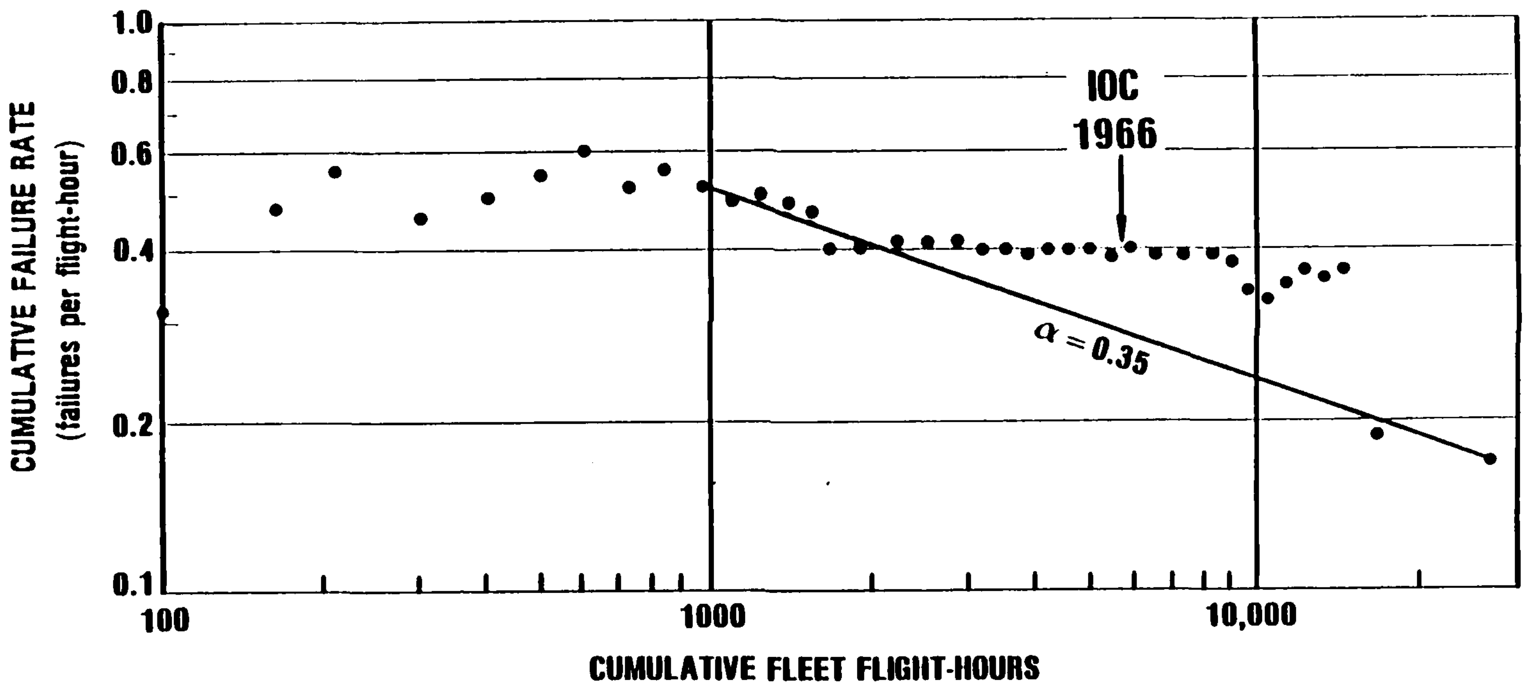


Figure 33. OH-6A CUMULATIVE FAILURE RATE VERSUS CUMULATIVE FLIGHT HOURS

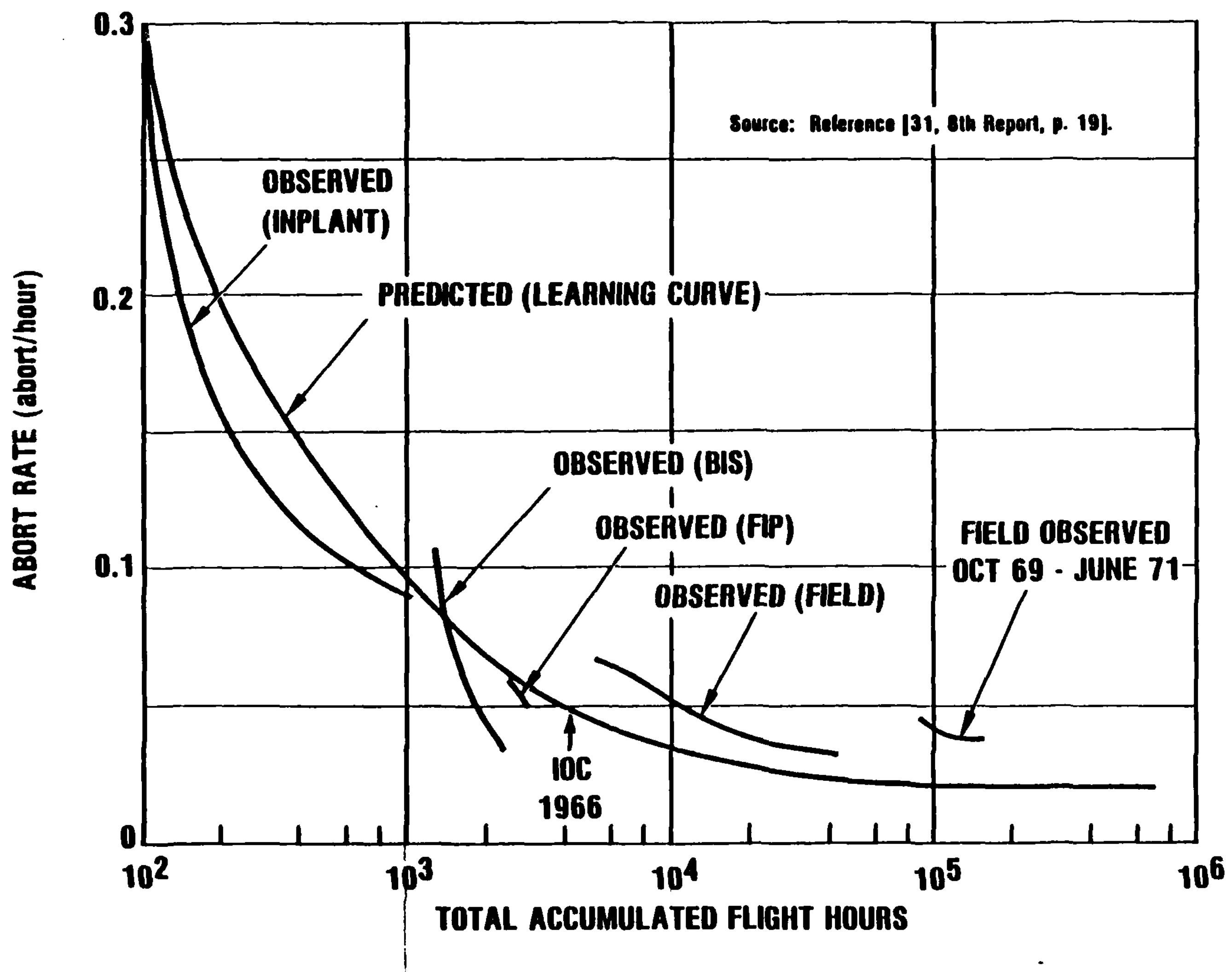


Figure 34. CH-53A/D ABORT RATE (Experience versus Predicted)

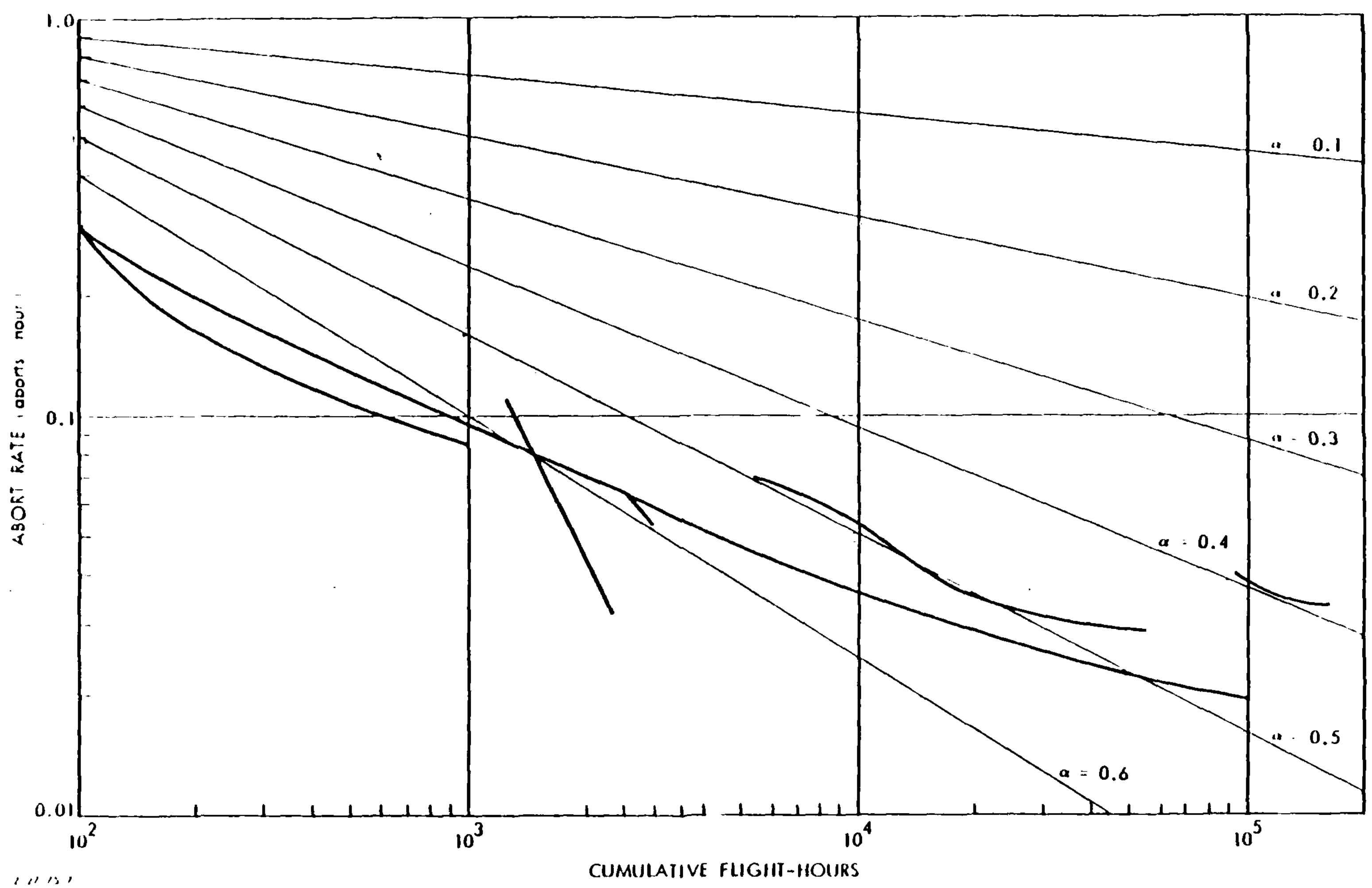


Figure 35. CH-53A/D ABORT RATE VERSUS CUMULATIVE FLIGHT HOURS

and production flight hours. The first approximately 5,000 flight hours were developmental and the rest were production. If we neglect the first point at 100 flight hours, the data indicate a decreasing failure rate that roughly follows a Duane curve with a cumulative failure rate of about 0.6 at 100 flight hours decreasing to about 0.4 at 5,000 flight hours. Figure 34 for the CH-53A/D is taken directly from a Sikorsky report; it was replotted in Figure 35 on log-log paper. The developmental flying (through FIP) roughly follows a Duane curve.

The CH-53A/D data were for aborting failures while the other data were for all failures. The growth rate for the CH-53A/D (α=0.4) was much greater than for the AH-56A (α=0.16) or the OH-6A (α=0.10). (Note that α = 0.10 for the OH-6A is for the first 5,000 flight hours. The α = 0.35 shown on Figure 33 is determined by some suspiciously low failure rates after 10,000 flight hours.)

Figures 9 and 10 of Section I indicate that the Black Hawk roughly followed a Duane curve during the Basic Engineering Development phase (if we ignore the point at 2.6 flight hours). It then departed sharply from a Duane curve as indicated in Figure 9. Some possible reasons for this departure are discussed in Section I. The growth rates and cumulative failure rates at 100 flight hours for the three programs for which we have failure rates for all failures are:

	α	Cumulative Failure Rate at 100 Flight Hours
AH-56A	0.16	1.7
OH-6A	0.10	0.6
YUH-60A (BED)	0.13	0.7

We have increased the YUH-60A failure rate from that of Figures 9 and 10 of Section I to account for early contractor flying that was not included.

The above data indicate somewhat erratic trends of failure rate improvement during helicopter development programs. However, in at least a very approximate way, the programs tend to be characterized by the Duane growth process. Because of the mathematical convenience of the Duane equation, let us hypothesize a "typical" helicopter development program characterized by $\alpha = 0.13$ and a cumulative failure rate at 100 flight hours = 0.7. These two values permit us to calculate $\lambda = 1.274$. The cumulative and instantaneous failure rates for the "typical" helicopter are shown in Figure 36. Note that the basic characteristic of the Duane curves is that the failure rate is reduced by the same proportion for each order of magnitude increase in cumulative flight hours. In the case of Figure 36, the failure rate at 100 flight hours is about 74 percent of that at 10 flight hours; at 1,000 flight hours it is 74 percent of that at 100 flight hours, etc. The nature of the relationship becomes much more dramatic visually when the instantaneous failure rate is replotted on a linear grid (see Figure 37). On Figure 37 we have added a dashed line (α=0.4) representing the fastest rate of improvement we are aware of for any helicopter development program (the CH-53 abort rate). For comparison with the "typical" helicopter (α=0.13), we have assumed the same cumulative failure rate at 100 flight hours of 0.7.

The failure rate is driven down during the development phase by a continuous cycle of "fail and fix" consisting of the following basic steps:

1. Test hours accumulated:
   a. bench test
      (1) transmission test stand
      (2) rotor blade fatigue tests
      (3) flight control fatigue tests
      (4) miscellaneous component fatigue tests
      (5) failure data collected

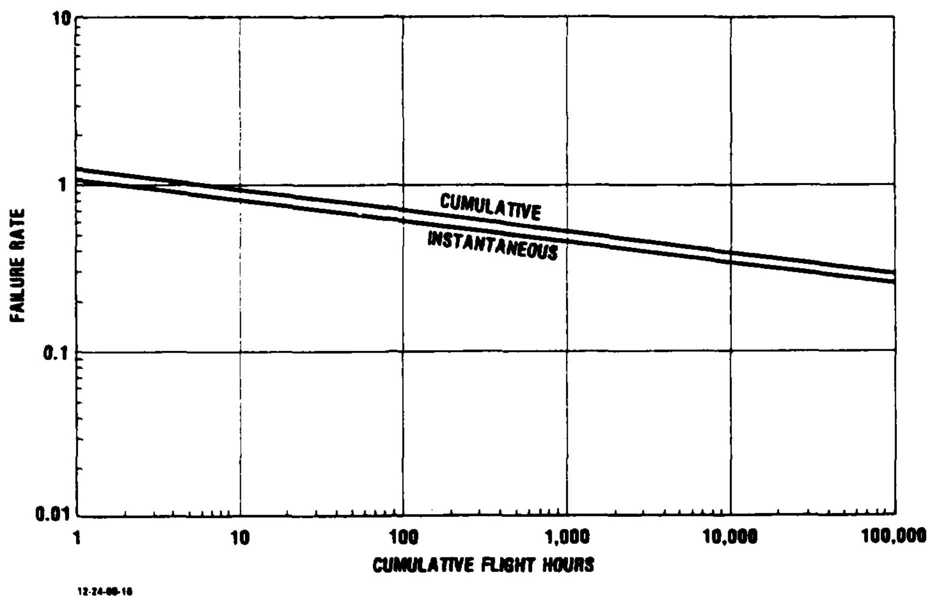


Figure 36. FAILURE RATE VERSUS FLIGHT HOURS FOR "TYPICAL" HELICOPTER DEVELOPMENT PROGRAM

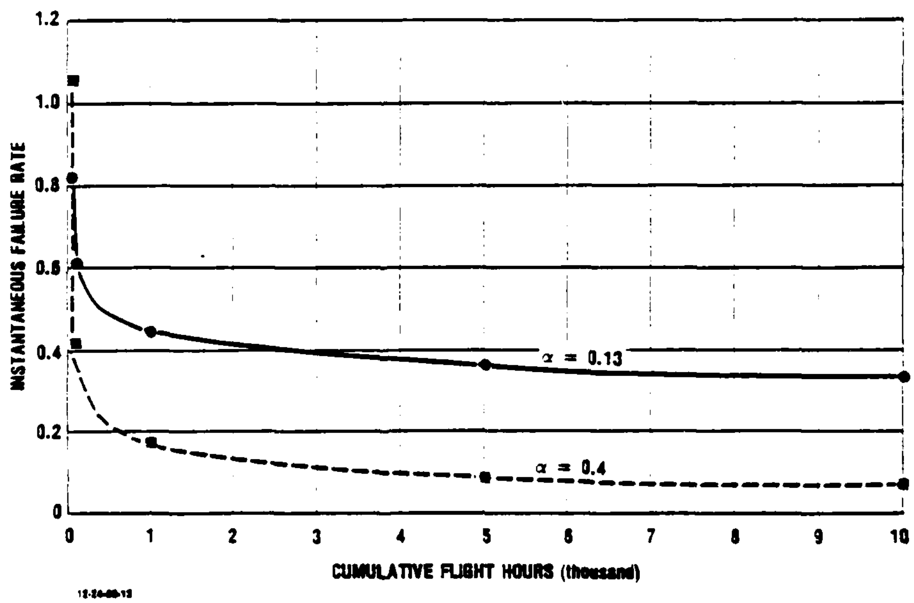


Figure 37. INSTANTANEOUS FAILURE RATE VERSUS FLIGHT HOURS

b. rotor whirl tower test

c. ground test vehicle

d. flight test.

2. Failures analyzed:

a. failure mode identified

(1) design deficiency
(2) quality control
(3) unanticipated environmental conditions

b. corrective action established.

3. Redesign/rework to eliminate cause of failure.

4. Test redesigned/reworked component to verify adequacy of corrective action.

5. Replace old part by new part in the system (test aircraft, spares, etc.).

The cost of this R&M growth process during the helicopter development phase (Basic Engineering Development) is associated with bench tests, whirl tests, and ground test vehicles since the flight test vehicles are almost totally committed to verification of basic qualification specification requirements. However, the flight test vehicles accumulate a significant amount of time in the operating environment and are an important contribution to the R&M growth process during this phase of the development program. This could also be true of the maturity phase where design changes require requalification and R&M growth results from the same test, analyze, and redesign/rework process.

Later in the helicopter life cycle, it has been industry practice to eliminate the ground test vehicle (for cost reasons) but maintain the bench test facilities. Qualification of product improvement programs is usually accomplished by a combination of bench tests by the contractor and accelerated service flight tests--generally at military test centers where this testing can be combined with other flight tests such as avionics functional tests, pilot training, etc.

As can be seen, the reliability growth process involves many interrelated elements. The conventional way of analyzing changes in helicopter R&M characteristics over time is to plot their values as a function of cumulative flight hours (see Figures 32-36). When using such data, one must realize that the flying per se is only one element in the R&M growth process. For example, the mix of bench, whirl, GTV, and contractor and Army flight teets used in the Black Hawk development phase is presented in Figure 38 taken directly from a Sikorsky report.

We were not able to estimate the associated dollar expenditures for R&M improvement because current cost accounting systems do not clearly separate expenditures for R&M improvement from expenditures for the many other aspects of helicopter development and production programs.

There is a schedule time involved in accomplishing R&M improvement programs such as those depicted in Figure 37. Figure 39 shows the rate of accumulation of developmental flight hours versus years for several helicopter programs. The AH-56A, OH-6A and CH-53A data were developed from information in the 1975 IDA Study [1]. Figure 39 indicates that the OH-6A program accumulated more developmental hours more rapidly than the other programs. The OH-6A was a much smaller aircraft and thus the cost of accumulating hours was much less. Ten OH-6A prorotypes were built (versus three Army and one contractor for the Black Hawk). Programs similar to the AH-56A and Black Hawk programs would require about seven years to accumulate 3,000 flight hours; the OH-6A type program would accumulate 10,000 flight hours in five to six years. As discussed above, the accumulation of flight hours is only one element in the R&M growth process; nevertheless, the above data on time required to accumulate flight hours indicate that extensive R&M growth programs could take years to accomplish. The cost

COMPONENT/SUBSYSTEM	SUBSYSTEM & GROUND TESTS						FLIGHT TESTS				PROJECTED TOTAL TEST HOURS (1)		
	BENCH		WHIRL (2)		GTV (3)		CONTRACTOR		ARMY		BED	MATUR-ITY	TOTAL
MAIN TRANSMISSION & SHAFT	1315	500			1200	700	654	791	760	525	3929	2516	6445
ENGINE SHAFTING					2400	1400	1308	1582	1520	1050	5228	4032	9260
TAIL ROTOR DRIVE SHAFTING					1200	700	654	791	760	525	2614	2016	4630
TAIL ROTOR TRANSMISSION	1523	400	305	250	1200	700	654	791	760	525	4442	2666	7108
INTERMEDIATE TRANSMISSION	1523	400	40		1200	700	654	791	760	525	4177	2416	6593
SWASHPLATE			570	20	1200	700	654	791	760	525	3184	2026	5210
ROTATING MAIN ROTOR CONTROLS			2280	80	4800	2800	2616	3164	3040	2100	12736	8144	20880
MAIN ROTOR HUB			570	20	1200	700	654	791	760	525	3184	2036	5220
MAIN ROTOR HEAD COMPONENTS			2280	80	4800	2800	2616	3164	3040	2100	12736	8144	20880
MAIN ROTOR BLADES			2280	80	4800	2800	2616	3164	3040	2100	12736	8144	20880
TAIL ROTOR HEAD			305	250	1200	700	654	791	760	525	2919	2266	5185
TAIL ROTOR BLADES			610	500	2400	1400	1308	1582	1520	1050	5838	4532	10370
MAIN ROTOR SERVOS					3600	2100	1962	2369	2280	1575	7842	6044	13886
FLIGHT CONTROL, HYDRAULIC					1200	700	654	791	760	525	2614	2016	4630
ELECTRICAL SUBSYSTEMS	560				1200	700	654	791	760	525	3174	2016	5190

NOTES:
(1) FATIGUE TEST TIME NOT INCLUDED IN HOURS SHOWN IN TABLE. TOTAL COMPONENT TEST HOURS SHOWN. IGNORE REDESIGNS FOR MATURITY.
(2) INCLUDES 40 HOURS OF WIND TUNNEL TESTING ACCUMULATED ON TAIL ROTOR, TAIL & INTERMEDIATE TRANSMISSIONS DURING BED PHASE.
(3) INCLUDES TOTAL OPERATING TIME PROJECTED THROUGH EGLIN CLIMATIC HANGAR TESTING.
(4) INCLUDES 17 HOURS OF PAE AND 310 HOURS OF PILOT TRAINING IN MATURITY FLIGHT HOURS.

Figure 38. BLACK HAWK RELIABILITY/MAINTAINABILITY TEST HOUR SUMMARY

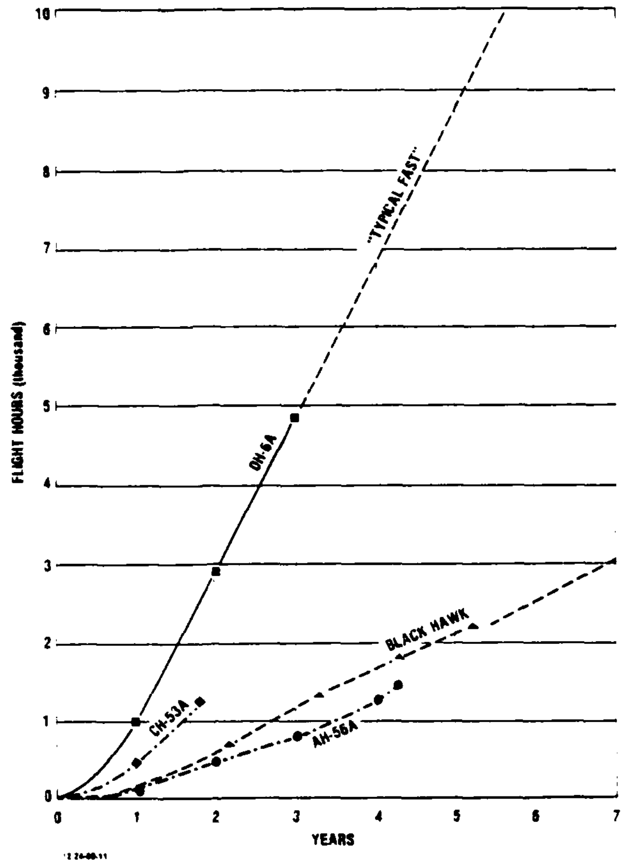


Figure 39. HELICOPTER DEVELOPMENT FLIGHT HOURS VERSUS CALENDAR TIME

and time required for such programs may be justified by the necessity for achieving the R&M program goals which would result in improved operational capability and reduction in ownership costs in service use.

The Duane equation indicates that failure rate as a given number of flight hours is a function of both initial failure rate (λ) and the rate of improvement (α). Figure 40 shows for various α's the cumulative MTBF at 100 flight hours, in percent of mature program goal, required to achieve the mature program goal. A program is generally considered to have reached maturity after 20,000 to 100,000 flight hours, and Figure 40 shows the relationships for both values. For example,

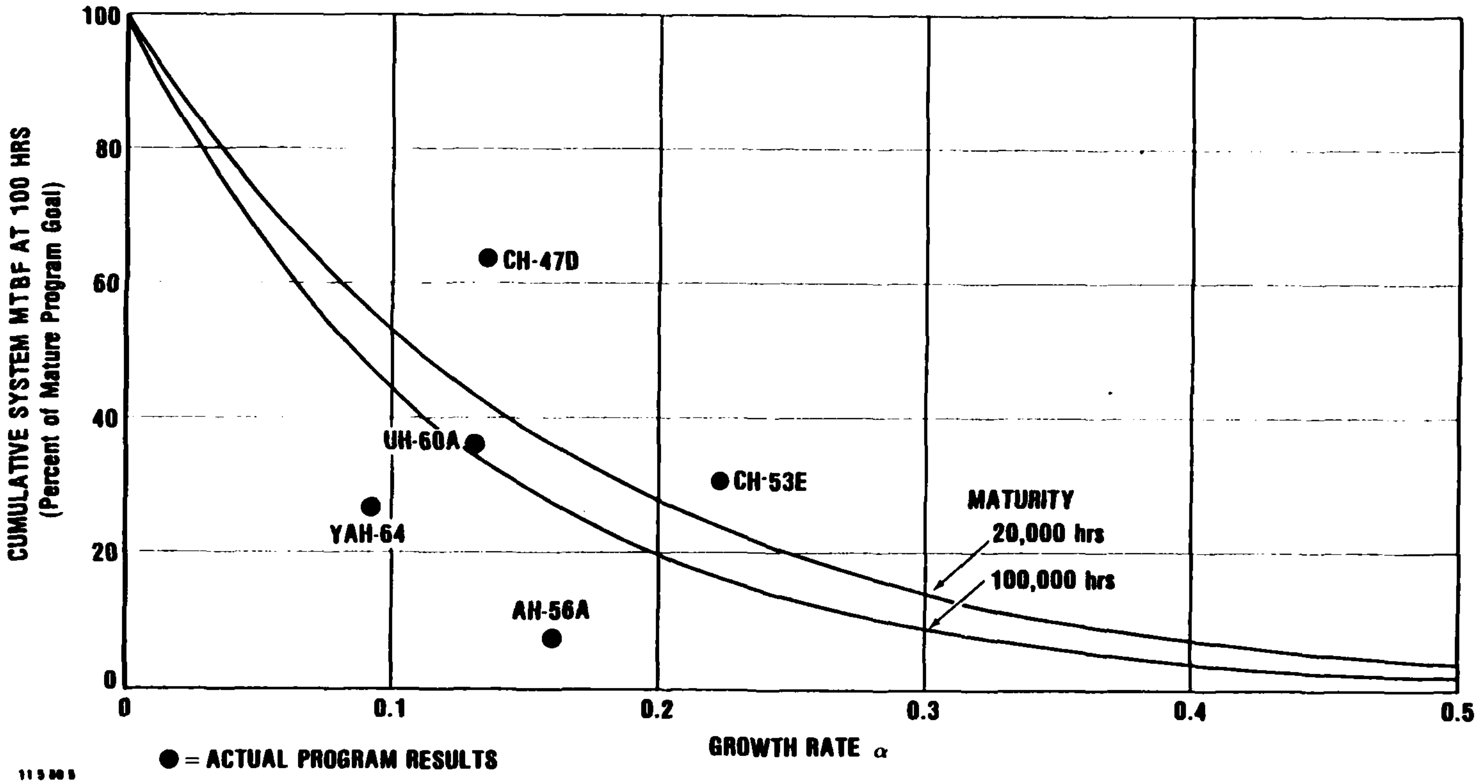


Figure 40. CUMULATIVE SYSTEM MEAN TIME BETWEEN FAILURES (MTBF) AT 100 HOURS VERSUS GROWTH RATE REQUIRED TO ACHIEVE MATURE PROGRAM GOALS

if failure rate improves at the rate $\alpha = 0.2$, the goal at 100,000 flight hours will be achieved if the cumulative MTBF at 100 flight hours is 20 percent of the mature program goal.

On Figure 40 are plotted the values for the following helicopters for which goals were established and for which we were able to obtain Duane curves:

	Mature Program MTBF Goal	Cumulative System MTBF at 100 Hours	Growth Rate (α)
AH-56A	10.60	0.59	0.16
UH-60A	4.00	1.40	0.13
YAH-64	3.25	0.87	0.09
CH-53E	0.92	0.28	0.22
CH-47D	1.40	0.90	0.14

Note that most of the α's lie in the 0.1 to 0.2 range. If that rate of growth can be maintained to 20,000 or 100,000 flight hours, then the cumulative MTBF at 100 flight hours must be approximately one-third of the mature goal in order for the helicopter to meet its mature program goal.

The UH-60A, CH-47D and CH-53E all appear to be capable of meeting their mature program goals. The two major modification programs (the CH-47D and CH-53E) appear much more likely to meet their failure rate objectives than the completely new helicopter programs. The AH-56A was unlikely to meet its mature program goal (which was much more ambitious than those of the other programs). Since its cumulative MTBF at 100 hours was only 5.6 percent of its mature goal, its α would have had to increase from 0.16 to approximately 0.4 in order to achieve its mature goal. In fact, the AH-56A program was terminated after 1,426 flight hours of developmental testing. The AH-64 may have difficulty in meeting its goal; its α will have to increase from the 0.09 experienced to date to approximately 0.17 in order to meet its goal by 100,000 flight hours.

Chapter III

PRODUCTION PHASE R&M DATA

Section I

Navy 3-M Data

Navy aircraft maintenance data are reported under the Maintenance Material Management (3-M) reporting system, a computerized system operated by the Navy Maintenance Support Office, Mechanicsburg, Pennsylvania. Data are submitted on all Navy aircraft in service use; the test period prior to service use is not covered. Data are available on a monthly basis. The Navy advised against our use of its 3-M data before CY 1968 because of reliability problems prior to that time.

Data are assembled by major operating command--for example, the UH-1N reports show separate data for the following operating commands:

FMFLANT (Fleet Marine Force Atlantic)
CNAP (Commander, Naval Air Force Pacific)
MARNFMF (Marine Non-FMF)
NATRA (Naval Air Training)
CNAL (Commander, Naval Air Force Atlantic).

Data for helicopters operating under combat conditions in Vietnam probably are not representative of normal noncombat operations. Accordingly, we excluded data from the Pacific commands in our use of the 3-M data.

The 3-M system permits the ready calculation of three R&M measures: (1) mean flight hours between maintenance[1] actions (MFHBMA);[2] (2) mean flight hours between failures[1] (MTBF); and (3) maintenance[1] manhours per flight hour (MMH/FH).[3] It is also possible, with great effort, to obtain mission abort rates; however, in our use of the 3-M data we developed only the first three R&M measures.

The 3-M data are coded by numerical work unit codes (WUCs) which identify the various parts of the helicopter; this coding permits one to assemble data by helicopter system. We assembled data into the following systems: (1) airframe, (2) rotors and hubs, (3) gear boxes and drives, (4) power plant, (5) instruments, communication, and navigation, (6) weapon systems (where applicable), and (7) total. In many cases the weapon systems are responsible for relatively few maintenance actions, failures, and maintenance manhours; in those cases the data for the weapon systems shown in the tables are not plotted on the graphs. 3-M data are available for five basic types of Navy helicopters: the H-1, H-2, H-3, H-46, and H-53.

Our 1975 study presented 3-M data for 1968 through 1973 [1]. For the present study we obtained 3-M data for the period January 1973 through June 1979. In comparing the new 1973 figures with those in our earlier study, we found slight differences. The new quantities (of flight hours, failures, etc.) in many cases were higher, indicating that all of the 1973 data had not been entered in the 3-M data files which we obtained for our earlier

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[1]Reference [1] includes the following definitions:
Maintenance. All actions necessary for retaining an item in or restoring it to a specified condition.
Failure. The inability of an item to perform within previously specified limits.

[2]Unscheduled maintenance actions only.

[3]Unscheduled maintenance only at the organizational and the intermediate maintenance-activity levels.

study. For that reason, we have replaced the old 1973 figures in both tables and graphs with the new figures, and we have not plotted the data for the first half of 1979 on the figures. In the tables below we have not repeated the data for 1968 through 1972 which were included in our 1975 study.

1. The H-1

In Table 26 we have combined the data for all the single-engine types in this series except the AH-1G gunship (i.e., the UH-1D, UH-1E, UH-1H, UH-1L, TH-1L, and HH-1K models). Since all models in Table 26 are quite similar, we feel that a more meaningful fleet average is obtained by combining these types rather than by considering them individually. Tables 27 through 29 present data for three other H-1 models in Navy service: the UH-1N, AH-1G, and AH-1J. The UH-1N and AH-1J are twin-engine models. These three are sufficiently different (from the H-1 models of Table 26) and we felt they should be treated separately. Using the data of Tables 26 through 29, the three R&M measures are plotted for the various H-1 models in Figures 41 through 52. For all H-1 models, the three R&M measures worsened markedly over the years these helicopters have been in service.[1]

The trends for the various components do not appear to differ systematically from the trends for the total aircraft. The R&M characteristics in the most recent years of the UH-1/HH-1/TH-1 series, the UH-1N, and the AH-1G were all about the same. However, the AH-1J was markedly worse than the other models. The AH-1G deliveries began in 1967, while the first AH-1J deliveries were in 1970 [57]. Surprisingly, the AH-1J, which was based on the AH-1G, exhibited R&M characteristics that were about twice as bad as those of the AH-1G.

[1]In some cases when a helicopter was entering service and the data for these years were not meaningful, they were not plotted.

Table 26. NAVY 3-M DATA FOR UH-1D, UH-1E, UH-1H, UH-1L, TH-1L, AND HH-1K MODELS

YEAR	FLIGHT HOURS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
AIRFRAME							
1973	45165	9804	4.61	5427	8.32	36256	.80
1974	47243	14125	3.34	7027	6.72	41616	.88
1975	48559	15375	3.16	7257	6.69	50996	1.05
1976	37833	15898	2.38	7601	4.98	53796	1.42
1977	40098	16682	2.40	8172	4.91	59040	1.47
1978	35283	19768	1.78	7389	4.78	68319	1.94
1979	15046	6487	2.32	2867	5.25	21068	1.40
ROTORS AND HUBS (MAIN/TAIL)							
1973	45165	4057	11.13	2409	18.75	18645	.41
1974	47243	5634	8.39	2902	16.28	17982	.38
1975	48559	6017	8.07	2924	16.61	23333	.48
1976	37833	6356	5.95	3211	11.78	20671	.55
1977	40098	6431	6.24	3235	12.40	21724	.54
1978	35283	7741	4.56	3097	11.39	27224	.77
1979	15046	2099	7.17	1121	13.42	11125	.74
GEAR BOXES AND DRIVES							
1973	45165	1602	28.19	989	45.67	7491	.17
1974	47243	2767	17.07	1429	33.06	10395	.22
1975	48559	2969	16.36	1437	33.79	9527	.20
1976	37833	3576	10.58	1502	25.19	12714	.34
1977	40098	3049	13.15	1277	31.40	12445	.31
1978	35283	2932	12.03	1339	26.35	14690	.42
1979	15046	1227	12.26	529	28.44	5831	.39
POWER PLANT							
1973	45165	3257	13.87	2174	20.78	12876	.29
1974	47243	4645	10.17	2677	17.65	15499	.33
1975	48559	4672	10.39	2502	19.41	15555	.32
1976	37833	4396	8.61	2361	16.02	20171	.53
1977	40098	4715	8.50	2814	14.25	23988	.60
1978	35283	6429	5.49	3216	10.97	42947	1.22
1979	15046	2226	6.76	1230	12.23	14453	.96
INSTRUMENTS, COMMUNICATION AND NAVIGATION							
1973	45165	5219	8.65	3048	14.82	25287	.56
1974	47243	5870	8.05	3407	13.87	23123	.49
1975	48559	7663	6.34	4195	11.58	28364	.58
1976	37833	7308	5.18	4404	8.59	28571	.76
1977	40098	7021	5.71	4103	9.77	30137	.75
1978	35283	7277	4.85	3864	9.13	34739	.98
1979	15046	2961	5.08	1515	9.93	12848	.85
WEAPON SYSTEMS							
1973	45165	19	2377.11	7	6452.14	74	.00
1974	47243	12	3936.92	4	11810.75	26	.00
1975	48559	10	4855.90	5	9711.80	63	.00
1976	37833	19	1991.21	7	5404.71	71	.00
1977	40098	165	243.02	61	657.34	993	.02
1978	35283	219	161.11	93	379.39	1182	.03
1979	15046	125	120.37	44	341.95	529	.04
* * * T O T A L * * *							
1973	45165	23958	1.89	14054	3.21	100629	2.23
1974	47243	33053	1.43	17446	2.71	108641	2.30
1975	48559	36706	1.32	19320	2.65	127938	2.63
1976	37833	37553	1.01	19086	1.99	135994	3.59
1977	40098	38063	1.05	19602	2.04	148327	3.70
1978	35283	44366	.80	19990	1.36	189101	5.36
1979	15046	15125	.99	7306	2.06	65254	4.38

Table 27. NAVY 3-M DATA FOR MODEL UH-1N

YEAR	FLIGHT HOURS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
AIRFRAME							
1973	15790	4256	3.71	2351	6.72	14377	.91
1974	15608	4249	3.67	2347	6.65	13679	.88
1975	16536	6523	2.54	3413	4.85	21553	1.30
1976	16385	8354	1.96	4130	3.97	27439	1.67
1977	17671	9705	1.82	4795	3.69	31836	1.80
1978	18030	9154	1.97	4772	3.78	44726	2.48
1979	7888	3924	2.01	2235	3.53	19605	2.49
ROTORS AND HUBS(MAIN/TAIL)							
1973	15790	1430	11.04	545	28.97	4134	.26
1974	15608	1228	12.71	552	28.28	3686	.24
1975	16536	2854	5.79	898	18.41	8490	.51
1976	16385	2496	6.56	1081	15.16	9528	.58
1977	17671	2601	6.79	1170	15.10	12631	.71
1978	18030	2004	9.00	915	19.70	12015	.67
1979	7888	544	14.50	303	26.03	2551	.32
GEAR BOXES AND DRIVES							
1973	15790	675	23.39	418	37.78	2966	.19
1974	15608	719	21.71	361	43.24	3145	.20
1975	16536	1142	14.48	455	36.34	4449	.27
1976	16385	1173	13.97	568	28.85	5451	.33
1977	17671	1391	12.70	611	28.92	7873	.45
1978	18030	1513	11.92	700	25.76	11855	.66
1979	7888	449	17.57	225	35.06	1676	.21
POWER PLANT							
1973	15790	2364	6.68	1483	10.65	15382	.97
1974	15608	1982	7.87	1242	12.57	16407	1.05
1975	16536	2654	6.23	1704	9.70	16565	1.00
1976	16385	3559	4.60	2356	6.95	23329	1.42
1977	17671	3601	4.91	2290	7.72	22467	1.27
1978	18030	3405	5.30	2179	8.27	26236	1.46
1979	7888	1444	5.46	953	8.28	14009	1.78
INSTRUMENTS, COMMUNICATION AND NAVIGATION							
1973	15790	2892	5.46	1428	11.06	10737	.68
1974	15608	2610	5.98	1456	10.72	10039	.64
1975	16536	2919	5.66	1612	10.26	11586	.70
1976	16385	3579	4.58	1999	8.20	16614	1.01
1977	17671	3876	4.56	1940	9.11	16098	.91
1978	18030	4283	4.21	1867	9.66	22722	1.26
1979	7888	1662	4.75	818	9.64	9641	1.22
WEAPON SYSTEMS							
1973	15790	10	1579.00	4	3947.50	9	.00
1974	15608	12	1300.67	5	3121.60	9	.00
1975	16536	9	1837.33	2	8268.00	12	.00
1976	16385	9	1820.56	5	3277.00	11	.00
1977	17671	9	1963.44	4	4417.75	11	.00
1978	18030	10	1803.00	4	4507.50	18	.00
1979	7888	3	2629.33	2	3944.00	5	.00
* * * T O T A L * * *							
1973	15790	11627	1.36	6229	2.53	47605	3.01
1974	15608	10800	1.45	5963	2.62	46965	3.01
1975	16536	16101	1.03	8084	2.05	62655	3.79
1976	16385	19170	.85	10139	1.62	82372	5.03
1977	17671	21183	.83	10810	1.63	90916	5.14
1978	18030	20369	.89	10437	1.73	117572	6.52
1979	7888	3026	.38	4536	1.74	47487	6.02

Table 28. NAVY 3-M DATA FOR MODEL AH-1G

YEAR	FLIGHT HOURS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
AIRFRAME							
1973	1362	587	2.32	333	4.09	1765	1.30
1974	1396	531	2.63	286	4.88	1611	1.15
1975	1287	808	1.59	437	2.95	2611	2.03
1976	1472	784	1.88	366	4.02	3272	2.22
1977	2691	1224	2.20	694	3.88	4936	1.82
1978	361	371	.97	192	1.88	1467	4.06
1979	0	4	0.00	2	0.00	6	0.00
ROTORS AND HUBS(MAIN/TAIL)							
1973	1362	95	14.34	61	22.33	411	.30
1974	1396	174	8.02	66	21.15	586	.42
1975	1287	172	7.48	90	14.30	1147	.89
1976	1472	259	5.68	122	12.07	1717	1.17
1977	2691	384	7.01	224	12.01	2968	1.10
1978	361	95	3.80	47	7.68	449	1.24
1979	0	4	0.00	2	0.00	3	0.00
GEAR BOXES AND DRIVES							
1973	1362	72	18.92	49	27.80	216	.16
1974	1396	77	18.13	50	27.92	344	.25
1975	1287	173	7.44	105	12.26	761	.59
1976	1472	186	7.91	81	18.17	1019	.69
1977	2691	249	10.81	122	22.06	1491	.55
1978	361	51	7.08	24	15.04	273	.76
1979	0	1	0.00	0	0.00	1	0.00
POWER PLANT							
1973	1362	217	6.28	133	10.24	518	.38
1974	1396	149	9.37	83	16.82	599	.43
1975	1287	289	4.45	158	8.15	938	.73
1976	1472	249	5.91	126	11.68	1518	1.03
1977	2691	309	8.71	188	14.31	1230	.46
1978	361	114	3.17	58	6.22	427	1.18
1979	0	7	0.00	2	0.00	17	0.00
INSTRUMENTS,COMMUNICATION AND NAVIGATION							
1973	1362	315	4.32	122	11.16	1063	.78
1974	1396	328	4.26	125	11.17	862	.62
1975	1287	268	4.80	127	10.13	1557	1.21
1976	1472	360	4.09	158	9.32	1603	1.09
1977	2691	688	3.91	355	7.58	3805	1.41
1978	361	161	2.24	66	5.47	1066	2.95
1979	0	1	0.00	1	0.00	4	0.00
WEAPON SYSTEMS							
1973	1362	63	21.62	17	80.12	177	.13
1974	1396	24	58.17	8	174.50	54	.04
1975	1287	44	29.25	12	107.25	82	.06
1976	1472	79	18.63	35	42.06	385	.26
1977	2691	190	14.16	90	29.90	2158	.80
1978	361	25	14.44	10	36.10	93	.26
1979	0	5	0.00	5	0.00	15	0.00
* * * TOTAL * * *							
1973	1362	1349	1.01	715	1.90	4150	3.05
1974	1396	1283	1.09	619	2.26	4056	2.91
1975	1287	1754	.73	929	1.39	7096	5.51
1976	1472	1917	.77	988	1.50	9514	6.46
1977	2691	3044	.88	1673	1.61	16558	6.15
1978	361	317	1.14	397	.91	3775	10.46
1979	0	22	0.00	12	0.00	46	0.00

Table 29. NAVY 3-M DATA FOR MODEL AH-1J

YEAR	FLIGHT HOURS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
AIRFRAME							
1973	6524	4569	1.43	2439	2.67	12021	1.84
1974	5376	3350	1.60	1923	2.80	11402	2.12
1975	7640	5356	1.43	2812	2.72	14140	1.85
1976	5162	4789	1.08	2659	1.94	13823	2.68
1977	6088	7100	.86	3950	1.54	19331	3.18
1978	4435	5068	.88	2940	1.51	17557	3.96
1979	1115	1126	.99	604	1.85	6065	5.44
ROTORS AND HUBS(MAIN/TAIL)							
1973	6524	914	7.14	411	15.87	4367	.67
1974	5376	781	6.88	413	13.02	4048	.75
1975	7640	1159	6.59	525	14.55	4291	.56
1976	5162	967	5.34	410	12.59	4562	.38
1977	6088	1111	5.48	516	11.80	4170	.68
1978	4435	810	5.48	340	13.04	3434	.77
1979	1115	203	5.49	97	11.49	678	.61
GEAR BOXES AND DRIVES							
1973	6524	708	9.21	432	15.10	3843	.59
1974	5376	461	11.66	269	19.99	2046	.38
1975	7640	796	9.60	368	20.76	3036	.40
1976	5162	820	6.30	403	12.81	5063	.98
1977	6088	926	6.57	417	14.60	4205	.69
1978	4435	653	6.79	319	13.90	5375	1.21
1979	1115	146	7.64	86	12.97	935	.84
POWER PLANT							
1973	6524	2167	3.01	1324	4.93	10253	1.57
1974	5376	1905	2.82	1347	3.99	12389	2.30
1975	7640	2234	3.42	1368	5.58	8594	1.12
1976	5162	1693	3.05	1042	4.95	6877	1.33
1977	6088	2247	2.71	1336	4.56	11762	1.93
1978	4435	1737	2.55	1142	3.88	12590	2.84
1979	1115	352	3.17	217	5.14	2154	1.93
INSTRUMENTS,COMMUNICATION AND NAVIGATION							
1973	6524	2218	2.94	1054	6.19	6460	.99
1974	5376	1507	3.57	821	6.55	7228	1.34
1975	7640	2093	3.65	983	7.77	6285	.82
1976	5162	1599	3.23	860	6.00	8212	1.59
1977	6088	2112	2.88	1009	6.03	10084	1.66
1978	4435	1582	2.80	741	5.99	8887	2.00
1979	1115	322	3.46	170	6.56	1857	1.67
WEAPON SYSTEMS							
1973	6524	1037	6.29	461	14.15	2991	.46
1974	5376	701	7.67	349	15.40	3271	.61
1975	7640	969	7.88	447	17.09	5239	.69
1976	5162	932	5.54	443	11.65	6613	1.28
1977	6088	995	6.12	464	13.12	5734	.94
1978	4435	717	6.19	269	16.49	3737	.84
1979	1115	224	4.98	79	14.11	1310	1.17
* * * T O T A L * * *							
1973	6524	11613	.56	6121	1.07	39935	6.12
1974	5376	8705	.62	5122	1.05	40384	7.51
1975	7640	12607	.61	6503	1.17	41585	5.44
1976	5162	10800	.48	5817	.89	45150	8.75
1977	6088	14491	.42	7692	.79	55296	9.08
1978	4435	10567	.42	5751	.77	51580	11.63
1979	1115	2373	.47	1253	.89	12999	11.66

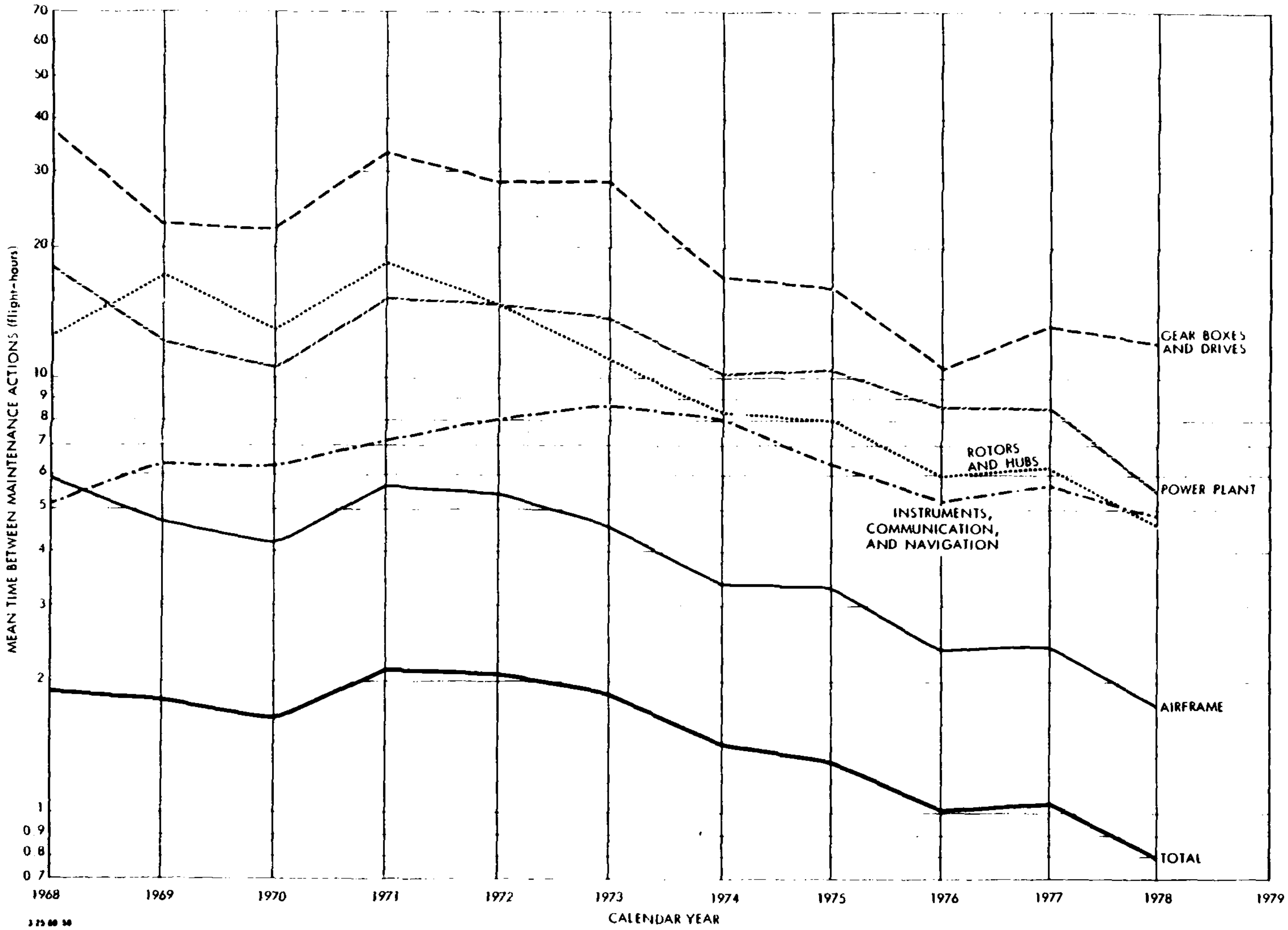

Figure 41. MTBMA FOR THE NAVY SINGLE ENGINE UH-1/HH-1/TH-1 SERIES

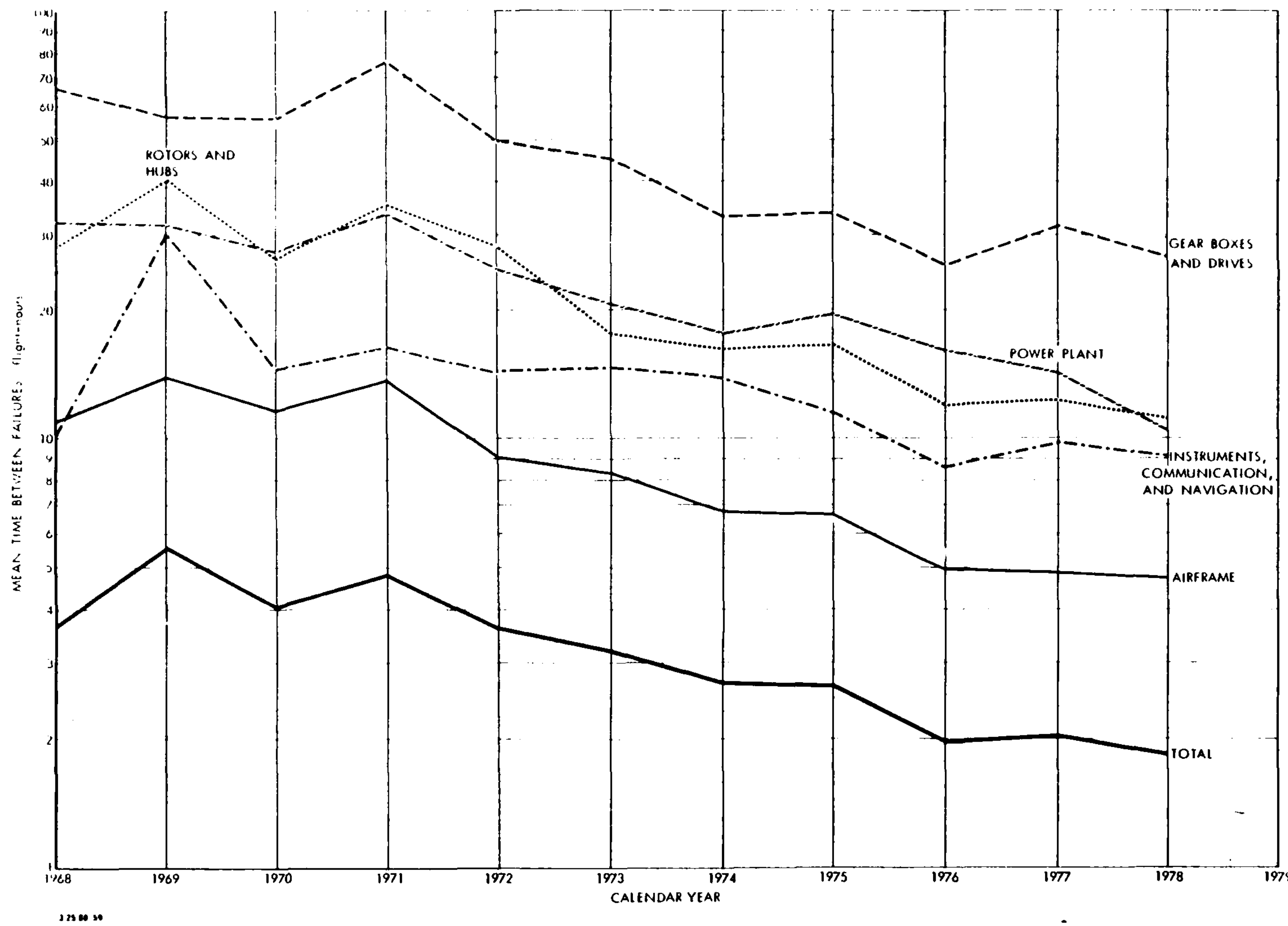

Figure 42. MTBF VERSUS YEAR FOR THE NAVY SINGLE ENGINE UH-1/HH-1/TH-1 SERIES

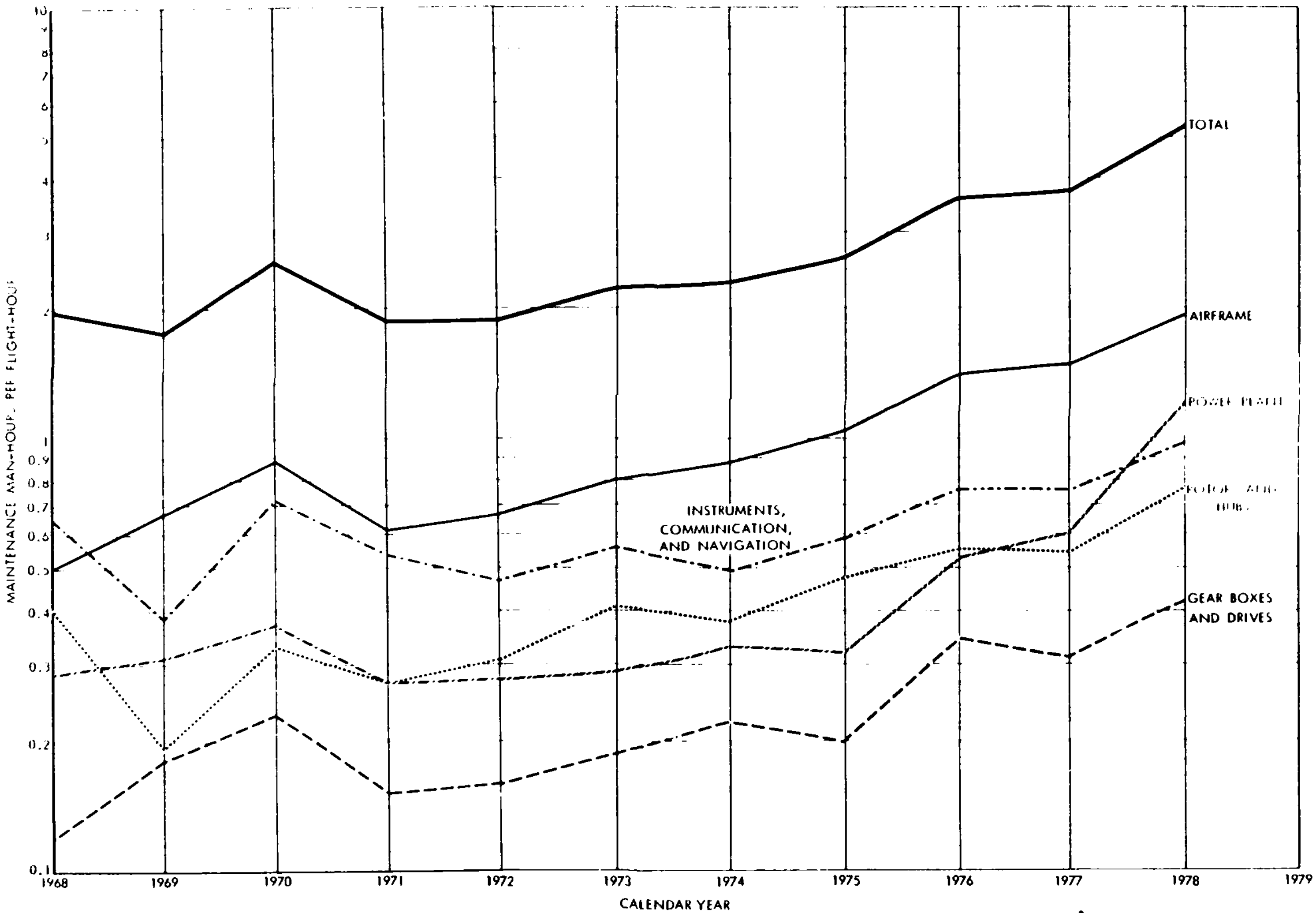

Figure 43. MMH/FH FOR THE NAVY SINGLE ENGINE UH-1/HH-1/TH-1 SERIES

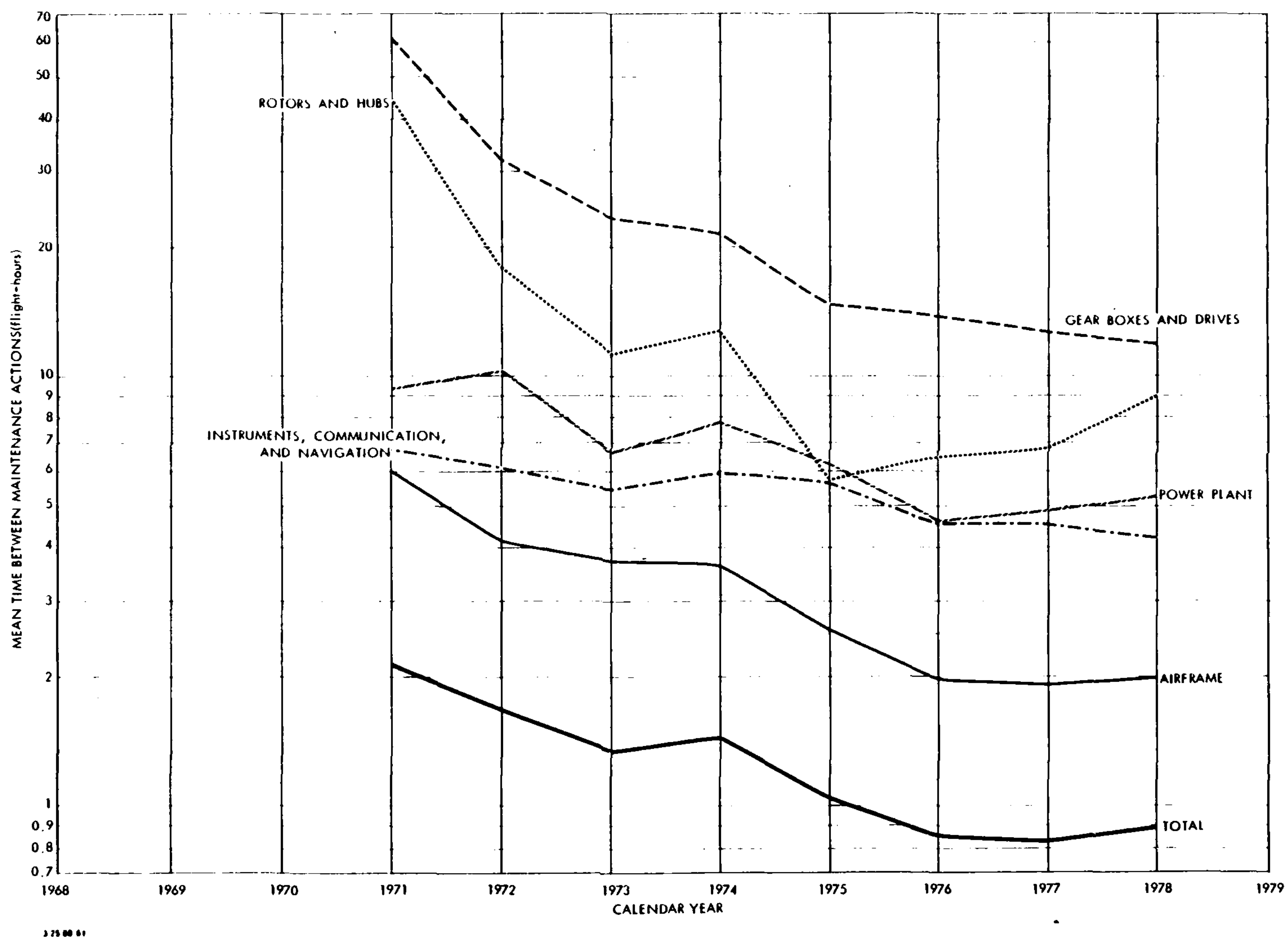

Figure 44. MTBMA FOR THE NAVY UH-1N

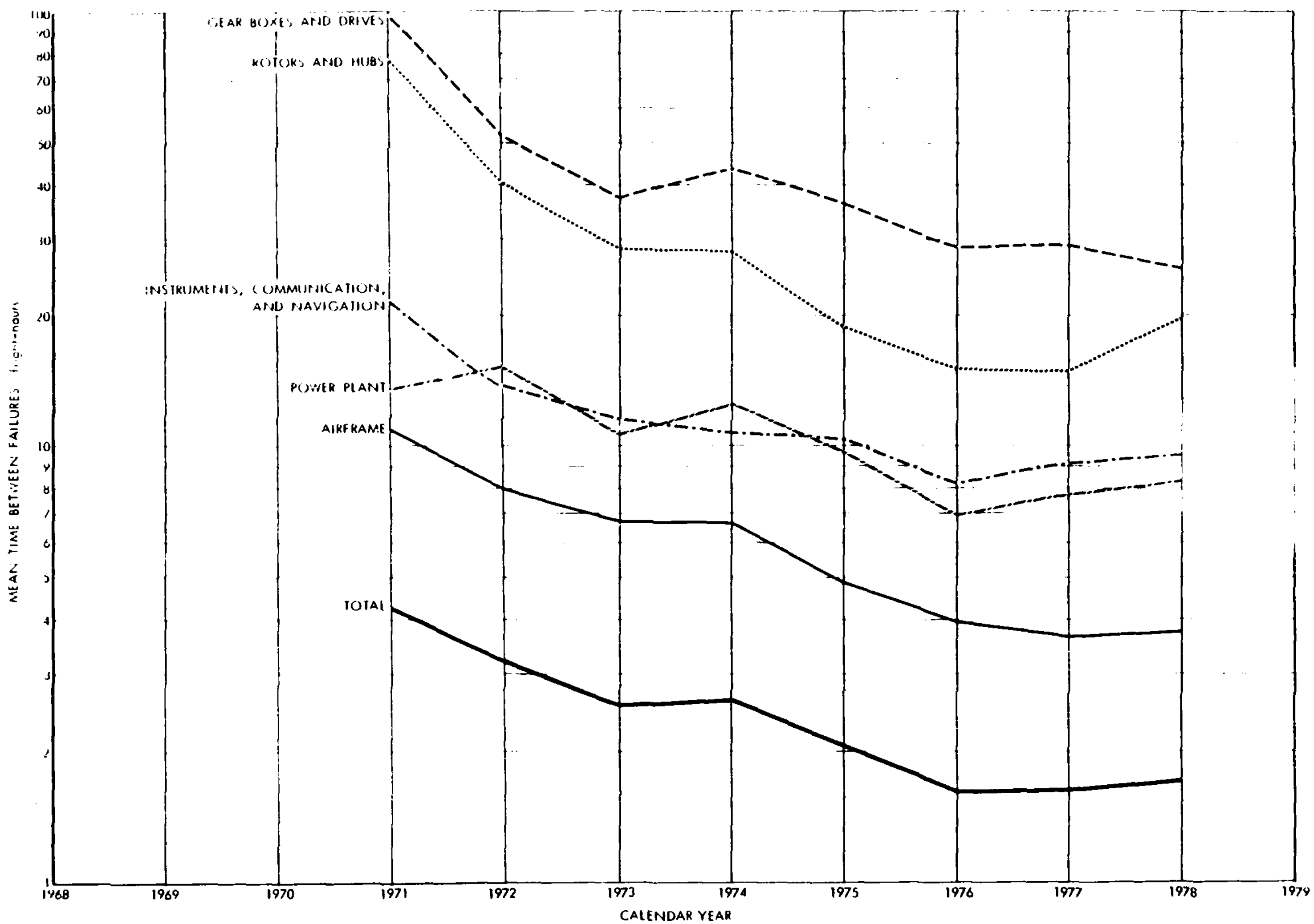

Figure 45. MTBF VERSUS YEAR FOR THE NAVY UH-1N

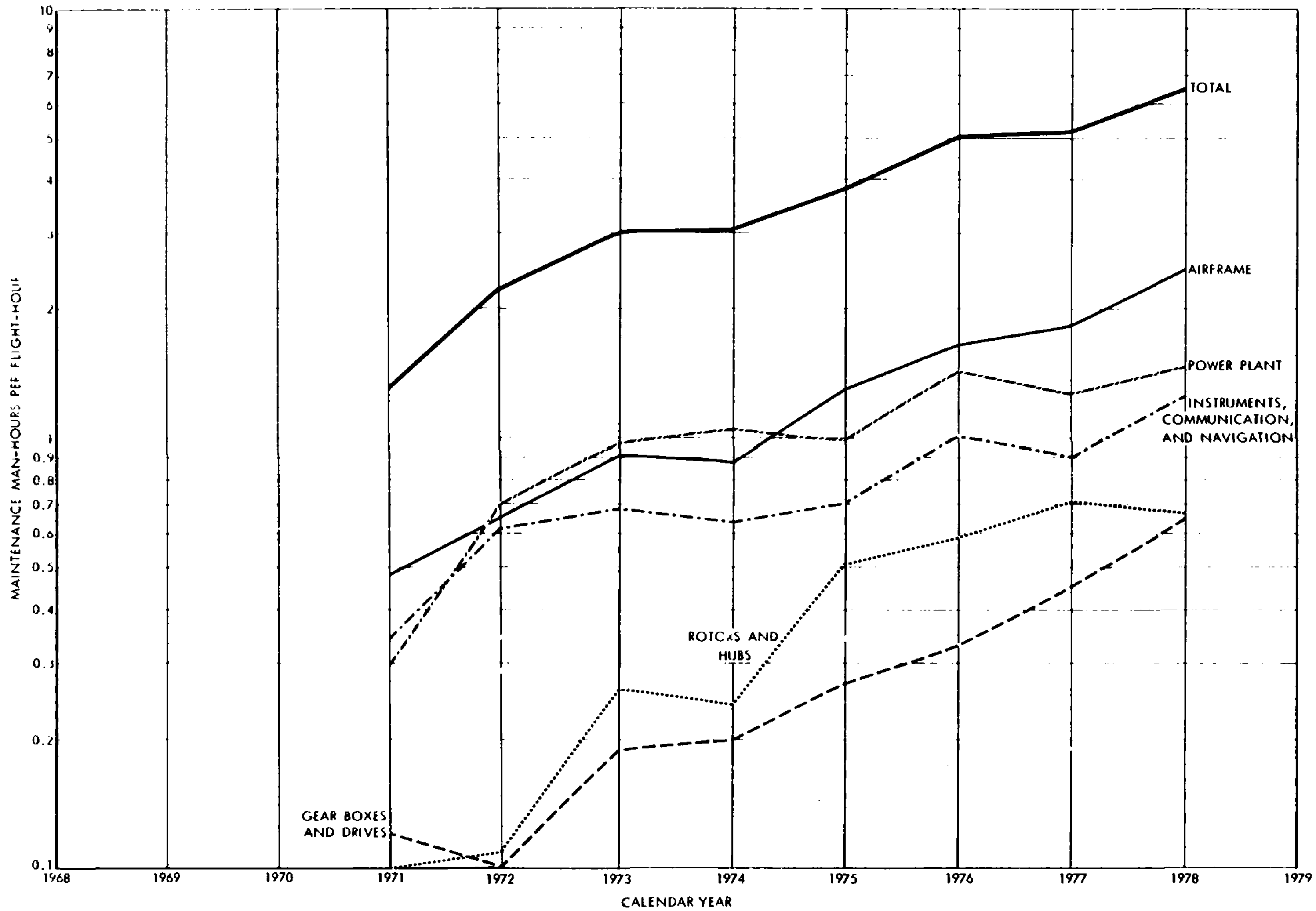

Figure 46. MMH/FH FOR THE NAVY UH-1N

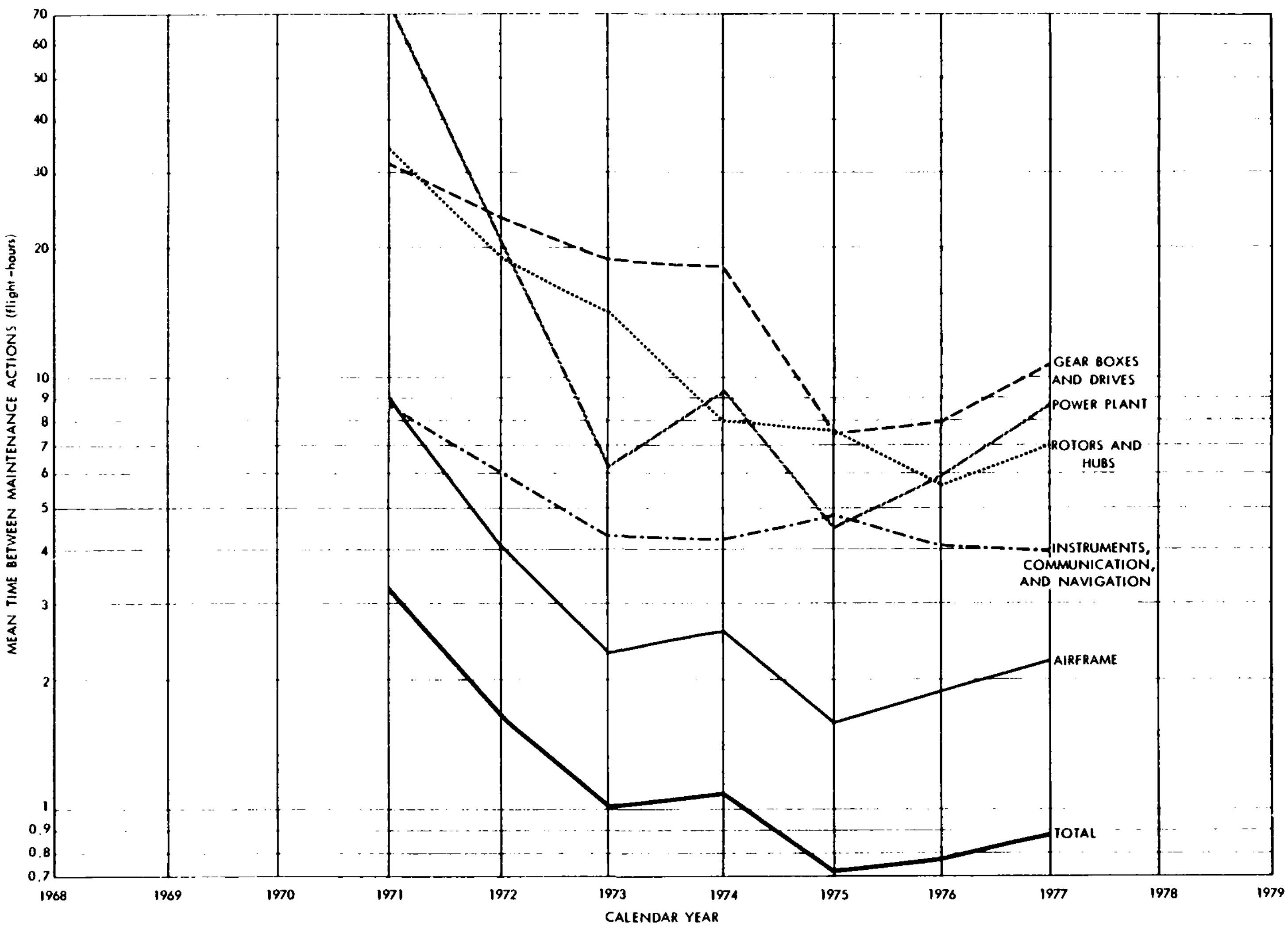

Figure 47. MTBMA FOR THE NAVY AH-1G

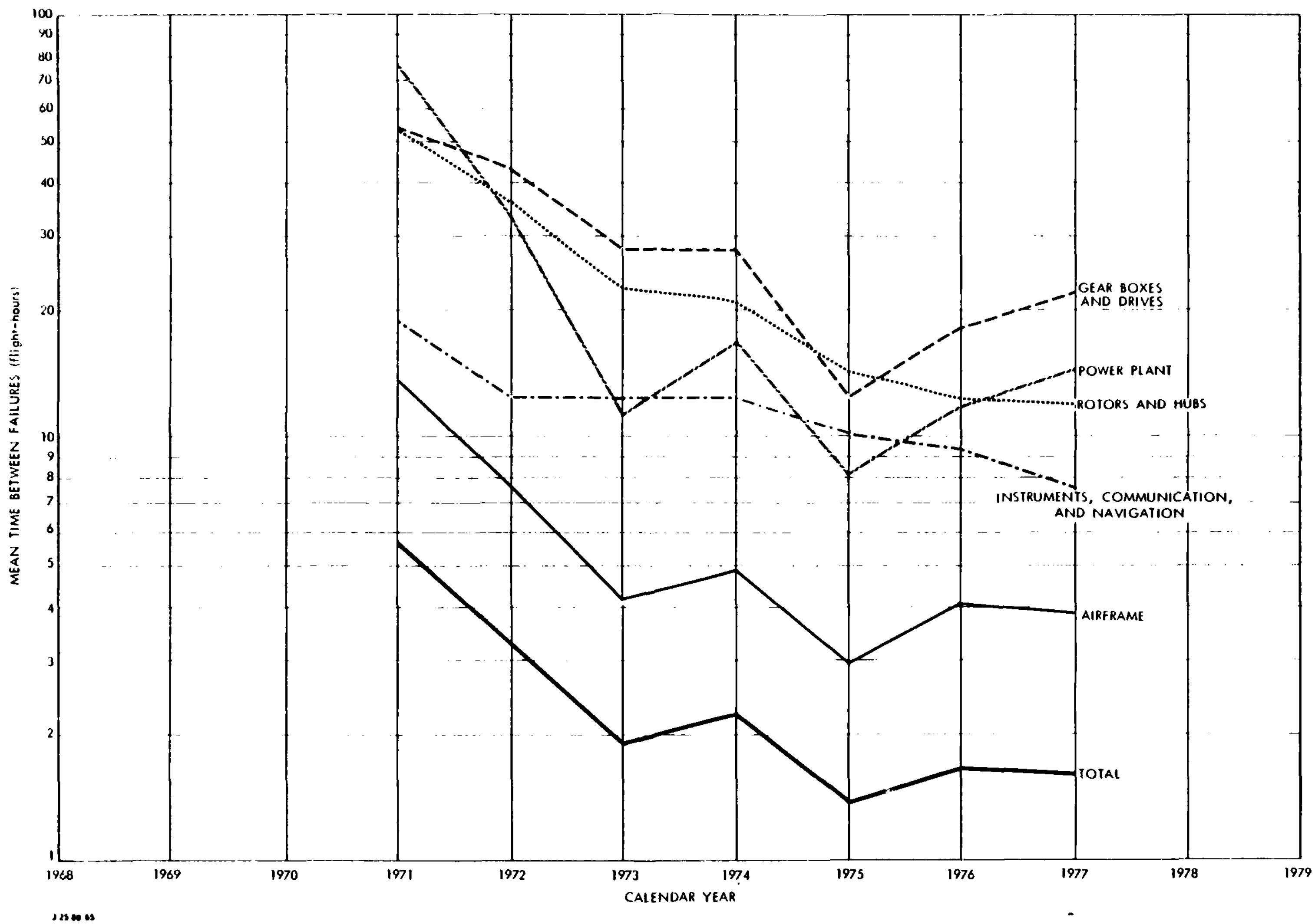

Figure 48. MTBF VERSUS YEAR FOR THE NAVY AH-1G

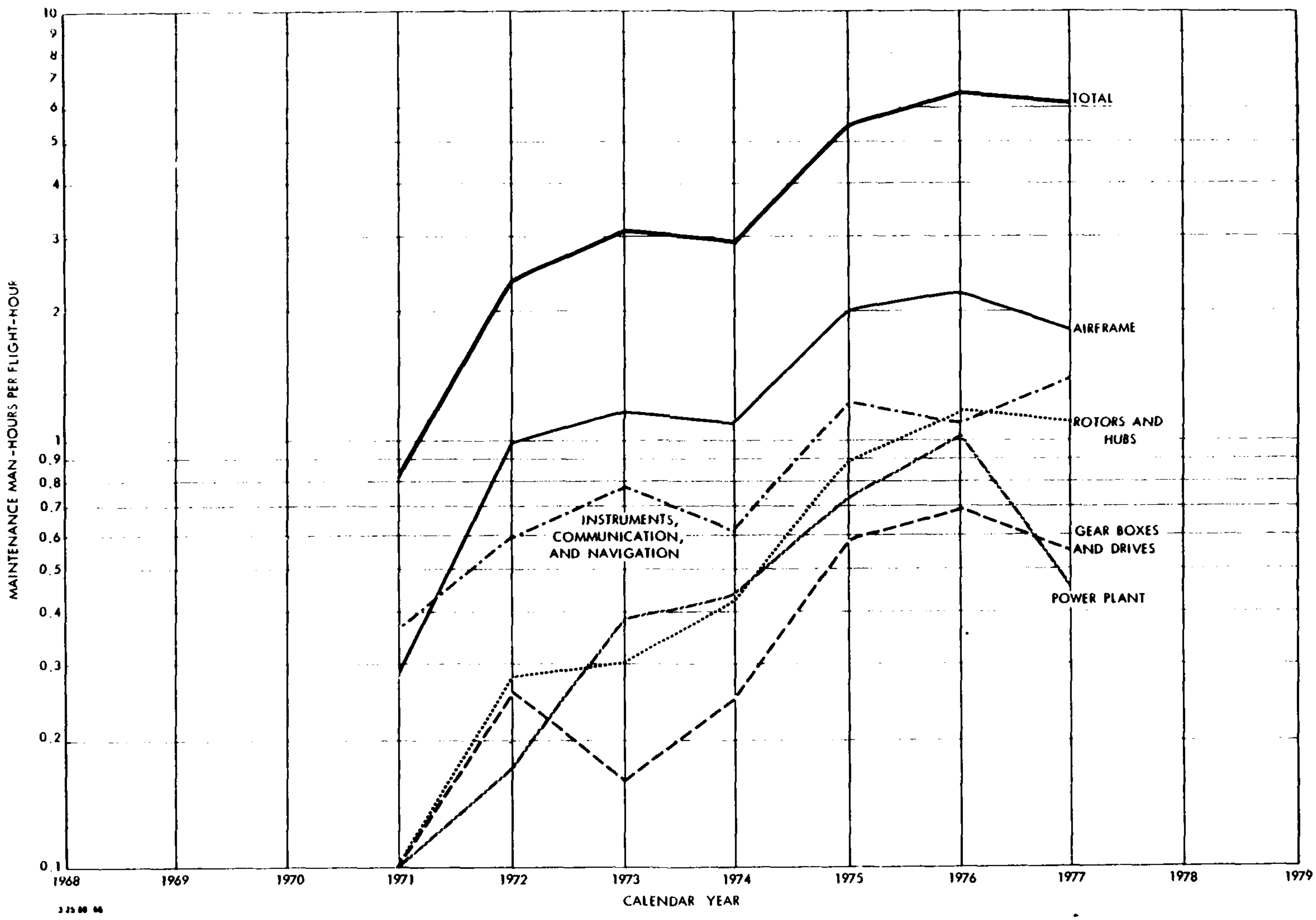

Figure 49. MMH/FH FOR THE NAVY AH-1G

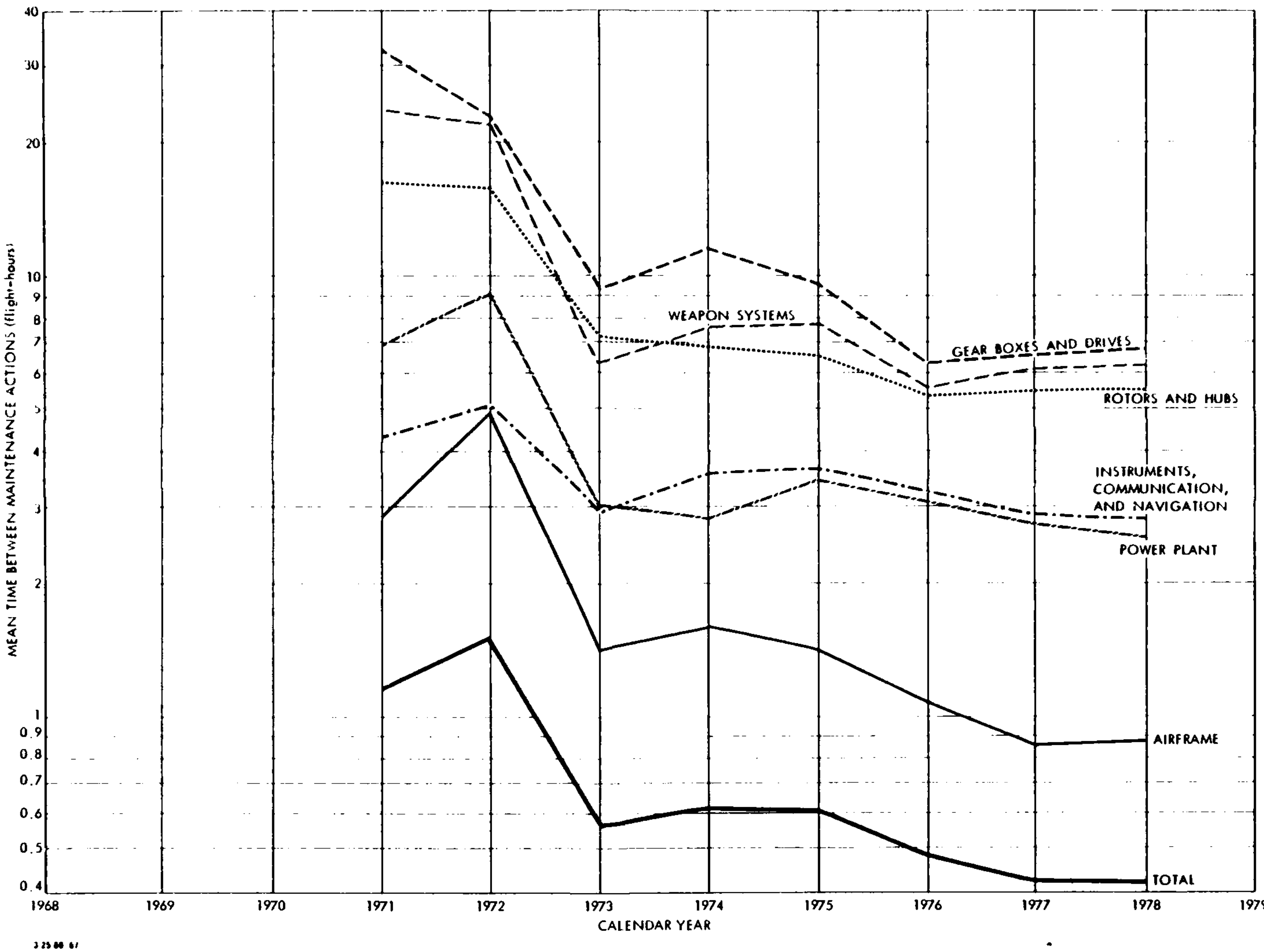

Figure 50. MTBMA FOR THE NAVY AH-1J

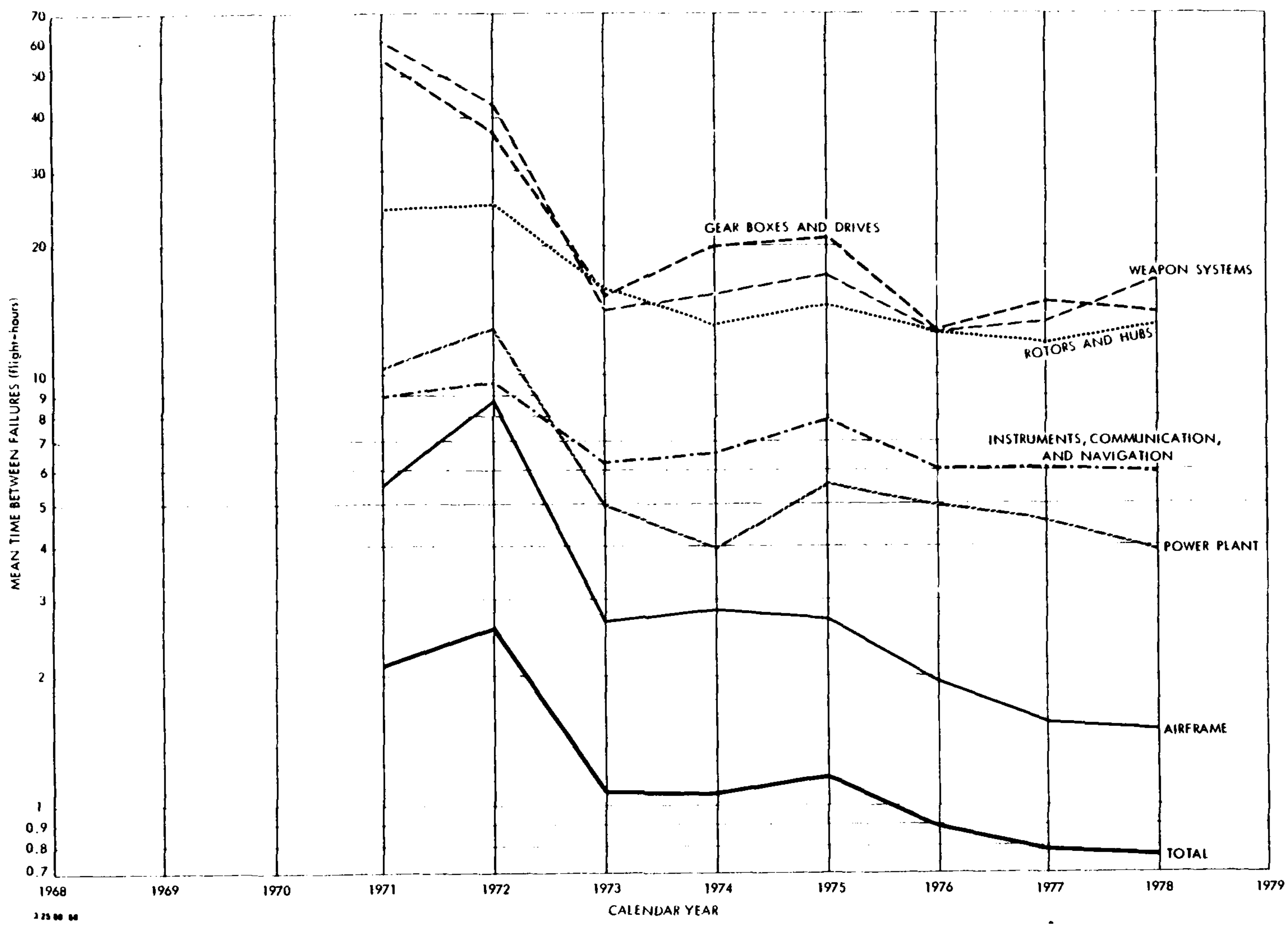

Figure 51. MTBF VERSUS YEAR FOR THE NAVY AH-1J

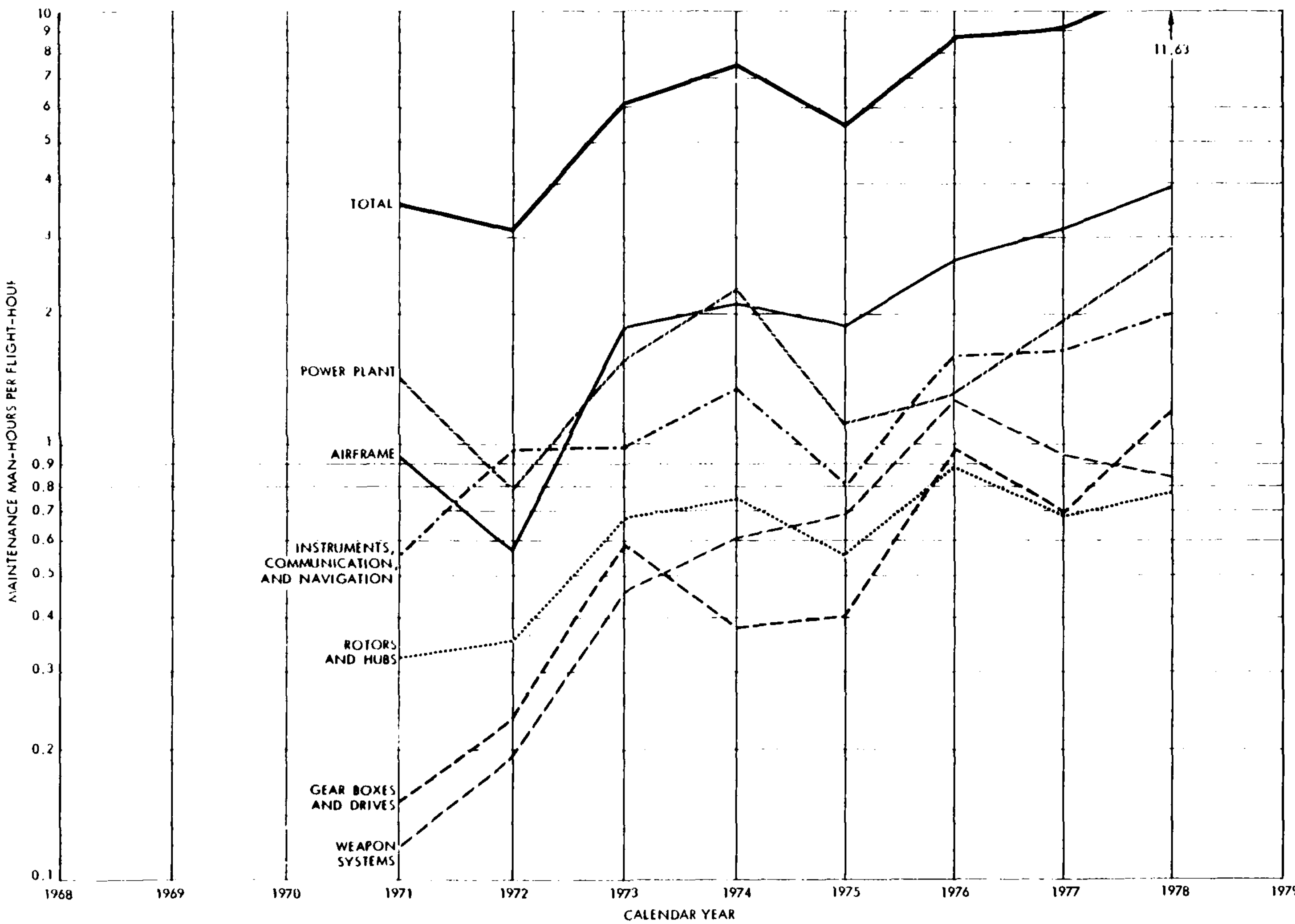

Figure 52. MMH/FH FOR THE NAVY AH-1J

2. The H-2

The U.S. Navy is the only operator of the H-2. A total of 190 were built--each with a single T-58 engine. Eighty-eight were UH-2A aircraft and 102 were UH-2B aircraft, which differed only in the noninstallation of certain electronic navigation equipment. Starting in 1967, the survivors of these 190 aircraft were all converted to twin T-58 engines and were redesignated as the UH-2C, HH-2C, HH-2D, SH-2D, and SH-2F. We first segregated the 3-M data for the H-2's into three groups: (1) the UH-2A and UH-2B; (2) the UH-2C, HH-2C, and HH-2D; and (3) the SH-2D and SH-2F. However, the three R&M measures for these three groups were all quite similar in total and by component, both in levels of R&M and in trends over time. Accordingly, in Table 30 and Figures 53 through 55, we have aggregated data for all the H-2 aircraft. Figures 53 through 55 indicate that the three R&M measures have all worsened somewhat over time. The trends for the various components do not appear to differ systematically from the trends for the total aircraft.

Compared with the other Navy helicopter types, the H-2 R&M characteristics are poor, particularly relative to the H-1 aircraft, which are approximately the same size. There are probably several causes contributing to this result:

- The H-2 generally has been operated in detachments of one or a few aircraft. Economies of scale thus have been lacking in their operating environment.
- Fewer H-2 aircraft than any of the other types were built. Accordingly, the economic incentives to introduce product improvements have not been as great as for the other types.
- Insofar as years of experience and production quantities are concerned, Kaman is somewhat behind the other manufacturers.

AD-A105 775 INSTITUTE FOR DEFENSE ANALYSES ARLINGTON VA PROGRAM --ETC F/G 1/3
HELICOPTER RELIABILITY AND MAINTAINABILITY TRENDS DURING DEVELO--ETC(U)
JUL 81 N J ASHER, L L DOUGLAS, R H JAKOBOVITS MDA903-79-C-0320

UNCLASSIFIED IDA-S-520 IDA/HQ-81-23636 NL

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Table 30. NAVY 3-M DATA FOR ALL H-2 MODELS

YEAR	FLIGHT HOURS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
AIRFRAME							
1973	12185	14880	.32	7535	1.62	37618	3.09
1974	11053	17083	.65	7713	1.43	40027	3.62
1975	10473	17141	.61	8184	1.28	41840	4.00
1976	14634	18890	.77	9087	1.61	53024	3.62
1977	13471	18564	.73	7943	1.70	59927	4.45
1978	12494	21561	.58	8189	1.53	60286	4.83
1979	4998	8945	.56	3831	1.30	25780	5.16
ROTORS AND HUBS (MAIN/TAIL)							
1973	12185	4905	2.48	2893	4.21	17459	1.43
1974	11053	4026	2.75	2131	5.19	13584	1.23
1975	10473	3133	3.34	1607	6.52	10349	.99
1976	14634	3436	4.26	1783	8.21	11980	.82
1977	13471	3515	3.83	1689	7.98	13554	1.01
1978	12494	4560	2.74	2191	5.70	18719	1.50
1979	4998	2030	2.46	1030	4.85	8894	1.78
GEAR BOXES AND DRIVES							
1973	12185	2202	5.53	1255	9.71	9849	.81
1974	11053	2717	4.07	1247	8.86	10309	.93
1975	10473	2788	3.76	1209	8.66	10203	.97
1976	14634	3331	4.39	1521	9.62	13015	.89
1977	13471	3094	4.35	1416	9.51	14173	1.05
1978	12494	3065	4.08	1525	8.19	15070	1.21
1979	4998	1143	4.37	587	8.51	4102	.82
POWER PLANT							
1973	12185	4211	2.89	2385	5.11	16017	1.31
1974	11053	4732	2.34	2359	4.69	16110	1.46
1975	10473	4400	2.38	2176	4.81	14356	1.37
1976	14634	5146	2.84	2310	6.34	21563	1.47
1977	13471	4381	3.07	1820	7.40	16577	1.23
1978	12494	4278	2.92	2000	6.25	19000	1.52
1979	4998	1458	3.43	688	7.26	7200	1.44
INSTRUMENTS, COMMUNICATION AND NAVIGATION							
1973	12185	5248	2.32	2629	4.63	17687	1.45
1974	11053	4776	2.31	2286	4.84	18685	1.69
1975	10473	4754	2.20	2148	4.88	20961	2.00
1976	14634	5203	2.81	2286	6.40	25021	1.71
1977	13471	4933	2.73	2136	6.31	23397	1.74
1978	12494	4638	2.69	2131	5.86	22579	1.81
1979	4998	2160	2.31	955	5.23	9548	1.91
WEAPON SYSTEMS							
1973	12185	219	55.64	114	106.89	703	.06
1974	11053	363	30.45	159	69.52	900	.08
1975	10473	615	17.03	278	37.67	1989	.19
1976	14634	613	23.87	264	55.43	2032	.14
1977	13471	577	23.35	229	58.83	1696	.13
1978	12494	604	20.69	209	59.78	1590	.13
1979	4998	302	16.55	109	45.85	582	.12
* * * T O T A L * * *							
1973	12185	31665	.38	16811	.72	99333	8.15
1974	11053	33697	.33	15895	.70	99615	9.01
1975	10473	32831	.32	15602	.67	99698	9.52
1976	14634	36619	.40	17251	.85	126635	8.65
1977	13471	35064	.38	15233	.88	129324	9.60
1978	12494	38706	.32	16245	.77	137244	10.98
1979	4998	16038	.31	7200	.69	56106	11.23

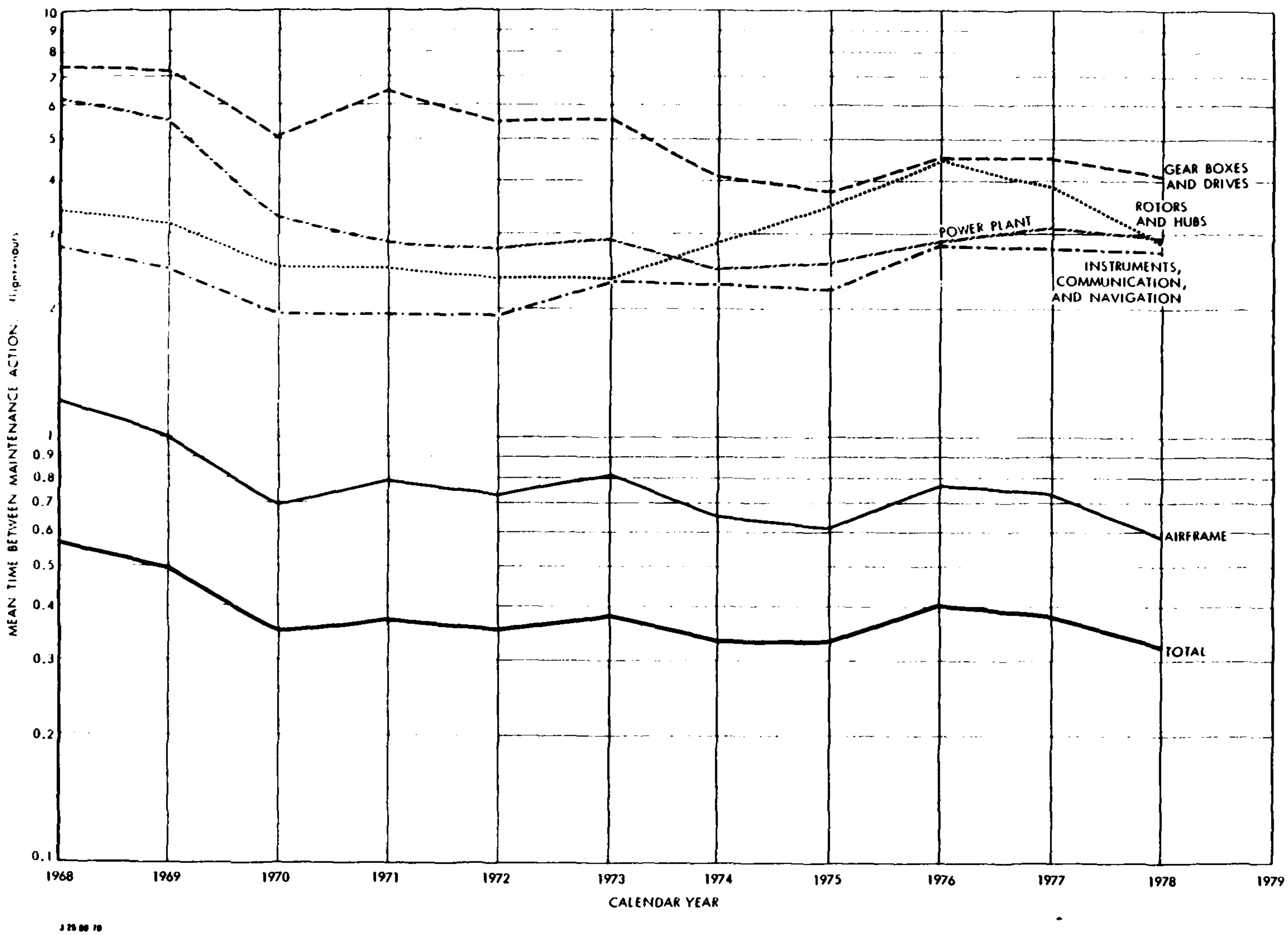

Figure 53. MTBMA FOR ALL NAVY H-2 MODELS

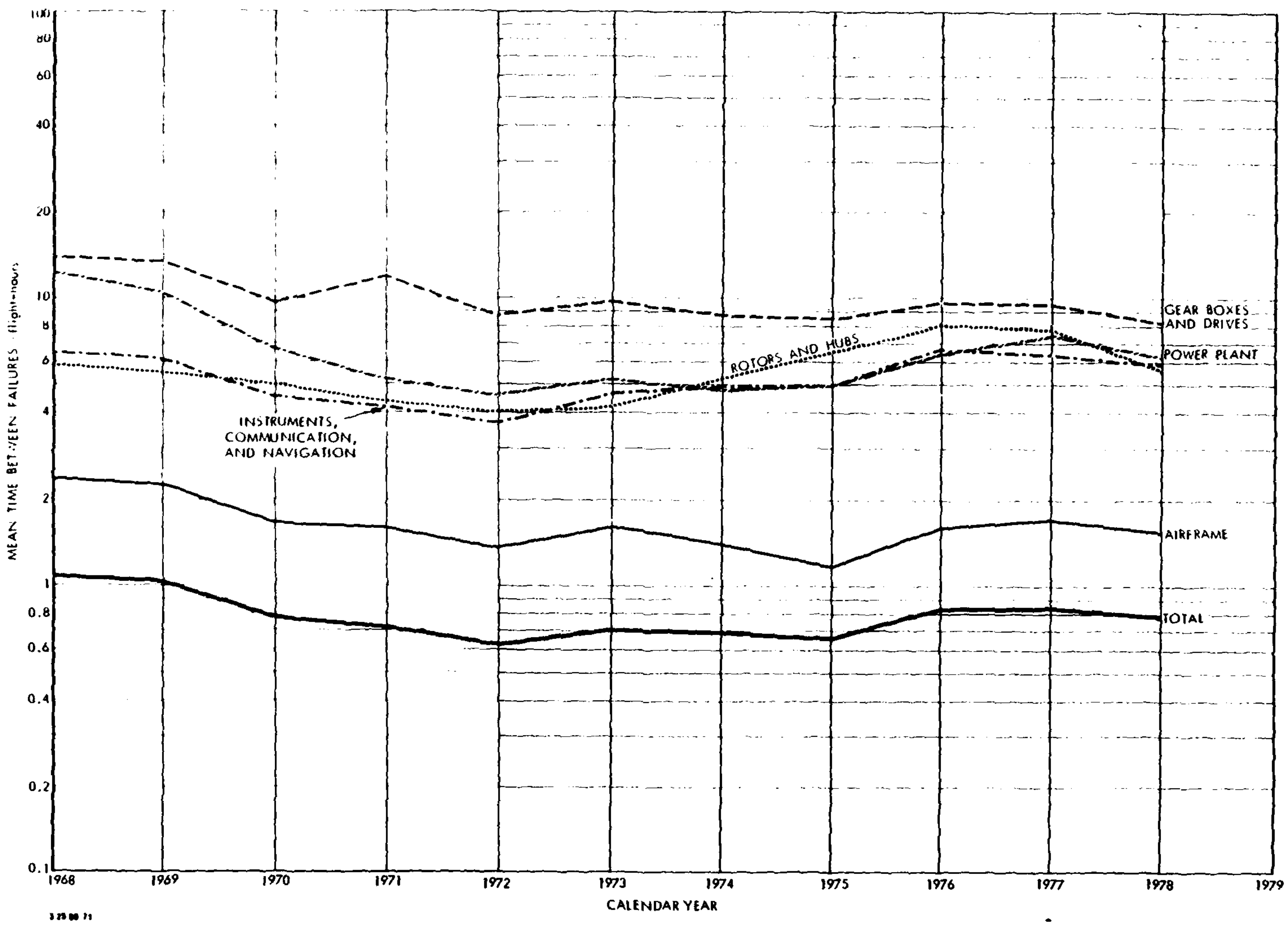

Figure 54. MTBF VERSUS YEAR FOR ALL NAVY H-2 MODELS

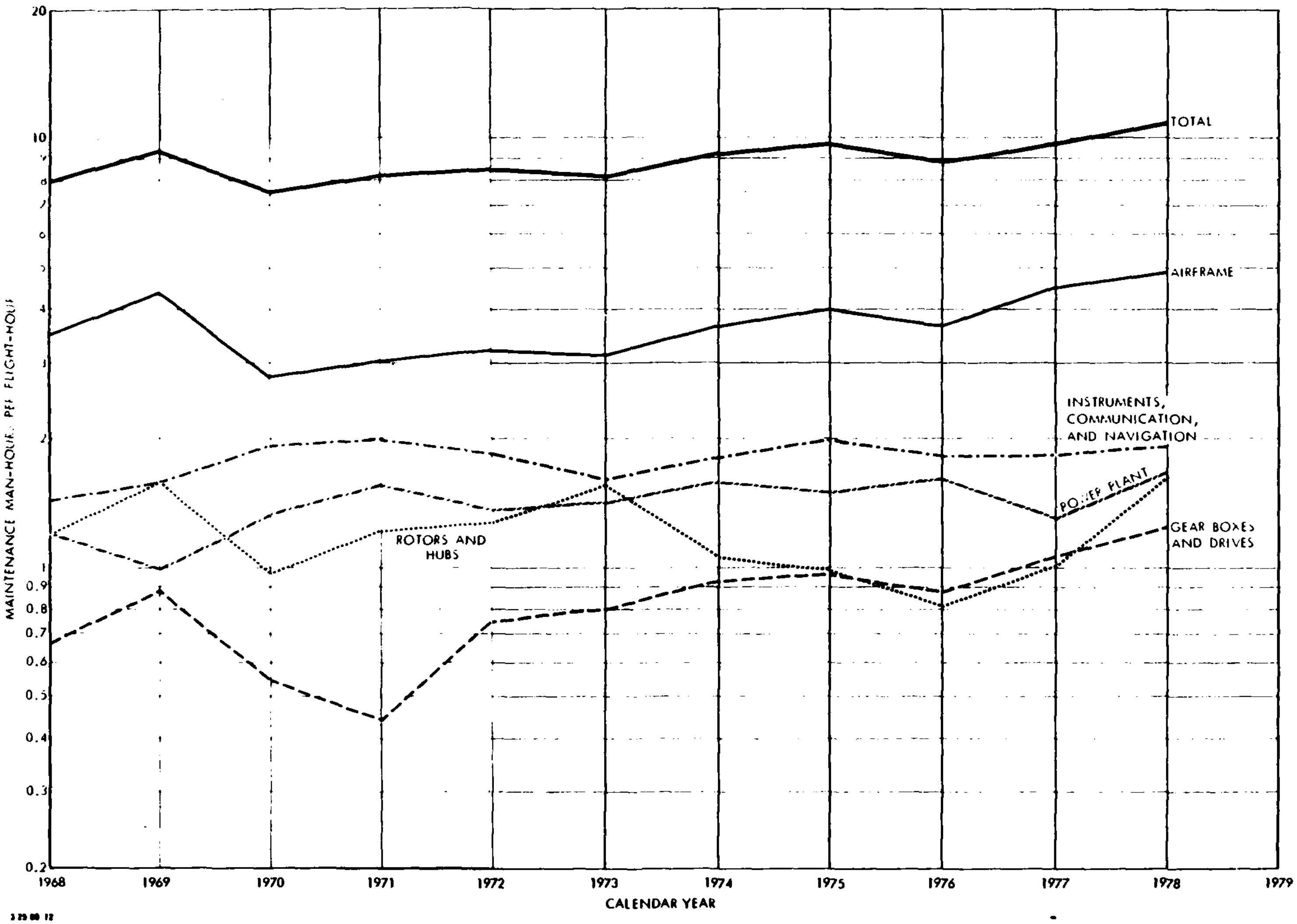

Figure 55. MMH/FH FOR ALL THE NAVY H-2 MODELS

3. The H-3

Most H-3 aircraft in Navy service over the 1968-1978 time period were SH-3 aircraft (antisubmarine-warfare helicopters)--mainly SH-3A, SH-3D, SH-3G, and SH-3H aircraft. Table 31 presents 3-M data for all H-3 models; the three R&M measures are plotted in Figures 56 through 58. Relative to 1968, all three measures improved markedly in 1969, but after 1969 they worsened fairly steadily over time, until they were considerably worse in 1978 than they were in 1968. The trends for the various components do not appear to differ systematically from the trends for the total aircraft.

Table 31. NAVY 3-M DATA FOR ALL H-3 MODELS

YEAR	FLIGHT HOURS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
AIRFRAME							
1973	42463	36636	1.16	19749	2.15	95432	2.25
1974	43415	42022	1.03	19426	2.23	111873	2.58
1975	46129	46730	.99	21512	2.14	139375	3.02
1976	47138	51410	.92	23125	2.04	149949	3.18
1977	47547	55391	.86	23891	1.99	165679	3.48
1978	45646	61699	.74	26790	1.70	163063	3.57
1979	18137	26094	.70	11474	1.58	64599	3.56
ROTORS AND HUBS(MAIN/TAIL)							
1973	42463	6324	6.71	3248	13.07	25476	.60
1974	43415	6912	6.28	3314	13.10	29146	.67
1975	46129	7989	5.77	3887	11.87	34414	.75
1976	47138	8098	5.82	3962	11.90	36632	.78
1977	47547	8342	5.70	4022	11.82	37816	.80
1978	45646	8353	5.46	3778	12.08	33222	.73
1979	18137	3516	5.16	1748	10.38	13859	.76
GEAR BOXES AND DRIVES							
1973	42463	3277	12.96	1770	23.99	20174	.48
1974	43415	3268	13.29	1675	25.92	20481	.47
1975	46129	3468	13.30	1807	25.53	22093	.48
1976	47138	3494	13.49	1829	25.77	22279	.47
1977	47547	4099	11.60	2063	23.05	28318	.60
1978	45646	4620	9.88	2331	19.58	26287	.58
1979	18137	1785	10.16	991	18.30	7925	.44
POWER PLANT							
1973	42463	6347	6.69	3234	13.13	25177	.59
1974	43415	7148	6.07	3081	14.09	28008	.65
1975	46129	8506	5.42	3535	13.05	37261	.81
1976	47138	9367	5.03	3841	12.27	42001	.89
1977	47547	9316	5.10	3670	12.96	43356	.91
1978	45646	10384	4.40	3718	12.28	50344	1.10
1979	18137	4218	4.30	1442	12.58	19897	1.10
INSTRUMENTS,COMMUNICATION AND NAVIGATION							
1973	42463	16225	2.62	7573	5.61	54913	1.29
1974	43415	16896	2.57	7457	5.82	59344	1.37
1975	46129	19073	2.42	8507	5.42	74151	1.61
1976	47138	19303	2.44	8358	5.64	82497	1.75
1977	47547	19693	2.41	8425	5.64	81323	1.71
1978	45646	19168	2.38	8177	5.58	81392	1.78
1979	18137	7736	2.34	3228	5.62	32068	1.77
WEAPON SYSTEMS							
1973	42463	1314	32.32	573	74.11	2885	.07
1974	43415	1645	26.39	549	79.08	4240	.10
1975	46129	1808	25.51	612	75.37	4736	.10
1976	47138	1883	25.03	572	82.41	5118	.11
1977	47547	2822	16.85	715	66.50	6849	.14
1978	45646	3893	11.73	1132	40.32	9520	.21
1979	18137	1629	11.13	437	41.50	3535	.19
* * * T O T A L * * *							
1973	42463	70123	.61	36147	1.17	224117	5.28
1974	43415	77891	.56	35502	1.22	253092	5.83
1975	46129	87574	.53	39864	1.16	312030	6.76
1976	47138	93555	.50	41687	1.13	338475	7.18
1977	47547	99603	.48	42786	1.11	363341	7.64
1978	45646	108119	.42	45926	.99	363828	7.97
1979	18137	44981	.40	19320	.94	141983	7.82

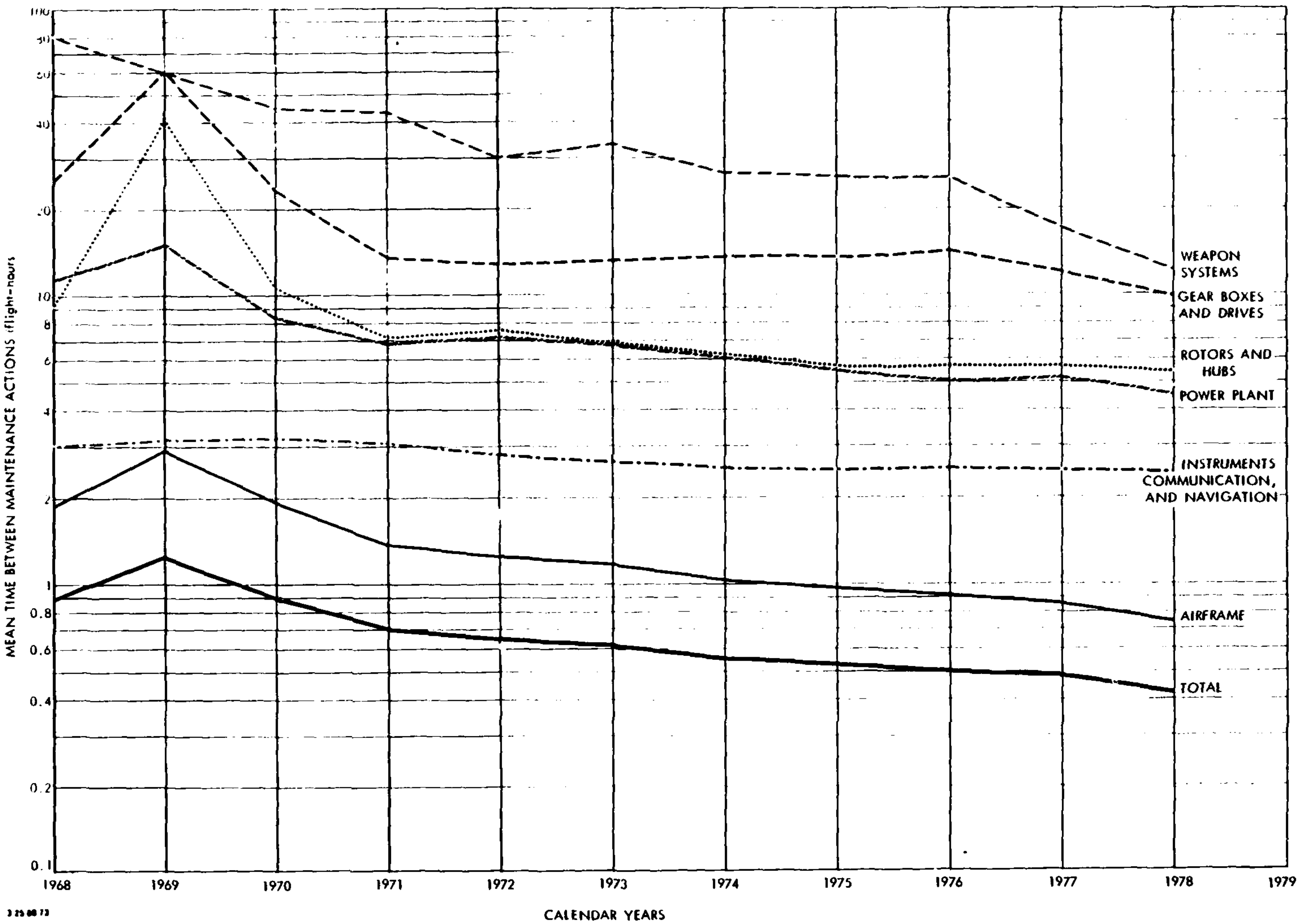

Figure 56. MTBMA FOR THE NAVY H-3(S)

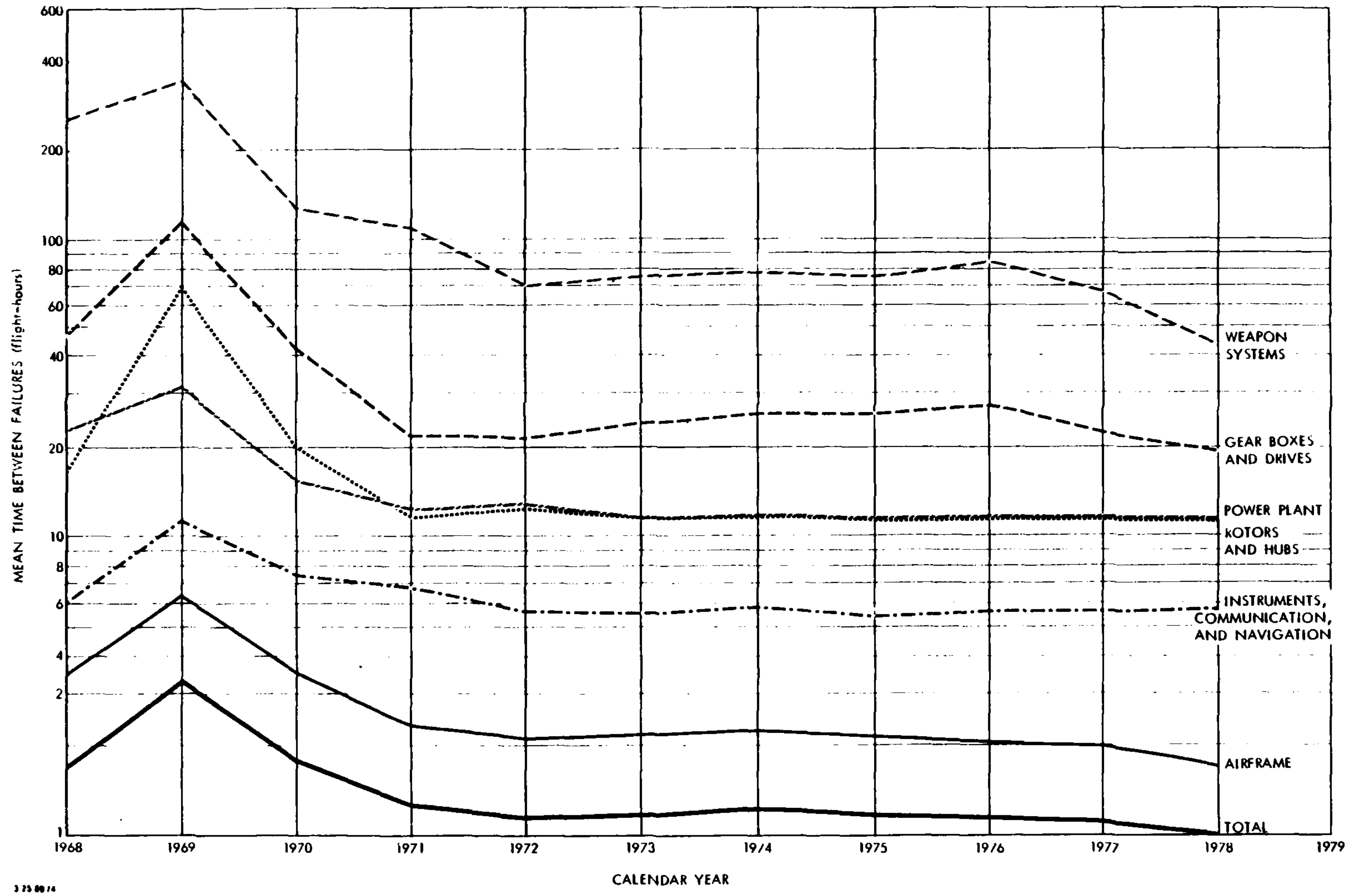

Figure 57. MTBF VERSUS YEAR FOR THE NAVY H-3(S)

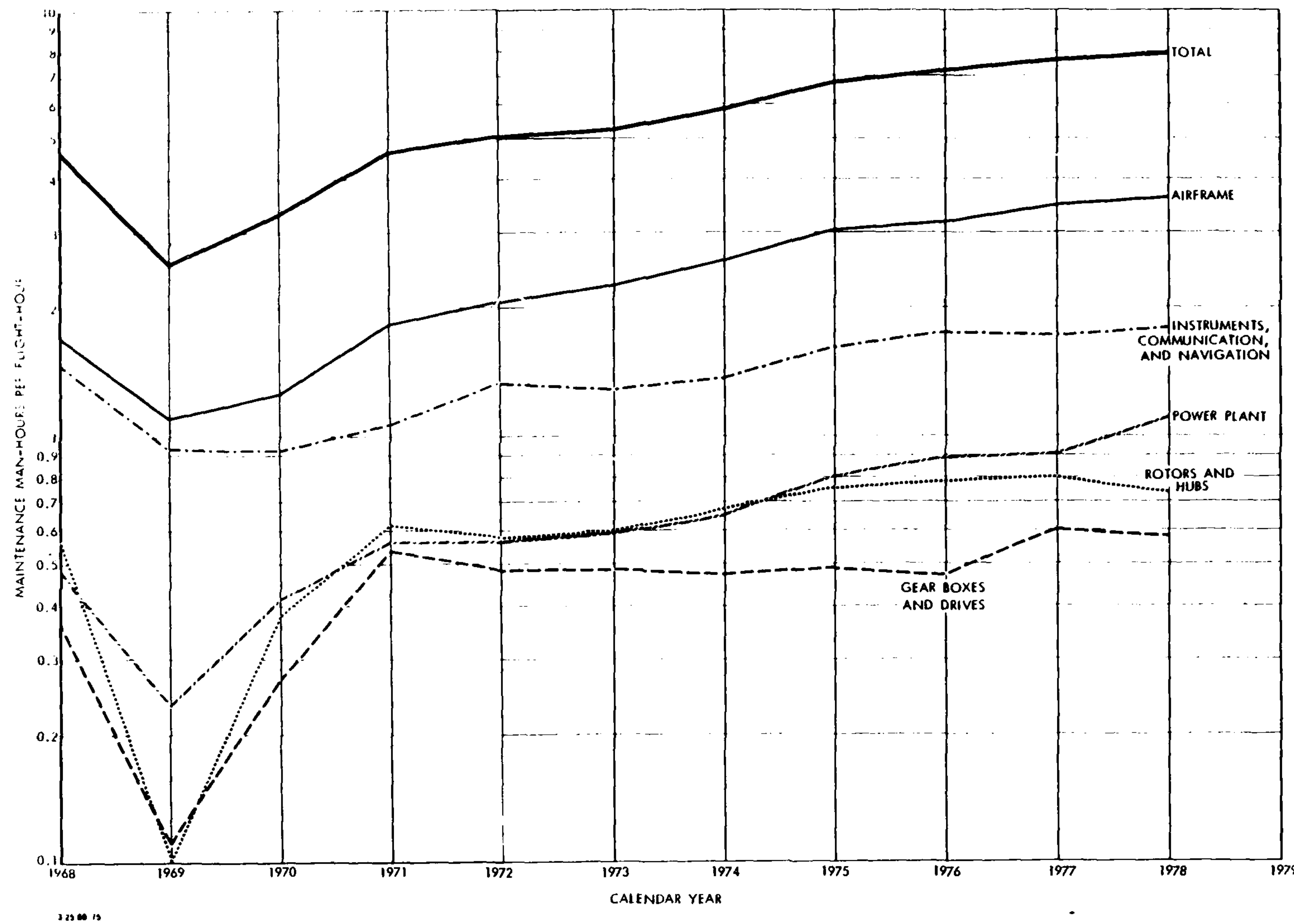

Figure 58. MMH/FH FOR THE NAVY H-3(S)

4. The H-46

Most H-46 aircraft in Navy service are CH-46 aircraft (cargo helicopters)--mainly CH-46A, CH-46D, and CH-46F aircraft. Table 32 presents 3-M data for all H-46 models; the three R&M measures are plotted in Figures 59 through 61. The R&M measures show the same general pattern as those of the H-3 aircraft; relative to 1968, all three measures improved markedly in 1969, but after 1969 they worsened considerably, until they were much worse in 1978 than they were in 1968. The trends for the various components do not appear to differ systematically from the trends for the total aircraft.

Table 32. NAVY 3-M DATA FOR ALL H-46 MODELS

YEAR	FLIGHT HOURS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
AIRFRAME							
1973	36307	28587	1.27	16298	2.23	93413	2.57
1974	37874	35079	1.08	18471	2.05	110631	2.92
1975	40367	43844	.92	21003	1.92	141114	3.50
1976	40279	43151	.93	20201	1.99	158496	3.93
1977	44892	53632	.84	24311	1.85	200353	4.46
1978	42155	52659	.80	27121	1.55	198950	4.72
1979	17835	20510	.87	10884	1.64	77760	4.36
ROTORS AND HUBS(MAIN/TAIL)							
1973	36307	11160	3.25	4127	8.80	40975	1.13
1974	37874	12226	3.10	4427	8.56	51619	1.36
1975	40367	11310	3.57	5345	7.55	53021	1.31
1976	40279	11081	3.63	5192	7.76	57603	1.43
1977	44892	13877	3.23	6140	7.31	79923	1.78
1978	42155	13531	3.12	6684	6.31	82872	1.97
1979	17835	5376	3.32	2710	6.58	29817	1.67
GEAR BOXES AND DRIVES							
1973	36307	3682	9.86	1979	18.35	20355	.56
1974	37874	3854	9.83	2005	18.89	24536	.65
1975	40367	5017	8.05	2505	16.11	32613	.81
1976	40279	4802	8.39	2319	17.37	39748	.99
1977	44892	5902	7.61	2737	16.40	40737	1.04
1978	42155	6025	7.00	3299	12.78	41696	.99
1979	17835	2450	7.28	1285	13.88	15215	.85
POWER PLANT							
1973	36307	5647	6.43	2756	13.17	31073	.86
1974	37874	6071	6.24	2879	13.16	39435	1.04
1975	40367	8464	4.77	3645	11.07	54742	1.36
1976	40279	8720	4.62	3680	10.95	56753	1.41
1977	44892	9235	4.86	3854	11.65	55994	1.25
1978	42155	9041	4.66	4096	10.29	57055	1.35
1979	17835	3355	5.32	1500	11.89	19660	1.10
INSTRUMENTS,COMMUNICATION AND NAVIGATION							
1973	36307	11685	3.11	6244	5.81	41135	1.13
1974	37874	12743	2.97	6873	5.51	46482	1.23
1975	40367	13533	2.98	6955	5.80	51583	1.28
1976	40279	13334	3.02	6894	5.84	60629	1.51
1977	44892	16048	2.80	8552	5.25	75031	1.67
1978	42155	16075	2.62	8355	5.05	80298	1.90
1979	17835	6335	2.82	3344	5.33	32153	1.80
WEAPON SYSTEMS							
1973	36307	34	1067.85	6	6051.17	41	.00
1974	37874	37	1023.62	7	5410.57	58	.00
1975	40367	23	1755.09	11	3669.73	70	.00
1976	40279	43	936.72	10	4027.90	60	.00
1977	44892	31	1448.13	4	11223.00	38	.00
1978	42155	33	1277.42	10	4215.50	87	.00
1979	17835	16	1114.69	1	17835.00	25	.00
* * * T O T A L * * *							
1973	36307	60795	.60	31410	1.16	226992	6.25
1974	37874	70010	.54	34661	1.09	272771	7.20
1975	40367	82191	.49	39464	1.02	333143	8.25
1976	40279	81131	.50	38296	1.05	373289	9.27
1977	44892	98725	.45	45598	.98	458126	10.21
1978	42155	97364	.43	49565	.85	460958	10.93
1979	17835	38042	.47	19724	.90	174630	9.79

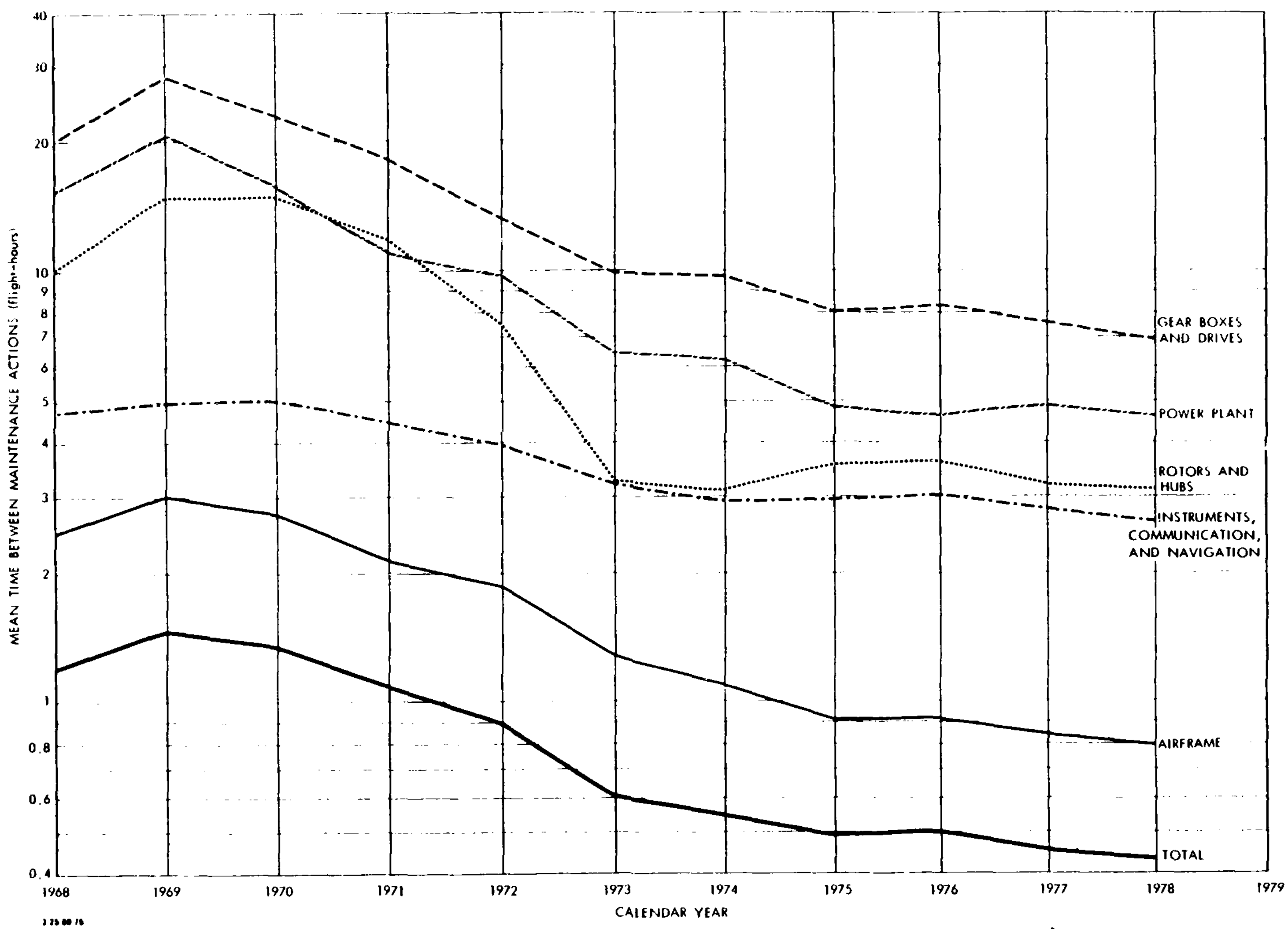

Figure 59. MTBMA FOR THE NAVY H-46

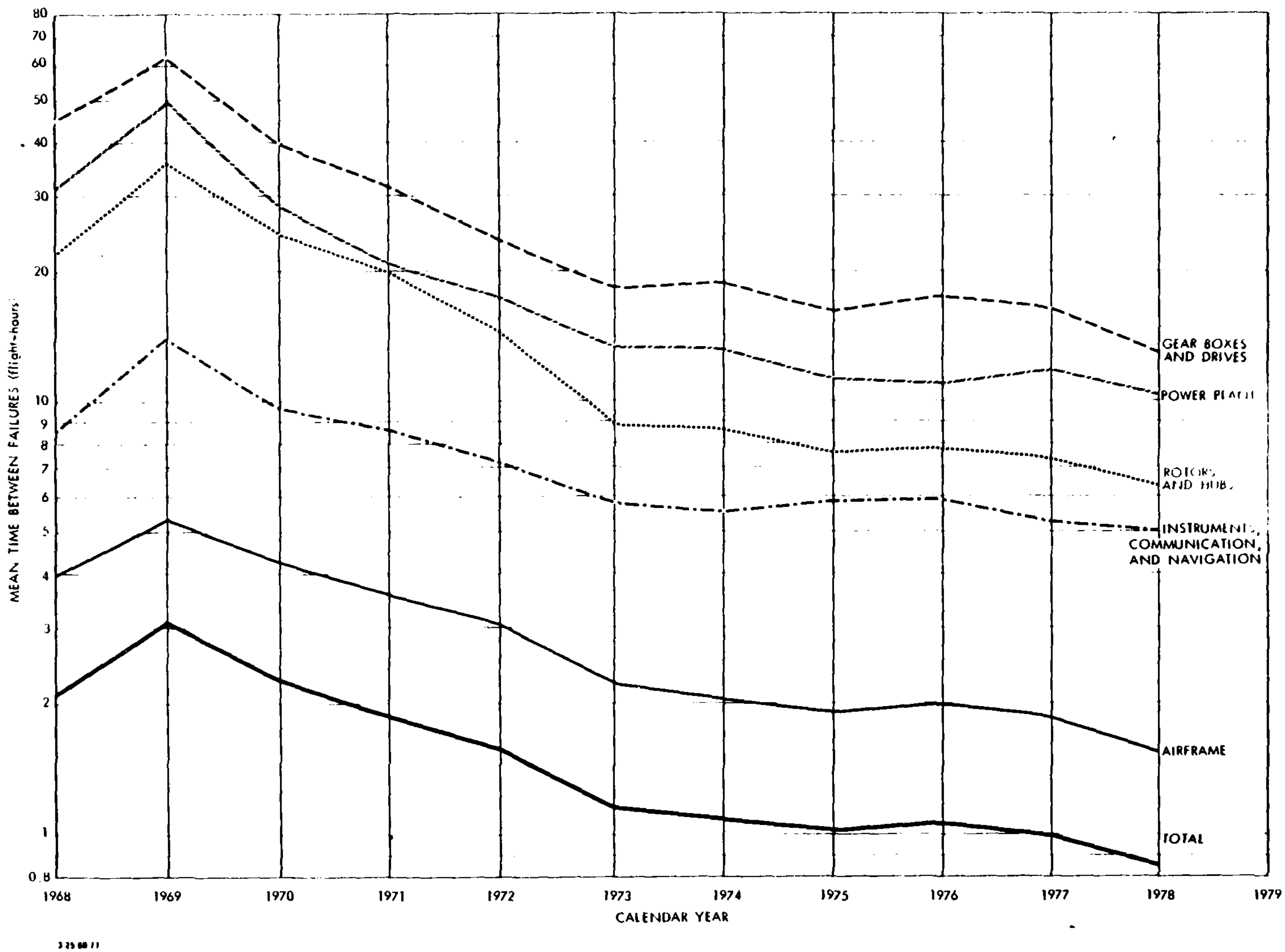

Figure 60. MTBF VERSUS YEAR FOR THE NAVY H-46

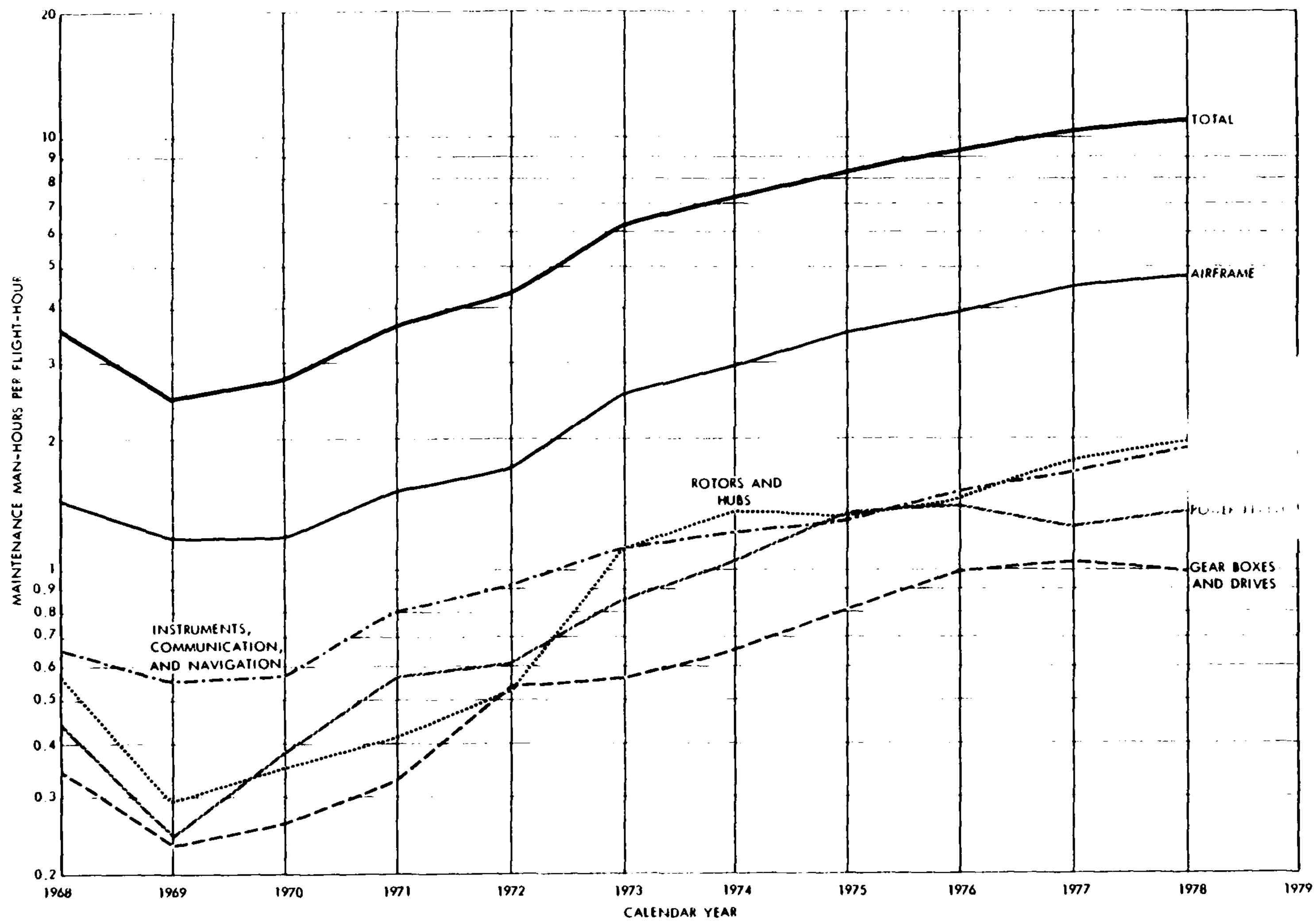

Figure 61. MMH/FH FOR THE NAVY H-46

5. The H-53

Most H-53 aircraft in Navy/Marine service are CH-53 A and D cargo helicopters; the remaining H-53s are RH-53D minesweeping helicopters. Table 33 presents 3-M data for all CH-53 models; the three R&M measures are plotted in Figures 62 through 64. Table 33 includes R&M measures for CH-53 weapon systems. However, since the weapon systems accounted for such a small portion of the total R&M activity, the weapon system data points in most cases did not fall on the R&M scales used in Figures 62 through 64 and therefore were not plotted on these figures. All three measures show a generally worsening trend over the 1968-1978 period. Rotors and hubs exhibit trends worse than those of the other components. The trends for the other components do not appear to differ systematically from the trends for the total aircraft.

Table 33. NAVY 3-M DATA FOR ALL H-53 MODELS

YEAR	FLIGHT HOURS	ACTIONS	MFHBMA	FAIL.	MTBF	MAINT MAN-HRS	MH/FH
AIRFRAME							
1973	18503	20749	.89	12420	1.49	67213	3.63
1974	20770	20863	1.00	12209	1.70	75004	3.61
1975	16798	19749	.85	10853	1.55	92493	5.51
1976	18709	23309	.80	12262	1.53	109519	5.85
1977	20907	24125	.87	13395	1.56	124649	5.96
1978	22414	31919	.70	17701	1.27	157014	7.01
1979	10924	13133	.83	7487	1.46	59855	5.48
ROTORS AND HUBS(MAIN/TAIL)							
1973	18503	5056	3.66	2854	6.48	26057	1.41
1974	20770	5258	3.95	3013	6.89	26648	1.28
1975	16798	5917	2.84	2874	5.84	41721	2.48
1976	18709	6263	2.99	2877	6.50	47216	2.52
1977	20907	6316	3.31	3408	6.13	47130	2.25
1978	22414	[illegible]	3.53	3387	6.62	54320	2.42
1979	10924	[illegible]	4.29	1467	7.45	20387	1.87
GEAR BOXES AND DRIVES							
1973	18503	3360	5.51	2019	9.16	12284	.66
1974	20770	3207	6.48	1871	11.10	14114	.68
1975	16798	2728	6.16	1605	10.47	14586	.87
1976	18709	3044	6.15	1647	11.36	19951	1.07
1977	20907	3071	6.81	1750	11.95	20585	.98
1978	22414	3705	6.05	2058	10.89	33662	1.50
1979	10924	1362	8.02	781	13.99	8843	.81
POWER PLANT							
1973	18503	[illegible]	4.70	2139	8.65	12967	.70
1974	20770	3854	5.39	2098	9.90	15510	.75
1975	16798	3753	4.48	1948	8.62	21076	1.25
1976	18709	4390	4.26	2340	8.00	30551	1.63
1977	20907	4529	4.62	2617	7.99	49337	2.36
1978	22414	[illegible]	3.93	3312	6.77	48400	2.16
1979	10924	2285	4.78	1361	8.03	16995	1.56
INSTRUMENTS,COMMUNICATION AND NAVIGATION							
1973	18503	6718	2.75	3688	5.02	23896	1.29
1974	20770	6455	3.22	3697	5.62	25564	1.23
1975	16798	5304	3.17	2805	5.99	22289	1.33
1976	18709	6595	2.84	3267	5.73	32992	1.76
1977	20907	6716	3.11	3663	5.71	32229	1.54
1978	22414	7751	2.89	4118	5.44	38602	1.72
1979	10924	2815	3.88	1646	6.64	14740	1.35
WEAPON SYSTEMS							
1973	18503	9	2055.89	4	4625.75	11	.00
1974	20770	12	1730.83	8	2596.25	32	.00
1975	16798	11	1527.09	5	3359.60	41	.00
1976	18709	31	603.52	5	3741.80	90	.00
1977	20907	28	746.68	6	3484.50	48	.00
1978	22414	27	830.15	15	1494.27	52	.00
1979	10924	6	1820.67	2	5462.00	31	.00
* * * T O T A L * * *							
1973	18503	39831	.46	23124	.80	142328	7.69
1974	20770	39649	.52	22896	.91	156872	7.55
1975	16798	37462	.45	20090	.84	192206	11.44
1976	18709	43632	.43	22398	.84	240319	12.85
1977	20907	44784	.47	24839	.84	273978	13.10
1978	22414	55465	.40	30591	.73	332050	14.81
1979	10924	22154	.49	12744	.86	120851	11.06

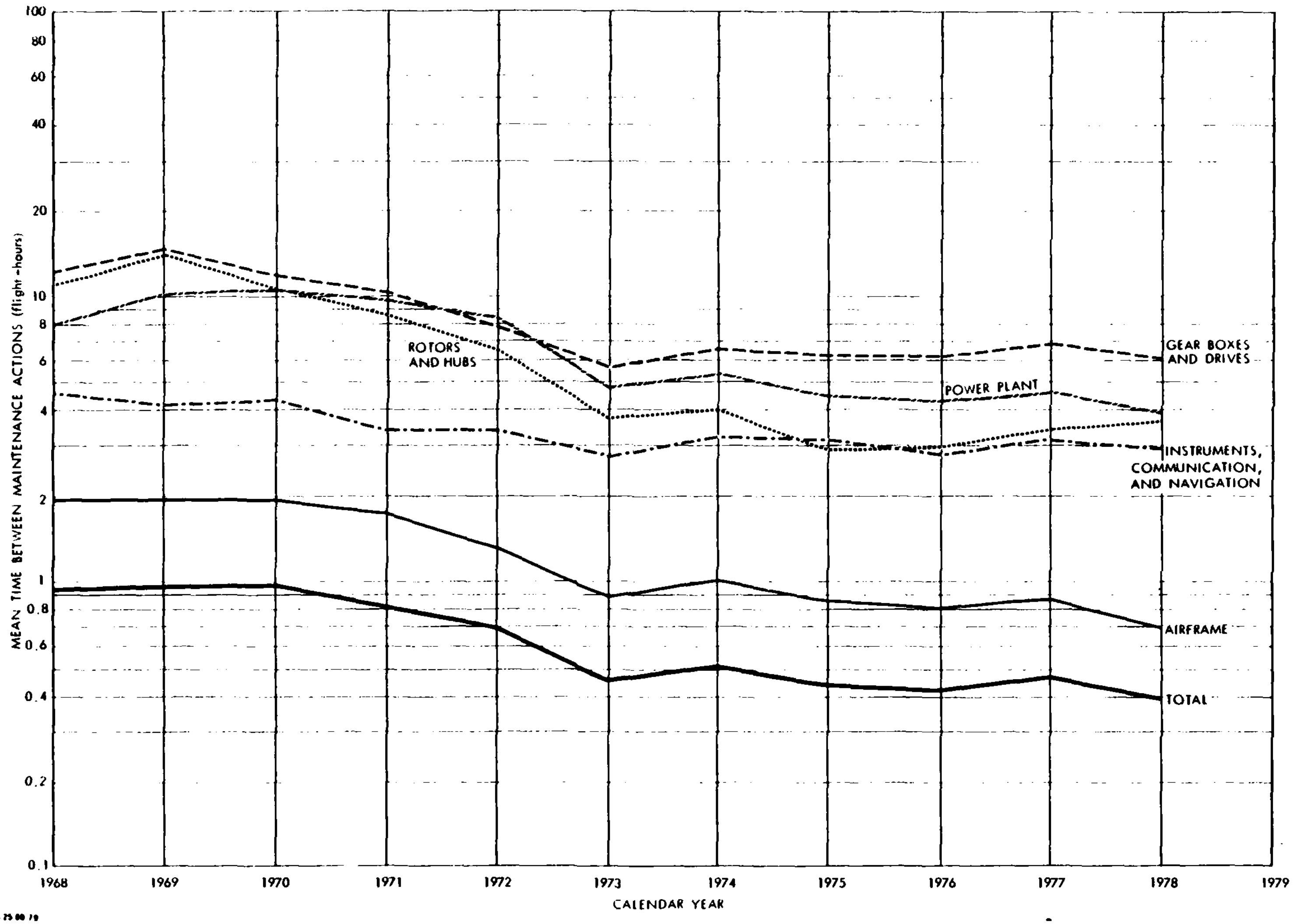

Figure 62. MTBMA FOR THE NAVY H-53

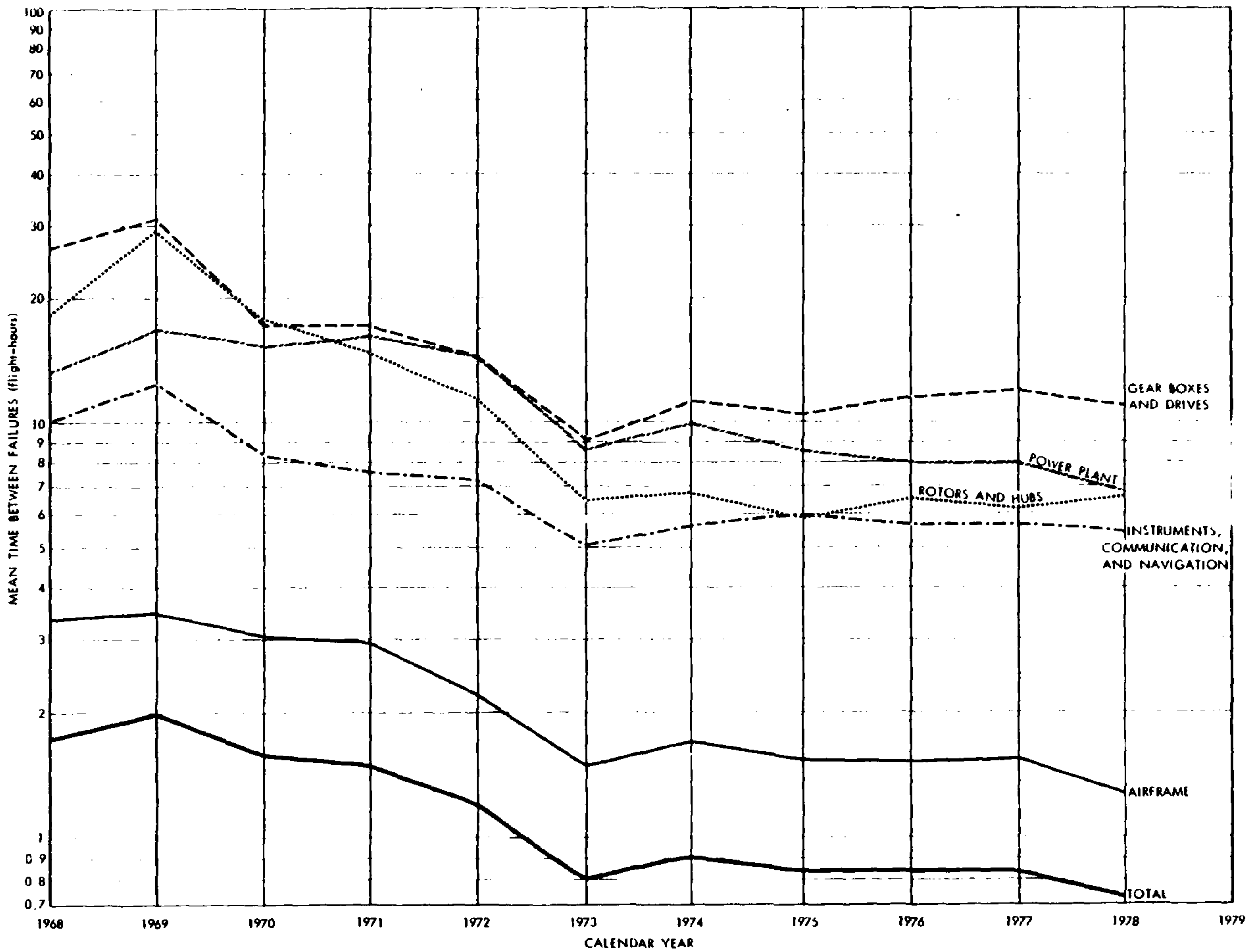

Figure 63. MTBF VERSUS YEAR FOR THE NAVY H-53

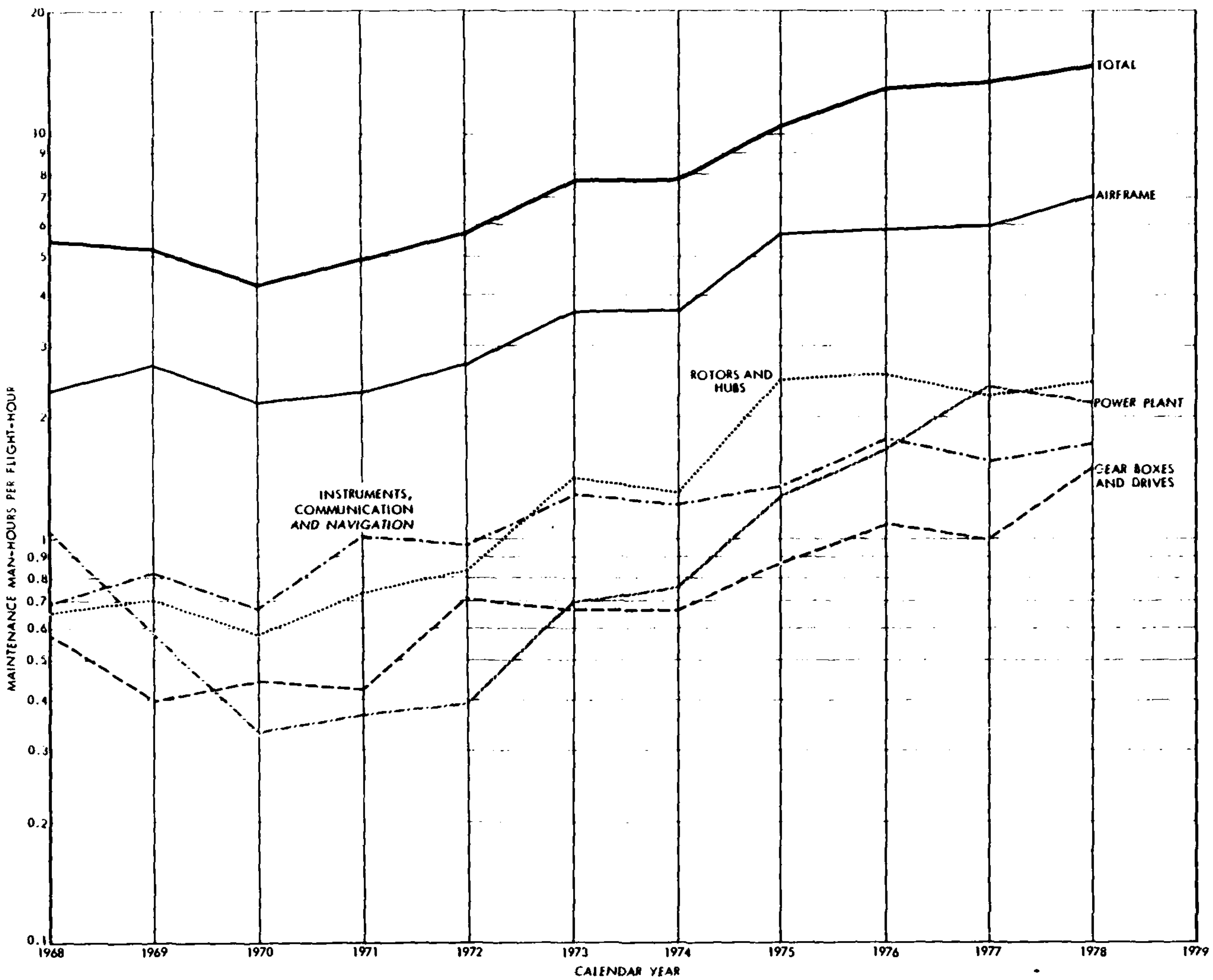

Figure 64. MMH/FH FOR THE NAVY H-53

6. General Trends

The time trends of Figures 41 through 64 indicate that the R&M measures for every major component group for every basic Navy helicopter type worsened from 1968 to 1978. Unfortunately, for all five basic types of helicopters, the year of introduction into Navy inventory was before 1968. Hence, we cannot say definitely what the trend in R&M measures is from year of first introduction into service. However, mishap rates from the Naval Safety Center are available from time of introduction for all the Navy helicopters (see Figure 71 in Section III below). The Naval Safety Center data show a general worsening in mishap rates from time of introduction into the Navy inventory. Hence, it is probable that the three R&M measures worsen from time of introduction into the inventory. Evidently, the aging of the fleet that occurs over time outweighs the beneficial effects of product improvements and results in an overall worsening of R&M measures during the service life of the aircraft.

Section II

U.S. Air Force Reliability and Maintainability Data

The Air Force publishes reliability and maintainability (R&M) data based on the D056 Product Performance data system. These data are published in reference [58] at the two-digit work unit code level for all USAF aircraft. Data are presented for six-month periods starting 1 April 1972 and ending 31 March 1978.

The data report numbers of maintenance events and corresponding maintenance manhours are given for "inherent," "induced," and "no defect" maintenance events. "Inherent" maintenance events are defined as "activity resulting from malfunctions that are coded as occurring internal to the equipment," while "induced" maintenance events are "coded as induced in the equipment from external sources." "Inherent" maintenance events should provide a truer picture of trends in the inherent R&M characteristics of the equipment since external influences are removed insofar as possible. Accordingly, we have extracted only "inherent" maintenance event data.

Data for the five helicopter types included in reference [58] are summarized in Table 34 and plotted in Figures 65 through 69. At the end of each trend line in the figures, the trend is characterized as "better," "worse," or "constant." These characterizations are summarized in Table 35, which indicates a majority of worsening trends for each of the three R&M measures.

Table 34. USAF HELICOPTER RELIABILITY AND MAINTAINABILITY DATA

Helicopter Type & Report Period	Flying Hours	Inherent Maintenance Events	MTBME	Inherent Maintenance MH		Inherent Maintenance MH/FH	
				Organizational	Intermediate	Organizational	Intermediate
UH-1F							
Apr 72 - Mar 73	39,164	21,761	1.80	77,982	14,158	1.99	0.36
Apr 73 - Mar 74	26,543	14,795	1.79	62,251	10,094	2.35	0.38
Apr 74 - Mar 75	23,983	11,458	2.09	44,357	5,790	1.84	0.24
Apr 75 - Mar 76	17,833	26,618	1.50	33,944	3,267	1.90	0.18
Apr 76 - Mar 77	11,961	7,906	1.51	33,595	3,160	2.81	0.26
Apr 77 - Mar 78	19,279	9,183	2.10	37,253	4,317	1.93	0.22
UH-1N							
Apr 72 - Mar 73	19,636	8,111	2.42	43,028	6,298	2.19	0.32
Apr 73 - Mar 74	17,949	7,499	2.39	39,590	7,689	2.20	0.43
Apr 74 - Mar 75	20,558	9,107	2.26	42,135	3,624	2.05	0.18
Apr 75 - Mar 76	20,221	11,006	1.84	52,871	4,528	2.62	0.24
Apr 76 - Mar 77	13,267	11,001	0.83	63,670	5,607	4.80	0.42
Apr 77 - Mar 73	23,639	12,014	1.97	60,197	6,464	2.55	0.27
HH-1H							
Apr 72 - Mar 73	0	0	-	0	0	-	-
Apr 73 - Mar 74	5,083	1,576	3.22	6,234	427	1.23	0.08
Apr 74 - Mar 75	5,975	2,137	2.79	9,649	1,066	1.61	0.18
Apr 75 - Mar 76	7,549	3,614	2.09	13,835	1,979	1.83	0.26
Apr 76 - Mar 77	5,379	3,177	1.69	10,873	1,716	2.02	0.32
Apr 77 - Mar 78	7,896	2,606	3.03	9,022	2,207	1.14	0.28
CH-3C							
Apr 72 - Mar 73	26,421	21,579	1.22	125,039	16,421	4.73	0.62
Apr 73 - Mar 74	26,534	21,517	1.23	127,683	18,359	4.81	0.69
Apr 74 - Mar 75	28,080	22,703	1.24	142,575	18,411	5.08	0.66
Apr 75 - Mar 76	22,873	21,722	1.05	133,246	16,506	5.82	0.72
Apr 76 - Mar 77	16,621	22,083	0.75	142,465	21,809	8.57	1.31
Apr 77 - Mar 78	27,963	22,557	1.24	150,441	22,109	5.38	0.79
HH-53							
Apr 72 - Mar 73	22,313	26,262	1.18	139,617	21,079	6.26	0.94
Apr 73 - Mar 74	16,218	20,361	1.26	126,658	19,585	7.81	1.21
Apr 74 - Mar 75	16,272	19,620	0.83	118,460	20,655	7.28	1.27
Apr 75 - Mar 76	13,639	18,598	0.73	115,865	17,159	8.45	1.26
Apr 76 - Mar 77	8,676	22,790	0.38	157,771	24,285	18.18	2.80
Apr 77 - Mar 78	14,883	25,063	0.59	165,879	23,374	11.14	1.57

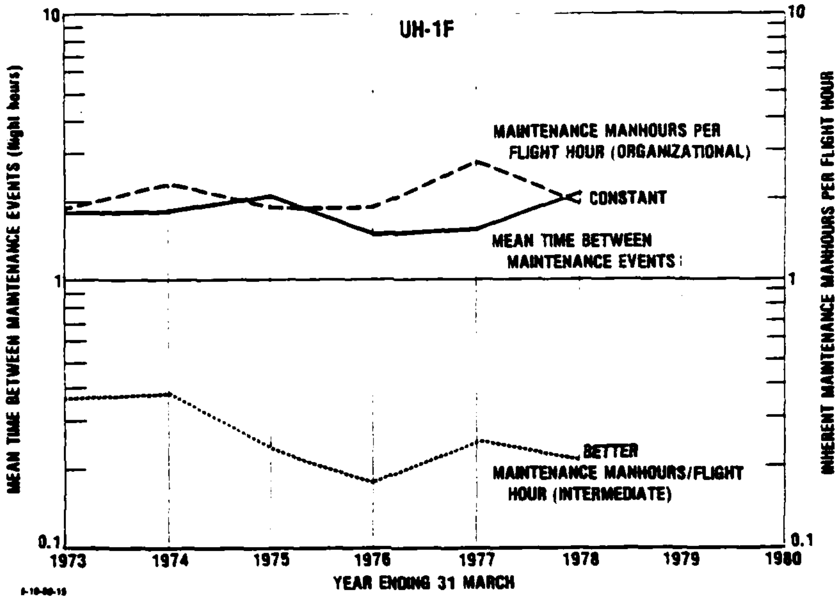

Figure 65. MEAN TIME BETWEEN MAINTENANCE EVENTS AND MAINTENANCE MANHOURS PER FLIGHT HOUR FOR UH-1F

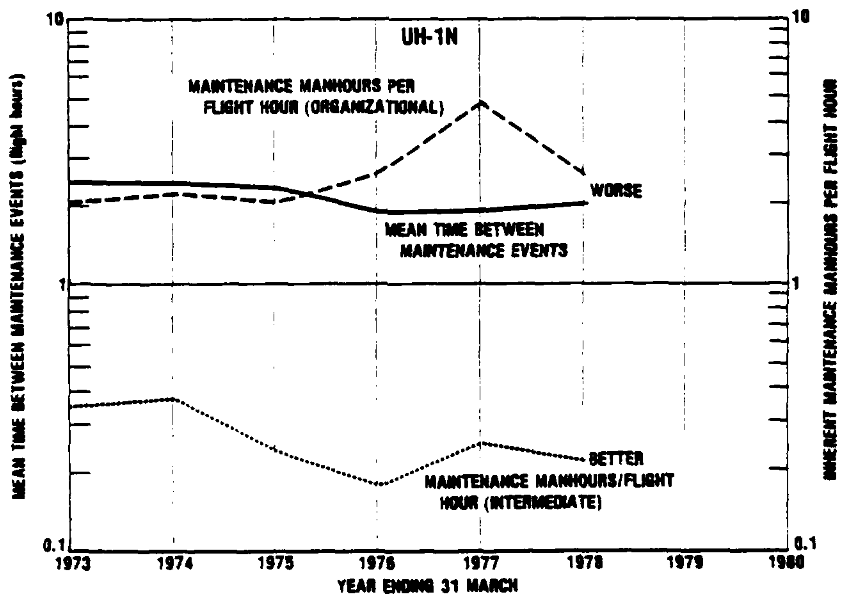

Figure 66. MEAN TIME BETWEEN MAINTENANCE EVENTS AND MAINTENANCE MANHOURS PER FLIGHT HOUR FOR UH-1N

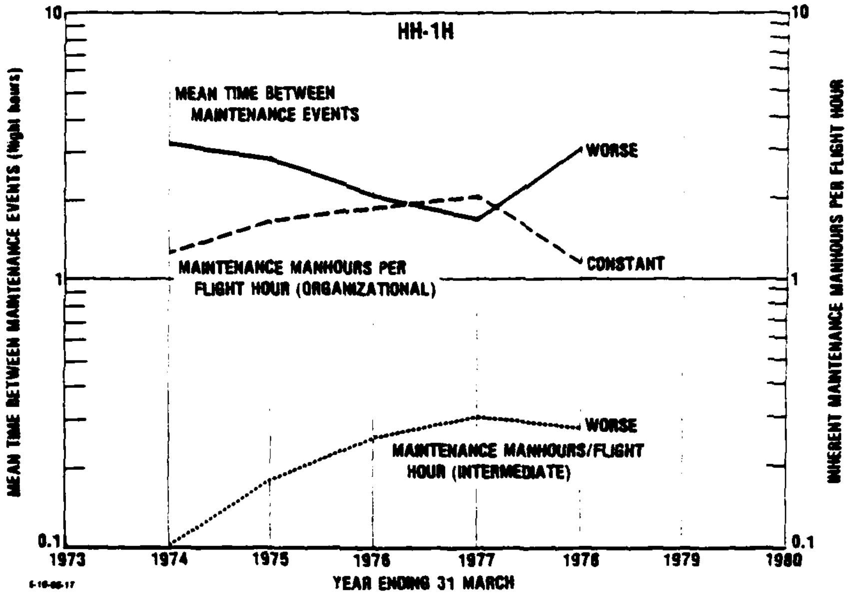

Figure 67. MEAN TIME BETWEEN MAINTENANCE EVENTS AND MAINTENANCE MANHOURS PER FLIGHT HOUR FOR HH-1H

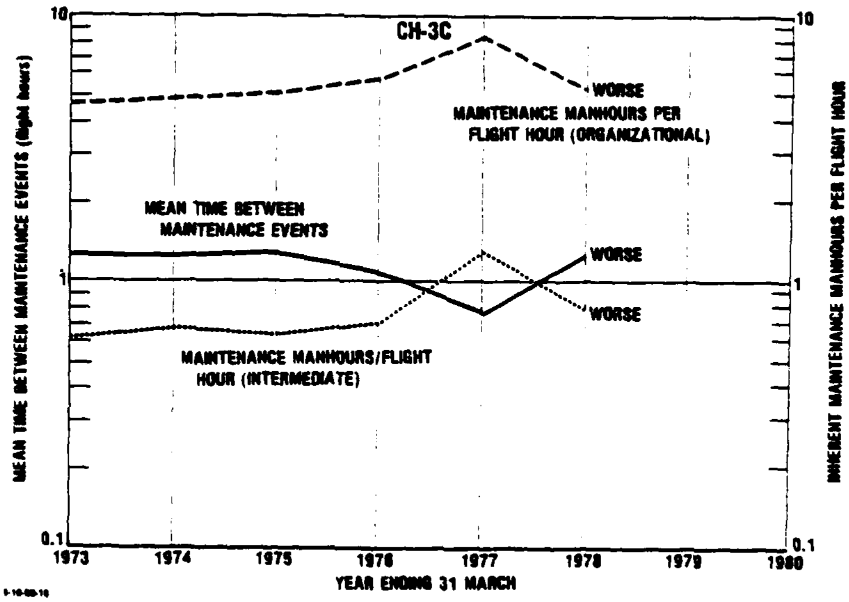

Figure 68. MEAN TIME BETWEEN MAINTENANCE EVENTS AND MAINTENANCE MANHOURS PER FLIGHT HOUR FOR CH-3C

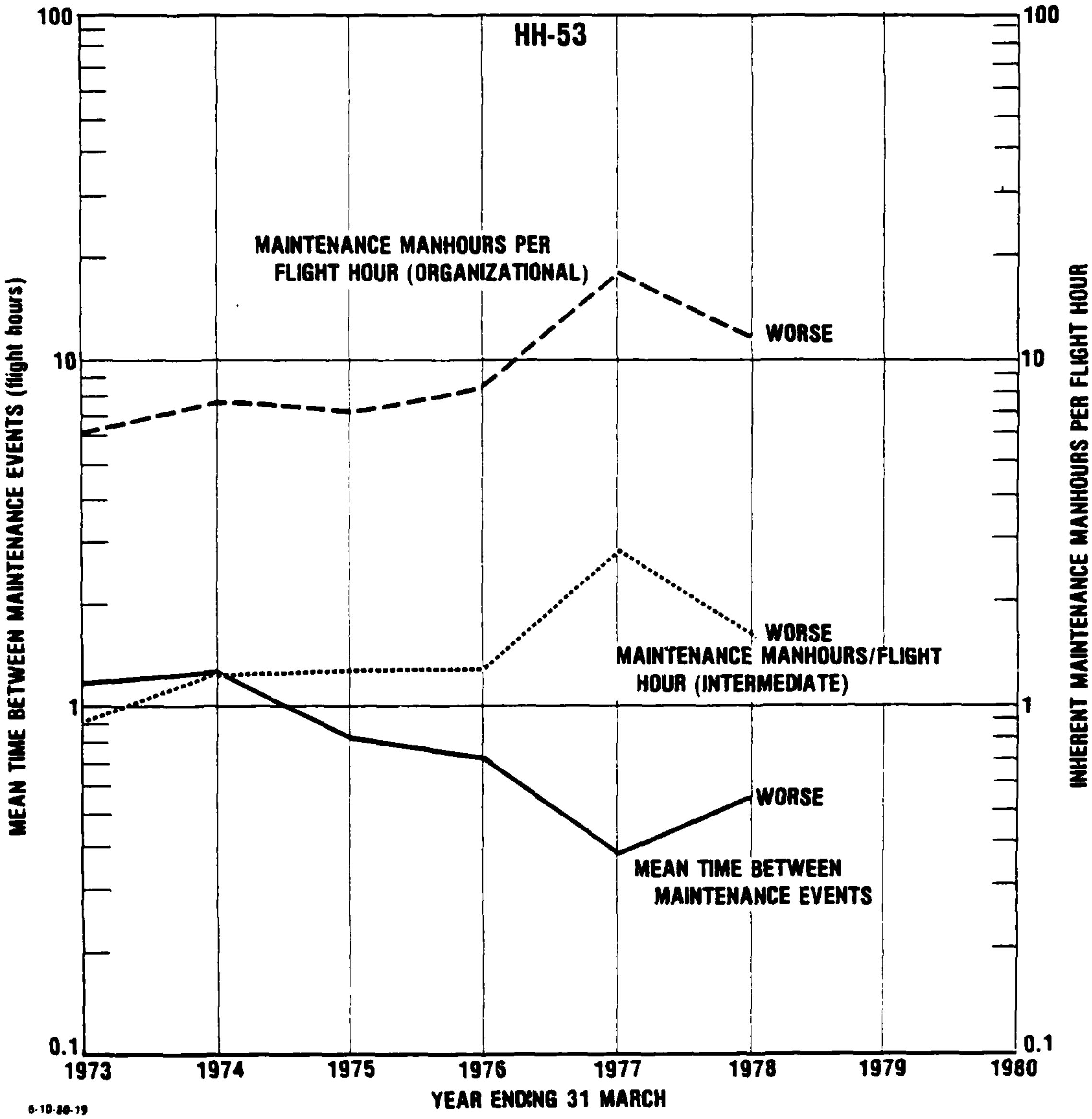

Figure 69. MEAN TIME BETWEEN MAINTENANCE EVENTS AND MAINTENANCE MANHOURS PER FLIGHT HOUR FOR HH-53

Table 35. USAF HELICOPTER RELIABILITY AND MAINTAINABILITY TRENDS, 1972-1978

Helicopter Type	Mean Time Between Maintenance Events	Inherent Maintenance Manhours per Flight Hour	
		Organizational	Intermediate
UH-1F	Constant	Constant	Better
UH-1N	Worse	Worse	Better
HH-1H	Worse	Constant	Worse
CH-3C	Worse	Worse	Worse
HH-53	Worse	Worse	Worse

Section III

Service Mishap Rates

All three Services maintain reporting systems for aircraft "mishaps." Prior to January 1, 1977, these reporting systems were all similar in concept but differed in detail among the Services. Effective January 1, 1977, Department of Defense Instruction 1000.19 prescribed standardized procedures for mishap reporting [59]. There are different categories of mishaps, but in general they cover all incidents of a dangerous or potentially dangerous character--from minor incidents (such as precautionary landings) through major accidents, in which the aircraft is heavily damaged or lost. The cause of the accident is also reported; there are a number of cause categories, and more than one may be involved in a single mishap. For example, if a transmission warning light indicates an incipient transmission failure and the pilot damages the landing gear in making an emergency landing, that mishap may show both "Materiel Failure" and "Pilot Error" as having contributed to the accident.

A. REPORTING SYSTEMS AND AVAILABLE DATA

Each Service's reporting system and available data are discussed separately below.

1. Army

The Army mishap data are reported by the U.S. Army Safety Center (USASC), Fort Rucker, Alabama. The reporting starts with the introduction of the aircraft into regular service use; the test period prior to service use is not covered.

In the Army reporting system prior to 1977, mishaps were categorized as total losses, major accidents, minor accidents, incidents, forced landings, precautionary landings, ground, and other. The difference between major and minor accidents and between minor accidents and incidents was established for each aircraft type by the cost to repair. Since January 1, 1977, mishaps have been categorized in five classes as follows:

<u>Class A</u>. Cost $\geq$ \$200,000; or aircraft missing, abandoned, destroyed, uneconomically repairable; or fatality.

<u>Class B</u>. \$50,000 $\leq$ Cost < \$200,000.

<u>Class C</u>. \$300 $\leq$ Cost < \$50,000; or lost workdays.

<u>Class D</u>. Cost < \$300 and lost workday case involving days of restricted work activity.

<u>Class E</u>. Cost < \$300 and no injury requiring more than first aid.

Class A plus B mishaps are substantially equal to the pre-1977 total losses plus major accidents and minor accidents. Classes C + D + E are substantially equal to the old incidents plus forced landings, plus precautionary landings, plus ground, plus other.

The Army reporting system (both before and after DODI 1000.19) includes the following summary "Cause Factors":

- Personnel
  - Flight Crew
  - Ground Crew
  - Supervisory
- Environmental
  - Facilities
  - Command
  - Training

- Materiel[1]
  - Failure/Malfunction
  - Maintenance
  - Design
- Weather
- Undetermined.

As already noted, it is possible that a single mishap may involve more than one cause factor--which is true even within the major cause-factor categories. For example, a mishap involving materiel may be charged to more than one of the three subfactors under materiel.

For each helicopter type, we received mishap data from USASC for the active Army worldwide inventory; these data exclude mishaps caused by combat. The Army indicated that its mishap data before FY 1968 were less reliable and advised against our using them. Accordingly, the data reported herein cover the twelve FYs 1968-79. For each helicopter type, we assembled the following data by fiscal year:

- Number of flight hours
- Number of accidents (total of total losses plus both major and minor accidents; or Classes A + B):
  - Materiel failure
  - Total.
- Number of mishaps (total of three accident types plus incidents, forced landings, precautionary landings, ground, and other; or Classes A through E):
  - Materiel failure
  - Total.

Using these data, we calculated mishap rates per 10,000 flight hours (Table 36). Table 36 does not repeat the data for FYs 1968-73 which were included in our 1975 study [1]. In Table 36 the accident figures for FY 1977-79 are Class A + B mishaps

[1]The Army and Air Force use this spelling; the Navy uses "Material." In this report we use "Materiel" throughout.

Table 36. MISHAPS OF ARMY HELICOPTERS

Helicopter Series	FY	Number: Accidents: Materiel Failure	Number: Accidents: Total	Number: Mishaps: Materiel Failure	Number: Mishaps: Total	Flight-Hours	Rate (per 10,000 flight-hours): Accidents: Materiel Failure	Rate: Accidents: Total	Rate: Mishaps: Materiel Failure	Rate: Mishaps: Total
UH-1	74	10	29	604	943	611,086	0.20	0.5	9.9	15.4
	75	13	31	695	1,088	552,488	0.20	0.6	12.6	19.7
	76	15	30	676	901	497,506	0.30	0.6	13.6	19.8
	77	2	25	686	922	510,496	0.03	0.5	13.4	18.0
	78	11	42	934	1,304	513,545	0.20	0.8	18.2	25.4
	79	7	21	1,302	1,722	515,076	0.10	0.4	25.2	33.4
AH-1	74	3	11	122	221	64,404	0.50	1.8	18.9	34.3
	75	6	11	171	276	65,637	0.90	1.7	26.0	42.0
	76	4	12	153	259	60,135	0.70	2.0	25.4	43.0
	77	5	22	149	232	69,884	0.70	3.1	21.3	33.2
	78	6	17	188	287	75,954	0.80	2.2	24.7	37.8
	79	4	14	244	385	83,341	0.50	1.7	29.2	46.2
CH-47	74	2	1	91	156	40,165	0.50	0.2	22.7	38.8
	75	3	3	103	183	37,584	0.80	0.8	27.4	48.7
	76	0	0	128	174	39,907	0.00	0.0	32.0	43.6
	77	3	12	132	172	44,015	0.70	2.7	30.0	39.0
	78	1	7	152	224	43,899	0.20	1.6	34.6	51.0
	79	6	9	195	246	41,253	1.50	2.2	47.3	59.6

(continued on next page)

Table 36 (concluded)

Heli-copter Series	FY	Number: Accidents: Materiel Failure	Number: Accidents: Total	Number: Mishaps: Materiel Failure	Number: Mishaps: Total	Flight-Hours	Rate (per 10,000 flight-hours): Accidents: Materiel Failure	Rate: Accidents: Total	Rate: Mishaps: Materiel Failure	Rate: Mishaps: Total
CH-54	74	0	1	8	11	6,383	0.0	1.6	12.5	17.2
	75	0	0	14	20	6,069	0.0	0.0	23.1	32.9
	76	0	1	12	25	6,170	0.0	1.6	19.4	40.5
	77	0	0	10	13	4,221	0.0	0.0	23.7	30.8
	78	0	0	13	14	4,756	0.0	0.0	27.3	29.4
	79	0	0	9	12	3,467	0.0	0.0	26.0	34.6
OH-6A	74	1	2	4	8	4,902	2.0	4.0	8.2	16.3
	75	0	0	5	9	4,364	0.0	0.0	11.5	20.6
	76	0	2	5	9	4,628	0.0	4.3	10.8	19.4
	77	0	0	1	3	1,570	0.0	0.0	6.3	19.1
OH-58A	74	3	12	221	405	237,608	0.1	0.5	9.3	17.0
	75	3	18	230	460	229,816	0.1	0.8	10.0	20.0
	76	4	19	218	397	217,505	0.2	0.9	10.0	18.3
OH 58	77	5	15	181	316	214,970	0.2	0.7	8.4	14.7
	78	9	18	249	438	214,410	0.4	0.8	11.6	20.4
	79	3	9	325	535	214,777	0.1	0.4	15.1	24.9

Source: U.S. Army Safety Center, Fort Rucker, Alabama.

under the new classification system. The four mishap rates are plotted versus fiscal year in Figure 70. In some cases when a helicopter was entering or being phased out of service and the mishap rates were not meaningful, the data for those years were not included in our tables or figures.

Mishap rates involving materiel were shown because they should reflect reliability growth (if any) in the helicopter fleet being achieved through design or process improvement. The mishap rates were plotted on semi-log paper so that equal rates of change would be parallel at any location on the paper.[1] For both accident rates and total mishap rates, the change in rates involving materiel generally followed the total rates. In most cases, surprisingly, the rates for all mishaps tended to increase over time, while the accident rates tended to decrease. In discussing these results, USASC personnel offered the following probable reasons for these two trends.

(1) Serious problems causing accidents tend to be corrected first (thus reducing the accident rate), while minor problems receive less attention.

(2) With the deceleration of the Vietnam conflict, less mission pressure encouraged pilots to make precautionary landings in order to reduce the possibility of accidents.

(3) Though the development of better fault-warning systems has increased precautionary landings and other incidents, it has reduced accidents.

(4) Progressively more mishaps occur as the fleet ages, much as is the case with old automobiles.

Hence, though there appears to be increasing reliability insofar as accidents are concerned, there appears to be a deterioration in reliability insofar as all mishaps (both those involving materiel and total) are concerned.

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[1]Since log paper does not go to 0.0, a zero accident rate (whenever it occurred) was plotted at the bottom of the mishap-rate scale.

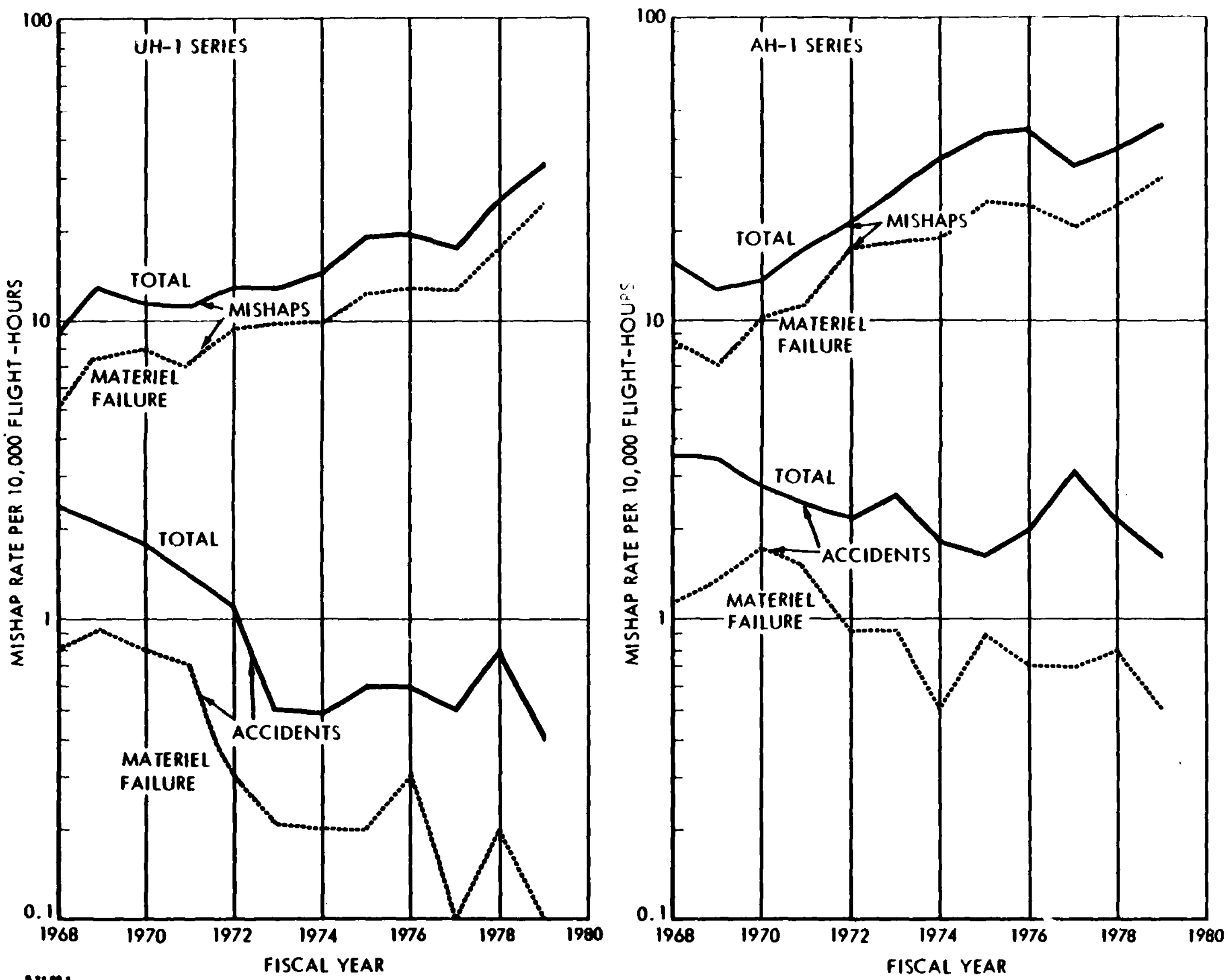

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Figure 70. MISHAP RATES FOR ARMY HELICOPTERS

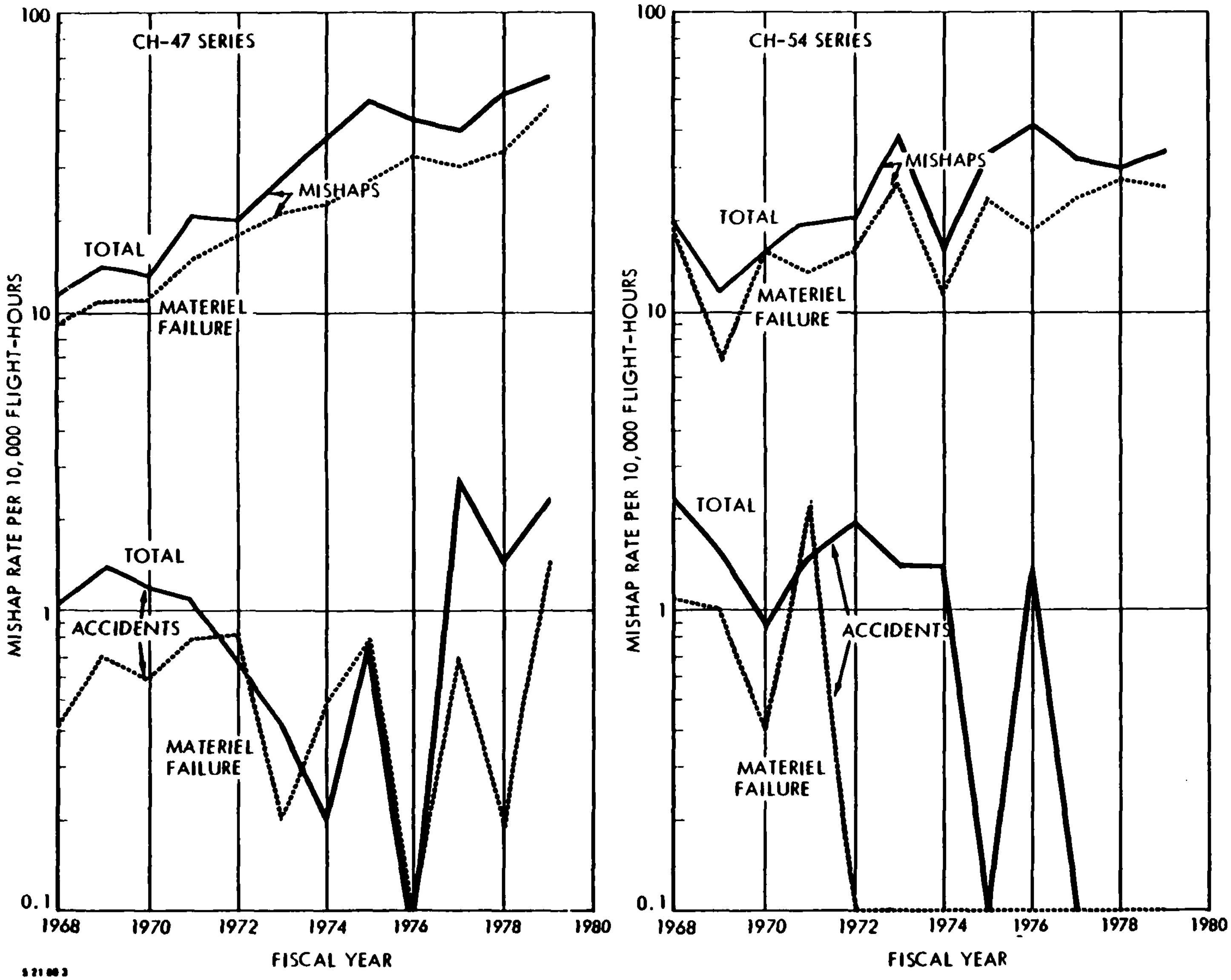

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Figure 70 (continued)

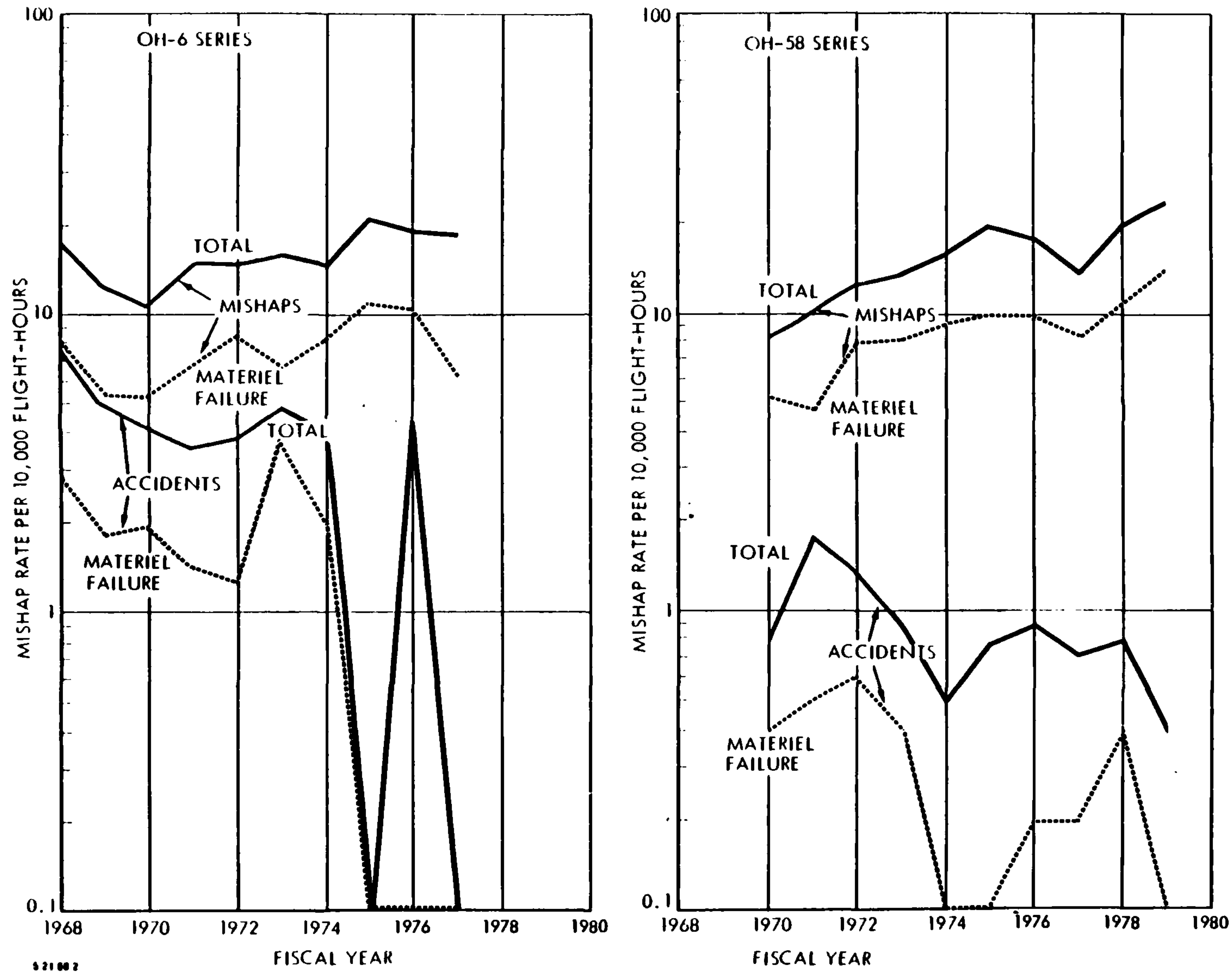

Figure 70 (concluded)

2. Navy

Navy mishap data are reported by the Naval Safety Center (NSC), Norfolk, Virginia. The reporting starts with the testing of the aircraft at the Naval Air Test Center, Patuxent River. However, the data we obtained for helicopters during this period appeared unreliable, and only data for regular Service use appeared usable for our purposes. In the Navy reporting systems, mishaps are broken down as follows:

- Major Accident - Involves loss or substantial damage to aircraft.
- Minor Accident - Minor or limited damage.
- Incident - Very minor damage or no damage (e.g., an engine failure followed by a successful autorotative landing, or an abort following main engine start).
- Ground Mishap - No intent to fly (includes injuries to maintenance personnel during maintenance).

The difference between major and minor accidents is established for each aircraft type by the cost to repair.

The Navy reporting system includes the following "Contributing Causes":

- Pilot
- Other Personnel
- Materiel
  - Failure or Malfunction
  - Design
  - Maintenance-Personnel-Induced
  - Pilot-Induced
- Weather
- Airport Facility
- Carrier/LPH Facility.

There are a number of other contributing causes, in addition to those listed above. However, the great majority of mishaps involve the first three categories above (including the subcategories under "Materiel"). As with the Army, it is possible that a single mishap may involve more than one cause.

For each helicopter type now in Navy service, we received mishap data from the fiscal year of introduction into service through FY 1974 and for CY 1975 through 1979 for the Navy worldwide inventory; the Navy excluded mishaps caused by combat in these data. For each helicopter type, we assembled the following data by fiscal year:

- Number of flight hours.
- Number of major accidents:
    - Involving pilot error
    - Involving other personnel error
    - Involving materiel failure
    - Total.
- Number of minor accidents or incidents:
    - Involving pilot error
    - Involving other personnel error
    - Involving materiel failure
    - Total.
- Ground Mishaps:
    - Involving pilot error
    - Involving other personnel error
    - Involving materiel failure
    - Total.
- Total Mishaps:
    - Involving pilot error
    - Involving other personnel error
    - Involving materiel failure
    - Total.

Although the present Navy system reports minor accidents separately from incidents, prior to FY 1968 the two were reported as a single category. For this reason, in order to have a consistent time series we have combined them, since all Navy helicopter types presently in service were in the inventory before FY 1968. Using these data, we calculated mishap rates per 10,000 flight hours (Table 37). Table 37 does not repeat the data for FYs through 1973 which were included in our 1975

Table 37. MISHAPS OF NAVY HELICOPTERS

Helicopter Series	Year	Mishap Type*	Number: Pilot Error	Number: Other Personnel Error	Number: Materiel Failure	Number: Total	Flight-Hours	Rate (per 10,000 flight-hours): Pilot Error	Rate: Other Personnel Error	Rate: Materiel Failure	Rate: Total
H-1	FY 74	Major	7	4	4	10	102,451	0.7	0.4	0.4	1.0
		Minor/Incident	21	144	209	275		2.1	14.3	20.4	26.8
		Ground	3	13	2	20		0.3	1.3	0.2	2.0
		Total	*31*	*61*	*215*	*305*		*3.0*	*6.0*	*21.0*	*29.8*
	CY 75	Major	2	2	3	5	102,263	0.2	0.2	0.3	0.5
		Minor/Incident	22	40	324	386		2.2	3.9	31.7	37.8
		Ground	0	17	2	22		0.0	1.7	0.2	2.2
		Total	*24*	*59*	*329*	*413*		*2.4*	*5.8*	*32.2*	*40.4*
	CY 76	Major	6	4	6	10	91,786	0.7	0.4	0.7	1.1
		Minor/Incident	17	33	334	385		1.9	3.6	36.4	42.0
		Ground	2	21	2	26		0.2	2.3	0.2	2.8
		Total	*25*	*58*	*342*	*421*		*2.7*	*6.3*	*37.3*	*45.9*
	CY 77	Major	4	1	3	7	100,082	0.4	0.1	0.3	0.7
		Minor/Incident	20	40	436	505		2.0	4.0	43.6	50.5
		Ground	4	37	8	51		0.4	3.7	0.8	5.1
		Total	*28*	*78*	*447*	*563*		*2.8*	*7.8*	*44.7*	*56.3*
	CY 78	Major	4	0	4	8	101,476	0.4	.0	0.4	0.8
		Minor/Incident	27	64	521	606		2.7	6.3	51.3	59.7
		Ground	2	43	14	63		0.2	4.2	1.4	6.2
		Total	*33*	*107*	*539*	*677*		*3.3*	*10.5*	*53.1*	*66.7*
	CY 79	Major	10	7	4	14	107,500	0.9	0.7	0.4	1.3
		Minor/Incident	23	50	501	578		2.1	4.7	46.6	53.8
		Ground	1	33	3	40		0.1	3.1	0.3	3.7
		Total	*34*	*90*	*508*	*632*		*3.2*	*8.4*	*47.3*	*58.8*

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Table 37 (continued)

Heli-copter Series	Year	Mishap Type*	Number: Pilot Error	Number: Other Personnel Error	Number: Materiel Failure	Number: Total	Flight-Hours	Rate (per 10,000 flight-hours): Pilot Error	Rate: Other Personnel Error	Rate: Materiel Failure	Rate: Total
H-2	FY 74	Major	0	0	1	1	24,981	0.0	0.0	0.4	0.4
		Minor/Incident	12	39	156	212		4.8	15.6	62.5	84.9
		Ground	0	19	1	24		0	7.6	0.4	9.6
		Total	*12*	*58*	*158*	*237*		*4.8*	*23.2*	*63.3*	*94.8*
	CY 75	Major	1	0	0	1	27,031	0.4	0.0	0.0	0.4
		Minor/Incident	13	44	316	376		4.8	16.3	116.9	139.1
		Ground	1	21	5	27		0.4	7.8	1.9	10.0
		Total	*15*	*65*	*321*	*404*		*5.6*	*24.1*	*118.8*	*149.5*
	CY 76	Major	0	0	1	1	33,227	0.0	0.0	0.3	0.3
		Minor/Incident	11	71	495	587		3.3	21.4	149.0	176.7
		Ground	0	13	4	19		0.0	3.9	1.2	5.7
		Total	*11*	*84*	*500*	*607*		*3.3*	*25.3*	*150.5*	*182.7*
	CY 77	Major	2	3	2	4	33,396	0.6	0.9	0.6	1.2
		Minor/Incident	16	67	596	671		4.8	20.1	178.5	200.9
		Ground	1	41	13	59		0.3	12.3	3.9	17.7
		Total	*19*	*111*	*611*	*734*		*5.7*	*33.2*	*183.0*	*219.8*
	CY 78	Major	1	1	1	2	30,687	0.3	0.3	0.3	0.7
		Minor/Incident	16	67	544	622		5.2	21.8	177.3	202.7
		Ground	1	38	25	73		0.3	12.4	8.2	23.8
		Total	*18*	*106*	*570*	*697*		*5.9*	*34.5*	*185.8*	*227.1*
	CY 79	Major	1	0	2	3	29,513	0.3	0.0	0.7	1.0
		Minor/Incident	2	62	622	692		0.7	21.0	210.8	234.5
		Ground	1	26	2	30		0.3	8.8	0.7	10.2
		Total	*4*	*87*	*626*	*725*		*1.4*	*29.5*	*212.1*	*245.7*

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Table 37 (continued)

Heli-copter Series	Year	Mishap Type*	Number				Flight-Hours	Rate (per 10,000 flight-hours)			
			Pilot Error	Other Personnel Error	Materiel Failure	Total		Pilot Error	Other Personnel Error	Materiel Failure	Total
H-3	FY 74	Major	4	4	2	5	77,698	0.5	0.5	0.3	0.6
		Minor/Incident	20	61	339	421		2.6	7.9	43.6	54.2
		Ground	1	47	0	52		0.1	6.1	0.0	6.7
		Total	*25*	*112*	*341*	*478*		*3.2*	*14.4*	*43.9*	*61.5*
	CY 75	Major	2	1	1	3	76,405	0.3	0.1	0.1	0.4
		Minor/Incident	18	95	459	572		2.4	12.4	60.1	74.9
		Ground	0	49	8	56		0.0	6.4	1.1	7.3
		Total	*20*	*145*	*468*	*631*		*2.6*	*19.0*	*61.3*	*82.6*
	CY 76	Major	3	2	1	5	79,016	0.4	0.3	0.1	0.6
		Minor/Incident	13	93	486	597		1.7	11.8	61.5	75.6
		Ground	1	41	4	47		0.1	5.2	0.5	6.0
		Total	*17*	*136*	*491*	*649*		*2.2*	*17.2*	*62.1*	*82.1*
	CY 77	Major	1	1	2	3	83,550	0.1	0.1	0.2	0.4
		Minor/Incident	20	78	432	526		2.4	9.3	51.7	63.0
		Ground	3	63	10	83		0.4	7.5	1.2	9.9
		Total	*24*	*142*	*444*	*612*		*2.9*	*17.0*	*53.1*	*73.3*
	CY 78	Major	1	3	4	8	80,710	0.1	0.4	0.5	1.0
		Minor/Incident	23	83	525	628		2.9	10.3	65.1	77.8
		Ground	1	72	23	103		0.1	8.9	2.9	12.8
		Total	*25*	*158*	*552*	*739*		*3.1*	*19.6*	*68.4*	*91.6*
	CY 79	Major	1	0	2	6	72,887	0.1	0.0	0.3	0.8
		Minor/Incident	10	79	473	564		1.4	10.8	64.9	77.4
		Ground	1	63	3	69		0.1	8.6	0.4	9.5
		Total	*12*	*142*	*478*	*639*		*1.7*	*19.5*	*65.9*	*87.2*

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Table 37 (continued)

Heli-copter Series	Year	Mishap Type*	Number				Flight-Hours	Rate (per 10,000 flight-hours)			
			Pilot Error	Other Personnel Error	Materiel Failure	Total		Pilot Error	Other Personnel Error	Materiel Failure	Total
H-46	FY 74	Major	2	4	3	6	68,509	0.3	0.6	0.4	0.9
		Minor/Incident	26	75	247	349		3.8	11.0	36.1	51.0
		Ground	0	37	1	40		0.0	5.4	0.2	5.8
		Total	*28*	*116*	*251*	*395*		*4.1*	*16.9*	*36.6*	*57.7*
	CY 75	Major	4	4	0	5	86,428	0.5	0.5	0.0	0.6
		Minor/Incident	33	93	383	519		3.8	10.8	44.3	60.1
		Ground	0	31	1	40		0.0	3.6	0.1	4.6
		Total	*37*	*128*	*384*	*564*		*4.3*	*14.8*	*44.4*	*65.3*
	CY 76	Major	1	2	3	5	87,319	0.1	0.2	0.3	0.6
		Minor/Incident	43	95	442	589		4.9	10.9	50.6	67.5
		Ground	1	28	2	36		0.1	3.2	0.2	4.1
		Total	*45*	*125*	*447*	*630*		*5.1*	*14.3*	*51.2*	*72.2*
	CY 77	Major	4	5	3	9	93,500	0.4	0.5	0.3	1.0
		Minor/Incident	24	73	407	519		2.6	7.8	43.5	55.5
		Ground	2	66	17	86		0.2	7.1	1.8	9.2
		Total	*30*	*144*	*427*	*614*		*3.2*	*15.4*	*45.7*	*65.7*
	CY 78	Major	3	3	3	5	97,307	0.3	0.3	0.3	0.5
		Minor/Incident	36	77	470	596		3.7	7.9	48.3	61.3
		Ground	0	53	14	75		0.0	5.5	1.4	7.7
		Total	*39*	*133*	*487*	*676*		*4.0*	*13.7*	*50.1*	*69.5*
	CY 79	Major	1	1	4	4	95,716	0.1	0.1	0.4	0.4
		Minor/Incident	14	85	571	685		1.5	8.9	59.7	71.6
		Ground	1	46	4	51		0.1	4.8	0.4	0.5
		Total	*16*	*132*	*579*	*740*		*1.7*	*13.8*	*60.5*	*77.3*

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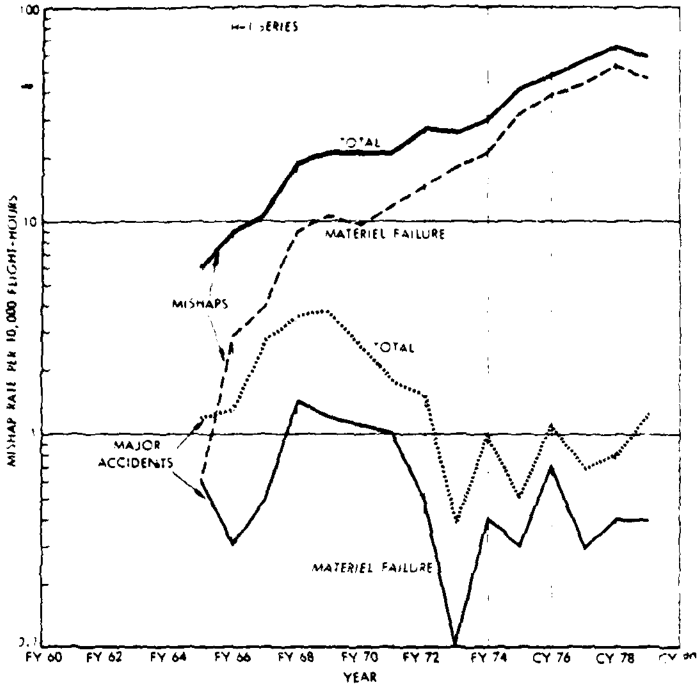
Table 37 (concluded)

Heli-copter Series	Year	Mishap Type*	Number				Flight-Hours	Rate (per 10,000 flight-hours)			
			Pilot Error	Other Personnel Error	Materiel Failure	Total		Pilot Error	Other Personnel Error	Materiel Failure	Total
H-53	FY 74	Major	3	1	2	4	43,701	0.7	0.2	0.5	0.9
		Minor/Incident	18	53	299	372		4.1	12.1	68.4	85.1
		Ground	2	31	7	44		0.5	7.1	1.6	10.1
		Total	*23*	*85*	*308*	*420*		*5.3*	*19.5*	*70.5*	*96.1*
	CY 75	Major	3	4	2	4	36,005	0.8	1.1	0.6	1.1
		Minor/Incident	8	53	270	328		2.2	14.7	75.0	91.1
		Ground	0	44	10	62		0.0	12.2	2.8	17.2
		Total	*11*	*101*	*282*	*394*		*3.1*	*28.1*	*78.3*	*109.4*
	CY 76	Major	5	2	0	6	46,723	1.1	0.4	0.0	1.3
		Minor/Incident	21	70	439	539		4.5	15.0	94.0	115.4
		Ground	2	42	8	61		0.4	9.0	1.8	13.1
		Total	*28*	*114*	*447*	*606*		*6.0*	*24.4*	*95.7*	*129.7*
	CY 77	Major	4	2	3	8	51,407	0.8	0.4	0.6	1.6
		Minor/Incident	26	56	397	477		5.1	10.9	77.2	92.8
		Ground	0	35	18	57		0.0	6.8	3.5	11.1
		Total	*30*	*93*	*418*	*542*		*5.8*	*18.1*	*81.3*	*105.4*
	CY 78	Major	1	1	1	4	52,172	0.2	0.2	0.2	0.8
		Minor/Incident	31	58	522	618		5.9	11.1	100.1	118.5
		Ground	1	52	28	85		0.2	10.0	5.4	16.3
		Total	*33*	*111*	*551*	*707*		*6.3*	*21.2*	*105.6*	*135.5*
	CY 79	Major	1	1	2	4	49,564	0.2	0.2	0.4	0.8
		Minor/Incident	19	76	565	669		3.8	15.3-	114.0	135.0
		Ground	2	45	15	63		0.4	9.1	3.0	12.7
		Total	*22*	*122*	*582*	*736*		*4.4*	*24.6*	*117.4*	*148.5*

Source: Naval Safety Center, Norfolk, Virginia study [1]. In general, there are somewhat fewer major accidents than ground mishaps, while the great majority of mishaps involve minor accidents or incidents. However, even though major accidents account for the fewest mishaps of the three categories, they are probably the most important in terms of total cost (both in materiel loss and in injuries and fatalities). Major accident rates (involving materiel and total) and all mishaps (involving materiel and total) were plotted versus year (Figure 71). In some cases when a helicopter was entering service and the mishap rates were not meaningful, the data for those years were not included in our tables or figures.

NSC has made no change in their reporting system as a result of DODI 1000.19; they are considering some changes that may become effective in 1981.

The general pattern of the Navy mishap rates is similar to that for the Army. In general, the major accident rates decreased over time while the total mishap rates increased. In addition to the reasons proposed by USASC personnel, personnel at NSC felt that the quality and attitude of maintenance personnel were also factors in the worsening mishap rate. They indicated that (1) the better maintenance personnel are assigned to the newer aircraft types, and (2) their degree of eagerness decreases with the age of the aircraft. They also believe that the increasing total mishap rates may be partially caused by more complete reporting of mishaps over time.



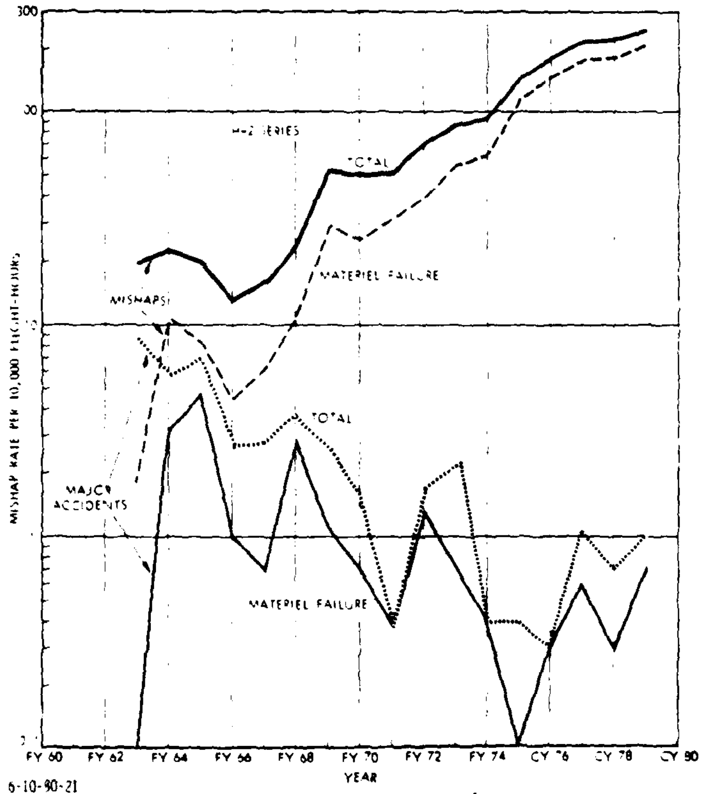


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Figure 71. MISHAP RATES FOR NAVY HELICOPTERS

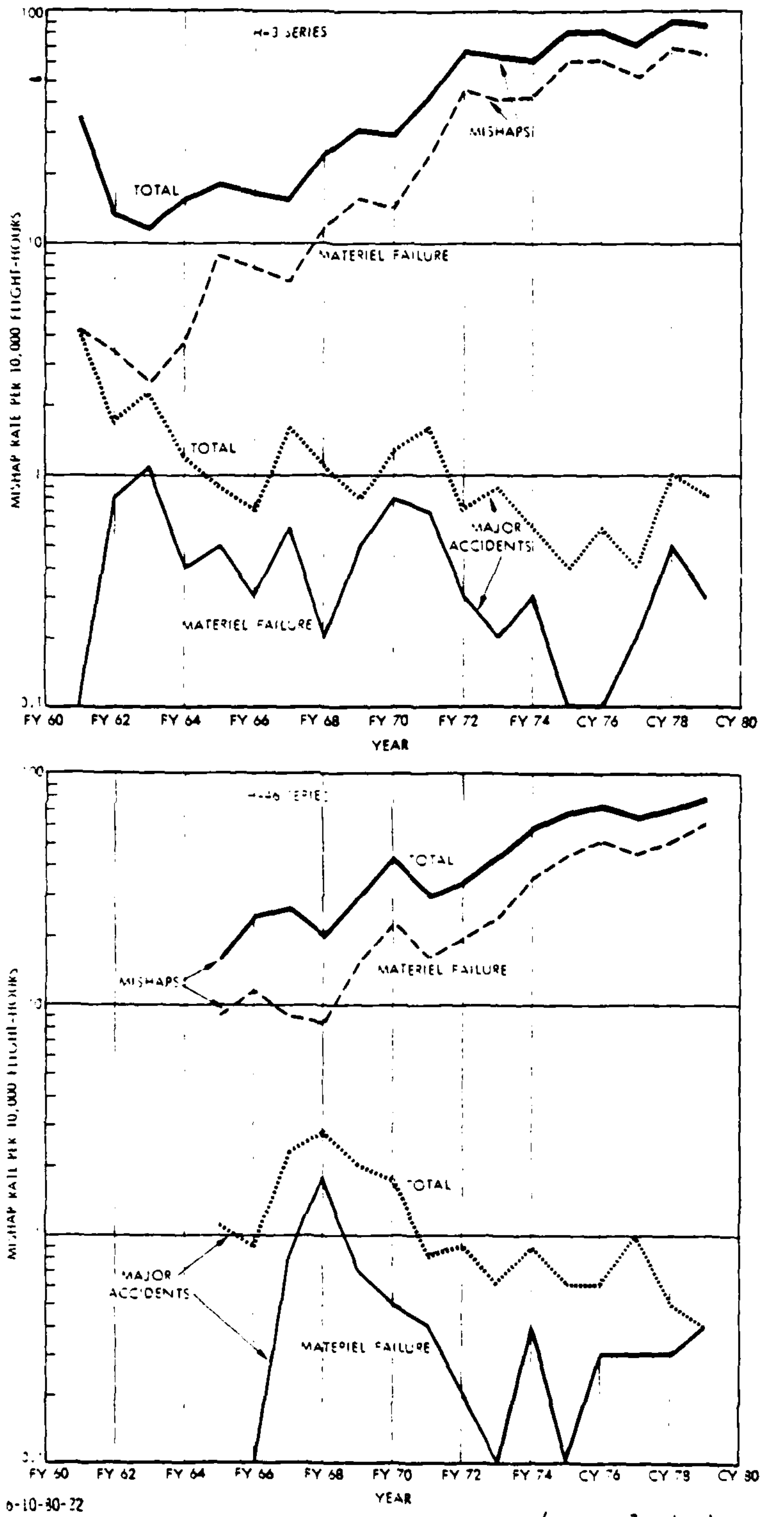

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Figure 71 (continued)

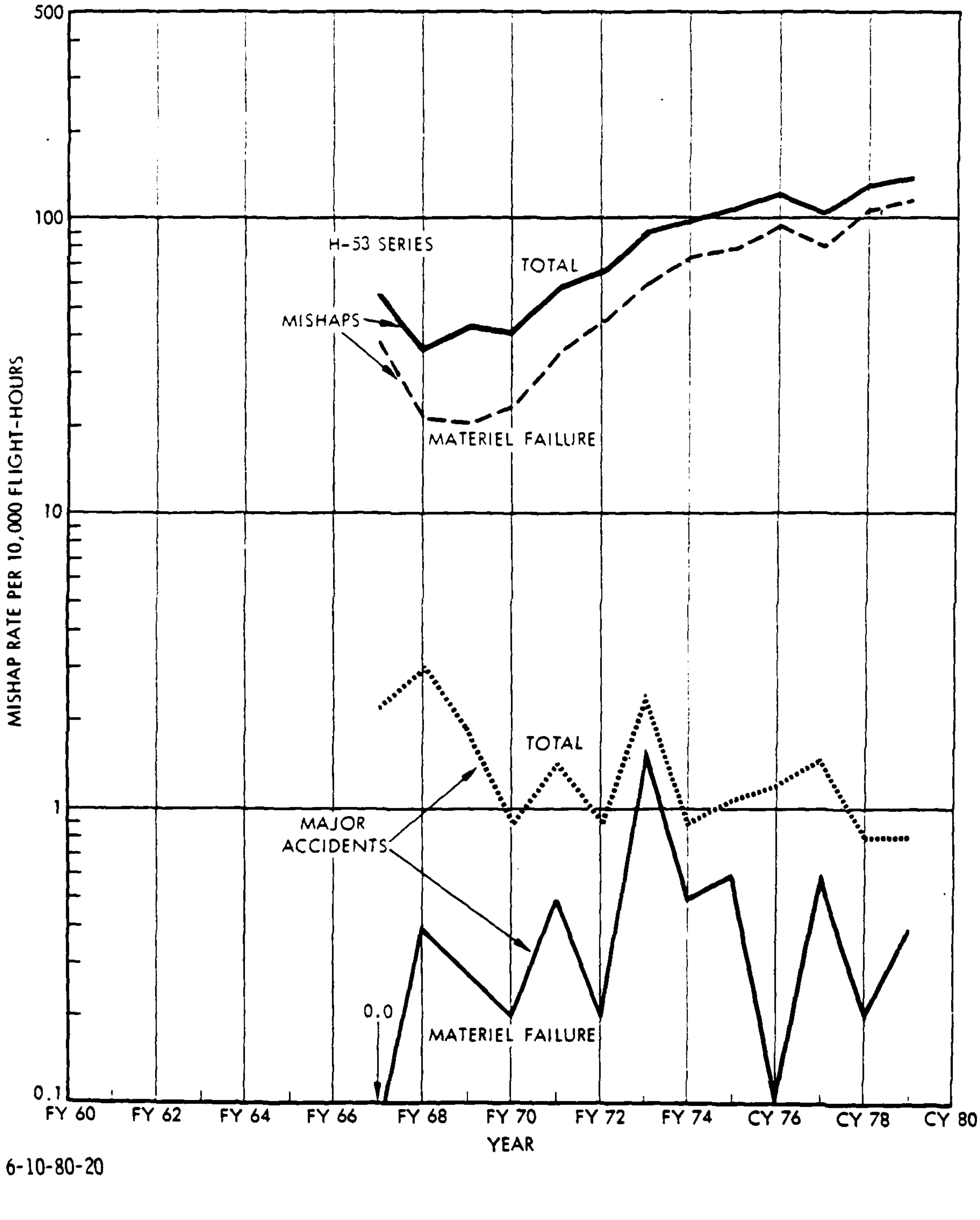

Figure 71 (concluded)

Section IV

Helicopter Product Improvement Programs

After helicopters enter service use, changes are often incorporated in them under Product Improvement Programs (PIPs). Depending upon the nature of the modification, the work may be accomplished at the organizational, intermediate, or depot level of service maintenance activity, or by the manufacturer.

The Army assigns one of the following eight justification codes (JCs) to each PIP:

(1) Safety
(2) New or Improved Operational Capabilities
(3) Cost Reduction
    P = Production
    O&S = Operations and Support
(4) RAM
(5) Deficiency Corrections
(6) Compatibility/Standardization/Environmental/Simplification
(7) Legislative Compliance
(8) Energy Conservation.

Table 38 shows Army PIP dollars for all current basic helicopter types in service use. PIPs designated as RAM (JC4) are shown separately in Table 38. Although each PIP is assigned to a single JC, in reality PIPs almost always have implications in more than one JC. Virtually any PIP will have some impact on R&M characteristics; depending on the particulars of the modification involved, it could either improve or degrade R&M characteristics. Indeed, the same

Table 38. U.S. ARMY HELICOPTER PRODUCT IMPROVEMENT PROGRAMS
(Million Dollars)

End-Item	JC	Prior	FY 80	FY 81	FY 82	FY 83
AH-1	4	0.18	0.00	0.00	0.00	0.00
	Other	301.49	296.34	157.77	131.57	258.82
	1-8	301.67	296.34	157.77	131.57	258.82
CH-47	4	24.67	34.57	51.25	54.53	36.95
	Other	139.89	55.54	181.89	222.68	230.19
	1-8	164.56	90.11	233.14	277.21	267.14
CH-54	4	0.33	1.11	1.36	0.95	0.27
	Other	1.54	1.27	0.72	1.11	0.08
	1-8	1.87	2.38	2.08	2.06	0.35
EH-1	4	0.00	0.00			
	Other	50.17	19.25			
	1-8	50.17	19.25	-------Classified-------		
EH-60	4	0.00	0.00			
	Other	0.98	16.88			
	1-8	0.98	16.88	-------Classified-------		
OH-58	4	0.00	0.04	0.07	0.78	0.75
	Other	101.55	1.68	19.32	44.86	38.26
	1-8	101.55	1.72	19.39	45.64	39.01
OH-6	4	0.07	0.20	0.81	0.90	0.95
	Other	2.06	0.25	0.67	0.26	0.00
	1-8	2.13	0.45	1.48	1.16	0.95
TH-55	4	0.00	0.00	0.00	0.00	0.00
	Other	0.00	0.00	0.00	0.48	0.00
	1-8	0.00	0.00	0.00	0.48	0.00
UH-1	4	10.96	0.00	2.84	4.79	3.65
	Other	38.77	7.88	51.19	68.34	57.69
	1-8	49.73	7.88	54.03	73.13	61.34
UH-60	4	0.00	0.00	0.00	0.00	0.00
	Other	0.00	0.34	0.21	10.91	17.95
	1-8	0.00	0.34	0.21	10.91	17.95
Grand Total		672.66	435.36	468.10[a]	542.16[a]	645.56[a]

[a] Excludes EH-1 and EH-60.

Source: Office of Product Improvement, U.S. Army Materiel Development & Readiness Command

PIP could both improve and degrade different aspects of R&M characteristics. For example, some helicopters have been equipped with blade inspection method (BIM) indicators. These indicators sense the pressure within the rotor blade spar and give a cockpit warning if the blade is losing pressure, which could be caused by blade crack propagation. These devices tend to reduce crashes, but at the same time they give many false indications leading to precautionary landings. Hence, this device, which is primarily RAM in nature, may reduce the number of catastrophic failures slightly but at the same time cause many more minor failures so that the overall failure rate is higher with the BIM than without it.

Total PIP program dollars for each basic helicopter type in Army, Navy, and Air Force service use are available in the Procurement Annex to the Five Year Defense Program under the budget appropriation subtitle "Modification of Aircraft." These data are available starting with FY 1969. Unfortunately, the Procurement Annex is classified Confidential. In order to keep this study unclassified, they are not included. The Navy helicopter modification dollars are comparable to those of the Army; the Air Force modification program is much smaller since helicopters are not as widely used in the Air Force as in the other services, and tend to be used more in support roles than in combat mission roles.

The Army and Navy helicopter modification programs are each running in the hundreds of millions of dollars annually. Yet with the single exception of accidents, we found no R&M characteristic time series that indicates improvement in fleet R&M characteristics over time. Indeed, the Navy 3-M time series show marked degradation in R&M characteristics over time. Although PIP dollars do not appear to be effective in improving R&M characteristics (other than accident rates), this cannot be a firm conclusion. It is possible that R&M degradation over time might be even worse in the absence of the PIPs.

Section V

Army Operationally Ready (OR) Data

Operationally ready data show the percent of assigned aircraft that are operationally ready to perform their assigned mission. Those not operationally ready are classified as either awaiting spare parts (NORS) or maintenance personnel (NORM) to work on them. Accordingly, the operationally ready (OR) rate reflects the basic R&M characteristics of the aircraft, and also the level of spares support, the level and quality of assigned maintenance personnel, the flying hour rate, and the operating environment of the aircraft (climatic, maintenance facilities, type of flying, etc.). Hence, the OR rate is not a pure measure of R&M characteristics, but it is an important one in that it represents the prime objective of all R&M efforts--to have aircraft ready to perform their assigned missions. Assuming the other factors affecting the OR rate remain constant, then any improvement (or worsening) of R&M characteristics should be reflected in changes in this rate.

The Army publishes aircraft operationally ready data monthly. At IDA's request TSARCOM made a special run of all helicopters for the period 1967-1980. The data were limited to "Forces Command" aircraft--those aircraft operated by the First, Fifth and Sixth Armies, all based in the continental U.S. (CONUS). The data were limited to CONUS-based aircraft in order to eliminate (insofar as possible) the effects of variable operating environments--particularly the Vietnam War environment. Data in this special run were presented both monthly and as annual averages.

The operationally ready rate (in percent) is calculated as follows:

$$OR = 100 - NORS - NORM$$

where

NORS = the percent of aircraft that are not operationally ready because they are awaiting spare parts,

NORM = the percent of aircraft that are not operationally ready because they are awaiting maintenance (personnel).

In addition to the OR, NORS, and NORM figures, the data show the number of aircraft assigned and the hours flown. The TSARCOM data file appears to be incomplete for some months and years. Accordingly, we dropped some helicopter types from our data base completely, and for others we restricted the number of years to those where we felt sufficient data existed to be statistically significant. This process left us with the nine helicopter types whose data are presented in Table 39 and Figure 72.

Referring to Figure 72, the difference between the top line and 100 percent represents the NORS percent; the difference between the two lines represents the NORM percent; and the lower line shows the resulting OR percent. We have noted whether the overall trend of the OR rate appears to become better, worse, or remain constant over time. These overall trends are summarized in Table 40. As can be seen, the trends for five helicopters remained approximately constant, two worsened slightly, and two improved slightly. The overall conclusion based on these data is that, on average, Army OR rates generally remain constant over time.

Table 39. ARMY FORCES COMMAND HELICOPTER STATUS

Helicopter Type and Year	OR[1] (%)	NORS[2] (%)	NORM[3] (%)	Total Aircraft-July	Hours Flown
<u>CH-47A</u>					
1974	60.7	7.0	32.4	24	1,555
1975	66.3	13.8	19.9	25	3,249
1976	57.9	15.1	26.9	35	3,111
1977	60.7	12.3	27.0	27	2,158
1978	55.5	14.9	29.7	22	1,282
1979	65.5	12.6	21.9	21	1,710
1980	65.4	10.1	24.6	22	768
<u>CH-47B</u>					
1973	65.7	10.5	23.9	44	3,289
1974	70.1	9.0	20.9	48	6,068
1975	67.3	8.0	24.7	56	6,386
1976	60.5	12.4	27.1	57	5,527
1977	66.4	9.7	23.9	55	5,892
1978	72.2	5.8	22.0	59	6,875
1979	76.8	5.0	18.3	60	6,412
1980	65.0	5.5	29.8	63	3,971
<u>CH-47C</u>					
1973	72.3	10.1	17.6	72	4,986
1974	57.3	19.3	23.4	78	8,708
1975	66.0	13.7	20.3	96	11,622
1976	69.4	11.7	18.9	100	10,940
1977	72.6	8.2	19.2	109	14,046
1978	70.9	10.5	18.6	107	14,222
1979	66.7	13.0	20.3	103	12,383
1980	59.8	10.6	29.6	80	6,898

[1]Operationally ready.

[2]Not operationally ready for supply.

[3]Not operationally ready for maintenance.

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Table 39 (continued)

Helicopter Type and Year	OR (%)	NORS (%)	NORM (%)	Total Aircraft-July	Hours Flown
UH-1H					
1967	83.2	3.9	12.9	42	6,788
1968	70.4	10.2	19.5	5	883
1969	71.4	14.0	14.6	8	1,713
1970	73.7	9.2	17.1	37	11,638
1971	69.4	13.6	17.0	59	18,272
1972	71.3	11.1	17.6	70	23,549
1973	76.3	9.2	14.5	960	115,217
1974	77.2	7.2	15.6	1,015	206,873
1975	74.7	7.9	17.4	1,128	220,697
1976	76.0	6.7	17.3	1,149	207,893
1977	77.6	4.7	17.7	1,144	218,794
1978	76.0	5.4	18.5	1,143	206,285
1979	77.0	5.6	17.4	1,104	182,376
1980	73.0	5.8	21.2	926	89,336
TH-1G					
1972	64.5	20.2	15.3	2	180
1973	68.8	15.8	15.4	10	686
1974	52.7	32.4	14.9	10	747
1975	54.9	18.7	26.4	11	997
1976	57.4	12.9	29.7	12	808
1977	66.3	5.2	28.4	9	844
1978	58.1	8.6	33.3	7	484
1979	69.9	4.8	25.3	7	166
OH-58A					
1969	81.7	10.0	8.3	-[a]	3,241
1970	84.5	6.2	9.4	13	7,323
1971	79.0	10.1	10.9	32	11,149

[a] 0 in July; 2 in August increasing to 8 in December.

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Table 39 (continued)

Helicopter Type and Year	OR (%)	NORS (%)	NORM (%)	Total Aircraft-July	Hours Flown
OH-58A (cont'd)					
1972	71.2	14.1	14.7	53	16,774
1973	74.4	11.1	14.6	617	65,469
1974	73.8	10.3	15.8	653	107,807
1975	75.7	8.9	15.4	729	124,684
1976	75.5	9.4	15.2	785	117,368
1977	78.5	7.0	14.6	800	124,359
1978	76.4	7.3	16.3	692	119,013
1979	76.6	8.8	14.6	641	105,236
1980	75.7	7.2	17.1	603	54,625
AH-1G					
1971	82.1	4.4	13.5	-[a]	543
1972	77.9	10.7	11.4	29	5,837
1973	71.2	12.5	16.3	388	22,931
1974	65.3	17.4	17.3	440	41,082
1975	69.0	11.7	19.3	467	46,690
1976	64.3	11.7	24.0	357	33,713
1977	71.4	6.6	22.1	311	35,736
1978	67.0	8.8	24.2	325	31,159
1979	71.6	9.3	19.1	267	21,421
1980	68.6	8.8	22.6	169	8,398
AH-1S					
1976	73.5	8.8	17.8	-[b]	635
1977	84.2	2.2	13.6	46	6,514
1978	80.3	7.4	12.3	120	14,733
1979	77.1	11.5	11.5	200	22,188
1980	78.8	7.8	13.5	243	17,848

[a] 0 in July; 4 in August increasing to 7 in December.

[b] 0 in July; 3 in August increasing to 25 in December.

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Table 39 (concluded)

Helicopter Type and Year	OR (%)	NORS (%)	NORM (%)	Total Aircraft-July	Hours Flown
CH-54B					
1971	64.0	23.6	12.4	4	226
1972	61.6	23.9	14.5	8	1,283
1973	70.2	12.2	17.6	18	2,073
1974	77.3	9.6	13.1	22	2,869
1975	71.4	9.7	18.9	22	3,355
1976	63.0	16.2	20.9	23	2,986
1977	73.3	10.5	16.2	23	2,842
1978	71.1	12.8	16.2	23	3,733
1979	72.3	8.8	18.9	13	2,037

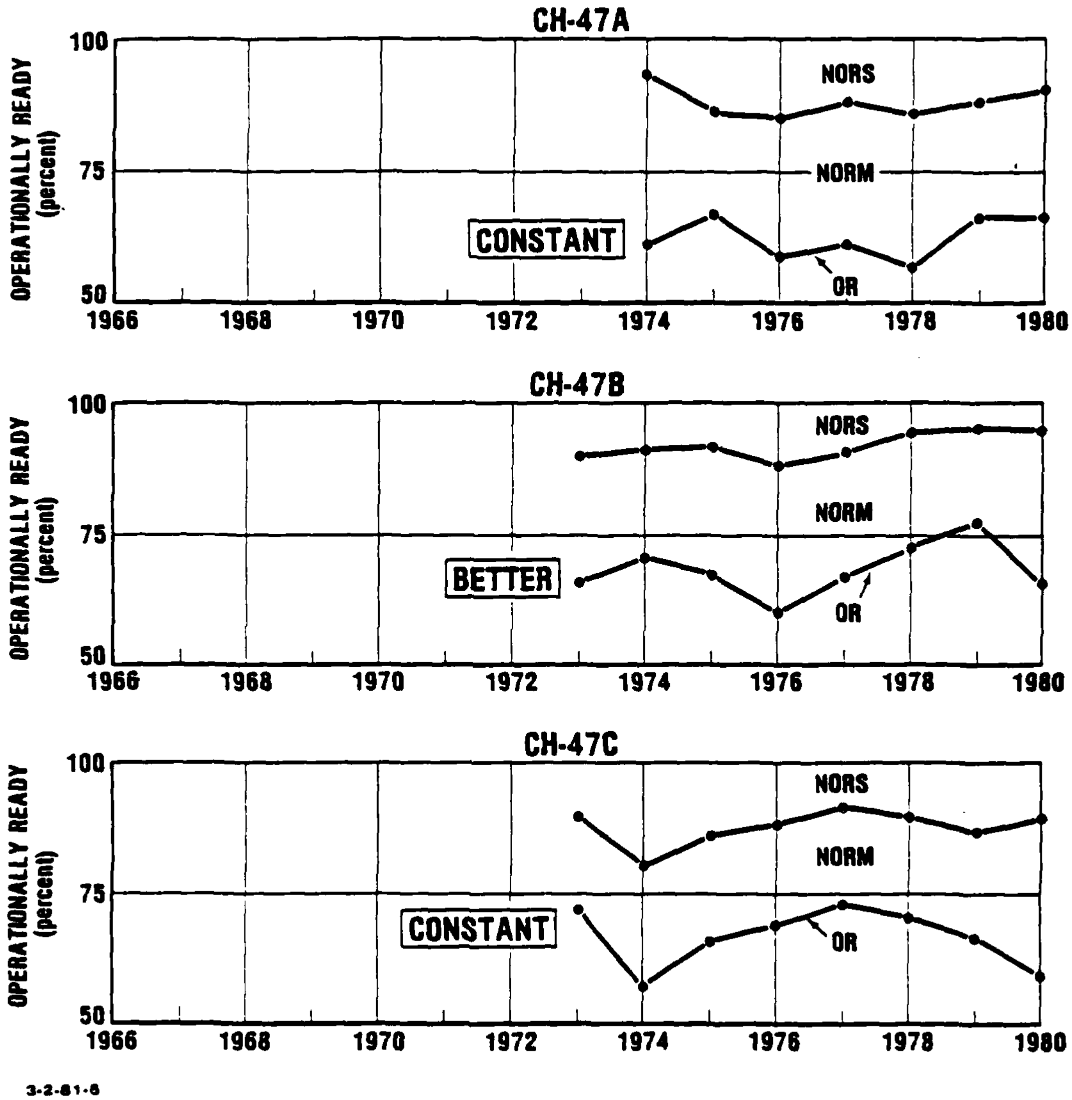

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Figure 72. ARMY FORCES COMMAND HELICOPTER STATUS

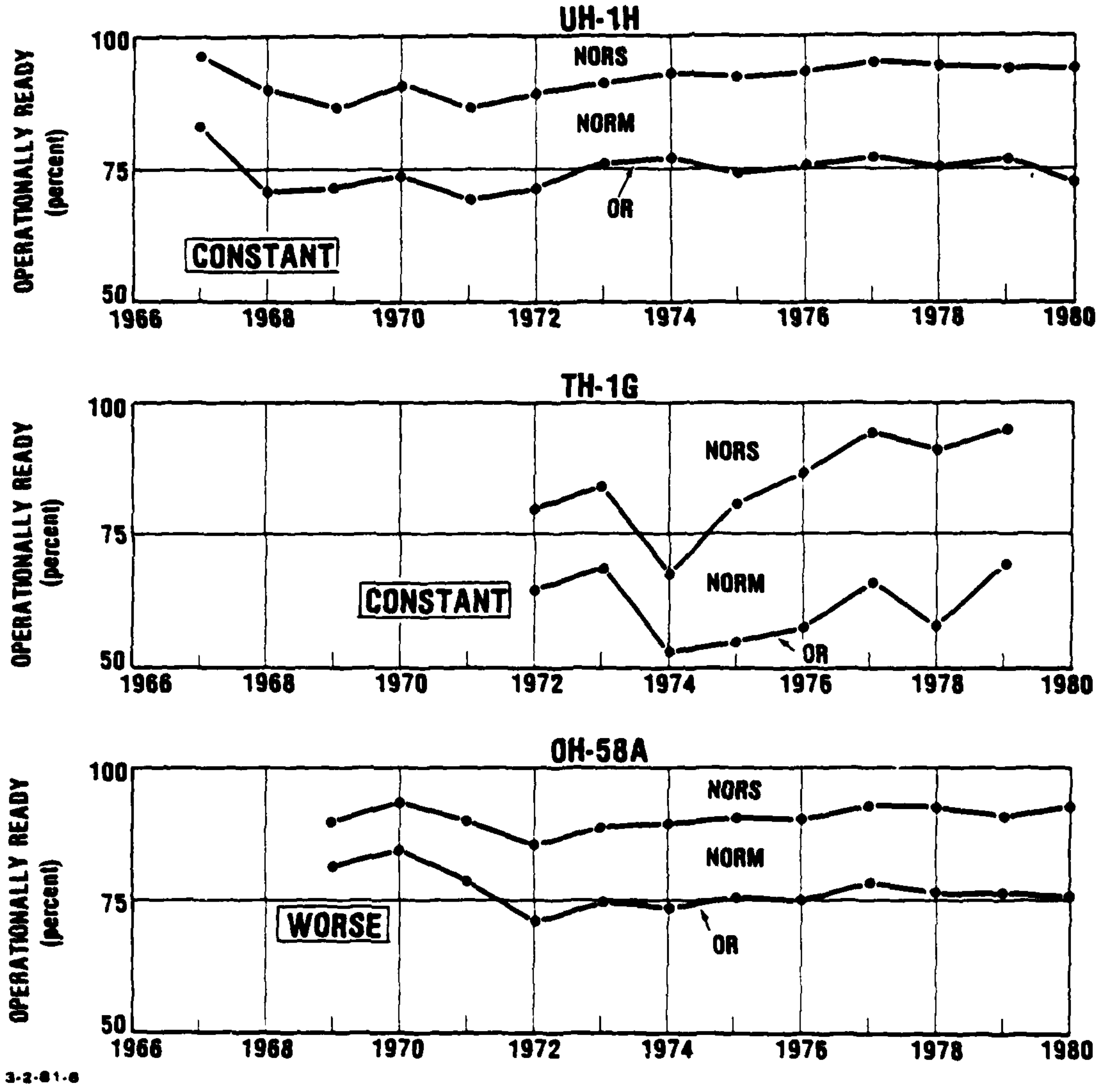

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Figure 72 (continued)

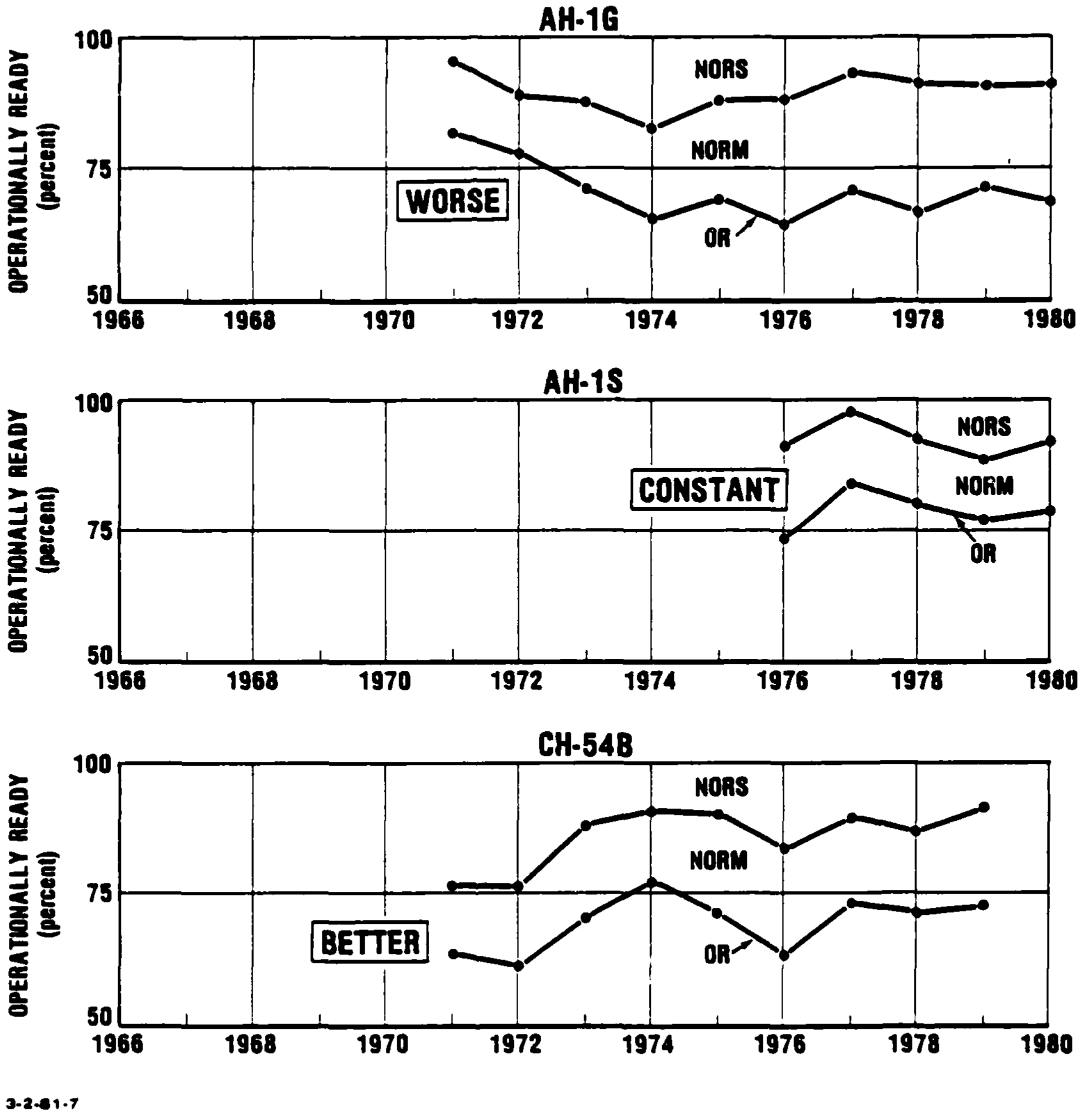


Figure 72 (concluded)

Table 40. U.S. ARMY FORCES COMMAND HELICOPTER OPERATIONALLY READY TRENDS

Helicopter Type	Operationally Ready Trend
CH-47A	Constant
CH-47B	Better
CH-47C	Constant
UH-1H	Constant
TH-1G	Constant
OH-58A	Worse
AH-1G	Worse
AH-1S	Constant
CH-54B	Better

Section VI

Changes in Commercial Aircraft Reliability/Maintainability Characteristics Over Time

Over 80 percent of the Free World's commercial airliners are produced in the U.S. and are widely acknowledged to be the best in the world. Accordingly, their R&M characteristics are probably close to optimum and may provide insights useful in formulating R&M policies for military aircraft.

A. MAINTENANCE COSTS AND MAN-HOURS

Figures 73 through 84 are a series of figures obtained from McDonnell Douglas Corporation reports which depict maintenance cost and manhour trends for three generations of U.S. commercial jet transports. These figures are based on data reported by all U.S. air carriers to the Civil Aeronautics Board on CAB Form 41 reports.

Figure 73 shows annual direct maintenance costs in current dollars for the first generation of four-engine jets. Figures 74 and 75 show the breakdown of these costs by airframe/accessories and engines. Figure 74 is presented in cumulative terms while Figure 75, like Figure 73, is in annual terms. Since Figure 74 shows quite stable costs, the annual airframe and accessories maintenance costs would be quite similar to the cumulative costs shown. The engine costs generally decreased through 1971 and then almost doubled from 1971 to 1978.

If these costs are corrected for inflation using the Consumer Price Index, the real costs (for the entire aircraft,

Figure 73), decreased by about 35 percent from 1960 through 1977. Figure 76 confirms this decrease in real costs; it shows that maintenance manhours per flying hour decreased by about 50 percent over this 17-year period.

The second generation of U.S. commercial jets were the twin and tri jets shown in Figure 77: the Boeing 727 and 737 and the McDonnell Douglas DC-9. Figure 77 shows the cumulative direct maintenance costs in constant 1977 dollars, and Figures 78 and 79 show the breakdown of these costs by airframe/ other flight equipment and engines. Although these are cumulative plots, the fact that they are all fairly constant after the first couple of years indicates that annual costs stabilized at roughly constant levels after about two years. This general pattern is confirmed by Figure 80, which shows that manhours per flying hour were quite constant for the DC-9-30 and B-737, while they decreased somewhat for the B-727.

Plots similar to those for the twin and tri jets are presented for the most recent generation (the wide body DC-10, B-747, and L-1011) in Figures 81 through 84. The direct maintenance costs per revenue flight hour are again fairly constant after the first couple of years for the B-747 and L-1011, while the DC-10 exhibits an increase over the entire period due entirely to increasing engine maintenance costs. Manhours per flying hour are again fairly constant for all three wide body jets.

B. MECHANICAL SCHEDULE RELIABILITY

Figures 85 through 90 depict mechanical schedule reliability (also called "dispatch reliability" or "mechanical dispatch reliability") for the Boeing 707, 727, 737, 747; the McDonnell Douglas DC-8, DC-9, DC-10; and the Lockheed L-1011 aircraft. Schedule interruptions due to mechanical problems include cancellations, air turnbacks, diversions, and departure delays greater than 15 minutes. This measure of reliability is similar to the "Mission Reliability" used by the military services.

The first jet airliner produced in this country (the 707-100) required about five years to reach its mature level of schedule reliability. Later models (the 707-300 and -300B/C) required only two or three years. The next completely new Boeing aircraft (the 727) reached its mature level of schedule reliability in only about six months, while the next Boeing (the 737) had a very high schedule reliability when it was first put into service. The most recent Boeing aircraft to enter service (the 747) exhibited a growth in schedule reliability much like that of the 707-100. The 747, mainly due to engine reliability problems, required about three years to reach its mature level of schedule reliability.

The DC-8, which closely followed the Boeing 707-100, also required about five years to reach its mature level of schedule reliability, but it was somewhat more reliable than the 707-100 throughout this growth period. The next generation McDonnell Douglas transport, the DC-9, was quite similar in schedule reliability to the Boeing 727 and 737 (see Figures 86 and 88); all three aircraft exhibited a high initial reliability. The DC-9's reliability grew slightly during the first three years of service and stabilized slightly above the levels of the Boeing 727 and 737. The most recent McDonnell Douglas aircraft, the DC-10, had a fairly high initial reliability and reached its mature level of reliability after about three years in service (see Figure 89).

The Lockheed L-1011 (Figure 90) required roughly two years to reach its mature level of schedule reliability.

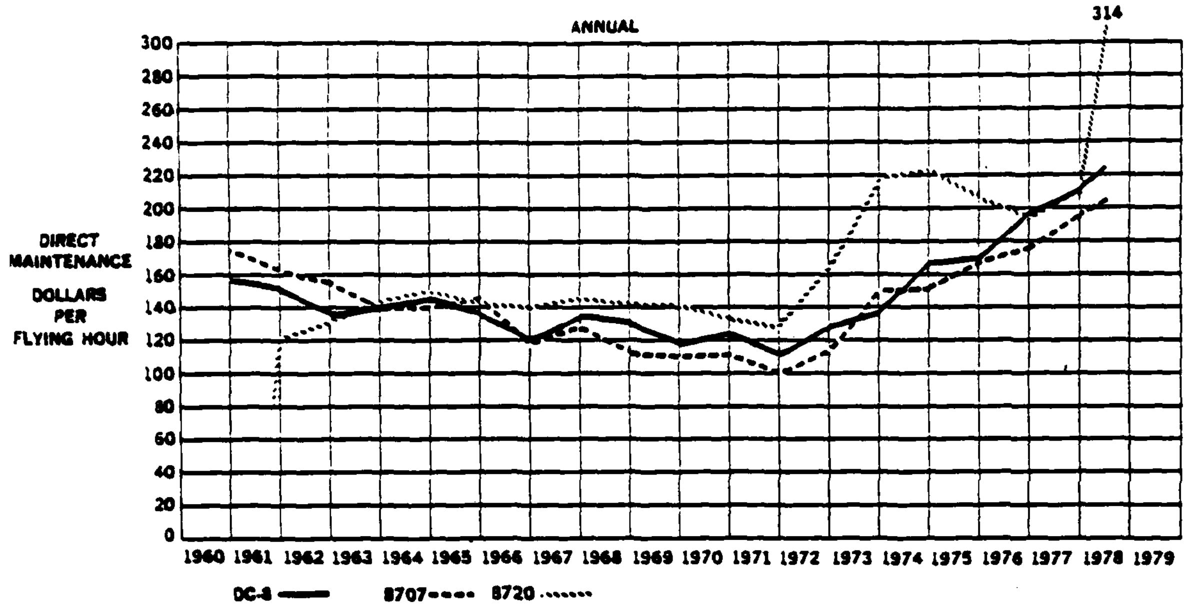
These reliability trends indicate some improvement in the later models relative to the first generation jet transports, the Boeing 707-100 and the DC-8. As indicated by the

Boeing 727 and 737 and the McDonnell Douglas DC-9, it is possible (and certainly desirable) to develop new aircraft with very high initial levels of schedule reliability. When problems are encountered early in the service life (as in the case of the latest generation of wide body jet transports), they are corrected within two or three years after introduction into service use.

C. SUMMARY AND CONCLUSIONS

The trends in maintenance costs, maintenance manhours, and mechanical schedule reliability are summarized in Table 41. First generation commercial jets were the only ones to show long term (i.e., greater than three year) improvement trends. Second generation jets showed little improvement in any R&M measure after introduction into service; they were basically good when introduced. Third generation jets experienced some reliability problems with their high by-pass ratio engines, but R&M characteristics stabilized after two or three years.

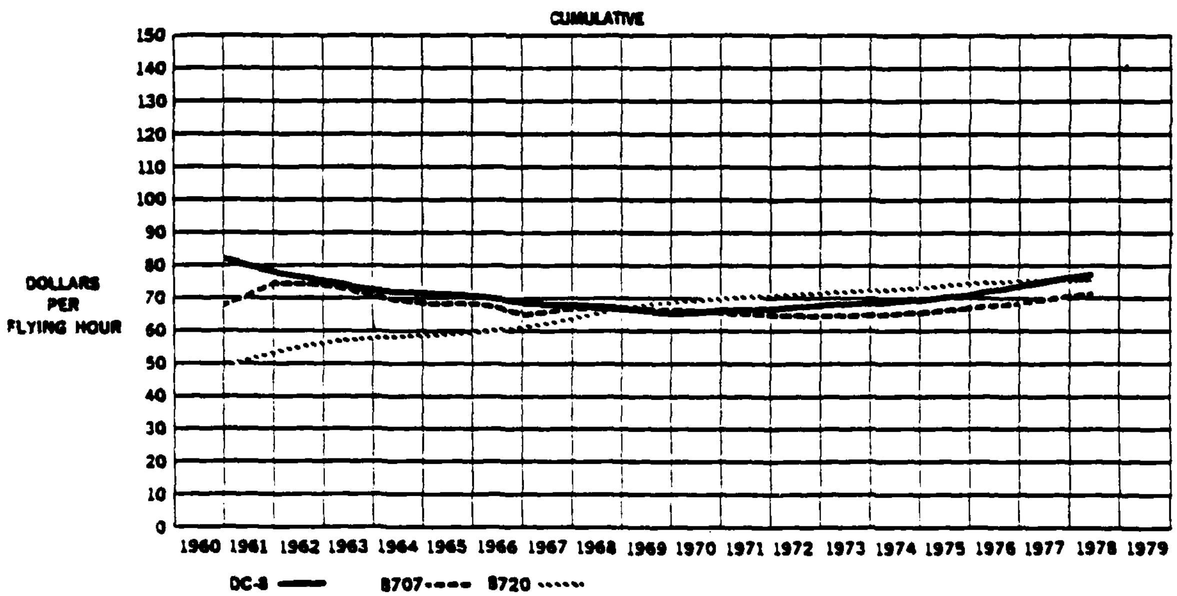
It appears that the commercial aircraft manufacturers strive to develop their aircraft to a mature level of R&M characteristics prior to introduction of the aircraft into service. When problems have developed in the last two generations of jets, they have been corrected within two or three years following introduction into service; thereafter, R&M characteristics have remained quite constant.



Source: *Commercial Transport Operations & Maintenance Data Summary*, McDonnell Douglas Corporation, December 1978.

DATA SOURCE: CAB-41 REPORTS

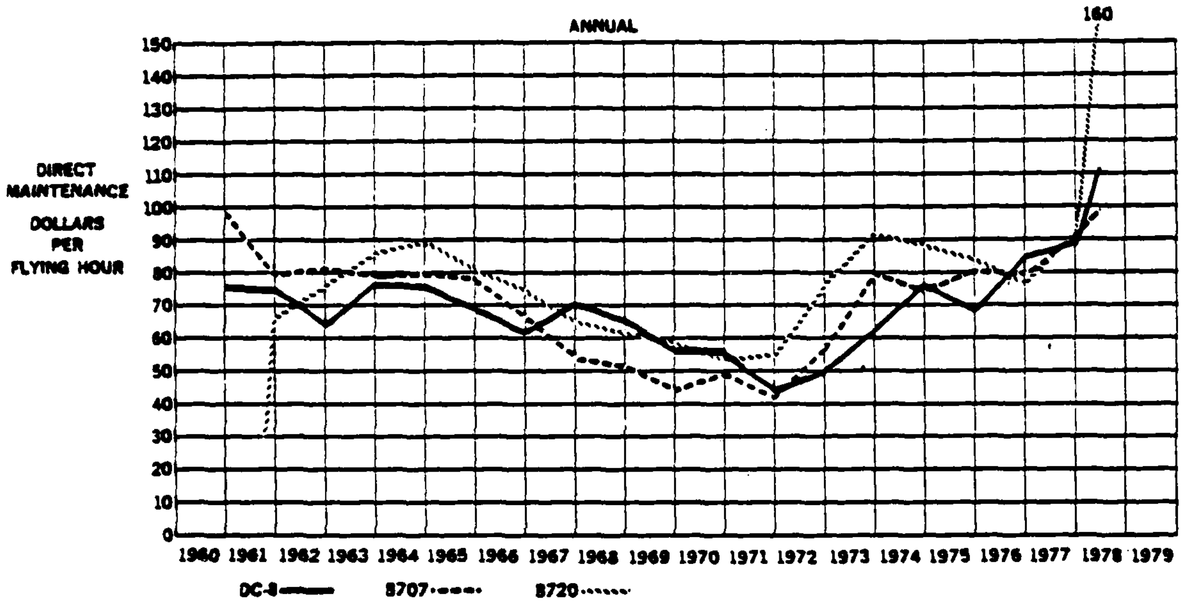
Figure 73. DIRECT MAINTENANCE COSTS, U.S. OPERATORS, FOUR ENGINE JETS



Source: *Commercial Transport Operations & Maintenance Data Summary*, McDonnell Douglas Corporation, December 1978.

DATA SOURCE: CAB-41 REPORTS

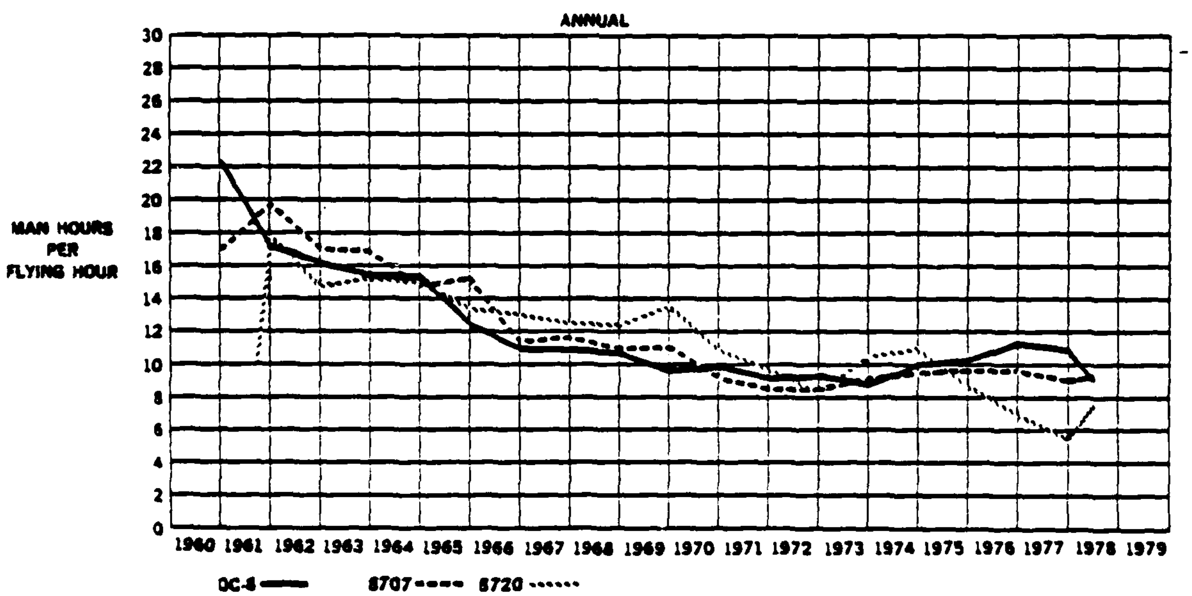
Figure 74. DIRECT MAINTENANCE COSTS, AIRFRAME AND ACCESSORIES, FOUR ENGINE JETS



Source: *Commercial Transport Operations & Maintenance Data Summary*, McDonnell Douglas Corporation, December 1978.

DATA SOURCE: CAB-41 REPORTS

Figure 75. DIRECT MAINTENANCE COSTS, U.S. OPERATORS, ENGINES, FOUR ENGINE JETS



Source: *Commercial Transport Operations & Maintenance Data Summary*, McDonnell Douglas Corporation, December 1978.

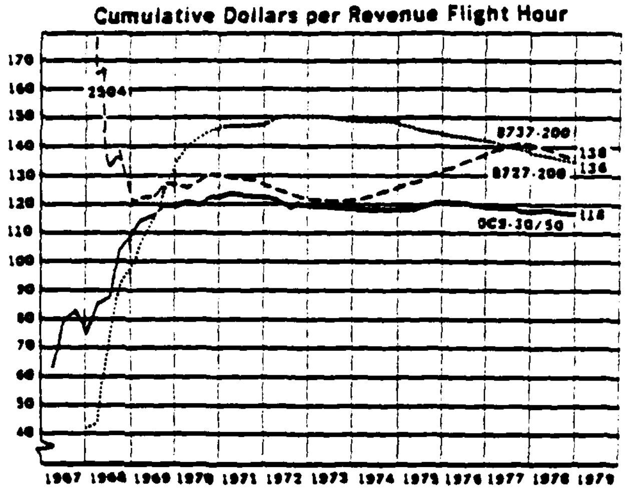
DATA SOURCE: CAB-41 REPORTS

Figure 76. MAINTENANCE MANHOURS PER FLYING HOUR, U.S. OPERATORS, FOUR ENGINE JETS

• OUTSIDE REPAIR EQUATED TO "IN-HOUSE" COSTS
• EXPENSES EQUATED TO CONSTANT 1977 DOLLARS
• STAGE LENGTH EQUATED TO 1.0 HOUR PER FLIGHT

U.S. Trunkline

Cumulative Dollars per Revenue Flight Hour



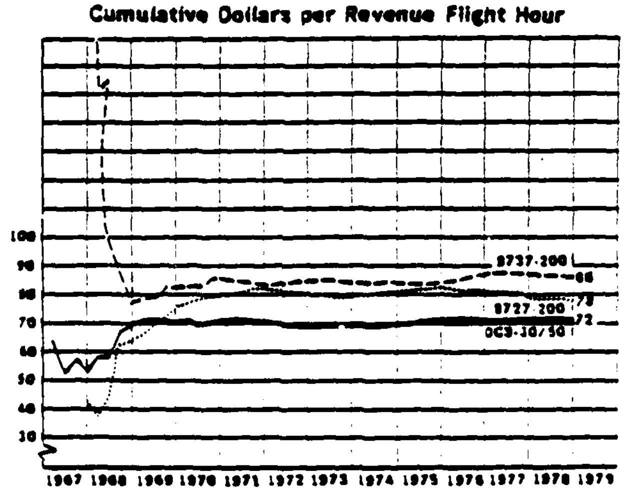
Source: *DC-9-30/50, B727-200, B737-200 Total Maintenance Cost Comparisons*, McDonnell Douglas Corporation, January 1980.

Figure 77. EQUIVALENT DIRECT MAINTENANCE COSTS (TOTAL)

• OUTSIDE REPAIR EQUATED TO "IN-HOUSE" COSTS
• EXPENSES EQUATED TO CONSTANT 1977 DOLLARS
• STAGE LENGTH EQUATED TO 1.0 HOUR PER FLIGHT

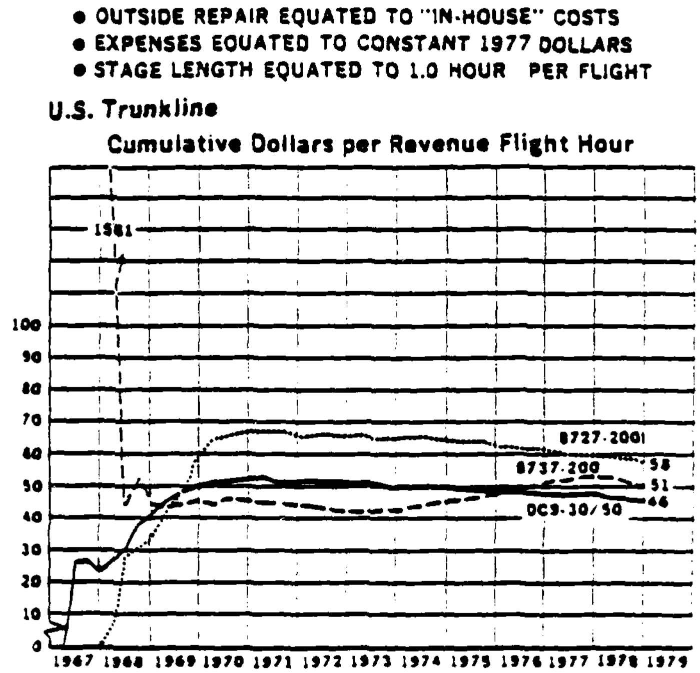
U.S. Trunkline

Cumulative Dollars per Revenue Flight Hour



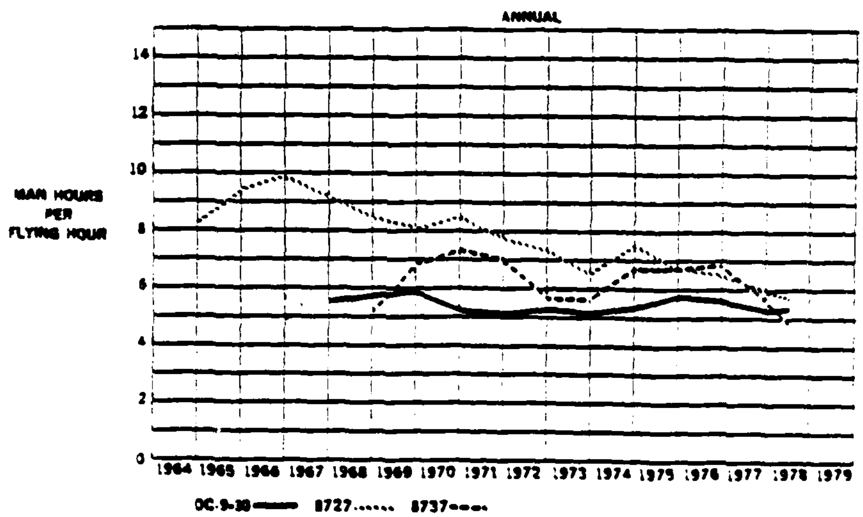
Source: *DC-9-30/50, B727-200, B737-200 Total Maintenance Cost Comparisons*, McDonnell Douglas Corporation, January 1980.

Figure 78. EQUIVALENT DIRECT MAINTENANCE COSTS (AIRFRAME AND OTHER FLIGHT EQUIPMENT)



Source: *DC-9-30/50, B727-200, B737-200 Total Maintenance Cost Comparisons*, McDonnell Douglas Corporation, January 1980.

Figure 79. EQUIVALENT DIRECT MAINTENANCE COSTS, ENGINES

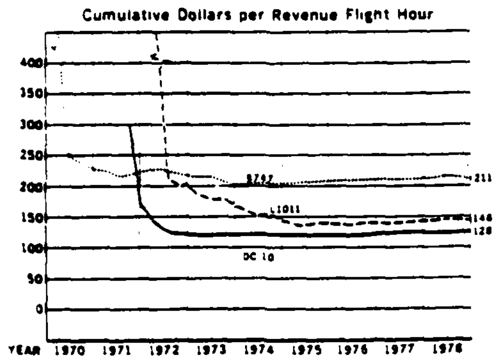


Source: *Commercial Transport Operations and Maintenance Data Summary*, McDonnell Douglas Corporation, December 1978.

DATA SOURCE: CAB-41 REPORTS

Figure 80. MAINTENANCE MANHOURS PER FLYING HOUR, U.S. OPERATORS, TWIN & TRI JETS

- OUTSIDE REPAIR EQUATED TO "IN-HOUSE" COSTS
- EXPENSES EQUATED TO CONSTANT 1977 DOLLARS
- STAGE LENGTH EQUATED TO 3.2 HOURS PER FLIGHT



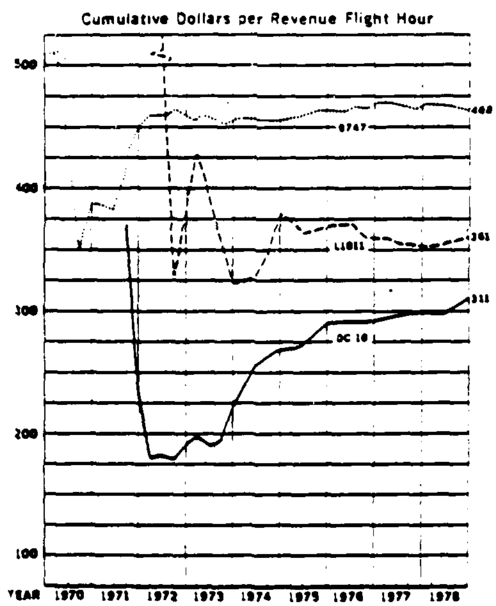
Current Dollars
per
Revenue Flight Hour*
B747= 216
L1011= 156
DC-10= 109

Source: *DC-10, B747, L-1011 Total Maintenance Cost Comparisons*, McDonnell Douglas Corporation, 1979

*12 Months ending 12-31-78

Figure 81. EQUIVALENT DIRECT MAINTENANCE COSTS (TOTAL)

- OUTSIDE REPAIR EQUATED TO "IN-HOUSE" COSTS
- EXPENSES EQUATED TO CONSTANT 1977 DOLLARS
- STAGE LENGTH EQUATED TO 3.2 HOURS PER FLIGHT



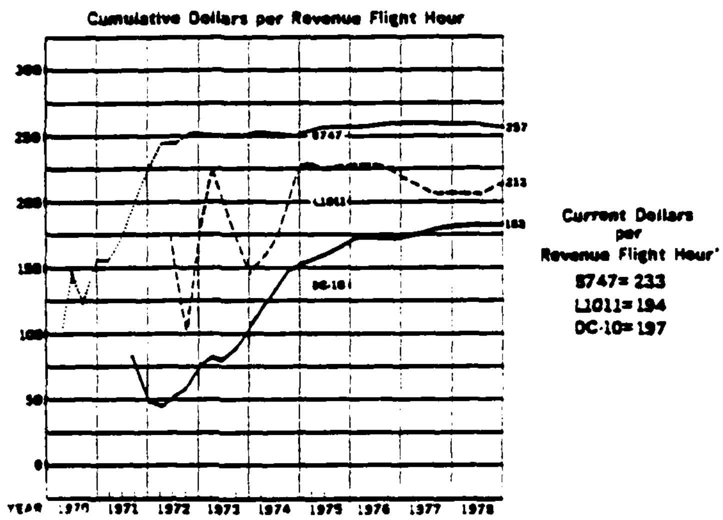
Current Dollars
per
Revenue Flight Hour*
B747=449
L1011=350
DC-10=306

Source: *DC-10, B747, L-1011 Total Maintenance Cost Comparisons*, McDonnell Douglas Corporation, 1979

*12 Months ending 12-31-78

Figure 82. EQUIVALENT DIRECT MAINTENANCE COSTS (AIRFRAME AND OTHER FLIGHT EQUIPMENT)

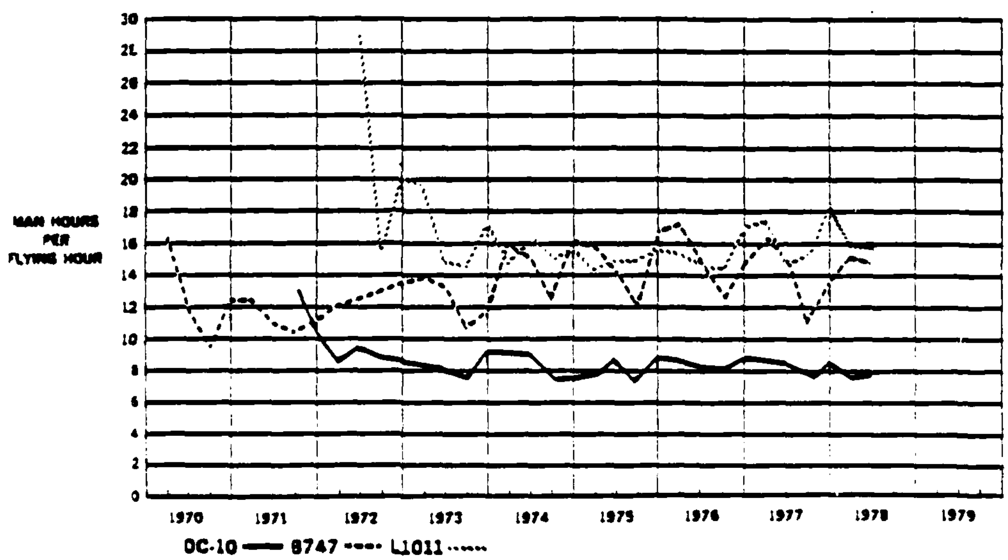
●OUTSIDE REPAIR EQUATED TO "IN-HOUSE" COSTS
●EXPENSES EQUATED TO CONSTANT 1977 DOLLARS
●STAGE LENGTH EQUATED TO 3.2 HOURS PER FLIGHT



Source: *DC-10, B747, L-1011 Total Maintenance Cost Comparisons*, McDonnell Douglas Corporation, 1979

*12 Months ending 12-31-78

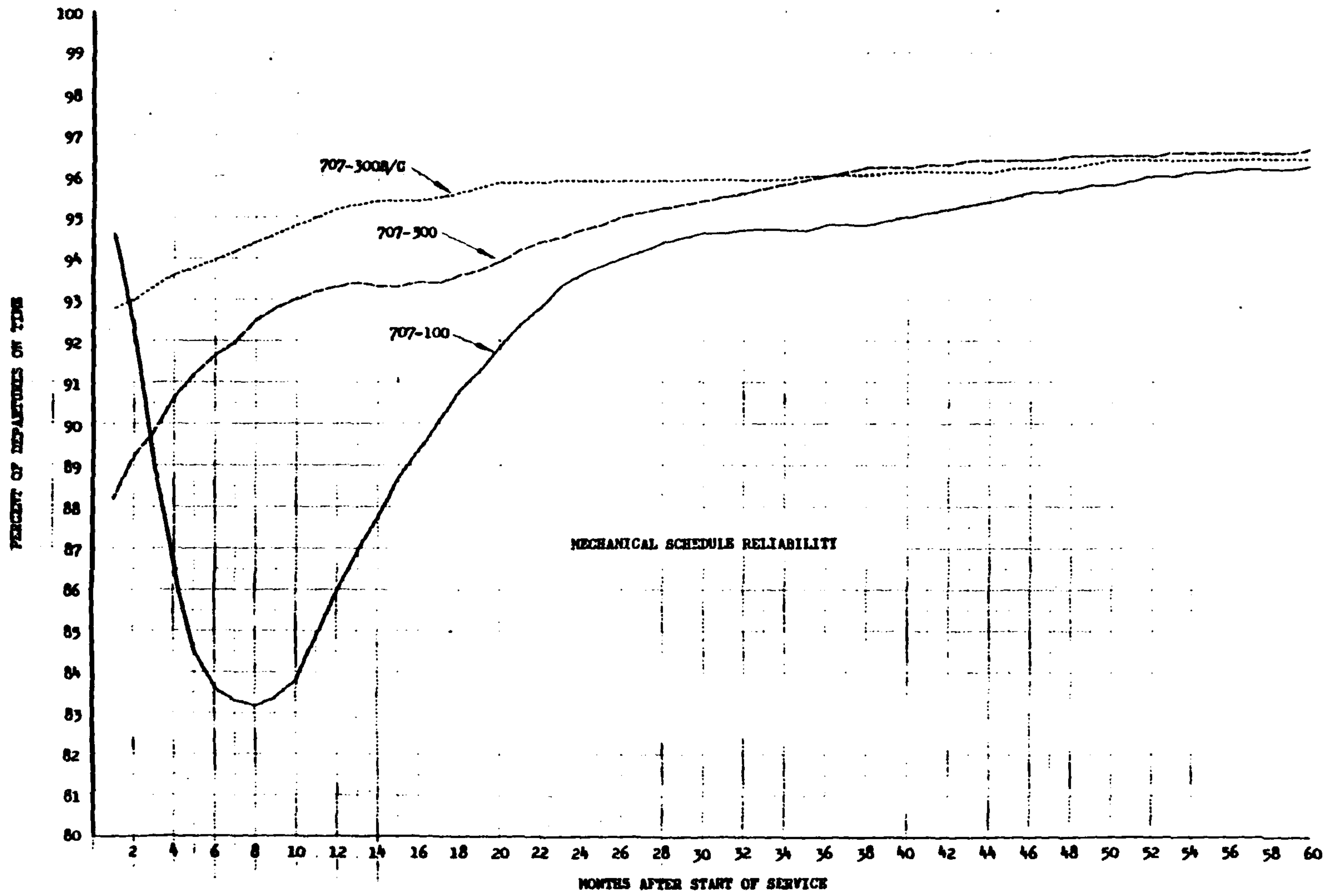
Figure 83. EQUIVALENT DIRECT MAINTENANCE COSTS, ENGINES



DATA SOURCE: CAB-41 REPORTS

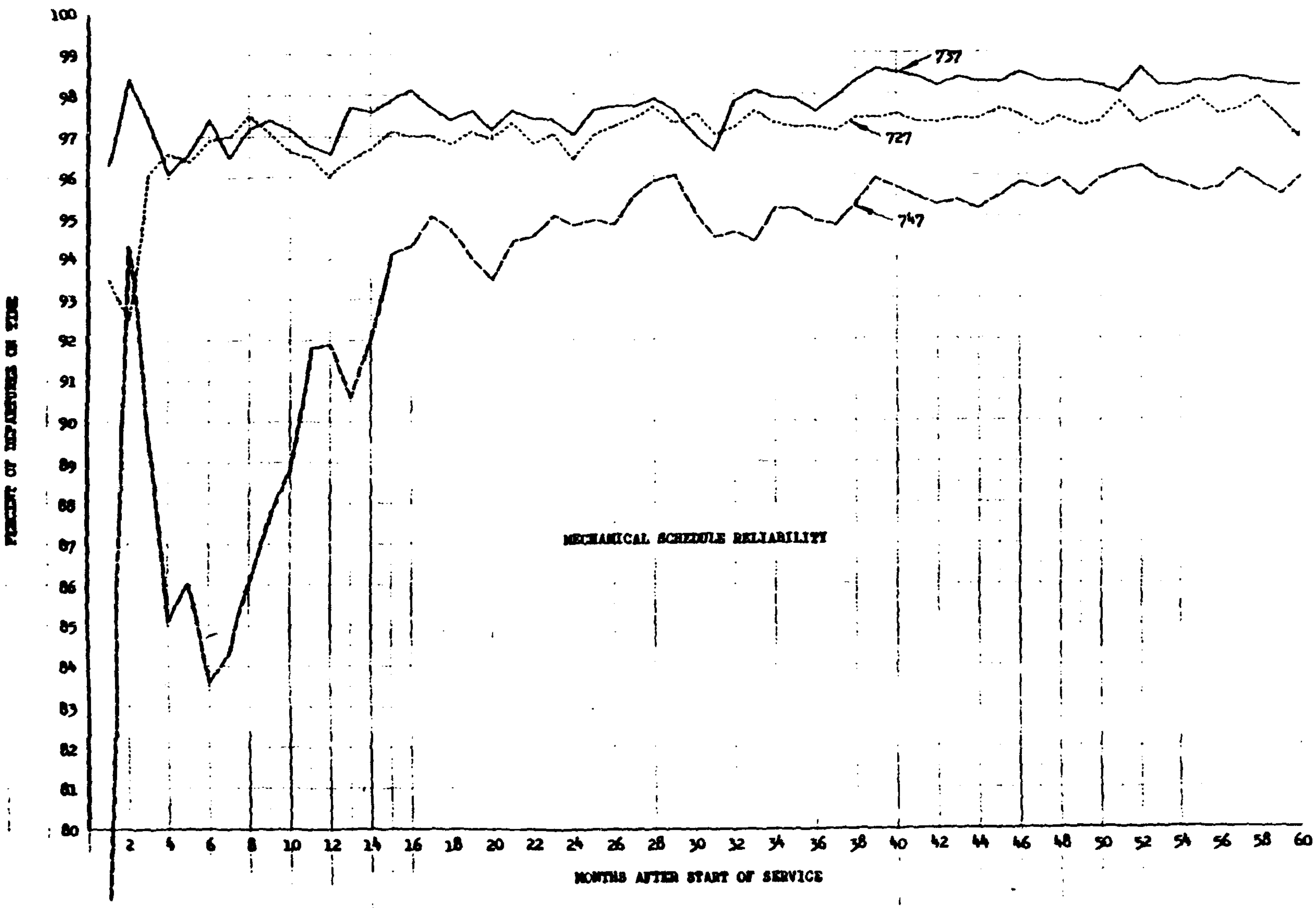
Source: *Commercial Transport Operations and Maintenance Data Summary*, McDonnell Douglas Corporation, December 1978.

Figure 84. MAINTENANCE MANHOURS PER FLYING HOUR, U.S. OPERATORS, WIDE BODY JETS



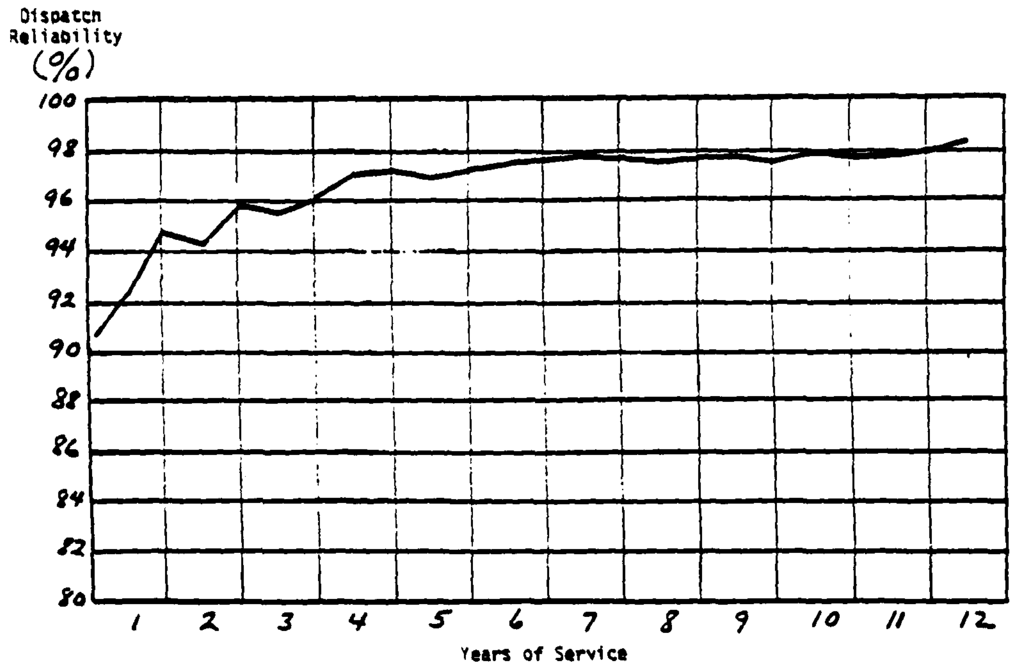
Source: Boeing Commercial Airplane Company

Figure 85. MECHANICAL SCHEDULE RELIABILITY, 707-100, 707-300, AND 707-300 B/C



Source: Boeing Commercial Airplane Company

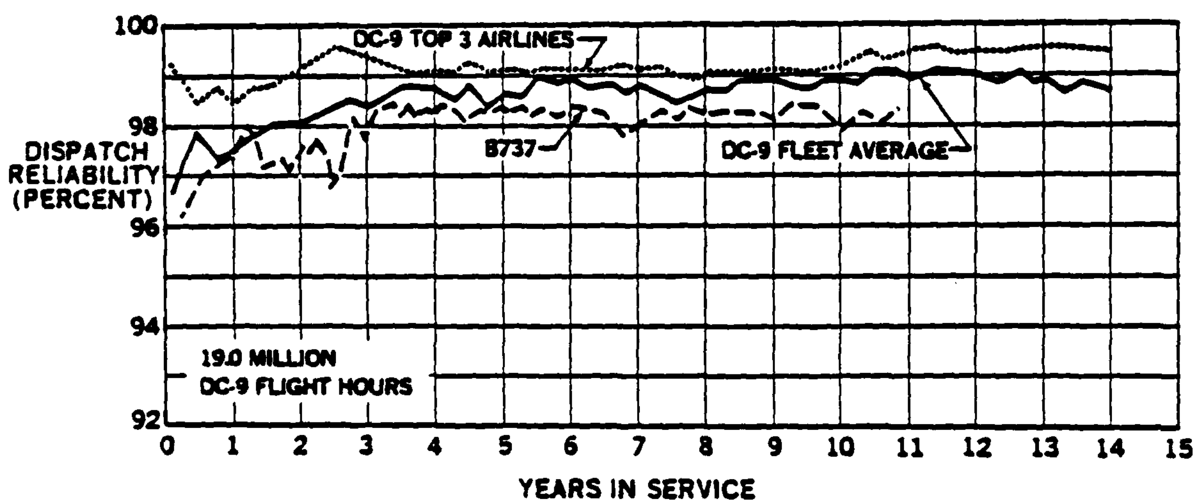
Figure 86. MECHANICAL SCHEDULE RELIABILITY, 727, 737, AND 747



Based on major user reports (plotted at 6-month intervals)

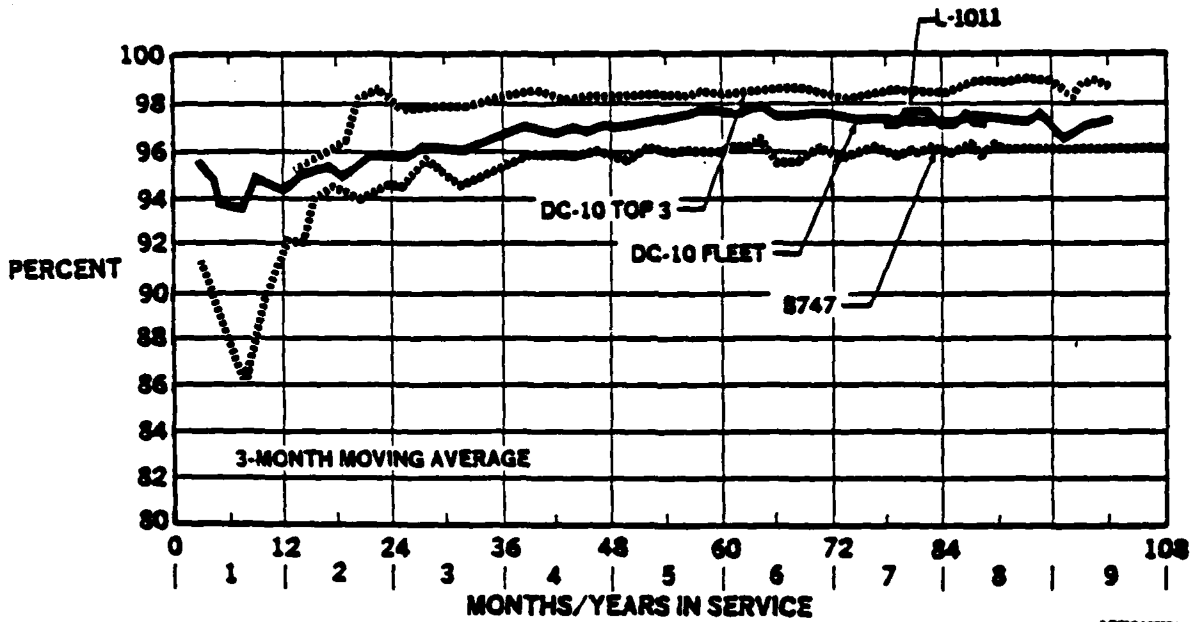
Source: McDonnell Douglas Corporation

Figure 87. MECHANICAL SCHEDULE RELIABILITY, DC-8



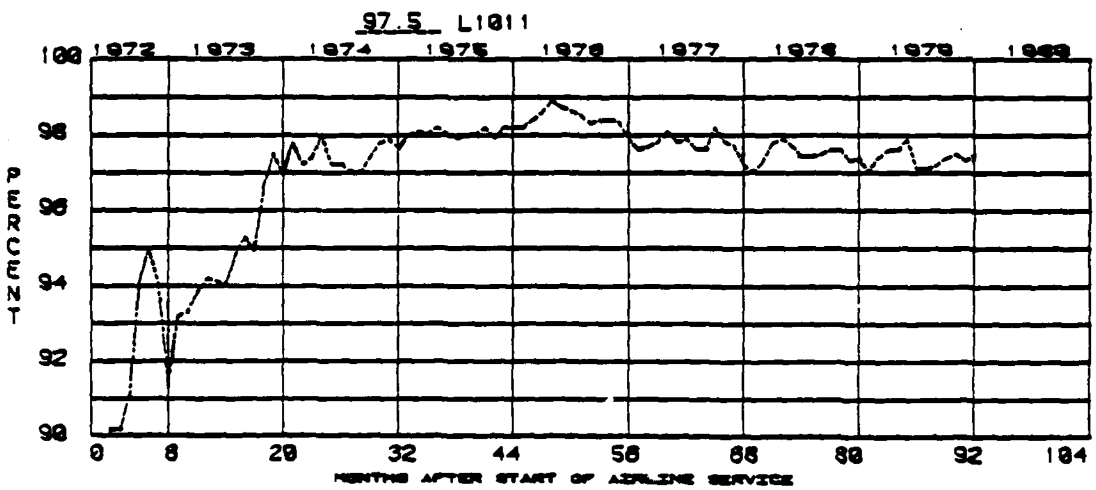
Source: McDonnell Douglas Corporation

Figure 88. MECHANICAL SCHEDULE RELIABILITY, DC-9 AND B-737



Source: McDonnell Douglas Corporation

Figure 89. MECHANICAL SCHEDULE RELIABILITY, B-747, DC-10, AND L-1011



Source: *L-1011 Quarterly Operational Report*, Lockheed California Company, December 1979.

Figure 90. MECHANICAL SCHEDULE RELIABILITY, L-1011

Table 41. SUMMARY OF TRENDS IN COMMERCIAL AIRCRAFT RELIABILITY/MAINTAINABILITY CHARACTERISTICS

Jet Transport Generation	Direct Maintenance Costs in Constant Dollars	Maintenance Manhours per Flying Hour	Mechanical Schedule Reliability
First Generation (Four Engine Jets)	Decreased about 35% over first 17 years.	Decreased about 50% over first 17 years.	B-707-100 and DC-8 required about five years to maturity; later B-707 models required two or three years.
Second Generation (Twin and Tri Jets)	Approximately constant	Slight reduction	B-727 and 737 and DC-9 all had high initial reliability; DC-9 grew to a slightly higher level during first three years of service.
Third Generation (Wide Body Jets)			
B-747 & L-1011	Approximately constant	Approximately constant	Required two to three years to maturity
DC-10	Some increase due to engines	Approximately constant	Required two to three years to maturity

Chapter IV

CONSIDERATIONS IN THE ALLOCATION OF RESOURCES FOR R&M GROWTH DURING THE DEVELOPMENT PHASE VERSUS DURING THE PRODUCTION PHASE

There are a number of factors that should be considered in deciding whether to allocate resources for R&M growth during the development phase or during the production phase of a helicopter program. Factors that favor allocation of resources during each phase are summarized in Table 42 and are discussed below; the discussion is tied to the numerical listing of factors in the Table.

Table 42. FACTORS THAT FAVOR ALLOCATION OF RESOURCES FOR R&M GROWTH DURING THE DEVELOPMENT PHASE AND DURING THE PRODUCTION PHASE

Development Phase	Production Phase
1. Should achieve a greater improvement in R&M per unit cost and time because of Duane curve characteristics.	1. Development phase costs less (but production phase will cost more if R&M growth is deferred to it).
2. R&M growth program should be more cost-effective because of controlled management and operating environment.	2. Development phase may take less time, resulting in possible earlier IOC date.
3. Improvements do not have to be retrofitted on delivered aircraft.	3. Earlier discovery of those failure modes induced by field environment.
4. Improved R&M characteristics available over entire life of aircraft.	

A. FACTORS FAVORING R&M GROWTH DURING DEVELOPMENT PHASE

1. As discussed in Chapter II, helicopter development programs, in a very rough way, tend to follow the Duane growth process. This process is characterized by a continual reduction in the degree of R&M improvement per unit of cost or time required to achieve the improvement (see Figures S-2 and S-3). Since fewer flight hours have been accumulated in the development phase than in the production phase, it should be possible to achieve a greater degree of R&M improvement per unit of cost or time in the development phase. Further, while virtually all programs exhibit R&M improvement during the development phase, there is no clear-cut evidence that R&M characteristics in general improve during the production phase. Indeed, some data indicate that they worsen (see 3-M data of Chapter III, Section I).

2. R&M growth programs during the development phase would be conducted at the manufacturer's plant or at a service test facility in CONUS where manufacturer's personnel could be stationed. Accordingly, the operating environment is such that information on failures can be quickly collected and fixes developed, thus facilitating the R&M growth process. On the other hand, once a helicopter is in production and operating in the field (perhaps overseas), the collection and transmittal of failure data is much less complete and fast, and the time required to incorporate fixes into aircraft in the field is much greater. Further, in order to incorporate changes in a production program it is necessary to change production drawings/processes/tooling and in general interfere with the smooth functioning of the production process. Hence R&M growth programs should be considerably more cost-effective during the development phase because of the more favorable management and operating environment. One quantitative survey concluded that production phase changes are ten times as costly as development phase changes [3].

3. If design changes to achieve R&M growth are incorporated in the development phase, then later production aircraft will have the improved designs incorporated in them when they are built. However, if changes are made during the production phase, then the changes must be retrofitted into those aircraft which have already been produced. This retrofitting is more expensive than incorporating changes in the initial construction of the aircraft. Further, retrofitting aircraft in the field degrades the mission operational readiness of the units to which they are assigned.

4. If R&M-related changes are incorporated during the development phase, the benefits of these changes are available over the entire life of the aircraft. If changes are made during the production phase, then the benefits are not realized in the already-produced aircraft until they are retrofitted.

B. FACTORS FAVORING R&M GROWTH DURING PRODUCTION PHASE

1. and 2. The principal advantage of deferring R&M growth resources from the development phase to the production phase is that the cost and schedule time required for development may be reduced. As a result, an earlier IOC date can be achieved. This could be a very important consideration in some programs, depending on the military threat situation.

3. Some R&M problems only become apparent when an aircraft is operating in its normal field environment. These problems will be discovered earlier because of the earlier IOC date, but a special process involving data collection, engineering follow-up and production modification is required for timely incorporation of fixes (as in the Black Hawk program).

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