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RELIABILITY GROWTH TESTING EFFECTIVENESS

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This in-house report documents the results of an RADC Systems Reliability and Engineering Branch in-house study on reliability growth testing. The study involved examination of DoD policy regarding this form of testing, an extensive literature search on techniques and applications as well as consultation with Air Force reliability experts on the subject. The results address a general overview of models and techniques applied with particular attention to unique approaches found in the literature. Numerous current

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) and past Air Force applications are cited indicating the range of possible approaches. The report concludes by addressing many of the questions regarding reliability growth testing expressed by those skeptical of it.

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1.0 Objective: The use of reliability growth testing and test-analyze-and-fix (TAAF) testing has become widespread within the Department of Defense as a complement to and substitute for formal reliability qualification testing. Many different models, tools and techniques for their use have been presented in the literature, military standards and handbooks. Still, many reliability experts within DoD question the utility and cost effectiveness of reliability growth testing and describe it as rewarding contractors for sloppy initial designs. The objective of this study was to fully investigate the subject of reliability growth testing to enable a better understanding by reliability engineers as well as to present guidance for its potential application in the development of Air Force systems.

2.0 Approach: The approach used in performing the in-house study included the following:

A. Existing Department of Defense and Air Force regulations, directives, standards, handbooks and policies were reviewed to determine their impact on the forms of reliability testing under study.

B. A literature search regarding reliability growth testing and test-analyze-and-fix testing was performed to determine how requirements have been/are being implemented, what management and analysis techniques have been developed and what the results have been of the application of those techniques.

C. Various reliability experts (government/industry) were consulted to benefit from their experience in applying reliability growth testing. Opinions and data were sought with respect to applying reliability growth and TAAF testing.

D. DoD research and development data bases were searched to determine what R&D study efforts are currently under way regarding these forms of reliability testing.

E. The results of the above four tasks were reviewed and analyzed by an objective RADC team of experienced reliability engineers and conclusions were developed.

2.1 Issues: While reliability growth testing is being applied widely in DoD systems development, there are a number of questions that are often expressed by those skeptical of its effectiveness which can be summarized as follows:

- Who pays for the reliability growth testing (RDGT)? Does the government end up paying more?

- Does RDGT allow DoD contractors to "get away with" a sloppy initial design because they can fix it later at the government's expense?

- Should reliability growth testing be dedicated or integrated?

- When should a reliability growth test begin?

- Should reliability growth be planned for beyond the FSED phase?

- Should the equipment operate at the fully specified performance level prior to the start of RDGT?

- Should all development programs have some sort of reliability growth testing?

- How does the applicability of reliability growth testing vary with the following points of a development program?

  a. Complexity of equipment and its challenge to the state-of-the-art.
  b. Operational environment
  c. Quantity of equipment to be produced

- What growth model(s) should be used?

- What starting points and growth rates should be used for planning?

- How much test time (and calendar time) will be required to conduct the testing?

- When will corrective actions be implemented?

- How will failures be counted?

- Will there be an accept/reject criteria?

- Should the contractor be responsible for intermediate milestones?

- Can/should growth testing be incentivized?

- Does the type of contract affect RDGT decisions?

- What is adequate time for verifying a design fix?

- What is the relationship between an RQT and RDGT?

- Who will do the growth tracking? How and to whom will the results/status be reported?

- How much validity/confidence should be placed on the numerical results of RDGT?

Based on the research conducted, an attempt will be made to answer many of these questions in the remainder of the report. The results of the study are organized as follows in the remainder of the report.

3.0 Reliability Growth Testing Terminology
4.0 DoD Policy on Reliability Growth Testing
5.0 Reliability Growth Analysis
6.0 Reliability Growth Management Techniques
7.0 Reliability Growth Application Experience
8.0 Conclusions

3.0 Reliability Growth Testing Terminology

3.1 Reliability Testing: The use and misuse of many reliability testing terms necessitates inclusion of the Table 3-1 definitions. It should be noted that Reliability Growth Testing (RGT) and Reliability Development/Growth Testing (RDGT) are used synonymously in this report. Test-Analyze-and-Fix (TAAF) is the process by which reliability growth is achieved and, in itself, does not necessarily include the structured planning and tracking associated with an RGT. MIL-STD-785B considers the Reliability Development/Growth Test as an engineering test while the other two forms of reliability testing are considered accounting tests. Before considering the applicability of reliability growth testing, some preliminary concepts need to be addressed:

TABLE 3-1: MIL-STD-785B RELIABILITY TEST DEFINITIONS

Environmental Stress Screening (ESS): A series of tests conducted under environmental stresses to disclose weak parts and workmanship defects for correction.
Reliability Development/Growth Test (RDGT): A series of tests conducted to disclose deficiencies and to verify that corrective actions will prevent recurrence in the operational inventory. (Also known as "TAAF" testing)
Reliability Qualification Test (RQT): A test conducted under specified conditions, by, or on behalf of, the government, using items representative of the approved production configuration, to determine compliance with specified reliability requirements as a basis for production approval. (Also known as a "Reliability Demonstration," or "Design Approval" test.)
Production Reliability Acceptance Test (PRAT): A test conducted under specified conditions, by, or on behalf of, the government, using delivered or deliverable production items, to determine the producer's compliance with specified reliability requirements.

3.2 Growth and Failures: PH Mead (Ref 5) states that there are three distinct ways in which reliability can grow:

"Growth Mode 1. By operating each equipment (or portion of it) to expose and eliminate rogue components or manufacturing errors.

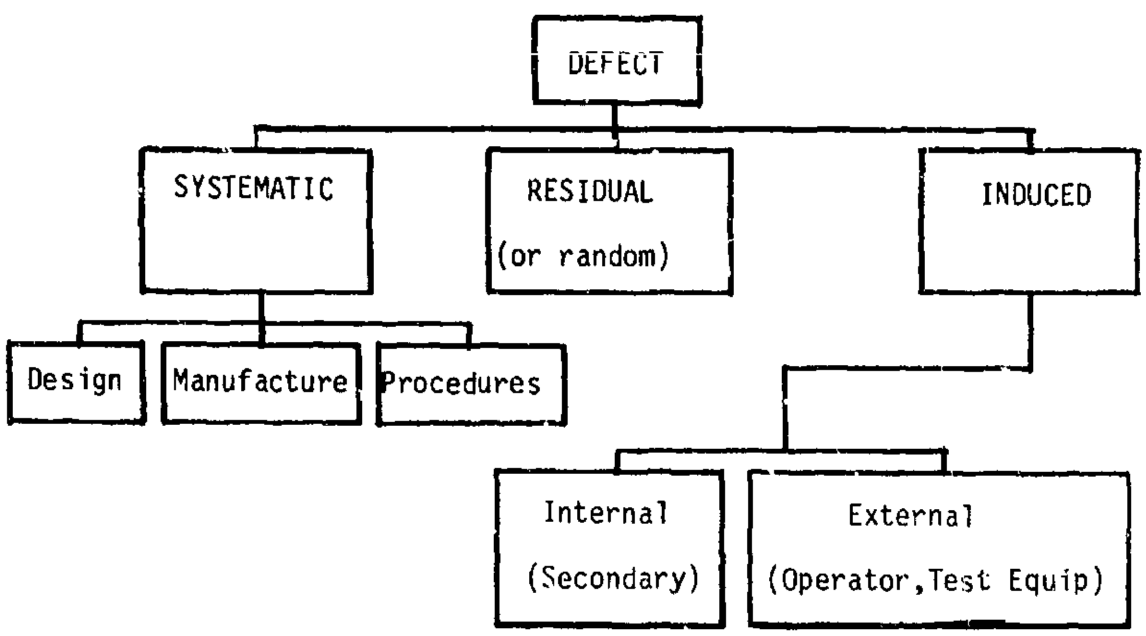
Growth Mode 2. By familiarization, increased operator skill and general "settling down" in manufacturing, use and servicing.

Growth Mode 3. By discovering and correcting errors or weaknesses in design, manufacturing or related procedures."

Reliability of electronic equipment can improve both at the collective and individual equipment level. Burn-in improves the reliability of the equipment subjected to it while design changes improve (or degrade) the reliability of all equipment subject to the changes. Each of the three growth or evolution modes can be made more effective by planned activities.

Regardless of how well the reliability of an equipment is designed in, the complexity of today's electronics make it impossible to foresee all errors and imperfections. Green (Ref 3) found that 75% of all systematic design problems could not be foreseen prior to testing. Defects or failure causes in electronic equipment can be categorized as shown in Figure 3.1

FIGURE 3.1: CATEGORIZATION OF DEFECTS



Mead defined the three failure classes as:

A. Systematic - repetitive (or from their nature liable to be repetitive).

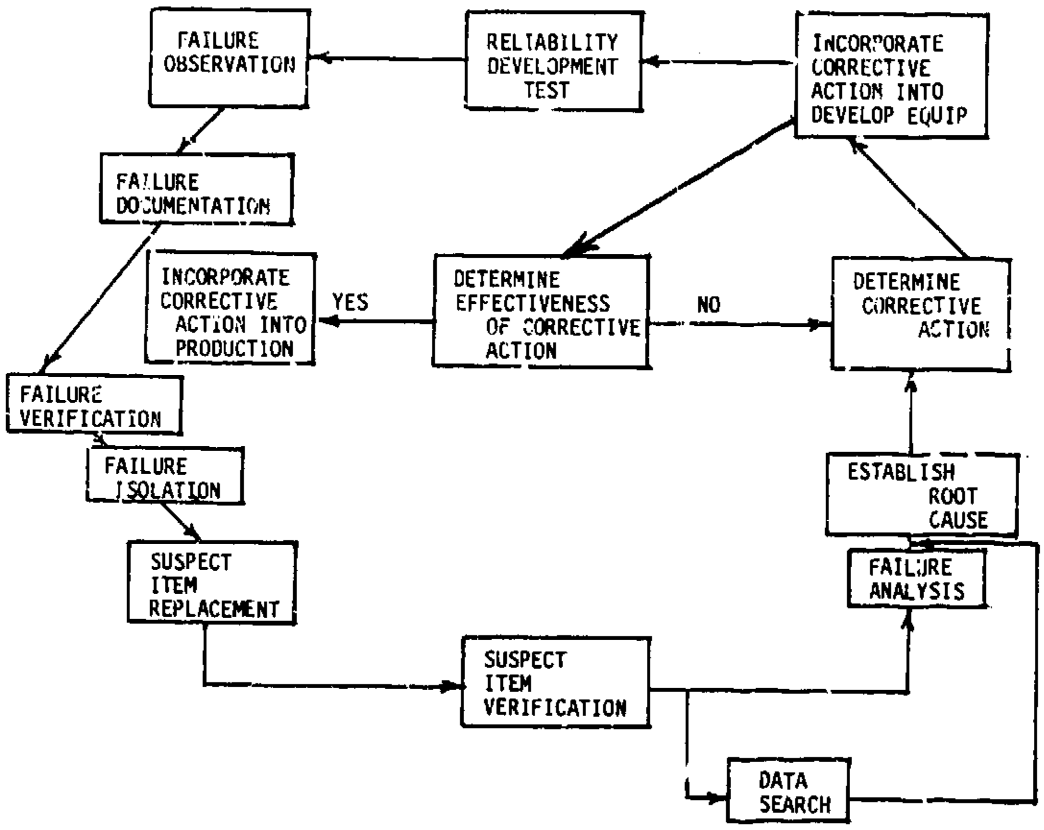
B. Induced - Due to accident from causes internal or external to the equipment.

C. Residual - Neither of the above.

A constant review of defects is necessary to ensure that random and induced categorized events aren't alibis for performing no corrective action. He found that an exponential law applied to the appearance of systematic failures in complex airborne equipment. Most authors speak of reliability growth testing as a means of eliminating these systematic failures.

3.3 <u>Failure Reporting and Corrective Action System (FRACAS)</u>: A well accepted military reliability program task is a closed loop FRACA system as shown in Figure 3.2. The reliability growth test can be thought of as a better controlled and more structured form of a FRACAS system.

FIGURE 3.2: FAILURE REPORTING AND CORRECTIVE ACTION SYSTEM

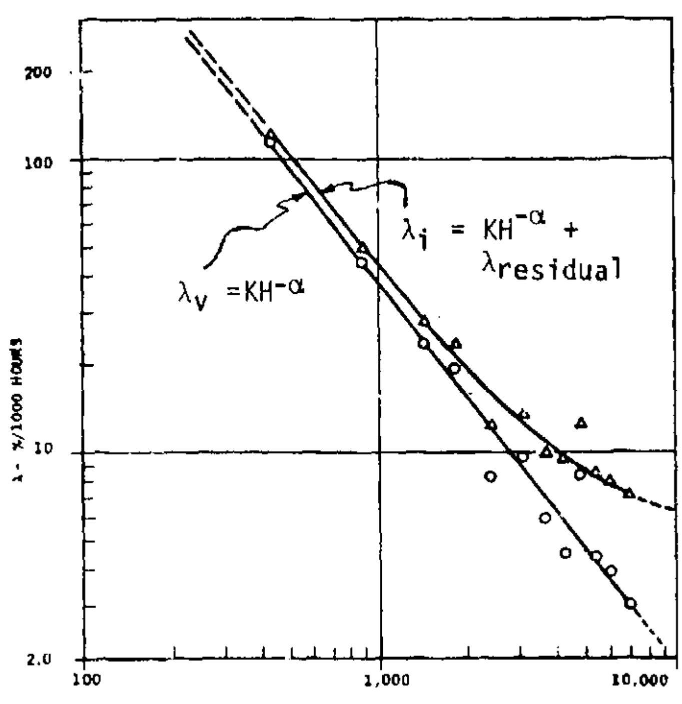


Almost all programs recognize the payoff of such a task. In fact, it could be argued that any system or equipment development, military or commercial, must have some sort of FRACAS system to be successful over the long term. Differences among FRACAS programs are in the depth of failure analysis and in the implementation of corrective action (the degree to which the system is "closed loop"). Whether quantified or planned for, a FRACAS is a cost effective process which results in improved system reliability.

3.4 Reliability Growth Limiting Values: Bezat (Ref 6) postulated the sources of growth to be two categories, (1) reliability growth due to conscious corrective action, and, (2) "endless burn-in" maturing factor. He showed that growth continues to a limiting reliability level even without further design corrective activity. The idea of "endless burn-in" means that "infant mortality" is a misnomer and that the magnitude of its effects extend far out in life. The effect was categorized as follows:

"Endless Burn-In includes all the intangible maturity factors associated with undocumented improvements in test, repair, build processes, and control of environment/application to original objectives." Bezat states that the instantaneous failure rate of an LRU includes a residual component which becomes significant only when the average age of the LRU's becomes about 2500 hours (Fig 3.3).

FIGURE 3.3: ENDLESS BURN-IN CONCEPT



3.5 Reliability Growth in Management: If the premise of reliability improvement through design change is believed, the question becomes how effective is the process and how much resources are required to meet the reliability requirements? Meade (Ref 8) said: "Reliability growth management facilitates early warning by helping a manager in at least four ways: First is the preparation of planned, time phased profiles of reliability growth. Next, the methodology can be used to assess reliability progress against this plan. Third, projections of reliability trends can be developed. Finally, the methodology can be used as a powerful planning tool for determining the time and resources needed for the test phases of a reliability program and in evaluating the impact of limitations and changes in the program." In the context of reliability growth in this report, it is important to emphasize that growth results from redesign effort that eliminates failure sources that were discovered through analysis of test results. An important distinction to be made is that in the burn-in of an item, defective parts are replaced with good parts of the same design resulting in an improved reliability of the one unit being burned-in. Redesign to eliminate failure sources involves changing the design configuration of all units, not just the one under test.

3.6 Reliability Growth vs Other Reliability Tasks: Mead (Ref 5) described as a necessity for a successful growth process "starting with a healthy plant" which results from the other reliability program tasks. The reliability growth management process provides an orderly way to control the development process, surface problems and redirect assets.

3.7 No-Growth Growth: Clark (Ref 42) cautioned against the misuse of reliability growth concepts by indicating case histories which had been previously portrayed as reliability growth in the literature that really weren't. In his work he referred to situations where growth was portrayed by using reliability demonstration data and individual equipment burn-in data as "no-growth growth." These were misapplications of growth management and he cautioned, "to effect a growth in inherent reliability, one or more of the basic design or process parameters (number and types of component parts, their material quality and stress levels and structural and thermal characteristics) must be improved." An example of no-growth growth would be the purging of systematic failures from reliability demonstration test data to show what the system reliability could be if a perfect fix could be found for these problems. Unless the fixes are actually implemented and proven, you will have a case of no-growth growth.

3.8 Reliability Growth Misconceptions: In order to further clarify reliability growth it is important to point out the following misconceptions regarding it:

A. Reliability growth is a naturally occurring phenomenon in electronic equipment. (It is not)

B. Reliability growth occurs as a natural course of events after a system is introduced into the operational inventory. (It does not)

C. Equipment burn-in to remove infant mortality type failures causes reliability growth. (It does not, except for that particular equipment)

D. Replacing early equipment failures with good parts to repair the observed weaknesses causes reliability growth. (It does not)

E. Reliability predictions that improve with more detailed design disclosure reflect reliability growth. (They do not)

In the context of this report, reliability growth is the result of the iterative process of sample testing; identification of design, part and workmanship defects; and correction of the causes of these defects. The basic equipment design establishes the point from which reliability growth starts and the upper bound on potential reliability.

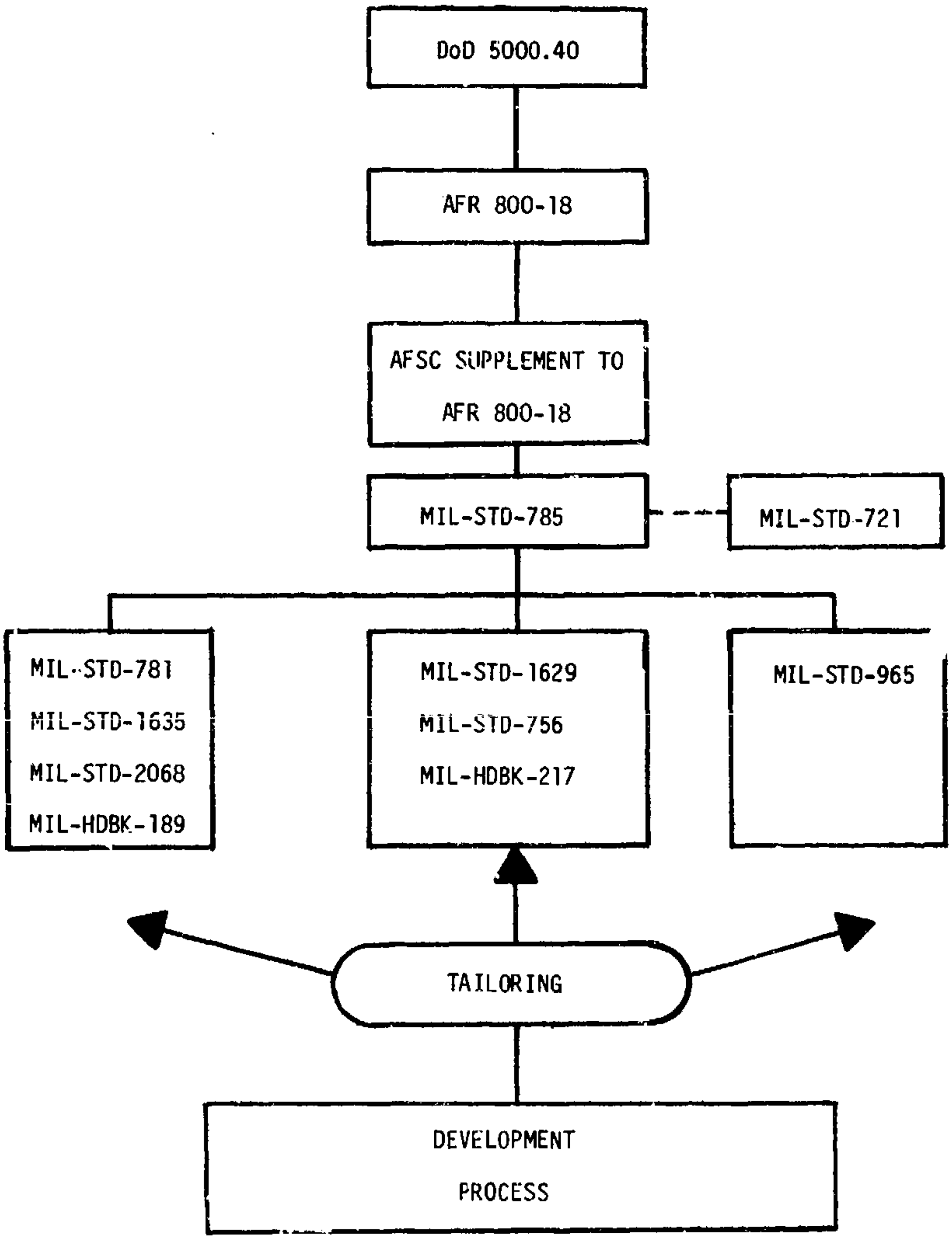
4.0 DoD Policy on Reliability Growth Testing

4.1 Standards: Reliability as an engineering discipline is controlled by a series of directives, regulations, standards, handbooks and policies within the DoD acquisition and development arena. Some of these are triservice (apply to all DoD components) others are uniquely designed for one or more services' use. Table 4-1 is a representation of these documents. Figure 4.1 shows a hierarchy of how RADC, in particular, is effected by these reliability documents on development and acquisition programs.

TABLE 1-1: DOD RELIABILITY RELATED DOCUMENTS (RELIABILITY TEST IMPACT)

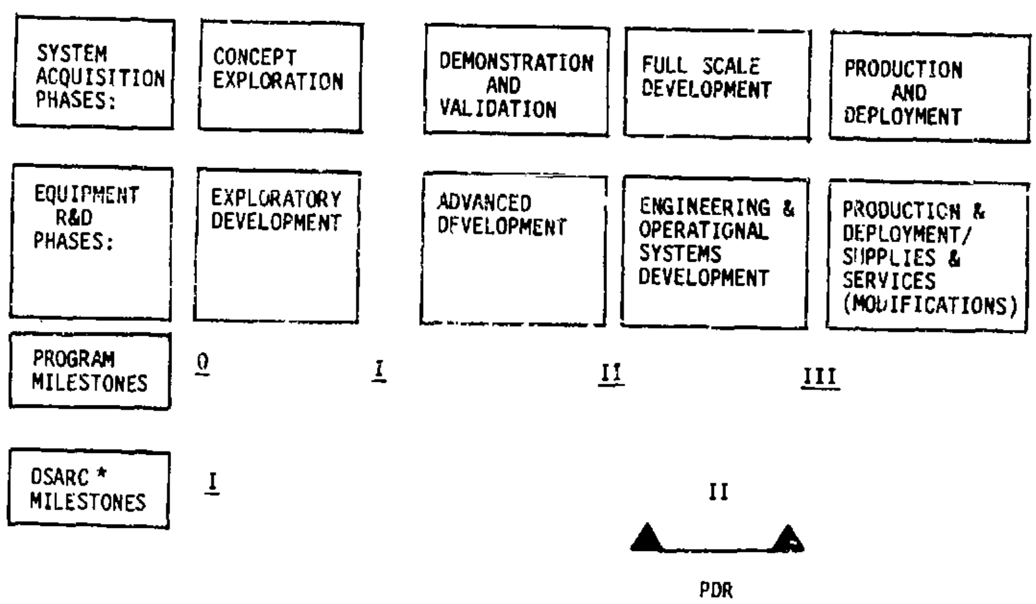
NUMBER	TITLE
DoD 5000.40	Reliability and Maintainability (8 July 1980)
AFR 800-18	Air Force Reliability and Maintainability Program (15 June 1982)
MIL-STD-785B	Reliability Program for Systems and Equipment Development and Production (15 September 1980)
MIL-STD-781C	Reliability Design, Qualification and Production Acceptance Tests: Exponential Distribution (21 October 1977)
MIL-STD-721C	Definitions of Terms for Reliability and Maintainability (12 June 1982)
MIL-STD-1635	Reliability Growth Testing (3 February 1978)
MIL-STD-2068	Reliability Development Tests (21 March 1977)
MIL-HDBK-189	Reliability Growth Management (13 February 1981)

FIGURE 4.1: RELIABILITY DOCUMENT IMPACT ON RADC



4.2 Development Process: In the context of discussions regarding acquisition and development programs within the Air Force, confusion sometimes exists with regard to the program development phases. Figure 4.2 clarifies how these phases are interrelated. It is on the basis of where a particular program is in relation to a potential production decision that determines the tailoring of reliability program tasks. Programs have been known to go directly from an Advanced Development Model to Production. For this reason RADC has structured its reliability task tailoring guidance in terms of the following:

FIGURE 4.2: SYSTEM DEVELOPMENT PHASES



*Defense Systems Acquisition Review Council

4.2.1 Reliability Development Phases:

A. Pre-Reliability Phase: Those early phases in a development process where no structured reliabilty tasks are appropriate.

B. Reliability Study Phase: This early phase has reliability activities related to trade studies accessing the reliability potential of various system configurations.

C. Reliability Design/Analysis Phase: This phase begins the significant application of reliability engineering tasks to the system development. Activities will provide the framework for the next phase (usually FSED). It is not the last development phase before a potential production decision.

D. Reliability Definition and Demonstration Phase: This phase is the final development process prior to a production decision. Reliability engineering is a major part of this phase's development process. Reliability quantitative parameters are specified, predicted and demonstrated.

E. Reliability Assurance Phase: This phase is the build, test and deliver of the reliability designed in during prior development. Reliability activities are devoted mainly to "assurance" type tasks such as environmental stress screening and production reliability acceptance testing.

Table 4-2 has been extracted from MIL-STD-785B "Reliability Program For Systems and Equipment Development and Production" to show how particular reliability tasks are to be tailored for a particular development phase.

The terminology used for phase definitions of Table 4-2 are that of AFR 800-1 "Major System Acquisitions." Many RADC development programs are covered by the AFR "80" series regulations with such phases as "exploratory development," "advanced development," "engineering development" and others. In some instances phases are omitted from the development cycle. A program can transition directly from an advanced development model (ADM) to production. Therefore, the key to effective implementation of reliability requirements and tasks is not in tying them to development phase names but in defining them in terms of how close the development phase is to a production decision which must include reliability consideration. Table 4-3 indicates the general reliability considerations as a function of reliability design phase terminology.

4.3 Tailoring Tasks: While MIL-STD-785B recommends reliability tasks for the various phases of development, as indicated by Table 4-2, it is important to note that each program is different in terms of funding/schedule, equipment performance requirements, challenge to the state-of-the-art, and personnel and contractors involved. Therefore, a "boiler plate" approach to reliability is never the correct approach. Recently, RADC's reliability experts prioritized standard reliability tasks in accordance with their payoff for varying environments and development phases. Table 4-4 shows the results. These results were based on a mix of the "80" series and "800" series AF regulations terminology in that the phases ADM-FSED-PROD are considered. After recognizing (as previously pointed out) that there are cases where an ADM goes directly to production without further development, RADC formulated reliability task application guidelines based on the reliability phase terminology. These results are represented by Table 4-5. In line with all recent reliability literature, the emphasis is placed on "up front" reliability engineering tasks, rather than reliability accounting tasks.

4.4 Direction: While tailoring is key to successful cost effective reliability accomplishment, certain reliability aspects are required by reliability directives, regulations and standards. The following paragraphs address how the documents of Table 4-1 relate to reliability growth and TAAF testing.

TABLE 4-2: APPLICATION MATRIX FOR PROGRAM PHASES

TASK	TITLE	TASK TYPE	PROGRAM PHASE			
			CONCEPT	VALID	FSED	PROD
101	RELIABILITY PROGRAM PLAN	MGT	S	S	G	G
102	MONITOR/CONTROL OF SUBCONTRACTORS AND SUPPLIERS	MGT	S	S	G	G
103	PROGRAM REVIEWS	MGT	S	S(2)	G(2)	G(2)
104	FAILURE REPORTING, ANALYSIS, AND CORRECTIVE ACTION SYSTEM (FRACAS)	ENG	NA	S	G	G
105	FAILURE REVIEW BOARD (FRB)	MGT	NA	S(2)	G	G
201	RELIABILITY MODELING	ENG	S	S(2)	G(2)	GC(2)
202	RELIABILITY ALLOCATIONS	ACC	S	G	G	GC
203	RELIABILITY PREDICTIONS	ACC	S	S(2)	G(2)	GC(2)
204	FAILURE MODES, EFFECTS, AND CRITICALITY ANALYSIS (FMECA)	ENG	S	S (1)(2)	G (1)(2)	GC (1)(2)
205	SNEAK CIRCUIT ANALYSIS (SCA)	ENG	NA	NA	G(1)	GC(1)
206	ELECTRONICS PARTS/CIRCUITS TOLERANCE ANALYSIS	ENG	NA	NA	G	GC
207	PARTS PROGRAM	ENG	S	S (2)(3)	G (2)	G (2)
208	RELIABILITY CRITICAL ITEMS	MGT	S(1)	S(1)	G	G
209	EFFECTS OF FUNCTIONAL TESTING, STORAGE, HANDLING, PACKAGING, TRANSPORTATION, AND MAINTENANCE	ENG	NA	S(1)	G	GC
301	ENVIRONMENTAL STRESS SCREENING (ESS)	ENG	NA	S	G	G
302	RELIABILITY DEVELOPMENT/GROWTH TESTING	ENG	NA	S(2)	G(2)	NA
303	RELIABILITY QUALIFICATION TEST (RQT) PROGRAM	ACC	NA	S(2)	G(2)	G(2)
304	PRODUCTION RELIABILITY ACCEPTANCE ACCEPTANCE TEST (PRAT) PROGRAM	ACC	NA	NA	S	G (2)(3)

CODE DEFINITIONS

TASK TYPE:

ACC - RELIABILITY ACCOUNTING

ENG - RELIABILITY ENGINEERING

MGT - MANAGEMENT

PROGRAM PHASE:

S - SELECTIVELY APPLICABLE

G - GENERALLY APPLICABLE

GC - GENERALLY APPLICABLE TO DESIGN CHANGES ONLY

NA - NOT APPLICABLE

(1) - REQUIRES CONSIDERABLE INTERPRETATION OF INTENT TO BE COST EFFECTIVE

(2) - MIL-STD-785 IS NOT THE PRIMARY IMPLEMENTATION REQUIREMENT. OTHER MIL-STDS OR STATEMENT OF WORK REQUIREMENTS MUST BE INCLUDED TO DEFINE THE REQUIREMENTS.

TABLE 4-3: RELIABILITY PHASE TERMINOLOGY

PRE R/M	R/M STUDY	R/M DESIGN & ANALYSIS	R/M DEFINITION & DEMONSTRATION	R/M ASSURANCE
o Research o Mission Area Analysis o R/M Deficiencies Identified o No Quantitative or Qualitative R/M Requirements	o R/M Trade vs Op and Support Constraints o Similar System Measurement o Risk Assessment o Quantitative R/M Objectives Established o Quantitative Requirements Not Required	o Realistic Range of R&M Values o R&M Predictions o R&M Analyses of Test Data o Design Deficiencies Identified o Update of Operational R&M Requirements o Risk Assessment o Tailored R&M Quantitative Requirements o No Formal R&M Testing	o Firm Quantitative R&M Requirements o Formal R&M Testing o Growth, TAAF & CERT o MIL-STD-470 & 785 Programs o Design Review o Repair Level Analysis o Independent R&M Review o Deficiencies Identified & Corrected	o Firm Quantitative R&M Requirements o Sample Tests o Deficiencies Resolved o ESS (Parts/Equip) o Failure Free Screening

TABLE 4-4: PRIORITIZATION OF STANDARD RELIABILITY TASKS

RELIABILITY TASK	GROUND			AVIONICS			SPACE		
	ADM	FSED	PROD	ADM	FSED	PROD	ADM	FSED	PROD
Establish Valid Numerical Rqm't		1			1				
Parts Selection & Control	1	2		1	2		1	1	
Derating	3	3		2	3		2	2	
FMEA		X		5	4		4	3	
R Model Prediction & Allocation	2	4		4	5		3	5	
FRACAS	4	5	2	X	8	2	X	6	3
RQT		6			7				
ESS			3			3			2
PRAT			4			4			
QA		X	1			1			1
'DGT		X		X	6			4	
ıeak Analysis				X	X		X	X	X
/iews	X	X							
Failure Review Board			X			X			X
Cri cal Items		X	X	X	X	X	X	X	X
Subcontractor Control		X	X		X	X		X	X
O. ization	X	X							
Thermal Management & Analysis	X	X		3	X		5	X	
Storage Effects		X	X		X	X		X	X

NOTE: Numbered tasks are essential; for a given phase the lower the number the greater the payoff.

1 = Greatest payoff X = Should be considered

TABLE 4-5: TASK APPLICATION GUIDELINES BASED ON RELIABILITY PHASE TERMINOLOGY

PRE RELIABILITY	RELIABILITY STUDY	RELIABILITY DESIGN AND ANALYSIS PHASE				RELIABILITY DEFINITION AND DEMONSTRATION PHASE		RELIABILITY ASSURANCE
RESEARCH	PAPER PRODUCT	LIMITED POTENTIAL	LIMITED QTY FIELD USE	HI POTENTIAL (FURTHER DEVELOPMENT)	COMM OFF THE SHELF	MILITARIZED	COMM OFF THE SHELF	PRODUCTION
o Not Applicable	o Trade Study for several configurations o Prediction Type C/D/E	o Model o Allocation o Prediction Type B/E/C o FRACAS (w/o CA) o Reviews o Rel Select Criteria o Verification by Analysis o In-House Rel Data Collection/ Analysis	o Model o Allocation o Prediction Type B/C o FRACAS (w/o CA) o Reviews o Rel Select Criteria o Verification by Analysis o Verification Hi Risk Test o In-House Rel Data Collection/ Analysis o Rel Design(2) - Parts - Thermal - Derating	o Model o Allocation o Prediction Type A/B/C/ o FRACAS (with CA) o Reviews o Rel Select Criteria o Rel Design(2) - Parts - Thermal - Derating o Verification by Analysis o FMEA o TAAF o RQT	o Model o Allocation o Prediction Type B/C/D o FRACAS (with CA) o Reviews o Rel Select Criteria o Rel Design(3) - Parts - Thermal - Derating o Verification by Analysis o Verification Hi Risk Test	o Model o Allocation o Prediction Type A/C o FRACAS (with CA) o Reviews o Subcontract Control o Rel Design(1) - Parts - Thermal - Derating o RQT o FMECA o Critical Items o Growth Test o Program Plan o Storage/ Handling o SCA o ESS	o Model o Allocation o Prediction Type B/C/D o FRACAS (with CA) o Reviews o Subcontract Control o Rel Design(3) - Parts - Thermal - Derating o RQT o Storage/ Handling o FMECA o Program Plan o SCA o ESS	o FRACAS (with CA) o ESS (Env Stress Screen) o PRAT (Prod Rel) o ECP Review (Eng Change Proposals) o Subcontractor o Critical Items o FRB o Storage/ Handling o SCA

PREDICTION TYPE A - Stress Analysis
B - Part Type/Count
C - Vendor Data
D - Similar Equipment
E - Procuring Activity

Reliability Design (1) - Full MILSPEC Parts, Stringent Thermal Design and Derating
(2) - Substitution of Lower Quality Parts Permissible With Minimum Screens, Reduced Thermal Design and Derating
(3) - Modified Design Areas Only
FRACAS (CA) - Corrective Actions Implemented

4.4.1 DoD Directive 5000.40 "Reliability and Maintainability" (8 Jul 80): This directive requires a "balanced mix" of reliability engineering and accounting tasks tailored for maximum efficiency. Under the reliability engineering policy, reliability growth testing is listed as a design fundamental to "disclose design deficiencies and to verify the effectiveness of corrective actions." The directive further states that "requirements and achievements for each applicable system R&M parameter shall be numerically traceable: (a) through all phases of the system life cycle, ..." It emphasizes the importance of reliability growth as a high payoff reliability engineering task by stating:

> "R&M growth is required during full scale development, concurrent development and production (where concurrency is approved), and during initial deployment. Predicted R&M growth shall be stated as a series of intermediate milestones, with associated goals and thresholds, for each of these phases."
>
> > "A. A period of testing shall be scheduled in conjunction with each intermediate milestone The purpose of these tests shall be to find design deficiencies and manufacturing defects. A block of time and resources shall be scheduled for the correction of deficiencies and defects found by each period of testing, to prevent their recurrence in the operational inventory. Administrative delay of R&M engineering change proposals shall be minimized.

B. The differences between required values for system R&M parameters shall be used to concentrate R&M engineering effort where it is needed (for example, enhance mission reliability by correcting mission-critical failures; reduce maintenance manpower cost by correcting any failures that occur frequently).

C. Approved R&M growth shall be assessed and enforced. Enforcement of intermediate R&M goals shall be left to the acquiring activity. Failure to achieve an intermediate R&M threshold is a projected threshold breach, and if it occurs, an immediate review by the program decision authority is required."

With regard to reliability demonstration, the directive says "R&M demonstration, qualification tests and acceptance tests shall be tailored for effectiveness and efficiency (maximum return on cost and schedule investment) in terms of management information they provide." Reliability growth testing is considered an engineering task while reliability demonstration testing is considered an accounting task. Accounting tasks measure reliability (demonstrate a value) while engineering tasks improve reliability.

4.4.2 <u>AFR 800-18: "Air Force Reliability and Maintainability Program (15 June 1982)</u>: This document is intended to revise the previous AF Regulation 80-5 to comply with DoD 5000.40. Requirements of DoD 5000.40 are restated with phrases such as "...it is necessary to address R&M thresholds at each program decision milestone. These thresholds will be derived from mature system requirements," and "each R&M program will include a balanced mix of R&M engineering and accounting tasks. Early investment shall be made in R&M engineering. R&M accounting will provide management information. Cost and schedule investment in the R&M program will be clearly visible and carefully controlled." Reliability growth is implied by such statements as "terms are expressed in mature system values along with interim thresholds."

The regulation states for Full Scale Development (Full Scale Engineering Development) (from Milestone II to Production Decision) "a numerical value for each selected (reliability requirement) is determined, contractually specified, and verified by test prior to a production decision. Testing will be scheduled to allow enough time to review the results prior to the production decision." It further states:

> "For each R&M characteristic identified at Milestone II, projected reliability growth curves are established and used by the program manager to manage the growth process. The purpose of the growth program will be to insure that testing is programmed to find design deficiencies and manufacturing defects, that time and resources are scheduled to correct deficiencies and defects, and that corrective design changes are implemented and verified."

A. Projected growth must show achievement of the threshold values of R&M characteristics at intermediate milestones and at the completion of full scale development testing so the achieved values can be reviewed at a production decision point.

B. Growth curves shall not be used to predict achievement of requirements in the production phase unless either concurrent development and production are specifically authorized, or funds have been identified to correct specific R&M deficiencies.

C. A projected growth curve is established for each contractually specified parameter. These curves must show adequate progress to achieve the specified value before commencement of reliability qualification testing.

D. Use test-analyze-and-fix (TAAF) techniques to accomplish necessary reliability growth. Actual growth will be tracked through monitoring of functional, environmental, and evaluation testing conducted during development. However, specific reliability growth tests, such as Combined Environmental Reliability Test (CERT), should be conducted when compatible with the overall program schedule." (This applies also for concurrent FSD and production).

The regulation defines the FSD program by:

"The FSD program is intended to mature the system R&M characteristics as soon as possible by finding and correcting design deficiencies, reducing producibility risks and by identifying and pursuing R&M improvement opportunities. To do this:

A. The approved design approach shall be matured through development testing of equipment and the incorporation of specific design improvements.

B. The maturation process shall be monitored through growth tracking and design review ev luations."

4.4.3 MIL-STD-785B "Reliability Programs for Systems and Equipment Development and Production" (15 Sep 80): This revision of the main DoD reliability standard presents a "shopping list" of reliability tasks to be tailored to a given application. The recommendations given for task application were already cited in Table 4-2. Increased emphasis (over MIL-STD-785A) is placed on reliability engineering tasks and tests with the thrust toward prevention, detection, and correction of design deficiencies, weak parts and workmanship defects. This standard stresses reliability engineering:

"Reliability Engineering. Tasks shall focus on the prevention, detection, and correction of reliability design deficiencies, weak parts, and workmanship defects. Reliability engineering shall be an integral part of the item design process, including design changes. The means by which reliability engineering contributes to the design, and the level of authority and constraints on this engineering discipline, shall be identified in the reliability program plan. An efficient reliability program shall stress early investment in reliability engineering tasks to avoid subsequent costs and schedule delays."

With respect to demonstration of contractual reliability requirements (electronics), the standard states "conformance to the minimum acceptable MTBF requirement shall be demonstrated by tests selected from MIL-STD-781, or alternative specified by the PA (procuring activity)." Reproduced for completeness as Tables 4-6, 4-7 and 4-8 are respectively: Task 104, "Failure Reporting, Analysis, and Corrective Action System"; Task 302, "Reliability Development/Growth Test (RDGT) Program"; Task 303, "Reliability Qualification Test (RQT) Program."

TABLE 4-6: TASK 104 - FAILURE REPORTING, ANALYSIS AND CORRECTIVE ACTION SYSTEM (FRACAS)

104.1 Purpose. The purpose of task 104 is to establish a closed loop failure reporting system, procedures for analysis of failures to determine cause, and documentation for recording corrective action taken.

104.2 Task Description

104.2.1 The contractor shall have a closed loop system that collects, analyzes, and records failures that occur for specified levels of assembly prior to acceptance of the hardware by the procuring activity. The contractor's existing data collection, analysis and corrective action system shall be utilized, with modification only as necessary to meet the requirements specified by the PA.

104.2.2 Procedures for initiating failure reports, the analysis of failures, feedback of corrective action into the design, manufacturing and test processes shall be identified. Flow diagram(s) depicting failed hardware and data flow shall also be documented. The analysis of failures shall establish and categorize the cause of failure.

104.2.3 The closed loop system shall include provisions to assure that effective corrective actions are taken on a timely basis by a follow-up audit that reviews all open failure reports, failure analyses, and corrective action suspense dates, and the reporting of delinquencies to management. The failure cause for each failure shall be clearly stated.

104.2.4 When applicable, the method of establishing and recording operating time, or cycles, on equipments shall be clearly defined.

104.2.5 The contractor's closed loop failure reporting system data shall be transcribed to Government forms only if specifically required by the procuring activity.

104.3 Details to be Specified by the PA (reference 1.2.2.1)

104.3.1 Details to be specified in the SOW shall include the following, as applicable:

a. Identification of the extent to which the contractor's FRACAS must be compatible with PA's data system.

(R) b. Identification of level of assembly for failure reporting.

c. Definitions for failure cause categories.

d. Identification of logistic support requirements for LSAR.

e. Delivery identification of any data item required.

TABLE 4-7: TASK 302 - RELIABILITY DEVELOPMENT/GROWTH (RDGT) PROGRAM

302.1 Purpose. The purpose of task 302 is to conduct pre-qualification testing (also known as TAAF) to provide a basis for resolving the majority of reliability problems early in the development phase, and incorporating corrective action to preclude recurrence, prior to the start of production.

302.2 Task Description

302.2.1 A reliability development/growth test (TAAF test) shall be conducted for the purpose of enhancing system reliability through the identification, analysis, and correction of failures and the verification of the corrective action effectiveness. Mere repair of the test item does not constitute corrective action.

302.2.1.1 To enhance mission reliability, corrective action shall be focused on mission-critical failure modes. To enhance basic reliability, corrective action shall be focused on the most frequent failure modes regardless of their mission criticality. These efforts shall be balanced to meet predicted growth for both parameters.

302.2.1.2 Growth testing will emphasize performance monitoring, failure detection, failure analysis, and the incorporation and verification of design corrections to prevent recurrence of failures.

302.2.2 A TAAF test plan shall be prepared and shall include the following, subject to PA approval prior to initiation of testing:

a. Test objectives and requirements, including the selected growth model and growth rate and the rationale for both selections.

b. Identification of the equipment to be tested and the number of test items of each equipment.

c. Test conditions, environmental, operational and performance profiles, and the duty cycle.

d. Test schedules expressed in calendar time and item life units, including the test milestones and test program review schedule.

e. Test ground rules, chargeability criteria and interface boundaries.

f. Test facility and equipment descriptions and requirements.

g. Procedures and timing for corrective actions.

h. Blocks of time and resources designated for the incorporation of design corrections.

i. Data collection and recording requirements.

j. FRACAS.

k. Government furnished property requirements.

l. Description of preventive maintenance to be accomplished during test.

m. Final disposition of test items.

n. Any other relevant considerations.

302.2.3 As specified by the procuring activity, the TAAF test plan shall be submitted to the procuring activity for its review and approval. This plan, as approved, shall be incorporated into the contract and shall become the basis for contractual compliance.

302.3 Details to be Specified by the PA (reference 1.2.2.1)

302.3.1 Details to be specified in the SOW shall include the following, as applicable:

(R) a. Imposition of task 104 as a requisite task.

(R) b. Identification of a life/mission/environmental profile to represent equipment usage in service.

c. Identification of equipment and quantity to be used for reliability development/growth testing.

d. Delivery identification of any data items required.

TASK 4-8: TASK 303 - RELIABILITY QUALIFICATION TEST (RQT) PROGRAM

303.1 Purpose. The purpose of task 303 is to determine that the specified reliability requirements have been achieved.

303.2 Task Description

303.2.1 Reliability qualification tests shall be conducted on equipments which shall be identified by the PA and which shall be representative of the approved production configuration. The relaibility qualification testing may be integrated with the overall system/equipment qualification testing, when practicable, for cost-effectiveness; the RQT plan shall so indicate in this case. The PA shall retain the right to disapprove the test failure relevancy and chargeability determinations for the reliability demonstrations.

303.2.2 An RQT plan shall be prepared in accordance with the requirements of MIL-STD-781, or alternative approved by the PA, and shall include the following, subject to PA approval prior to initiation of testing:

a. Test objectives and selection rationale.

b. Identification of the equipment to be tested (with identification of the computer programs to be used for the test, if applicable) and the number of test items of each equipment.

c. Test duration and the appropriate test plan and test environments. The test plan and test environments (if life/mission profiles are not specified by the PA) shall be derived from MIL-STD-781. If it is deemed that alternative procedures are more appropriate, prior PA approval shall be requested with sufficient selection rationale to permit procuring activity evaluation.

d. A test schedule that is reasonable and feasible, permits testing of equipment which are representative of the approved production configuration, and allows sufficient time, as specified in the contract, for PA review and approval of each test procedure and test setup.

303.2.3 Detailed test procedures shall be prepared for the tests that are included in the RQT plan.

303.2.4 As specified by the procuring activity, the RQT plan and test procedures shall be submitted to the procuring activity for its review and approval. These documents, as approved, shall be incorporated into the contract and shall become the basis for contractual compliance.

303.3 Details to be Specified by the PA (reference 1.2.2.1)

303.3.1 Details to be specified in the SOW shall include the following, as applicable:

(R) a. Identification of equipment to be used for reliability qualification testing.

(R) b. Identification of MIL-STD-781, MIL-STD-105 or alternative procedures to be used for conducting the RQT (i.e., test plan, test conditions, etc.).

c. Identification of a life/mission/environmental profile to represent equipment usage in service.

d. Logistic support coordinated reporting requirements for LSAR.

e. Delivery identification of any data items required.

The standard cites three objectives of a reliability test program as:

A. Disclose deficiencies in item design, material and workmanship.

B. Provide measured reliability data as input for estimates of operational readiness, mission success, maintenance manpower cost and logistics support cost.

C. Determine compliance with quantitative reliability requirements.

This is the priority order of the objectives to be met subject to cost and schedule constraints. The previously mentioned tasks (302 and 303) along with Task 301, "Environmental Stress Screening" and Task 304, "Production Reliability Acceptance Testing" are the elements of a reliability test program to be tailored to accomplish the above objectives. The standard says "a properly balanced reliability program will emphasize ESS and RDGT, and limit, but not eliminate, RQT and PRAT."

This is in line with emphasis on engineering tasks and "up front" reliability spending. Integrated testing is stressed with environmental tests (MIL-STD-810) considered as the early portion of RDGT. With regard to the use of ESS and RDGT as methods of determining contractual compliance, the standard states: "ESS and RDGT must not include accept/reject criteria that penalizes the contractor in proportion to the number of failures he finds, because this would be contrary to the purpose of the testing so these tests must not use statistical test plans that establish such criteria. RQT and PRAT must provide a clearly defined basis for determining compliance, but they must also be tailored for effectiveness and efficiency (maximum return on cost and schedule investment) in terms of the management information they provide."

TABLE 4-9: MIL-STD-785B RELIABILITY GROWTH APPLICATION GUIDANCE

50.3.2.2 Reliability development/growth testing (RDGT) (task 302). RDGT is a planned, prequalification, test-analyze-and-fix process, in which equipment are tested under actual, simulated, or accelerated environments to disclose design deficiencies and defects. This testing is intended to provide a basis for early incorporation of corrective actions, and verification of their effectiveness, thereby promoting reliability growth. However:

TESTING DOES NOT IMPROVE RELIABILITY. ONLY CORRECTIVE ACTIONS THAT PREVENT THE RECURRENCE OF FAILURES IN THE OPERATIONAL INVENTORY ACTUALLY IMPROVE RELIABILITY.

50.3.2.2.1 It is DoD policy that reliability growth is required during full-scale development, concurrent development and production (where concurrency is approved) and during initial deployment. Predicted reliability growth shall be stated as a series of intermediate milestones, with associated goals and thresholds, for each of those phases. A period of testing shall be scheduled in conjunction with each intermediate milestone. A block of time and resources shall be scheduled for the correction of deficiencies and defects found by each period of testing, to prevent their recurrence in the operational inventory. Administrative delay of reliability engineering change proposals shall be minimized. Approved reliability growth shall be assessed and enforced.

50.3.2.2.2 Predicted reliability growth must differentiate between the apparent growth achieved by screening weak parts and workmanship defects out of the test items, and the step-function growth achieved by design corrections. The apparent growth does not transfer from prototypes to production units; instead, it repeats in every individual item of equipment. The step-function growth does transfer to production units that incorporate effective design corrections. Therefore, RDGT plans should include a series of test periods (apparent growth), and each of the test periods should be followed by a "fix" period (step-function growth). There two or more items are being tested, their "test" and "fix" periods should be out of phase, so one item is being tested while the other is being fixed.

50.3.2.2.3 RDGT must correct failures that reduce operational effectiveness, and failures that drive maintenance and logistic support cost. Therefore, failures must be prioritized for correction in two separate categories; mission criticality, and cumulative ownership cost criticality. The differences between required values for the system reliability parameters shall be used to concentrate reliability engineering effort where it is needed (for example: enhance mission reliability by correcting mission-critical failures; reduce maintenance manpower cost by correcting any failures that occur frequently).

50.3.2.2.4 It is imperative ant RDGT be conducted using one or two of the first full-scale engineering development items available. Delay forces corrective action into the formal configuration control cycle, which then adds even greater delays for administrative processing of reliability engineering changes. The cumulative delays create monumental retrofit problems later in the program, and may prevent the incorporation of necessary design corrections. An appropriate sequence for RDGT would be: (1) ESS to remove defects in the test items and reduce subsequent test time, (2) environmental testing such as that described in MIL-STD-810, and (3) combined-stress, life profile, test-analyze-and-fix. This final portion of RDGT differs from RQT in two ways: RDGT is intended to disclose failures, while RQT is not; and RDGT is conducted by the contractor, while RQT must be independent of the contractor if at all possible.

Table 4-9 has been extracted from the MIL-STD-785 Application Guidance Section. The key point to notice is the difference in purpose of the RDGT and RQT, "RDGT is intended to disclose failures; and RQT is not" and "testing does not improve reliability, only corrective actions that prevent the recurrence of failures in the operational inventory actually improve reliability." It should also be highlighted that "RDGT is a planned, prequalification, test-analyze-and-fix process..." For completeness in differentiating RDGT from RQT, the MIL-STD-785 application guidance with respect to Task 303 RQT has also been included as Table 4-10. It should be noted that there are no data item descriptions specifically associated with reliability growth/TAAF testing although DI-R-7033 "Reliability Test Plan," DI-R-7035 "Reliability Test and Demonstration Plan" and DI-R-7034 "Reliability Test and Demonstration Reports" cover this area.

TABLE 4-10: MIL-STD-785B RELIABILITY QUALIFICATION TEST APPLICATION GUIDANCE

50.3.3.1 Reliability qualification test (RQT) (task 303). RQT is intended to provide the government reasonable assurance that minimum acceptable reliability requirements have been met before items are committed to production. RQT must be operationally realistic, and must provide estimates of demonstrated reliability. The statistical test plan must predefine criteria of compliance ("accept") which limit the probability that true reliability of the item is less than the minimum acceptable reliability requirement, and these criteria must be tailored for cost and schedule efficiency. However:

TESTING TEN ITEMS FOR TEN HOURS EACH IS NOT EQUIVALENT TO TESTING ONE ITEM FOR ONE HUNDRED HOURS, REGARDLESS OF ANY STATISTICAL ASSUMPTIONS TO THE CONTRARY.

50.3.3.1.1 It must be clearly understood that RQT is preproduction test (that is, it must be completed in time to provide management information as input for the production decision). The previous concept that only required "qualification of the first production units" meant that the government committed itself to the production of unqualified equipment.

50.3.3.1.2 Requirements for RQT should be determined by the PA and specified in the request for proposal. RQT is required for items that are newly designed, for items that have undergone major modification, and for items that have not met their allocated reliability requirements for the new system under equal (or more severe) environmental stress. Off-the-shelf (government or commercial) items which have met their allocated reliability requirements for the new system under equal (or more severe) environmental stress may be considered qualified by analogy, but the PA is responsible for ensuring there is a valid basis for that decision.

50.3.3.1.3 Prior to the start of RQT, certain documents should be available for proper conduct and control of the test. These documents include: the approved TEMP and detailed RQT procedures document, a listing of the items to be tested, the item specification, the statistical test plan (50.3.1.6), and a statement of precisely who will conduct this test on behalf of the government (50.3.1.7). The requirements and submittal schedule for these documents must be in the CDRL.

4.4.4 MIL-STD-781C "Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution" (21 Oct 77) (Currently under revision to MIL-STD-781D, see paragraph 4.4.5): This document in its present form does not address reliability growth or TAAF testing. It covers RQT and PRAT. Under this standard, contractor compliance with numerical reliability is determined using an accept/reject criteria of a specific test plan. Corrective actions to improve the system reliability based on failure occurrences are not required.

Although TAAF testing is not covered, the standard's example of a time-phased reliability program's activities lists TAAF testing as an FSED "Related Task" in addition to the RQT as a "Key Task." The standard says with respect to reliability development testing "sufficient testing should be conducted to provide confidence that the reliability meets or exceeds θ_0 (upper test MTBF). This is a test-analyze-and-fix (TAAF) type test and normally con[illegible]ts of a sequence of testing, analyzing all failures, incorporating [illegible]ctive [illegible]ction, and retesting, with the sequence repeated until as[illegible]ance is obtained that the required reliability can be demonstrated during the reliability qualification test." On the other hand, with respect to RQT's it states "reliability qualification tests in accordance with MIL-STD-781 should be performed to provide a high degree of confidence that hardware r[illegible]bility meets or exceeds the requirement."

4.4.5 MIL-STD-781D (31 Dec 80 draft): Along with various other changes, this draft expanded previous edition by the incorporation of reliability growth testing. The draft has not been approved and the publication of MIL-STD-1635(EC) and MIL-HDBK-189 have caused the scope of MIL-STD-781D to be reduced in the reliability growth testing area. The new draft is to be released second quarter of FY84.

4.4.6 MIL-STD-1635(EC) "Reliability Growth Testing" (3 February 1978): "This standard covers the requirements and procedures for reliability development (growth) tests. These tests are conducted during the hardware development phase on samples which have completed environmental tests prior to production commitment, and do not replace other tests described in the contract or equipment specification. These tests provide engineering information on failure modes and mechanisms of a test item under natural and induced environmental conditions of military operations. Reliability improvement (growth) will result when failure modes and mechanisms are discovered and identified and their recurrence prevented through implementation of corrective action."

"The standard is applicable to Naval Electronic Systems Command procurements for development of all systems and equipment subject to contract definition and to the development of other systems and equipment when specified in the equipment specification."

The document allows the contractor to determine the reliability growth test subject to procuring activity approval. His model should be one "based on previous development programs - for systems/equipment of the same type." Unless otherwise specified, it requires the use of the Duane Model. The performance level of the test item is established prior to the start of testing. It calls for a fixed length period of testing to be approved by the procuring activity and states that 5-25 multiples of the required MTBF will generally provide sufficient time for the desired growth. The standard states that the "probable" range of Duane growth rates is between 0.3 and 0.6.

In terms of assessment, the standard says "as long as the achieved reliability growth corresponds favorably with the planned growth, as presented in the reliability growth test plan procedures, satisfactory performance may be assumed." Satisfactory is further defined as any one of:

"A. The plotted MTBF values remain on or above the planned growth line.

B. The best-fit straight line is congruent with or above the planned line.

C. The best-fit straight line is below the planned line but its slope is such that a projection of the line crosses the horizontal required MTBF line by the time that the planned growth line reaches the same point."

An important point to be made regarding failure counting is that the cumulative MTBF to be plotted is calculated based on all failures. "This plot shall not be adjusted by negating past failures because of present or future design changes."

The standard offers an alternative moving average technique for reliability assessment and states MTBF estimation will be in accordance with

MIL-STD-781. It suggests "a successful reliability growth test program may result in the deletion of reliability demonstration tests if reliability requirements are fully achieved prior to production commitment.

The standard concludes:

> "Failure to provide the time and dollar resources necessary for reliability growth is an error committed much too often in research, development, test and evaluation planning."

4.4.7 MIL-STD-2068 "Reliability Development Testing" (21 March 1977): "This standard established requirements and procedures for a reliability development test to implement the MIL-STD-785 requirement for such a test. The purpose of the reliability development test is reliability growth and assessment to promote reliability improvement of systems and equipment in n ordinary and standarized manner. This standard is applicable to Naval Air Systems Command procurements for development of systems and equipment. The reliability development tests do not replace the design, qualification, or other required tests specified for the systems or equipment."

Regarding establishment of a pretest performance baseline, the standard states "unless otherwise specified prior to conducting any test, the test item shall be tested and a record shall be made of all data to determine compliance with required performance." Regarding reliability assessment it states "a plot of achieved reliability expressed as a point estimate shall be used to depict the results of the reliability growth test. This plot shall be made showing the cumulative reliability versus cumulative test time. This plot shall not be adjusted by negating past failures because of present or future design changes." The standard calls for the presentation of a second "Adjusted Reliability" curve to depict the level at which the achieved reliability would be if these failures were discounted for which acceptable corrective action has resolved a failure to the satisfaction of the procuring activity." With respect to test time, it states "unless otherwise specified, when two or more test items are used, the minimum operating time for each test item shall be not less than one half the average operating time for all items on test." It further states "the reliability development test should be planned as a fixed length test and the test duration must be specified. Fixed length tests of 10-25 multiples of the specified MTBF will generally provide a test length sufficient to achieve the desired reliability growth for equipment MTBF's in the 50 to 2000 hours range. For equipment MTBF's over 2000 hours, test lengths should be based on equipment complexity and the needs of the program, but as a minimum, should be one multiple of the specified MTBF. In any event, the test length should not be less than 2000 hours or more than 10000 hours." The standard supersedes Aeronautical Requirements documents AR-104, AR-108 and AR-111 through AR-118 which addressed reliability development testing for specific types of systems.

4.4.8 MIL-HDBK-189 "Reliability Growth Management" (13 February 1981): "This handbook provides procuring activities and development contractors with understanding of the concepts and principles of reliability growth, advantages of managing reliability growth and guidelines and procedures to be used in managing reliability growth."

Methods are presented for planning, evaluating and controlling reliability growth. It states "reliability growth management is part of system engineering procedures (MIL-STD-497). It does not take the place of other reliability program activities (MIL-STD-785) such as prediction (MIL-STD-756), apportionment, FMEA and stress analysis. Instead, reliability growth management provides a means of viewing all the reliability program activities in an integrated manner."

Rather than the monitoring of reliability program tasks in a subjective manner, reliability growth management provides a quantitative means of making timely program decisions regarding schedule and funds.

Different concepts of continuous and phase-by-phase reliability growth are discussed as they apply to planning and tracking a program. The different approaches of implementing of design "fixes" and the risks associated with them are discussed. Emphasis is on applying growth techniques on a phase-by-phase basis. Tracking methodology addresses assessing the demonstrated reliability as well as the projected reliability. The projected reliability "serves the basic purpose of quantifying the present reliability effort relative to the achievement of future milestones."

The planning for reliability growth is addressed on a phase-by-phase basis and statistical tests are presented for determining whether growth is occurring. With respect to models the handbook says "generally speaking, the simplest model which is realistic and justifiable from previous experience, engineering consideration, goodness of fit, etc., will probably be a good choice."

The document details a "how to" approach for contracting for reliability growth including what should be in the request for proposal, the contractor's proposals and the contract. Planning, testing and tracking provisions are addressed. With respect to failure purging, the handbook is quite explicit:

> "Failure purging as a result of design fixes is an unnecessary and unacceptable procedure when applied to determining the demonstrated reliability value. It is unnecessary because of the recently developed statistical procedures to analyze data whose failure rate is changing. It is unacceptable for the following reasons:
>
> a. The design fix must be assumed to have reduced the probability of a particular failure to zero. This is seldom, if ever, true. Usually a fix will only reduce the probability of occurrence; and in some cases, fixes have been known to actually increase the probability of a failure occurring.
>
> b. It must be assumed that the design fix will not interact with other components and/or failure modes. Fixes have frequently been known to cause an increase in the failure rate of other components and/or failure modes."

Further rationale is presented by "if there has been sufficient testing to establish the effectiveness of a design fix, then an appropriate reliability growth model will, by then, have sufficient data to reflect the effect of the fix in the current reliability estimate."

The document's appendices present a variety of continuous and discrete reliability growth models but the AMSAA model is the one recommended as "the most versatile for tracking growth." An entire detailed appendix is devoted to applying the AMSAA model including parameter estimation, confidence interval calculation, and goodness of fit tests for the three failure data types; time terminated testing, failure terminated testing, and grouped data. With regard to the type of failure data preferred it states: "In general, time to failure data are preferred over data in which the time of each failure is unknown and all that is known is the number of failures that occurred in each period of time (grouped data). Time to failure data will obviously provide more information for estimating system reliability and growth rates."

5.0 <u>Reliability Growth Analysis</u>: If the concept of reliability improvement by test, detection of failure causes, and design changes to eliminate these causes is accepted, means must be considered for planning this process, assessing the current status, and projecting future results. A number of types of models have been postulated to enable these goals to be accomplished. While the intent of this report is not to be a complete tutorial on analysis techniques, to be complete, an overview must be included.

5.1 <u>Reliability Growth Model Types</u>: Reliability Growth Models are generally categorized as statistical or probabilistic models (Ref 43):

Probabilistic Models - Because no unknown parameters are associated with these models, the data obtained during programs cannot be incorporated and make this type of limited use.

Statistical Models - Unknown parameters are associated with these models, in addition, these parameters are estimated throughout the development of the product in question.

Another way of distinguishing among models is whether they are parametric or not, where parametric models imply there is a pattern to the growth. Nonparametric models allow the growth curve to fall where it will. Some models are based on the assumption of a particular failure distribution, such as exponential. Another distinction is whether a model is continuous or discrete. In general, the discrete models are useful for reliability tests which involve repeated trials. Continuous models tend to be used more in cases where the equipment is operated until failure and then repaired.

An Army report (Ref. 74) described a different classification of reliability growth models as:

A. Deterministic models are ones in which the precise form of the reliability growth curve is known for a particular development program and system before development is initiated. Consequently, the parameters associated with a deterministic model are fixed by the model user prior to any development effort.

B. Parametric models are ones that utilize early growth patterns exhibited by the system to project reliability through later stages of development.

C. Bayesian models assume that related parameters are random variables governed by appropriate probability density functions. Whereas parametric techniques utilize recorded test data to estimate model parameters, Bayesian models employ statistical distributions of the parameters, as well as available test data.

D. Special models are those that don't exhibit the distinguishing features of the previous classifications.

Table 5-1 summarizes a comparative analysis of models classified in the USAMC study.

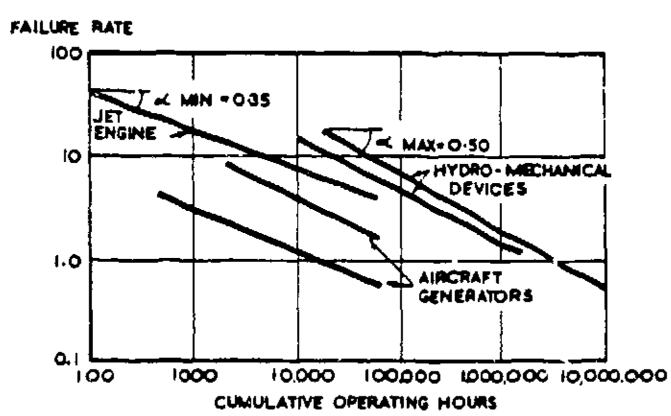
TABLE 5-1: RELIABILITY GROWTH MODEL COMPARISON (USAMC)

MODEL	TYPE	INPUT (REQUIRED TEST DATA)	OUTPUT (RELIABILITY INDICATOR)	PROJECTIVE CAPABILITY?
DUANE	DETERMINISTIC	TIMES-TO-FAILURE	MEAN-TIME-TO-FAILURE	YES
LLOYD & LIPOW HYPERBOLIC	PARAMETRIC	SUCCESS-FAILURE DATA FOR EACH BLOCK OF TEST TRIALS	PROBABILITY OF SYSTEM SUCCESS DURING THE NEXT TESTING BLOCK	YES
LLOYD & LIPOW TWO-STATE	PARAMETRIC	NA	PROBABILITY OF SYSTEM SUCCESS DURING THE NEXT TEST TRIAL	YES
WEISS	PARAMETRIC	TIMES-TO-FAILURE WITH RESTRICTION ON MAXIMUM TIME	MEAN-TIME-TO-FAILURE	YES
VIRENE	PARAMETRIC	ANY CONSISTENT MEASURE OF RELIABILITY	ANY CONSISTENT MEASURE OF RELIABILITY	YES
CHERNOFF & WOODS	PARAMETRIC	NUMBER OF SUCCESSES BETWEEN CONSECUTIVE TRIAL FAILURES	PROBABILITY OF SYSTEM SUCCESS DURING THE NEXT TEST TRIAL	CORCORAN AND REED EXTENSION MUST BE USED
POLLOCK	BAYESIAN	TIME-TO-FAILURE OR SUCCESS-FAILURE DATA FOR EACH TRIAL	MTBF OR PROBABILITY OF SYSTEM SUCCESS DURING NEXT TEST TRIAL	YES
BARLOW & SCHEUER	SPECIAL	SUCCESS-FAILURE DATA FOR EACH BLOCK OF TEST TRIALS	PROBABILITY OF SYSTEM SUCCESS EXHIBITED IN PREVIOUS TESTING BLOCK	NO
WOLMAN	SPECIAL	NA	PROBABILITY OF SYSTEM SUCCESS DURING THE NEXT TEST TRIAL	CORCORAN AND REED EXTENSION MUST BE USED

5.2 Reliability Growth Models

5.2.1 The Duane Model: Among the most popular models for reliability growth is the Duane Model. In 1962, J.T. Duane of General Electric Company's Motor and Generator Department published a report in which he presented his observations during development programs at GE. These systems include complex hydromechanical devices, complex types of aircraft generators and an aircraft jet engine. The study of the failure data was conducted in an effort to determine if any systematic changes in reliability occurred during the development programs for these systems. His analysis revealed that for these systems the observed cumulative failure rate versus cumulative operating hours closely approximated a straight line when plotted on log-log paper (see Figure 5.1). Similar plots have been noted in industry for other types of electrical and mechanical systems, and by the US Army for various military weapon systems during development.

FIGURE 5.1: FAILURE RATE VERSUS CUMULATIVE OPERATING HOURS FOR DUANE'S ORIGINAL DATA



DUANE'S ORIGINAL DATA

Duane's postulate was that as long as reliability-improvement continues, his mathematical expression would hold (Equ. 5.1).

$$\lambda_{cum} = KT^{-\alpha} \qquad \text{(Equ. 5.1)}$$

or $$MTBF_{CUM} = \frac{1}{K} T^{\alpha} \qquad \text{(Equ. 5.2)}$$

also $$\lambda_{cum} = \frac{F}{T} \qquad \text{(Equ. 5.3)}$$

λ_{cum} = cumulative failure rate

T = cumulative test time (Σt)

F = total number of failures occurring during T

K = constant determined by the initial MTBF and the initial conditioning period

α = growth rate

From this empirical relationship (Equ. 5.1) the cumulative MTBF can be related to the instantaneous or attained MTBF (MTBF of design if no further design changes are implemented) as follows:

$$F = T\lambda_{cum} \qquad \text{(From Equ. 5.3)}$$

$$F = TKT^{-\alpha} \qquad \text{(Substituting } \lambda_{cum} = KT^{-\alpha}\text{)}$$

$$F = KT^{(1-\alpha)}$$

$$\frac{dF}{dT} = (1-\alpha)KT^{-\alpha}$$

$$\lambda(t) = (1-\alpha)KT^{-\alpha} \qquad \text{(Equ. 5.4)}$$

or $$MTBF_{inst} = \frac{T^{\alpha}}{K(1-\alpha)} \qquad \text{(Equ. 5.5)}$$

Since $KT^{-\alpha}$ is the cumulative failure rate (Equ. 5.1), Duane concluded:

$$\lambda(t) = (1-\alpha)\ \lambda_{cum}$$

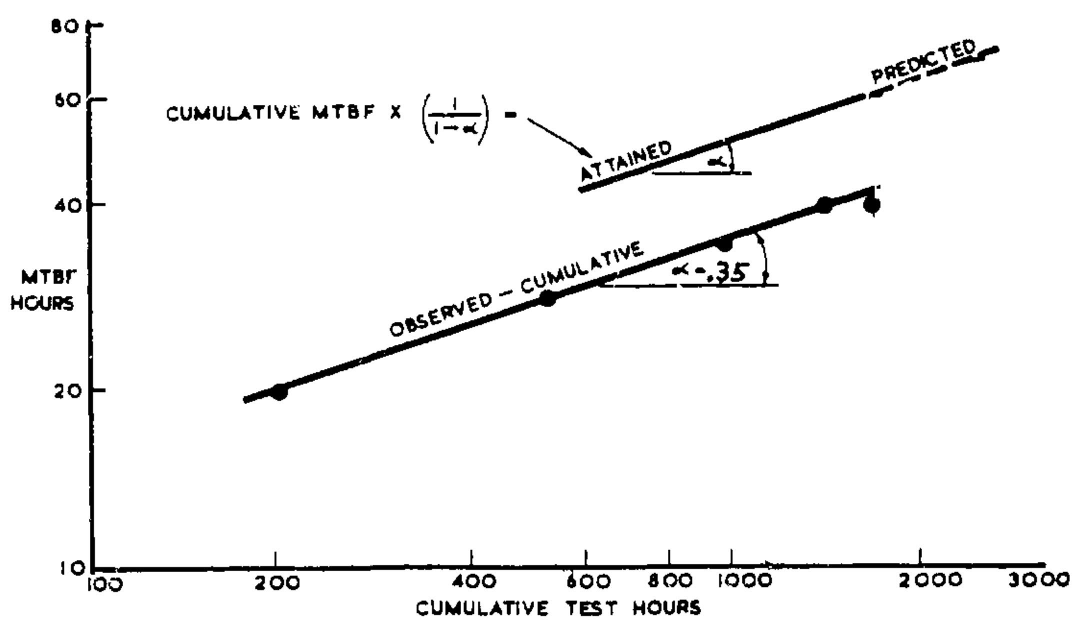
or

$$MTBF_{inst} = \frac{MTBFcum}{(1-\alpha)} \qquad \text{(Equ. 5.6)}$$

For many systems, the plot of cumulative MTBF versus cumulative test time is a straight line with slope alpha (α), when plotted on log-log paper. If alpha is calculated from this plot, then the instantaneous MTBF may be calculated at any point during the reliability growth program using Equ. 5.6.

Figure 5.2 shows the cumulative MTBF versus cumulative test time. The current (or instantaneous) MTBF is drawn parallel to the cumulative MTBF on a log-log scale and has a value of $\frac{1}{1-\alpha}$ X $MTBF_{cum}$.

FIGURE 5.2: DUANE PLOT FOR RELIABILITY GROWTH OF AN AIRBORNE RADAR



In order to plan a growth test or to predict the reliability at some future time the model parameters α and K must be known. Depending on how the model is being used, the parameters α and K in Equ. 5.1 may be determined by one particular method or a combination of methods listed below in order of preference:

A. Historical data from similar systems that experienced reliability growth.

B. Plot initial failure data on log-log paper and calculate α and K when a linear relationship becomes evident.

C. Assign α and K based on an engineering analysis and on management's judgment regarding how quickly failures may be revealed, analyzed and fixed.

Methods A and C are used when the model is used as a planning tool to give management an idea of the test time and the costs of implementing a reliability growth test.

Method B is used when the model is used as a tracking tool to project into future time whether the equipment will reach its goal in the allotted test time. In some cases up to 1000 hours of test time is needed before the characteristic straight line is observed. This is shown in Figure 5.3 by the initially high log MTBF decreasing and then increasing linearly with log time. It is believed that this initial "hook" in the Duane plot could result from:

A. An initial hook in the bathtub curve as shown in Figure 5.4 which would give an early high MTBF (low failure rate) until the early defects had time to reveal themselves. This may indicate that the equipment is still experiencing a burn-in effect.

B. The unavoidable reaction time before the effects of the corrective actions begin to show as reliability growth.

FIGURE 5.3: DUANE PLOT SHOWING THE INITIAL "HOOK" DURING THE EARLY TIME PERIOD

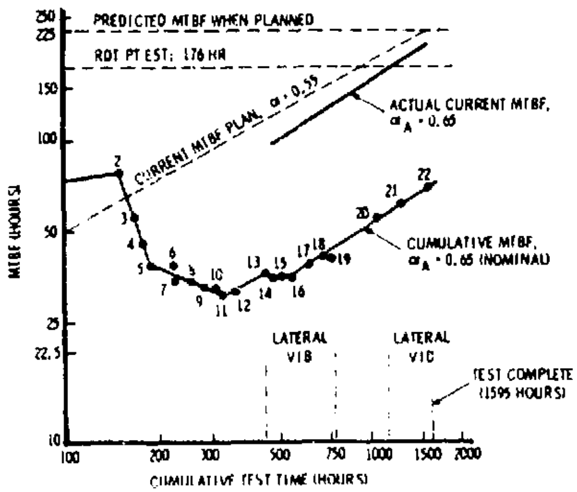
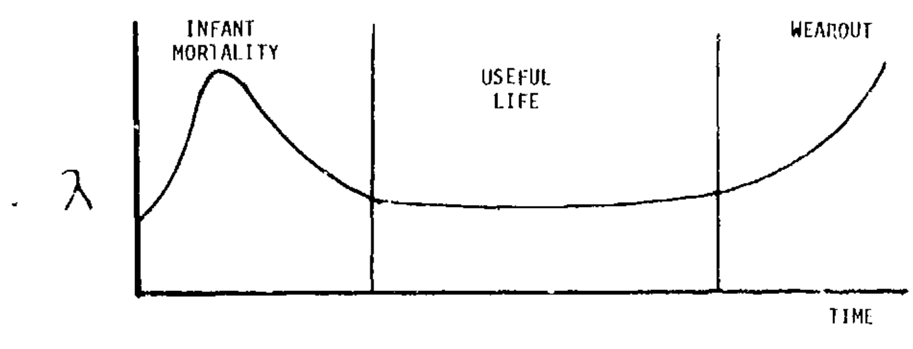


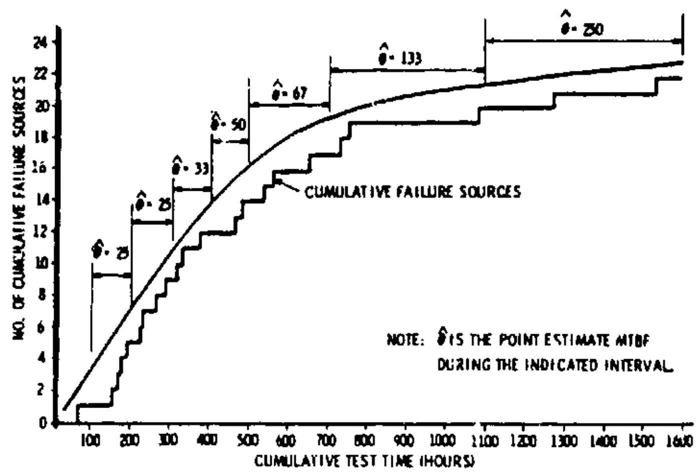
FIGURE 5.4: INITIAL HOOK IN BATHTUB CURVE SHOWING AN INITIALLY LOW FAILURE RATE (HIGH MTBF)



In order to provide needed visibility during the early stages of the test ("hook" portion of the log-log plot) an alternative approach may be taken to assess the RDGT program's status and effectiveness.

Figure 5.5 portrays this approach, introduced by General Electric (Ref 24), which is a simple linear/staircase plot of the identified failure sources versus test time. Superimposed on this plot are the point-estimate MTBF's (Θ) over test intervals ranging from 2 to 4 "meantimes." In this manner initial MTBF of the equipment (about 25 hours in this example) can be assessed. This would be difficult to determine from the log-log plot in Figure 5.3 because of the appearance of a decreasing MTBF during the initial test period. However, the "staircase" approach during this period indicates that reliability is actually growing as shown in Figure 5.5.

FIGURE 5.5: LINEAR/STAIRCASE PLOT OF RDGT TEST DATA



An example of parameter estimation and growth test time needed is given in Section 6.3.3.

The Duane parameters α and K can also be determined from a regression analysis of the failure data using equations 5.7 and 5.8.

$$\alpha = \frac{\sum_{i=1}^{N} (\log X_i \log M_i) - (\sum_{i=1}^{N} \log X_i \sum_{i=1}^{N} \log M_i)/N}{\sum_{i=1}^{N} (\log X_i)^2 - (\sum_{i=1}^{N} \log X_i)^2/N} \qquad \text{(Equ. 5.7)}$$

$$\log \frac{1}{K} = (\sum_{i=1}^{N} \log M_i)/N - \alpha (\sum_{i=1}^{N} \log X_i)/N \qquad \text{(Equ 5.8)}$$

Where: X_i = the time to failure of failure i.

M_i = the cumulative MTBF at time X_i.

N = the total number of failures encountered during the test.

This method of calculating the Duane parameters provides better accuracy than graphical techniques and can easily be programmed on the computer.

5.2.2 The AMSAA Model: Another popular model is the AMSAA reliability growth model which is more complicated than the Duane model but enables the calculation of statistical goodness of fit information and confidence limits. For a more extensive treatment of this model the reader is referred to references 9, 28 and 53. This model lends itself more to tracking reliability growth than planning growth and should be programmed on the computer to reduce the chance of error during the long calculations that are required.

For an empirical development of the AMSAA model, the Duane postulate given previously is considered. Using the fact that the plot of the log of the cumulative observed failure rate (λ'_{cum}) versus the log of time is a straight line leads to the empirical development of the AMSAA model. Letting primes ('s) denote the observed quantities, the equation of this line is:

$$\log \lambda'_{cum} = K' + \alpha' \log T \qquad \text{(Equ. 5.9)}$$

Equating λ'_{cum} to its expected (or theoretical) value and assuming an exact linear relationship, we have:

$$\lambda'_{cum} = \lambda_{cum}$$
$$\log \lambda'_{cum} = \log \lambda_{cum}$$

Substituting into Equ. 5.9

$$\log \lambda_{cum} = K' + \alpha' \log T$$

Taking exponentials gives

$$\lambda_{cum} = e^{(K' + \log T^{\alpha'})}$$

$$\lambda_{cum} = e^{K'} T^{\alpha'}$$

Defining $\lambda_o = e^{K'}$ as the scale parameter. Since, $\lambda_{cum} = \frac{F}{T}$, where F = cumulative failures and T = cumulative test time, we have:

$$\frac{F}{T} = \lambda_o T^{\alpha'}$$

$$F = \lambda_o T^{\alpha'+1}$$

Defining $\beta = \alpha'+1$, as the shape parameter

$$F = \lambda_o T^{\beta} \qquad \text{(Equ. 5.10)}$$

The instantaneous failure rate, r(t), of the system is:

$$r(t) = \frac{dF}{dT} = \lambda_o \beta T^{\beta-1} \qquad \text{(Equ. 5.11)}$$

and the instantaneous MTBF is:

$$MTBF_{inst} = r(t)^{-1} = \frac{T^{1-\beta}}{\lambda_o \beta} \qquad \text{(Equ. 5.12)}$$

which is the AMSAA model.

The AMSAA reliability growth model assumes that system failures during a development testing phase follow the nonhomogeneous Poisson process with Weibull intensity function $r(t) = \lambda_0 \beta T^{\beta-1}$, where $\lambda_0 > 0$, $\beta > 0$. For $\beta = 1$, $r(t) = \lambda_0$, which is the exponential case. For $\beta < 1$, $r(t)$ is decreasing, implying reliability growth. For $\beta > 1$, $r(t)$ is increasing indicating a deterioration in system reliability. The important fact to note is that the model assumes a Poisson process with Weibull intensity function $r(t) = \lambda_0 \beta T^{\beta-1}$, and not the Weibull distribution. Therefore, statistical procedures for Weibull distribution do not apply for this model.

A common sense method for estimating the parameters λ_0 and β is to plot the cumulative number of failures versus cumulative test time on log-log paper and fit a line to these points. λ_0 is the ordinate of the line corresponding to a cumulative test time of one hour and β is the slope of the line.

An improved estimation and goodness of fit procedure has been developed by Crow (Ref. 9). Using the result that the plots on log-log paper imply that the successive failure times of a system follow a certain stochastic process (i.e., the nonhomogeneous Poisson process with Weibull intensity $\lambda_0 \beta t^{\beta-1}$) a variety of useful statistical procedures for this model have been derived.

If the successive times of failures are being recorded for a system undergoing development testing, then a Cramer-von Mises statistical goodness of fit test can be performed to determine if the AMSAA reliability growth model is appropriate. If the model is acceptable, then maximum likelihood

(ML) estimates of λ_0 and β may be used to estimate and project the system MTBF. Using these procedures one can avoid the drawbacks (no confidence intervals and goodness of fit measures) associated with tracking reliability growth from log-log plots. Reference 53 presents tables for confidence intervals and critical values for the Cramer-von Mises equations that apply to the following three types of data: (1) time terminated test data, (2) failure terminated test data, and (3) grouped data. For these various situations, the reader is referred to Appendix C of reference 53 for in-depth coverage of these areas.

It should be noted that although the AMSAA model requires all failure times for estimating the parameters λ and β, it is, in effect, a self-purging model. To see this, let $\hat{\beta}$ be the estimate of β. The estimate of λ is $\hat{\lambda} = N/T^{\hat{\beta}}$. The estimate of the current failure rate $r(T) = \lambda\beta T^{\beta-1}$ is, therefore, $r(T) = \hat{\lambda}\hat{\beta}T^{\hat{\beta}-1} = \frac{N}{T^{\hat{\beta}}}\hat{\beta}T^{\hat{\beta}-1} = \frac{\hat{\beta}N}{T}$. Note that N/T would be the failure rate estimate assuming the exponential situation of no growth. However, in the presence of reliability growth $\beta < 1$, so that $\hat{\beta}N < N$. The estimate $r(T)$ using the AMSAA model is equivalent to using the exponential method but purging $(1-\beta)N$ failures and retaining βN failures.

5.2.3 Duane - vs - AMSAA Model: The Duane model is often expressed as $C(t) = \lambda t^{-\alpha}$, which describes the same pattern of growth as the AMSAA model when $\alpha = \beta-1$. However, the Duane model considers growth to be deterministic, while the AMSAA model gives the probabilistic properties describing the growth process. The probabilistic nature of the AMSAA model allows a statistical treatment of the data. Statistical estimates can be made for assessment purposes, confidence bounds can be found, and the data can be subjected to an objective goodness-of-fit test. On the other hand, the deterministic nature of the Duane model is particularly suitable for determining the planned growth curve for a program.

Some practical difficulties in applying growth models are listed below:

A. The parameter estimates are dependent on how much test time has accumulated before they are calculated. However, the parameters need to be determined early in a growth program to predict future reliability and determine if the requirement will be met within the allotted test time.

B. The plotting methods depend on the subjective appraisal of whether or not the plotted points appear to lie nearly on a straight line. The best fit straight line is sometimes a problem because of the tendency of failures to bunch. In cases of difficulty, less importance should be attached to the early plots. Green (Ref 3) has found that instead of plotting as each failure occurs, it is better to do so after time intervals of approximately twice the target MTBF. However, this method should only be used within systems having low target MTBF's.

The Duane and AMSAA models have become the most popular because of their particular advantages as follows:

DUANE MODEL

A. It is mathematically simple.

B. It has considerable empirical justification, particularly in development of electronic hardware.

C. The parameter α is directly related to the level of effort of the reliability program.

D. The model plots as a straight line on log-log paper allowing for very simple illustration of the reliability growth curve.

AMSAA MODEL

A. Its probabilistic nature allows a statistical treatment of the data.

5.2.4 Other Models: Although the Duane and AMSAA models are the most widely used, a number of other models have been proposed in the literature in addition to those already mentioned. Some of the models utilize a continuous time scale, others utilize a discrete time scale, implying that the testing is performed in stages. (Ref. 53) provides an overview of eight discrete and nine continuous reliability growth models. This overview may be used as a guide for choosing a candidate model for a particular application.

In 1975 Hughes Aircraft, under contract to RADC, performed a study (Ref 10) of the applicability of six reliability growth models to various classes of ground based and airborne systems in two basic environments:

A. "In-house" where failure reporting and analysis is closely controlled and corrective actions are taken.

B. "In-field" where the equipment or system operates in its intended use environment and where failures are reported.

The six models compared (see Ref 10 for a complete model description) were:

A. Duane Model

B. IBM Model

C. Exponential-Single Term Power Series Model

D. Lloyd-Lipow Model

E. Aroef Model

F. Simple Exponential Model

Each of the six models was fitted to data sets (186 data sets for ground equipment and 84 for airborne equipment). Most of the study data was obtained from Hughes built systems; however, some external data from the Naval Ship Weapon Systems Engineering Station, Port Hueneme, California, was obtained for ground computers and displays. Although old (1975), its the latest comparison of model fit we know of. Table 5-2 indicates the types of equipment/systems studied. Table 5-3 provides more details of the equipment.

TABLE 5-2: RELIABILITY GROWTH STUDY SYSTEM/EQUIPMENT DESCRIPTIONS

Shipboard Radar	Ground Based Radar
Satellite Microwave Link	Shipboard Satellite Microwave Communication
Weapon Control	Radar Display
Computer	Ground Based Radar
Laser Range Finder	Radar Display and Computer
Visual Scan System	Laser Bombing System
Airborne Computer	Infrared System

TABLE 5-3: RELIABILITY GROWTH STUDY EQUIPMENT CATEGORIES

1.	Antenna	Pedestal, dish, driver gears, motor, hydraulics
2.	Radar	Receiver, exciter, signal processor, transmitter, power supplies
3.	Microwave	Reciever, exciter, klystron, transmitter, power supplies
4.	Display	CRT, data input console, display controls, power supplies
5.	Computer	Computer circuits, CPU, memory, power supplies
6	Communication	Radio receiver, teletype, etc.
7	System-Radar	Complete radar system
8.	System-Microwave	Complete microwave system
9.	System-Laser	Complete laser system
10.	System-Infrared	Complete infrared system
11.	System-Visual Scan	Complete system for nighttime sighting
12.	Laser Transmitter	Laser transmitter and optics, control electronics, power supplies
13.	Laser Receiver	Photo diode detector and optics
14.	Laser Xmtr/Rcvr	Laser transmitter and receiver, control electronics, power supplies
15.	Infrared Receiver	IR receiver and amplifier, power supplies

In addition to including reliability growth information, the data set for each equipment also included information relative to the scope of the reliability program associated with that equipment.

In order to determine the degree of fit of the models to the data, two goodness of fit parameters were calculated, $\bar{R}$ and R.E. $\bar{R}$ is defined as the absolute percentage error in the predicted versus the observed values. R.E. measures the fraction of unexplained variation to the total variation. The smaller the values of $\bar{R}$ and R.E, the better the fit (ideally $\bar{R}$ = R.E. = 0). Table 5-4 provides a comparison of the models in terms of fit to ground and airborne equipment. Table 5-5 provides a comparison of models by equipment category.

TABLE 5-4: RELIABILITY GROWTH STUDY: JOINT GOODNESS OF FIT ANALYSIS FOR AIRBORNE/GROUND AND IN-HOUSE FIELD CLASSIFICATIONS

	GROUND				AIRBORNE			
	IN-HOUSE		FIELD		IN-HOUSE		FIELD	
	$\bar{R}$	R.E.	$\bar{R}$	R.E.	$\bar{R}$	R.E	$\bar{R}$	R.E.
Duane	28.64	0.73	24.38	1.01	25.44	0.54	67.88	4.1373
IBM	23.43	1.15	26.85	1.73	23.96	0.42	13.66	0.51
Exponential	24.41	1.21	32.05	2.11	11.41	0.10	7.38	0.07
Lloyd-Lipow	25.32	0.64	20.35	0.66	28.42	0.58	11.79	0.27
Aroef	22.30	0.62	19.21	0.63	23.70	0.55	10.57	0.18
Simple Exponential	16.95	0.36	13.08	0.35	13.76	0.24	12.20	0.31

The following conclusions are evident from Table 5-4:

A. The Duane Model cannot be recommended for airborne field data.

B. Conversely, the IBM model is excellent, at its best, for airborne field data.

C. The exponential model is excellent for all airborne data, but is best for airborne field data.

D. The Lloyd-Lipow and Aroef models do quite well for airborne field data.

E. The simple exponential model is good everywhere although the exponential model is clearly better for all airborne systems/equipment.

TABLE 5-5: RELIABILITY GROWTH STUDY: MODEL COMPARISONS BY EQUIPMENT CATEGORIES

	DUANE	IBM	EXPONENTIAL	LLOYD	AROEF	SIMPLE EXPONENTIAL	
Antenna	35.9850 1.0482	16.7530 0.7259	23.0410 0.5796	22.3320 0.5841	21.5580 0.5548	16.2990 0.4177	$\bar{R}$ R.E.
Radar	20.0280 0.4015	50.1790 1.7720	72.3920 6.2718	26.6380 0.6765	22.6870 0.6580	12.3960 0.3157	$\bar{R}$ R.E.
Microwave	19.0350 0.7838	25.4430 0.9908	15.4510 0.6356	20.2110 0.7973	18.7690 0.8172	11.6750 0.3025	$\bar{R}$ R.E.
Display	28.4680 1.1747	24.8820 0.7958	33.0450 1.1845	22.2150 0.5284	18.6920 0.4772	12.0720 0.2424	$\bar{R}$ R.E.
Computer	28.5570 1.1587	46.8850 2.0800	44.9850 2.9100	19.0615 0.0677	17.0070 0.5948	11.7310 0.3171	$\bar{R}$ R.E.
Communications	30.7875 2.4698	19.5005 0.8457	30.8080 0.9524	21.8400 0.6223	20.5840 0.6389	16.0990 0.6372	$\bar{R}$ R.E.
System-Radar	14.5100 0.1688	26.7090 1.3847	189.3860 8.1803	33.2090 0.7514	27.7325 0.7769	12.1090 0.1978	$\bar{R}$ R.E.
System-Microwave	19.3220 0.9852	19.1505 0.7591	16.0805 0.7144	20.2900 0.9157	19.1680 0.9182	11.3010 0.3717	$\bar{R}$ R.E.
System-Laser	19.3820 0.7010	219.9044 2.3913	8.2890 0.0189	80.0380 0.7265	48.1175 0.7111	30.7790 0.2242	$\bar{R}$ R.E.
System-Infrared	65.9675 4.2379	14.2100 0.5450	11.6100 0.1148	12.3915 0.3028	11.5110 0.2184	12.5170 0.3516	$\bar{R}$ R.E.
System Visual Scan	13.4620 0.2909	44.3915 1.6316	8.7840 0.1942	23.8460 0.6400	19.6965 0.5550	18.2945 0.3932	$\bar{R}$ R.E.
Laser Transmitter	33.6590 0.2355	138.9970 0.6332	15.6250 0.0243	42.9715 0.3465	28.8185 0.2770	31.0705 0.3234	$\bar{R}$ R.E.
Laser Receiver	51.2480 0.3118	126.7180 0.9517	12.0280 0.0394	52.5700 0.6944	32.5030 0.6537	31.7310 0.2164	$\bar{R}$ R.E.
Laser Xmtr/ Rcvr	25.2970 0.1163	158.5710 0.9805	11.4100 0.0293	66.1775 0.6072	42.6435 0.5273	36.0765 0.3072	$\bar{R}$ R.E.
Infrared Receiver	41.4885 0.9573	16.1805 0.3365	22.4500 0.0816	21.4965 0.5767	16.2760 0.5047	19.4350 0.6174	$\bar{R}$ R.E.

The following conclusions can be drawn from Table 5-5:

A. For antennas, all the models except the Duane Model are quite good.

B. For radar and microwave systems/equipment, the Duane Model and the simple exponential model are very good.

C. For display, computer and communications equipment, the Lloyd-Lipow, Aerof and simple exponential models are good.

D. For infrared systems equipment, all models but the Duane are excellent.

E. For all laser systems/equipment, the exponential is vastly superior to all other models.

F. For the visual scan equipment, the exponential model is again superior to the remaining models.

G. The Duane model, while rarely fitting "best" was seen to fit in almost all the cases.

5.2.5 <u>Nonrelevant Failures</u>: Reference 56 presents a technique for determining the learning equation, and thereby, for predicting nonrelevant failure occurrences. The decrease of nonrelevant failure occurrences over an equipment's life, especially those due to infant mortality, is a result of a learning process and can be mathematically predicted. This relationship has been demonstrated through use of data obtained from systems composed of many different electronic equipments.

6.0 Reliability Growth Management Techniques: Reliability growth programs for sophisticated complex systems require considerable resources such as time, money and manpower to achieve the level of system reliability acceptable to the user. During the growth process, the total system or major subsystems are tested to failure, system failure modes are determined and design and/or process changes are implemented to eliminate these modes or, at least, to decrease their rate of occurrence. If this process is continued and design and process modifications are made in a competent manner, then the system reliability will increase.

It is advantageous for the program manager to plan and track this increase in system reliability during the development program. He may then determine as early as possible whether or not the system reliability is growing at a sufficient rate to meet the required goal and allocate available resources accordingly. In this regard, a program manager needs to determine from test data the current reliability status of the system, estimate the rate of growth, and obtain projections of future expected reliability.

Some of the important questions that need to be addressed in planning a reliability growth program are:

A. Is a growth test appropriate for this program?

B. Is the final reliability objective similar to reliability achievements made on past programs?

C. What is the expected starting reliability level for the reliability growth curve (e.g., 10% of the prediction) and how many hours must the equipment be preconditioned before this starting point is realized?

D. How much time needs to be allotted for growth testing?

E. How many units should be allocated to reliability testing as part of the overall test program?

F. What minimum test time should be required on each unit on test?

G. What milestones for reliability growth achievement need to be established?

It must be stressed that the answers to the above questions are not "cookbook" and each program has to be carefully tailored to the particular situation and the particular system.

The basic tools for planning a reliability growth program, and thus providing guidelines to answer the aforementioned questions, are discussed in the following sections.

6.1 Reliability Growth Test or Not: The costs of implementing reliability growth into a contract may seem excessive, expecially when one argues that a contractor may perform an informal growth program anyway to discover gross design errors. However, in past programs discovery of noncompliance (reject decision in the reliability qualification test) has occurred many times after full scale engineering development. Because the costs of design changes are more expensive the later they are implemented, the customer has only four options after this discovery, none of which is appetizing:

A. Accept the deficient hardware, which means added life cycle costs because of additional maintenance, repair and logistics actions along with lower operational availability.

B. Require correction of defects, which means accepting added delays and costs.

C. Contract to another supplier for an equivalent equipment, which undoubtedly involves delays and costs at least as great as option (B).

D. Cancel the entire program.

The limited customer options, together with the historical record that shows an overwhelming preference for option (A) indicates that the threat of failing a demonstration test if design problems exist may be no threat at all. This is one reason that the costs of a reliability growth program are justified. The customer is not only buying a more reliable product, but is buying visibility to guarantee that the actual status of reliability is known throughout the engineering development phase. With this visibility, a program manager can assess the program's reliability status and take a good hard look at why the reliability milestones are not being met. By doing so, he is in a position to redirect resources in the early phases of development to avoid having to settle for one of the four options listed above.

The most cost effective way to grow reliability in a large complex system is to first identify low reliability equipment via a prediction and then place extra emphasis on the growth programs of the low reliability equipment. Fixed length tests have been found to be most appropriate for reliability growth in terms of cost-effectiveness, since suppliers faced with testing of uncertain duration tend to protect themselves against worst case test durations in their pricing. Cox and Keely (Ref. 11) have noted that in many successful reliability programs using reliability growth philosophy, approximately 40 to 50% of the total reliability dollar was allocated for growth testing.

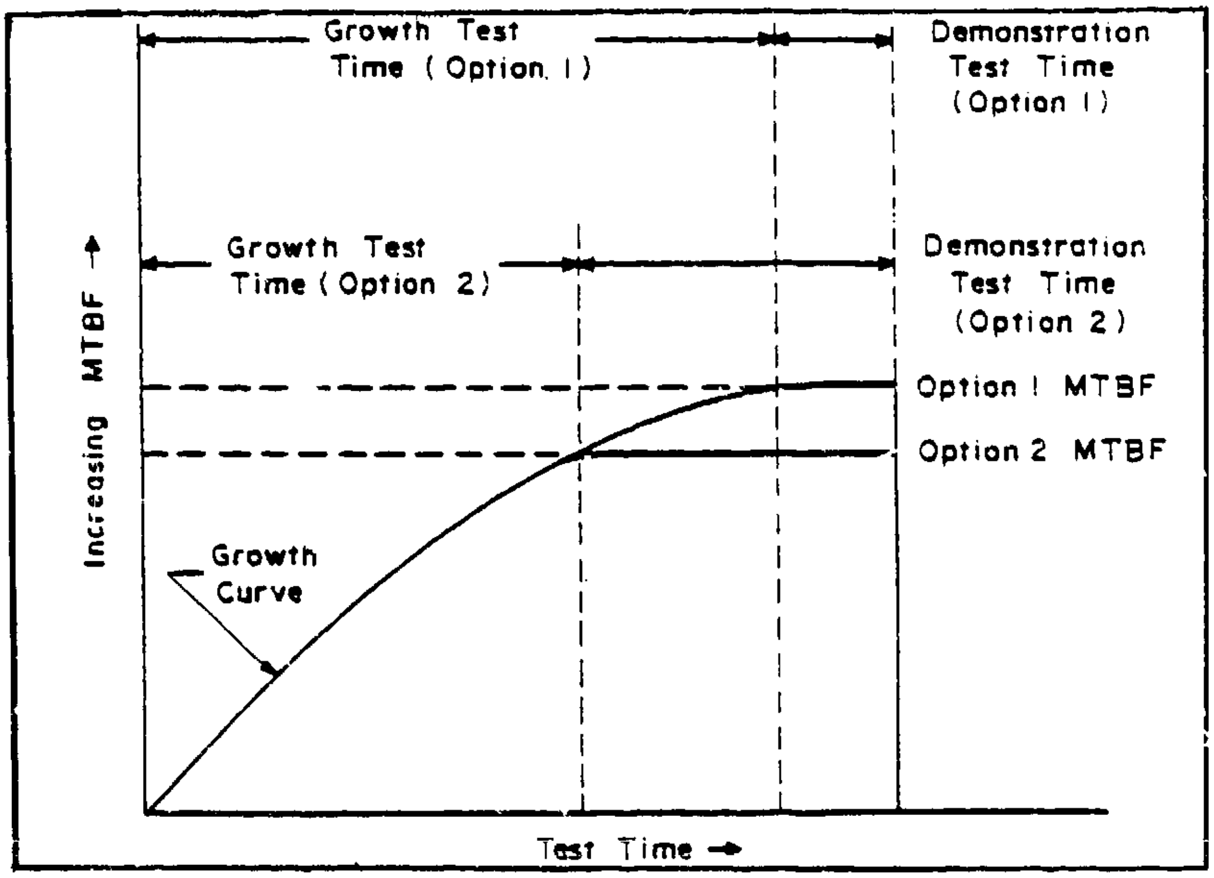
The program manager has two options for a fixed amount of reliability test time. The options are:

1. A higher reliability level through more growth testing at a cost of less time for demonstration , and thus a lower confidence in demonstrated reliability.

2. A higher confidence through demonstration testing at a cost of less time for growth testing, and thus lower achieved reliability.

These options are shown graphically in Figure 6.1.

FIGURE 6.1: OPTIONS AVAILABLE TO A PROGRAM MANAGER FOR A FIXED RELIABILTY TEST TIME



Once the extent of testing has been determined through a review of the reliability specified and its relationship to the state-of-the-art, then evaluations and tradeoffs should be made to determine what tests to include and/or emphasize.

The nature of the procurement (i.e., new development, production, off-the-shelf, etc.) will dictate to a large extent the type of tests. If hardware to be procured is an off-the-shelf commercial product, RDGT may not be appropriate since the equipment is probably mature and any design change would be difficult to obtain. However, if the off-the-shelf equipment requires complex rfaces then RDGT becomes more feasible. Figure 6.2 provides some g ance as to the type of test required as a function of contract ty e (Ref 23). For example, for a new development contract reliability growth testing is applicable for R&M level A and B but not level C (see Table 6-9 for application levels).

FIGURE 6.2: RELIABILITY TESTS AS A FUNCTION OF CONTRACT TYPE

CONTRACT TYPE / TEST		STUDY	DEVELOPMENT						PRODUCTION									OFF THE SHELF (COMMERCIAL)
									DEVELOPMENT FOLLOW ON						BUILD-TO PRINT			
			NEW			MODIFIED			NEW			MODIFIED						
			R&M LEVEL			R&M LEVEL			R&M LEVEL			R&M LEVEL			R&M LEVEL			
			A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
TEST PLAN			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
R GROWTH			•	•		•	•		•			•						
R DEMONSTRATION (ACHIEVEMENT)			•	•	•	•	•	•										•
M DEMONSTRATION			•	•	•	•	•	•										
R ACCEPTANCE	LOT									•	•		•	•	•	•	•	•
	100%								•			•						

A - HIGHEST RELIABILITY EFFORT

C - LOWEST RELIABILITY EFFORT (SEE TABLE 6-9)

Reference 21 presents the following guidelines on when a Reliability Demonstration Test or Reliability Qualification Test (RQT) is most cost effective. A demonstration test should be specified only if:

A. Demonstration can be completed sufficiently early for a major redesign cycle and timely incorporation into production hardware.

B. Realistic incentives and penalties are defined and implemented for reliability achievement or failure.

C. The customer is prepared to take drastic action, up to contract cancellation, to enforce reliability and schedule guarantees.

Obviously, when included in the program plan, RQT should be employed selectively, applied only to those specific procurement items that satisfy these criteria.

6.2 Planning for Reliability Growth: Initially, one wishes to depict the generalized growth pattern for a particular class of systems developed utilizing historical data on similar systems and equipments and development programs in order to make estimates of test time and resources needed. The data includes expected growth rates and expected initial levels of reliability. System characteristics that affect growth patterns include challenge to the state-of-the-art, system complexity, the nature of the system (ground or airborne, mechanical or electrical, etc.) along with characteristics of the development program. Other characteristics that affect growth patterns are test facilities, failure analysis capabilities and management's attitude toward a growth program. Thus, the growth rate is not only a function of the type of equipment being built, but is also dependent, to some extent, upon the company performing the work. Two different approaches are commonly used in the analysis of historical data and the development of planned growth curves. The more traditional approach has been to treat the entire development program as in idealized (smooth) process. The other approach treats the development program as a phase-by-phase process. Figure 6.3 illustrates the st[illegible] involved for planning a growth program with continuous fixes implemented during the program. A similar procedure is used for planning a phase-by-phase type test (Figure 6.4).

FIGURE 6.3: PLANNED RELIABILITY GROWTH (CONTINUOUS)

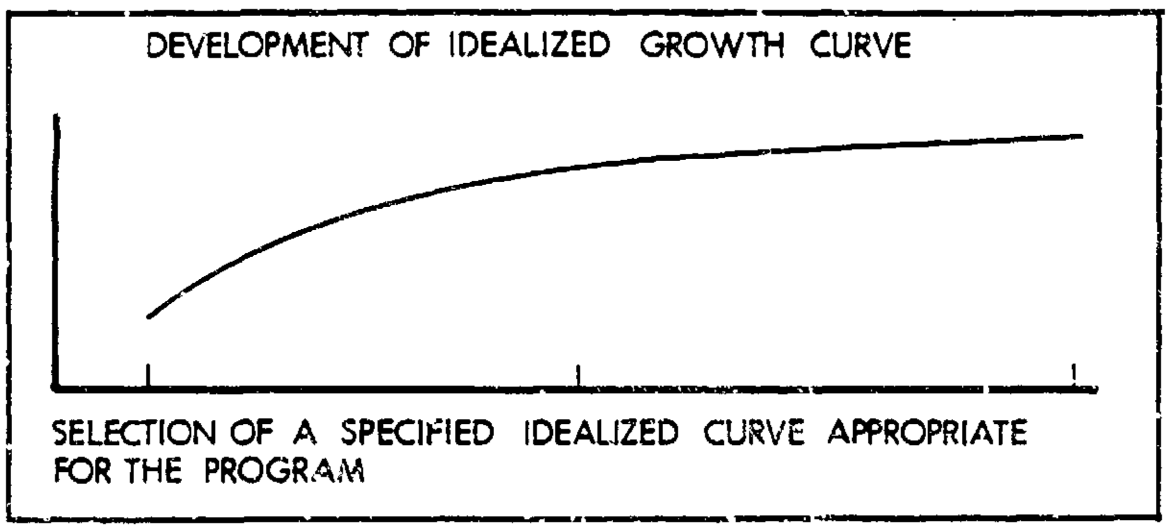
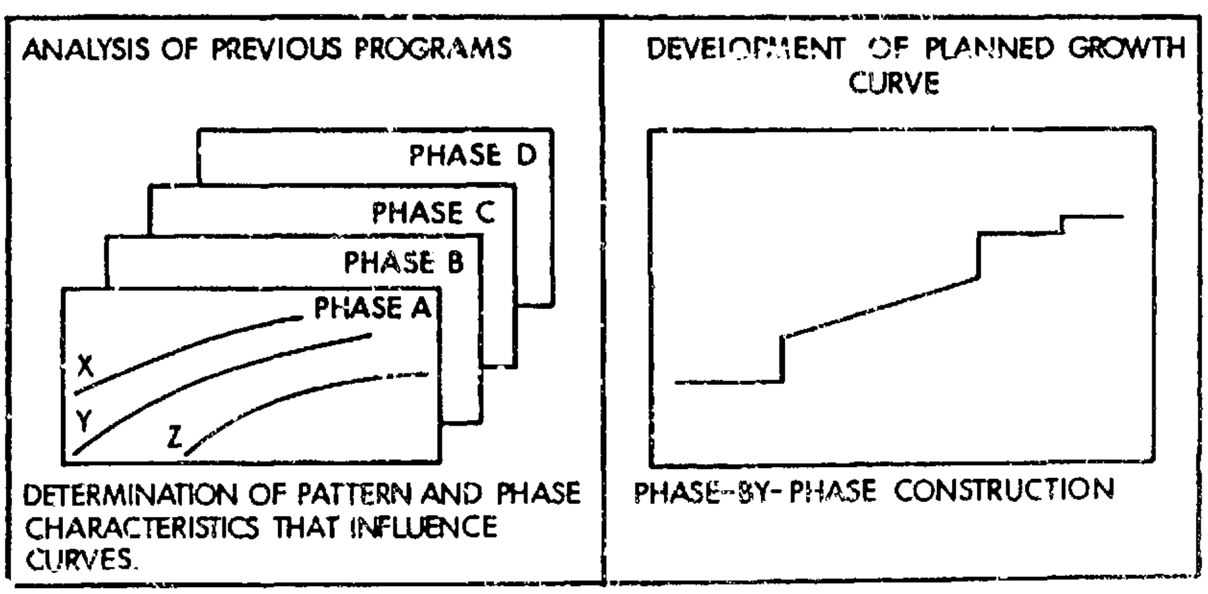


FIGURE 6.4: PLANNED RELIABILITY GROWTH (PHASE-BY-PHASE)



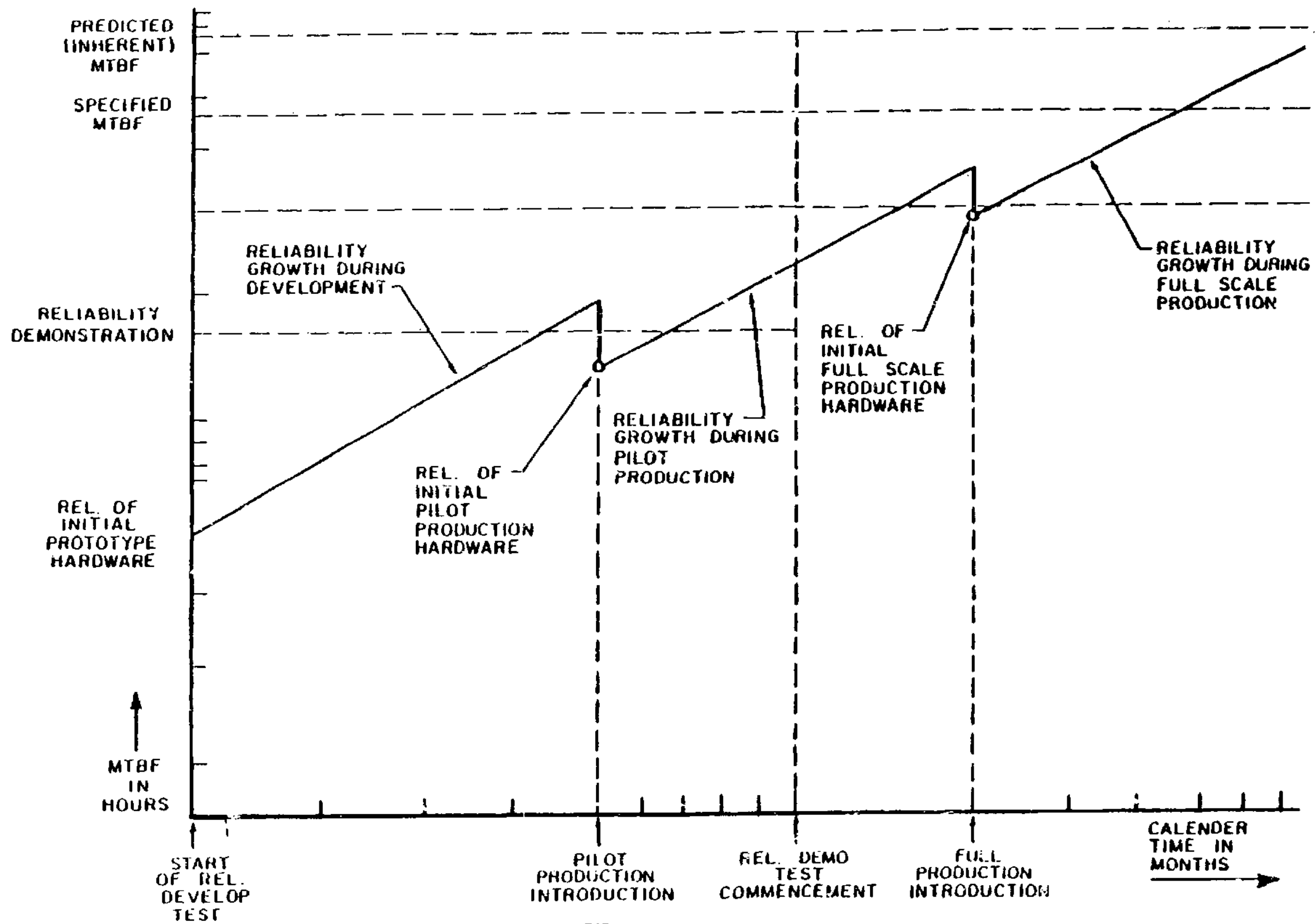
In analyzing historical data for planning purposes, care should be exercised to assure that the parameter values are those for the system configuration that was being tested and not theoretical values for some hypothetical "paper" configuration.

When the "delayed method" (of implementing fixes) is used, the growth rate α will be much smaller than it would be using the continuous method. This is because most of the growth occurs between test phases rather than during them. One problem with this approach is that neither the Duane, the AMSAA, nor any other model predicts the magnitude of the jump in reliability from one phase to another. However, with the continuous method, the test has to be stopped for every failure and the cost of tying up test resources while waiting for failure analysis and design changes is prohibitive, making the delayed method more practical. One should plan what method (delayed fixes or continuous implementation of fixes) will be used. A mixture of methods can also be used, for example, if a corrective action is obvious and can be taken in a timely manner, then the test can be stopped and the fix implemented; however, if no obvious corrective action can be found, then for practical reasons, an in-depth failure analysis must begin and the fix implemented at the end of a test phase or as soon as a corrective action becomes available. In many cases, where the delayed method is used, an additional equipment is made available to go on test when a failure occurs.

If the planned test time will take too much calendar time, then more than one equipment must be put on test. If this is the case, then one must take into account how many equipments will fit into one chamber and how many chambers must be available for the test in addition to how many work shifts a test must run in order to keep a program on schedule. Reference 38 described an overall test efficiency (defined as a ratio of weekly accumulated relevant test hours to possible relevant test hours) and found it to be approximately 50 percent. Contributing to the inefficiency of testing are delays associated with definition of corrective actions, lack of test articles to replace equipment in troubleshooting and repair, and downtime for repair of test equipment.

In some cases, jumps in reliability associated with delayed fixes are negative (dips) as shown in Figure 6.5. This situation often occurs at such times as the beginning of low rate production when the manufacturing process is in the early stages of a "production learning curve." A new production reliability growth process must then take place to regain pre-production reliability. "Dips" may also be caused by new problems that crop up with a design change to fix some other problem or by equipment interface problems if the initial testing is not performed on the complete system configuration.

FIGURE 6.5: RELIABILITY GROWTH PROCESS SHOWING A DECREASE IN RELIABILITY ("DIPS") AT CERTAIN PROGRAM MILESTONES



6.2.1 Initial Reliability: The starting point represents an initial value of reliability for the newly developed hardware and usually falls within the range of 10 to 40 percent of the inherent or predicted reliability after some preconditioning period. Estimates of the starting point can be derived from prior experiences or based on percentages of the estimated inherent reliability. Historical data should be used whenever possible; however, if no prior data is available from a similar system then a commonly used estimate of 10 to 20 percent of the predicted reliability can be used. Starting points must take into account the amount of reliability control exercised during the design program and the relationship of the system under development to the state-of-tne-art. Higher starting points minimize test time. It should be noted that the starting point reliability applies to the system after preconditioning that allows the data to "settle down." This means that the preconditioning period is unplotted, but since the basic plot is cumulative MTBF, the data accumulated during this initial period do influence later results.

Other types of development programs, particularly those for mechanical systems, may not have as extensive an historical data base to draw upon. In those cases, starting points can be based on advanced development prototype test data or on synthesis of component and subsystem results.

6.2.2 The Growth Rate (α)

The growth rate, which is the slope of the growth curve, is governed by the amount of control, rigor and efficiency by which failures are discovered, analyzed and corrected through design and quality actions. A large value of α (α>0.5) reflects a hard-hitting, aggressive reliability program with management support spanning all functions of a knowledgeable organization, while a low value of α ($\alpha < 0.1$) reflects the growth in reliability that is due largely to the need to resolve obvious problems that impact production, and to implement corrective action resulting from user experience and complaints. Green (Ref 3) noted that a high growth rate (α) does not necessarily indicate a good design as is often thought, but it does show a very thorough effort by the whole organization and particularly by the reliability engineers, to discover the cause of the failures and eliminate them. In fact, with excellent design and manufacture α could approach zero. Negative growth can sometimes be observed when engineering changes are implemented to improve "performance," at the risk of loss in reliability. The maximum value of α that can be expected is not greater than 0.7 because of the lag time associated with revealing failures, analyzing them, and implementing corrective actions. In many growth programs α ranges from .3 to .5 as shown in Tables 6-1, 6-2, and 6-3 (Ref 34) which show the variation of growth rates from in-service use improvement programs, development tests, and reliability improvement warranties. Table 6-4 summarizes the data showing that the effectiveness of a growth effort as a function of time, with the development phase growth effort the most beneficial.

Herd (Ref 34) found that the mean growth rate for a large electronic system with a single program manager that placed considerable emphasis on development testing and had different subcontractors for the component systems was 0.41, with a standard deviation of 0.20.

Codier (Ref 1) presented some general observations pertaining to growth rate values. They are that the growth rate (α) is higher:

A. For analog hardware than for digital hardware.

B. For equipment of low maturity than in production hardware.

C. In equipment exposed to severe test conditions than in equipment undergoing bench tests.

D. In proportion to the hardware oriented reliability improvement effort.

The differences in growth parameters observed in the various programs reflect the amount and timeliness of critical engineering information available for corrective action determination and the nature of the system (Mechanical, Electronic, etc.).

The Analytical Sciences Corporation (TASC), under contract to RADC, is developing methodology for predicting reliability growth characteristics as a function of equipment attributes and program characteristics. The results will be available as a decision and planning tool around April 1985.

TABLE 6-1: RELIABILITY GROWTH RATES FOR ELECTRONIC EQUIPMENT FROM IMPROVEMENT PROGRAMS DURING SERVICE USE

EQUIPMENT	OBSERVED α-VALUE
Airborne Teletypewriter	-0.10
Airborne Radar Altimeter	-0.08
Airborne Search Radar	+0.01
Airborne Computer Recorder	+0.11
Airborne HF Communications	+0.12
Airborne UHF Communications	+0.13
Airborne Navigation Set	+0.14
Shipborne Acquisition Radar	+0.14
Shipborne Data Processor	+0.17
Airborne Radio Navigation	+0.19
Airborne Sonobuoy Receiver	+0.19
Airborne Tactical Data Display (A)	+0.19
Airborne Radar Scan Converter	+0.23
Airborne Tactical Data Display (B)	+0.24
Airborne Inertial Navigation	+0.30

TABLE 6-2: RELIABILITY GROWTH RATES OBSERVED FOR DIFFERENT HARDWARE SYSTEMS IN DEVELOPMENT TESTS

ITEM	OBSERVED α-VALUE
Gatling Type AA Gun	+0.40
Hydro-Mechanical Devices	+0.49
Pulse Transmitter, Radar	+0.35
Continuous Wave Transmitter	+0.35
Aircraft Generators	+0.39
Analog Receivers	+0.49
Airborne Radar	+0.48
Airborne Radar (UK)	+0.43
Digital Computer	+0.48
Jet Engines	+0.35
High-Power Equipment (Power Supply, Microwave Amps)	+0.30
Satellite Comm. Terminal	+0.34
Modem (Digital Comm. Terminal)	+0.29

TABLE 6-3: EXAMPLES OF RELIABILITY GROWTH RATES UNDER RIW PROGRAMS

ITEM	PLANNED α-VALUE	ACTUAL α-VALUE
Gyro	+0.13	+0.11
Hydraulic Pump	+0.22	+0.29
Airborne Navigation	+0.15	-
TACAN	+0.17	-

TABLE 6-4: COMPARISON OF RELIABILITY GROWTH RATES

TYPE OF PROGRAM	TYPICAL GROWTH RATE PARAMETER (α)	OPER. TIME TO DOUBLE MTBF (T_1 MULTIPLES)
Development Testing	+0.41	5.4
RIW In-Svc Operation	+0.18	47.0
In-Service Improvement Prog.	+0.15	101.6
In-Service Experience	+0.05	1,047,587.0

6.3 <u>Reliability Growth Test Time</u>: The test time required to grow the reliability to the specified level is an important consideration for determining costs, manpower and other resources and is extremely dependent upon the growth rate and initial reliability level.

In order to expose latent defects as quickly as possible, efforts can be made to operate equipment in on/off cycles while applying an environment including temperature and vibration cycling. High temperature will accelerate chemical deterioration, while extreme temperature cycling will produce thermal stresses and expose mechanical weaknesses, as will vibration. Repeated on-off switching will produce both transient thermal stresses and electrical stresses.

Various references recommend test times to be used for growth testing. There appears to be conflict with regard to these times as shown in Table 6-5. This conflict may be attributed to differences in the magnitude of the reliability numerical requirements.

TABLE 6-5: VARIATIONS OF RECOMMENDED TEST TIMES PRESENTED IN THE LITERATURE

Recommended Test Time	Reference
1. 20-50 multiples of the required MTBF when the required MTBF is not greater than a few hundred hours (tested in severe environment)	3
2. Not less than a few multiples of the specified MTBF	21
3. 5 to 25 multiples of the required MTBF	37
4. 50 to 100 multiples of the required MTBF	34
5. 10 to 25 multiples of the required MTBF	72

6.3.1 <u>Reliability Growth Test Time Estimation for a System</u>: By solving equation 5.5 for time we have a convenient equation for estimating the test time needed to "grow" a system from some initial MTBF to the required (instantaneous) MTBF.

$$T = \left[(MTBF_{INST})\ (K)\ (1-\alpha)\right]^{\frac{1}{\alpha}} \qquad \text{(Equ. 6.1)}$$

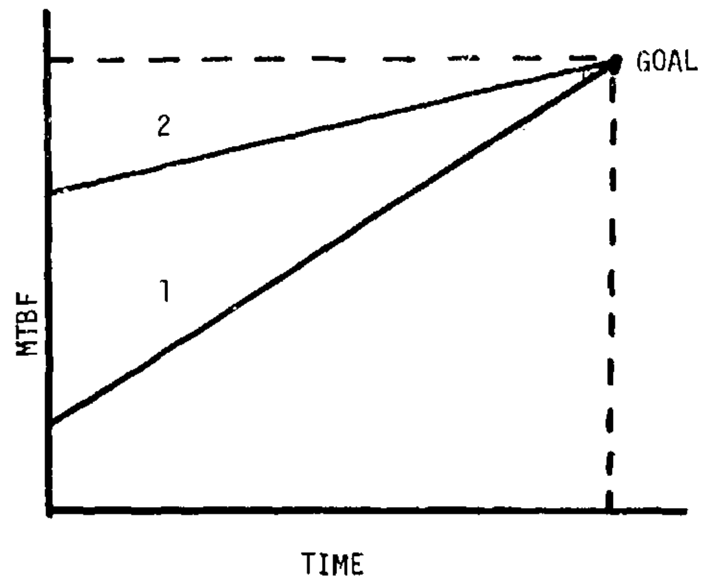
To calculate the test time needed, one must first calculate the constant K. This is done by using equation 5.2 and substituting an expected growth rate and an expected initial $MTBF_{cum}$ after some initial preconditioning period T_{PC} and then solving for K. Experience with previous reliability growth programs should provide a means of estimating the initial $MTBF_{cum}$ point. However, if experience data is not available, as a last resort, the following general approximations can be used for planning purposes.

$$MTBF_{cum\ initial}\ at\ T_{PC} = .1 \times (MTBF_{predicted}) \qquad (Equ.\ 6.2)$$

$$and\ T_{PC} = \frac{1}{2} (MTBF_{predicted}) \qquad (Equ\ 6.3)$$

This provides an estimate of the initial reliability and the length of time needed to stabilize the data to the point where meaningful assessments and projections can be made. The lower and upper limits on T_{PC} per equipment should be in the range of 50 hours and 300 hours respectively. Smaller equipments usually have higher MTBF's and thus the initial condition times calculated from equation 6.3 may seem excessive. However, T_{PC} is the total conditioning period for all equipments to be put on test, and when it is divided among the equipments that are going to be tested, the initial conditioning time per equipment should fall in the range given above. It is important to understand that there is more than one way to reach the same goal MTBF for a given amount of test time. This is shown in Figure 6.6. Curve 1 depicts an equipment with a lower initial starting reliability and a higher growth rate that takes T hours to reach its goal MTBF. Curve 2 represents the same equipment with a higher initial reliability and a smaller growth rate except with increased emphasis placed on other reliability tasks such as: derating, higher quality parts, and better thermal management, etc.

FIGURE 6.6: DIFFERENT WAYS OF REACHING THE SAME MTBF GOAL



6.3.2 <u>Allocating Reliability Growth Test Time to Subsystems</u>: Reference 21 presents a method of allocating reliability growth test time to the most critical subsystems in order to concentrate the test effort on the region of maximum potential benefit. This method serves as a check to assure that test time is not wasted on high MTBF subsystems. An example best illustrates this method.

Suppose a system was comprised of the five subsystems shown in Table 6-6 and 5000 hours are available for reliability growth testing.

TABLE 6-6: SUBSYSTEMS AND THEIR REQUIRED MTBF'S

Subsystem	Required MTBF
A	100
B	50
C	750
D	300
E	150

The procedure used to allocate the 5000 hours is to rank the subsystems in order from the lowest $MTBF_{required}$ to the highest $MTBF_{required}$ and then divide the total test time available evenly among each subsystem and calculate the number of test multiples of the required MTBF as shown in Table 6-7.

TABLE 6-7: TEST TIME IN TERMS OF MULTIPLES OF THE REQUIRED MTBF

Subsystem	$MTBF_{required}$	Test Multiples of $MTBF_{Required}$
B	50	1000/50 = 20
A	100	1000/100 = 10
E	150	1000/150 = 6.7
D	300	1000/300 = 3.3
C	750	1000/750 = 1.3

Testing for small multiples of the required MTBF is not generally as beneficial, thus subsystems D and C probably should not undergo reliability growth testing. The next step would be to go back and reallocate the test time given to subsystems D and C in order to obtain greater test multiples of $MTBF_{required}$ (for each subsystem) are in the range of the recommended test times given in Table 6-5. Another point to be noted is that excessive test time on a subsystem may also be inefficient; therefore, a reallocation may be warranted should the multiples of the $MTBF_{required}$ be too high.

6.3.3 Test Time Example: Suppose the early part of a reliability growth test generated failure data as shown in Table 6-8 and one wanted to make an estimate of the test time needed to achieve an MTBF of 70 hours using this failure data.

TABLE 6-8: INITIAL GROWTH TEST DATA

Cumulative Test Hours	Cumulative MTBF (Hrs)
200	20
525	30
980	35
1500	39
1700	39

Plotted on log-log paper (Figure 6.7) this data shows that reliability is improving in a linear manner.

After a linear relationship becomes apparent, a straight line can be drawn through the data points and the parameters of the Duane model can be calculated as follows:

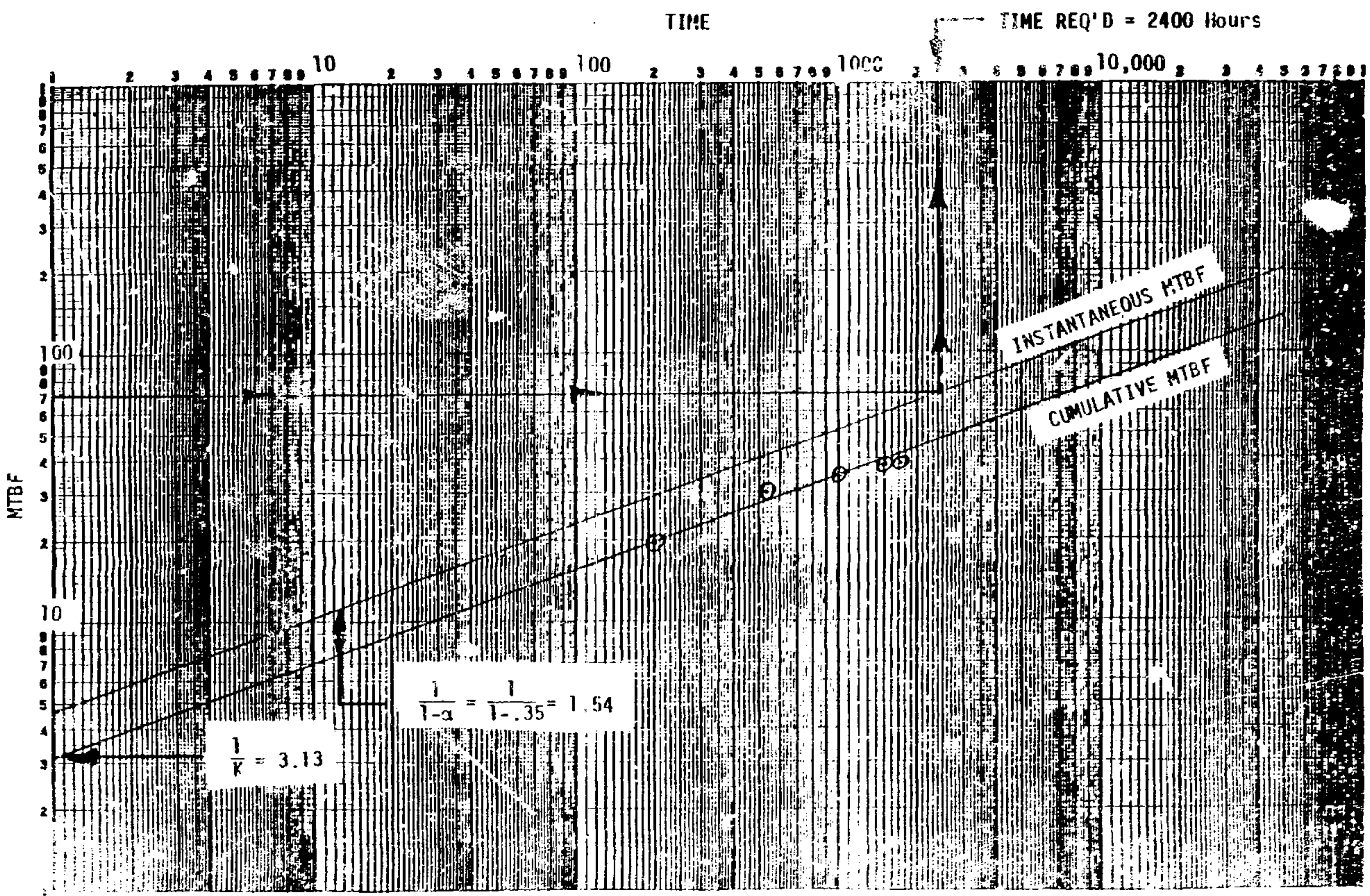
The growth rate: $\alpha = \frac{\Delta MTBF}{\Delta Time}$

$$\alpha = \frac{\log 35 - \log 20}{\log 980 - \log 200}$$

$$\alpha = .35$$

The practice of using only two data points to calculate α should be avoided. However, it is done in this example because the two points used lie on the "eyeballed" line in Figure 6.7 and because equations 5-7 and 5-8 are too lengthy for this simple example.

FIGURE 6.7: PLOTTED DATA FOR TEST TIME CALCULATION EXAMPLE



As an alternative method, the slope may be calculated by measuring $\Delta MTBF$ and ΔT from the plot with a ruler.

The constant K is calculated using Equation 5.2 as follows:

$$MTBF_{cum} = \frac{1}{K}T^{\alpha}$$

at T = 200 hours, $MTBF_{cum}$ = 20, substituting we have:

$$20 = \frac{1}{K}(200)^{.35}$$

$$K = .32$$

$$\frac{1}{K} = 3.13$$

Using another alternative method (see Figure 6.7) the cumulative MTBF line may be extended back to the ordinate and $\frac{1}{K}$ can be read from the plot at an abscissa value of 1 hour. It should be noted that if a graphical method is used to find $\frac{1}{K}$ (or K if failure rate versus time is plotted), then the abscissa scale must start at 1. The above method for calculating $\frac{1}{K}$ is considered only an approximation as was the case for the previous α calculation. Better accuracy can be obtained by the use of equations 5-7 and 5-8.

Thus, for this example the characteristic growth equation is:

$$MTBF_{cum} = 3.13T^{.35}$$

An estimate of the [illegible] time needed to achieve an instantaneous 70 hour MTBF is calculated as follows:

$$MTBF_{inst} = \frac{MTBF_{cum}}{1 - \alpha} \qquad \text{(Equ. 5.6)}$$

$$70 = \frac{MTBF_{cum}}{1 - .35}$$

$$MTBF_{cum} = 45.4 \text{ hours}$$

Substituting this into the characteristic growth equation for this example we have:

$$MTBF_{cum} = 3.13T^{.35}$$

$$45.4 = 3.13T^{.35}$$

$$T = 2095 \text{ hours}$$

This compares roughly with the graphical solution of 2400 hours shown in Figure 6.7.

Equation 6.1 could have been used as a more direct analytical approach.

$$T = \left[(70)\ (.32)\ (1-.35)\right]^{1/.35} = 2095$$

6.3.4 Planning Test Time: Many reliability growth planners fall into the trap of determining test time based on the cumulative MTBF reaching the predicted MTBF. Clarke (Ref 42) showed analytically that there is a region of "no growth" after the current MTBF reaches the predicted MTBF. Failures precipitated during this period will likely be nonpattern, noncorrectable ones occurring at a rate of the reciprocal of the predicted (inherent) MTBF. Therefore, a test structured on the cumulative MTBF reaching the predicted MTBF would never be completed.

Koo, in a 1981 Westinghouse paper (Ref 51), showed how to manipulate growth models based on random effect and systematic failures to arrive at test times required to find a certain percentage of systematic failures, to reduce the hazard rate to a certain level or to ensure that a certain number o systematic failures occur.

6.4 The Exponential Law for the Appearance of Systematic Failures: Green (Ref 3) states that through severe environmental test cycles the appearance of systematic failures may follow an exponential law.

The general equation for describing the appearance of systematic failures is:

$$F_{TSO} = F_{TSP} \; (1 - e^{-t/z}) \qquad \text{(Equ. 6.4)}$$

where: F_{TSO} = Types of systematic failure observed

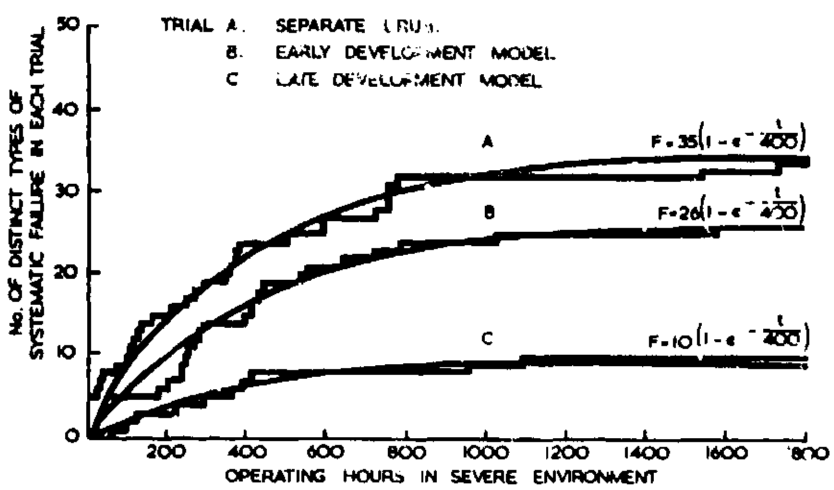
F_{TSP} = Types of systematic failures present

z = Time constant for the environmental test condition (z decreases with increasing test severity)

t = Cumulative operating time

A time constant of 400 hours has been observed in complex airborne radar systems. This indicates that on any one equipment, after testing for 1000 hrs under a severe environment, 90% of the systematic defects are revealed (i.e., $1 - e^{(-1000/400)} = 0.9$). This is shown graphically in Figure 6.8.

FIGURE 6.8: EXPONENTIAL LAW FOR THE APPEARANCE OF SYSTEMATIC FAILURES



The optimum test duration per equipment depends on the target MTBF, and only in the case of an MTBF of several hundred hours or of investigation into long term wearout failures is it worth extending the test on any one equipment beyond 1000 to 1500 hours if other equipment are available for testing.

Green also states that in his experience no single equipment has accumulated more than 3000 hours of operation per annum following a burn-in test. 2500 hours is a typical maximum rate per equipment for accumulating operating hours.

Reference 54 applied the following criteria in order to identify systematic failures (as opposed to random failures). If either of the criteria below is met, a possible systematic reliability problem was identified:

A. The ratio of the number of failed parts to the parts applications was greater than, or equal to 5 percent, for parts population of greater than 100.

B. The ratio of the number of failed parts to the parts application was greater than 20 percent and the number of failures was greater than 1, for parts population of less than 100.

From a mathematical aspect, the exponential law is not compatible with Duane's model. By differentiating, it is apparent that log of failure rate will be proportional to time, and not log time as is the case with the Duane model. The reason for this is that the Duane model tracks additional failures such as random failures, quality control type failures, wear-out failures and repetitive systematic failures where the complete cure has not been found.

For a high target MTBF of several hundred or thousands of hours, the limitations on development time and money and the inability to use multiple samples may preclude extensive growth testing and accelerated stress testing may be essential for equipment requirements to be achieved in a cost effective manner. However, accelerated testing must be planned and used with caution so unrealistic failure modes will not be revealed.

6.5 Tracking Techniques: The basic reasons to track reliability growth (or decline) are to make assessments of reliability against the planned values and to project future reliability.

The planned reliability growth provides a standard to which results can be compared. Assessments can be made without a planned reliability growth curve; however, the comparison is subjective because there is no standard against which to judge and it is a matter of opinion whether or not the program is progressing satisfactorily. Further, assessment provides a clear indicator to a program manager when something has gone wrong so he may know when corrective action needs to be taken.

Growth assessment should only be made after some settling down period if a development phase or test phase change has just taken place or new equipment interfaces have been added. Substantial reliability decline (dips) may result from infant mortalities resulting from new interfaces and from the need for a learning process at the start of a new phase as mentioned earlier.

Reliability growth projection is used after a trend has been established. It is particularly useful when the current estimate of reliability varies significantly from the planned value because it can be used to allot more or less test time to the current test phase or to intensify the growth effort to stimulate a greater growth rate.

Another method that can be used to track reliability and signal trouble in a growth program is the Triple Tracking method presented by Simkins (Ref 44). This method is a real-time reliability measurement, tracking, and control approach that is implemented during the development of a new system. It allows for multitier growth tracking (equipment, subsystem, and system) and provides a high degree of management visability into the effectiveness of corrective actions.

The basic approach is to establish cumulative and instantaneous target curves using Duane techniques and then plot failures as they occur to develop actual cumulative and instantaneous curves. The instantaneous plot is obtained by censoring all correctible failures and not by jumping up the cumulative plot by a factor of $\frac{1}{1-\alpha}$, as is done with a Duane plot.

The cumulative plot is obtained by plotting all relevant failures. Confidence bounds for both the cumulative and instantaneous plots are then calculated using the chi-squared method. There are three conditions that must exist for a "red flag" condition which necessitates major redesign, major change in management control, overhaul or new negotiations on specification requirements. These out-of-tolerance conditions, all of which must be present for a "red flag" condition are:

A. Confidence bands about each best estimate of the instantaneous MTBF do not include the instantaneous targeted curve (planned instantaneous MTBF curve).

B. Confidence bands about each best estimate of cumulative MTBF do not include the cumulative targeted curve (planned cumulative MTBF curve).

C. The projections do not reach the MTBF goal before the end of each of the three major test periods: development, integration and postintegration.

If only one or two of the above conditions exist then a minor out-of-tolerance condition, "yellow flag" condition will exist. Minor out-of-tolerance conditions are those conditions requiring limited actions such as only one equipment out of a system needing redesign, more frequent design reviews, special task studies on pattern problems, or more direct subcontractor control.

A benefit of the triple tracking scheme is that, once an out-of-tolerance condition exists, the program manager knows more about what might be the cause of it. For example, if the projection and cumulative tracking are within bounds, but the instantaneous measurements are below target, then he knows that not enough censoring, at least recent censoring, has taken place. That is, not enough corrective actions have been found, implemented and verified, at least recently.

Another useful indicator that can be used in tracking reliabilty growth has been observed by Green (Ref 3). He states that if the failures are classified as systematic or random, then the ratio of systematic to random provides a useful indicator of progress. Initially, the ratio is about 5:1. When the ratio falls to between 1:1 and 2:1, the reliability target has usually been attained and by that time there is uncertainty in the categorization of failures.

6.6 Confidence Levels: Since the system configuration is continually changing during a reliability growth program, there is usually limited test data available on the system for a fixed configuration. Consequently, direct estimates of system reliability for a fixed configuration would generally not enjoy a high degree of confidence and may, therefore, have little practical value. However, relatively recently confidence intervals were presented in MIL-HDBK-189 for use with the AMSAA Model.

A unique method for calculating confidence intervals for the Duane model is presented by Mead (Ref 18). A "least squares" technique is used to fit a line to Duane growth points. As each successive point contains more information than its predecessor, the points are progressively weighted in proportion to the number of failures. A programmable hand calculator performs this operation rapidly.

With a different program, the same calculator can perform a Monte Carlo simulation to produce a family of Duane characteristics and to compute the mean and standard deviation of the log of final MTBF. This enables confidence limits to be obtained for the latter, at less cost than by computer.

Mead states that by obtaining confidence intervals from a growth test a separate reliability demonstration test may not be necessary. However, it is believed that this practice should be avoided in order to eliminate any motivation a contractor might have to hide failures and thus defeat the purpose of a growth test.

6.7 Cost of a Growth Program: Section 6.1 addressed some cost aspects of reliability growth testing to be considered in deciding whether a program is suitable for this test approach. Reference 23 presents additional cost information pertaining to a reliability program that does and does not implement reliabilty growth testing.

Six factors play a significant role in reliability improvement and comprise the major portion of reliability attributable costs. Table 6-9 shows these six reliability factors and their various application levels as defined for FAA equipment. Level A represents the highest reliability level; level C the lowest.

TABLE 6-9: RELIABILITY ATTRIBUTES AND APPLICATION LEVELS

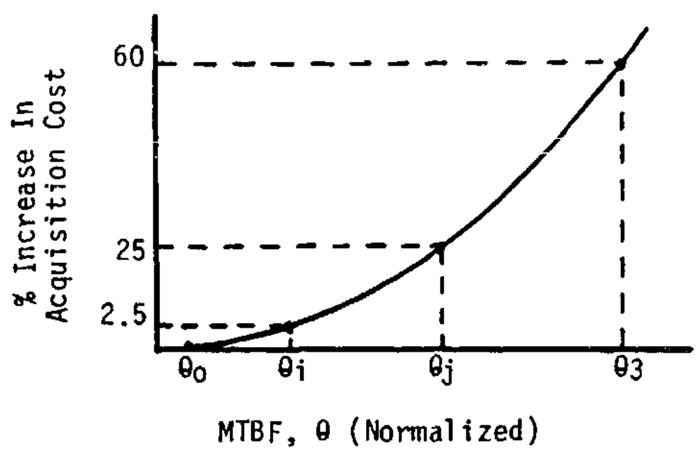
ATTRIBUTES	A	APPLICATION LEVEL B	C
PART SELECTION MICROCIRCUITS SEMICONDUCTORS RESISTORS CAPACITORS	CLASS A JAN TXV S T,S	CLASS B, B1, B2 JANTX R R	CLASS C, COMMERCIAL JAN, COMMERCIAL P,M P,M,L
DERATING	MOST ACCEPTABLE	ACCEPTABLE	MINIMALLY ACCEPTABLE
ASSEMBLY SCREENING	APPLIED	NOT APPLIED	————
VENDOR 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

Table 6-10 and Figure 6.9 present the results of an investigation involving the quantification of the attributes as they are applied to a complex radar system to determine acquisition cost versus reliability relationships.

TABLE 6-10: RELIABILITY ATTRIBUTE LEVELS FOR A GIVEN STATE

RELIABILITY ATTRIBUTE	ATTRIBUTE LEVEL FOR A GIVEN STATE			
	θ_0	θ_i	θ_j	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

FIGURE 6.9: PERCENT INCREASE IN ACQUISITION COST - VS - NORMALIZED MTBF



Where: θ_0 - represents the MTBF of the equipment when applying the lowest level associated with each reliability attribute

θ_3 - represents the MTBF of the equipment when applying the highest level associated with each reliability attribute.

FIGURE 6.10: RELIABILITY TASK COST RELATIONSHIPS

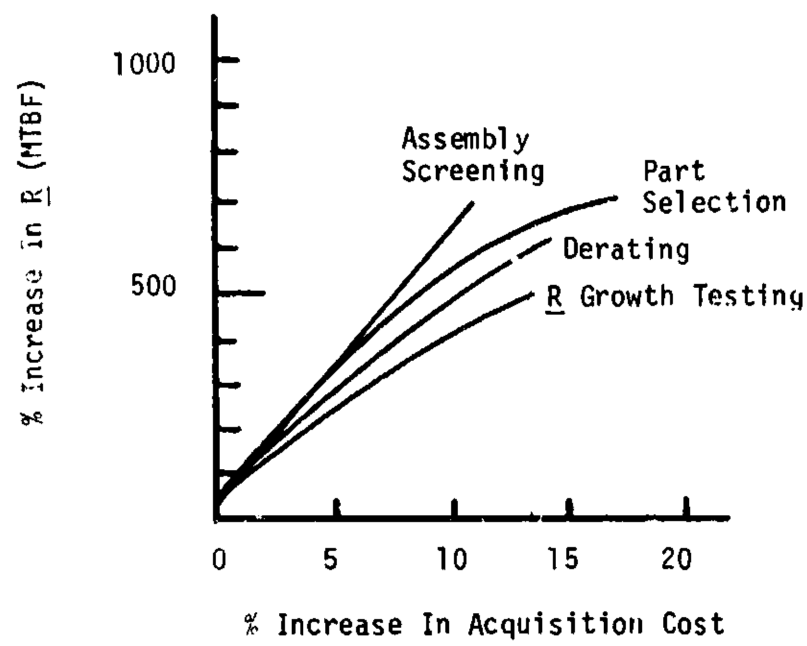


Figure 6.10 shows different reliability task cost relationships on the data given in Table 6-10 and their payoffs. As can be seen, reliability growth testing has about the same magnitude of cost effectiveness as other well accepted reliability program tasks such as parts selection and derating.

There is reason to believe this data may be pessimistic with respect to the cost effectiveness of reliability growth testing because:

A. The data represents only the Federal Aviation Administration's (FAA) findings and therefore may not be representative of the complexity of DoD systems. The greater the complexity of the system, the less likely it is that all the problems will be found during the design phase and the more cost effective growth testing becomes.

B. RDGT is a cost effective complement to, not substitute for, other reliability tasks.

C. The systems represented are likely to have greater maturity than DoD systems. The FAA uses many more off-the-shelf or modified designs.

7.0 Reliability Growth Application Experience: This section will present an overview of some interesting observations and unique test approaches that have been found in the course of the study.

7.1 Current Air Force Applications: A number of Air Force system program offices (SPO's) were contacted to determine where reliability growth testing has been applied or is being planned. Table 7-1 lists the program name, the organization responsible for the program and the type of system/equipment under development for the information gathered.

TABLE 7-1: AIR FORCE RELIABILITY GROWTH APPLICATIONS

PROGRAM NAME	ORGANIZATION	TYPE OF SYSTEM/ EQUIPMENT
HAVE CLEAR (Formerly SEEK TALK)	ESD	UHF Radio
SACDIN	ESD	Communications
AFSATCOM	ESD	Communications
JTIDS	ESD	Class II Terminal
Simulator SPO	ASD	Aircraft Simulators
F-16	ASD	Aircraft Radar
B1-B	ASD	Different Electronic Systems and Some Electro-Mechanical Systems
AMRAAM	AD	Missile
B-52 Offensive Avionics System (OAS)	ASD	Various Onboard Electronic Systems
AWACS	ESD	Airborne Surveillance Radar, Data Processing Displays, Communication, Navigation
AN/ARC-164(V)	ASD	Communications

A brief overview of the programs listed in Table 7-1 follows:

7.1.1 HAVE CLEAR (Formerly SEEK TALK) - A dedicated reliability growth test is planned on the airborne equipment at the end of development prior to a formal RQT. The test length is 2000 hours to grow from an initial MTBF of 55 hours to an MTBF of 250 hours at the start of low rate initial production. Reliability growth testing will continue through low rate initial production with the final goal being 550 hours.

7.1.2 SACDIN - The initial reliability program included a Failure Reporting and Corrective Action System (FRACAS) and a reliability demonstration test. Past experience showed that little attention was given to analysis of failures and corrective action. Thus, an integrated growth test is being conducted both as a development tool and as a determination of contractual compliance with the required reliability. The Duane model is being used for planning and tracking purposes.

Thus far, the results of this growth test are showing a growth rate of .3 to .4. Since testing continued before corrective actions were taken and all failures were counted, some functional areas failed to meet reliability milestones.

7.1.3 AFSATCOM - A reliability growth assessment was performed on the Terminal Segment in a modification of a standard MIL-STD-781 RQT accept/reject criteria. In order to use the contractually required MIL-STD-781B test plan for a combined growth and demonstration test a ground rule was made which allowed failures caused by design deficiencies to be censored from the accept/reject count after the corrective action design change was implemented and verified. A typical verification test time was used 2 or 3 times the specified MTBF. The procedure used was the topic of a 1977 Reliability and Maintainability Symposium paper "AFSATCOM Terminal Segment Reliability Test Program" (Ref. 19).

7.1.4 JTIDS - The Class II terminal of the JTIDS System will undergo a period of reliability growth testing of between 1000 hours and 2000 hours. The exact length of the growth test is dependent upon whether the current MTBF equals or exceeds a required MTBF of 500 hours. A formal reliability demonstration test is required at the completion of growth testing.

7.1.5 Simulator SPO - Because of the small number of aircraft simulators usually procured (10-15), the design changes are implemented during the program which makes all systems slightly different. This factor, along with the use of some commercial off-the-shelf equipment, makes for the use of a reliability growth test as a means to determine contractual compliance on some programs. The goal MTBF's are usually in the range of 10 to 40 hours and the tests are performed in a laboratory environment since that is the usual field environment.

7.1.6 F-16 - A dedicated reliability growth test was performed on the first generation Westinghouse radar with good results. A new avionics package is under development for the F-16 and a growth test is planned for the new radar. Originally, two equipments were to be tested for 500 hours each. However, field experience from the first generation radar showed that most failures occurred soon after the system was started. Because of this past experience, it was decided to test 7 radars for 107 hours each, for a total test time of about 750 hours. This test length is about 10 times the goal MTBF of 70 hours. The growth testing will be part of a full reliability program.

Field reliability growth on the F-16 fleet is also tracked using a computer software package. The program can track monthly, quarterly, or cumulative trends in reliability. It also tracks the trends of different work unit codes to pinpoint developing problem areas. A cumulative growth rate of about .25 has been observed for the fleet.

7.1.7 B1-B - A dedicated reliability growth test of 1000 to 2000 hours is planned. The testing will take place on complex equipment that is either new or modified. Two first production units of each LRU will be tested. Each test unit must accumulate a minimum of 25% of the total test time allotted for the two units. The Duane Model will be used for planning and tracking purposes and a growth rate of about .3 is expected.

Because of funding and schedule constraints, Environmental Stress Screening and Reliability Growth Testing are the only reliability tasks required and contractual compliance with reliability will be determined based on their results.

7.1.8 AMRAAM - It is planned that six missiles will be put on test to accumulate 12,500 hours of reliability growth testing. A seventh missile has been allocated to the test to replace any missile that is undergoing failure analysis. A conservative 10% of the goal MTBF has been assumed for the initial starting point. The goal MTBF is 1000 hours. An assumed growth rate of .5 is being planned and up to 18,000 hours of test time may be used if a lower starting point or growth rate is realized.

All missiles will undergo Environmental Stress Screening and ten missiles will be allocated for a reliability demonstration test following growth testing.

7.1.9 B-52 OAS - Initially, reliability requirements were minimal. When additional funding became available, a dedicated reliability growth test of 2400 hours per system was chosen. No specific growth rate, starting point or target MTBF were set before the test started.

The test results indicated that 70% of all failures occurred within the first 1200 hours on most systems. Observations after the test also showed that the initial MTBF was about 25% of the final MTBF and the growth rate varied between .3 and .6.

7.1.10 AWACS - The AWACS program used all test data (laboratory, flight line, flight) to evaluate reliability growth using the Duane concept. The following types of equipment were tested: data processing, display, identification, navigation and communication. A brassboard program was implemented which involved a competitive flyoff of two prototype surveillance radars, each installed in a Boeing 707 aircraft test bed, followed by evaluation and selection of a winner. The competitive nature of the brassboard phase produced intensive efforts by both competing companies to quickly identify and eliminate the cause of failure problems. In addition, reliability growth testing was used as demonstration of contractual requirements. The equipment was accepted if the slope of the current system MTBF was positive and the current system MTBF was at least the specified level at any time after the first 500 valid flight hours (about 12 MTBF's). The AWACS reliability growth program was the subject of the 1975 Reliability and Maintainability Symposium paper entitled "Reliability Developments - AWACS" (Ref 7).

7.1.11 AN/ARC-164 - The radios accumulated a total of 10,135 valid test hours with 16 relevant failures occurring during this time. MTBF growth data was presented weekly throughout the test to provide some indication of how well the systems were doing. Initial reliability was about 32 percent of the final reliability after a period of 250 hours per system. A growth rate between .32 and .35 was realized during the test.

7.2 Program Application Summary

From the preceeding program highlights, it can be seen that reliability growth testing has been and is being applied to a wide variety of systems under development. Each growth test was tailored (or is being planned) to meet the specific constraints of the overall development program. Scheduling, funding, the number of systems being built and the complexity of the system seem to be the deciding factors on what type of testing will take place and whether growth testing will substitute any other reliability tasks.

8.0 CONCLUSIONS: The impact of equipment and system reliability on operational readiness and life cycle costs is tremendous. The cost effective development of reliable equipment for the Air Force is an important responsibility. While the complexity of today's electronic systems makes it virtually impossible to assure high reliability based on the results of a "drawing board" design, some elements of the Air Force have been hesitant to apply reliability growth techniques.

The reliability achieved on previous military systems has been highly dependent on the emphasis placed on reliability by program management. This so-called reliability implementation has been referred to as "ad hoc" depending on the strength of the program office reliability engineer. Use of a reliability growth approach gives the status of the reliability program more visibility and provides the program manager with a tool for planning, tracking and projecting. Current Air Force directives and regulations require that program managers track and manage the reliability growth process. Earlier revisions assumed that the specified reliability could be designed into the equipment. Many programs reached an "accept" MIL-STD-781 decision only after several restarts. Although the unsuccessful attempts weren't called "growth testing," that's what they amounted to. Like a growth test, the equipment reliability improved by design or manufacturing changes. While reliability growth can and does occur in all program phases (i.e., development, production, and initial operation), it is clear that the cost effectiveness of the process becomes greatly diminished the later the process takes place. By the same token, all potential problems cannot be surfaced during DT&E, so full growth can't be expected in development. With the start of each new phase, changes in manufacturing processes and workers introduce a temporary reliability degradation. The RIW (Reliability Improvement Warranty) is a means of continuing the growth process into the initial deployment phase.

It should be recognized that reliability growth testing is not a panacea for developing a reliable product. It is also not a substitute for other reliability engineering tasks such as parts control and stress derating. Swett (Ref. 25) several years ago likened reliability development testing to the linebackers on a football team with the design phase as the defensive line. Both elements are necessary for success whether in football or reliability design. The key is to "nail the potential reliability problems as early as possible." A multitude of cases of misunderstanding and misapplication of the growth testing concept could be cited where after the fact data has been used to show a growth success story, or as Clarke stated, there was a "no-growth growth" process. With the complexity of today's electronic equipment, it is impossible to catch all reliability problems with the defensive line.

While it is generally agreed that some sort of RDGT is needed as part of the development process many questions remain regarding implementation of the concept. Table 8-1 (Previously presented in Section 2.1) lists many of the questions often expressed by those skeptical of RDGT.

TABLE 8-1: QUESTIONS REGARDING RDGT IMPLEMENTATION

1. Who pays for the RDGT? Does the government end up paying more?

2. Does RDGT allow contractors to "get away with" a sloppy initial design because they can fix it later at the government's expense?

3. Should reliability growth testing be dedicated or integrated?

4. When should a reliability growth test begin?

5. Should reliability growth be planned for beyond the FSED phase?

6. Should the equipment operate at the fully specified performance level prior to the start of RDGT?

7. Should all development programs have some sort of reliability growth testing?

8. How does the applicability of reliability growth testing vary with the following points of a development program?

   a. Complexity of equipment and its challenge to the state-of-the-art
   b. Operational environment
   c. Quantity of equipment to be produced

9. What model(s) should be used?

10. What starting points and growth rates should be used for planning?

11. How much test time will be required?

12. When will corrective actions be implemented and how will failures be counted?

13. Will there be an accept/reject criteria?

14. Should the contractor be responsible for intermediate milestones?

15. Can/should growth testing be incentivized?

16. Does the type of contract affect RDGT decisions?

17. What is adequate time for verifying a design fix?

18. What is the relationship between an RQT and RDGT?

19. Who will do the tracking? How and to whom will the results/status be reported?

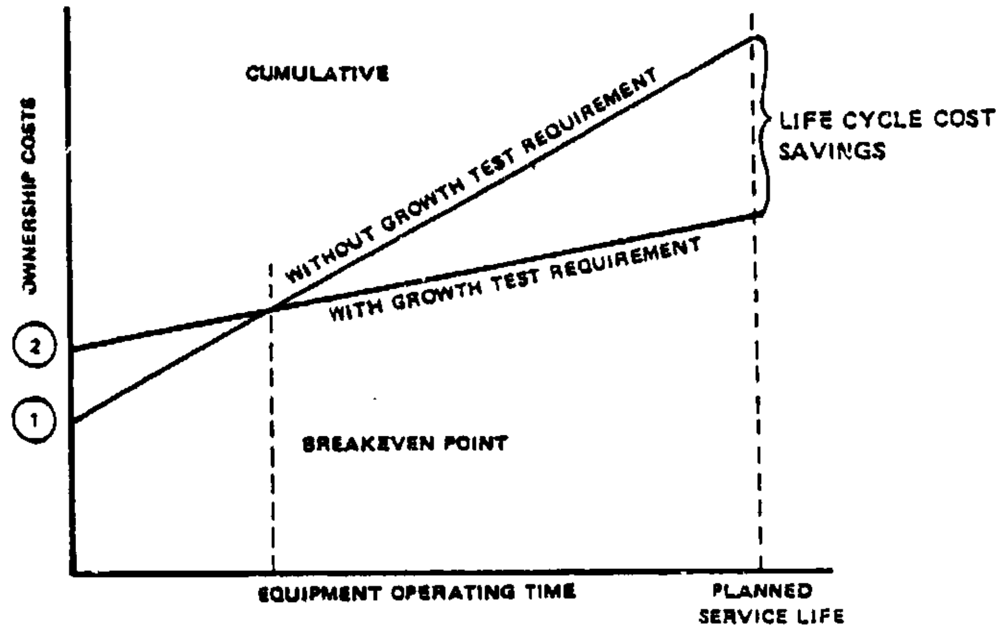
20. How much validity/confidence should be placed on the numerical results of RDGT?

Based on the findings of the study, the following paragraphs will address each of these questions:

1. Who pays for the RDGT? Does the government end up paying more?

The usual case is that the government pays for the RDGT as an additional reliability program cost and in stretching out the schedule. There have been situations where contractors have tested on their own prior to an RQT as their means of reducing the risk of an RQT reject decision. In a competitive environment, usually the offeror's will not risk losing the contract because of the extra cost of nonrequired growth testing. The point to be made with regard to the RDGT cost is that, regardless of who pays, the reliability will be improved and the support cost element of the total life cycle cost equation will be reduced. The savings in support costs (recurring logistics costs) exceed the additional initial acquisition cost, resulting in a net savings in LCC. The amount of these savings is dependent on the quantity to be fielded, the maintenance concept, the sensitivity of LCC to reliability and the level of development required. It is the old "pay me now or pay me later situation" which in many cases makes a program manager's situation difficult because his performance is mainly based on the "now" performance of cost and schedule. Figure 8.1 shows how the extra development cost of an RDGT is "paid back" by reduced life cycle costs.

FIGURE 8.1: COMPARISON OF CUMULATIVE LIFE CYCLE COST; WITH AND WITHOUT SPECIFIED RELIABILITY GROWTH TEST REQUIREMENTS



2. Does RDGT allow contractors to "get away with" a sloppy initial design because they can fix it later at the government's expense?

This is a legitimate question because all contractors are driven by profit motives. Most experts believe that contractors do not allow this to happen which is borne out by the Mead (Ref 5) concept of starting the growth program with a "healthy plant." It has been pointed out that a growth program is not a panacea, or a substitute for other reliability engineering tasks, but is a means of maturing the design through the correction of unforeseen reliability problems preferably prior to production. It has been shown that these unforeseen problems account for 75% of the failures due to the complexity of today's equipment (Ref 3). Too low an initial reliability (resulting from an inadequate contractor design process) will necessitate an unrealistic growth rate in order to attain an acceptable level of reliability in the allocated amount of test time. The growth test should be considered as an organized search and correction system for reliability problems that allows problems to be fixed when it is least expensive. It is oriented towards the efficient determination of corrective action. Solutions are emphasized rather than excuses. It can give a nontechnical person an appreciation of reliability and a way to measure its status.

3. Should the RDGT be dedicated or integrated?

The decision regarding whether to allot a specified number of hours for a dedicated growth test has many pro's and con's. Dedicated tests have the following advantages:

A. Better control is maintained with respect to failure occurrence, documentation and reporting.

B. There is less chance of inducement of failures by operators, test equipment, etc.

C. The environmental conditions are easier to control.

D. Use of the resulting data for assessment and projection has greater validity.

E. The equipment usually has a pre-established baseline performance (including meeting environmental qualification) against which to judge failures.

F. The equipment more closely represents the configuration and manufacturing processes to be used in production.

On the other side of the coin are the following arguments for an integrated RDGT:

A. Since a separate period of testing is not required, the cost is obviously less.

B. This form of testing is more in line with the cost effective spirit of RDGT via earlier detection and correction of failures.

The attributes of dedicated and integrated testing change when an attempt is made to use the testing as a determination of contractual compliance with numerical requirements. Reliability problems should be uncovered and corrected as early as possible to be most cost effective. As pointed out earlier, an RDGT implies more structured planning, assessment and tracking than TAAF and FRACAS. As such, a performance baseline needs to be established prior to the start of the RDGT which implies a later start and a dedicated test. Integrated tests may be more appropriate for small quantity very complex systems and ones with very limited test resources.

Waiting for a well controlled dedicated test time with the equipment performing to full specified capacity will in most cases be less cost effective in providing a vehicle for correction of deficiencies; however, it offers a better vehicle for assessment and projection. Carrying this to an extreme, to count on reliability growth later in the equipment life cycle from the development phase will be very cost ineffective due to the difficulty in incorporating design changes.

. When should a reliability growth test begin?

This is partially answered by question number 3 regarding a dedicated vs an integrated RDGT approach. It should be obvious that the earlier a problem is found and analyzed, the less costly it is to implement a corrective design change. Of course, if too early, it is difficult to determine whether the problem uncovered is a reliability problem or a question of the design not yet meeting the specified performance criteria. The definition of reliability reflects the ability to perform to some specified criteria over time. Therefore, tracking of growth can only really be done after the equipment performs at or near its specified levels. This is not to say that uncovered reliability problems should not be corrected as early as possible. It has been said that growth occurs up to two years after IOC but this includes growth processes involving the human element.

5. Should reliability growth be planned for beyond the FSED phase?

As several authors have mentioned (as referenced in earlier sections), there are different types of reliability growth in the general sense. Our discussions have been purposely limited to the strict definition of reliability growth to include only reliability improvement as the result of finding, analyzing and implementing design corrections for reliability problems uncovered during testing. In this sense, the cost of incorporating design changes past FSED (Reliability Definition and Demonstration Phase) may be prohibitive in terms of ECP's and possible retrofit. The cost effectiveness of reliability growth varies inversely with the program phase. Therefore, this type of reliability testing should be used in FSED. Of course, exceptions to this rule have occurred in the past and will continue to occur. Cases in point are usually the result of poor field reliability, where, as the result of an LCC analysis, it becomes cost effective to undertake some sort of reliability improvement program. Other situations where the growth approach may be appropriate are Low Rate Initial Production (LRIP) programs. While determined to be cost effective at that point, it would have been much more cost effective to find those problems and correct them during development. Reliability Improvement Warranty (RIW) efforts can be thought of as reliability growth in the production phase. These efforts aren't always effective if a contractor determines he can make a profit without higher reliability because of inexpensive maintenance. Other forms of growth as expressed in the previously mentioned comments on "no-growth growth" and "endless burn-in" will occur in production and operational use but are not appropriate for development.

6. Should the equipment operate at the fully specified performance level prior to the start of RDGT?

Waiting until every specified parameter is met is wasting valuable test, analysis, corrective action and verification time. But on the other hand, the ability to determine "when is a failure a failure" without a defined baseline is difficult. If an equipment is performing "almost" to specification, determination can be made with respect to most problems as to whether they are performance related or reliability related. Because this is the case, the time to start is when any meaningful equipment level reliability data can be developed with respect to acceptable measures of performance. In other words, if a radar is not fully meeting it's specification with respect to range, that should not prevent test, analysis and implementation of corrective design on the power supply, signal processor or other functional elements. Of course, this will result in exposure to risk because a performance design fix could introduce reliability problems. If the growth is to be used as an assessment and projection vehicle, then the configuration should meet all performance requirements.

7. Should all development programs have some sort of growth programs?

The answer to this question is yes in that all programs should analyze and correct failures when they occur in prequalification testing. A distinction should be in the level of formality of the growth program. The less challenge there is to the state-of-the-art, the less formal (or rigorous) a reliability growth program should be. An extreme example would be the case of procuring off-the-shelf equipment to be part of a military system. In this situation, which really isn't a development, design flexibility to correct reliability problems is mainly constrained to newly developed interfaces between the "boxes" making up the system. A rigorous growth program would be inappropriate but FRACAS should still be implemented. The other extreme is a developmental program applying technology that challenges the state-of-the-art. In this situation a much greater amount of design flexibility to correct unforeseen problems exists. Because the technology is so new and challenging, it can be expected that a greater number of unforeseen problems will be surfaced by growth testing. All programs can benefit from testing to find reliability problems and correcting them prior to deployment, but the number of problems likely to be corrected and the cost effectiveness of fixing them is greater for designs which are more complex and challenging to the state-of-the-art.

8. How does the applicability of reliability growth testing vary with the following points of a development program?

A. Complexity of equipment? And challenge to state-of-the-art?

The more complex or challenging the equipment design is, the more likely there will be unforeseen reliability problems which can be surfaced by a growth program. However, depending on the operational scenario, the number of equipments to be deployed and the maintenance concept, there may be a high LCC payoff in using a reliability growth program to fine tune a relatively simple design to maximize its reliability. This would apply in situations where the equipments have extremely high usage rates and LCC highly sensitive to MTBF.

B. Operational environment?

All other factors being equal, the more severe the environment, the higher the payoff from growth testing. This is because severe environments are more likely to inflict unforeseen stress associated reliability problems that need to be corrected.

C. Quantity of equipment to be produced?

The greater the quantities of equipment, the more impact on LCC by reliability improvement through a reliability growth effort.

9. What reliability growth model(s) should be used?

The model to be used, as MIL-HDBK-189 says, is the simplest one that does the job. Section 5 went into detail on what models apply best for a variety of situations. Certainly, the Duane is most common, probably with the AMSAA second. They both have advantages; the Duane being simple with parameters having an easily recognizable physical interpretation, and the AMSAA having rigorous statistical procedures associated with it. MIL-STD-189 suggests the Duane for planning and the AMSAA for assessment and tracking. When an RQT is required, the RDGT should be planned and tracked using the Duane model; otherwise, the AMSAA model is recommended for tracking because it allows for the calculation of confidence limits around the data.

10. What starting points and growth rates should be used for planning?

For planning an RDGT, growth rates and starting periods should be based on experience with the development of similar systems. Rules of thumb, such as a starting point of 10% of the inherent (predicted) MTBF at a test time of one half the inherent MTBF and a growth rate of 0.4 or 0.5, have been suggested. Growth is not a naturally occurring process but rather takes place when failure modes/mechanisms are systematically removed. Therefore, it is always better to use historical data based on the experience of the particular contractor on similar programs. As a planning tool, RADC has currently underway (reference Section 6.2.2) a research effort that will provide guidance regarding the characteristics to be expected on a particular reliability growth program based on both equipment characteristics and program attributes.

11. How much test time will be required?

The test time required, as shown previously, is a function of the initial level of reliability as well as the growth rate. Appendix A gives tables for various final target MTBF's. The literature is rather confusing regarding growth test time recommendations as shown in Table 6-5. Because of the rates at which systematic defects are likely to occur and potential wearout mechanisms, test planning must also address test time on a per-equipment basis. Test efficiency is a driver in determining how much calendar time will be required to accumulate the required test hours. All these factors make a fixed time reliability growth test the best choice for planning and for costing by a contractor in a competitive situation. Various persons have suggested accelerating the test by way of more severe stress levels as a means of shortening the time; however, extreme caution must be exercised so that new failure modes aren't introduced that wouldn't occur in the operational environment. Some authors have described associating an acceleration factor during growth testing as a "black art."

12. When should corrective actions be implemented?

Ideally the corrective actions should be put in right after the discovery of the problem so that the growth process is continuous and the verification time for each fix is maximized. In this situation plotted data would be smooth. To carry this out in practice would mean tying up test resources until a fix is found for every failure, which cannot be done in real life. The AMSAA (MIL-HDBK-189) approach is to use a phase-by-phase process where fixes are implemented at the end of each test phase so that within phases the growth is continuous and between phases there are reliability "jumps." The problem with this approach is that there isn't any way of judging how large (or small) the jumps will be. Several authors advocate plotting only "failure sources," or first time failure occurrences, during growth tracking. With this approach, further incidents of these modes, following the first occurrence, are not counted as long as a corrective action is implemented with adequate verification time prior to test completion. Others keep track of the progress both ways, "culled" data and all data. The mathematics of models show that the growth process is a self purging one where the model itself takes care of eliminating earlier failures.

13. Will there be an accept/reject criteria?

The purpose of reliability growth testing is to uncover failures and take corrective actions to prevent their recurrence. Having an accept/reject criteria is a negative contractor incentive towards this purpose. Monitoring the contractors progress and loosely defined thresholds are needed but placing accept/reject criteria, or using a growth test as a demonstration, defeat the purpose of running them.

14. Should the contractor be responsible for intermediate milestones?

A degree of progress monitoring is necessary even when the contractor knows that following the reliability growth test he will be held accountable by a final RQT. Tight thresholds make the test an RQT in disguise. General guidance for determining the acceptability of progress is expressed in MIL-STD-1635 (reference Section 6.5) and in the IBM triple tracking method. It must be remembered what the purpose of the test is; there should be no incentives for contractors to hide failures.

15. Can/should growth testing be incentivized?

Reliability growth can be incentivized but shouldn't be. To reward a contractor for meeting a certain threshold in a shorter time or by indicating "if the RDGT results are good, the RQT will be waived," the contractor's incentive to "find and fix" is diminished. The growth test's primary purpose is to improve the design, not to evaluate the design.

16. Does the type of contract affect RDGT decisions?

The type of development contract is a procurement strategy decision and is usually determined as a function of program risks. Development contracts are generally a "cost plus" type which may or may not include incentives. Production contracts which are much easier to price, because costs can be defined, are usually some form of "fixed price" ones. It has already been stated that contracts with incentives based on reliability growth give contractors a reason to hide failures, which is counterproductive. If fixed length reliability growth testing is used, it really doesn't matter what the contract type is because the test can easily be priced, even as a separately priced contract item.

17. What is adequate time to verify a design fix?

Most persons agree that the verification time to prove that a design fix has eliminated a particular failure mode depends on what the mode is, what the fix is and how the fix interacts with the rest of the design. It must be long enough to assure that, even though the original problem has been corrected, new time dependent failure modes haven't been introduced by the fix. A good rule of thumb is that the time should be at least one MTBF (predicted).

18. What is the relationship between an RQT and RDGT?

The RQT is an "accounting task" used to measure the reliability of a fixed design configuration. It has the benefit of holding the contractor accountable some day down the road from his initial design process. As such, he is encouraged to seriously carry out the other design related reliability tasks. The RDGT is an "engineering task" designed to improve the design reliability. It recognizes that the drawing board design of a complex system cannot be perfect from a reliability point of view and allocates the necessary time to fine tune the design by finding problems and designing them out. Monitoring, tracking and assessing the resulting data gives insight into the efficiency of the process and provides nonreliability persons with a tool for evaluating the development's reliability status and for reallocating resources when necessary. The forms of testing serve very different purposes and complement each other in development of systems and equipments. An RDGT is not a substitute for an RQT, or other reliability design tasks.

19. Who will do the tracking? How and when will the results/status be reported?

When an RDGT is invoked in conjunction with an RQT, as recommended, the close monitoring of contractor results isn't as critical as when only an RDGT is being required. If an RQT is providing the accountability at some later time, the RDGT can be thought of as a means of increasing the chances of passing the RQT. Of course, as has not been the case in many RQT's in the past, the procuring activity has to exercise its redesign options should a reject decision be reached in RQT. Still, with an RQT hanging over his head, a contractor may still shortcut his reliability design approaches hoping to pass the RQT by the usual practices of declaring failures nonrelevant, induced by test equipment and the like. Therefore, the growth process should always be monitored by the AF program office, with the degree of scrutiny dependent on how the results are to be used. Reporting of the results and status is not clearly defined under present reliability standards and data item descriptions (DID's). No specific DID's exist for reliability growth. Existing ones written for the RQT must be tailored for this application.

20. How much validity/condifence should be placed on the numerical results of RDGT?

Associating a hard reliability estimate from a growth process, while mathematically practical, has the tone of an assessment process rather than an improvement process, especially if an RQT assessment will not follow the RDGT. In an ideal situation, where contractors are not driven by profit motives, a reliability growth test could serve as an improvement and assessment vehicle. Since this is not the real world, the best that can be done if meaningful quantitative results are needed without an RQT, is to closely monitor the contractor RDGT. Use of the AMSAA model provides the necessary statistical procedures for associating confidence levels with reliability results. In doing so, closer control over the operating conditions and failure determinations of the RDGT must be exercised than if the test is for improvement purposes only. A better approach is to use a less closely controlled growth test as an improvement technique (or a structured extension of FRACAS, with greater emphasis on corrective action) to fine tune the design as insurance of an accept decision in an RQT. With this approach, monitoring an improvement trend is more appropriate than development of hard reliability estimates. Then use a closely controlled RQT to determine acceptance and predict operational results.

8.1 Summary of Conclusions: Certainly no one in the development business can argue against uncovering problems and correcting them. The RDGT has been proved to be an organized approach to doing just that. It does not replace other design oriented reliability tasks. It may add to the acquisition cost of a system, but the reduced risk of failing a reliability demonstration and the reduction in operation and support costs more than offset this. Most skeptical comments regarding the growth concept have their origin in situations where growth techniques have been misapplied or used as a panacea trying to bail out a poor design. When applied properly and not substituted for an RQT, an RDGT is an extremely cost effective task in the development process. Unfortunately, many success stories written around the concept are of the misapplication type which have resulted in "turning-off" reliability practioners to the concept. The complexity of today's equipment necessitates recognition of the fact that designs cannot be perfect off the drawing board. As such, a properly defined and managed reliability growth program is a must for today's development efforts. RADC's new R&D study "Reliability Growth Prediction" will serve as an excellent complement to MIL-HDBK-189 and MIL-STD-1635 in assuring that the concept is properly applied.

APPENDIX A

TEST TIME TABLES

The following tables contain estimated test times calculated by using equations 6.1, 6.2, 6.3 and 5.2. These times are the number of hours needed for the instantaneous Duane plot to reach the MTBF goal (θ_0). The predicted MTBF and the initial conditioning period (assuming Equ. 6.3 holds) are given at the top of each page. The starting MTBF, stated as a percentage of the predicted MTBF, is varied in increments of 5 percent across the top of each table. The growth rate (α) is varied along the left side of the table in increments of .05. The blank spaces in the table represent test time results which are less than five times the predicted MTBF and are therefore not recommended. A minimum test time of 5 times the predicted MTBF should be used in these cases.

TABLE A.1: RELIABILITY GROWTH TEST TIME (θ_p = 25 HOURS)

PREDICTED MTBF (θ_p) = 25 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 12.5 HOURS

α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
	Starting Point % of θ_p							
.20	13,107,200	409,600	53,939	12,800	4,194	1,685	779	400
.25	63,[illegible]12	39,550	7,812	2,471	1,012	488	263	154
.30	82,667	8,201	2,122	813	386	210	125	
.35	19,037	2,627	824	362	191			
.40	6,235	1,102	399	194				
.45	2,577	552	224					
.50	1,249	312	138					
.55	679	192						
.60	399	125						

TABLE A.2: RELIABILITY GROWTH TEST TIME (θ_p = 50 HOURS)

PREDICTED MTBF (θ_p) = 50 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 25 HOURS

	Starting Point % of θ_p							
α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
.20	26,214,400	819,200	107,878	25,600	8,388	3,371	1,559	800
.25	1,265,625	79,101	15,625	4,943	2,025	976	527	308
.30	165,335	16,403	4,245	1,627	773	421	251	
.35	33,074	5,254	1,649	725	383			
.40	12,470	2,204	799	389				
.45	5,154	1,104	448					
.50	2,499	624	277					
.55	1,358	385						
.60	799	251						

TABLE A.3: RELIABILITY GROWTH TEST TIME (θ_p = 75HOURS)

PREDICTED MTBF (θ_p) = 75 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 37.5 HOURS

	Starting Point % of θ_p							
α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
.20	39,321,600	1,228,800	161,817	38,400	12,582	5,056	2,339	1,200
.25	1,898,437	118,652	23,437	7,415	3,037	1,464	790	463
.30	248,003	24,605	6,368	2,441	1,160	631	377	
.35	57,111	7,882	2,474	1,087	575			
.40	18,706	3,306	1,200					
.45	7,731	1,656	672					
.50	3,749	937	416					
.55	2,037	577						
.60	1,199	377						

TABLE A.4: RELIABILITY GROWTH TEST TIME (θ_p = 100 HOURS)

PREDICTED MTBF (θ_p) = 100 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 50 HOURS

	Starting Point % of θ_p							
α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
.20	52,428,800	1,638,400	215,756	51,200	16,777	6,742	3,119	1,599
.25	2,531,250	158,203	31,250	9,887	4,050	1,953	1,054	617
.30	330,671	32,806	8,491	3,254	1,547	842	503	
.35	76,149	10,509	3,299	1,450	766			
.40	24,941	4,409	1,599	779				
.45	10,308	2,209	897					
.50	4,999	1,249	555					
.55	2,716	770						
.60	1,599	503						

TABLE A.5: RELIABILITY GROWTH TEST TIME (θ_p = 150 HOURS)

PREDICTED MTBF (θ_p) = 150 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 75 HOURS

	Starting Point % of θ_p							
α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
.20	78,643,200	2,457,600	323,634	76,800	25,165	10,113	4,679	2,400
.25	3,796,875	237,304	46,875	14,831	6.075	2,929	1,581	926
.30	496,007	49,210	12,737	4,882	2,320	1,263	755	
.35	114,223	15,764	4,949	2,175	1,150			
.40	37,412	6,613	2,400	1,169				
.45	15,462	3,313	1,345					
.50	7,499	1,874	833					
.55	4,074	1,155						
.60	2,399	755						

TABLE A.6: RELIABILITY GROWTH TEST TIME (θ_p = 200 HOURS)

PREDICTED MTBF (θ_p) = 200 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 100 HOURS

α Growth Rate	Starting Point % of θ_p 5%	10%	15%	20%	25%	30%	35%	40%
.20	104,857,599	3,276,799	431,512	102,399	33,554	13,484	6,238	3,199
.25	5,062,500	316,406	62,500	19,775	8,100	3,906	2,108	1,235
.30	661,343	65,613	16,983	6,509	3,094	1,684	1,007	
.35	152,298	21,018	6,599	2,900	1,533			
.40	49,883	8,818	3,199	1,558				
.45	20,616	4,418	1,794					
.50	9,999	2,499	1,111					
.55	5,432	1,540						
.60	3,199	1,007						

TABLE A.7: RELIABILITY GROWTH TEST TIME (θ_p = 250 HOURS)

PREDICTED MTBF (θ_p) = 250 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 125 HOURS

α Growth Rate	Starting Point % of θ_p 5%	10%	15%	20%	25%	30%	35%	40%
.20	131,072,000	4,096,000	539,390	128,000	41,943	16,855	7,798	4,000
.25	6,328,125	395,507	78,125	24,719	10,125	4,882	2,635	1,544
.30	826,678	82,016	21,229	8,137	3,867	2,106	1,259	
.35	190,372	26,273	8,249	3,626	1,916			
.40	62,353	11,022	4,000	1,948				
.45	25,770	5,522	2,243					
.50	12,499	3,124	1,388					
.55	6,790	1,925						
.60	3,999	1,259						

TABLE A.8: RELIABILITY GROWTH TEST TIME (θ_p = 300 HOURS)

PREDICTED MTBF (θ_p) = 300 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 150 HOURS

	Starting Point % of θ_p							
α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
.20	157,286,400	4,915,200	647,269	153,600	50,331	20,227	9,358	4,799
.25	7,593,750	474,609	93,750	29,663	12,150	5,859	3,162	1,853
.30	992,014	98,420	25,474	9,764	4,641	2,527	1,511	
.35	228,447	31,528	9,898	4,351	2,300			
.40	74,824	13,227	4,799	2,338				
.45	30,924	6,627	2,691					
.50	14,999	3,749	1,666					
.55	8,148	2,310						
.60	4,799	1,511						

TABLE A.9: RELIABILITY GROWTH TEST TIME (θ_p = 350 HOURS)

PREDICTED MTBF (θ_p) = 350 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 175 HOURS

α Growth Rate	Starting Point % of θ_p 5%	10%	15%	20%	25%	30%	35%	40%
.20	183,500,800	5,734,400	755,147	179,200	58,720	23,598	10,918	5,599
.25	8,859,375	553,710	109,375	34,606	14,175	6,835	3,689	2,162
.30	1,157,350	114,823	29,720	11,391	5,414	2,948	1,763	
.35	266,522	36,783	11,549	5,076	2,683			
.40	87,295	15,431	5,599	2,727				
.45	36,078	7,731	3,140					
.50	17,499	4,374	1,944					
.55	9,506	2,695						
.60	5,599	1,763						

TABLE A.10: RELIABILITY GROWTH TEST TIME (θ_p = 400 HOURS)

PREDICTED MTBF (θ_p) = 400 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 200 HOURS

α Growth Rate	Starting Point % of θ_p 5%	10%	15%	20%	25%	30%	35%	40%
.20	209,715,200	6,553,600	863,025	204,800	67.108	26;969	12,477	6,399
.25	10,125,000	632,812	125,000	39,550	16,200	7,812	4,216	2,471
.30	1,322,686	131,227	33,966	13,019	6,188	3,369	2,015	
.35	304,596	42,037	13,198	5,801	3,066			
.40	99,766	17,636	6,399	3,117				
.45	41,232	8,836	3,588					
.50	19,999	4,999	2,222					
.55	10,864	3,080						
.60	6,399	2,015						

TABLE A.11: RELIABILITY GROWTH TEST TIME (θ_p = 500 HOURS)

PREDICTED MTBF (θ_p) = 500 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 250 HOURS

	Starting Point % of θ_p							
α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
.20	262,144,000	8,192,000	1,078,781	256,000	83,886	33,711	15,597	8,000
.25	12,656,250	791,015	156,250	49,438	20,250	9,765	5,271	3,089
.30	1,653,357	164,033	42,458	16,274	7,735	4,212	2,519	
.35	380,745	52,547	16,498	7,252	3,833			
.40	124,707	22,045	7,999	3,897				
.45	51,540	11,045	4,486					
.50	24,999	6,249	2,777					
.55	13,580	3,851						
.60	7,999	2,519						

TABLE A.12: RELIABILITY GROWTH TEST TIME (θ_p = 600 HOURS)

PREDICTED MTBF (θ_p) = 600 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 300 HOURS

α Growth Rate	Starting Point % of θ_p: 5%	10%	15%	20%	25%	30%	35%	40%
.20	314,572,800	9,830,400	1,294,538	307,200	100,663	40,454	18,716	9,600
.25	15,187,500	949,218	187,500	59,326	24,300	11,718	6,325	3,707
.30	1,984,029	196,840	50,949	19,529	9,282	5,054	3,023	
.35	456,895	63,056	19,797	8,702	4,600			
.40	149,649	26,454	9,599	4,676				
.45	61,848	13,254	5,383					
.50	29,999	7,499	3,333					
.55	16,296	4,621						
.60	9,599	3,023						

TABLE A.13: RELIABILITY GROWTH TEST TIME (θ_p = 800 HOURS)

PREDICTED MTBF (θ_p) = 800 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 400 HOURS

	Starting Point % of θ_p							
α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
.20	419,430,400	13,107,200	1,726,051	409,600	134,217	53,939	24,955	12,800
.25	20,250,000	1,265,625	250,000	79,101	32,400	15,625	8,433	4,943
.30	2,645,372	262,454	67,933	26,038	12,376	6,739	4,031	
.35	609,193	84,075	26,396	11,603	6,133			
.40	199,532	35,272	12,799	6,235				
.45	82,464	17,673	7,177					
.50	39,999	9,999	4,444					
.55	21,729	6,161						
.60	12,799	4,031						

TABLE A.14: RELIABILITY GROWTH TEST TIME (θ_p = 1000 HOURS)

PREDICTED MTBF (θ_p) = 1000 HOURS

INITIAL CONDITIONING PERIOD .5 (θ_p) = 500 HOURS

	Starting Point % of θ_p							
α Growth Rate	5%	10%	15%	20%	25%	30%	35%	40%
.20	524,288,001	16,384,000	2,157,563	512,000	167,772	67,423	31,194	16,000
.25	25,312,500	1,582,031	84,916	98,876	40,500	19,531	10,542	6,179
.30	3,306,715	328,067	312,500	32,548	7,666	8,424	5,039	
.35	761,491	105,094	15,999	14,504				
.40	249,415	44,090	8,972	7,794				
.45	103,080	22,091	5,555					
.50	49,999	12,499						
.55	27,161	7,702						
.60	15,999	5,039						

APPENDIX B

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BIBLIOGRAPHY

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