AD-A213 600

AL-TR-89-013 AD:

(2)

Final Report
for the Period
April 1984 to
September 1989

Current Launch Vehicle Practive and Data Base Assessment

Volume I: Executive Summary and Report Body

June 1989

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prepared for the **Astronautics Laboratory (AFSC)**

Air Force Space Technology Center
Space Systems Division
Air Force Systems Command
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Foreword

This document represents the final report for Task 8 Propulsion System Reliability Development, of the Research Applications SETA program. The work was performed over the period 30 June 88 to 24 February 1989.

The Air Force Project Officer for this task was Mr. David Perkins, AFAL/VSAB. The SAIC Program Managers were Dr. Robert Long and Mr. William Haynes. The task leader at SAIC was Mr. Joseph R. Fragola. The other principal technical contributors at SAIC were Lewie Booth and Dr. Yu Shen. We appreciate the assistance of Larry Quinn of AFAL in administering this task and Ms. Zun-Yan Wang and Ms. Carol Heymsfield of SAIC in the preparation of this report.

This report has been reviewed and is approved for distribution in accordance with the distribution statement on the cover and on the DD Form 1473.

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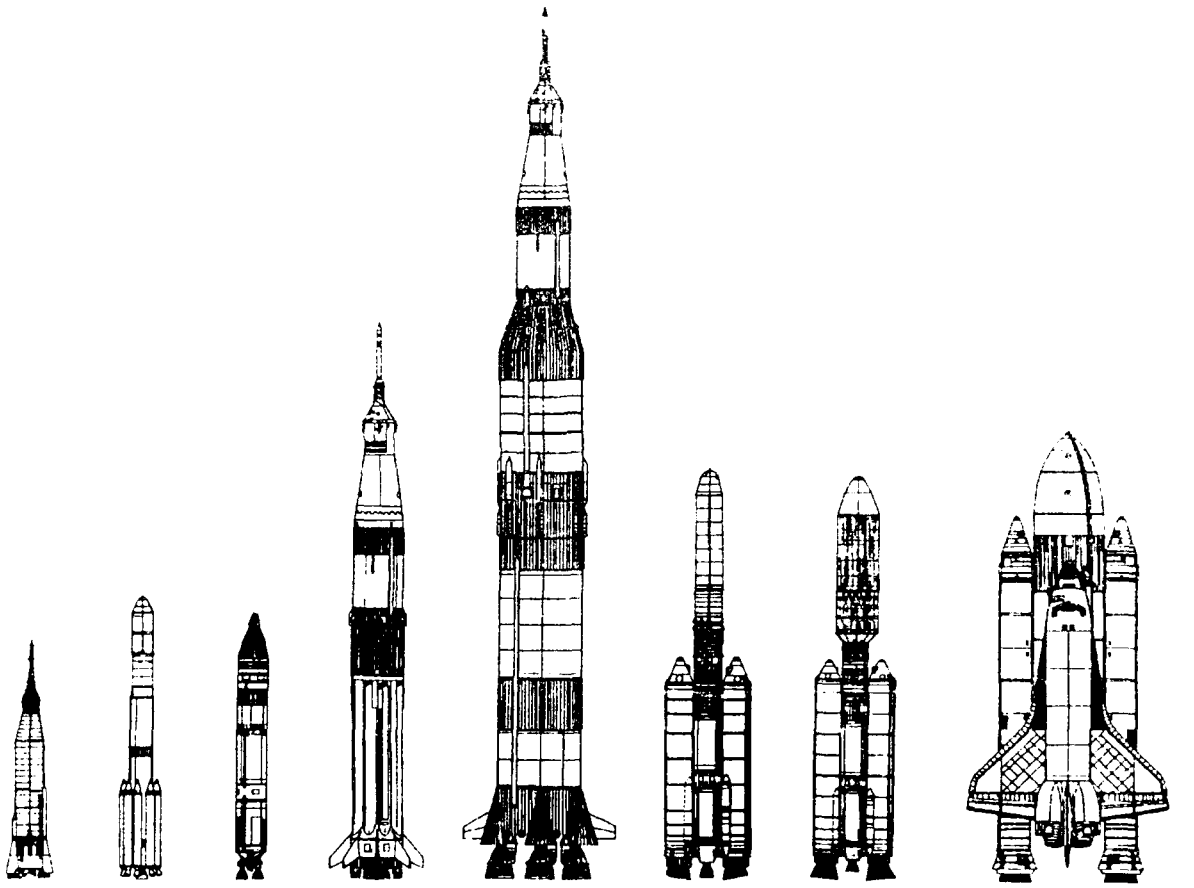
Astronautics Laboratory (AFSC)
Edwards Air Force Base, CA

TECHNICAL REPORT (FINAL) / TASK 8

CURRENT LAUNCH VEHICLE RELIABILITY PRACTICE AND DATA BASE ASSESSMENT

VOLUME I: EXECUTIVE SUMMARY AND REPORT BODY



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Report No. AL-TR-89-013

Contract No. F04611-88-C0014

CDRL 3003

Science Applications International Corporation

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public Release; Distribution is Unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S) AL-TP-89-013

6a NAME OF PERFORMING ORGANIZATION Science Applications International Corporation	6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION Astronautics Laboratory (AFSC)
6c ADDRESS (City, State, and ZIP Code) 260 Madison Avenue, Suite 1100 New York NY 10173		7b ADDRESS (City, State, and ZIP Code) AL/LSVF Edwards AFB CA 93523-5000
8a NAME OF FUNDING/SPONSORING ORGANIZATION	8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F04611-88-C-0014
8c ADDRESS (City, State, and ZIP Code)		10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO
62302F	3058	00	2S

11 TITLE (Include Security Classification)
CURRENT LAUNCH VEHICLE PRACTICE AND DATA BASE ASSESSMENT
Volume 1: Executive Summary and Report Body

12 PERSONAL AUTHOR(S)
Fragola, Joseph R.; Booth, Lewie; and Shen, Yu

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final	FROM 88/04 TO 89/09	89/06	202

16 SUPPLEMENTARY NOTATION
Volume 2 of this report contains Appendix B.

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
19	07		reliability, launch vehicle, propulsion development, engine out, failure correlation, variability control, reusability, risk management, reliability performance indicators (PTO), reliability growth analysis.
21	08		

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This report describes the effort to identify liquid and solid propulsion design parameters, development methodologies, and production/operations techniques related to the improvement of propulsion reliability for future launch vehicles. Six key recommendations are made. There is a section on current practice and data base assessment. This is followed by a section on reliability enhancing methods. Finally, there is a section on quantification and prioritization of methodologies. Volume 1 contains Appendix A which includes an investigation of historical failure correlation factors using the SSME test and flight history as an example, a quick calculation of failure correlation factor versus engine out capability, a reliability analysis of current US launch vehicles, and a hitory of US launch vehicles. Volume 2 contains only Appendix B which is a compendium of trip reports accomplished during the performance of this study.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code)	22c OFFICE SYMBOL
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DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE

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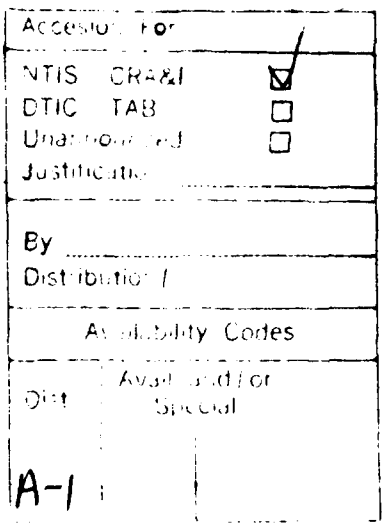


EXECUTIVE SUMMARY

The Air Force currently has several ongoing propulsion technology development programs including the significant joint development with NASA of the Advanced Launch System (ALS). Previous investigation by Air Force Astronautics Laboratory and others has indicated that launch vehicle reliability is perhaps the key driving parameter for development program success.

Given the key role played by reliability, AFAL requested that SAIC undertake a study of propulsion system reliability development. The objective of this study was to identify, and where possible quantify and prioritize, propulsion techniques related to launch vehicle reliability.

The study was to include visits to an engine manufacturer, a launch vehicle systems contractor, and NASA sites to develop information to supplement literature searches and independent research to provide a base of information sufficient to allow SAIC to:

- Assess Current Practice and the Resulting Historical Reliability Data Base
- Investigate Potential Reliability Enhancing Methodologies and to
- Quantify and Prioritize the Methodologies

The Study results indicated that current launch vehicle reliability levels are in the order of 90 - 95%. This is substantially below future Air Force system requirements of 99 - 99.9%. Investigation into how these historical levels of reliability could be significantly improved resulted in the development of the following six key recommendations for the consideration of the Air Force and AFAL.

1. Failure correlation factors are key factors of interest to design decision makers. Specific studies, which address what factors have been achieved in the past and what design trades have been made to ensure the low factors quoted by contractors are achievable, appear to be lacking. The Air Force should consider requiring that such studies be undertaken.

2. Variability Control, especially of residual variability, may be the key barrier to high launch reliability achievement. The Air Force should consider requiring that some specific program for variability control be included in future propulsion technology development programs.

3. Reusability has been shown to have indirect, potentially negative, impacts on high reliability achievement. The trade-offs which exist between high reliability and reusability should be clearly identified and included in propulsion programmatic decision making.

4. Risk Management has been shown to have potential benefits in maintaining the high reliability of programs in other industries. The advisability of risk management being included as an integral part of propulsion system development should be considered.

5. Reliability Performance Indicators should be developed whose trend trajectories lead, or presage, the occurrence of reliability problems so that program management action can be taken prior to the development of reliability problems.

6. Reliability Growth Forecasting is important during the development of systems with high reliability requirements. This is especially true when program economics prohibit extensive development test flights. Reliability growth approaches should be investigated and applied as appropriate to propulsion system development programs.

OBJECTIVE

The objective of this effort was to identify, and where possible quantify and prioritize, liquid and solid propulsion design parameters, development methodologies, and production/operations techniques related to launch vehicle reliability.

KEY RECOMMENDATIONS

The following areas have been identified as having significant reliability impact. These areas each warrant further in-depth study if the high reliability goals of the Air Force advanced launch vehicle programs are to be achieved in an operational system.

Failure Correlation*

The percentage of failures which are likely to impact more than one engine in a multi-engine design is a critical design import. This percentage, or "failure correlation factor," must be well below 20% for reliability oriented design approaches such as engine out capability to be effective. The lower this percentage the more effective is this hueristically pleasing design option. Not surprisingly, designers of major new engine design characteristics quote extremely low factors (as low as 1%). Is a reliability of as 1 out of 100 do not seem consistent with other design parameters specified such as high chamber pressures) and are considerably lower than factors achieved on recent engine designs (e.g. 17% for the SSME main engine test program). Finally, there did not appear to be any significant consideration given to how these low factors would be achieved in practice.

Recommendation 1 - Failure correlation factors are key reliability parameters to Air Force launch vehicle design decision makers. Specific studies such as parameter design studies which address what factors have been achieved in the past and what design trades have been made to ensure the low factors quoted will be evident in the reliability designs appear to be lacking. It is recommended that these investigations be made prior to the selection of any design alternative.

Variability Control

The currently achieved launch vehicle reliability has been shown by this investigation to be below 0.95. However, the investigation uncovered examples of reliabilities in other somewhat similar systems, such as tactical missile systems, which routinely achieve 0.99 and some which approach 0.999. These systems and operational reliabilities currently meet or exceed the reliability requirements for the Air Force advanced launch system have achieved these high reliability levels through the use of intensive variability control programs. While it would be inappropriate to make any direct correlation between tactical missiles and launch vehicles, it is also clear from a review of the failure data of mature launch systems that the path to significantly higher reliabilities may be the residual variability [illegible] manufacturing process. A cursory review of other somewhat [illegible] and gas turbines and recent Air Force variability reduction studies performed as part of the [illegible] program, provide further support for this argument.

Recommendation 2 - Residual variability may be the key barrier to high launch vehicle reliability movement. For this reason, it is recommended that investigations be made into the effectiveness of the variability control programs such as Taguchi methods or alternatives. These investigations should

* definition cited here is broader than that used traditionally by propulsion system designers. See Appendix [illegible] discussion of the difference

be directed at determining the applicability of the methods to the launch vehicle production process. It is further recommended that some specific program for variability control be included throughout all phases of the advanced launch system program.

3. Reusability

Reusability is, on the surface, a design goal of significant program benefit. However, the benefits of reusability are significantly compromised if the reliability of an engine is adversely affected by the requirement. Besides the direct costs involved in developing a reusable design, there also appears to be significant indirect costs which are required to maintain reliability in a reusable design. For example, reusability by its very nature tends to decrease the production run. When production runs are decreased, investments in automated production equipment become less economical and the production process therefore tends to become more prototypical. Prototypical production, especially of complex equipment, increases the problems associated with variability control and therefore substantial postproduction testing may be required to ensure high reliabilities. A good example of such an indirect impact on reusability was seen at the Rocketdyne SSME production facility in Canoga Park, California.

Recommendation 3 - Reusability has been shown to have indirect and potentially negative impacts on the achievement of high reliabilities at reasonable cost. The indirect impacts of reusability on reliability and cost through such mechanisms as variability control problems should be thoroughly investigated and the results of this investigation included in the programmatic decision making related to reusability.

4. Risk Management

Achievement of high operational reliabilities in such areas as nuclear power plant safety systems have been significantly supported by a continually active program that attempts to identify the risks to reliable operation and to address them according to their importance. Such a risk management program has been investigated and recommended by NASA SRM & QA for future projects, but it is not clear whether a risk management program is planned for the acquisition of advanced launch systems.

Recommendation 4 - The Air Force should investigate the advisability of incorporating a risk management program as an integral part of any launch system program.

5. Reliability Performance Indicators and Trending

For high reliability programs it is important to identify, early on, symptoms of the process which presage deterioration in performance. This has been done in the financial community, in the commercial aircraft community and in the nuclear power safety community by the development of a set of "leading" performance indicators and developing performance trends based upon the indicator trajectories through time. If such a set of indicators could be developed and trended for advanced propulsion system development programs, the indicator trajectories might provide early warning of problems arising during development and operation. This early warning could provide the time required to institute corrective action before actual program reliability performance is affected.

Recommendation 5 - The Air Force should develop as part of advanced propulsion system development programs a set of potential indicators of programmatic reliability performance. This indicator set should be based originally on historical information, but later updated and validated as advanced propulsion system development programs specific information becomes available.

Reliability Growth Analysis

In all developmental systems a certain degree of reliability growth is to be expected. However, program managers need to know the pace of the expected growth so that they can determine if the program is likely to meet the operational reliability goals within developmental time constraints. An understanding of the growth process is therefore essential to the determination of the proper role to be played by history in the forecasting of future system reliability. If an historical failure has been analyzed and its cause determined and suitable corrective action is implemented to prevent its recurrence, it is recognized that it would have its probability of occurring again diminished when it is utilized for predicting future performance. But by how much? The determination of how much each failure should be counted is important in order to establish the proper "calibration" for the reliability growth characteristic to be used to determine how well reliability development is proceeding. Several approaches have been developed to address the issue of growth. Among those developed are the early works of Duane at GE, that of David Lloyd of TRW, and that developed by Dr. Yu Shen of SAIC as part of this study. In addition, Bayesian approaches may show promise for improved growth forecasting.

Recommendation 6 - Reliability growth forecasting is important during the development of systems with high reliability requirements such as ALS. Accurate growth forecasts allow program managers to know early on if reliability requirements are likely to be met. This is especially important when program economics prohibit extensive development test flights as is [illegible] Several methods currently exist to allow for forecasts to be generated; however, further development is required to assure that reasonable growth forecast is developed for advanced propulsion system development programs. It is therefore recommended that the concept of reliability growth be further developed as it applies to advanced propulsion system development programs.

BACKGROUND

The AFAL currently has several ongoing propulsion technology development programs that are aimed at launch vehicle applications. A fundamental goal for any new launch vehicle is low cost. One element of cost that is receiving increasing levels of national attention is the cost of unreliability. This issue was highlighted by the recent series of catastrophic launch failures. These failures included two Titans, a Delta, an Atlas, and a Shuttle. All were lost in a period of 2 years. Historical data bases indicate that in general, launch vehicle reliability against catastrophic failure is approximately 0.92. This value is dominated by propulsion system failures and is unacceptably low for any future launch vehicles.

The traditional methodologies for the development of propulsion systems have involved the use of traditional manufacturing methodologies coupled with traditional design methodologies that assume some measure of safety factor in the design process. The traditional issue that was fundamental to launch vehicle applications was that the vehicle payload capability was highly sensitive to the mass properties. Hence, margins were decreased to the maximum extent possible during the design phase. There remains a distinct development transition to flight weight hardware in most aerospace developments. Reliability was only subsequently evaluated as a secondary concern. Point estimate techniques for estimating application reliability were employed rather than rigorous statistical testing. Manufacturing process control was instituted after development in order to qualify vehicles for manned flight or higher confidence of success following catastrophic failures. It is apparent that in order to achieve higher levels of reliability in propulsion systems, and hence in the launch vehicles, alternative development approaches need to be explored.

There have been several suggested approaches to achieving higher reliability. Design for reliability philosophies include redundancy techniques and higher design margins. Process control advocates point to human error contributions to failure and article to article variations, proposing that more automated production and higher levels of quality control and non-destructive testing will achieve desired reliability. It is fundamentally assumed that design engineers should be more aware of ultimate reliability and producibility issues as they pursue designs. Inevitably, the greatest stumbling block to achieving higher reliability goals is limited funding available for development and qualification programs and the historical reliability approach perspective, which consigns probablistic techniques to only the top most levels of program analysis and evaluation. While history has shown it to be true that in the ultimate design reliability not only costs nothing but will produce significant cost benefits, this is not true in the near term design development phase. Here reliability tasks increase, at least initially, the cost and they do so in an environment where funding is scarce and where reliability needs must compete with other more visible programmatic needs (such as performance upgrades). In such an environment of new program development within strict resource constraints reliability resources can be eroded in favor of programmatic needs considered more immediate unless investments in reliability are "fenced in" early and not confused with management reserves.

1.0 (TASK 1) CURRENT PRACTICE AND DATA BASE ASSESSMENT

1 Current Practice

1.1 1 Current Practice Background

Corporations involved in the design, manufacture, test and operation of propulsion systems generally have infrastructures that result from specific government agency requirements. Those controls which exist within any given infrastructure that have an impact on reliability also exist largely due to government requirements. At the highest level these controls consist primarily of Failure Modes and Effects Analysis (FMEAs) and Problem (or Failure) Reporting and Corrective Action Systems (PRACAs/FRACAs). Although these controls have had a positive impact on reliability the impact, because it is often somewhat indirect, is not readily measurable. Thus, it is difficult to ascertain quantitatively that spending a given amount of resources on FMEAs or PRACAs will in fact pay off. In addition, there are, at least in the initial phases of program development, few financial incentives for "better" reliability even though the costs of failure dictate substantial down stream benefits from investing in reliability. Furthermore, even if there were reliability incentives, it would be difficult for manufacturers to know where to spend their scarce resources to obtain the best reliability returns. This is primarily due to inconsistent or non-existent reliability data bases.

The problem is further compounded by the constraint of sample size on the measurement of achieved reliability in highly reliable systems. In other words, to demonstrate that a given reliability has been achieved at a reasonable confidence level, a large number of systems must be tested. It is obvious that in most cases this approach is not practical from a cost/schedule standpoint. This is not to say that presently attained reliabilities are inadequate to satisfy the previously and currently existing requirements. In fact, the attained reliability of any propulsion system is generally based on relatively small sample sizes and the underlying assumption that each propulsion system firing is independent of all others. This simply means that while we may not know precisely (from a reliability standpoint) where we are now, we do know where we are well enough to understand that we are far from the high reliability goals desired of future manned propulsion systems.

However, the relevant question is not where we are now, but how can an improvement in reliability be achieved? Because of the relative nature of this question, it may turn out that accurately predicting reliability improvements is easier than measuring attained reliability.

1.1.2 Major Activities Constituting Infrastructures

Due to funding limitations it was not possible to revisit manufacturers in order to benefit from the total information obtained from the initial visit. The revisits would have concentrated not just on design, manufacture and test, but on transportation and storage as well.

The second visits would be used to form a clearer picture of the detailed approaches taken by liquid and solid manufacturers.

However, based on the initial visits taken, six major activities have been identified in the life cycle of a propulsion system: design, manufacturing, test, transportation, storage, and operation. The infrastructure that has evolved has centered on design, manufacturing and test. Activities related to transportation, storage and operation tend to be restricted to problem correction rather than a planned strategy to anticipate problems.

Design - The Design activity primarily involves the creation of a system that meets the specified requirements of a contract. Typically a design is generated and goes through a design review process usually consisting of preliminary, critical, and final design reviews. The review of reliability requirement achievement during these reviews is currently based (because of the lack of a detailed historical data base for propulsion systems), upon the manufacturer's engineering judgement or on qualitative review of design specific failure modes whose elimination or mitigation is again based upon manufacturer's recommendations which are judgementally based and therefore difficult to objectively assess as to their probability of being successfully achieved in the implemented design.

Manufacturing - Once the transition is made from design to manufacturing, the activities focus on how to best minimize the manpower and materials required to produce the system while satisfying quality control constraints. Manufacturing procedures and flow diagrams are the primary mechanisms for this activity. Quality Control plans mutually prescribed by clients, primes and major subcontractors are also imposed.

Test - Testing activities primarily involve qualification and feasibility testing. They are primarily intended to test the functional adequacy or the potential of a given design implementation. In this way they can clearly indicate that a propulsion system performance specification such as thrust to weight ratio, a specific impulse has not been achieved, but they only indirectly indicate lack of reliability achievement. This is especially true of new designs. These tests do not usually involve enough test time for numbers of systems to produce a statistically significant indication of system reliability capability. When failures do occur, they may have been induced by consciously over extending the design limits. In fact, the tests may be conducted to determine design weaknesses through test failure so that the failures can be examined and corrective action taken to improve the design. These tests therefore may not always provide useful information concerning the assessment of system reliability capability although they certainly do produce information useful to reliability improvement.

Transportation - Transportation activities can have obvious negative impacts on reliability due to the influence of shock, vibration, humidity, and thermal transients. These and other environmental factors can act independently or synergistically to decrease reliability. Controls are in place dictating packaging and handling requirements primarily through specifications. Unfortunately, not all problem (or failure) reporting and corrective action systems feedback problems that occur because of inadequate package and handling requirements. Such a closed loop system would provide a mechanism for rewriting of specifications.

Storage - Like transportation, storage activities can also have a negative impact on reliability. This is true not only from the standpoint of environmental conditions, but storage time as well. When rocket booster dependent programs experience a delay, then all limited life items become factors affecting reliability.

Operation - The operating time for booster rockets is a matter of a few hundred seconds with the proviso that some of the rocket engines or solid booster casings are reusable. Achieved reliability is measured classically by using operating data and applying statistical distributions such as the binomial. As with the testing activity, when failures occur, the devices are reexamined and corrective action is initiated followed by retest. Since the corrective action taken obviously is intended to eliminate failure mechanisms and thereby improve reliability, it is difficult, if not impossible, to use a classical approach to measure reliability achievement in developmental systems with high reliability goals and limited operating histories.

1.1.2 Current Infrastructure Activities Affecting Reliability

Although there are some specific differences between prime contractors and major subcontractors, in general the controls affecting reliability which are the responsibility of the reliability discipline are Reliability Predictions, Failure Modes and Effect Analysis (FMEAs) and Failure Reporting and Corrective Action systems (FRACAs). The quality control discipline has a direct impact on reliability but is not normally a part of the reliability discipline. "Lessons Learned" is often a semi-formal approach to reliability improvement and when used, it is as likely to be found in the design group as the reliability group.

Only the FRACA system provides a closed loop means of correcting problems. In their present form, PRACAs are not structured to quantify reliability or to become a proactive part of measured (quantified) reliability enhancement.

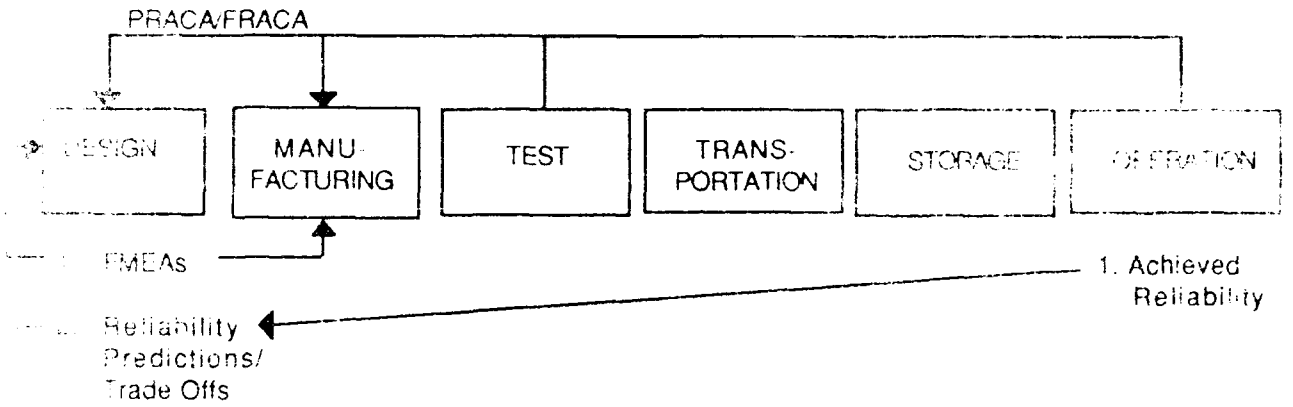


Figure 1. Existing infrastructure controls intended to enhance reliability.

Figure 1 illustrates the six infrastructure activities as they relate to reliability activities. The most commonly used reliability activities are:

- FMEAs
- Reliability Predictions/Trade-offs
- PRACA/FRACA Systems
- Measurement of Achieved Reliability

What FMEAs are and how they are used is described in the following section under "Reliability Engineering Analysis". Reliability Predictions/Trade-offs are also discussed in the same section under the heading of "Quantitative Reliability Engineering Design Tools" along with other tools that are available to reliability engineers. Figure 2 contains a comprehensive list of reliability Tools and Techniques. PRACA/FRACA Systems are discussed in detail in Section 1.1.3.2.

Measurement of Achieved Reliability due to its complexity is treated separately in Section 2.2, "Historical Data Analysis (Reliability Growth)" and in Appendix A.3, "Reliability Analysis of Current US Launch Vehicles".

The purpose of Figure 1 is to illustrate the limited use of presently available reliability engineering techniques and tools as well as the limited use of information from activities such as transportation and storage.

It is clear, based on the information gathered to date, that no single company has utilized all the tools and techniques available to reliability engineers on any given project nor has the information from transportation and storage been fully utilized. The fact that all the resources of reliability technology have not been utilized is not a result of negligence on the part of manufacturers. Often they may not be provided with specific requirements to address all these issues by their government customers and are not normally funded to conduct these types of analyses.

Although not directly related to launch vehicle reliability, a recent example of how the storage activity can affect reliability is given by the recently launched TDRSS spacecraft. After the Challenger accident the spacecraft spent an extra 2 1/2 years on the ground. Deterioration was suspected in the bolt cutter ordinance and for this reason a reliability study was conducted by the contractor. The study resulted in the determination that the bolt cutters required replacement. The successful launch of TDRSS is now a matter of record. Total credit for this success cannot be taken by the individuals involved in this reliability analysis, but a significant contribution was made to this success as a result of diligent ordinance and reliability engineers taking the initiative and going beyond typical practice. The only way to make such protection "routine" is to expand current reliability practice so as to create an infrastructure such as the one depicted on Figure 8 in Section 2.3.

Reliability Engineering Analysis - There are a number of tasks that are specifically related to reliability as shown in Figure 2. It is not the purpose of this report to fully describe each technique and design tool but to highlight those most commonly used in the rocket industry. The two most commonly used methods for reliability analysis are:

- Failure Modes and Effects Analysis (FMEA) or Failure Modes, Effects and Criticality Analysis (FMECA).

- Quantitative Reliability Engineering Design Tools such as predictions or Trade-offs.

Failure Modes and Effects Analysis is a "bottom up" method intended to identify, classify and document failure modes and their effects as well as possible corrective actions or compensating or mitigating provisions.

The purpose of an FMEA is to:

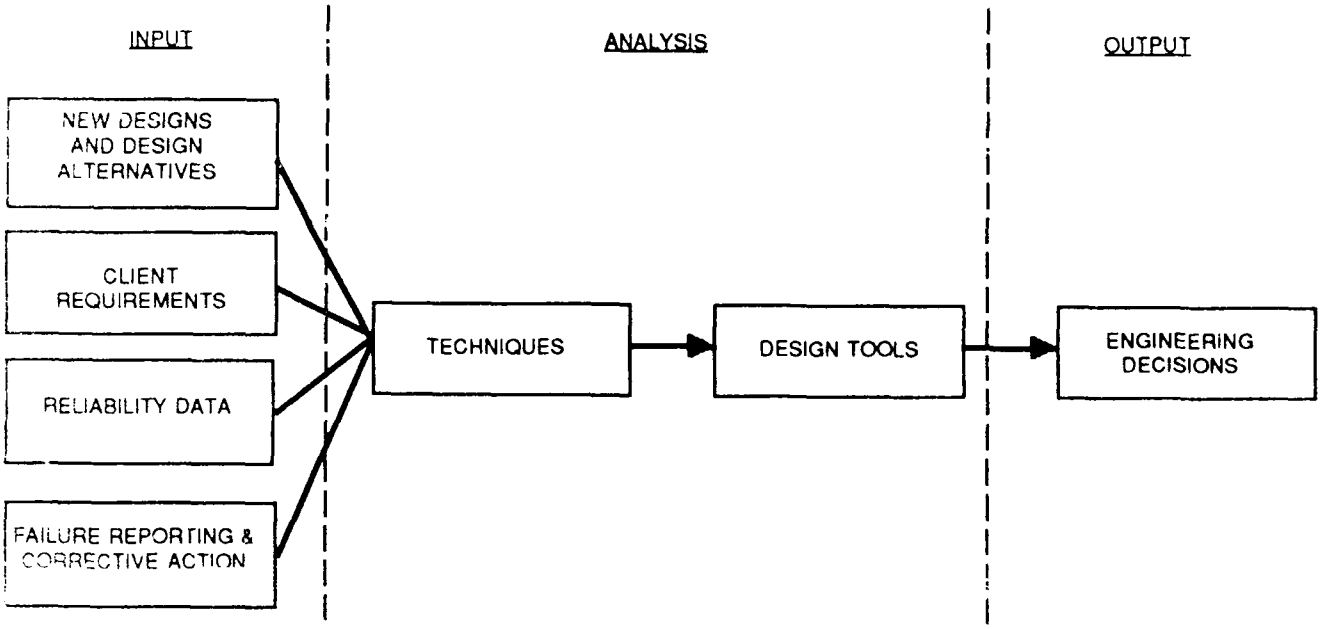
1. Assist in selecting design alternatives with high reliability and high safety potential during early design phase.

2. Ensure that all conceivable failure modes and their effects on operational success of the system have been considered.

3. List potential failures and identify the magnitude of their effects.

4. Develop early criteria for test planning and the design of the test and checkout systems.

5. Provide a basis for quantitative reliability and availability analyses.



TECHNIQUES

1. QUANTITATIVE ANALYSIS

   - FORMATS-RELIABILITY GRAPHS RELIABILITY BLOCK DIAGRAMS, FAULT TREE DIAGRAMS, MARKOV TRANSITION DIAGRAMS, DECISION TREES, TRUTH TABLES, DIGRAPHS

   - ANALYTICAL METHODS-BOOLEAN ALGEBRA, MARKOV MATRIX ALGEBRA, EVENT SPACE ANALYSIS, MINIMUM CUT SETS, TIE SETS, MONTE CARLO SIMULATION, PATH TRACING, DECOMPOSITION

2. QUALITATIVE ANALYSIS

   - FORMATS-FMEA'S, CRITICAL ITEMS LIST, FAULT TREE DIAGRAMS

   - ANALYTICAL METHODS-FAILURE ANALYSIS, ROOT CAUSE, COMMON MODE, CRITICALITY RANKING

DESIGN TOOLS

1. COMPARATIVE ANALYSIS
   - ENGR. TRADE OFF'S
   - SENSITIVITY
   - OPTIMIZATION STUDIES
2. ABSOLUTE ANALYSIS
   - APPORTIONMENT
   - PREDICTION/MEASUREMENT OF ACHIEVED RELIABILITY

ENGINEERING DECISIONS

1. RECOMMEND DESIGN ALTERNATIVES
2. MAINTANINABILITY RECOMMENDATIONS
3. PREVENTIVE MAINTENANCE PROGRAMS
4. SPARE PARTS PROVISIONS
5. RECOMMENDED TEST INTERVALS

Figure 2. Reliability engineering tasks typically used in design

6. Provide historical documentation for future reference to and in analysis of field failures and consideration of design changes.

7. Provide input data for tradeoff studies.

8. Provide a basis for establishing corrective action priorities.

9. Assist in the objective evaluation of design requirements related to redundancy, failure detection systems, fail-safe characteristics and automatic and manual override.

When considering reliability analysis of a design, one usually thinks of all the analytical steps leading to an estimate of the reliability of a given item. A complete analysis requires comprehensive input data that include material properties, design details and component failure rates; however, it is not necessary to wait until all of these are known before much can be determined about the reliability of the design.

Failure Mode Effects and Criticality Analysis (FMECA), is essentially similar to a Failure Mode and Effects Analysis but in this case the criticality of the failure is analyzed in greater detail (and may in some instances be quantitatively evaluated) and assurances and controls are described for limiting the likelihood of such failure. The four fundamental facets of such an approach are (1) Failure Identification; (2) Potential Effects of the Failure; (3) Existing or Projected Compensation and/or Control; and (4) Summary of Findings.

The most hazardous pitfall is the potential of mistaking form for substance. If the project becomes simply a matter of filling out the FMEA forms instead of conducting a proper analysis, the exercise will be ineffective. For this reason, it might be better for the analyst not to restrict himself to any prepared formalism. Another point: if the system is at all complex, it is risky for a single analyst to imagine that he alone can conduct a correct and comprehensive survey of all system failures and their effects on the system. When applied to complicated systems, these techniques call for a well coordinated team approach.

Comparative Analysis and Absolute Analysis are the two general types of quantitative reliability engineering design tools.

Comparative Analysis - When alternative designs for achieving given (or desired) levels of reliability are under consideration, characteristics for each design are expressed quantitatively as a means of comparing the relative reliability of each design alternative. For this particular type of analysis, failure and repair data need not be exact since the purpose is to compare alternatives rather than to obtain estimates of absolute values.

There are three types of comparative analysis commonly undertaken:

- Trade-offs
- Sensitivity Studies
- Optimization Studies

Trade-offs, among various design alternatives, are conducted so that the alternatives with the best Benefit to Cost Ratio may be selected. The Benefit/Cost Ration is determined by incorporating the effects of reliability factors, installation and operating costs, degraded modes of operation, etc. Trade-offs involve achieving the proper balance among reliability, performance, and cost.

Sensitivity analysis involves the variation of input parameters to mathematical models in order to assess the relative effect of component characteristics and data accuracy on a given system's reliability. The results are used to identify areas where improvement in design will have the greatest potential impact on reliability.

Optimization studies carry the concept of sensitivity analysis one step further by varying the input parameters until a set which appears best from a reliability perspective within the system constraints is obtained.

Absolute Analysis involves the use of numerical results of an analysis in an absolute sense (Design A has a reliability of 0.90"). It results in a "stand alone" number, not a "relative comparison" type number.

The two types of absolute analysis are:

- Apportionment
- Prediction

Apportionment is used when a specific level of reliability is prescribed. For instance, a client may prescribe a certain percent increase in the reliability of an existing propulsion system. The procedure (greatly simplified) is:

1. Apportion the reliability of the system to each subsystem based on past performance.

2. Identify those subsystems which have the least desirable reliability performance. Include all factors which affect this performance such as random failures, common cause failures, distribution of downtimes, human reliability, etc.

3. Determine what corrective measures may be taken to increase the reliability of each subsystem.

Prediction requires utilizing mathematical models, input data, and probability theory for predicting reliability, taking design actions based upon the predictions, measuring (or gaining new knowledge)and then repredicting, and acting again or remeasuring continually throughout a program of development or test.

Reporting and Corrective Action Systems - "Failure Reporting and Corrective Action" (FRACA) as well as "Problem Reporting and Corrective Action" (PRACA) are the two types of reporting and corrective action systems that presently exist in the rocket industry. The FRACA system is required by the Air Force and the PRACA system is required by NASA. Although these two systems may differ in minor detail, the intent of the requirements and methods used by manufacturers to carry them out is very similar. The following is an example of a typical manufacturer.

Company XYZ maintains a closed-loop failure reporting and corrective action system to ensure investigation of the cause of failures and to provide appropriate corrective action and failure recurrence control. The FRACAs place emphasis on analysis of failure data to provide early detection of defects. Subsequent investigation and corrective action attempts to find and correct failure causes early in the build cycle in order to minimize costs associated with higher level failures.

FRACAs incorporate the following features:

1. Use of a failure report form which provides a failure description, analysis and corrective action, as well as basic information including: hardware name; operational level, type and environment; hardware identification number; date of failure; name of responsible unit engineer and failure reporting engineer.

2. A project failure reporting procedure or RAM program plan section which defines:

- The level at which failure reporting begins.

- The types of anomalies for which failure reports will and will not be written.

- The flow of hardware and paperwork associated with failure analysis.

- The responsibilities of the R&M and QA organizations.

3. The completed failure reports incorporate the corrective action implemented both immediately (e.g., part removed and replaced) and long term (e.g., engineering order to implement design change).

4. Every failure report requires a close out.

5. The program/project maintains a current list of all failures and the status of those failures.

Basic terminology used in FRACAs is as follows:

1. TRS - Test Record Sheet - Running log of spacecraft area test events; initiated by test inspector.

2. SQUAWK (Log)- Narrative which records spacecraft or space propulsion system area assembly and test problems; initiated by test inspector.

3. TDR - Test Discrepancy Report - Records test failures at various levels of assembly and test; initiated by test inspector.

4. TRF - Test Failure Report - Records the problem descriptions, failure analyses, and corrective actions; initiated by reliability engineer.

5. RAR - Reliability Analysis Report - Computerized output of combined information from TDR and TFR.

6. FRB - Failure Review Board - Joint meeting of Contractor/Customer personnel to review and closeout failure.

Sequence of Activities - A typical flow of failure reporting paperwork and the associated hardware is shown in Figure 3.

Although FRACA/PRACA systems are intended to be a "cradle to grave" system, manufacturers tend to emphasize manufacturing (using Q.C. as the control and corrective action system) and test (using the process of Figure 3 as a corrective action system). This is primarily because these are the two areas over which they have complete control. Feedback from the customer (except, of course, for catastrophic failures) is often inconsistent.

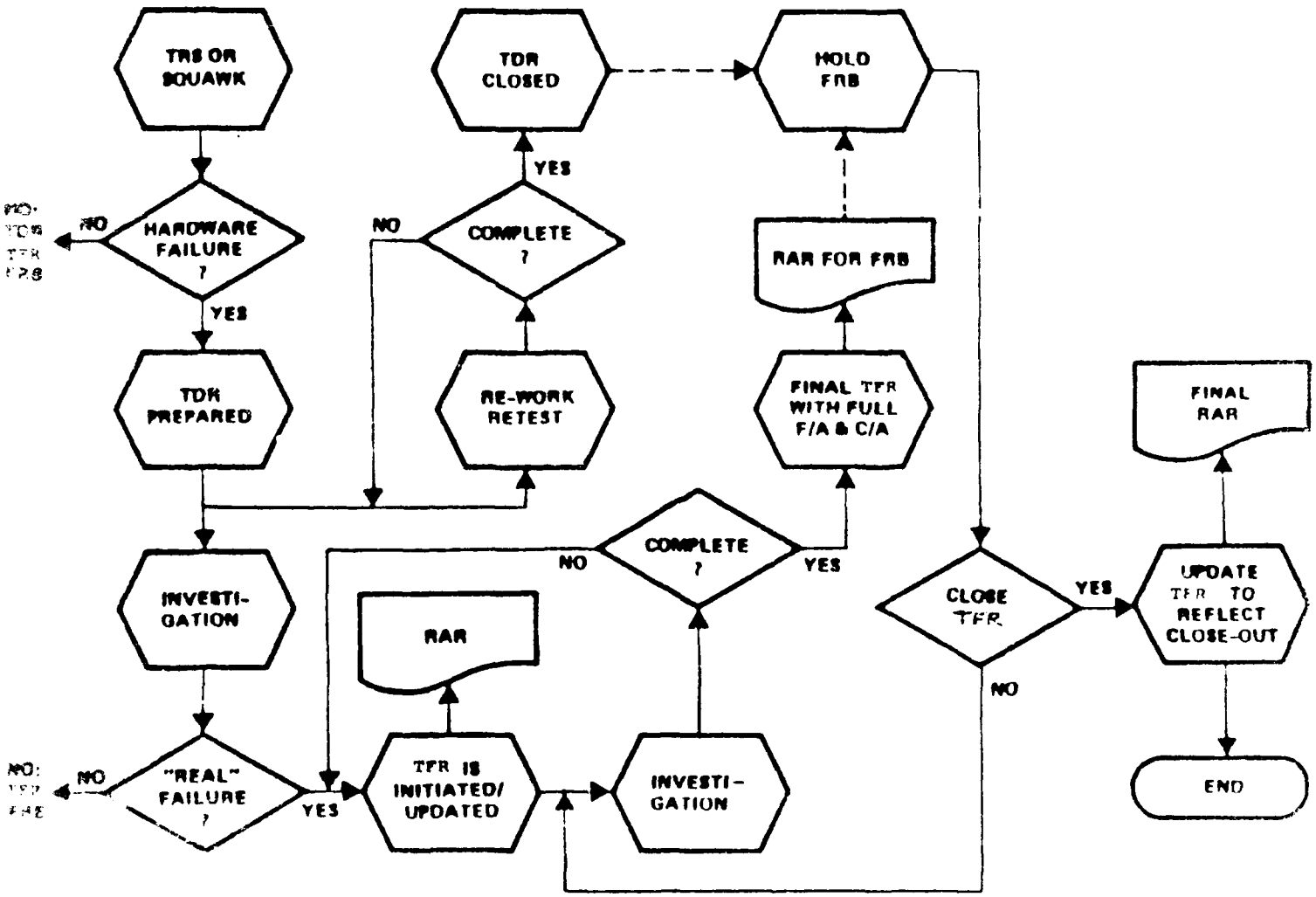


Figure 3. TDR/TFR/RAR paper flow.

For example, if a failure occurs and the equipment is pulled for repair, the paper work often does not state why the equipment failed. In the case of the SSME, a recent review of non-conference reports (UCRs) indicated that only 20% were included in the NASA PRACA system according to one contractor. 80% were excluded by the reporting requirements. These requirements are intended to limit the reporting to serious problems and to prevent the system from becoming overwhelmed by problems of a minor nature. Such a system serves well to aid in serious problem tracking and close out, but can sometimes eliminate the detailed background information required for definitive problem analysis and root cause determination. In the case of the SSME, such investigations required use of the UCRs combined with the contractor's (Rocketdyne) in house problem tracking systems. Thus, the problem is two-fold: not all problems are reported and those that are reported are not always adequately described.

Comments - Failure reporting is most effective when viewed as an engineering activity rather than as a bookkeeping function. Opportunities exist for failure reporting personnel to enhance screening effectiveness, identify potential trends, and to minimize costly downstream anomalies. Increased computerization of FRACAs allows for rapid information dissemination and less time spent on routine paperwork tasks, as long as increased use of computers must not be made by sacrificing detailed problem descriptions.

The FRACAs begin with procurement and continue through receiving inspection manufacturing, test, launch-site activities and mission operation. Control of discrepancies found in receiving and in-process inspection, all non-test discrepancies and Material Review Board (MRB) activities are primarily the responsibility of Quality Assurance and are described in the Quality Assurance Program Plan. Reporting of parts and materials problems (including Alerts, etc.) is the responsibility of Parts, Materials and Processes (PM&P) personnel. Test discrepancy control is primarily the responsibility of the reliability organization. In the course of performing this function, a reliability engineer may encounter conflicting priorities within the project in assuring that proper failure analysis and corrective action occur in response to test discrepancies. Examples include:

1. Manufacturing personnel want units repaired and out of their hands.

2. System Integration personnel want units back into stores or back into their hands.

3. The unit engineer wants a test discrepancy to be due to a manufacturing defect or a parts problem, and he may now, due to the passage of time, be assigned to a new project.

4. The project manager doesn't want to spend any more money on the situation.

5. The project engineer believes whatever the unit engineer tells him.

6. The system engineer is worrying about link performance or something of the sort.

In the face of these conflicts, the reliability engineer's objectives must prevail. The Failure Review Board exists to help assure that each failure is properly closed out. Satisfactory closeout of a failure will occur when:

1. A failed unit is fixed and has passed the test which it failed.

2. The probability of the problem recurring in the unit is negligibly small.

3. The problem has been shown not to exist in any other unit.

A computer system is often used to record and track test discrepancies from the time of occurrence through Failure Review Board closeout and beyond. The computerized system provides:

1. A reporting vehicle for alerting Quality Assurance, Reliability, Engineering, Manufacturing, Test and Program Management of failures and need for action.

2. A permanent record of the cause, significance, effect, and corrective action for each failure.

3. A vehicle for requesting remedial action of the procurement, design, manufacturing, test and handling organizations.

4. A retrieval system for identifying failure trends, providing status summaries and locating historical failure information.

While PRACAs/FRACAs perform well in the failure tracking and problem close out system mode for which they were intended, they were not designed to be reliablity data bases even though they may contain information considered for this latter purpose. It should therefore not be surprising that PRACAs often lack the information required for reliability analysis and prediction. The reasons for this vary but the primary reason is as follows. PRACAs are intended primarily to keep reliability management and program management informed that serious problems have been identified and are being attended to. Including minor problems or supplemental information which is not critical to management tracking (such as the part exposure time at failure) may overload management and therefore this information is screened out of the system by the reporting requirements. While this may be desired from a problem tracking standpoint, it eliminates the precursor information essential to a reliability data base. For example, the SSME PRACA system only includes 20% of the UCR information which would be required for a reliability data base and it includes almost no exposure at time of failure information.

1.2 Data Base (Historical)

1.2.1 Data Collection

The objective of this subtask was to collect the material necessary to understand the present state of design, the current manufacturing techniques and the operational parameters of solid and liquid propulsion rockets. Collection methods included visits to NASA and Air Force sites responsible for solid and liquid propulsion rockets. Collection methods also included visits to the sites of rocket manufacturers and users and access to in-house publications, technical and public libraries for text books, reports and articles on rockets.

Trip reports (see Volume II: Appendix B) documented the names of contacts made, insights gained through formal or informal question and answer sessions with these contacts, the type of information collected (hard copy reports, historical data sets and for which rockets and time frames) and the type of process viewed during facility tours (production, maintenance, design). Information gathering focused on the retrieval of sets of historical rocket launch and test performance data, textbook discussions of the physical attributes of solid and liquid rockets and subtypes, and studies conducted to evaluate design and performance tolerances of individual or collective rocket performance parameters. The output of this task was a set of rocket characteristic and performance data.

1.2.2 Data Organization

The data gathered from the site visits and the information collection process described above was organized to facilitate its use. For hardcopy material and site trip reports, a filing system was constructed,

separating solid from liquid rocket data, then categorizing by rocket use (booster, strap-on, Orbit Adjust, Payload Assist Module), followed by sorts on fuel type and rocket type. The Data Summary Sheets that follow were constructed to allow at-a-glance review of the data available on the various rocket types in these rocket use and fuel type categories. Historical data on rocket test/launch were organized by entering it into a computerized data base system, DBase III+, when the data was available, to allow data to be more easily stored and sorted.

1.2.3 Representative Design Parameter Development

Using the information gathered and organized, a candidate design configuration was selected for solid and liquid rockets as a baseline case. This baseline was used to establish a structure of rocket mission and performance characteristics which also define a structure for data entry and storage. The rocket mission data vector, or the column headings for a data table, reflects data categories from historical performance sets, such as data of test/launch, success or failure, rocket designation (name, production lot), and type of mission (R&D, space Mission). Rocket performance vector entries were determined by the technical literature search and site visit discussions citing rocket attributes such a fuel, oxidizer, thrust and diameter. The baseline structure which these vectors constitute was expanded and defined further as more insight was gained into the characteristics which drive rocket reliability.

Following the Data Summary Sheets is a matrix containing the reliability of U.S. launch vehicle failures, tabulated in Table 1 and 1a-1f. The details of how this matrix was generated are contained in Appendix A 3.

1.3 Deficiencies of Current Aerospace Reliability Practice In Application to Current Advanced Launch System Needs

Current Aerospace Reliability practice has not been able to affect the high reliabilities specified for Air Force advanced launch systems. Current practice, as it seems from the investigations undertaken as part of this effort, is relevant toward the production of launch vehicle systems whose range of achieved reliability is upper bounded at 95%, and these levels have been achieved only after significant development programs over which significantly lower reliabilities were the norm (80% - 90%). Many of the deficiencies in current practice are a product of the developmental history of aerospace reliability technology and its resulting evolution rather than direct misapplications of reliability techniques. It has taken almost 30 years for a systematic reliability discipline to be developed since its early beginnings in the Titan and Apollo programs. At the time of its creation, the US and world industrial base was quite different. Failures of small electronic components because of their use in great numbers in complex aerospace designs had a tendency to defeat the best efforts of system designers and render embarrassingly useless, expensively developed systems. In the case of early launch vehicles, national prestige and credibility of ICBM deterence required that these problems be eliminated quickly. The electronic systems were the roots of aerospace reliability, especially in the era when quantitative information was completely unavailable (if not unheard of).This tended to influence reliability technology development toward the generation of techniques which could help quickly to improve the performance of systems without undertaking the long term development of more reliable individual devices. Papers which touted the development of reliable systems from less reliable devices, the initiation of qualitative investigatory techniques such as FMEAs, and the use of redundancy to shore up the areas of weakness graduated from the academic classroom of the 50's and early 60's to become the industrial practice of the late 60's and early 70's. Finally, they became institutionalized in the late 70's and 1980's.

While exposure of component functional failure effects through FMEAs and their elimination through redundancy works, and works well for electronic systems where weight and operational constraints are minimized and the effect of a single failure is to some degree localized, the usefulness of this approach has always been limited in propulsion systems. In fact, the use of this currently institutionalized qualitative

DATA SUMMARY SHEET

ENGINE or MOTOR NAME	MOTOR 1 UA 1205	MOTOR 2 UA 1207	MOTOR 3 THIOKOL TX526-2	MOTOR 4 THIOKOL TX-780	MOTOR 5 THIOKOL STAR 48
Agency	USAF, Commercial	USAF	NASA	USAF	NASA
Manufacturer	UTC	UTC	Thiokol	Thiokol	Thiokol
Designation (stage or motor)			Castor 4	Castor 4A	PAM-D
Engine or Motor Weight (lb)			3,222		400
Propellant weight (lb)	232,000		20,556		4,400
Mode number	0	0	1	1	3
Oxidizer/Fuel	solid	solid	solid	solid	solid
Mixture ratio (O/F)					
Diameter					
Length	90.4/10.2	112.9/10.2	36.6/3.3	36.6/3.3	7.2/4.0
Thrust (sea lev) (lb)	123,144,000*	159,700,000*	83,640	97,556	
* (lb/sec)					
Thrust (vacuum) (lb)			92,400		15,000
Chamber pressure (psia)			540		570
Spec impuls (sea level)			230		
Spec impuls (vacuum) (sec)			256		293
Total burn time (sec)			56		85.3
Nozzle expansion ratio			8.0		54.9
Nozzle exit area (ft^2)			6.1		4.75
Engine cant angle (deg)			11		0
Case material					
Segment number					
Stabilization (Spin/3-Axis)					Spin Stabilized
Thrust Coefficent Cf			1.411		2.1
Nozzle discharge coefficent Cd g			6.13E-3		7.2E-3
Engine cycle					
Mass Discharge Rate (lb/sec)			363.7		51.2
Engine cost					
Engine Reliability	0.9975		0.9993		0.9769
Launch Vehicle Name	Titan 340 Titan 3	Titan 4 C.G.P. Titan 4 IUS	Delta 3914/3924 3910/3920/PAM-D	Delta 6925	Delta 3910/PAM-D, 3920/PAM-D

04/19/89

DATA SUMMARY SHEET

NUM	ENGINE or MOTOR NAME	MOTOR 6 THIOKOL 48B	MOTOR 7 HERCULES GEM	MOTOR 8 SPACE SRB	MOTOR 9 THIOKOL TE364-4	MOTOR 10 UTC ALGO 3
1	User Agency	USAF	USAF	NASA	NASA	NASA,USAF
2	Manufacturer	Thiokol	McD/Douglas		Thiokol	UTC
3	Designation (stage or motor)	PAM-D	Gr-Ep Motor (GEM)		TE-M-364-4	Algol 3A
4	Engine or Motor weight (lb)			285,000	200	4,000
5	Propellant weight (lb)			1,115,000	2,300	28,000
6	Stage number	3	1	1	3	1
7	Oxidizer/Fuel	solid	solid	Alumium powder/ Ammonium perchlorate	solid	solid
8	Mixture ratio (O/F)			4.4		
9	[illegible]					
10	Length/Diameter (ft)/(ft)	7.2/4.0	36.6/3.3	149.0/12.0	6.8/3.2	30.8/3.74
11	Thrust(sea lev) (lb)* * = lb.sec		94,556	2,650,000		93,250
12	Thrust (vacuum) (lb)	15,000			14,800	105,112
13	Chamber pressure (psia)				550	450
14	Spec impuls (sea level)					229
15	Spec. impuls (vacuum) (sec)				283	259
16	Total burn time (sec)			120	44	56.11
17	Nozzle expansion ratio				33	6.48
18	Nozzle exit area (ftxft)				3.14	5.67
19	Engine cant angle (deg)				0	0
20	Case material					
21	Case segment number					
22	Thrust vector control (T.V.C)				Spin Stabilized	Aerodynamic Fins and Jet Vanes
23	Thrust Coeffiecnt Cf				1.96	1.645
24	Nozzle discharge coefficent Cd g				6.94E-3	7.18E-3
25	Engine cycle					
26	Mass Discharge Rate (lb/sec)				52.3	407.2
27	Engine cost					
28	Engine Reliability			0.9813	0.9769	
29	Vehicle Name	Delta 6925/7925	Delta 7925	Space shuttle	Delta 3914/3924	Scout Launch Vehicle (SLV)

DATA SUMMARY SHEET

NUM ENGINE or MOTOR NAME	MOTOR 11 THIOKOL TX354-3	MOTOR 12 THIOKOL TE-M-762	MOTOR 13 THIOKOL TE-M-640	MOTOR 14 THIOKOL TE-M-364-4	MOTOR 15 THIOKOL TE-M-616
1 User Agency	NASA,USAF	NASA,USAF	NASA,USAF	USAF	USAF
2 Manufacturer	Thiokol	Thiokol	Thiokol	Thiokol	Thiokol
3 Designation (stage or motor)	Castor 2A	Antares 3A	Altair 3A	SGB Blk.1	OIS
4 Engine or Motor weight (lb)	3,000	1,000	100		
5 Propellant weight (lb)	8,000	3,000	600		
6 Stage number	2	3	4	upstage 2	upstage 1
7 Oxidizer Fuel	solid	solid	solid	solid	solid
8 Mixture ratio (O/F)					
9 [illegible]					
10 Length/Diameter (ft)/(ft)	20.7/2.59	11.3/2.49	12.4/3.50	5.2/4.6	5.9/4.6
11 Thrust(sea lev) (lb) • lb.sec					
12 Thrust (vacuum) (lb)	63,970	18,700	5,710	15,500	6,000
13 Chamber pressure (psia)	700	700	670		
14 Spec impuls (sea level)					
15 Spec impuls (vacuum) (sec)	280	295	288		
16 Total burn time (sec)	35.32	43.96	29.30		
17 Nozzle expansion ratio	21.2	46.0	50.3		
18 Nozzle exit area (sq.ft)	7.95	4.48	1.5		
19 Engine cant angle (deg)	0	0	0		
20 Case material					
21 Case segment number					
22 Thrust vector control (T.V.C)	H2O2 RCS	H2O2 RCS	Spin Stabilized		
23 Thrust coefficent Cf	1.692	1.905	1.985		
24 Nozzle discharge coefficent Cd g	6.04E-3	6.46E-3	6.89E-3		
25 Engine cycle					
26 Mass Discharge Rate (lb/sec)	228.5	63.4	19.8		
27 Engine cost					
28 Engine Reliability					
29 Vehicle Name	Scout	Scout	Scout	Stage Vehicle System	Orbit Insertion Sys

NUM	ENGINE or MOTOR NAME	MOTOR 16 THIOKOL (MM3)	MOTOR 17 THIOKOL PAM-DII	MOTOR 18 UTC SRM 1	MOTOR 19 UTC SRM-2	MOTOR 20 Thiokol Caster 2
1	User Agency	NASA	Varies	USAF	NASA	NASA, USAF
2	Manufacturer	Thiokol	Thiokol	UTC	UTC	Thiokol
3	Designation (stage or motor)	PAM-A	PAM DII	Boeing Orbital Sciences	Boeing	Castor 2A
4	Engine or Motor Weight (lb)					
5	Propellant Weight (lb)					
6	Stage number	upstage 1	upstage 1	3	3	2
7	Oxidizer/Fuel	solid	solid	solid	solid	solid
8	Mixture ratio (O/F)					
9	Coolant					
10	Length/Diameter (ft)/(ft)	7.5/5.0	6.5/5.3	10.7/9.5	5.7/9.5	
11	Thrust(sea lev) (lb) * = lb.sec					
12	Thrust (vacuum) (lb)	35,200	17,600	44,100	16,800	61,800
13	Chamber pressure (psia)					
14	Spec impuls (sea level)					
15	Spec. impuls (vacuum) (sec)					
16	Total burn time (sec)					
17	Nozzle expansion ratio					
18	Nozzle exit area (ftxft)					
19	Engine cant angle (deg)					
20	Case material					
21	Case segment number					
22	Thrust vector control (T.V.C)					
23	Thrust Coeffiecnt Cf					
24	Nozzle discharge coefficent Cd g					
25	Engine cycle					
26	Mass Discharge Rate (lb/sec)					
27	Engine cost					
28	Engine Reliability					
29	Vehicle Name	STS/PAM-A	STS/PAM-DII	Titan 4 IUS Transfer orbit stage	Titan 4 IUS	Scout SLV 1A

NUM	ENGINE or MOTOR NAME	MOTOR 21 Thiokol Antares 3	MOTOR 22 Thiokol Altair 3	MOTOR 23 Hercules X259-B4	MOTOR 24 Thiokol Castor 4H	MOTOR 25 Thiokol Star-30
1	User Agency	NASA, USAF	NASA, USAF	NASA, USAF		
2	Manufacturer	Thiokol	Thiokol	Hercules	Thiokol	Thiokol
3	Designation (stage or motor)	Antares 3	Altair 3	Antares 2B	Castor 4H	Star-30
4	Engine or Motor weight (lb)					
5	Propellant weight (lb)					
6	Stage number	3	4	3	1,2	4
7	Oxidizer/Fuel	solid	solid	solid	solid	solid
8	Mixture ratio (O/F)					
9	Coolant					
10	Length/Diameter (ft)/(ft)					
11	Thrust(sea lev) (lb) * = lb.sec					
12	Thrust (vacuum) (lb)	21,000	5,700	28,000	138,000	7,500
13	Chamber pressure (psia)					
14	Spec. Impuls (sea level)					
15	Spec. Impuls (vacuum) (sec)					
16	Total burn time (sec)					
17	Nozzle expansion ratio					
18	Nozzle exit area (ftxft)					
19	Engine cant angle (deg)					
20	Case material					
21	Case segment number					
22	Thrust vector control (T.V.C)					
23	Thrust Coeffiecnt Cf					
24	Nozzle discharge coefficent Cd g					
25	Engine cycle					
26	Mass Discharge Rate (lb/sec)					
27	Engine cost					
28	Engine Reliability					
29	Vehicle Name	Scout SLV-1A	Scout SLV-1A	Scout SLV-1A	Conestoge II	Conestoge II

NUM	ENGINE or MOTOR NAME	MOTOR 26 Thiokol TE-M-364-2	MOTOR 27 Thiokol TE-M-442-1	Motor 28 Thiokol TE-M-360 4		
1	User Agency	USAF	USAF	USAF		
2	Manufacturer	Thiokol	Thiokol	Thiokol		
3	Designation (stage or motor)	Burner 2, 2A	Burner 2A	S65		
4	Engine or Motor weight (lb)					
5	Propellant weight (lb)					
6	Stage number	upstage (varies)	upstage 2	upstage 2		
7	Oxidizer/Fuel	solid	solid	solid		
8	Mixture ratio (O/F)					
9	Coolant					
10	Length/Diameter (ft)/(ft)	5.8/5.2	5.8/5.2	10.0/4.5		
11	Thrust(sea lev) (lb) * = lb.sec					
12	Thrust (vacuum) (lb)	10,000	8,000	7,325		
13	Chamber pressure (psia)					
14	Spec impuls (sea level)					
15	Spec. impuls (vacuum) (sce)					
16	Total burn time (sec)					
17	Nozzle expansion ratio					
18	Nozzle exit area (ftxft)					
19	Engine cant angle (deg)					
20	Case material					
21	Case segment number					
22	Thrust vector control (T.V.C)					
23	Thrust Coeffiecnt Cf					
24	Nozzle discharge coefficent Cd g					
25	Engine cycle					
26	Mass Discharge Rate (lb/sec)					
27	Engine cost					
28	Engine Reliability					
29	Vehicle Name	Burner 2, 2A	Burner 2A	Stage Vehicle sys		

NUM	ENGINE or MOTOR NAME	ENGINE 1 Aerojet LR-87-AJ-11	ENGINE 2 Aerojet LR-91-AJ-11	ENGINE 3 Aerojet AJ10-138	ENGINE 4 Aerojet LR-87-AJ-5	ENGINE 5 Aerojet LR-91-AJ-5
1	User Agency	USAF, Commercial	USAF, Commercial	USAF	USAF	USAF
2	Manufacturer	Aerojet	Aerojet	Aerojet	Aerojet	Aerojet
3	Designation (stage or motor)			Transtage		
4	Engine or Motor weight (lb)					
5	Propellant weight (lb)	294,000	69,000	9,000		
6	Stage number	1	2	3	1	
7	Oxidizer/fuel	N2O4/N2H4-UDMH	N2O4/N2H4-UDMH	N2O4/N2H4-UDMH	N2O4/N2H4-UDMH	N2O4/N2H4-UDMH
8	Mixture ratio (O/F)					
9	Coolant					
10	Length/Diameter (ft)/(ft)					
11	Thrust*(sea lev) (lb) * = lb.sec	264,500 / 273,000			215,000	
12	Thrust (vacuum) (lb)		101,000 / 104,000	8,000		100,000
13	Chamber pressure (psia)					
14	Spec impuls (sea level)					
15	Spec. impuls (vacuum) (sec)					
16	Total burn time (sec)					
17	Nozzle expansion ratio					
18	Nozzle exit area (ftxft)					
19	Engine cant angle (deg)					
20	Case material					
21	Case segment number					
22	Thrust vector control (T.V.C)					
23	Thrust Coeffiecnt Cf					
24	Nozzle discharge coefficent Cd g					
25	Engine cycle					
26	Mass Discharge Rate (lb/sec)					
27	Engine cost					
28	Engine Reliability		0.9800			
29	Vehicle Name	Titan 34D, 3, 4CGP, 4IUS	Titan 34D, 3, 4CGP, 4IUS	Titan 34D	Titan 2 SLV	Titan 2 SLV

NUM	ENGINE or MOTOR NAME	ENGINE 6 Rocket. YLR-89-NA7	ENGINE 7 Rocket. YLR-105-NA7	ENGINE 8 P&W RL10A-3-3A	ENGINE 9 Rocket. RS-27	ENGINE 10 TRW TR201
1	User Agency	NASA	NASA	NASA	NASA, USAF	NASA
2	Manufacturer	Rocketdyne	Rocketdyne	P&W	Rocketdyne	TRW
3	Designation (stage or motor)	MA-5		Centaur	ELT Thor	Delta
4	Engine or Motor weight (lb)					
5	Propellant weight (lb)	111,506	77,825	14,867	175,000	10,000
6	Stage number	1/2	1	2	1	2
7	Oxidizer/Fuel	LOX/RP-1	LOX/RP-1	LOX/LH2	LOX/RP-1	N2O2/N2H4-UDMH
8	Mixture ratio (O/F)	2.25	2.22	5.0	2.23	1.6
9	Coolant					
10	Length/Diameter (ft)/(ft)					
11	Thrust(sea lev) (lb) * = lb.sec	188,750	60,500		205,000	
12	Thrust (vacuum) (lb)			16,500	229,600	9,530
13	Chamber pressure (psia)	650	733	474	650	100
14	Spec impuls (sea level)	259	220		261	
15	Spec. impuls (vacuum) (sce)	292	312	446.4	294	303
16	Total burn time (sec)	153	283	404	227	318
17	Nozzle expansion ratio	8	25	61	8	46
18	Nozzle exit area (ftxft)	11.24	11.56	8.22	12.0	17.4
19	Engine cant angle (deg)	0	0	0	0	0
20	Case material					
21	Case segment number					
22	Thrust vector control (T.V.C)	Gimballed Engines and Verniers	Gimballed Engines and Verniers	Gimballed Engines	Gimballed Engine	Gimballed Engine
23	Thrust Coeffiecnt Cf	1.44	1.24	1.79	1.46	1.75
24	Nozzle discharge coefficent Cd g	5.54e-3	5.64e-3	4.01e-3	5.59e-3	5.78e-3
25	Engine cycle					
26	Mass Discharge Rate (lb/sec)	728.8	275.0	37.0	785.4	31.45
27	Engine cost					
28	Engine Reliability	0.9907	0.9905	0.9854	0.9833	0.9774
29	Vehicle Name	Atlas G Centaur D 1A/Atlas H	Atlas G, Centaur D-1A/Atlas H	Atlas G,Centaur D-1A /D-1T, Titan 4CGP	Delta3914/3924/6920/ 6925,3910/3920/PAM-D	Delta 3914/3924 3910/3920/PAM D

NUM	ENGINE or MOTOR NAME	ENGINE 11 Aerojet AJ10-118k	ENGINE 12 Rocket. RS-51	ENGINE 13 P&W RL10A-3-3B	ENGINE 14 Rocket. LR-89_NA5	ENGINE 15 Rocket. LR-105-NA5
1	User Agency	NASA,USAF	Varies	USAF	USAF	USAF
2	Manufacturer	Aerojet	Rocketdyne	P&W	Rocketdyne	Rocketdyne
3	Designation (stage or motor)	Delta	AMS	Centaur	MA-3	MA-3
4	Engine or Motor weight (lb)		2,790			
5	Propellant weight (lb)	13,200				
6	Stage number	2	upstage	upstage	1/2	1
7	Oxidizer/Fuel	N2O2/N2H4-UDMH	N2O4/MMH	LOX/LH2	LOX/RP-1	LOX/RP-1
8	Mixture ratio (O/F)	1.9				
9	Coolant					
10	Length/Diameter (ft)/(ft)					
11	Thrust(sea lev) (lb) * = lb.sec				165,000	60,000
12	Thrust (vacuum) (lb)	9,710	2,650	15,000		
13	Chamber pressure (psia)	114				
14	Spec impuls (sea level)					
15	Spec. impuls (vacuum) (sce)	320.2				
16	Total burn time (sec)	43532				
17	Nozzle expansion ratio	65.2				
18	Nozzle exit area (ftxft)	19.9				
19	Engine cant angle (deg)	0				
20	Case material					
21	Case segment number					
22	Thrust vector control (T.V.C)	Gimballed Engine				
23	Thrust Coeffiecnt Cf	1.93				
24	Nozzle discharge coefficent Cd g	6.03e-3				
25	Engine cycle					
26	Mass Discharge Rate (lb/sec)	30.32				
27	Engine cost					
28	Engine Reliability	0.9774				
29	Vehicle Name	Delta3914/3924/7920/ 7925,3910/3920/PAM-D	Stage	STS/Centaur 9	Atlas E	Atlas E

NUM	ENGINE or MOTOR NAME	ENGINE 16 Bell 8096	ENGINE 17 AGC Trnstge			
1	User Agency	USAF, NASA	NASA			
2	Manufacturer	Bell	AGC			
3	Designation (stage or motor)	YLR-81BA-11	Delta			
4	Engine or Motor weight (lb)					
5	Propellant weight (lb)					
6	Stage number	upstage (varies)	2			
7	Oxidizer/Fuel	IRFNA/UDMH	N2O4/A-50			
8	Mixture ratio (O/F)					
9	Coolant					
10	Length/Diameter (ft)/(ft)					
11	Thrust(sea lev) (lb) * = lb.sec					
12	Thrust (vacuum) (lb)	16,000	10,000			
13	Chamber pressure (psia)					
14	Spec impuls (sea level)					
15	Spec. impuls (vacuum) (sce)					
16	Total burn time (sec)					
17	Nozzle expansion ratio					
18	Nozzle exit area (ftxft)					
19	Engine cant angle (deg)					
20	Case material					
21	Case segment number					
22	Thrust vector control (T.V.C)					
23	Thrust Coeffiecnt Cf					
24	Nozzle discharge coefficent Cd g					
25	Engine cycle					
26	Mass Discharge Rate (lb/sec)					
27	Engine cost					
28	Engine Reliability					
29	Vehicle Name	Agena D	Delta 3920/PAM-D			

TABLE 1: RELIABILITY COMPARISON OF U.S. LAUNCH VEHICLE FAMILIES

Vehicle Name / Data Collection Period		Thor / Delta			Titan					Atlas										
		Thor	Delta	Combine	Titan I	Titan II	Titan III	Titan 34D	Combine	Atlas A	Atlas B	Atlas C	Atlas D	Atlas E	Atlas F	Atlas SLV	Atlas G	Atlas H	Atlas/ Centaur	Combine
		57-83	60-87	57-87	59-65	62-76	64-87	82-87	59-87	57-58	58-59	58-59	58-67	60-88	61-81	67-83	84-87	83-87	62-87	57-88
Success Ratio:	Mean	0.8982	0.9402	0.9192	0.6427	0.8864	0.9406	0.7355	0.8013	3.4218	0.5556	0.5833	0.8401	0.7426	0.8863	0.9445	no failure	no failure	0.9089	0.7883
	5%	0.8750	0.9110	0.8789	0.5585	0.8323	0.9055	0.4978	0.8075	0.1827	0.3010	0.2642	0.8015	0.6454	0.8359	0.8736	0.6313	0.8313	0.8450	0.4781
	95%	0.9181	0.9615	0.9551	0.7202	0.8272	0.9651	0.8990	0.9546	0.8977	0.7896	0.8565	0.8734	0.8240	0.9276	0.9653			0.9489	0.9053
STAGE NO.	Stage 0	0.9965	0.9950				0.9946	0.8678												
	Stage 1/2													0.8713	0.9573	0.986			0.9814	
	Stage 1	0.9346	0.9850		0.8214	0.9574		0.8476						0.8523	0.9279	0.9716			0.9810	
	Stage 2	0.9764	0.9746		0.7825	0.9238	0.9763									0.9856			0.9420	
	Stage 3	0.9877	0.9843				0.9667													
	Stage 4																			
SYSTEM	Propulsion	0.9566	0.9701		0.6725	0.9280	0.9622	0.7355		0.8844	0.6887			0.8713	0.9212	0.9824			0.9535	
	Guidance	0.9830	0.9850			0.9829	0.9892							0.9571	0.9889					
	Flight Control	0.9807	0.9851			0.9858	0.9946			0.7686	0.8869			0.9428	0.9889	0.9824			0.9907	
	Structure	0.9969			0.9702		0.9946			0.7686				0.9857					0.9814	
	Electrical	0.9815	0.9850			0.9829								0.9857		0.9824			0.9907	
	Separation	0.9969	0.9950			0.9858										0.9824			0.9907	
	Other or (UK)	0.9823													0.9934					

Vehicle Name / Data Collection Period		Saturn "Family"						Scout "Family"			STS
		Jupiter	Juno	Saturn I	Saturn IB	Saturn V	Combine	Vanguard	Scout	Combine	Space Shuttle
		58-58	58-61	62-65	66-75	67-73	58-75	57-59	60-88	57-88	81-88
Success Ratio:	Mean	0.3811	0.4300	no failure	no failure	0.9822	0.7547	0.8888	0.9420	0.8404	0.9275
	5%	0.1026	0.2135	0.7943	0.7743	0.8180	0.2852	0.1556	0.9023	0.1821	0.8147
	95%	0.8679	0.8743			0.9887	0.9405	0.5723	0.9683	0.9744	0.9805
STAGE NO.	Stage 0										
	Stage 1/2										
	Stage 1		0.8575					0.8347	0.9917		0.9275
	Stage 2	0.5741	0.7009			0.9822		0.5046	0.9875		
	Stage 3		0.7629			0.9822		0.8288	0.9746		
	Stage 4	0.6290	0.9378						0.9870		
SYSTEM	Propulsion	0.7870						0.7921	0.9793		0.9275
	Guidance							0.9174	0.9917		
	Flight Control							0.8347	0.9917		
	Structure										
	Electrical								0.9876		
	Separation	0.5741							0.9959		
	Other or (UK)							0.8347	0.9959		

TABLE 1A: RELIABILITY OF THE THOR/DELTA FAMILY

Vehicle Name Data Collection Period		Thor / Delta		
		Thor 57-83	Delta 60-87	Combine 57-87
Success Ratio: Mean 5% 95%		0.8982 0.8750 0.9181	0.9402 0.9110 0.9615	0.9192 0.8789 0.9551
STAGE NO.	Stage 0	0.9965	0.9950	
	Stage 1/2			
	Stage 1	0.9346	0.9850	
	Stage 2	0.9764	0.9746	
	Stage 3	0.9877	0.9843	
	Stage 4			
SYSTEM	Propulsion	0.9568	0.9701	
	Guidance	0.9830	0.9950	
	Flight Control	0.9907	0.9851	
	Structure	0.9969		
	Electrical	0.9815	0.9950	
	Separation	0.9969	0.9950	
	Other or (UK)	0.9923		

TABLE 1B: RELIABILITY OF THE TITAN FAMILY

Vehicle Name Data Collection Period		Titan				
		Titan I 59-65	Titan II 62-76	Titan III 64-87	Titan 34D 82-87	Combine 59-87
Success Ratio:	Mean	0.6427	0.8864	0.9406	0.7355	0.8013
	5%	0.5585	0.8323	0.9055	0.4978	0.6075
	95%	0.7202	0.9272	0.9651	0.8990	0.9546
STAGE NO.	Stage 0			0.9946	0.8678	
	Stage 1/2					
	Stage 1	0.8214	0.9574		0.8476	
	Stage 2	0.7825	0.9258	0.9783		
	Stage 3			0.9667		
	Stage 4					
SYSTEM	Propulsion	0.6725	0.9290	0.9622	0.7355	
	Guidance		0.9929	0.9892		
	Flight Control		0.9858	0.9946		
	Structure	0.9702		0.9946		
	Electrical		0.9929			
	Separation		0.9858			
	Other or (UK)					

TABLE 1C: RELIABILITY OF THE ATLAS FAMILY

Vehicle Name / Data Collection Period		Atlas										
		Atlas A 57-58	Atlas B 58-59	Atlas C 58-59	Atlas D 59-67	Atlas E 60-88	Atlas F 61-81	Atlas SLV 67-83	Atlas G 84-87	Atlas H 83-87	Atlas/ Centaur 62-87	Combine 57-88
Success Ratio: Mean		0.4219	0.5558	0.5833	0.8401	0.7426	0.8883	0.9445	no failure	no failure	0.9069	0.7883
5%		0.1827	0.3010	0.2642	0.8015	0.6454	0.8359	0.8736	0.6313	0.6313	0.8450	0.4761
95%		0.6977	0.7896	0.8585	0.8734	0.8240	0.9276	0.9652			0.9489	0.9953
STAGE NO.	Stage 0											
	Stage 1/2					0.8713	0.9573	0.9861			0.9814	
	Stage 1					0.8523	0.9279	0.9719			0.9810	
	Stage 2							0.9856			0.9420	
	Stage 3											
	Stage 4											
SYSTEM	Propulsion	0.8844	0.6667			0.8713	0.9212	0.9824			0.9535	
	Guidance					0.9571	0.9869					
	Flight Control	0.7688	0.8889			0.9428	0.9869	0.9824			0.9907	
	Structure	0.7688				0.9857					0.9814	
	Electrical					0.9857		0.9824			0.9907	
	Separation							0.9824			0.9907	
	Other or (UK)						0.9934					

TABLE 1D: RELIABILITY OF THE SATURN FAMILY

Vehicle Name Data Collection Period		Saturn "Family"					
		Jupiter 58-58	Juno 58-61	Saturn I 62-65	Saturn IB 66-75	Saturn V 67-73	Combine 58-75
Success Ratio:	Mean	0.3611	0.4300	no failure	no failure	0.9822	0.7547
	5%	0.1026	0.2135	0.7943	0.7743	0.8180	0.2652
	95%	0.6879	0.6743			0.9997	0.9935
STAGE NO.	Stage 0						
	Stage 1/2						
	Stage 1		0.8575				
	Stage 2	0.5741	0.7009			0.9822	
	Stage 3		0.7629			0.9822	
	Stage 4	0.6290	0.9378				
SYSTEM	Propulsion	0.7870					
	Guidance						
	Flight Control						
	Structure						
	Electrical						
	Separation	0.5741					
	Other or (UK)						

TABLE 1E: RELIABILITY OF THE SCOUT FAMILY

Vehicle Name Data Collection Period		Scout "Family" Vanguard 57-59	 Scout 60-88	 Combine 57-88
Success Ratio:	Mean	0.3388	0.9420	0.6404
	5%	0.1555	0.9023	0.1821
	95%	0.5723	0.9683	0.9744
STAGE NO.	Stage 0			
	Stage 1/2			
	Stage 1	0.8347	0.9917	
	Stage 2	0.5049	0.9875	
	Stage 3	0.8039	0.9746	
	Stage 4		0.9870	
SYSTEM	Propulsion	0.7521	0.9793	
	Guidance	0.9174	0.9917	
	Flight Control	0.8347	0.9917	
	Structure			
	Electrical		0.9876	
	Separation		0.9959	
	Other or (UK)	0.8347	0.9959	

TABLE 1F: RELIABILITY OF THE SPACE SHUTTLE

Vehicle Name Data Collection Period		STS Space Shuttle 81-88
Success Ratio: Mean 5% 95%		0.9275 0.8147 0.9806
STAGE NO.	Stage 0	
	Stage 1/2	
	Stage 1	0.9275
	Stage 2	
	Stage 3	
	Stage 4	
SYSTEM	Propulsion	0.9275
	Guidance	
	Flight Control	
	Structure	
	Electrical	
	Separation	
	Other or (UK)	

system of reliability techniques can lead designers and decision makers to make incorrect decisions even if correctly applied as is demonstrated below. Finally, it appears that the currently institutionalized reliability technology base, because of its qualitative nature, will be unable to address just the residual reliability related issues such as residual variability reduction, risk management and human reliability that limit launch systems to their current operational reliability levels.

Here are some examples why. The examples fall into two broad categories: either they are the result of performing FMEAs/FMECAs or quantitative reliability analysis.

1.3.1 FMEAs/FMECAs

FMEAs/FMECAs are structured to detect single point failures. When single point failures are identified they are either controlled or compensated for by use of redundancy.

Redundancy and Correlation Factors - When applied to electronics, redundancy can be a very effective way to enhance reliability. However, as Section 2.3.1.2, "Product Design FMEAs" points out, even electronics can be susceptible to "common cause" or "correlation" failure. These are the types of failures that can negate the benefits of redundancy due to a single event. Product Design FMEAs have proven beneficial in reducing vulnerability to correlated failures in electronics systems and may prove to be beneficial in the analysis of propulsion systems. None-the-less, propulsion systems, like any high energy system, are inherently more vulnerable to correlated failures. This is supported by the study of the shuttle main engine development history which is summarized in Section 2.1.4 and provided in detail in Appendix A.1 "An Investigation of Historical Failure Correlation Factors Using the Shuttle SSME Flight History as an Example."

Controls and Variability - When redundancy, for whatever reason, is not an option when conducting an FMEA, the failure mode is "controlled" either by designing the failure mechanism directly out of the system or by placing more stringent controls on manufacturing and/or testing. Designing a failure mechanism out is usually not a viable option because it requires a physically different way of obtaining the same function. Thus, manufacturing or testing is the most practical way of constraining the failure mode. The only problem with this approach is that if methods are not in place to measure the effects in terms of reduced variability, there is no way to measure the impact on reliability.

Reusability - Another potential problem with FMEAs is that they tend not to be "living" documents in the sense that if a system is reused or is reusable, the FMEA is not structured to handle the potential results. For instance, weld failures on the Space Shuttle Main Engine can result from thermal cycling and fatigue through reuse. The FMEA is not structured to conveniently handle this situation.

"Bottom Up" Methodology - As has been previously discussed, FMEAs/FMECAs are "bottom up" methodologies and as such are not designed to list all potential malfunctions of a system, only those which propagate from known failure modes of components within the system. Without a comprehensive way of anticipating system or subsystem malfunctions in a global sense, the analyst can never be comfortable that the FMEA/FMECA is exhaustive. A "Top Down" methodology as described in Section 2.3.1.2 would help overcome this "Bottom Up" obstacle.

1.3.2 Quantitative Reliability Analysis

In order for quantitative reliability analysis to be effective the three following constituents must be present:

1. Meaningful Reliability Data/Issues
2. Proper Reliability Analysis Tools
3. Risk Analysis and Management Capabilities

Meaningful Reliability Data/Issues - For the current generation of launch vehicles, the historical data set (see Appendices A.1 and A.3) appears to be both meaningful and capable of addressing the key reliability issues. To be meaningful, the reliability data must:

1. Be complete for both success and failure.

2. Have failure causes consistently identified.

3. Have chronologies of failure history established.

4. Have design change chronologies established.

In order to be effective, however, the following issues must be resolved:

1. How relevant is history in predicting future performance in a developmental system?

2. How is historical reliability growth to be accounted for?
- old failures less than new?
- How are design changes factored in?

3. What effect does hold down time just prior to launch have on prevention of failures which otherwise would occur after launch?

These issues can only be addressed by applying the appropriate quantitative reliability models using a properly developed and structured historical data set.

Quantitative Reliability Analysis Tools Specifically for Propulsion Systems - Until now the only quantitative methodology available for propulsion systems which addresses the developmental nature of such systems have been traditional reliability growth methods (such as the Duane approach and Weibull methods) and D. Lloyd's methodology (see Section 2.2.2). Even if these methodologies were adequate in addressing overall launch vehicle reliability, three other areas should be considered in order for a quantitative reliability analysis to be fully effective.

They are:

- Estimation of Stage Reliability
- Estimation of System Reliability
- Estimation of Engine or Motor Reliability

A method of estimating launch vehicle reliability is summarized in Section 2.2.1 and all four methods are described in detail in Appendix A.3, "Reliability Analysis for Current US Launch Vehicles".

Risk Assessment/Management - Section 1.3.1 has described the limited value of FMEAs/FMECAs in the quantification of reliability. Although they are useful in constructing logic models (see reliability techniques, Figure 2), strictly speaking they can only be used to quantify consequences. For instance, they can be used to quantify total number of welds whose failure could cause loss of an engine, cluster, stage, or vehicle (consequences), but this approach does not provide the analyst with the quantitative risk discriminating information required of a decision making tool. A decision making tool allows the analyst to rank individual weld failures, for example, with other sources of propulsion system failures in order to determine where to best expend resources. If a decision is made to expend the funds, the funds must be dedicated or "fenced off" and made distinct from management reserve funding. Even well developed criticality ranking techniques do not do the job sufficiently because they do not develop rankings at the system level but only at subsystem or lower levels, since their system level rankings are often developed only on a near relative basis. This approach can give the impression that a thrust vector control system single failure is just as important as other propulsion system elements such as a heat exchanger or turbo-pump, even though the latter may have several orders of magnitude higher failure probability. The solution to this problem is to use the quantitative reliability analysis tools of Section 1.3.2.2 in conjunction with Risk Analysis/Assessment techniques as described in Sections 2.3.1.3 and 2.3.2.

Figure 8 (Section 2.3) shows the relationship of risk management and assessment to infrastructure controls that have an impact on reliability.

2.0 (TASK 2) RELIABILITY ENHANCING METHODOLOGIES

2.1 Lessons Learned

This section is concerned with lessons learned either as a direct result of plant visits or from a related analysis.

2.1.1 Variability Control

Variability control was highlighted as a reliability enhancer at Hercules (West Virginia) and McDonnell Douglas (Huntington Beach, CA), as noted in Appendix B.

The Hercules trip indicated that solid rocket motors can achieve high reliabilities (>.999) and maintain these reliabilities over reasonable production runs (as many as 1000 units/year), if the proper reliability considerations are included in the design and development phases of the program and the proper process controls are in place, and if the proper test program remains in place. The process control system must be able not only to detect penetrations of the Upper Quality Limit (UQL) and Lower Quality Limit (LQL), but also trends toward unacceptable quality. These trends must be thoroughly investigated and tied to causes, the causes addressed, solutions derived and implemented, and control mechanisms directed at controlling key process parameters verified as being reestablished.

2.1.2 Reusability

Reusability is, on the surface, a design goal of significant program benefit. However, the benefits of reusability are significantly compromised if the reliability of an engine is adversely affected by the requirement for reuse. Besides the direct costs involved in developing a reusable design, there now appears to be a significant indirect cost required to maintain reliability in reusable design. For example, reusability by its very nature tends to decrease the production run. When production runs are decreased, investments in automated production equipment becomes less economical and the production process therefore tends to become more prototypical. Prototypical production, especially of complex equipment, increases the problem of variability control and therefore substantial post production testing may be required to ensure high reliabilities. A good example of such an indirect impact on reusability was seen at the Rocketdyne SSME production facility in Canoga Park, California.

2.1.3 Performance Indicators

For high reliability programs it is important to identify early on symptoms of the process which presage deterioration in performance. This has been done in the financial community by the development of a set of "leading" performance indicators and developing performance trends based upon the indicator trajectories through time. If such a set of indicators could be developed and trended for advanced propulsion system development programs, the indicator trajectories might provide early warning of problems arising during development and operation. This early warning could provide the time required to institute corrective action before actual program reliability performance is affected.

2.1.4 Correlation Factors (See Appendix A.1)

Given the current state of rocket engine technology, there exists a finite probability of catastrophic engine failure during a vehicle launch. A catastrophic engine failure is considered one in which the engine does not shut down in a controlled manner and includes uncontrolled fire, explosion, breach of the pressure boundary, shrapnel, complete loss of fuel or oxidizer supply, or a combination of these. Given that an engine

has failed catastrophically in flight, an immediate concern is for other critical hardware in the vicinity of the failed engine. For vehicles configured with multiple engines in a cluster, the question becomes whether the catastrophic failure of one engine will result in the catastrophic loss of the entire engine cluster.

In the present study, the correlation between a catastrophic failure of a Space Shuttle Main Engine (SSME) and the propagation of that failure to include the entire SSME three engine cluster has been developed based upon the SSME Test History.

Conclusions - In the development of future launch vehicles, the potential benefit of engine out capabilities must be weighed against the risks that if an engine fails in an uncontrolled manner, it will result in the loss of the entire engine cluster. This study evaluated the SSME which is flown in a three engine cluster. No uncontrolled SSME failures have occurred in flight. Only a limited amount of ground testing has actually been done in a three engine cluster and although failures have occurred, none have propagated to involve the entire cluster.

However, the test data evaluated here indicates there is a reasonable probability, approximately 17%, that an uncontrolled SSME failure will propagate to the adjacent engines given that an uncontrolled failure occurs. The confidence interval is between 4% and 41% that a failure will propagate to the cluster (at 95% confidence).

A summary of the results of the data review is given in Table 2.

2.1.5 Correlation vs. Engine Out Capability(See Appendix A.2)

A preliminary correlation factor vs engine out capability study was conducted using the following assumptions:

- Smaller engines are more reliable than larger ones.
- Increased plumbing due to a larger number of engines decreases reliability.

The results of the study indicate that a four engine configuration would be the most reliable if correlation factors are not taken into account.

When correlation factors are between 20 and 27% the four engine configuration is no better than a single engine configuration. Section 2.1.4 indicates that the 95% interval for correlation failure is 4 to 41%. Therefore, there is a substantial probability that correlated failure on an engine design which is comparable to the SSME could negate engine out capability.

TABLE 2: SSME CORRELATION OF FAILURE FACTOR

3 2 TEST NUMBER	DATE	ENG	CONFIG	UCR	UNCNTD SHTDN	UNCONT HDWR FAILR	ENGN RETRD	APPLICBL FAILURE	SURRDG HARDWR DAMAGE *	CLUSTR DAMAGE **	STAND DOWN TIME	R/L	COMP	COMMENT	TEST DURATN	C/O PWR LVL
901.110	24-Mar-[illegible]	[illegible]	PRE FMOF	[illegible]	YES	YES	YES	YES	NO	NO	[illegible]	[illegible]	HPOTP	HPOTP FIRE EXT DAM	[illegible]	[illegible]
[illegible]	[illegible]-Aug	0004	PRE FMOF	[illegible]	[illegible]	YES	NO	NO			6	[illegible]	FPB	HOLE IN FPB BODY	48.2[illegible]	90
[illegible]	[illegible]-Sep	[illegible]	PRE FMOF	[illegible]	[illegible]	YES	YES	YES	NO	NO	[illegible]	[illegible]	[illegible]	HPOTP BRG FAILURE - EXT DAM	[illegible]	[illegible]
902.[illegible]	[illegible]-Nov	[illegible]	PRE FMOF	[illegible]	[illegible]	[illegible]	NO	NO			[illegible]	[illegible]	HPFTP	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	YES	YES	NO	NO	[illegible]	[illegible]	[illegible]	[illegible] TURB BL FAILURE	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	NO	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] DAM	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	NO			[illegible]	[illegible]	[illegible]	MFV BODY FAILURE	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	YES	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] IN INJ [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	YES	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] DISPLACED [illegible] DAM	[illegible]	[illegible]
[illegible]	[illegible]-Aug-[illegible]	[illegible]	FMOF	[illegible]	[illegible]	[illegible]	NO	[illegible]			[illegible]	[illegible]	[illegible]	HOLE BURNED IN FPB	[illegible]	[illegible]
[illegible]	[illegible]		FMOF		[illegible]	YES	YES	YES	NO	NO	[illegible]		[illegible]	FPB INJECTOR BURNT [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]0110	FMOF		[illegible]	[illegible]	NO	NO					[illegible]	MAIN INJECTOR BURN [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	PHASE I	[illegible]	[illegible]	[illegible]	[illegible]	YES	NO	NO	[illegible]		MCC	MCC BURN CUT EXT DAM	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	PHASE I	[illegible]	YES	[illegible]	NO	NO			[illegible]	[illegible]	[illegible]	[illegible] BURN OUT/REPLACED RING	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	PHASE I	[illegible]	YES	[illegible]	[illegible]	[illegible]	YES	NO	[illegible]	[illegible]	[illegible]	TURB BL FAIL/VOLUTE RUPTURE EXT DAM	[illegible]	[illegible]
[illegible]	[illegible]-Oct-[illegible]	[illegible]107	PHASE I	A01[illegible]	[illegible]	[illegible]	NO	[illegible]			[illegible]	[illegible]	HPFTP	HPFTP T/A DUCT SM BULGED	[illegible]	[illegible]
[illegible]	[illegible]-82	[illegible]0110	PHASE I	A0[illegible]	YES	YES	YES	YES	NO	NO	[illegible]	[illegible]	[illegible]	[illegible] EXT DAMAGE [illegible]	[illegible]	[illegible]
[illegible]	[illegible]-Aug-[illegible]	[illegible]	PHASE I	[illegible]	YES	YES	YES	YES	YES	YES	[illegible]	[illegible]	[illegible]	KAISER HAT TURB BRG EXT DAM	[illegible]	[illegible]
[illegible]	[illegible]-Apr-[illegible]	[illegible]07	PHASE I		NO	NO	NO	NO			3		OPOV	OPOV SEAL EROSION	[illegible]	
[illegible]	[illegible]-May-82	[illegible]10	PHASE I		NO	NO	YES	NO			42		OPOV	OPOV SEAL CRACKED AND ERODED	300.00	
[illegible]	[illegible]-Aug-82	2208	PHASE I	A011[illegible]	YES	YES	YES	YES	YES	[illegible]	63	HOACC	[illegible]	HPO DUCT RUPTURE - EXT DAM	115.64	[illegible]
[illegible]	[illegible]-Feb-84	2015	PHASE I		NO	NO	NO	NO					OPB	OPB ASI CHAMBER EROSION	527.8[illegible]	65
901.4[illegible]	[illegible]-Feb-84	[illegible]	PHASE II	A013[illegible]	YES	YES	YES	YES	NO		[illegible]	F ID I	[illegible]	CENT LNR PR MAJOR DAMAGE	611.00	109
901.486	[illegible]-Feb-85	0207	PHASE II	A014585	YES	NO	NO	NO	-		9	PH/T	[illegible]	CRACK AT F-13 FLANGE eng retred	203.88	109
750.259	[illegible]-Mar-85	2208	PHASE II	A015710	YES	YES	YES	YES	YES	YES	160	HFACC	[illegible]	DISCH MAN RUPTURE - EXT DAM	101.47	109
750.28[illegible]	[illegible]-May-87	[illegible]10	PHASE II		YES	YES	NO	NO	-	-	26		NOZZLE	CLASS I NOZZLE LEAK	223.56	109
902.427	26-Jun-87	2106	PHASE II		YES	NO	NO	NO	-	-	5		DUCT	LPFTP TURBINE DISCHARGE DUCT FAIL/FIRE	138.36	104
902.429	1-Jul-87	2106	PHASE II		YES	YES	NO	NO	-	-	41		[illegible]	OPB INTERPROPELLANT PLATE CRACK	204.12	104

NOTES:

- ENG - ENGINE NUMBER
- CONFIG - ENGINE CONFIGURATION
- UCR - UNACCEPTABLE CONDITION REPORT
- UNCNTD SHTDN - UNCONTROLLED ENGINE SHUTDOWN
- UNCCNT HDWR FAILR - UNCONTAINED HARDWARE FAILURE
- ENGN RETRD - ENGINE RETIRED FOLLOWING THIS EVENT
- APPLICBL FAILURE - FAILURE IS APPLICABLE TO THIS STUDY
- SURRDG HARDWR DAMAGE - EVENT RESULTED IN DAMAGE TO SURROUNDING HARDWARE
- CLUSTR DAMAGE - FAILURE WOULD RESULT IN DAMAGE TO THE ENGINE CLUSTER
- STAND DOWN TIME - DAYS FROM THIS EVENT UNTIL THE NEXT TEST ON THIS STAND
- R/L - REDLINE ISSUED FOR CUTOFF
- COMP - MAJOR COMPONENT INVOLVED IN EVENT
- C/O PWR LVL - CUTOFF POWER LEVEL

2.2 Historical Data Analysis

"Historical Data Analysis" is intended only to acquaint the reader with the various analytical options presently available. In fact, as is discussed in Section 3.0 (Comparison of the Methods of Section 2.2), there is insufficient information, as well as limited time and resources available to the study, to make a thorough comparison of methodologies. Further studies are, however, recommended as stated in the Recommendations Section.

2.2.1 Y. Shen's Methodology (Reliability Analysis for Launch Vehicles)

The performance history of any launch vehicle can be considered as having two time periods, the early development period and the stable performance period. During the early development period, the unreliability of a launch vehicle is generally high and unstable. After a "failure analysis and fix" process in combination with technical and design improvements, the unreliability of a launch vehicle goes down and stabilizes.

This effect of early transient behavior followed by stable reliability behavior is indicated in Table 11a for the Thor/Delta family and Table 11b for the Titan family. In both cases, oscillating reliability histories are observed early on with later stable performance. It is also interesting to note that Titan I appears to have never reached stability and the Delta, being based on the significant Thor history, reached a stable, high level of reliability very quickly.

These historical reliability growth curves are developed according to the following method.

The maximum-likelihood estimator (failure ratio) for unreliability can be defined as:

$$\hat{U} = F/L$$

Where F is a cumulative failure number, L is a cumulative launch number and F is a function of L.

The easiest way then to estimate the average unreliability of a launch vehicle is:

$$U_e = F/L \qquad (1)$$

where U_e is the estimated average unreliability, and F and L are the cumulative failure and launch numbers.

As was mentioned before, the reliability growth effect must be considered to get a more realistic estimation of the unreliability. In the present model, the average unreliability is defined as

$$U = U_e - \Delta U \qquad (2)$$

where ΔU is the correction reliability caused by the reliability growth effect and can be explained as

$$\Delta U = \Delta F/L$$

or

$$\Delta F = \Delta U \cdot L \qquad (3)$$

where ΔF is the correction cumulative failure number.

Averaging both sides of equation (3), we get

$$\overline{\Delta F} = \Delta U \cdot \frac{L}{2}$$

or

$$\Delta U = \frac{2}{L} \cdot \overline{\Delta F} \qquad (4)$$

Substitute equation (1) and equation (4) into equation (2)

$$U = \frac{F}{L} - \frac{2}{L} \cdot \overline{\Delta F} \qquad (5)$$

The estimation of the unreliability of the launch vehicle at the nth launch can then be approximated as

$$U_n = \frac{F_n}{L_n} - \frac{2}{L_n} \cdot \frac{\sum_{i=1}^{N} (F_i - \frac{F_n}{L_n} \cdot L_i)}{N} \qquad (6)$$

where L_i is the i^{th} launch number, and F_i is the cumulative failure number at i^{th} launch.

The reliability R_n at the n^{th} launch is

$$R_n = 1 - U_n = 1 - \left[\frac{F_n}{L_n} - \frac{2}{L_n} \cdot \frac{\sum_{i=1}^{N} (F_i - \frac{F_n}{L_n} \cdot L_i)}{N} \right] \qquad (7)$$

The concepts of confidence level based on the value of average reliability from equation (7) are now illustrated as the following.

Let N be the launch number, then $X = N \cdot R_n$ is the success number. In this case, the 5th percentile confidence is given by -

$$R_{0.05} = \frac{x}{x + (n - x + 1) F_{0.95}(2n - 2x + 2, 2x)} \qquad (8)$$

and the 95th percentile confidence is given by-

$$R_{0.95} = \frac{(x+1) F_{0.95}(2x+2, 2n-2x)}{(n-x) + (x+1) F_{0.95}(2x+2, 2n-2x)} \qquad (9)$$

where $F_r(n_1, n_2)$ is the 100 r^{th} percentile of F-distribution with n_1 numerator and n_2 denominator degrees of freedom.

TABLE 3: AN EXAMPLE OF A TEST SEQUENCE PERFORMED ON A SOLID ROCKET, ITS RESULTS AND RELIABILITY COMPUTATION USING D. LLOYD'S METHOD

Test no. (N)	Months of testing*	Results	Value of failure $f = 1 - (1-\gamma)^{1/n}$					Σf	$R = 1 - \Sigma f/N$	Remarks
			f_1	f_2	f_3	f_4	f_5			
1	0	S						0.000	1.000	Successful test
2	3	S						0.000	1.000	Successful test
3	5	F	1					1.000	0.667	Failure mode, f_1 case burnthrough
4	8	S	1					1.000	0.750	Successful test
5	11	S	0.900					0.900	0.820	f_1 corrected, internal installation added, success
6	12	S	0.684					0.684	0.886	Successful test
7	13	S	0.536					0.536	0.923	Successful test
8	14	F	0.438	1				1.438	0.820	Failure mode, f_2 TVA failure
9	16	S	0.369	1				1.369	0.848	TVA not tested
10	18	S	0.319	0.900				1.219	0.878	Successful test of TVA fix
11	20	F	0.280	1	1			2.280	0.793	Failure mode f_2 recurs, f_3
12	21	S	0.250	1	1			2.250	0.812	TVA not tested
13	23	S	0.226	0.900	0.900			2.026	0.844	Successful test of 2nd TVA fix
14	25	S	0.206	0.684	0.684			1.574	0.888	Successful test
15	28	S	0.189	0.536	0.536			1.261	0.916	Successful test
16	29	F	0.175	0.438	0.438	1		2.051	0.872	Spec. violation, f_4
17	30	F	0.162	0.369	0.369	1	1	2.900	0.829	2nd spec violation, f_5
18	32	S	0.152	0.319	0.319	0	0	0.790	0.956	Spec. change eliminates f_4, f_5
19	32	S	0.142	0.280	0.280	0	0	0.702	0.963	Successful test
20	33	S	0.134	0.250	0.250	0	0	0.634	0.968	Successful test
21	35	S	0.127	0.226	0.226	0	0	0.579	0.972	Successful test
22	37	S	0.120	0.206	0.206	0	0	0.532	0.976	Successful test
23	39	S	0.114	0.189	0.189	0	0	0.492	0.979	Successful test
24	40	S	0.109	0.175	0.175	0	0	0.459	0.981	Successful test
25	42	S	0.104	0.162	0.162	0	0	0.428	0.983	Successful test

* Number of months after start of test program, not length of test.

Notes: Test no. 4: failure from test no. 3 (f_1) is not yet diminished because corrective action is not implemented until test no. 5; f_1 continues to diminish in all subsequent tests since it does not recur.
Test no. 9: failure from test no. 8 (f_2) is not diminished because the thrust vector actuator (TVA) subsystem is not "hooked up" until fix is implemented and successfully tested in test no. 10.
Test no. 11: failure from test no. 8 (f_2) recurs; therefore, fix implemented in test no. 10 is not considered successful, and both TVA failures are reinstated as full failures.
Test no. 12: TVA is not tested while failure mode is undergoing engineering analysis, therefore, f_2 and f_3 are not diminished;
Test no. 13: successful test of new TVA fix applies to both failures (f_2, f_3); therefore, values of both failures are diminished. TVA failure does not recur in the remainder of the example and, therefore, both failure values continue to diminish.
Test no. 16: small performance anomaly occurs; however, it is outside current specification limits and, therefore, must be considered a failure (f_4).
Test no. 17: same as test no. 16 (f_5).
Test no. 18: Corrective action for f_4 and f_5 is to change specifications/conditions (with customer approval). With this change, tests 16 and 17 become "non-failures" and f_4 and f_5 immediately become zero.
Test nos. 19-25: all are successful, demonstrating a lower probability of failure for f_1, f_2 and f_3 failure modes.

For a complete discussion of this methodology, see Appendix A.3.

2.2 2 D. Lloyd's Methodology (Taken from Reference 14)

D. Lloyd developed a method for estimating and forecasting reliability from attribute data, using the binomial model, when reliability requirements are very high and test data are limited. Integer data—specifically, numbers of failures—are converted, using this approach, into non-integer data. The rationale is that when engineering corrective action for a failure is implemented, the probability of recurrence of that failure is reduced; therefore, such failures should not be carried as full failures in subsequent reliability estimates. The reduced failure value for each failure mode is the upper limit on the probability of failure based on the number of successes after engineering corrective action has been implemented. Each failure value is less than one and diminishes as successes continue. These numbers replace the integral numbers (of failures) in the binomial estimate.

In Lloyd's research, this method of reliability estimation was applied to attribute data from the life history of a previously tested system, and a reliability growth equation was fitted. It was then "calibrated" to allow for reliability projections to be developed for a new similar system. In this way, the model allows for management to discern early on whether the system's ultimate reliability requirement will be met and, if so, when is it likely to be achieved. By comparing current estimates of reliability with the expected value computed from the model, a reliability growth forecast can be obtained by extrapolation.

An example application of Lloyd's method to a solid rocket program is shown in Table 3. As can be seen, the methodology predicts a significantly higher success ratio (.983 vs .80) than would be obtained without considering growth.

2.2.3 Curve Fitting (Polynomial)

Polynomial trends are of the form

$$Y = A + BX + CX^2 + DX^3 + \ldots + JX^k$$

The straight line is a special case, having only the first two terms on the right of the equality sign. With three terms on the right, the polynomial is of quadratic form, and so forth. Typical forms are shown in Figure 3. Generally speaking, it is unwise to fit a high-degree polynomial to the data because doing so almost assures the mixing of trend and cycle. Also, a glance at the figure below will show that none of the polynomials, other than the straight line, can be extended or projected very far without going off the page. Keep in mind that only a portion of the curve is used to represent the trend.

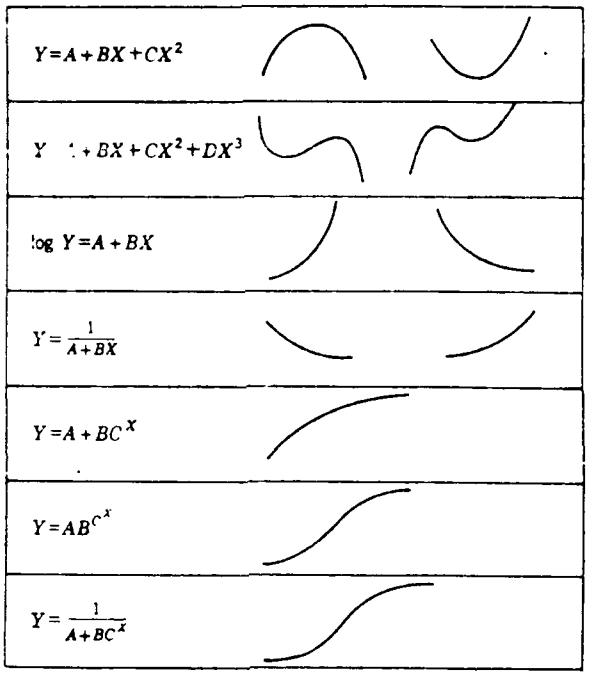


Figure 3. Typical forms of some trend equations.

Of course, a polynomial can be forced to fit the data quite closely by adding enough terms. A well known theorem in algebra states that a polynomial of degree k can be passed through $k+1$ points on a plane. Accomplishing this, or anything near to it, does not contribute any information about trend. This becomes evident when it is recalled that 1 degree of freedom is lost for error for every parameter that is estimated from the data. Thus, if there are n observations and n degrees of freedom are lost in fitting a polynomial of degree n-1, 0 degrees of freedom left for error.

All polynomials can be fitted utilizing the method of least squares.

2.2.4 Bayesian (Reference 15)

Suppose a propulsion system is being built with a 0.95 reliability requirement at the 90% confidence level. The system goes through a number of tests: component, environmental, subsystem, system, extended time, etc. There are failures which are corrected (permanently, it is hoped). A final configuration is attained. It is also assumed that the project is at least 50% sure that a 0.95 reliable system has been achieved If thirteen tests are run with no failures, has the 0.95 requirement been met? The classical binomial approach (see section 2.2.5) would indicate that the requirement has not been met.

This problem is typical of today's work in the aerospace industry: few systems, few tests, compressed schedules and high reliability requirements and costs. The limited number of samples for test permit no failures since even one failure would imply an intolerably high failure rate. Indeed, all "hi-rel" programs have "failure recurrence prevention" systems. All failures are "fixed" and "closed". These activities, in effect, imply that at time of "buy off," no failures should occur on qualification or demonstration tests. Hence, any solution to the reliability demonstration problem should, as a practical matter, address itself to zero failures and few trials.

Bayes Theorem, in the continuous case, states:

$$\text{Prob}\ (R \le p \le 1 \mid r) = \frac{\int_R^1 g_n(r \mid p)\, w(p)\, dp}{\int_0^1 g_n(r \mid p)\, w(p)\, dp} \qquad (1)$$

Here, R = lower (Bayesian) confidence limit of the true reliability, p;

r = observed number of failures in n trials;

$g_n(r \mid p)$ = the conditional probability density function of r given p; and

$w(p)$ = the a priori frequency function of p.

In the binomial case,

$$g_n(r \mid p) = \binom{n}{r} p^{n-r} q^r \qquad (2)$$

Here $\binom{n}{r}$ = The number of combinations of n things taken r at a time;

$$q = 1 - p$$

It is assumed that the engineer is capable of assigning a probability, P (degree of belief) to the event that the required reliability, or more, has been attained prior to test. It is also assumed that this prior belief declines linearly to zero at P = 0 and P = 100%.

Thus, w(p) takes the form of the triangle distribution as follows:

$$w(p) = \frac{2(1-P)p}{R^2} \quad \text{for } 0 \le p \le R \qquad (3)$$

$$w(p) = \frac{2P(1-p)}{(1-R)^2} \quad \text{for } R \le p \le 1 \qquad (4)$$

Here, P = prior probability of having the required reliability, R.

That w(p) does have the proper values can be seen by obtaining the required heights at R and multiplying these frequencies by the bases R and (1-R) of the triangles of (3) and (4). Then for the left hand interval, (0, R), we have at p = R,

$$w(R) = \frac{2(1-P)R}{R^2} = \frac{2(1-P)}{R}$$

Area over $(0,R) = \frac{R \cdot w(R)}{2} = 1 - P$

Similarly at p = R for the right hand interval, (R, 1), we have

$$\text{Area over } (R,1) = \frac{(1-R)\,w(R)}{2} = \frac{(1-R)\,2P(1-R)}{2(1-R)^2} = P$$

Note: The discontinuity at R is of probability measure zero.

Inserting (2), (3), and (4) in (1) yields, after cancellation and simplication,

$$Prob(R \le p \le 1) = \frac{1}{1 + \dfrac{(1-P)(1-R)\,2\int_0^R p^{n-r+1} q^r \, dp}{(P)(R)\,2\int_R^1 p^{n-r} q^{r+1} \, dp}} \qquad (5)$$

Figure 4 graphically displays equation (5). Note that in this case, thirteen tests with zero failures are adequate to demonstrate a reliability of 0.95 at 90% confidence (given a 0.5 on the Bayesian Prior scale).

While there can be no doubt that Bayesian methods, as can be seen from this example, can provide significant test reduction to demonstrate a reliability requirement, performing the analysis requires the development of a prior distribution which is, at least to some degree, subjectively based. Also, Bayesian approaches are highly sensitive to the prior distributions used. If no meaningful estimate of the prior probability of success can be made, none of the above conclusions apply. Particularly, one must be wary of consistent optimism or pessimism when records of success do not support the prior probabilities.

For example, if optimism about a new design is guarded and feasibility tests are few or non-existent, then the analysis is driven towards a rectangular prior (equally probable prior intervals), and the results are just as unfavorable (in terms of the large number of tests required) as they are for the binomial distribution. In other words, since one cannot be over 0.5 on the prior scale, 11 tests are required with zero failures to be .90 reliable at 90% confidence, the same as the binomial. This defeats the purpose of the Bayesian approach.

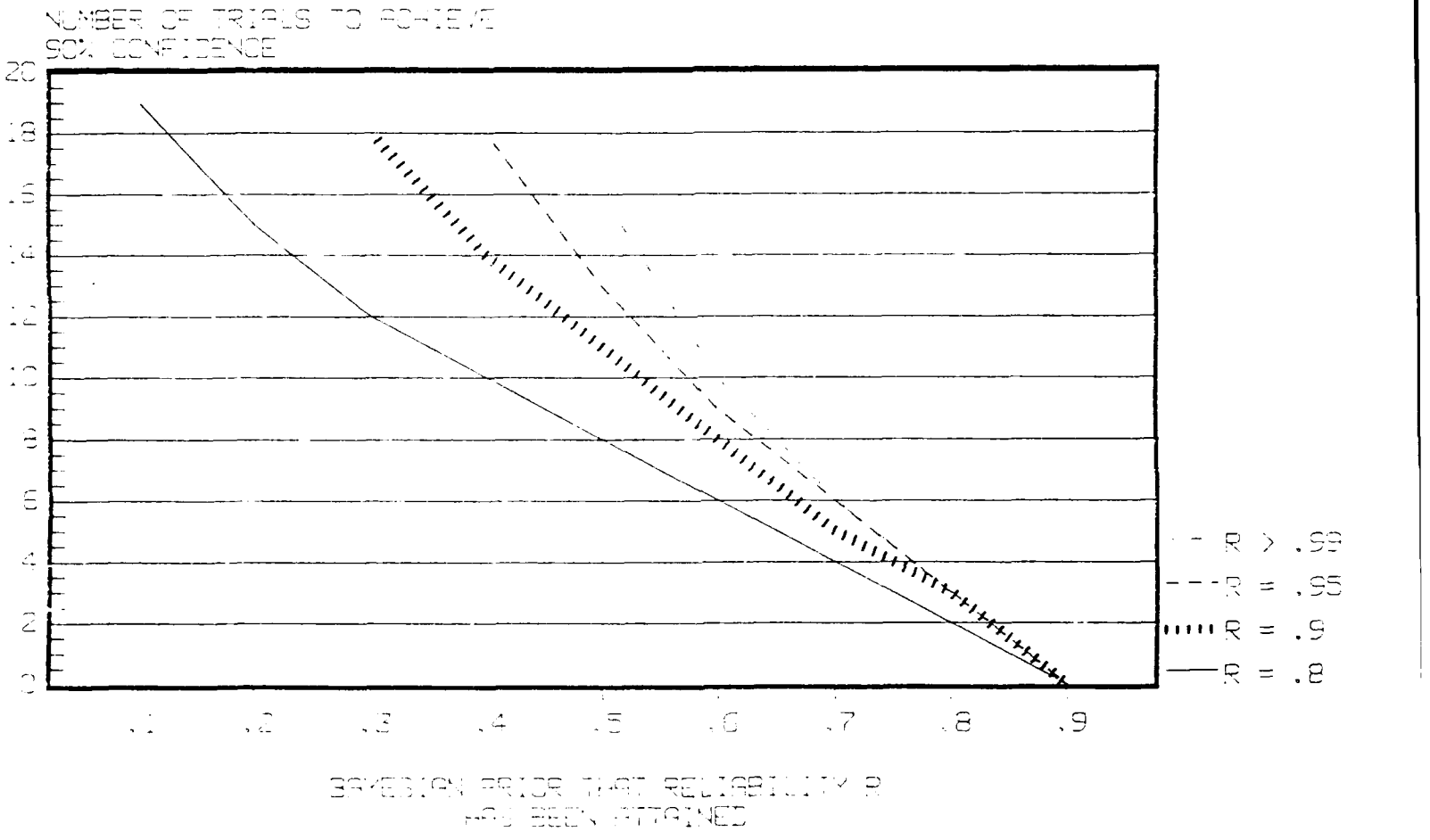


Figure 4. Number of trials with 0 failures to achieve 90% confidence that reliability R has been attained when a Bayesian prior is used.

The following are two examples of applying Bayes Theorem.

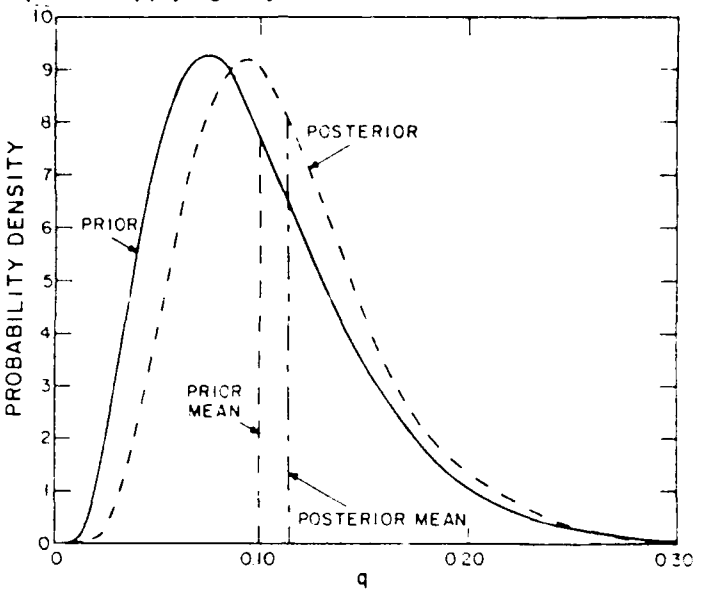


Figure 5. The prior and posterior distribution in example 1.

Figure 5 portrays the results of applying Bayes Theorem to estimate the unreliability of the material (LX-13 or Exter) which is an extrudable high explosive used in a variety of systems (Ref. 15). As can be seen, the posterior distribution is not much different from the prior distribution. In this case, the present observed data (failure numbers, test numbers) is relatively small compared with the previous data, and the prior distribution is given great weight in the final unreliability estimation.

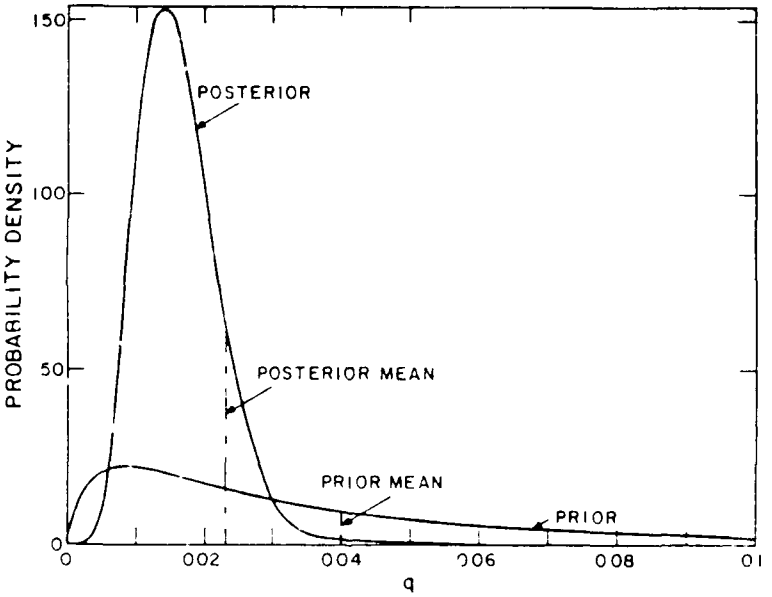


Figure 6. The prior and posterior distribution in example 2

Figure 6, on the other hand, portrays the results of applying Bayes Theorem to estimate the annual pump unreliability for pressurized water reactor (PWRS) in commercial operation in the United States (Ref. 15). It is observed that the posterior distribution is much less diffuse than the prior distribution as a consequence of incorporating the obeserved data. In this case, the present observed data set is large and it is given much weight in the final estimation.

2.2.5 Classical Binomial Approach

The "traditional" approach to reliability demonstration in a go-no-go type environment is the well known Binomial distribution.

Stated mathematically the Binomial Distribution is as follows:

$$\sum_{X=S}^{N} \binom{N}{N-X} R^{X} (1-R)^{N-X} = 1 - C, \text{ if } N \leq S \leq 0$$

where;

S = number of successful start tests

N = number of trials

R = reliability

C = Confidence level

where it is assumed that

- Trials or tests are independent
- Each trial results in success or failure
- The reliability (probability of success) of each system is the same on each trial
- The number of tests is fixed in advance of the demonstration test

Note that it would take 45 tests with no failures to demonstrate 0.95 reliability at 90% confidence (see Table 4).

TABLE 4: BINOMIAL TABLES

Number of Tests Without Failure Vs Reliability and Confidence Level

Reliability (R)	Confidence Level, Percent											
	50	60	70	75	80	85	90	95	97.5	99	99.5	99.9
0.999999	693150	916290	1203970	1386290	1609440	1897120	2302590	2995730	3688889	4605170	5298320	6907760
0.99999	69315	91629	120397	138629	160944	189712	230259	299573	368889	460517	529832	690776
0.9999	6932	9163	12040	13863	16094	18971	23026	29957	36889	46052	52983	69078
0.999	693	916	1204	1386	1609	1897	2303	2996	3689	4605	5298	6908
0.998	347	458	602	694	805	949	1152	1493	1845	2303	2650	3454
0.997	231	305	401	462	537	632	768	999	1230	1535	1766	2303
0.996	173	229	301	346	401	473	575	747	920	1149	1322	1723
0.995	138	183	241	277	321	379	460	598	737	920	1058	1379
0.994	115	152	201	230	267	315	383	498	613	765	880	1148
0.993	99	130	174	198	229	270	328	427	526	657	755	985
0.992	86	114	150	173	200	236	287	373	460	574	660	860
0.991	77	101	134	153	178	210	255	332	408	510	586	764
0.99	69	92	120	138	160	188	229	298	367	459	527	688
0.98	34	45	60	69	80	94	114	149	183	228	263	342
0.97	23	30	40	45	53	62	76	99	121	151	174	227
0.96	17	23	30	34	39	46	57	74	91	113	130	170
0.95	14	18	24	27	31	37	45	58	72	90	103	135
0.94	11	15	20	22	26	31	37	49	60	75	86	112
0.93	10	13	17	19	22	26	32	42	51	64	74	96
0.92	9	11	15	17	19	23	28	36	45	55	64	83
0.91	8	10	13	15	17	20	25	32	39	49	57	74
0.9	7	9	12	13	15	18	22	29	35	44	51	66
0.8	3	4	6	6	7	9	11	14	17	21	24	31
0.7	2	3	4	4	5	6	7	9	11	13	15	20
0.6	2	2	3	3	4	4	5	6	8	9	11	14
0.5	1	1	2	2	3	3	4	5	6	7	8	10

2.3 Baseline Reliability Enhancement Methodology Identification

2.3.1 Proposed Infrastructure Controls Affecting Reliability

Figure 7 illustrates how various activities related to the categories of design, manufacturing, test, transportation, storage and operation can have an effect on reliability. Each category has listed underneath it examples of reliability enhancing technique and tools. They represent a cross section of ideas accumulated during the site visits of Task 1. Some of the techniques are well known and proven, such as reliability predictions/trade offs. Others are not, such as operating characteristic curves vs. reliability.

The following is a discussion of proposed infrastructure controls intended to enhance reliability. The discussion is divided into quantitative and qualitative approaches followed by a discussion of risk assessment as a decision making tool.

Quantitative Approaches - Analysis of Historical Data (See Section 2.2), PRACA/FRACA Trending - In order for a Problem/Failure Reporting and Corrective Action system to be suitable for mathematical trending, basic changes must take place in the way information is recorded and tracked (see Section 1.1.3.2). These changes include as a minimum:

- Recording total operating times on failed as well as unfailed components
- Total number of cycles or trials (both successes and failures)
- Inclusion of reports of all component malfunctions, even those which were non-catastrophic and occured on non-critical components.

Operating Characteristic Curves Correlated to Failure Modes/Rates - The example that follows illustrates one method of connecting defect rates from Q.C. sampling plans to reliability calculations for hardware. Although this example is for solar array calculations, there is every reason to believe that a similar approach could be used for propulsion systems.

- Data

- If entire population had random defect rate of 0.65%, one would expect to reject 10% of lots due to the randomness of sampling process. Figure 12 (page 73) illustrates the use of MIL-STD-414 for the purpose of determining the 10% reject rate. The 0.65% defect rate corresponds to a 90% confidence for the lots expected to be accepted or, conversely, 10% are expected to be rejected. Assume that the MIL-STD 414 plan has thus far rejected 58/434 = 13.4% of lots

- This result is indicative of non-homogeneous population wherein some lots are worse than 0.65% and therefore have a higher probability of being rejected; clustering of bad lots is also indicative of non-homogeneous population

- Thus, residual defect rate in the accepted lot subpopulation will be less than 0.65% per test; assume observed rate in lots accepted to date is 0.65%

- For purposes of an example, consider estimating solar array reliability, a failure probability of 0.25%, will be assumed for each interconnect over the course of the three year mission (conservative)

- Each quarter string consists of an average quantity of 39 cells

- Power margin allows subsystem to accept 22 quarter string failures in each of two sets of 992 quarter strings

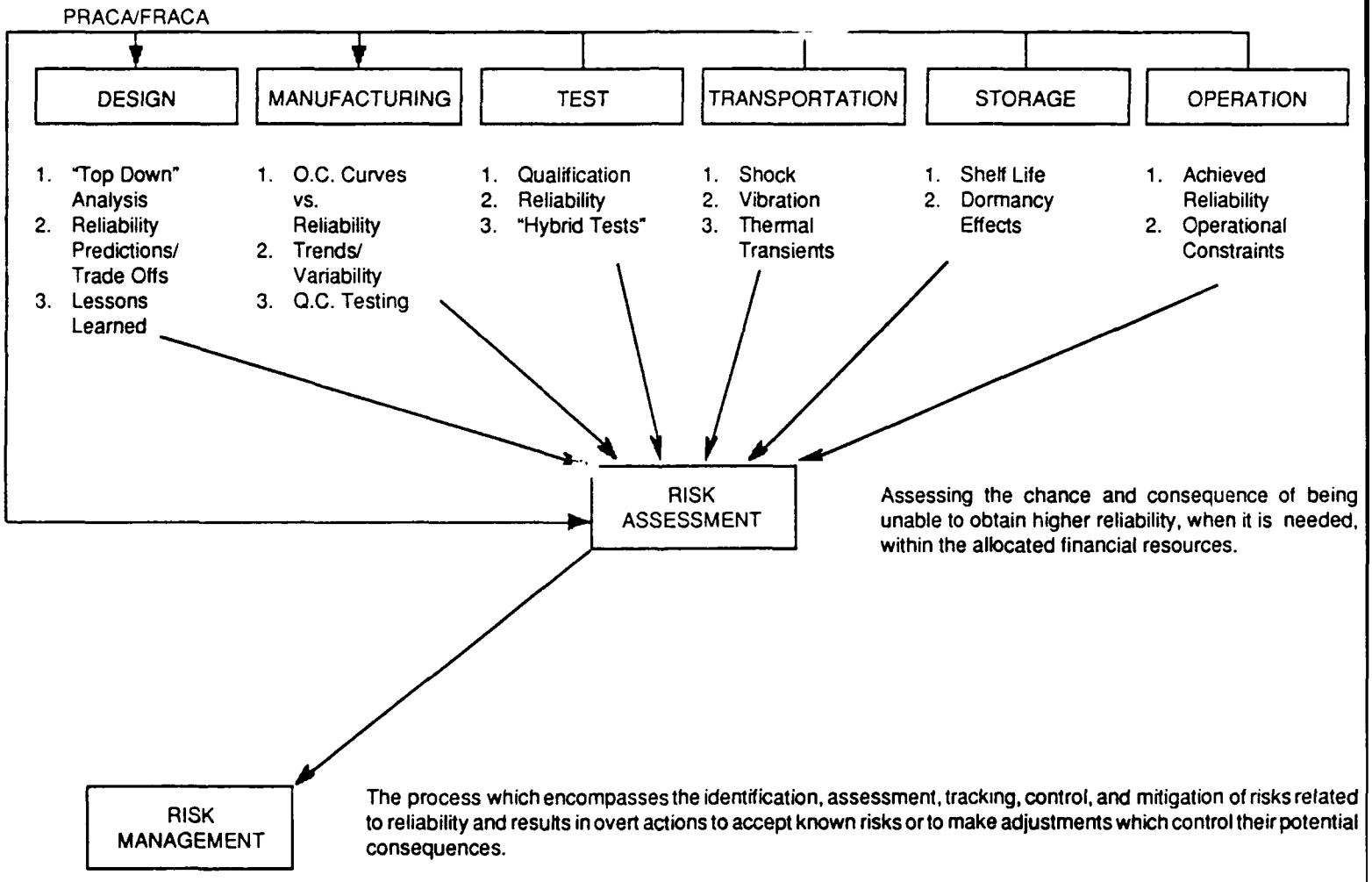


Figure 7. Infrastructure controls proposed to enhance reliability.

• Two of four interconnects on a cell are pulled as part of sampling test; failure probability per pull estimated as 0.25%; two tested interconnects are from either end of cell; data from immediately adjacent interconnects is not available.

- Correlation between pull strength values from same cell analyzed and found to be .38 for all lots tested, .54 for the ten "bad" lots tested, and .32 for "unknown" lots; value would be somewhat smaller yet if attention were restricted only to lots accepted by sampling process

- Correlation of .32 means that knowing the strength of one interconnect helps one predict the strength of a second interconnect on the same cell (.32 .32) = .10 or 10% more accurately than one could predict it without knowing the first value; the square of the correlation is known in statistics as the coefficient of determination.

• Probability of both interconnects failing is:

- PR (first failing) * PR (second failing/first fails);

- PR (A/B) read as probability of A given that B is known to occur

- If totally independent, PR (Second Failing/First Fails) = 0.0025

- If totally dependent, PR(Second Failing/First Fails)=1.0

- Since the 10% factor developed above measures the strength of the dependency which exists, it may be used to interpolate between .0025 and 1.0 to estimate PR (Second Failing/First Fails)

(1.0 - .0025) *.10 + .0025 = .10225

• Probability of two interconnect failures out of two on same cell is thus estimated at .0025 * .10225 = .00026

• Since adjacent interconnects are probably somewhat more correlated than those at either end of cell, and since degree of correlation is not known, if we assume that interconnects fail at both ends of the cell, then the cell will fail totally . Using this assumption will, of course, produce somewhat of an overestimate of probabilities. This overestimate is, however, small compared to the effect being observed.

- This means we will estimate the mission failure probability for a cell to be .00026.

- This equates to a cell failure rate of:

-LN(1-.00026)/26298 = 9.9E-9/HR

- A quarter string with 39 cells will thus have a failure rate due to interconnects conservatively estimated at 39 * 9.9E-9 or 386E-9/HR

• The impact of this new cell failure mode on the array is to change the failure probability from 6.25×10^{-6} to 6.21×10^{-4}, an approximate two order of magnitude change.

Qualitative Approaches - Product Design FMEAs - Although Product Design FMEAs are not unheard of in the aerospace industry, very few companies perform them. In essence, product design FMEAs are structured to identify sources of common cause failures (sometimes called "coverage factors" or "correlation factors" by propulsion manufacturers).

Although the following product design description is directed towards electrical/electronics components, a similar approach could be used for propulsion system components.

Product design Failures Modes and Effects Analyses (FMEAs) are performed to verify that hardware reliability and integrity is maintained when electrical/mechanical designs are implemented as hardware during the product design phase. This type of analysis is typically done between PDR and CDR after drawings become available, but before they are released.

This analysis is particulaly appropriate for examining areas where redundant or backup paths are in proximity.

When redundancy is implemented by using separate units, there is generally no need to do a product design FMEA inside each unit. However, this may not be true for high energy systems such as propulsion. In either case, unit external interfaces, e.g., input/output cross-straps, should be examined. Example: product design criteria are listed below. Results are documented on Product Design FMEA Forms. Where negative findings occur, remedial action is recommended. Adverse conditions are to be justified at design audits.

The following Reliability Criteria for Product Design are applied in performing product design FMEAs for printed circuit boards, connectors, and wiring interfaces:

Cabling, Hardnesses, and Wire Bundles

a) Assure that fault isolation exists.

b) The routing of all wire bundles shall be such that all possible locations where wire pinching or chaffing could occur are eliminated to prevent shorts to ground or shorts to different voltage or signal source.

c) Assure that the design prevents screw threads from coming into contact with wire/leads during assembly.

d) Provide for special sleeving where wire routing is adjacent to sharp edges.

e) Prevent excessive pinching of wires by cable clamps by properly dressing bundle and sizing clamps.

f) Spot bond or tie wire adjacent to standoffs and with reasonable distance between supports such that loads/joints are not degraded during exposure to vibration or shock.

g) No single wires or single solder joints shall be system single point failures.

Connectors

a) Similar connectors on a unit shall be keyed, color-coded, or have other mismating protection.

b) Physically separate power and ground pins.

c) Different polarity signals shall not have adjacent pin assignments (Vis.; +28Vdc, -15Vdc).

d) Sensitive low level signals should have pin assignments physically separated from high level power, high level signals, or ungrounded returns This should also apply to grounds.

e) Critical power or signal lines shall not have adjacent pin assignments.

f) Redundant power or signal lines shall not have adjacent pin assignments.

g) Review pin and slip ring assignments to assure that shorts between adjacent pins will not result in single point failures.

h) No single connector pin shall be a system single point failure.

Printed Circuit Boards

a) Review that redundant paths are kept physically separated as much as possible.

b) Traces carrying heavy current loads shall be verified as having adequate load carrying capacity per MIL-STD-275.

c) There shall be no open daisy chains for power or ground paths.

d) Sufficiency in the spacing between traces depends on trace voltages and conformal coating provisions. These should be reviewed against Standard Engineering Design Systems to confirm that trace-to-trace shorts will not occur.

e) A grounding circuit trace leading to board edge common ground should be filleted at the lead-in line to prevent development of cracks in circuit conductors.

f) Check that redundant paths don't go through the same piece part, e.g., a dual transistor or quad IC.

g) If there are any single PC traces or plated-thru-holds where an open would result in a system single point failure, hardwire should be added.

h) Care shall be taken to assure that high heat generating parts are isolated from cirtical signal paths (via distance/shielding) to preclude burnout of PC traces, etc.

i) Ensure that solder joints are inspectable. Avoid soldering flush-mounted parts near heat sinks or other items which might make the presence of solder balls undetectable.

j) Ascertain that the block diagram or schematic-illustrated redundancy is reflected by the wiring diagram.

k) Assure that solder reflow practices for boards (or within parts) will not reflow or degrade prior connections.

l) Handling and installation loads for cards and assemblies must be reviewed to ensure that stresses imposed on joints are within their load-carrying capability.

m) PC traces and wiring should be physically separated such that a fault is isolated and will not cascade to redundant or adjacent elements.

n) Verify that PC boards which contain redundancy or cross-strapping elements are adequately protected against shorts to ground (internal and external to the board) which could represent a system single point failure.

o) Plated-thru-holes shall have an aspect ratio (board thickness to hole diameter) or no greater than 3 to 1.

Function Expected* or Output Required

FUNCTION PROVIDED OR RESULTING OUTPUT			0	1	2	3	4	5 . . . n
	(WRONG TYPE)	0						
		1						
		2						
		3						
		4						
		5 ⋮ n						
	(WRONG QUALITY)	More of (n+1)						
		Less Than (n+2)						
		As Well As (n+3)						
		Part of (n+4)						
		Reverse (n+5)						
		Other Than (n+6)						

*Obtained from a clear, concise, unambiguous set of Engineering functional descriptions

Figure 8. Top down matrix.

Manufacturing Control FMECAs (See Appendix B: MCDAC Trip report) - In the case of the manufacturing control FMECA, the FMECA should be conducted incrementally by reliability engineering during the design phase to identify single point failure modes. The FMECA should be used in the Critical Item Control process by identifying critical items and the causes of critical failure modes. Proper design controls would then be implemented for each critical item and can be verified by a Manufacturing Control Plan. FMECAs should be supplemented with failure history prior to FMECAs of related designs and, along with the failure history, should be made available to designers.

A manufacturing Control Plan should contain as a minimum the following task:

- Identify flight critical items (FCIs) using FMECAs
- Determine flight critical characteristics for each FCI
- Identify specific manufacturing methods for each FCI
- Prepare Manufacturing Flow Chart and annotate
- Identify Process Control for each select manufacturing method
- Identify test and/or inspection methods for each select manufacturing method

Top Down Analysis (L. Booth Method) - The most common criticism of FMEAs is the possibility that not all conditions causing system anomalies, malfunctions or failures are attributable to inherent component failures.

One way to address this concern is by conducting a "Top Down" analysis. A Top Down analysis is conducted by accomplishing the following tasks:

- Obtain a clear, concise, unambiguous set of engineering functional descriptions
- Form a matrix as shown on Figure 8
- For each intersection (square) on the matrix, describe the system condition (i.e., 0 = nominal thrust, n+6 (other than) = wrong direction). Therefore, (0, n+6) means correct thrust, wrong direction. The square (0,0) indicates correct nominal thrust was required and correct nominal thrust was delivered.
- Each square of the matrix is a potential "Top Event" (undesirable condition).
- Explore each top event (using fault trees, event trees or similar techniques) until all conditions leading to the top event have been exhausted.

Risk Assessment (reference Figure 7) - Risk assessment can be characterized as follows:

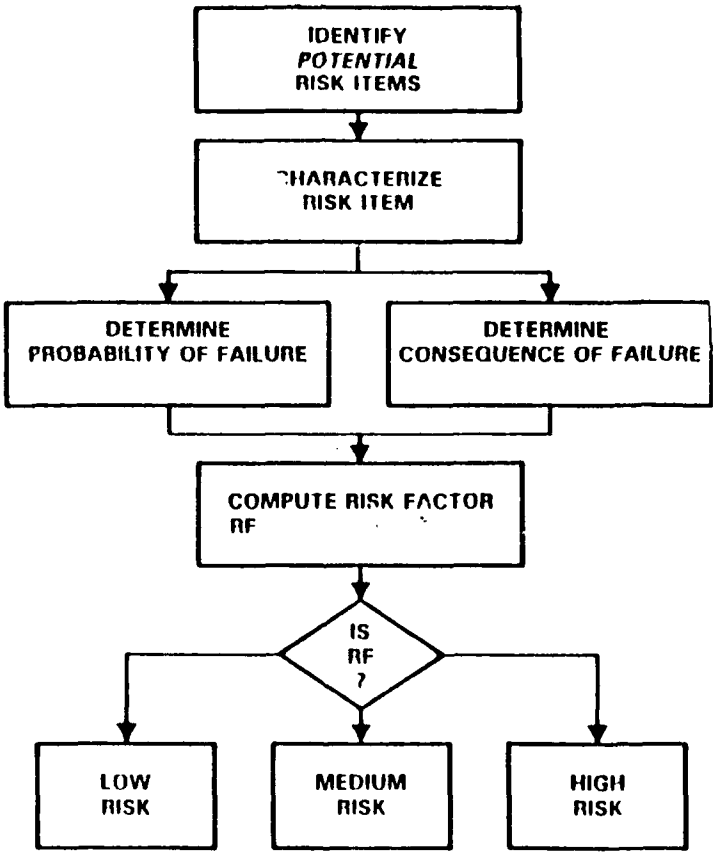
- Risk assessment is the process for estimating the risk associated with a particular alternative course of action
- Risk assessment considers probability of failure and consequence of failure as they relate to technical performance, schedule, and cost

Where

Risk is the probability and consequence of not achieving some defined program goal and is a function of:

- Probability of failure
- Consequence of failure
  - Increased Cost
  - Extended schedules
  - Reduced performance

Risk assessment involves these steps indicated in the following diagram:



Where risk levels are defined as:

High - The problem is obvious and there is a high probability of failure to meet reliability, performance, schedule or cost objectives. Monitoring and control must be rigorous, with frequent update of risk status. A fall-back or alternative system or plan is mandatory.

Medium - The problem is identifiable and would impact program reliability, performance, schedule, or costs. The probability of occurence is high enough to require close control of all contributing factors, establishing of risk management milestones, and an acceptable fall-back position.

Low - The problem is identifiable and would impact program objectives, but the probability of occurrence is low as to cause no concern other than normal monitoring and control.

2.3.2 Risk Management

Risk management is the process which encompasses the identification, assessment, tracking, control and mitigation of risks related to reliability and results in overt actions to accept known risks or to make adjustments which control their potential consequences.

Risk assessment assesses the chance and consequence of being unable to obtain higher reliability, when it is needed, within the allocated financial resources.

Establishing Factors - In order to assess and manage risk, factors must be established based on technical risks. Factors can be characterized by using the two following matrices (Figures 9 and 10).

Assessing Economic Risk - Given the information of sections 2.3.1.3 and 2.3.2.1 are available, the most efficient way to assess economic risk is to use an established model tailored to the rocket industry. The model accounts for both production and operational processes that would be impacted by unreliability. Additional economic modeling of the cost of unreliability to customer communities is essential to gain a meaningful estimate of economic risk. Economic models must evaluate the actual cost of finite activities required to reduce risk by finite amounts.

In the case of launch vehicles, most individuals recognize the direct costs of unreliability such as residual hardware that is scrapped due to more rigorous inspections or redesign effort. The incorporation of additional quality control that slows production rates and operational process timelines while increasing the total amount of personnel and facilities that are required to support the vehicle is a more subtle cost effect of unreliability. The largest cost is related to payload communities that suffer direct losses in the form of lost hardware and higher insurance rates, as well as launch schedule backlog effects that result in program slippage that has cost of money and cost of storage implications. Actual costs of unreliability are difficult to estimate accurately, but the costs may be bounded from documented historical events that give a real estimate of cost risk exposure.

Perhaps the greatest single "cost" of unreliability can be related to loss of strategic capability at critical time windows. For the military, this may be the absence of reconnaisance capability during evolving international crises or a less capable navigation or communications environment for operations. For the private sector, the strategic loss may be in the form of lost opportunity to penetrate specific markets at advantageous time windows. Unreliability also results in loss of national stature and a hinderance in the ability to successfully compete with the international community.

The economic risk of unreliability is but one element of the overall risk assessment. The overall risk is a combination of economic risk, schedule risk, and mission capability risk. In essence, the approach would be to assign relative figures of merit (ranging from 0 to 1) of each of the risk factors of Figures 9 and 10, then compare the summed risk factors against a cost of reducing the overall risk. The program manager can then look at the relative cost benefit of risk reduction investment options that assures ultimate program viability.

Maturity Factor		Complexity Factor		Dependency Factor
Hardware	Software	Hardware	Software	
Existing	Existing	Simple design	Simple design	Independent of existing system, facility, or associate contractor
Minor redesign	Minor redesign	Minor increases in complexity	Minor increases in complexity	Schedule dependent on existing system, facility, or associate contractor
Major change feasible	Major change feasible	Moderate increase	Moderate increase	Performance dependent on existing system performance, facility, or associate contractor
Technology available, complex design	New software, similar to existing	Significant increase	Significant increase/major increase in a number of modules	Schedule dependent on new system schedule, facility, or associate contractor
State of art, some research complete	State of art, never done before	Extremely complex	Extremely complex	Performance dependent on new system schedule, facility, or associate contractor

Figure 9. Typical top-level factors contributing to probabilty of failure.

Typical Top-Level Factors Contributing to Consequence of Failure

Technical Factor	Cost Factor	Schedule Factor
Minimal or no consequences, unimportant	Budget estimates not exceeded, some transfer of money	Negligible impact on program, slight development schedule change compensated by available schedule slack
Small reduction in technical performance	Cost estimates exceed budget by 1 to 5 percent	Minor slip in schedule (less than 1 percent), some adjustment in milestones required
Some reduction in technical performance	Cost estimates increased by 5 to 20 percent	Small slip in schedule (1 to 10 percent)
Significant degradation in technical performance	Cost estimates increased by 20 to 50 percent	Development schedule slip (10 to 30 percent)
Technical goals cannot be achieved	Cost estimates increased in excess of 50 percent	Large schedule slip that affects segment milestones or has possible affect on system milestones (greater than 30 percent)

Figure 10. Typical top-level factors contributing to consequence of failure.

3.0 (TASK 3) QUANTIFICATION AND PRIORITIZATION OF METHODOLOGIES

In many cases, there is insufficient information to completely quantify and prioritize the methodologies that have been identified. In other cases they are difficult to prioritize because of the qualitative nature of the methods. In any case, thorough testing of the various methodologies should be the subject of future studies (see recommendations).

3.1 Testing of Quantitative Methods

Three areas of study appear to be promising. They are:

- Comparison of the methods of Section 2.2
- PRACA/FRACA Trending
- Connecting Operating Characteristic Curves to Reliability

3.1.1 Comparison of the Methods of Section 2.2

Section 2.2 includes a description of a selected number of quantitative methods intended to indicate reliability growth as well as demonstrating the achievement of a prescribed reliability goal.

Four of the methodologies - Binomial model, Beta-Binomial model (Bayesian Estimation), Lloyd's model and Shen's model for estimating reliabilities of launch vehicles from attribute data are introduced and compared in a preliminary manner.

Binomial Model - The simplest way to estimate the reliabilities of launch vehicles is to use the Binomial model. It is easy to perform the calculations, but a large size sample is required to demonstrate high reliability. The results obtained by applying this model do not account for the reliability growth effect expected during the developmental history of the launch vehicles.

Beta-Binomial Model (Bayesian Estimation) - The Beta-Binomial model is based on the Bayesian Estimation. In this model, several similar components are treated as a single class. The probability p of each component in the class is assumed to be constant but will have different values from component to component [i.e., g(p)]. If the Binomial distribution is used to obtain the probability of K failures in n tests for each component, the conjugate distribution g (p) for the class is the Beta distribution. This model weights the reliability growth effect and can be applied to forecast the reliabilities of launch vehicles. The detailed theoretical analysis can be found in Ref. 19, "Bayesian Reliability Analysis" by Harry F. Martz and Ray A. Waller, 1982. The disadvantage of this model is that it is very difficult to separate the total sample data into several similar components, unless we have the detailed engineering analysis and each failure model at the different periods of the launch vehicle developmental history.

Lloyd's Model (Ref. 14) - In Lloyd's model, the rationale is that when engineering corrective action for a failure is implemented, the probability of recurrence of that failure is reduced; therefore, such failures should not be carried as full failures in subsequent reliability estimates. The failure value for each failure model is assumed to be

$$f = 1-(1-\gamma)^{1/n} \qquad (1)$$

where γ is the confidence level and n is the number of successful tests after corrective action.

Based on a detailed engineering analysis for each failure mode, the result of failure number for each failure mode can be obtained by solving eq. 1. The final result of the reliability estimation is $R = 1 - \Sigma f/N$, where Σf is the cumulative failure number of all failure modes. N is the test number.

This model weights the growth effect and can be extended to forecast the reliability. For this model one needs to know not only at which launch number the failure occured, but also at which launch number the failure was corrected. The confidence level chosen in eq. 1 directly affects the final results and is difficult to justify. The confidence level for the final result $R = 1 - \Sigma f/N$ is not clear.

Shen's model (Ref. Appendix A.3) - In Shen's model, the reliability Rn of a launch vehicle at the n^{th} launch is obtained as

$$R_n = 1 - U_n = 1 - [F_n / L_n - 2 / L_n \sum_{i=1}^{N} (F_i - F_{i-1} / L_n - L_i) / N] \quad (2)$$

where U_n is the unreliability at n^{th} launch

F_n is the cumulative failure number at n^{th} launch

L_n is the n^{th} launch number

F_i is the cumulative failure number at i^{th} launch

L_i is the i^{th} launch number.

The term F_n / L_n in eq.2 is the estimated average unreliability at the n^{th} launch. The term

$2 / L_n \sum_{i=1}^{N} (F_i - F_{i-1} / L_n - L_i) / N$ in eq.2 is the corrective unreliability caused by growth effect.

This model is simple and easy to apply. It weights the growth effect and can be extended to predict the future reliabilities of the launch vehicles. The final results of the model are obtained directly from the collected data in which only the launch numbers at which the failures occured need to be known.

However, since this model does not assume any knowledge of what changes were made subsequent to failures, it does not directly incorporate the effects of engineering analysis and corrective action taken after each failure. For this reason, its reliability growth forecast lags that of Lloyd's method.

From the above analysis of these four methodologies, the Lloyd's model and Shen's model are considered to be the better models for estimating reliabilities of launch vehicles.

Fig.11 illustrates the results by applying Lloyd s and Shen's models to an example from Ref. 1. As we can see, the tendencies of the results for both models are similar, the values of estimating reliability from Lloyd's model are higher then those from Shen's model.

In the present study, based on the collected data, the Shen model is used to estimate the reliabilities for twenty-four U.S launch vehicles. The growth trends obtained from the model are shown in Figures 11a, and 11b for the Delta and Titan families of launch vehicles.

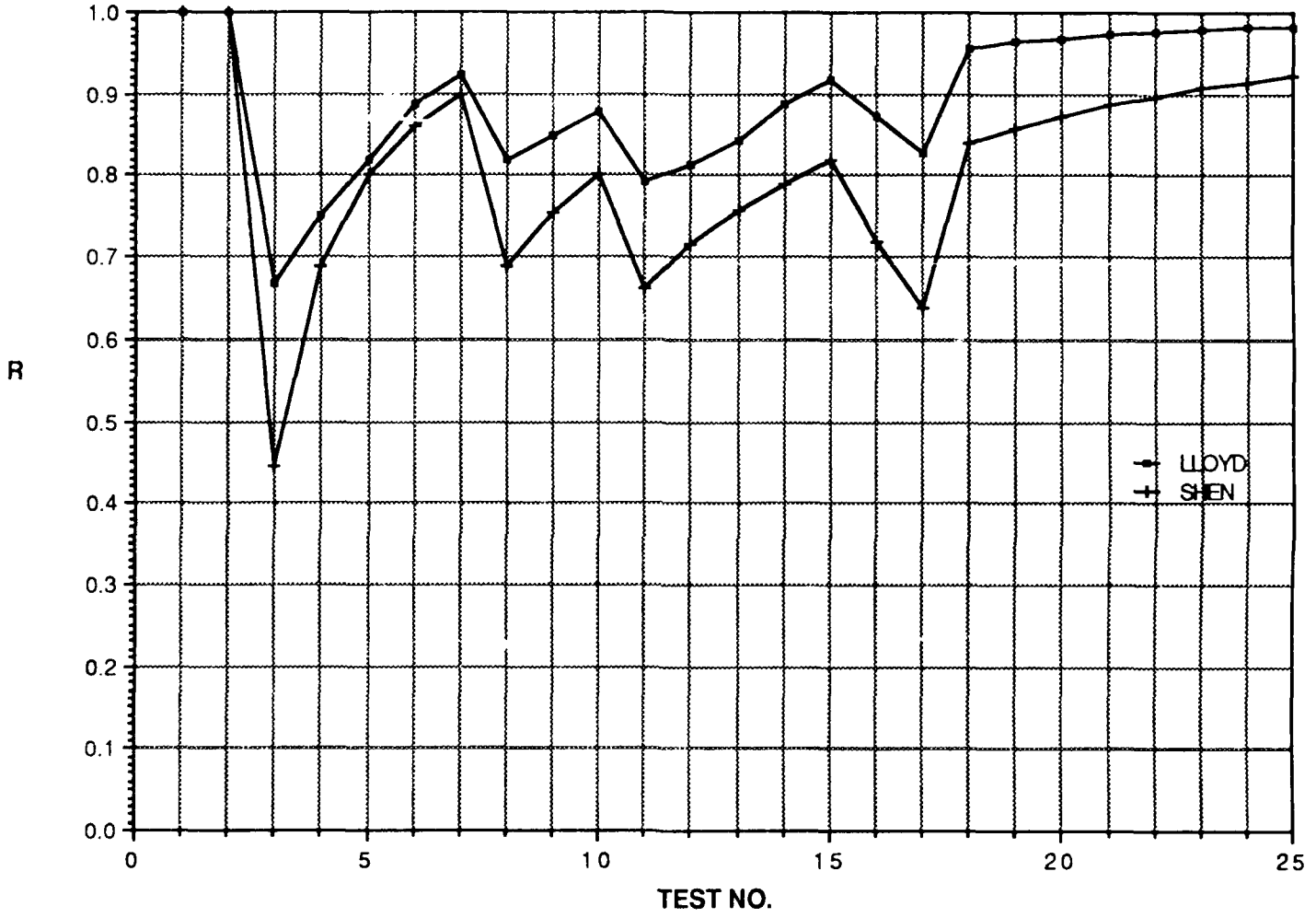


Figure 11. Lloyd vs. Shen comparison.

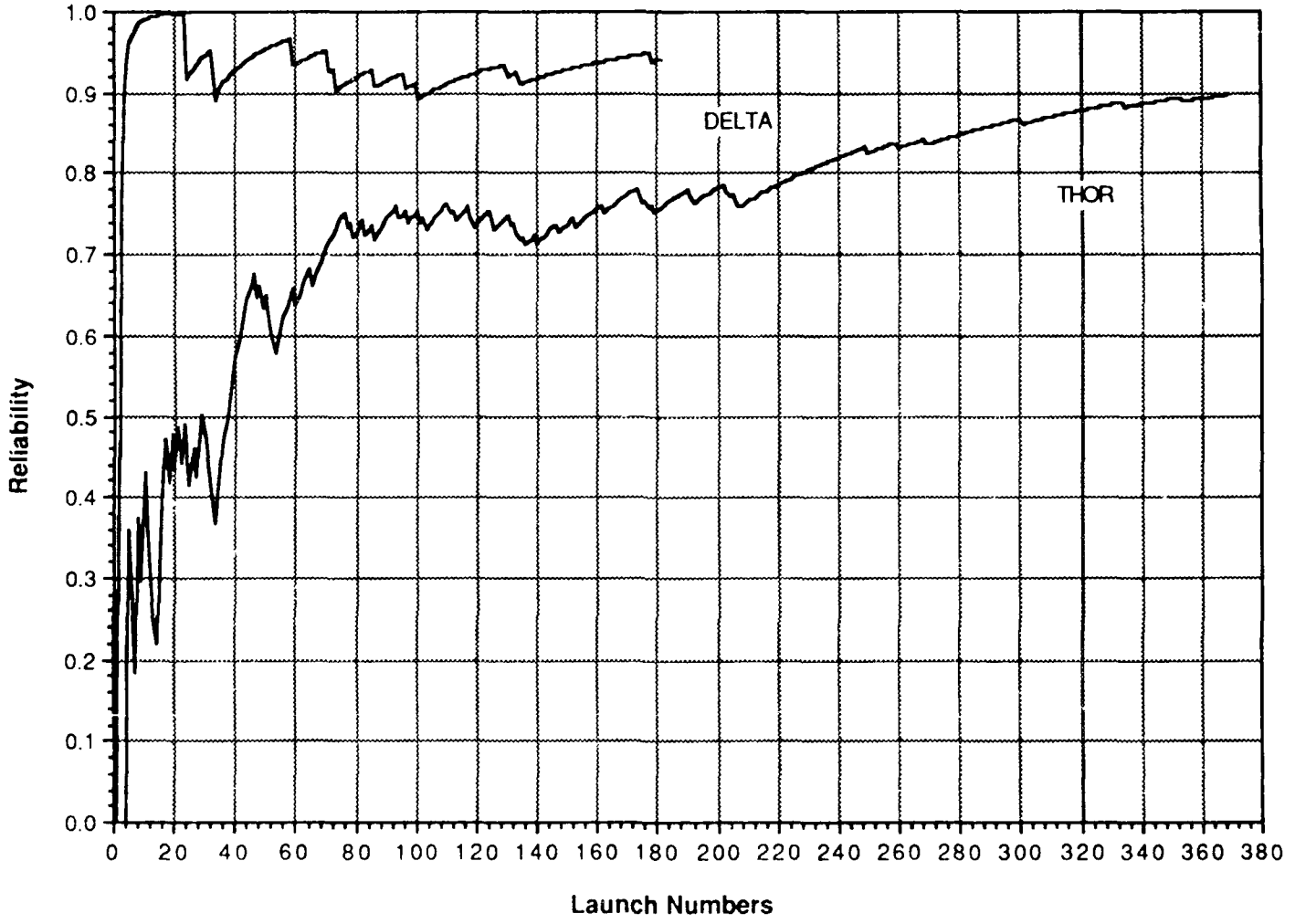


Figure 11a. Reliability estimation of Thor and Delta.

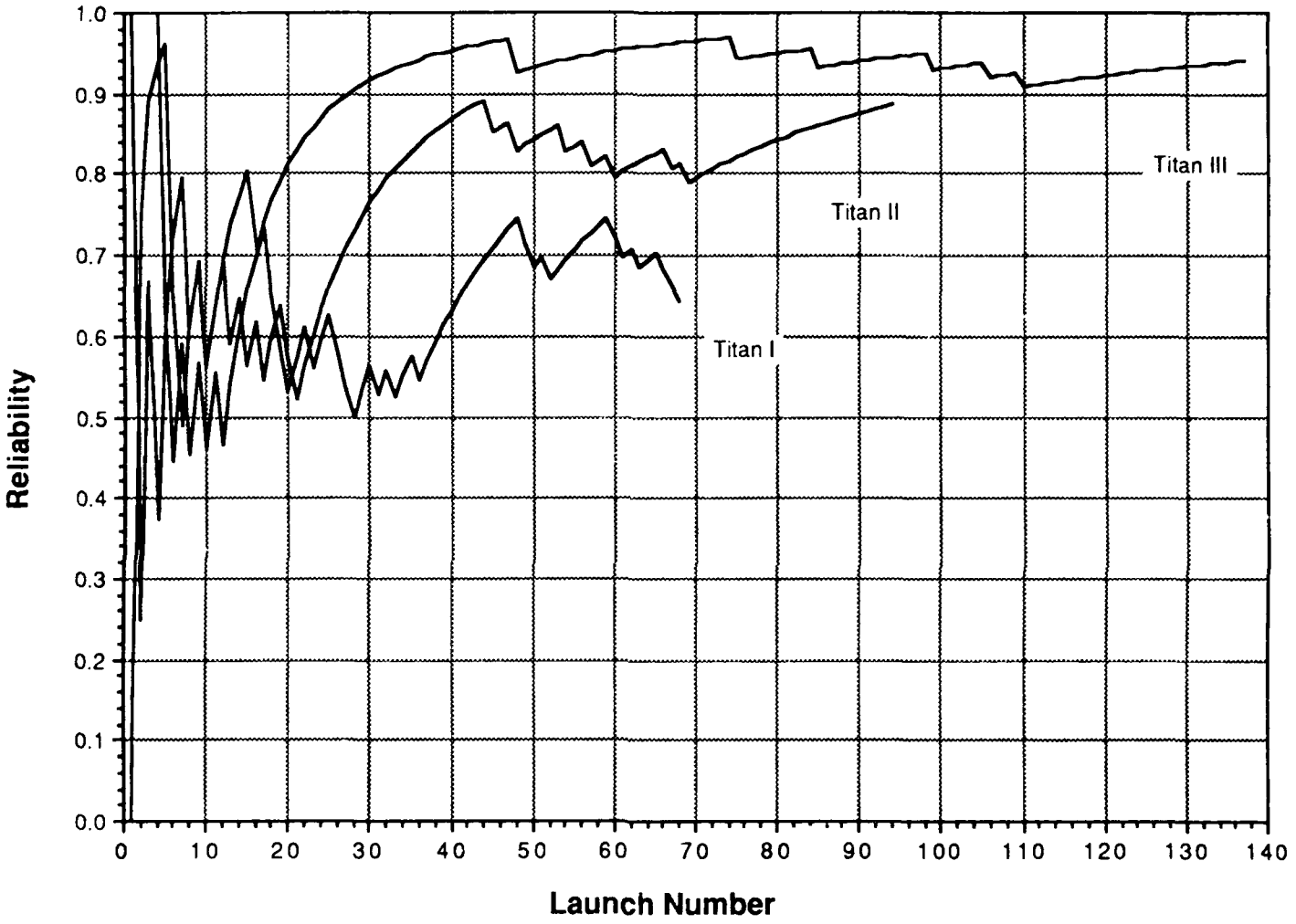


Figure 11b. Reliability estimation of Titan I, II, III.

3.1.2 PRACA/FRACA Trending

An additional dimension could be added to PRACA/FRACA system to allow trending if a "cradle to grave" concept were established. Under the current circumstances PRACA/FRACA systems frequently report only through the testing phase (except for reusable systems) and do not always report on total time and cycles on both failed and unfailed components.

In addition, PRACA/FRACA systems should include not only failure phenomenon but precursors to failure problems as well. Such precursor problems should include unexpectedly low margins or larger than expected variability. The corrective actions should be accomplished interactively with system functional descriptions and the FMECA to insure that those efforts are up to date while the search for root cause is pursued.

In order for an evaluation of PRACAs/FRACAs trending capabilities to be affected, a pilot program needs to be established using the trending techniques of reference 2.

3.1.3 Operating Characteristic Curves and Reliability

An example was given in Section 2.3.1.1 correlating operating characteristic curves to failure modes and failure rates. Reference 17 illustrates some recent work in this area. In this work an effort was made to tie safety factors developed in the traditional engineering approach to resulting structural reliability using a probabilistic representation of these traditionally developed factors.

Figure 12 illustrates the relationship of defect rates (quality of submitted lots) to operating characteristics (OC) curves. In this way, changes in sampling plans and procedures could be linked to criticality ranking in FMECAs.

For example, suppose the amount of moisture in a bonding liner polymer used in solid rocket motor cases is linked to poor quality of bonding, thus to separation. A change in the sampling procedure could reduce the defect rate and reduce the potential for failure by a similar amount.

A study should be undertaken to test the validity of such a link.

3 2 Evaluation of Qualitative Methods

As was noted earlier, it is difficult to prioritize qualitative methodologies. However, the three methods that do show promise based upon the information obtained from this study effort are:

- Top Down Analysis
- Product Design FMEAs
- Manufacturing Interfaces

Tests of these techniques could help to more firmly establish these capabilities. Suggested tests are defined below:

3.2.1 Top Down Analysis

In order to rate the value of "Top Down Analysis" when conducted in accordance with the method

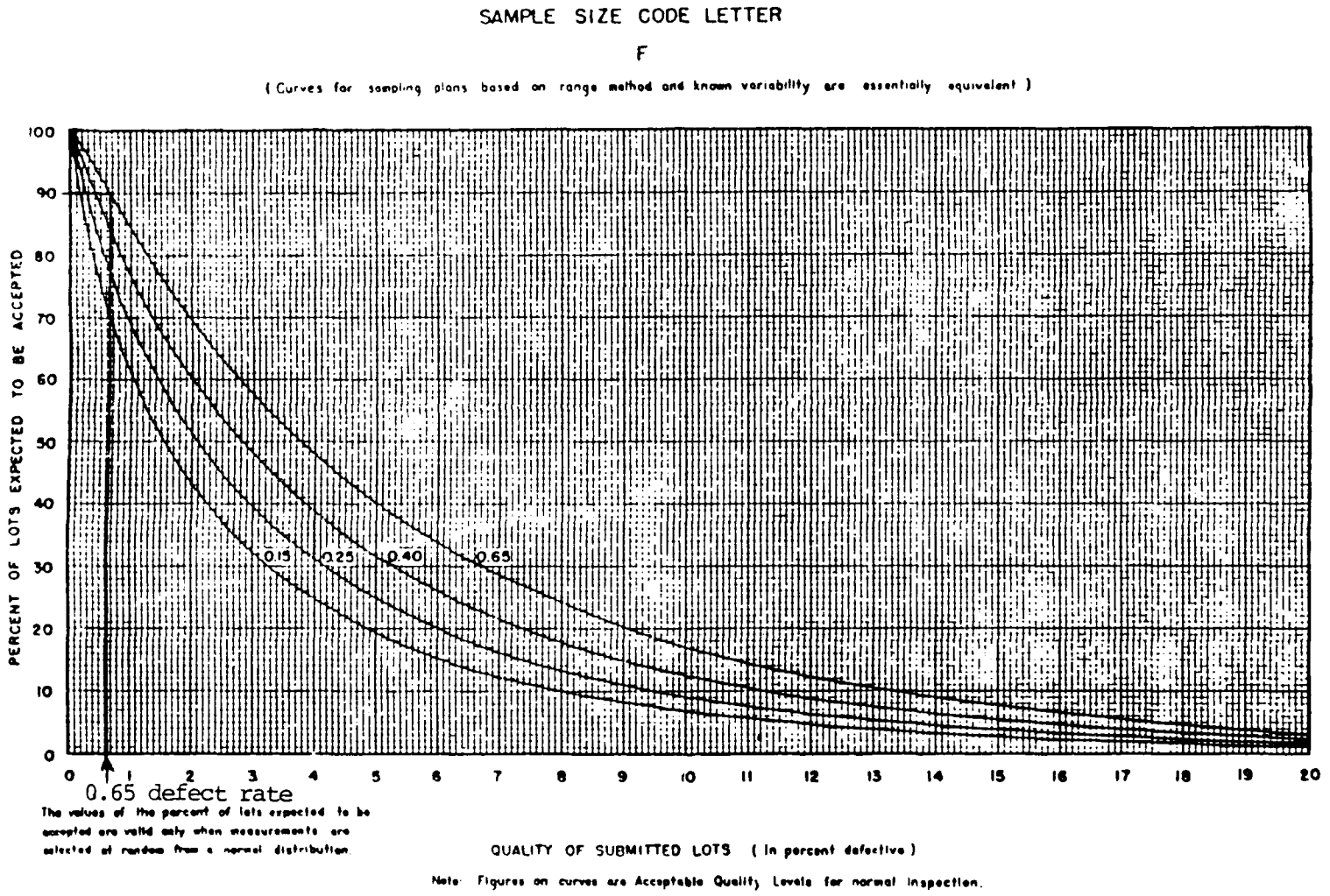


Figure 12. Operating characteristic curves for sampling plans based on standard deviation method.

described in Section 3.2.1.2, the results of an FMEA should be compared to the results of a Top Down analysis.

3.2.2 Product Design FMEAs

Product Design FMEAs have proved to be valuable in identifying and eliminating sources of common cause failures in electrical/electronics applications (see Section 2.3.1.2). A study should be undertaken to see if a Product Design FMEA would be fruitful when applied to the non-electronic propulsion subsystems.

3.2.3 Manufacturing Interfaces

Flight critical item and manufacturing control plans have a great deal of potential for controlling critical items as described in Section 2.3.1.2 "Manufacturing Control FMECAs". The effectiveness of such an approach remains to be demonstrated, however. A study should be undertaken to demonstrate the effectiveness of manufacturing control FMECAs.

3.3 Prioritization of Methodologies

The prioritization of methodologies cannot be completed until the studies described in this section are completed.

KEY RECOMMENDATIONS

The following areas have been identified as having significant reliability impact. These areas each warrant further in-depth study if the high reliability goals of the Air Force advanced launch vehicle programs are to be achieved in an operational system.

1. Failure Correlation*

The percentage of failures which are likely to impact more than one engine in a multi-engine design is of critical design import. This percentage, or "failure correlation factor," must be well below 20% for reliability oriented design approaches such as engine out capability to be effective. The lower this percentage the more effective is this hueristically pleasing design option. Not surprisingly therefore, contractor new engine design characteristics quote extremely low factors (as low as 1%). Correlations as low as 1 out of 100 do not seem consistent with other design parameters specified (such as high chamber pressures) and are considerably lower than factors achieved on recent engine designs (e.g. 17% for the shuttle main engine test program). Finally, there did not appear to be any significant consideration given to how these low factors would be achieved in practice.

Recommendation 1 - Failure correlation factors are key reliability parameters to Air Force launch vehicle design decision makers. Specific studies such as parameter design studies which address what factors have been achieved in the past and what design trades have been made to ensure the low factors quoted will be evident in the resulting designs appear to be lacking. It is recommended that these investigations be made prior to the selection of any design alternative.

2. Variability Control

The currently achieved launch vehicle reliability has been shown by this investigation to be below 0.95. However, the investigation uncovered examples of reliabilities in other somewhat similar systems, such as tactical missile systems, which routinely achieve 0.99 and some which approach 0.999. These systems whose operational reliabilities currently meet or exceed the reliability requirements for the Air Force advanced launch system have achieved these high reliability levels through the use of intensive variability control programs. While it would be inappropriate to make any direct correlation between tactical missiles and launch vehicles, it is also clear from a review of the failure data of mature launch systems that the barrier to significantly higher reliabilities may be the residual variability inherent in the current launch vehicle production process. A cursory review of other somewhat comparable products, such as commercial jet engines and gas turbines and recent Air Force variability reduction studies performed as part of the R&M 2000 program, provide further support for this argument.

Recommendation 2 - Residual variability may be the key barrier to high launch vehicle reliability achievement. For this reason, it is recommended that investigations be made into the effectiveness of specific variability control programs such as Taguchi methods or alternatives. These investigations should be directed at determining the applicability of the methods to the launch vehicle production process. It is further recommended that some specific program for variability control be included throughout all phases of the advanced launch system program.

* The definition cited here is broader than that used traditionally by propulsion system designers. See Appendix A.1 for discussion of the difference.

3. Reusability

Reusability is, on the surface, a design goal of significant program benefit. However, the benefits of reusability are significantly compromised if the reliability of an engine is adversely affected by the requirement. Besides the direct costs involved in developing a reusable design, there also appears to be significant indirect costs which are required to maintain reliability in a reusable design. For example, reusability by its very nature tends to decrease the production run. When production runs are decreased, investments in automated production equipment become less economical and the production process therefore tends to become more prototypical. Prototypical production, especially of complex equipment, increases the problems associated with variability control and therefore substantial postproduction testing may be required to ensure high reliabilities. A good example of such an indirect impact on reusability was seen at the Rocketdyne SSME production facility in Canoga Park, California.

Recommendation 3 - Reusability has been shown to have indirect and potentially negative impacts on the achievement of high reliabilities at reasonable cost. The indirect impacts of reusability on reliability and cost through such mechanisms as variability control problems should be thoroughly investigated and the results of this investigation included in the programmatic decision making related to reusability.

4. Risk Management

Achievement of high operational reliabilities in such areas as nuclear power plant safety systems have been significantly supported by a continually active program that attempts to identify the risks to reliable operation and to address them according to their importance. Such a risk management program has been investigated and recommended by NASA SRM & QA for future projects, but it is not clear whether a risk management program is planned for the acquisition of advanced launch systems.

Recommendation 4 - The Air Force should investigate the advisability of incorporating a risk management program as an integral part of any launch system program.

5. Reliability Performance Indicators and Trending

For high reliability programs it is important to identify, early on, symptoms of the process which presage deterioration in performance. This has been done in the financial community, in the commercial aircraft community and in the nuclear power safety community by the development of a set of "leading" performance indicators and developing performance trends based upon the indicator trajectories through time. If such a set of indicators could be developed and trended for the Advanced Propulsion Systems program, the indicator trajectories might provide early warning of problems arising during development and operation. This early warning could provide the time required to institute corrective action before actual program reliability performance is affected.

Recommendation 5 - The Air Force should develop as part of advanced propulsion system development programs a set of potential indicators of programmatic reliability performance. This indicator set should be based originally on historical information, but later updated and validated as advanced propulsion system development programs specific information becomes available.

6. Reliability Growth Analysis

In all developmental systems a certain degree of reliability growth is to be expected. However, program managers need to know the pace of the expected growth so that they can determine if the program is likely to meet the operational reliability goals within developmental time constraints. An understanding of the growth process is therefore essential to the determination of the proper role to be played by history in the forecasting of future system reliability. If an historical failure has been analyzed and its cause determined and suitable corrective action is implemented to prevent its recurrence, it is recognized that it would have its probability of occurring again diminished when it is utilized for predicting future performance. But by how much? The determination of how much each failure should be counted is important in order to establish the proper "calibration" for the reliability growth characteristic to be used to determine how well reliability development is proceeding. Several approaches have been developed to address the issue of growth. Among those developed are the early works of Duane at GE, that of David Lloyd of TRW, and that developed by Dr. Yu Shen of SAIC as part of this study. In addition, Bayesian approaches may show promise for improved growth forecasting.

Recommendation 6 - Reliability growth forecasting is important during the development of systems with high reliability requirements such as ALS. Accurate growth forecasts allow program managers to determine early on if reliability requirements are likely to be met. (This is especially important when program economics prohibit extensive development test flights as is the case with ALS). Several methods currently exist to allow for forecasts to be generated; however, further development is required to assure that a reasonable growth forecast is developed for advanced propulsion system development programs. It is therefore recommended that the concept of reliability growth be further developed as it applies to advanced propulsion system development programs.

Further Recommended Studies - The recommended studies as discussed in Section 3.0 are judged to be somewhat less in importance than the Key Recommendations above. Nonetheless, the following recommended studies could have a significant impact on reliability.

1. Detailed Comparison of the Methods of Secion 2.2

2. PRACA/FRACA Trending

3. O.C. Curves and Reliability

4. Top Down Analysis

5. Product Design FMEAs

6. Manufacturing Interfaces

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Appendix A.1

An Investigation of Historical Failure Correlation Using the Shuttle SSME Test and Flight History as an Example

INTRODUCTION

Given the current state of rocket engine technology there exists a finite probability of a catastrophic engine failure during a vehicle launch. A catastrophic engine failure is considered one in which the engine does not shut down in a controlled manner and includes uncontrolled fire, explosion, breach of the pressure boundary, shrapnel, or a combination of these. Given that an engine has failed catastrophically in flight an immediate concern is for other critical hardware in the vicinity of the failed engine. For vehicles configured with multiple engines in a cluster the question become whether the catastrophic failure of one engine will result in the catastrophic loss of the entire engine cluster.

This study develops the correlation between a catastrophic failure of a Space Shuttle Main Engine (SSME) and the propagation of that failure to include the entire SSME three engine cluster.+

SSME FAILURE DATABASE

The SSME database used for this study consists of ground test and flight data from May 19, 1975 through April 20, 1988. The database includes 1480 records detailing the SSME exposure history by test and date.

Significant SSME events which have resulted in damage or the loss of hardware are classified by NASA as major incidents. Catastrophic engine events are a subset of the events classified as major incidents. A catastrophic event is one in which its occurrence in flight results in significant uncontained engine damage and subsequently in the loss of crew and vehicle. The consideration of major incidents is the basis for developing the correlation of failure factor for the SSME.

Within the total SSME experience there have been 36 major incidents. Of these 32 of these incidents have been during single engine ground tests, which must be judged as applicable to this study and whether the event would have resulted in damage to an engine cluster. Three of the major incidents occurred during three engine cluster static firings and it should be noted that none of these events resulted in damage to the other engines in the cluster. The remaining major incident occurred in flight during the STS-11 mission and again did not result in damage to the cluster, however, this event occurred late in the engine burn with no consequence to the engine involved and the engine shut down at its programmed time.

The failure events included in the study consider all SSME history and has not been filtered. Since the major consideration is to determine the probability of cluster failure given an engine failure has occurred, all of the SSME experience is considered. Thus, engine configuration, test objectives, power level, subsequent hardware redesigns, etc., are considered irrelevant. The object of this study is not to determine whether the SSME will fail, but, given that one has failed, to determine the probability of an entire cluster failure.

Failure Criteria - Not all of the 36 major incidents are applicable to this study. Since the study involves failures which could potentially affect or damage other engines of the cluster an appropriate screening criteria is required in order to determine which of the major incidents in the database are applicable. The criteria used to develop the correlation of failures must consider only those events which either directly damage the cluster due to shrapnel, for example, or which indirectly result in cluster failure by disrupting the fuel flow to all engines.

+ During the course of this study a discrepancy in the definition of "correlation factor" was discovered between the propulsion system developers and the ultimate launch vehicle users (here the US Air Force). The propulsion system developers limit correlated failures only to catastrophic engine failures which would propagate to a cluster as discussed in this section. To the user any failure which causes loss of more than a single engine whether via catastrophic failure, unscheduled shut down, loss of fuel supply, improper thrust vectoring, etc. so that the payload to orbit capability is jeopardized is a correlated failure. In this way, catastrophic engine failures which propagate are only a subset, albeit an important one, of all correlated failures.

The following criteria were used to determine which of the major incidents should be considered applicable for this study:

Uncontrolled SSME Shutdown - The event occurred in such a way that the SSME controller was not in control of the shutdown sequence. That is, the failure mode is one which can not be or is not redline protected; or even though redline protection exists and may have been activated, the action of the controller is insufficient or is not fast enough to maintain control of the event.

Uncontained Hardware Failure - The failure of an engine component results in uncontained damage or damage propagation to other major components such as in the case of an uncontrolled oxygen fire or in the event of an explosion in which debris and shrapnel cause subsequent hardware failures. Of primary concern to the surrounding engines of the cluster is breach of the engine pressure boundary and the release of hot gas, fire or shrapnel.

Retirement of an Engine from Further Testing - Due to the limitations in some of the failure descriptions additional data is required to make a judgement as to the applicability of an event. One readily available piece of information is the subsequent disposition of an engine following an event. Retirement of an engine from the test program is generally a good indication that the damage to the engine resulting from the incident was severe enough to preclude use of the hardware in the future. It is recognized, however, that this is not a definitive indicator of severe engine damage since engines are retired as a function of their firing exposure as well as according to damage resulting from testing.

The above criteria are thus used to determine if a major incident should be considered an applicable failure to consider in developing the correlation of failure factor. Once the event is judged applicable a final criteria is used to determine if there is the potential for damage to the engine cluster.

Damage to Surrounding Hardware - Only in the flight configuration and in the three engine cluster static firing is direct indication of damage to an adjacent engine available. Thus, for single engine test firings an indirect indication of propagation of the failure to adjacent engines is damage to surrounding hardware, particularly the test stand itself. The extent of damage to the test stand is generally available and provides a good indication of the severity of the failure.

Due to the limited data available at the time of this study, for incidents in which the available failure description is not sufficient to determine the extent of damage to the surrounding hardware one available piece of data is the test stand down time following an event. Note that a long down time following an event is not necessarily an indication of damage to the test stand, but may indicate a lack of available test hardware, schedule considerations, ongoing failure investigation, or the installation of the next test engine. However, a short down time following an event is a definite indication of little or no damage to the test stand.

If essentially no damage to surrounding hardware resulted from the incident then propagation to the cluster is not considered likely. If damage was done to the surrounding hardware or the test stand the severity of the event is considered and a judgement is made as to whether the event would propagate to the cluster. Events in which the effect on adjacent engines is not clear are ranked as not propagating to the cluster.

Application of this criteria thus provides a framework within which to judge the 36 major incidents as to whether they are applicable to this study. Given that a failure is considered applicable for final consideration, and based on the severity of the post event damage, it is ranked as to whether the event would propagate to a cluster failure.

SSME FAILURE SUMMARY

There are a total of 36 major incidents in the SSME database which were evaluated for the purposes of this study. Of these, 18 are considered to be applicable to this study in that they meet the criteria described previously. They are indicated in the failure summaries by an asterik (*) following the test number. Of these 3 major incidents are considered failures which would have propagated to adjacent hardware and would result in failure of the entire cluster. These are indicated by an additional asterik (**).

Table 1 summarizes all 36 of the major incidents considered in this study. In addition to providing information about the event, such as test number, test date, engine number, configuration, the table details the results of implementing the criteria evaluation.

SSME MAJOR INCIDENT DESCRIPTIONS

The SSME major incidents are discussed chronologically in the following paragraphs. The event is described and the rationale for its use in developing the correlation of failure factor is discussed.

Test 901-110* - During test 901-110 (UCR A005353) rubbing in the HPOTP of engine 0003 caused failure of the primary lox seal and an uncontained engine fire. The redline cut was set by a HPOTP overspeed. This failure resulted in an increase of the intermediate seal purge pressure, revised redlines, and a design change from a lift-off seal to a labyrinth seal design.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-133 - Test 901-133 (UCR A005072) experienced a burn-through of the FPB wall during testing of engine 0004. The test was cut by an observer. This failure resulted in uncontrolled engine shutdown and damage to the engine. The engine survived this event and was used for later testing. Since the engine was not severely damaged and there is no indication of test stand damage (operational again in 6 days) this failure is not considered applicable to the study.

Test 901-136* - A failure of engine 0004 HPOTP turbine end bearings occurred during test 901-136 (UCR A005350) which resulted in an uncontained engine fire. The test was cut by an observer. The failure resulted in design changes to heavy duty 209 series bearings, improved bearing mounts and modifications to the coolant circuit orifice.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 902-095 - During test 902-095 of engine 0002 (UCR A008624) a leading edge airfoil crack resulted in blade failure, however, the engine damage was contained. The redline for the test cut was from the HPOTP radial accelerometer. Design and process changes have been implemented to increase blade life.

This failure resulted in uncontrolled engine shutdown, however, damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of damage to the test stand (operational within 11 days) in the available documentation. This failure is not considered applicable to this study.

Test 901-147* - HPFTP turbine blade failure of engine 0103 during test 901-147 (UCR A005094) resulted in a rapid power loss, reduced fuel flow and LOX rich operation of the engine. The test was cut by the HPOTP radial accelerometer redline. As a result, HPFTP turbine blade and damper redesigns were initiated.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand (operational within 11 days) in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-173* - Main injector lox post failure, cut off by HPFTP turbine discharge temperature.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-183 - Main injector lox post failure occurred during test 901-183 (UCR A018710) of engine 0002. Cutoff was by the HPFTP turbine radial accelerometer. The failure resulted in the incorporation of lox post flow shields.

This failure resulted in uncontrolled engine shutdown, however, damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of damage to the test stand in the available documentation. This failure is not considered applicable to this study.

Test 902-112 - During test 902-112 (UCR A019208) of engine 0101 on June 10, 1978 a blockage of the fuel supply resulted in a HPFTP turbine overspeed. The redline cut for the test was the HPFTP turbine speed.

This failure resulted in uncontrolled engine shutdown, however, damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of damage to the test stand in the available documentation. This failure is not considered applicable to this study.

Test 902-120 * - During test 902-120 (UCR A005745) of engine 0101 structural failure and rubbing of a capacitor position instrumentation sensor in the HPOTP resulting in engine fire and uncontained engine damage. The test was cut by the PBP axial accelerometer redline. The capacitance device is no longer used.

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although the capacitance device is no longer used it does demonstrate the result of a HPOTP failure, subsequent fire and shrapnel. This failure is considered applicable to the study and although some damage was noted to the test stand it would not have propagated to a cluster failure.

Test 902-132 - During test 902-132 (UCR A005780) of engine 0006 a f [illegible] occurred as the result of the MOV being clocked wrong. The test was cut by the low chamber pr[illegible] redline. The failure resulted in a guideline for the first test of a new engine to be only 1.5 seconds.

This failure resulted in uncontrolled engine shutdown, however, damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of damage to the test stand in the available documentation. This failure is not considered applicable to this study.

Test 901-222 - During test 901-222 (UCR A017972) of engine 0007 a failure occurred as a result of undetected internal HEX damage caused during arc welding which resulted in an engine fire. HEX coil leakage resulted in an uncontained engine fire and severe damage. The test was cut by the HEX discharge pressure redline. The leak was caused by wall thinning of the HEX coil which occurred during welding and reaming operations. The failure resulted in increased HEX proof test requirements.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 901-225* - During test 901-225 (UCR A01816) of engine 2001 flow induced fretting of the MOV sleeve resulted in autoignition, fire and explosion. The test was cut by the HPFTP turbine discharge temperature redline. The incident resulted in several design modifications (ECP's 248, 258, 271) including a redesigned MOV inlet sleeve/seal area and the incorporation of a vibration redline.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 750-041* - During testing of engine 0201 on May 14, 1978, the steerhorn tube fractured due to high structural loading (UCR A006466). The test was cut by the HPFTP turbine discharge temperature redline. The failure resulted from structural fatigue associated with high strain accelerations attributed to exhaust gas flow shock phenomena during start and cutoff transients causing failure of the flight nozzle steerhorn fuel distribution manifold. The failure resulted in fuel starvation and loss of mixture ratio control. Engine damage as a result of the high temperature was extensive and included the HPFTP, HPOTP, nozzle, main injector and the high pressure fuel distribution manifold steerhorn damage. The failure resulted in redesign of the feedline assembly and nickel plating of steerhorn tees.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Static Firing 6-01 - During Static Firing 6-01 (UCR A009437) high cycle fatigue resulted in the failure of engine 2002 MFV housing, fuel leakage and fire. The test was cut by the HPFTP turbine discharge temperature redline. The MFV housing crack extended from the cap flange to the outlet flange. The failure resulted in housing design modifications (ECR 09738). Rework housing cam bearing cutout to reduce stress concentration.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine during a three engine cluster firing. The failure resulted in fuel leakage and fire during the ground test. In flight, the chance of fire is a function of the available oxygen which is altitude dependent. There is no indication of significant damage to the other engines or to the test stand. The engine survived this event and was used for later testing. Damage to the engine was not significant and this event is not considered applicable to the study.

Static Firing 6-03* - Testing of engine 0006 (engine position 3) during a cluster firing on November 4, 1979, resulted in a nozzle steerhorn rupture (UCR A010997). The test was cut by the HPOTP intermediate seal purge pressure redline. The failure was traced to use of an incorrect weld filler wire during fabrication. The failure resulted in the implementation of stringent weld wire audits. Added nickel plating to tee weld joints and redesigned to incorporate steam loop.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine during a three engine cluster firing. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the adjacent engines or to the test stand in the available documentation this failure did not propagate to an engine cluster failure.

Test 902-198* - Main injector lox post failure resulted during test 902-198 of engine 2004. Cutoff was by the HPOTP turbine discharge temperature redline. The failure resulted in a change from the existing injectors to Haynes 188 lox post tips in rows 10 through 13. New injectors have all Haynes 188 lox posts.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-284* - During test 901-284 (UCR A015786) of engine 0010 a malfunctioning MCC chamber pressure lee jet caused the controller to lower the HPOTP output and resulted in HPOTP fire and external damage. The test was cut by HPOTP accelerometer redlines. The failure resulted in installation of a positive retainer in Pc port flange to prevent lee jet from backing out.

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although redesigns have been implemented this failure does demonstrate the result of a HPOTP failure, subsequent fire and shrapnel. This failure is considered applicable to the study and although some damage to the test stand was noted, it would not have propagated to a cluster failure.

Static Firing 10-01 - During Static Firing 10-01 (UCR A015391) of engine 0006 a burn-through of the FPB liner and housing occurred. The test was cut by an observer. The failure resulted in the addition of a molybdenum insulator and new divergent ring liner.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine during a three engine cluster firing. The failure resulted in external leakage of hot gas from the FPB burn through. There is no indication of significant damage to the other engines or to the test stand. The engine survived this event and was used for later testing. Damage to the engine was not significant and this event is not considered applicable to the study.

Test 901-307* - During test 901-307 of engine 0009 a failure occurred in which the FPB injector experienced a burn-through. This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 750-140 - Main injector lox post failure resulted during test 750-140 of engine 0110. This failure resulted in a controlled engine shutdown and contained engine damage. The engine survived this event and was used for later testing. Thus, this failure is not considered applicable to the study since it resulted in a controlled engine shutdown and minor damage.

Test 901-331* - During testing of engine 2108 on July 15, 1981, injector post and engine damage was caused by material failure of the lox posts (UCR A013786). The test was cut by the HPOTP turbine discharge temperature redline. The failure resulted in the application of new materials for the lox posts and the addition of flow shields.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 750-148 - Main injector lox post failure resulted during test 750-148 (UCR A016031) of engine 0110. Cutoff was by the HPOTP turbine discharge temperature redline. The failure resulted in the implementation of all Haynes 188 lox posts and extended flow shields.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 902-249* - The HPFTP inlet volute of engine 0204 failed during test 902-249 (UCR A018288) as a result of non-standard fuel preburner injector modifications which produced a hot FPB core. A group of plugged FPB LOX posts created a hot spot and delamination of the Ni/Rene first stage blade tip seal, resulting in blade failure, shrapnel and inlet volute rupture. The test was cut by the HPFTP radial accelerometer redline. The resulting fire destroyed both turbines, the powerhead, MCC and nozzle. This failure resulted in a design change to all Rene blade tip seals and preburner modification restrictions to preclude a "hot core."

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although fixes have been implemented this failure does demonstrate the result of turbine blade failure and subsequent fire and shrapnel. This failure is considered applicable to the study and although some damage to the test stand was noted, it would not have propagated to a cluster failure.

Test 901-340 - A HPFTP turbine discharge sheet metal failure of weld 56 during test 901-340 (UCR A018305) of engine 0107 caused turbine flow blockage and resulted in contained turbopump damage. The test was cut by exceeding the HPFTP turbine discharge temperature redline. The failure resulted in weld prep redesign to achieve 100% penetration and the inclusion of x-ray inspection where accessible.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 750-160* - A blockage of the fuel supply as a result of ice formation occurred during test 750-160 (UCR A016045) of engine 0110 which burned both turbines, HGM, main injector, MCC and nozzle. The test was cut by the HPFTP turbine discharge temperature redline. The failure resulted in revised engine drying procedures to remove all water following EDM operations.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-364** - A new redesigned Kaiser cap nut allowed hot gas leakage into the coolant circuit during test 901-364 (UCR A006810) of engine 2013 which resulted in bearing failure, uncontained engine damage and complete destruction of the engine. The failure produced significant shrapnel and test stand damage with the engine ultimately separating from the test stand. A redline cut was set by the PBP radial accelerometer. The redesigned nut was tested no further and all engines continue to use the original design.

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although this hardware configuration is no longer in use it does demonstrate the result of a loss or disruption of coolant flow to the turbomachinery. This failure is considered applicable to the study and would have propagated to a cluster failure.

Test 750-165 - During test 750-165 of engine 0107 the OPOV experienced seal erosion. The test continued for the programmed duration. This failure resulted in a controlled engine shutdown and contained engine damage. The engine survived this event and was used for later testing. Thus, this failure is not considered applicable to the study since it resulted in a controlled engine shutdown and minor damage.

Test 750-168 - During test 750-168 of engine 0107 ASI blowback caused post cut-off OPOV ball seal leakage. Inspection revealed the seal was cracked and eroded. The test continued through the programmed duration. The shutdown sequence and purge requirements were revised.

This failure resulted in a controlled engine shutdown and contained engine damage. The engine was retired following this event. Thus, the failure is not considered applicable to the study since it resulted in a controlled engine shutdown and minor damage.

Test 750-175** - The HPO duct of engine 2208 was modified with the installation of an ultrasonic flow meter. During test 750-175 (UCR A011506) a failure resulted in HPOTP overspeed to 44,000 rpm (nominal 27,300 rpm) causing disc rupture, pump fire, shrapnel and extensive engine damage. The test was cut by the PBP accelerometer redline. The failure occurred at the brazed joint between the prototype ultrasonic flowmeter and the high pressure oxidizer turbopump discharge duct and resulted in destruction of the HPO duct, the HPOTP, the HGM and the controller. Further use of ultrasonic flow meter on HPO duct was eliminated.

This failure was uncontrolled resulting in destruction of the engine and damage to the test stand. Although this hardware configuration is no longer in use it does demonstrate the result of a loss of oxidizer flow and subsequent HPOTP turbine overspeed, lox fire and shrapnel. This failure is considered applicable to the study and would have propagated to a cluster failure.

STS-11 - One major incident actually occurred in flight during STS-11 and was obviously not catastrophic. During the flight the ASI chamber of engine 2015 experienced erosion due to a drill chip lodged in an ASI orifice. Engine cut-off was by programmed duration The failure resulted in the addition of an ASI fuel filter to the supply line.

The engine burn continued for the programmed duration. This failure resulted in a controlled engine shutdown and contained engine damage. Although there was damage to the engine itself, there was no damage to the adjacent engines. The engine survived this event and was used for later testing. Thus, this failure is not considered applicable to the study since it resulted in a controlled engine shutdown and minor damage.

Test 901-436* - A hydrogen leak during test 901-436 (UCR A013338) of engine 0108 overpressurized the HPFTP coolant cavity and resulted in a coolant liner failure and major engine damage, destroying both turbines, the powerhead, MCC and nozzle. A redline cut was issued due to high HPFTP turbine discharge temperature. Design changes were incorporated to decrease hot gas leakage into the coolant circuit, a coolant liner pressure redline was implemented and inspection requirements were increased on the coolant liner close-out weld.

This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 901-468 - During test 901-468 (UCR A014585) of engine 0207 a stress concentration at the welded boss caused the FPB manifold to crack resulting in fire and major engine damage. This failure resulted in uncontrolled engine shutdown and uncontained engine damage. The engine was retired following this event. Thus, this failure is considered applicable to the study. Since there is no indication of significant damage to the test stand in the available documentation this failure would not have propagated to an engine cluster failure.

Test 750-259** - A failure of the MCC outlet manifold weld occurred during test 750-259 (UCR A015713) of engine 2308 and resulted in complete engine destruction. The failure resulted in shrapnel and test stand damage with the engine ultimately separating from the test stand. The test was cut by the HPFTP accelerometer and turbine discharge temperature redlines. Failure investigation determined that the MCC outlet assembly had ruptured due to fatigue or undetected flaws. The failure resulted in improved inspection of the assembly, redesign of the outlet neck and splitter and implementation of life limitations on other MCC's.

This failure resulted in uncontrolled engine shutdown, destruction of the engine and significant damage to the test stand. This failure is considered applicable to the study and would have propagated to an engine cluster failure.

Test 750-285 - A Class I leak was experienced during test 750-285 at the number 8 feedline. Engine 0210 (May 21, 1987) experienced a feedline crack at the saddle bracket stop weld. The test was cut by a facility ambient air thermocouple. The failure resulted in improved feedline/saddle bracket and weld interference inspections.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 902-427 - During testing of engine 2106 on June 26, 1987 at the NSTL A-2 test stand the low

pressure fuel pump discharge duct experienced a corrosion induced leak and subsequent external hydrogen fire. The test was cut by an ambient powerhead temperature redline. To preclude the possibility of corrosion induced failures, flight engines will use low pressure fuel turbopump discharge ducts with low calendar life and/or hotfire time (DAR 2074). Subsequent flight engines will use corrosion protected low pressure fuel turbopump discharge ducts (ECP 977).

This failure resulted in uncontrolled engine shutdown , however the damage to the engine was contained. The engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

Test 902-428 - During test 902-428 of engine 2106 a crack in the OPB interpropellant plate resulted in the formation and build up of ice, blocking the fuel supply which altered the OPB exhaust flow distribution and burned through the liner causing faceplate erosion and HPOTP turbine end damage. The test was cut by a facility redline. The failure was caused by cracks in the interpropellant plate-to-element braze joints. The cracks allowed propellant mixing and caused ice contamination to form in fuel manifold. The failure was determined to be the result of poor braze joints made during fabrication. Flight engines are cleared by a review of the manufacturing braze joint records.

This failure resulted in uncontrolled engine shutdown and uncontained damage to the engine. However, the engine survived this event and was used for later testing. There is no indication of significant damage to the engine in the available documentation so that this failure is not considered applicable to this study.

ANALYSIS

The results of applying the criteria to the SSME major incidents database results in a total of 18 applicable failures, of which 3 are considered to propagate to a cluster failure.

The mean is then computed by

$$\bar{X} = 3/18 = 0.167$$

Due to the small sample size the F distribution is assumed in order to develop the confidence interval for this case. For a 95% confidence interval the results of applying the F distribution are

$$0.036 < \bar{X} < 0.414$$

Thus, with a 95% confidence interval the probability that a failure will propagate to the adjacent engines in the cluster is between 4% and 41%, given that an uncontrolled engine failure occurs.

CONCLUSIONS

In the development of future launch vehicles the potential benefit of engine out capabilities must be weighed against the risks that if an engine fails in an uncontrolled manner it will result in the loss of the entire engine cluster. This study evaluated the SSME which is flown in a three engine cluster. No uncontrolled SSME failures have occurred in flight. Only a limited amount of ground testing has actually been done in a three engine cluster and although failures have occurred none have propagated to involve the entire cluster.

However, the test data evaluated here indicates there is a reasonable probability, approximately 17%, that an uncontrolled SSME failure will propagate to the adjacent engines given that an uncontrolled failure occurs. The confidence interval is between 4% and 41% that a failure will propagate to the cluster with a 95% confidence level.

TABLE A.1: SSME CORRELATION OF FAILURE FACTOR

32 TEST NUMBER	DATE	ENG	CONFIG	UCR	UNCNTD SHTDN	UNCONT HDWR FAILR	ENGN RETRD	APPLICBL FAILURE	SURRDG HARDWR DAMAGE	CLUSTR DAMAGE	STAND DOWN TIME	R/L	COMP	COMMENT	TEST DURATN	C/O PWR LVL
901.110	24-Mar-77	0003	PRE-FMOF	A005353	YES	YES	YES	YES	NO	NO	52	HO SPD	HPOTP	HPOTP FIRE EXT DAM	74.07	75
901.133	27-Aug-77	0004	PRE-FMOF	A005072	YES	YES	NO	NO	-	-	6	OBS	FPB	HOLE IN FPB BODY	48.21	90
901.136	8-Sep-77	0004	PRE-FMOF	A005350	YES	YES	YES	YES	NO	NO	53	CONT	HPOTP	HPOTP BNG FAILURE - EXT DAM	300.22	90
902.095	17-Nov-77	0002	PRE-FMOF	A008624	YES	NO	NO	NO	-		11	HO ACC C	HPFTP	HPFT TURBINE BLADE FAILURE-CROSSFEED	51.09	70
901.147	1-Dec-77	0103	PRE-FMOF	A005094	YES	YES	YES	YES	NO	NO	11	HO ACC C	HPFTP	HPFTURB BL FAILURE	31.36	81
901.173	31-Mar-78	0002	PRE-FMOF	A018710	YES	YES	YES	YES	NO	NO	34	F TD T	MINJ	MINJ BURN THRO/REPLACED ENG	201.17	92
901.183	5-Jun-78	0005	PRE-FMOF	A019050	YES	YES	NO	NO	-	-	39	HF ACC	MINJ	MINJ BURN THRO/REPLACE P/H	51.10	100
902.112	10-Jun-78	0101	PRE-FMOF	A019208	YES	YES	NO	NO	-	-	12	HF SDP	FAC	HPFTP CAVITION/LN2 ON FAC SCREEN	5.74	92
902.120	18-Jul-78	0101	PRE-FMOF	A005745	YES	YES	YES	YES	YES	NO	35	HO ACC A	HPOTP	SPEC CAP INSTR/FIRE/EXT DAM	41.80	100
902.132	3-Oct-78	0006	PRE-FMOF	A005780	YES	NO	NO	NO	-	-	17	PC IC L	MCV	MCV OFF POS AT PLATEAU/EXT DAM	2.35	20
901.222	6-Dec-78	0007	PRE-FMOF	A017972	YES	YES	NO	NO	-	-	14	HEX PR	HEX	HEX FAIFURE/PROOF & LK CKS	4.35	90
901.225	27-Dec-78	2001	PRE-FMOF	A010816	YES	YES	YES	YES	NO	NO	40	F TD T	MCV	MCV FRETTING-FIRE-EXT DAM	255.63	100
750.041	14-May-79	0201	PRE-FMOF	A006466	YES	YES	YES	YES	NO	NO	52	F TD T	NOZZLE	NOZZLE STEERHORN FAILED	4.32	100
SF0601	2-Jul-79	2002	PRE-FMOF	A009437	YES	YES	NO	NO	-	-	-	F TD T	MFV	MFV BODY FAILURE	18.49	100
SF0603	4-Nov-79	0006	PRE-FMOF	A010997	YES	YES	YES	YES	NO	NO	-	SATS	CLUSTR	AFTER S/D STEERHORN RUPTURE	9.72	100
902.198	23-Jul-80	2004	FMOF	A017566	YES	YES	YES	YES	NO	NO	47	O TD T	MINJ	HOLE IN INJ/LOX POST FAIL	8.49	102
901.284	30-Jul-80	0010	FMOF	A015786	YES	YES	YES	YES	YES	NO	28	HO ACC	MCC	LEE JET DISPLACED/EXT DAM	9.69	60
SF1001	12-Aug-80	0006	FMOF	A015391	YES	YES	NO	NO	-	-	-	OBS	FPB	HOLE BURNED IN FPB	106.50	102
901.307	28-Jan-81	9	FMOF		YES	YES	YES	YES	NO	NO	28		FPB	FPB INJECTOR BURNTHROUGH	75.02	65
750.140	20-Jun-81	0110	FMOF		NO	NO	NO	NO	-	-	7		MINJ	MAIN INJECTOR BURNTHOUGH	300.00	109
901.331	15-Jul-91	2108	PHASE I	A013786	YES	YES	YES	YES	NO	NO	24	O TD T	MINJ	MINJ BURN OUT EXT DAM	233.14	100
750.148	2-Sep-81	0110	PHASE I	A016031	YES	YES	NO	NO	-	-	66	O TD T	MINJ	MINJ BURN OUT/REPLACED MINJ	16.04	105
902.249	21-Sep-81	0204	PHASE I	A018288	YES	YES	YES	YES	YES	NO	75	HF ACC	HPFTP	TURB BL FAIL/VOLUTE RUPTURE/EXT DAM	450.57	109
901.340	15-Oct-81	107	PHASE I	A018305	YES	YES	NO	NO	-	-	15	F TD T	HPFTP	HPFTP T/A DUCT S/M BULGED	405.50	109
750.160	12-Feb-82	0110	PHASE I	A016045	YES	YES	YES	YES	NO	NO	33	F TD T	ICE	H2O FROM EDM/EXT DAMAGE (CG1B)	3.61	20
901.364	8-Apr-82	2013	PHASE I	A005547	YES	YES	YES	YES	YES	YES	38	HO ACC C	HPFTP	KAISER HAT /TURB BNG EXT DAM	392.15	109
750.165	21-Apr-82	107	PHASE I		NO	NO	NO	NO	-	-	8		OPOV	OPOV SEAL EROSION	280.00	
750.168	15 May-82	107	PHASE I		NO	NO	YES	NO	-	-	42		OPOV	OPOV SEAL CRACKED AND ERODED	300.00	
750.175	27-Aug-82	2208	PHASE I	A011506	YES	YES	YES	YES	YES	YES	63	HO ACC	DUCT	HPO DUCT RUPTURE - EXT DAM	115.64	11
STS-11	3-Feb-84	2015	PHASE I		NO	NO	NO	NO	-	-	-		OPB	OPB ASI CHAMBER EROSION	527.89	65
901.436	14-Feb-84	0108	PHASE II	A013338	YES	YES	YES	YES	NO	NO	36	F TD T	HPFTP	CLNT LNR PR-MAJOR DAMAGE	611.00	109
901.468	4-Feb-85	0207	PHASE II	A014585	YES	NO	NO	NO	-	-	19	PH/T	FPB	CRACK AT F-13 FLANGE-eng retired	203.86	109
750.259	27-Mar-85	2308	PHASE II	A015713	YES	YES	YES	YES	YES	YES	160	HF ACC	MCC	DISCH MAN RUPTURE - EXT DAM	101.47	109
750.285	21-May-87	210	PHASE II		YES	YES	NO	NO	-	-	26		NOZZLE	CLASS I NOZZLE LEAK	223.56	109
902.427	26-Jun-87	2106	PHASE II		YES	NO	NO	NO	-	-	5		DUCT	LPFTP TURBINE DISCHARGE DUCT FAIL/FIRE	138.36	104
902.428	1-Jul-87	2106	PHASE II		YES	YES	NO	NO	-	-	41		OPB	OPB INTERPROPELLANT PLATE CRACK	204.12	104

NOTES:

ENG - ENGINE NUMBER

CONFIG - ENGINE CONFIGURATION

UCR - UNACCEPTABLE CONDITION REPORT

UNCNTD SHTDN - UNCONTROLLED ENGINE SHUTDOWN

UNCONT HDWR FAILR - UNCONTAINED HARDWARE FAILURE

ENGN RETRD - ENGINE RETIRED FOLLOWING THIS EVENT

APPLICBL FAILURE - FAILURE IS APPLICABLE TO THIS STUDY

SURRDG HARDWR DAMAGE - EVENT RESULTED IN DAMAGE TO SURROUNDING HARDWARE

CLUSTR DAMAGE - FAILURE WOULD RESULT IN DAMAGE TO THE ENGINE CLUSTER

STAND DOWN TIME - DAYS FROM THIS EVENT UNTIL THE NEXT TEST ON THIS STAND

R/L - REDLINE ISSUED FOR CUTOFF

COMP - MAJOR COMPONENT INVOLVED IN EVENT

C/O PWR LVL - CUTOFF POWER LEVEL

SSME CHRONOLOGICAL EXPERIENCE

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901001	19-May-75	0001	0.00	0	0.00	0.00	0.00			
901002	22-May-75	0001	1.00	1	0.00	0.00	0.00			
901003	2-Jun-75	0001	1.50	3	0.00	0.00	0.00			
901004	6-Jun-75	0001	0.80	3	0.00	0.00	0.00			
901005	12-Jun-75	0001	0.80	4	0.00	0.00	0.00			
901006	14-Jun-75	0001	1.00	5	0.00	0.00	0.00			
901007	23-Jun-75	0001	1.00	6	0.00	0.00	0.00			
901008	30-Jun-75	0001	0.50	7	0.00	0.00	0.00			
901009	8-Jul-75	0001	1.40	8	0.00	0.00	0.00			
901010	17-Jul-75	0001	1.60	10	0.00	0.00	0.00			
901011	8-Aug-75	0001	1.00	11	0.00	0.00	0.00			
901012	29-Aug-75	0001	1.00	12	0.00	0.00	0.00			
901013	4-Sep-75	0001	1.40	13	0.00	0.00	0.00			
901014	10-Sep-75	0001	1.50	15	0.00	0.00	0.00			
901015	2-Oct-75	0001	1.69	16	0.00	0.00	0.00			
901016	10-Oct-75	0001	1.84	18	0.00	0.00	0.00			
901017	26-Oct-75	0001	1.70	20	0.00	0.00	0.00			
901018	29-Oct-75	0001	1.95	22	0.00	0.00	0.00			
901019	31-Oct-75	0001	2.15	24	0.00	0.00	0.00			
901020	3-Nov-75	0001	2.35	26	0.00	0.00	0 00			
901021	4-Nov-75	0001	2.55	29	0.00	0.00	0.00			
901022	7-Nov-75	0001	2.76	31	0.00	0.00	0.00			
901023	12-Nov-75	0001	2.99	34	0.00	0.00	0.00			
901024	14-Dec-75	0001	2.35	37	0.00	0.00	0.00			
901025	22-Dec-75	0001	0.90	38	0.00	0.00	0.00			
901026	23-Dec-75	0001	2.35	40	0.00	0.00	0.00			
901027	30-Dec-75	0001	1.90	42	0.00	0.00	0.00			
901028	3-Jan-76	0001	1.74	44	0.00	0.00	0.00			

SSME Chronological Experience with Power Levels

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901029	7-Jan-76	0001	1.93	46	0.00	0.00	0.00			
901030	13-Jan-76	0001	2.35	48	0.00	0.00	0.00			
901031	15-Jan-76	0001	2.73	51	0.00	0.00	0.00			
901032	16-Jan-76	0001	2.76	53	0.00	0.00	0.00			
901033	19-Jan-76	0001	2.86	56	0.00	0.00	0.00			
901034	21-Jan-76	0001	2.35	59	0.00	0.00	0.00			
901035	24-Jan-76	0001	3.16	62	0.00	0.00	0.00			
901036	27-Jan-76	0001	3.11	65	0.00	0.00	0.00			
901037	29-Jan-76	0001	3.36	68	0.00	0.00	0.00			
901038	5-Feb-76	0001	2.36	71	0.00	0.00	0.00			
901039	27-Feb-76	0001	2.88	74	0.00	0.00	0.00			
901040	2-Mar-76	0001	3.39	77	0.00	0.00	0.00			
901041	5-Mar-76	0001	3.84	81	0.00	0.00	0.00			
901042	8-Mar-76	0001	10.18	91	0.00	0.00	0.00			
901043	10-Mar-76	0001	23.20	114	0.00	0.00	0.00			
901044	12-Mar-76	0001	45.18	159	0.00	0.00	0.00			
901045	23-Mar-76	0001	4.20	164	0.00	0.00	0.00			
902001	31-Mar-76	0002	1.54	165	0.00	0.00	0.00			
901046	2-Apr-76	0001	6.27	171	0.00	0.00	0.00			
901047	5-Apr-76	0001	1.92	173	0.00	0.00	0.00			
901048	7-Apr-76	0001	2.35	176	0.00	0.00	0.00			
901049	8-Apr-76	0001	2.36	178	0.00	0.00	0.00			
902002	19-Apr-76	0002	2.35	180	0.00	0.00	0.00			
901050	20-Apr-76	0001	4.20	185	0.00	0.00	0.00			
902003	21-Apr-76	0002	2.35	187	0.00	0.00	0.00			
901051	22-Apr-76	0001	10.32	197	0.00	0.00	0.00			
902004	24-Apr-76	0002	1.68	199	0.00	0.00	0.00			
901052	26-Apr-76	0001	7.34	206	0.00	0.00	0.00			
902005	28-Apr-76	0002	2.35	209	0.00	0.00	0.00			
902006	30-Apr-76	0002	2.35	211	0.00	0.00	0.00			
902007	3-May-76	0002	2.35	213	0.00	0.00	0.00			
901053	5-May-76	0001	6.52	220	0.00	0.00	0.00			
902008	5-May-76	0002	2.35	222	0.00	0.00	0.00			
901054	8-May-76	0001	7.31	229	0.00	0.00	0.00			

SSME Chronological Experience with Power Levels

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
902009	15-May-76	0002	4.20	234	0.00	0.00	0.00			
901055	18-May-76	0001	6.29	240	0.00	0.00	0.00			
902010	19-May-76	0002	2.35	242	0.00	0.00	0.00			
901056	21-May-76	0001	7.27	250	0.00	0.00	0.00			
902011	22-May-76	0002	4.20	254	0.00	0.00	0.00			
902012	25-May-76	0002	8.20	262	0.00	0.00	0.00			
901057	26-May-76	0001	11.86	274	0.00	0.00	0.00			
902013	1-Jun-76	0002	11.10	285	0.00	0.00	0.00			
901058	3-Jun-76	0001	12.08	297	0.00	0.00	0.00			
901059	5-Jun-76	0001	3.97	301	0.00	0.00	0.00			
902014	7-Jun-76	0002	3.16	304	0.00	0.00	0.00			
901060	8-Jun-76	0001	2.35	307	0.00	0.00	0.00			
901061	10-Jun-76	0001	2.35	309	0.00	0.00	0.00			
902015	12-Jun-76	0002	3.27	312	0.00	0.00	0.00			
902016	15-Jun-76	0002	16.70	329	0.00	0.00	0.00			
901062	16-Jun-76	0001	16.40	345	0.00	0.00	0.00			
901063	18-Jun-76	0001	64.04	409	0.00	0.00	0.00			
901064	23-Jun-76	0001	1.81	411	0.00	0.00	0.00			
901065	7-Jul-76	0001	16.91	428	0.00	0.00	0.00			
901066	9-Jul-76	0001	4.24	432	0.00	0.00	0.00			
902017	9-Jul-76	0002	16.44	449	0.00	0.00	0.00			
902018	14-Jul-76	0002	22.07	471	0.00	0.00	0.00			
902019	23-Jul-76	0002	1.68	472	0.00	0.00	0.00			
901067	26-Jul-76	0001	41.45	514	0.00	0.00	0.00			
902020	27-Jul-76	0002	33.00	547	0.00	0.00	0.00			
902021	11-Aug-76	0002	3.73	551	0.00	0.00	0.00			
902022	13-Aug-76	0002	10.00	561	0.00	0.00	0.00			
902023	17-Aug-76	0002	3.43	564	0.00	0.00	0.00			
902024	18-Aug-76	0002	3.63	568	0.00	0.00	0.00			
902025	20-Aug-76	0002	1.08	569	0.00	0.00	0.00			
902026	21-Aug-76	0002	3.77	573	0.00	0.00	0.00			
901068	23-Aug-76	0003	0.30	573	0.00	0.00	0.00			
902027	24-Aug-76	0002	2.96	576	0.00	0.00	0.00			
901069	25-Aug-76	0003	1.64	577	0.00	0.00	0.00			

SSME Chronological Experience with Power Levels

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901070	27-Aug-76	0003	4.20	582	0.00	0.00	0.00			
902028	30-Aug-76	0002	2.35	584	0.00	0.00	0.00			
902029	31-Aug-76	0002	8.00	592	0.00	0.00	0.00			
901071	1-Sep-76	0003	18.30	610	0.00	0.00	0.00			
902030	10-Sep-76	0002	24.03	634	0.00	0.00	0.00			
902031	12-Sep-76	0002	46.00	680	0.00	0.00	0.00			
901072	13-Sep-76	0003	17.15	697	0.00	0.00	0.00			
902032	15-Sep-76	0002	22.19	720	0.00	0.00	0.00			
901073	16-Sep-76	0003	49.53	769	0.00	0.00	0.00			
902033	18-Sep-76	0002	85.00	854	0.00	0.00	0.00			
901074	20-Sep-76	0003	26.52	881	0.00	0.00	0.00			
902034	22-Sep-76	0002	27.00	908	0.00	0.00	0.00			
901075	23-Sep-76	0003	2.96	911	0.00	0.00	0.00			
901076	24-Sep-76	0003	3.05	914	0.00	0.00	0.00			
902035	25-Sep-76	0002	30.00	944	0.00	0.00	0.00			
901077	26-Sep-76	0003	150.00	1,094	0.00	0.00	0.00			
901078	28-Sep-76	0003	300.00	1,394	0.00	0.00	0.00			
902036	29-Sep-76	0002	26.52	1,420	0.00	0.00	0.00			
901079	30-Sep-76	0003	650.00	2,070	0.00	0.00	0.00			
902037	1-Oct-76	0002	33.88	2,104	0.00	0.00	0.00			
901080	27-Oct-76	0003	28.09	2,132	0.00	0.00	0.00			
901081	2-Nov-76	0003	20.03	2,152	0.00	0.00	0.00			
901082	10-Nov-76	0003	20.00	2,172	0.00	0.00	0.00			
901083	20-Nov-76	0003	2.35	2,175	0.00	0.00	0.00			
901084	24-Nov-76	0003	2.99	2,178	0.00	0.00	0.00			
901085	27-Nov-76	0003	4.23	2,182	0.00	0.00	0.00			
901086	30-Nov-76	0003	11.72	2,193	0.00	0.00	0.00			
902038	5-Dec-76	0002	1.08	2,195	0.00	0.00	0.00			
902039	8-Dec-76	0002	3.71	2,198	0.00	0.00	0.00			
902040	11-Dec-76	0002	4.20	2,202	0.00	0.00	0.00			
902041	14-Dec-76	0002	2.33	2,205	0.00	0.00	0.00			
902042	15-Dec-76	0002	8.20	2,213	0.00	0.00	0.00			
901087	16-Dec-76	0003	11.72	2,225	0.00	0.00	0.00			
902043	17-Dec-76	0002	33.20	2,258	0.00	0.00	0.00			

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Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901088	18-Dec-76	0001	6.20	2,264	0.00	0.00	0:00			
902044	20-Dec-76	0002	19.60	2,284	0.00	0.00	0.00			
901089	27-Dec-76	0003	8.00	2,292	0.00	0.00	0.00			
901090	28-Dec-76	0003	17.69	2,309	0.00	0.00	0.00			
901091	31-Dec-76	0003	64.00	2,373	0.00	0.00	0.00			
901092	3-Jan-77	0003	21.50	2,395	0.00	0.00	0.00			
901093	5-Jan-77	0003	18.08	2,413	0.00	0.00	0.00			
901094	6-Jan-77	0003	15.65	2,429	0.00	0.00	0.00			
901095	7-Jan-77	0003	26.44	2,455	5.00	0.00	0.00			
901096	11-Jan-77	0003	28.63	2,484	9.60	0.00	0.00			
902045	12-Jan-77	0002	1.06	2,485	0.00	0.00	0.00			
902046	13-Jan-77	0002	405.01	2,890	0.00	0.00	0.00			
902047	17-Jan-77	0002	1.62	2,891	0.00	0.00	0.00			
902048	18-Jan-77	0002	4.23	2,896	0.00	0.00	0.00			
901097	28-Jan-77	0003	4.25	2,900	0.00	0.00	0.00			
901098	29-Jan-77	0003	64.12	2,964	21.12	0.00	0.00			
901099	31-Jan-77	0003	39.80	3,004	15.30	0.00	0.00			
902049	6-Feb-77	0002	3.23	3,007	0.00	0.00	0.00			
901100	11-Feb-77	0003	14.18	3,021	0.00	0.00	0.00			
901101	13-Feb-77	0003	4.31	3,026	0.00	0.00	0.00			
901102	14-Feb-77	0003	29.85	3,055	0.00	0.00	0.00			
901103	18-Feb-77	0003	23.01	3,078	3.51	0.00	0.00			
902050	20-Feb-77	0002	6.00	3,084	0.00	0.00	0.00			
902051	22-Feb-77	0002	2.37	3,087	0.00	0.00	0.00			
902052	23-Feb-77	0002	2.37	3,089	0.00	0.00	0.00			
902053	25-Feb-77	0002	2.35	3,091	0.00	0.00	0.00			
901104	26-Feb-77	0003	10.61	3,102	0.00	0.00	0.00			
902054	28-Feb-77	0002	11.42	3,114	0.00	0.00	0.00			
901105	3-Mar-77	0003	35.33	3,149	15.83	0.00	0.00			
901106	6-Mar-77	0003	86.43	3,235	0.00	0.00	0.00			
901107	9-Mar-77	0003	8.50	3,244	0.00	0.00	0.00			
901108	10-Mar-77	0003	29.49	3,273	4.99	0.00	0.00			
901109	12-Mar-77	0003	80.49	3,354	60.99	0.00	0.00			
902055	14-Mar-77	0002	2.35	3,356	0.00	0.00	0.00			

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902056	16-Mar-77	0002	24.50	3,381	5.00	0.00	0.00			
902057	18-Mar-77	0002	22.01	3,403	0.00	0.00	0.00			
902058	21-Mar-77	0002	540.00	3,943	0.00	0.00	0.00			
901110	24-Mar-77	0003	74.07	4,017	0.00	0.00	0.00	X		
902059	27-Apr-77	0002	4.13	4,021	0.00	0.00	0.00			
902060	29-Apr-77	0002	10.01	4,031	0.00	0.00	0.00			
902061	2-May-77	0002	80.01	4,111	0.00	0.00	0.00			
902062	5-May-77	0002	29.93	4,141	0.00	0.00	0.00			
902063	10-May-77	0002	100.00	4,241	0.00	0.00	0.00			
902064	12-May-77	0002	104.02	4,345	0.00	0.00	0.00			
902065	14-May-77	0002	80.00	4,425	10.00	0.00	0.00			
901111	15-May-77	0004	2.35	4,427	0.00	0.00	0.00			
901112	17-May-77	0004	2.35	4,429	0.00	0.00	0.00			
901113	20-May-77	0004	17.34	4,447	0.00	0.00	0.00			
901114	23-May-77	0004	7.70	4,455	0.00	0.00	0.00			
901115	18-Jun-77	0004	100.01	4,555	0.00	0.00	0.00			
901116	21-Jun-77	0004	73.23	4,628	0.00	0.00	0.00			
901117	28-Jun-77	0004	0.54	4,628	0.00	0.00	0.00			
901118	29-Jun-77	0004	5.00	4,633	0.00	0.00	0.00			
901119	1-Jul-77	0004	31.74	4,665	0.00	0.00	0.00			
901120	2-Jul-77	0004	238.70	4,904	0.00	0.00	0.00			
901121	5-Jul-77	0004	4.65	4,908	0.00	0.00	0.00			
901122	6-Jul-77	0004	6.06	4,914	0.00	0.00	0.00			
901123	7-Jul-77	0004	149.48	5,064	0.00	0.00	0.00			
902066	13-Jul-77	0002	10.01	5,074	0.00	0.00	0.00			
902067	15-Jul-77	0002	30.00	5,104	0.00	0.00	0.00			
902068	18-Jul-77	0002	5.06	5,109	0.00	0.00	0.00			
902069	19-Jul-77	0002	35.01	5,144	9.00	0.00	0.00			
902070	21-Jul-77	0002	29.31	5,173	5.70	0.00	0.00			
901124	25-Jul-77	0004	6.64	5,180	0.00	0.00	0.00			
901125	27-Jul-77	0004	425.01	5,605	0.00	0.00	0.00			
901126	28-Jul-77	0004	415.00	6,020	10.00	0.00	0.00			
901127	30-Jul-77	0004	328.30	6,348	0.00	0.00	0.00			
901128	1-Aug-77	0004	424.94	6,773	0.00	0.00	0.00			

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901129	4-Aug-77	0004	257.10	7,030	0.00	0.00	0.00			
901130	5-Aug-77	0004	425.00	7,455	0.00	0.00	0.00			
901131	8-Aug-77	0004	425.00	7,880	0.00	0.00	0.00			
902071	9-Aug-77	0002	13.40	7,894	0.00	0.00	0.00			
902072	10-Aug-77	0002	4.41	7,898	0.00	0.00	0.00			
902073	15-Aug-77	0002	155.50	8,054	0.00	0.00	0.00			
902074	18-Aug-77	0002	7.05	8,061	0.00	0.00	0.00			
902075	20-Aug-77	0002	21.71	8,082	0.00	0.00	0.00			
902076	24-Aug-77	0002	230.39	8,313	5.00	0.00	0.00			
901132	25-Aug-77	0004	30.00	8,343	0.00	0.00	0.00			
902077	26-Aug-77	0002	321.00	8,664	301.01	0.00	0.00			
901133	27-Aug-77	0004	48.21	8,712	10.00	0.00	0.00	X		
902078	1-Sep-77	0002	335.99	9,048	10.00	0.00	0.00			
901134	2-Sep-77	0004	76.80	9,125	45.80	0.00	0.00			
901135	6-Sep-77	0004	335.00	9,460	0.00	0.00	0.00			
901136	8-Sep-77	0004	300.22	9,760	100.00	0.00	0.00	X		
902079	26-Sep-77	0002	3.05	9,763	0.00	0.00	0.00			
902080	28-Sep-77	0002	9.05	9,772	0.00	0.00	0.00			
902081	1-Oct-77	0002	15.01	9,787	0.00	0.00	0.00			
902082	9-Oct-77	0002	40.00	9,827	0.00	0.00	0.00			
902083	11-Oct-77	0002	34.94	9,862	0.00	0.00	0.00			
902084	13-Oct-77	0002	85.00	9,947	0.00	0.00	0.00			
902085	17-Oct-77	0002	2.35	9,949	0.00	0.00	0.00			
902086	20-Oct-77	0002	2.35	9,952	0.00	0.00	0.00			
902087	26-Oct-77	0002	2.35	9,954	0.00	0.00	0.00			
902088	27-Oct-77	0002	1.73	9,956	0.00	0.00	0.00			
902089	28-Oct-77	0002	55.01	10,011	0.00	0.00	0.00			
901137	31-Oct-77	0103	19.32	10,030	0.00	0.00	0.00			
902090	1-Nov-77	0002	48.63	10,079	0.00	0.00	0.00			
902091	3-Nov-77	0002	100.00	10,179	0.00	0.00	0.00			
901138	4-Nov-77	0103	100.00	10,279	0.00	0.00	0.00			
902092	6-Nov-77	0002	229.97	10,509	4.00	0.00	0.00			
901139	7-Nov-77	0103	54.83	10,564	0.00	0.00	0.00			
902093	9-Nov-77	0002	364.16	10,928	0.00	0.00	0.00			

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901140	10-Nov-77	0103	100.00	11,028	0.00	0.00	0.00			
901141	11-Nov-77	0103	400.00	11,428	0.00	0.00	0.00			
901142	13-Nov-77	0103	400.00	11,828	0.00	0.00	0.00			
902094	14-Nov-77	0002	200.00	12,028	0.00	0.00	0.00			
902095	17-Nov-77	0002	51.09	12,079	0.00	0.00	0.00			
901143	21-Nov-7	0103	100.00	12,179	0.00	0.00	0.00			
901144	23-Nov-77	0103	400.00	12,579	0.00	0.00	0.00			
901145	26-Nov-77	0103	350.00	12,929	0.00	0.00	0.00			
902096	28-Nov-77	0002	91.04	13,020	0.00	0.00	0.00			
901146	29-Nov-77	0103	400.00	13,420	0.00	0.00	0.00			
901147	1-Dec-77	0103	31.36	13,451	0.00	0.00	0.00			
901148	12-Dec-77	0002	2.35	13,454	0.00	0.00	0.00			
901149	13-Dec-77	0002	10.01	13,464	0.00	0.00	0.00			
901150	15-Dec-77	0002	9.83	13,473	0.00	0.00	0.00			
901151	17-Dec-77	0002	9.00	13,482	0.00	0.00	0.00			
901152	19-Dec-77	0002	9.00	13,491	0.00	0.00	0.00			
901153	20-Dec-77	0002	9.00	13,500	0.00	0.00	0.00			
901154	22-Dec-77	0002	8.00	13,508	0.00	0.00	0.00			
901155	4-Jan-78	0002	12.00	13,520	0.00	0.00	0.00			
901156	5-Jan-78	0002	100.00	13,620	0.00	0.00	0.00			
901157	9-Jan-78	0002	100.00	13,720	0.00	0.00	0.00			
902097	17-Jan-78	2001	49.01	13,769	0.00	0.00	0.00			
902098	25-Jan-78	2001	71.00	13,840	0.00	0.00	0.00			
902099	30-Jan-78	2002	60.00	13,900	0.00	0.00	0.00			
902100	2-Feb-78	2002	2.89	13,903	0.00	0.00	0.00			
901158	8-Feb-78	0002	100.00	14,003	0.00	0.00	0.00			
902101	9-Feb-78	2002	26.64	14,030	0.00	0.00	0.00			
901159	10-Feb-78	0002	96.33	14,126	0.00	0.00	0.00			
901160	12-Feb-78	0002	4.04	14,130	0.00	0.00	0.00			
901161	14-Feb-78	0002	4.25	14,135	0.05	0.00	0.00			
901162	15-Feb-78	0002	11.32	14,146	0.92	0.00	0.00			
902102	15-Feb-78	2002	41.49	14,187	0.00	0.00	0.00			
901163	17-Feb-78	0002	3.57	14,191	0.00	0.00	0.00			
901164	21-Feb-78	0002	6.08	14,197	0.00	0.00	0.00			

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902103	22-Feb-78	2002	60.00	14,257	0.00	0.00	0.00			
902104	5-Mar-78	2003	60.04	14,317	0.00	0.00	0.00			
902105	8-Mar-78	2003	60.04	14,377	0.00	0.00	0.00			
901165	13-Mar-78	0002	2.35	14,379	0.00	0.00	0.00			
901166	15-Mar-78	0002	2.03	14,382	0.00	0.00	0.00			
901167	17-Mar-78	0002	3.83	14,385	0.00	0.00	0.00			
901168	20-Mar-78	0002	7.95	14,393	0.00	0.00	0.00			
901169	21-Mar-78	0002	210.97	14,604	0.00	0.00	0.00			
901170	25-Mar-78	0002	310.74	14,915	0.00	0.00	0.00			
901171	27-Mar-78	0002	10.71	14,926	0.11	0.00	0.00			
901172	29-Mar-78	0002	360.03	15,286	0.00	0.00	0.00			
901173	31-Mar-78	0002	201.17	15,487	0.00	0.00	0.00			
902106	13-Apr-78	0101	5.90	15,493	0.00	0.00	0.00			
902107	16-Apr-78	0101	8.83	15,502	0.00	0.00	0.00			
902108	19-Apr-78	0101	8.55	15,510	0.00	0.00	0.00			
902109	21-Apr-78	0101	2.99	15,513	0.00	0.00	0.00			
SF01-02A	21-Apr-78	2001	1.19	15,514	0.00	0.00	0.00			
SF01-02B	21-Apr-78	2003	1.04	15,515	0.00	0.00	0.00			
SF01-02C	21-Apr-78	2002	0.98	15,516	0.00	0.00	0.00			
901174	4-May-78	0005	47.97	15,564	0.00	0.00	0.00			
901175	6-May-78	0005	119.07	15,683	114.94	0.00	0.00			
901176	8-May-78	0005	32.03	15,715	27.89	0.00	0.00			
901177	10-May-78	0005	520.00	16,235	515.97	0.00	0.00			
901178	13-May-78	0005	4.27	16,240	0.00	0.00	0.00			
901179	16-May-78	0005	122.90	16,363	90.08	0.00	0.00			
SF02-01A	19-May-78	2001	18.84	16,381	0.00	0.00	0.00			
SF02-01B	19-May-78	2003	20.52	16,402	0.00	0.00	0.00			
SF02-01C	19-May-78	2002	20.42	16,422	0.00	0.00	0.00			
901180	28-May-78	0005	1.41	16,424	0.00	0.00	0.00			
901181	30-May-78	0005	20.00	16,444	0.00	0.00	0.00			
901182	2-Jun-78	0005	7.82	16,452	3.88	0.00	0.00			
901183	5-Jun-78	0005	51.00	16,503	0.30	0.00	0.00			
902110	6-Jun-78	0101	2.35	16,505	0.00	0.00	0.00			
902111	8-Jun-78	0101	4.53	16,510	0.00	0.00	0.00			

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902112	10-Jun-78	0101	5.74	16,515	0.00	0.00	0.00			
SF03-01A	15-Jun-78	2001	41.82	16,557	0.00	0.00	0.00			
SF03-01B	15-Jun-78	2003	42.24	16,599	0.00	0.00	0.00			
SF03-01C	15-Jun-78	2002	42.63	16,642	0.00	0.00	0.00			
902113	22-Jun-78	0101	25.00	16,667	4.20	0.00	0.00			
902114	24-Jun-78	0101	281.03	16,948	0.83	0.00	0.00			
902115	27-Jun-78	0101	299.98	17,248	0.00	0.00	0.00			
902116	29-Jun-78	0101	10.85	17,259	0.00	0.00	0.00			
SF04-01A	7-Jul-78	2001	103.88	17,363	0.00	0.00	0.00			
SF04-01B	7-Jul-78	2003	93.70	17,456	0.00	0.00	0.00			
SF04-01C	7-Jul-78	2002	103.63	17,560	0.00	0.00	0.00			
902117	8-Jul-78	0101	6.08	17,566	0.00	0.00	0.00			
902118	10-Jul-78	0101	6.84	17,573	0.00	0.00	0.00			
901184	14-Jul-78	0005	30.00	17,603	6.00	0.00	0.00			
902119	14-Jul-78	0101	166.69	17,770	50.69	0.00	0.00			
902120	18-Jul-78	0101	41.81	17,811	21.01	0.00	0.00			
901185	12-Aug-78	0005	50.00	17,861	9.20	0.00	0.00			
901186	13-Aug-78	0005	240.39	18,102	199.59	0.00	0.00			
901187	18-Aug-78	0005	150.00	18,252	103.00	0.00	0.00			
901188	20-Aug-78	0005	300.00	18,552	274.20	0.00	0.00			
902121	22-Aug-78	2002	7.16	18,559	0.00	0.00	0.00			
901189	23-Aug-78	0005	64.64	18,624	60.42	0.00	0.00			
902122	24-Aug-78	2002	300.00	18,924	257.00	0.00	0.00			
901190	26-Aug-78	0005	137.83	19,061	133.77	0.00	0.00			
902123	27-Aug-78	2002	100.00	19,161	57.00	0.00	0.00			
901191	28-Aug-78	0005	300.00	19,461	295.92	0.00	0.00			
902124	29-Aug-78	2002	266.82	19,728	223.82	0.00	0.00			
901192	30-Aug-78	0005	300.00	20,028	295.99	0.00	0.00			
902125	31-Aug-78	2002	72.02	20,100	29.02	0.00	0.00			
902126	1-Sep-78	2002	300.00	20,400	247.00	0.00	0.00			
901193	2-Sep-78	0005	300.00	20,700	295.88	0.00	0.00			
902127	5-Sep-78	2002	111.56	20,812	68.56	0.00	0.00			
901194	6-Sep-78	0005	310.11	21,122	306.05	0.00	0.00			
902128	6-Sep-78	2002	300.00	21,422	247.00	0.00	0.00			

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Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901195	7-Sep-78	0005	520.00	21,942	515.92	0.00	0.00			
902129	8-Sep-78	2002	300.00	22,242	247.00	0.00	0.00			
901196	9-Sep-78	0005	520.00	22,762	515.92	0.00	0.00			
901197	11-Sep-78	0005	520.00	23,282	515.97	0.00	0.00			
901198	13-Sep-78	0005	520.00	23,802	515.91	0.00	0.00			
902130	14-Sep-78	2002	301.50	24,103	258.50	0.00	0.00			
901199	15-Sep-78	0005	520.00	24,623	355.94	0.00	0.00			
901200	18-Sep-78	0005	289.10	24,913	285.00	0.00	0.00			
902131	19-Sep-78	2002	300.04	25,213	132.50	0.00	0.00			
901201	25-Sep-78	0005	3.05	25,216	0.00	0.00	0.00			
901202	26-Sep-78	0005	138.51	25,354	134.41	0.00	0.00			
901203	28-Sep-78	0005	300.00	25,654	295.84	0.00	0.00			
901204	1-Oct-78	0005	300.00	25,954	0.00	0.00	0.00			
902132	3-Oct-78	0006	2.36	25,957	0.00	0.00	0.00			
901205	9-Oct-78	0005	300.00	26,257	219.00	0.00	0.00			
901206	11-Oct-78	0005	300.00	26,557	0.00	0.00	0.00			
901207	16-Oct-78	0005	2.35	26,559	0.00	0.00	0.00			
901208	17-Oct-78	0005	4.88	26,564	0.00	0.00	0.00			
901209	19-Oct-78	0005	100.00	26,664	0.00	0.00	0.00			
901210	20-Oct-78	0005	300.00	26,964	9.50	0.00	0.00			
902133	20-Oct-78	2002	50.00	27,014	0.00	0.00	0.00			
901211	23-Oct-78	0005	520.00	27,534	0.00	0.00	0.00			
901212	25-Oct-78	0005	300.00	27,834	199.00	0.00	0.00			
901213	27-Oct-78	0005	1.30	27,835	0.00	0.00	0.00			
901214	28-Oct-78	0005	290.38	28,125	189.38	0.00	0.00			
902134	28-Oct-78	2002	100.00	28,225	0.00	0.00	0.00			
901215	30-Oct-78	0005	823.00	29,048	0.00	0.00	0.00			
901216	2-Nov-78	0005	3.57	29,052	0.00	0.00	0.00			
902135	2-Nov-78	2002	2.79	29,055	0.00	0.00	0.00			
901217	3-Nov-78	0005	520.00	29,575	0.00	0.00	0.00			
902136	3-Nov-78	2002	285.00	29,860	226.50	0.00	0.00			
750001	7-Nov-78	0201	2.35	29,862	0.00	0.00	0.00			
901218	7-Nov-78	0005	520.00	30,382	0.00	0.00	0.00			
902137	7-Nov-78	2002	50.00	30,432	0.00	0.00	0.00			

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Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901219	9-Nov-78	0005	520.00	30,952	0.00	0.00	0.00			
902138	9-Nov-78	2002	100.00	31,052	0.00	0.00	0.00			
750002	10-Nov-78	0201	4.00	31,056	0.00	0.00	0.00			
901220	11-Nov-78	0005	197.80	31,254	0.00	0.00	0.00			
902139	13-Nov-78	2002	200.00	31,454	0.00	0.00	0.00			
901221	15-Nov-78	0005	665.00	32,119	0.00	0.00	0.00			
902140	15-Nov-78	2002	200.00	32,319	19.00	0.00	0.00			
902141	17-Nov-78	2002	300.00	32,619	185.96	0.00	0.00			
750003	22-Nov-78	0201	15.00	32,634	0.00	0.00	0.00			
750004	29-Nov-78	0201	50.00	32,684	9.00	0.00	0.00			
902142	2-Dec-78	2002	2.71	32,687	0.00	0.00	0.00			
902143	3-Dec-78	2002	2.81	32,689	0.00	0.00	0.00			
902144	4-Dec-78	2002	36.29	32,726	29.02	0.00	0.00			
750005	5-Dec-78	0201	1.50	32,727	0.00	0.00	0.00			
901222	5-Dec-78	0007	4.35	32,732	0.00	0.00	0.00	X		
750006	7-Dec-78	0201	40.90	32,773	0.00	0.00	0.00			
902145	8-Dec-78	2002	68.61	32,841	35.65	0.00	0.00			
750007	9-Dec-78	0201	300.00	33,141	0.00	0.00	0.00			
902146	11-Dec-78	2002	520.00	33,661	427.00	0.00	0.00			
750008	13-Dec-78	0201	300.00	33,961	0.00	0.00	0.00			
902147	15-Dec-78	2002	260.16	34,221	256.16	0.00	0.00			
750009	16-Dec-78	0201	35.00	34,256	10.00	0.00	0.00			
901223	19-Dec-78	2001	1.61	34,258	0.00	0.00	0.00			
750010	20-Dec-78	0201	264.30	34,522	244.00	0.00	0.00			
901224	23-Dec-78	2001	60.01	34,582	56.03	0.00	0.00			
901225	27-Dec-78	2001	255.63	34,838	222.57	0.00	0.00	X		
750011	30-Jan-79	0201	1.40	34,839	0.00	0.00	0.00			
750012	2-Feb-79	0201	1.50	34,841	0.00	0.00	0.00			
750013	4-Feb-79	0201	25.00	34,866	9.50	0.00	0.00			
901226	5-Feb-79	2003	1.40	34,867	0.00	0.00	0.00			
750014	8-Feb-79	0201	1.50	34,869	0.00	0.00	0.00			
750015	10-Feb-79	0201	25.00	34,894	9.52	0.00	0.00			
750016	12-Feb-79	0201	300.00	35,194	0.00	0.00	0.00			
750017	24-Feb-79	0201	41.00	35,235	25.62	0.00	0.00			

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750018	2-Mar-79	0201	107.81	35,342	42.33	0.00	0.00			
750019	4-Mar-79	0201	300.00	35,642	285.56	0.00	0.00			
901227	4-Mar-79	2003	4.35	35,647	0.00	0.00	0.00			
901228	7-Mar-79	2003	15.35	35,662	0.00	0.00	0.00			
750020	8-Mar-79	0201	1.55	35,664	0.00	0.00	0.00			
750021	9-Mar-79	0201	300.00	35,964	269.00	0.00	0.00			
901229	9-Mar-79	2003	23.01	35,987	7.51	0.00	0.00			
901230	12-Mar-79	2003	18.34	36,005	13.95	0.00	0.00			
901231	14-Mar-79	2003	60.00	36,065	56.07	0.00	0.00			
902148	14-Mar-79	2004	1.50	36,067	0.00	0.00	0.00			
750022	15-Mar-79	0201	300.00	36,367	249.00	0.00	0.00			
902149	16-Mar-79	2004	50.07	36,417	0.00	0.00	0.00			
750023	17-Mar-79	0201	300.00	36,717	275.62	0.00	0.00			
901232	17-Mar-79	2003	520.00	37,237	427.10	0.00	0.00			
750024	19-Mar-79	0201	300.00	37,537	295.56	0.00	0.00			
750025	21-Mar-79	0201	300.00	37,837	295.58	0.00	0.00			
750026	23-Mar-79	0201	289.41	38,126	284.97	0.00	0.00			
902150	24-Mar-79	2004	50.08	38,176	46.16	0.00	0.00			
902151	27-Mar-79	2004	520.00	38,696	424.66	0.00	0.00			
750027	29-Mar-79	0201	50.00	38,746	45.60	0.00	0.00			
750028	31-Mar-79	0201	300.00	39,046	295.55	0.00	0.00			
901233	31-Mar-79	0006	1.50	39,048	0.00	0.00	0.00			
902152	1-Apr-79	2004	520.00	39,568	424.66	0.00	0.00			
750029	2-Apr-79	0201	300.00	39,868	164.52	0.00	0.00			
902153	3-Apr-79	2004	823.07	40,691	519.15	0.00	0.00			
750030	4-Apr-79	0201	50.00	40,741	45.56	0.00	0.00			
901234	5-Apr-79	0006	60.02	40,801	56.16	0.00	0.00			
750031	6-Apr-79	0201	300.00	41,101	295.44	0.00	0.00			
901235	8-Apr-79	0006	520.02	41,621	427.15	0.00	0.00			
750032	13-Apr-79	0201	350.21	41,971	195.90	0.00	0.00			
750033	16-Apr-79	0201	252.51	42,223	248.42	0.00	0.00			
750034	18-Apr-79	0201	350.00	42,573	195.88	0.00	0.00			
750035	19-Apr-79	0201	343.90	42,917	195.90	0.00	0.00			
902154	19-Apr-79	2005	1.54	42,919	0.00	0.00	0.00			

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750036	21-Apr-79	0201	300.00	43,219	295.84	0.00	0.00			
902155	24-Apr-79	2005	80.07	43,299	62.70	0.00	0.00			
750037	25-Apr-79	0201	300.00	43,599	295.84	0.00	0.00			
901236	26-Apr-79	2007	1.50	43,600	0.00	0.00	0.00			
750038	27-Apr-79	0201	300.02	43,900	295.86	0.00	0.00			
750039	30-Apr-79	0201	350.00	44,250	195.80	0.00	0.00			
750040	2-May-79	0201	382.77	44,633	195.80	0.00	0.00			
901237	2-May-79	2007	100.05	44,733	96.17	0.00	0.00			
SF05-01A	4-May-79	2002	1.51	44,735	0.00	0.00	0.00			
SF05-01B	4-May-79	2003	1.52	44,736	0.00	0.00	0.00			
SF05-01C	4-May-79	0006	1.50	44,738	0.00	0.00	0.00			
901238	5-May-79	2007	61.87	44,800	29.10	0.00	0.00			
902156	7-May-79	2004	10.05	44,810	6.15	0.00	0.00			
901239	10-May-79	2007	285.30	45,095	252.42	0.00	0.00			
902157	10-May-79	2004	90.50	45,186	55.09	0.00	0.00			
901240	12-May-79	2007	520.06	45,706	427.13	0.00	0.00			
750041	14-May-79	0201	4.32	45,710	0.07	0.00	0.00			
902158	22-May-79	2004	27.67	45,738	23.77	0.00	0.00			
901241	23-May-79	2005	100.07	45,838	85.19	0.00	0.00			
901242	26-May-79	2005	520.04	46,358	427.14	0.00	0.00			
902159	31-May-79	2004	100.07	46,458	85.15	0.00	0.00			
902160	2-Jun-79	2004	520.00	46,978	424.60	0.00	0.00			
902161	8-Jun-79	2004	665.00	47,643	614.61	0.00	0.00			
901243	9-Jun-79	2006	1.50	47,644	0.00	0.00	0.00			
901244	12-Jun-79	2006	100.07	47,744	96.23	0.00	0.00			
SF05A-1A	12-Jun-79	2002	54.60	47,799	50.73	0.00	0.00			
SF05A-1B	12-Jun-79	2003	55.69	47,855	51.76	0.00	0.00			
SF05A-1C	12-Jun-79	0006	54.07	47,909	50.21	0.00	0.00			
902162	13-Jun-79	2004	4.45	47,913	0.58	0.00	0.00			
901245	16-Jun-79	2006	520.04	48,433	427.18	0.00	0.00			
902163	21-Jun-79	2004	520.06	48,953	424.61	0.00	0.00			
902164	25-Jun-79	2004	520.06	49,473	430.85	0.00	0.00			
902165	27-Jun-79	2004	823.06	50,296	519.18	0.00	0.00			
SF06-01A	2-Jul-79	2002	18.49	50,315	14.64	0.00	0.00	X		

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SF06-01B	2-Jul-79	2003	19.36	50,334	15.49	0.00	0.00			
SF06-01C	2-Jul-79	0006	19.96	50,354	16.12	0.00	0.00			
750042	6-Jul-79	0007	0.00	50,354	0.00	0.00	0.00			
750043	9-Jul-79	0007	0.00	50,354	0.00	0.00	0.00			
750044	10-Jul-79	0007	1.30	50,355	0.00	0.00	0.00			
750045	12-Jul-79	0007	1.56	50,357	0.00	0.00	0.00			
901246	12-Jul-79	2007	3.73	50,361	0.00	0.00	0.00			
901247	16-Jul-79	2007	100.05	50,461	96.23	0.00	0.00			
902166	20-Jul-79	2004	1.54	50,462	0.00	0.00	0.00			
902167	24-Jul-79	2004	10.07	50,472	6.25	0.00	0.00			
902168	26-Jul-79	2004	50.04	50,522	34.68	0.00	0.00			
902169	31-Jul-79	2004	100.07	50,623	56.68	0.00	0.00			
901248	3-Aug-79	0007	1.57	50,624	0.00	0.00	0.00			
901249	4-Aug-79	0007	50.05	50,674	46.24	0.00	0.00			
901250	11-Aug-79	0007	6.48	50,681	2.65	0.00	0.00			
902170	11-Aug-79	2004	1.51	50,682	0.00	0.00	0.00			
902171	13-Aug-79	2004	56.04	50,738	45.96	0.00	0.00			
901251	18-Aug-79	0007	10.05	50,748	6.23	0.00	0.00			
901252	21-Aug-79	0007	10.00	50,758	6.16	0.00	0.00			
901253	22-Aug-79	0007	1.53	50,760	0.00	0.00	0.00			
901254	27-Aug-79	0007	100.05	50,860	96.23	0.00	0.00			
902172	6-Sep-79	2004	6.63	50,866	2.84	0.00	0.00			
902173	8-Sep-79	2004	1.82	50,868	0.00	0.00	0.00			
901255	15-Sep-79	0007	34.55	50,903	29.18	0.00	0.00			
901256	17-Sep-79	0007	100.00	51,003	64.71	0.00	0.00			
902174	17-Sep-79	2004	135.96	51,139	100.66	0.00	0.00			
750046	19-Sep-79	0105	1.50	51,140	0.00	0.00	0.00			
902175	20-Sep-79	2004	257.48	51,398	222.17	0.00	0.00			
750047	22-Sep-79	0105	10.43	51,408	6.00	0.00	0.00			
902176	22-Sep-79	2004	520.06	51,928	424.68	0.00	0.00			
750048	25-Sep-79	0105	49.97	51,978	30.93	0.00	0.00			
750049	29-Sep-79	0105	5.16	51,983	1.53	0.00	0.00			
750050	1-Oct-79	0105	93.23	52,077	89.21	0.00	0.00			
902177	1-Oct-79	2004	520.06	52,597	424.62	0.00	0.00			

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750051	6-Oct-79	0105	300.01	52,897	295.97	0.00	0.00			
901257	6-Oct-79	0008	1.50	52,898	0.00	0.00	0.00			
901258	10-Oct-79	0008	1.57	52,900	0.00	0.00	0.00			
902178	10-Oct-79	2004	10.00	52,910	6.12	0.00	0.00			
901259	11-Oct-79	0008	100.00	53,010	96.16	0.00	0.00			
902179	12-Oct-79	2004	823.00	53,833	519.13	0.00	0.00			
750052	16-Oct-79	0105	96.13	53,929	92.24	0.00	0.00			
901260	18-Oct-79	0008	520.00	54,449	424.68	0.00	0.00			
902180	20-Oct-79	2004	10.00	54,459	6.09	0.00	0.00			
750053	23-Oct-79	0105	300.00	54,759	287.10	0.00	0.00			
750054	26-Oct-79	0105	60.00	54,819	19.11	0.00	0.00			
901261	26-Oct-79	0008	520.00	55,339	424.66	0.00	0.00			
902181	26-Oct-79	2004	665.02	56,004	314.64	0.00	0.00			
750055	1-Nov-79	0105	94.56	56,098	16.11	0.00	0.00			
750056	3-Nov-79	0105	1.50	56,100	0.00	0.00	0.00			
SF06-03A	4-Nov-79	2002	9.72	56,110	5.88	0.00	0.00			
SF06-03B	4-Nov-79	2003	10.35	56,120	6.45	0.00	0.00			
SF06-03C	4-Nov-79	0006	8.69	56,129	4.81	0.00	0.00			
901262	24-Nov-79	0008	100.05	56,229	86.18	0.00	0.00			
750057	15-Dec-79	0007	1.50	56,230	0.00	0.00	0.00			
SF06-04A	17-Dec-79	0008	553.70	56,784	336.16	0.00	0.00			
SF06-04B	17-Dec-79	2003	508.75	57,293	336.04	0.00	0.00			
SF06-04C	17-Dec-79	0006	553.97	57,847	336.15	0.00	0.00			
750058	19-Dec-79	0007	350.00	58,197	116.12	0.00	0.00			
750059	27-Dec-79	0007	313.25	58,510	116.13	0.00	0.00			
750060	29-Dec-79	0007	300.00	58,810	296.14	0.00	0.00			
902182	9-Jan-80	2004	520.04	59,330	424.50	0.00	0.00			
750061	11-Jan-80	0007	300.00	59,630	146.12	0.00	0.00			
750062	14-Jan-80	0007	300.00	59,930	286.12	0.00	0.00			
902183	14-Jan-80	2004	520.00	60,450	424.48	0.00	0.00			
902184	18-Jan-80	2004	520.00	60,970	424.42	0.00	0.00			
901263	22-Jan-80	0009	1.50	60,971	0.00	0.00	0.00			
901264	24-Jan-80	0009	1.50	60,973	0.00	0.00	0.00			
750063	25-Jan-80	0007	300.00	61,273	146.08	0.00	0.00			

SSME Chronological Experience with Power Levels

Test/Fli Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901265	25-Jan-80	0009	1.50	61,274	0.00	0.00	0.00			
750064	31-Jan-80	0007	300.00	61,574	145.96	0.00	0.00			
901266	31-Jan-80	0009	2.00	61,576	0.00	0.00	0.00			
SF07-01A	1-Feb-80	0008	5.00	61,581	0.92	0.00	0.00			
SF07-01B	1-Feb-80	2007	5.00	61,586	1.50	0.00	0.00			
SF07-01C	1-Feb-80	0006	4.61	61,591	0.66	0.00	0.00			
901267	2-Feb-80	0009	39.62	61,630	35.78	0.00	0.00			
902185	5-Feb-80	2004	520.00	62,150	430.52	0.00	0.00			
902186	7-Feb-80	2004	10.00	62,160	6.02	0.00	0.00			
901268	8-Feb-80	0009	520.00	62,680	424.70	0.00	0.00			
750065	11-Feb-80	0007	1.50	62,682	0.00	0.00	0.00			
750066	12-Feb-80	0007	300.00	62,982	248.38	0.00	0.00			
901269	15-Feb-80	0009	2.85	62,985	0.00	0.00	0.00			
750067	22-Feb-80	0007	300.00	63,285	254.34	0.00	0.00			
SF07-02A	28-Feb-80	0008	554.30	63,839	329.32	0.00	0.00			
SF07-02B	28-Feb-80	2003	523.43	64,362	329.26	0.00	0.00			
SF07-02C	28-Feb-80	0006	554.82	64,917	329.29	0.00	0.00			
901270	29-Feb-80	0009	520.00	65,437	424.36	0.00	0.00			
750068	1-Mar-80	0007	300.00	65,737	248.29	0.00	0.00			
902187	4-Mar-80	2004	100.00	65,837	95.88	0.00	0.00			
901271	5-Mar-80	0009	823.08	66,660	518.88	0.00	0.00			
750069	7-Mar-80	0007	300.00	66,960	254.26	0.00	0.00			
902188	7-Mar-80	2004	110.04	67,070	63.87	25.00	0.00			
902189	13-Mar-80	2004	125.06	67,195	89.96	10.00	10.00			
750070	15-Mar-80	0007	300.04	67,495	248.29	0.00	0.00			
901272	15-Mar-80	0009	665.03	68,161	614.34	0.00	0.00			
750071	18-Mar-80	0007	300.00	68,461	254.26	0.00	0.00			
SF08-01A	20-Mar-80	0008	539.38	69,000	357.11	0.00	0.00			
SF08-01B	20-Mar-80	2003	539.48	69,539	344.11	0.00	0.00			
SF08-01C	20-Mar-80	0006	539.61	70,079	357.11	0.00	0.00			
901273	22-Mar-80	0009	519.90	70,599	424.34	0.00	0.00			
902190	24-Mar-80	2004	241.04	70,840	236.14	0.50	0.24			
750072	26-Mar-80	0007	300.00	71,140	34.78	0.00	0.00			
901274	28-Mar-80	0009	520.00	71,660	430.60	0.00	0.00			

SSME Chronological Experience with Power Levels

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
750073	29-Mar-80	0007	300.00	71,960	28.72	0.00	0.00			
902191	31-Mar-80	2004	610.00	72,570	232.10	5.50	360.10			
750074	5-Apr-80	0007	300.00	72,870	254.28	0.00	0.00			
901275	8-Apr-80	0009	520.00	73,390	424.32	0.00	0.00			
750075	11-Apr-80	0007	10.00	73,400	5.74	0.00	0.00			
901276	12-Apr-80	0009	520.00	73,920	424.36	0.00	0.00			
750076	14-Apr-80	0007	10.00	73,930	5.74	0.00	0.00			
902192	14-Apr-80	2004	610.00	74,540	232.13	5.50	360.10			
SF09-01A	16-Apr-80	0008	5.84	74,546	1.64	0.00	0.00			
SF09-01B	16-Apr-80	2003	4.72	74,550	0.49	0.00	0.00			
SF09-01C	16-Apr-80	0006	6.62	74,557	2.46	0.00	0.00			
901277	18-Apr-80	0009	10.00	74,567	5.88	0.00	0.00			
902193	19-Apr-80	2004	610.00	75,177	232.18	5.50	360.10			
750077	21-Apr-80	0007	300.00	75,477	254.30	0.00	0.00			
901278	21-Apr-80	0009	10.00	75,487	5.87	0.00	0.00			
901279	24-Apr-80	0009	300.00	75,787	245.76	0.00	0.00			
901280	28-Apr-80	0009	520.00	76,307	424.32	0.00	0.00			
750078	30-Apr-80	0007	300.00	76,607	248.02	0.00	0.00			
750079	7-May-80	0007	300.00	76,907	248.33	0.00	0.00			
750080	15-May-80	0007	300.00	77,207	254.88	0.00	0.00			
750081	21-May-80	0007	300.00	77,507	285.83	0.00	0.00			
SF09-02A	30-May-80	0008	578.24	78,085	351.34	0.00	0.00			
SF09-02B	30-May-80	2003	548.81	78,634	351.14	0.00	0.00			
SF09-02C	30-May-80	0006	533.89	79,168	351.38	0.00	0.00			
902194	2-Jun-80	2005	520.00	79,688	427.14	0.00	0.00			
750082	5-Jun-80	0007	300.00	79,988	152.84	0.00	0.00			
901281	5-Jun-80	2006	520.00	80,508	424.30	0.00	0.00			
750083	9-Jun-80	0007	300.00	80,808	143.30	0.00	0.00			
750084	11-Jun-80	0007	300.00	81,108	145.88	0.00	0.00			
901282	16-Jun-80	2007	520.00	81,628	424.34	0.00	0.00			
750085	19-Jun-80	0007	300.00	81,928	227.50	0.00	0.00			
902195	20-Jun-80	2004	251.03	82,179	246.95	0.00	0.00			
750086	23-Jun-80	0007	300.00	82,479	254.12	0.00	0.00			
902196	24-Jun-80	2004	520.00	82,999	430.62	0.00	0.00			

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Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
902197	2-Jul-80	2004	520.00	83,519	430.60	0.00	0.00			
750087	3-Jul-80	0007	300.00	83,819	246.75	0.00	0.00			
SF10-01A	12-Jul-80	0008	105.29	83,924	69.49	0.00	0.00			
SF10-01B	12-Jul-80	2003	105.92	84,030	70.00	0.00	0.00			
SF10-01C	12-Jul-80	0006	106.52	84,137	70.76	0.00	0.00	X	X	X
750088	15-Jul-80	0007	300.00	84,437	241.80	0.00	0.00			
902198	23-Jul-80	2004	8.53	84,445	4.53	0.00	0.00		X	
750089	28-Jul-80	0007	130.00	84,575	95.82	0.00	0.00			
901283	28-Jul-80	0010	1.50	84,577	0.00	0.00	0.00			
901284	30-Jul-80	0010	9.89	84,587	0.00	0.00	0.00		X	
750090	16-Aug-80	0007	160.00	84,747	145.76	0.00	0.00			
750091	20-Aug-80	0007	100.00	84,847	85.78	0.00	0.00			
901285	27-Aug-80	0009	1.56	84,848	0.00	0.00	0.00			
901286	29-Aug-80	0009	10.00	84,858	5.80	0.00	0.00			
901287	2-Sep-80	0009	100.00	84,958	95.76	0.00	0.00			
750092	3-Sep-80	0007	174.84	85,133	160.80	0.00	0.00			
902199	8-Sep-80	2008	1.50	85,135	0.00	0.00	0.00			
750093	9-Sep-80	0007	300.00	85,435	285.80	0.00	0.00			
901288	11-Sep-80	0009	392.60	85,827	356.90	0.00	0.00			
902200	13-Sep-80	2008	100.00	85,927	95.72	0.00	0.00			
902201	16-Sep-80	2008	250.00	86,177	218.50	9.70	0.00			
901289	18-Sep-80	0009	520.00	86,697	430.30	0.00	0.00			
750094	20-Sep-80	0007	285.27	86,982	281.21	0.00	0.00			
902202	23-Sep-80	2008	50.00	87,032	45.72	0.00	0.00			
750095	27-Sep-80	0007	99.52	87,132	85.80	0.00	0.00			
750096	30-Sep-80	0007	99.52	87,232	85.80	0.00	0.00			
750097	2-Oct-80	0007	100.12	87,332	85.80	0.00	0.00			
750098	4-Oct-80	0007	100.12	87,432	85.78	0.00	0.00			
750099	7-Oct-80	0007	137.06	87,569	85.84	0.00	0.00			
901290	7-Oct-80	0009	520.00	88,089	430.40	0.00	0.00			
750100	9-Oct-80	0007	100.01	88,189	85.79	0.00	0.00			
901291	10-Oct-80	0009	520.00	88,709	13.40	423.20	0.00			
750101	11-Oct-80	0007	100.01	88,809	14.81	0.00	0.00			
902203	11-Oct-80	0006	1.50	88,810	0.00	0.00	0.00			

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902204	13-Oct-80	0006	260.00	89,070	231.80	0.00	0.00			
901292	15-Oct-80	0009	520.00	89,590	430.40	0.00	0.00			
750102	20-Oct-80	0007	300.00	89,890	248.30	0.00	0.00			
901293	22-Oct-80	0009	823.00	90,713	518.89	0.00	0.00			
901294	24-Oct-80	0009	665.00	91,378	610.40	0.00	0.00			
902205	28-Oct-80	2008	1.50	91,380	0.00	0.00	0.00			
902206	29-Oct-80	2008	100.00	91,480	95.76	0.00	0.00			
750103	3-Nov-80	0007	33.48	91,513	5.75	0.00	0.00			
SF11-01A	3-Nov-80	0008	20.70	91,534	16.61	0.00	0.00			
SF11-01B	3-Nov-80	2003	19.50	91,554	15.22	0.00	0.00			
SF11-01C	3-Nov-80	0006	21.44	91,575	17.36	0.00	0.00			
902207	4-Nov-80	2008	520.00	92,095	430.34	0.00	0.00			
750104	6-Nov-80	0007	10.00	92,105	5.71	0.00	0.00			
901295	6-Nov-80	0009	520.00	92,625	430.38	0.00	0.00			
750105	8-Nov-80	0007	10.00	92,635	5.82	0.00	0.00			
902208	10-Nov-80	2008	520.00	93,155	430.22	0.00	0.00			
750106	11-Nov-80	0007	15.00	93,170	5.96	0.00	0.00			
901296	11-Nov-80	0009	519.93	93,690	430.40	0.00	0.00			
750107	13-Nov-80	0007	3.64	93,694	0.00	0.00	0.00			
901297	13-Nov-80	0009	10.00	93,704	5.76	0.00	0.00			
750108	15-Nov-80	0007	15.00	93,719	5.98	0.00	0.00			
902209	15-Nov-80	2008	823.00	94,542	518.72	0.00	0.00			
750109	18-Nov-80	0007	15.00	94,557	5.72	0.00	0.00			
901298	19-Nov-80	0009	10.00	94,567	5.72	0.00	0.00			
902210	21-Nov-80	2008	665.00	95,232	610.46	0.00	0.00			
901299	24-Nov-80	0009	10.00	95,242	5.74	0.00	0.00			
750110	25-Nov-80	0007	450.00	95,692	10.76	0.00	0.00			
750111	1-Dec-80	0007	300.00	95,992	222.84	0.00	0.00			
901300	2-Dec-80	0009	10.00	96,002	5.82	0.00	0.00			
SF11-02A	4-Dec-80	0008	590.03	96,592	352.32	0.00	0.00			
SF11-02B	4-Dec-80	2003	441.76	97,033	352.08	0.00	0.00			
SF11-02C	4-Dec-80	0006	590.33	97,624	352.34	0.00	0.00			
902211	5-Dec-80	2008	250.00	97,874	245.80	0.00	0.00			
750112	6-Dec-80	0007	300.00	98,174	295.76	0.00	0.00			

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902212	10-Dec-80	2008	520.00	98,694	13.82	422.80	0.00			
901301	15-Dec-80	0009	823.00	99,517	518.78	0.00	0.00			
750113	16-Dec-80	0007	300.00	99,817	295.80	0.00	0.00			
750114	18-Dec-80	0007	300.00	100,117	295.80	0.00	0.00			
902213	18-Dec-80	2008	520.00	100,637	430.42	0.00	0.00			
750115	20-Dec-80	0007	300.00	100,937	295.79	0.00	0.00			
902214	23-Dec-80	2008	520.00	101,457	430.40	0.00	0.00			
902215	30-Dec-80	2008	520.00	101,977	430.20	0.00	0.00			
750116	2-Jan-81	0007	300.00	102,277	295.76	0.00	0.00			
902216	5-Jan-81	2008	520.00	102,797	430.20	0.00	0.00			
750117	9-Jan-81	0007	300.00	103,097	290.71	0.00	0.00			
901302	12-Jan-81	0009	1.50	103,098	0.00	0.00	0.00			
SF12-01A	17-Jan-81	0008	628.36	103,727	624.11	0.00	0.00			
SF12-01B	17-Jan-81	2003	628.46	104,355	623.90	0.00	0.00			
SF12-01C	17-Jan-81	0006	238.94	104,594	234.76	0.00	0.00			
901303	19-Jan-81	0009	53.10	104,647	5.74	0.00	0.00			
901304	21-Jan-81	0009	81.70	104,729	5.74	0.00	0.00			
750118	22-Jan-81	0007	300.00	105,029	295.72	0.00	0.00			
901305	23-Jan-81	0009	79.57	105,108	5.75	0.00	0.00			
901306	26-Jan-81	0009	80.29	105,189	5.79	0.00	0.00			
750119	28-Jan-81	0007	5.25	105,194	0.85	0.00	0.00			
901307	28-Jan-81	0009	75.02	105,269	5.77	0.00	0.00		X	
902217	31-Jan-81	2009	1.57	105,270	0.00	0.00	0.00			
750120	2-Feb-81	0007	235.00	105,505	230.68	0.00	0.00			
902218	3-Feb-81	2009	100.00	105,605	95.94	0.00	0.00			
750121	9-Feb-81	0007	20.00	105,625	5.68	0.00	0.00			
902219	9-Feb-81	2009	520.00	106,145	418.38	0.00	0.00			
FRF001-A	20-Feb-81	2007	21.86	106,167	15.26	0.00	0.00			
FRF001-B	20-Feb-81	2006	23.83	106,191	17.13	0.00	0.00			
FRF001-C	20-Feb-81	2005	23.97	106,215	17.24	0.00	0.00			
750122	23-Feb-81	0110	1.50	106,217	0.00	0.00	0.00			
750123	25-Feb-81	0110	300.00	106,517	223.72	0.00	0.00			
901308	25-Feb-81	0006	3.90	106,520	0.00	0.00	0.00			
901309	28-Feb-81	0006	67.26	106,588	5.72	0.00	0.00			

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750124	2-Mar-81	0110	99.96	106,688	58.18	0.00	0.00			
901310	3-Mar-81	0006	67.36	106,755	5.83	0.00	0.00			
901311	5-Mar-81	0006	64.30	106,819	5.80	0.00	0.00			
902220	6-Mar-81	0008	100.00	106,919	87.74	0.00	0.00			
902221	10-Mar-81	0008	610.00	107,529	236.39	361.00	0.00			
750125	11-Mar-81	0110	300.00	107,829	155.54	110.10	30.00			
902222	12-Mar-81	0008	610.00	108,439	236.36	361.00	0.00			
750126	14-Mar-81	0110	300.00	108,739	75.48	1.00	219.20			
901312	14-Mar-81	0006	60.11	108,799	5.80	0.00	0.00			
902223	17-Mar-81	0008	610.00	109,409	236.22	1.00	360.40			
901313	18-Mar-81	0006	63.66	109,473	5.88	0.00	0.00			
901314	20-Mar-81	0006	47.63	109,521	43.47	0.00	0.00			
902224	23-Mar-81	0008	610.00	110,131	236.26	1.00	360.40			
750127	24-Mar-81	0110	15.00	110,146	5.72	0.00	0.00			
750128	26-Mar-81	0110	10.00	110,156	5.68	0.00	0.00			
901315	26-Mar-81	0006	66.84	110,223	5.88	0.00	0.00			
750129	28-Mar-81	0110	15.00	110,238	5.56	0.00	0.00			
750130	31-Mar-81	0110	15.00	110,253	5.68	0.00	0.00			
STS001-A	12-Apr-81	2007	519.42	110,772	432.45	0.00	0.00			
STS001-B	12-Apr-81	2006	519.56	111,292	432.60	0.00	0.00			
STS001-C	12-Apr-81	2005	519.68	111,811	432.76	0.00	0.00			
750131	13-Apr-81	0110	118.14	111,929	55.65	57.84	0.00			
902225	13-Apr-81	0204	1.50	111,931	0.00	0.00	0.00			
901316	14-Apr-81	0006	15.00	111,946	5.84	0.00	0.00			
902226	15-Apr-81	0204	3.71	111,950	0.00	0.00	0.00			
750132	17-Apr-81	0110	300.00	112,250	42.16	1.00	190.20			
902227	17-Apr-81	0204	3.80	112,253	0.00	0.00	0.00			
901317	20-Apr-81	0006	15.00	112,268	5.86	0.00	0.00			
901318	21-Apr-81	0006	1.50	112,270	0.00	0.00	0.00			
902228	21-Apr-81	0204	100.00	112,370	95.48	0.00	0.00			
901319	23-Apr-81	0006	100.00	112,470	85.82	0.00	0.00			
902229	24-Apr-81	0204	100.00	112,570	95.39	0.00	0.00			
750133	27-Apr-81	0110	300.00	112,870	71.06	5.70	189.90			
902230	27-Apr-81	0204	270.00	113,140	5.94	1.00	239.20			

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902231	5-May-81	0204	268.80	113,409	45.96	1.00	199.20			
750134	7-May-81	0110	300.00	113,709	5.92	1.50	261.10			
902232	7-May-81	0204	520.00	114,229	12.09	9.70	402.80			
750135	9-May-81	0110	300.00	114,529	6.20	1.50	260.90			
902233	9-May-81	0204	500.00	115,029	12.28	9.70	382.60			
901320	11-May-81	2108	1.48	115,030	0.00	0.00	0.00			
750136	12-May-81	0110	300.00	115,330	5.80	1.50	261.10			
901321	13-May-81	2108	300.00	115,630	295.62	0.00	0.00			
750137	14-May-81	0110	1.33	115,632	0.00	0.00	0.00			
902234	14-May-81	0204	500.00	116,132	32.02	29.70	222.80			
750138	19-May-81	0110	300.00	116,432	6.06	1.50	261.00			
902235	19-May-81	0204	500.00	116,932	45.82	42.00	127.00			
901322	23-May-81	2108	290.00	117,222	160.82	85.00	20.00			
902236	23-May-81	0204	500.00	117,722	45.97	42.00	127.00			
750139	26-May-81	0110	300.00	118,022	6.00	1.50	261.10			
901323	26-May-81	2108	260.00	118,282	165.94	60.50	20.00			
901324	28-May-81	2108	520.00	118,802	65.45	1.00	449.20			
901325	30-May-81	2108	520.00	119,322	65.34	1.00	449.20			
902237	5-Jun-81	0204	50.00	119,372	10.76	1.00	15.00			
901326	6-Jun-81	2108	300.00	119,672	295.56	0.00	0.00			
902238	9-Jun-81	0204	475.00	120,147	6.03	2.00	385.90			
901327	11-Jun-81	2108	520.00	120,667	65.42	1.00	449.20			
901328	16-Jun-81	2108	520.00	121,187	65.46	1.00	449.20			
902239	19-Jun-81	0204	25.00	121,212	6.20	1.00	5.20			
750140	20-Jun-81	0110	300.00	121,512	5.50	1.50	261.10			
902240	22-Jun-81	0204	10.00	121,522	5.72	0.00	0.00			
901329	23-Jun-81	2108	500.00	122,022	13.50	10.25	377.40			
902241	24-Jun-81	0204	15.00	122,037	5.96	0.50	4.20			
750141	27-Jun-81	0110	300.00	122,337	5.52	1.50	261.10			
750142	30-Jun-81	0110	300.00	122,637	5.49	1.50	261.10			
902242	2-Jul-81	0204	300.00	122,937	6.89	2.00	215.60			
902243	8-Jul-81	0204	100.00	123,037	53.98	16.50	8.00			
901330	10-Jul-81	2108	170.00	123,207	75.11	75.50	15.00			
902244	14-Jul-81	0204	450.00	123,657	15.76	0.00	0.00			

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Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901331	15-Jul-81	2108	233.14	123,890	208.52	1.00	8.20		X	
750143	6-Aug-81	0110	39.00	123,929	8.91	8.60	7.20			
901332	8-Aug-81	0008	1.50	123,930	0.00	0.00	0.00			
750144	10-Aug-81	0110	48.00	123,978	14.46	8.60	7.20			
901333	11-Aug-81	0008	81.83	124,060	5.59	0.00	0.00			
902245	12-Aug-81	0204	25.00	124,085	6.20	1.00	4.20			
750145	14-Aug-81	0110	48.01	124,133	14.41	8.60	7.20			
901334	14-Aug-81	0008	84.18	124,217	5.66	0.00	0.00			
901335	17-Aug-81	0008	57.73	124,275	53.42	0.00	0.00			
750146	18-Aug-81	0110	10.00	124,285	5.62	0.00	0.00			
901336	19-Aug-81	0008	54.45	124,339	50.15	0.00	0.00			
902246	22-Aug-81	0204	25.00	124,364	6.22	1.00	4.20			
750147	24-Aug-81	0110	39.00	124,403	8.20	8.60	7.20			
902247	31-Aug-81	0204	200.00	124,603	6.12	1.00	179.20			
750148	2-Sep-81	0110	16.00	124,619	0.90	3.50	7.20			
902248	14-Sep-81	0204	500.00	125,119	6.46	1.00	479.20			
902249	21-Sep-81	0204	450.57	125,570	6.13	0.50	439.77	X		
901337	7-Oct-81	0107	1.50	125,571	0.00	0.00	0.00			
901338	9-Oct-81	0107	15.20	125,587	10.99	0.00	0.00			
901339	13-Oct-81	0107	300.00	125,887	276.35	1.00	9.20			
901340	15-Oct-81	0107	405.50	126,292	5.98	0.50	394.70			
901341	30-Oct-81	0107	100.00	126,392	46.30	1.00	39.20			
901342	5-Nov-81	0107	200.00	126,592	6.23	1.00	179.20			
750149	7-Nov-81	0110F	1.50	126,594	0.00	0.00	0.00			
901343	8-Nov-81	0107	500.00	127,094	6.23	1.00	479.20			
STS002-A	12-Nov-81	2007	520.13	127,614	435.78	0.00	0.00			
STS002-B	12-Nov-81	2006	520.24	128,134	436.03	0.00	0.00			
STS002-C	12-Nov-81	2005	520.36	128,654	436.07	0.00	0.00			
901344	14-Nov-81	0107	500.00	129,154	6.04	1.00	479.20			
750150	17-Nov-81	0110F	60.00	129,214	35.38	1.00	9.20			
901345	18-Nov-81	0107	270.00	129,484	5.96	1.00	249.20			
901346	19-Nov-81	0107	500.00	129,984	5.95	1.00	479.20			
901347	30-Nov-81	0107	95.40	130,080	90.70	0.00	0.00			
901348	2-Dec-81	0107	750.00	130,830	200.13	1.00	509.20			

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
750151	4-Dec-81	0110F	3.61	130,833	0.00	0.00	0.00			
901349	4-Dec-81	0107	463.58	131,297	5.45	0.50	452.78			
902250	5-Dec-81	2010	1.50	131,298	0.00	0.00	0.00			
750152	10-Dec-81	0110F	80.50	131,379	21.40	1.00	10.20			
902251	11-Dec-81	2010	100.00	131,479	95.88	0.00	0.00			
750153	14-Dec-81	0110F	60.00	131,539	15.38	1.00	9.20			
902252	14-Dec-81	2010	500.00	132,039	12.44	9.70	380.10			
901350	16-Dec-81	0107	300.00	132,339	264.52	0.00	0.00			
902253	18-Dec-81	2010	500.00	132,839	12.43	9.70	380.10			
902254	21-Dec-81	2010	250.00	133,089	5.20	0.50	240.10			
901351	28-Dec-81	0107	500.00	133,589	96.22	1.00	389.20			
750154	29-Dec-81	0110F	65.00	133,654	21.05	10.60	9.20			
901352	30-Dec-81	0107	500.00	134,154	11.98	9.70	380.20			
750155	2-Jan-82	0110F	65.00	134,219	21.00	10.60	9.20			
902255	2-Jan-82	2010	750.00	134,969	199.62	1.00	510.10			
902256	5-Jan-82	2010	500.00	135,469	12.14	9.70	380.10			
902257	7-Jan-82	2010	595.00	136,064	5.04	0.50	585.10			
750156	11-Jan-82	0110F	65.00	136,129	20.96	10.60	9.20			
750157	13-Jan-82	0110F	200.00	136,329	44.00	10.80	9.20			
901353	14-Jan-82	0107	424.09	136,753	5.18	0.50	414.19			
750158	15-Jan-82	0110F	200.00	136,953	120.56	1.00	9.20			
902258	16-Jan-82	2010	10.00	136,963	5.62	0.00	0.00			
901354	18-Jan-82	0107	270.00	137,233	46.04	0.50	219.20			
902259	18-Jan-82	2010	60.00	137,293	5.08	0.50	50.10			
901355	20-Jan-82	0107	500.00	137,793	46.02	0.50	449.20			
901356	25-Jan-82	0107	37.16	137,830	25.94	0.50	6.36			
902260	27-Jan-82	2010	250.00	138,080	5.16	0.50	240.10			
902261	29-Jan-82	2010	500.00	138,580	12.26	9.70	380.20			
901357	1-Feb-82	0107	500.00	139,080	26.04	0.50	469.20			
902262	2-Feb-82	2010	500.00	139,580	12.66	382.14	0.00			
750159	4-Feb-82	0110F	65.00	139,645	20.96	10.60	9.20			
902263	6-Feb-82	2010	500.00	140,145	12.14	9.70	384.08			
901358	8-Feb-82	0107	500.00	140,645	25.98	0.50	469.20			
902264	9-Feb-82	2010	10.00	140,655	5.74	0.00	0.00			

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750160	12-Feb-82	0110F	3.16	140,658	0.00	0.00	0.00	X	X	X
902265	19-Feb-82	2010	100.00	140,758	95.86	0.00	0.00			
902266	22-Feb-82	2010	500.00	141,258	12.38	9.70	380.10			
901359	7-Mar-82	2013	1.50	141,260	0.00	0.00	0.00			
902267	8-Mar-82	2010	500.00	141,760	12.40	9.70	380.10			
901360	10-Mar-82	2013	100.00	141,860	95.76	0.00	0.00			
750161	15-Mar-82	0107	100.00	141,960	83.88	1.00	9.20			
902268	15-Mar-82	2010	500.00	142,460	12.14	9.70	380.20			
750162	22-Mar-82	0107	133.80	142,594	129.12	0.00	0.00			
901361	22-Mar-82	2013	500.00	143,094	12.58	9.70	380.20			
STS003-A	22-Mar-82	2007	519.67	143,613	435.66	0.00	0.00			
STS003-B	22-Mar-82	2006	519.80	144,133	435.69	0.00	0.00			
STS003-C	22-Mar-82	2005	519.91	144,653	435.74	0.00	0.00			
902269	23-Mar-82	2010	500.00	145,153	11.96	9.70	384.08			
750163	25-Mar-82	0107	2.00	145,155	0.00	0.00	0.00			
901362	26-Mar-82	2013	500.00	145,655	12.58	9.70	380.20			
902270	29-Mar-82	2010	250.00	145,905	4.99	0.50	240.10			
901363	30-Mar-82	2013	250.00	146,155	5.12	0.50	240.10			
750164	1-Apr-82	0107	118.94	146,274	5.74	0.50	108.14			
901364	7-Apr-82	2013	392.16	146,666	6.01	1.50	352.36			
750165	21-Apr-82	0107	280.00	146,946	5.31	1.50	240.20			
750166	29-Apr-82	0107	300.00	147,246	5.68	1.50	260.20			
902271	30-Apr-82	2010	300.00	147,546	295.88	0.00	0.00			
750167	2-May-82	0107	269.92	147,816	5.60	1.50	230.12			
902272	5-May-82	2010	500.00	148,316	12.42	9.70	380.30			
902273	8-May-82	2010	500.00	148,816	12.42	9.70	380.30			
902274	11-May-82	2010	60.00	148,876	5.18	0.50	50.10			
902275	13-May-82	2010	750.01	149,626	199.68	1.00	510.10			
750168	15-May-82	0107	300.00	149,926	5.68	1.50	260.20			
901365	15-May-82	2014	1.50	149,928	0.00	0.00	0.00			
901366	19-May-82	2014	100.00	150,028	95.83	0.00	0.00			
901367	25-May-82	2014	500.00	150,528	12.44	9.70	380.20			
902276	29-May-82	2010	595.00	151,123	5.54	1.00	575.10			
901368	3-Jun-82	2014	60.00	151,183	5.49	1.00	40.10			

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901369	5-Jun-82	2014	500.00	151,683	12.34	9.70	380.20			
902277	6-Jun-82	2010	250.00	151,933	5.54	1.00	225.10			
901370	7-Jun-82	2014	750.00	152,683	199.70	1.00	510.10			
901371	15-Jun-82	2014	250.00	152,933	5.52	1.00	230.10			
901372	17-Jun-82	2014	250.00	153,183	5.50	1.00	230.10			
902278	18-Jun-82	2010	1.50	153,184	0.00	0.00	0.00			
901373	20-Jun-82	2014	50.00	153,234	35.89	0.00	0.00			
902279	20-Jun-82	2010	50.00	153,284	5.50	1.00	30.10			
STS004-A	27-Jun-82	2007	519.03	153,803	443.06	0.00	0.00			
STS004-B	27-Jun-82	2006	519.13	154,322	443.18	0.00	0.00			
STS004-C	27-Jun-82	2005	519.31	154,842	443.04	0.00	0.00			
902280	28-Jun-82	2010	1.50	154,843	0.00	0.00	0.00			
902281	29-Jun-82	2010	1.50	154,845	0.00	0.00	0.00			
901374	30-Jun-82	2014	500.00	155,345	12.46	9.70	380.20			
902282	1-Jul-82	2010	1.50	155,346	0.00	0.00	0.00			
901375	3-Jul-82	2014	50.00	155,396	35.83	0.00	0.00			
902283	3-Jul-82	2010	50.00	155,446	5.50	1.00	30.10			
902284	9-Jul-82	2010	500.00	155,946	12.25	9.70	380.20			
901376	10-Jul-82	2014	5.12	155,951	0.00	0.00	0.00			
902285	13-Jul-82	2010	10.00	155,961	5.75	0.00	0.00			
901377	14-Jul-82	2014	300.00	156,261	295.89	0.00	0.00			
902286	19-Jul-82	2010	250.00	156,511	14.62	1.00	230.10			
902287	21-Jul-82	2010	500.00	157,011	5.12	490.60	0.00			
901378	23-Jul-82	2014	1.50	157,013	0.00	0.00	0.00			
901379	25-Jul-82	2014	50.00	157,063	5.48	1.00	30.10			
750169	27-Jul-82	2208	1.49	157,064	0.00	0.00	0.00			
901380	27-Jul-82	2014	500.00	157,564	12.42	9.70	380.20			
902288	27-Jul-82	2010	250.00	157,814	5.38	1.00	230.10			
750170	29-Jul-82	2208	50.00	157,864	35.78	0.00	0.00			
901381	30-Jul-82	2014	500.00	158,364	12.40	9.70	380.20			
902289	1-Aug-82	2010	250.00	158,614	5.10	1.00	230.10			
901382	2-Aug-82	2014	500.00	159,114	12.15	9.70	384.08			
750171	4-Aug-82	2208	299.89	159,414	15.52	1.00	270.10			
902290	4-Aug-82	2010	750.00	160,164	199.44	1.00	510.10			

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750172	7-Aug-82	2208	300.00	160,464	15.47	1.00	270.10			
902291	7-Aug-82	2010	250.00	160,714	61.64	10.50	9.70			
902292	9-Aug-82	2010	146.02	160,860	4.96	0.50	136.12			
901383	15-Aug-82	2014	300.00	161,160	295.85	0.00	0.00			
750173	18-Aug-82	2208	41.76	161,202	5.16	0.50	31.86			
901384	24-Aug-82	2014	595.00	161,797	5.26	0.50	585.10			
750174	25-Aug-82	2208	300.00	162,097	5.54	1.00	270.10			
750175	27-Aug-82	2208	116.08	162,213	5.26	0.50	106.18			
901385	27-Aug-82	2014	250.00	162,463	5.22	0.50	240.10			
902293	2-Sep-82	2012	1.50	162,464	0.00	0.00	0.00			
902294	10-Sep-82	2012	120.00	162,584	96.49	9.70	0.00			
901386	13-Sep-82	2011	1.54	162,586	0.00	0.00	0.00			
901387	19-Sep-82	2011	1.50	162,587	0.00	0.00	0.00			
901388	21-Sep-82	2011	5.40	162,593	0.92	0.00	0.00			
902295	23-Sep-82	2015	1.50	162,594	0.00	0.00	0.00			
901389	25-Sep-82	2011	120.00	162,714	96.42	9.70	0.00			
902296	25-Sep-82	2015	120.00	162,834	96.32	9.70	0.00			
902297	30-Sep-82	2015	23.50	162,858	5.30	0.50	13.50			
901390	4-Oct-82	2011	175.06	163,033	146.48	10.60	9.60			
902298	6-Oct-82	2015	185.00	163,218	146.24	10.60	9.60			
901391	7-Oct-82	2011	500.00	163,718	12.90	380.20	0.00			
902299	8-Oct-82	2015	500.00	164,218	12.51	9.70	380.10			
901392	18-Oct-82	2012	1.50	164,219	0.00	0.00	0.00			
901393	21-Oct-82	2012	51.00	164,270	46.76	0.00	0.00			
902300	23-Oct-82	2016	1.50	164,272	0.00	0.00	0.00			
902301	25-Oct-82	2016	4.60	164,277	0.20	0.00	0.00			
901394	26-Oct-82	2012	210.00	164,487	126.26	60.60	9.60			
750176	29-Oct-82	2308	1.52	164,488	0.00	0.00	0.00			
901395	30-Oct-82	2012	500.00	164,988	12.22	9.70	380.20			
750177	2-Nov-82	2308	210.00	165,198	126.28	60.60	9.60			
750178	7-Nov-82	2308	300.00	165,498	46.26	170.60	69.60			
STS005-A	11-Nov-82	2007	517.04	166,015	439.02	0.00	0.00			
STS005-B	11-Nov-82	2006	517.21	166,532	439.06	0.00	0.00			
STS005-C	11-Nov-82	2005	517.29	167,050	439.06	0.00	0.00			

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902302	15-Nov-82	2016	215.40	167,265	85.80	125.10	0.00			
750179	16-Nov-82	2308	300.00	167,565	5.99	2.00	250.20			
750180	20-Nov-82	2308	300.9[illegible]	167,866	46.24	80.60	159.60			
750181	24-Nov-82	2308	160.00	168,026	35.36	100.10	20.10			
750182	1-Dec-82	2308	299.77	168,326	14.85	2.00	250.20			
901396	5-Dec-82	2014	1.50	168,327	0.00	0.00	0.00			
902303	5-Dec-82	2016	210.00	168,537	126.22	60.60	9.60			
901397	7-Dec-82	2014	100.00	168,637	85.80	0.00	0.00			
902304	7-Dec-82	2016	500.00	169,137	12.54	9.70	380.20			
750183	8-Dec-82	2308	299.95	169,437	86.08	124.60	85.05			
901398	14-Dec-82	2014	500.00	169,937	12.39	9.70	380.20			
750184	16-Dec-82	2308	300.00	170,237	5.52	1.50	260.20			
901399	18-Dec-82	2014	500.00	170,737	12.40	9.70	380.20			
FRF002-A	18-Dec-82	2011	21.80	170,759	17.68	0.00	0.00			
FRF002-B	18-Dec-82	2015	23.76	170,783	19.35	0.00	0.00			
FRF002-C	18-Dec-82	2012	23.88	170,807	19.51	0.00	0.00			
901400	23-Dec-82	2014	500.00	171,307	12.58	9.70	380.20			
901401	4-Jan-83	2014	500.00	171,807	12.31	9.70	380.20			
750185	5-Jan-83	2308	10.00	171,817	5.53	0.00	0.00			
901402	8-Jan-83	2014	250.00	172,067	5.55	1.00	230.10			
750186	10-Jan-83	2308	15.00	172,082	4.92	0.50	5.10			
902305	11-Jan-83	2017	1.50	172,083	0.00	0.00	0.00			
902306	13-Jan-83	2017	86.44	172,170	82.28	0.00	0.00			
750187	15-Jan-83	2308	15.00	172,185	4.88	0.50	5.10			
750188	19-Jan-83	2308	300.00	172,485	6.16	2.00	250.20			
901403	22-Jan-83	2014	50.00	172,535	35.88	0.00	0.00			
FRF003-A	25-Jan-83	2011	21.80	172,556	17.46	0.00	0.00			
FRF003-B	25-Jan-83	2015	23.80	172,580	19.40	0.00	0.00			
FRF003-C	25-Jan-83	2012	23.92	172,604	19.46	0.00	0.00			
750189	28-Jan-83	2308	3.65	172,608	0.00	0.00	0.00			
901404	28-Jan-83	2014	250.00	172,858	5.52	1.00	230.10			
750190	4-Feb-83	2308	250.00	173,108	65.49	140.60	9.60			
901405	4-Feb-83	2014	500.00	173,608	12.40	9.70	380.20			
750191	12-Feb-83	2308	250.00	173,858	6.08	2.00	208.30			

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Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
902307	15-Feb-83	2017	500.00	174,358	13.13	380.20	0.00			
901406	17-Feb-83	2014	60.00	174,418	6.13	40.10	0.00			
750192	2-Mar-83	2308	39.89	174,458	5.51	29.99	0.00			
901407	13-Mar-83	2014	500.00	174,958	12.99	380.20	0.00			
750193	23-Mar-83	2308	70.00	175,028	6.10	50.10	0.00			
STS006-A	4-Apr-83	2017	505.76	175,533	14.99	400.40	0.00			
STS006-B	4-Apr-83	2015	505.87	176,039	14.95	400.28	0.00			
STS006-C	4-Apr-83	2012	505.99	176,545	15.25	400.02	0.00			
901408	6-Apr-83	2014	520.64	177,066	6.28	510.10	0.00			
902308	8-Apr-83	2011	1.50	177,067	0.00	0.00	0.00			
750194	14-Apr-83	2308	16.84	177,084	5.66	6.94	0.00			
902309	14-Apr-83	2011	4.95	177,089	0.39	0.00	0.00			
902310	18-Apr-83	2011	190.00	177,279	96.53	79.70	0.00			
901409	20-Apr-83	2014	750.00	178,029	200.65	510.10	0.00			
750195	22-Apr-83	2308	300.00	178,329	12.85	240.20	0.00			
901410	23-Apr-83	2014	595.00	178,924	5.66	585.10	0.00			
902311	29-Apr-83	2011	500.00	179,424	13.08	380.20	0.00			
750196	2-May-83	2308	150.00	179,574	65.19	59.70	0.00			
750197	16-May-83	2308	320.00	179,894	13.05	240.20	0.00			
901411	18-May-83	2018	1.50	179,896	0.00	0.00	0.00			
901412	21-May-83	2018	5.22	179,901	0.82	0.00	0.00			
750198	23-May-83	2308	320.00	180,221	19.18	240.20	0.00			
901413	25-May-83	2018	190.00	180,411	96.46	79.70	0.00			
750199	28-May-83	2308	190.00	180,601	35.90	140.10	0.00			
902312	3-Jun-83	2019	1.56	180,602	0.00	0.00	0.00			
750200	4-Jun-83	2308	190.00	180,792	25.83	150.10	0.00			
901414	6-Jun-83	2018	500.00	181,292	13.06	380.20	0.00			
750201	9-Jun-83	2308	100.00	181,392	6.07	80.10	0.00			
902313	9-Jun-83	2019	190.00	181,582	96.47	79.70	0.00			
STS007-A	18-Jun-83	2017	506.50	182,089	13.98	402.10	0.00			
STS007-B	18-Jun-83	2015	506.60	182,596	13.89	402.10	0.00			
STS007-C	18-Jun-83	2012	506.71	183,102	14.09	401.95	0.00			
902314	20-Jun-83	2019	500.00	183,602	13.05	380.70	0.00			
750202	21-Jun-83	2308	2.20	183,604	0.00	0.00	0.00			

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750203	25-Jun-83	2308	100.00	183,704	6.06	80.10	0.00			
750204	30-Jun-83	2308	320.02	184,024	12.99	240.20	0.00			
750205	6-Jul-83	2308	320.00	184,344	12.98	240.20	0.00			
901415	7-Jul-83	2010	1.50	184,346	0.00	0.00	0.00			
750206	11-Jul-83	2308	320.00	184,666	28.66	224.80	0.00			
901416	11-Jul-83	2010	190.00	184,856	96.46	79.70	0.00			
901417	15-Jul-83	2010	510.00	185,366	18.80	390.00	0.00			
901418	20-Jul-83	2010	510.00	185,876	18.80	390.00	0.00			
750207	21-Jul-83	2308	100.10	185,976	20.90	74.70	0.00			
750208	2-Aug-83	2308	320.00	186,296	12.79	240.20	0.00			
750209	8-Aug-83	2308	320.00	186,616	13.36	240.00	0.00			
901419	13-Aug-83	2010	510.00	187,126	18.36	390.20	0.00			
750210	19-Aug-83	2308	15.00	187,141	5.52	0.00	0.00			
902315	22-Aug-83	2109	1.50	187,143	0.00	0.00	0.00			
750211	24-Aug-83	2308	300.00	187,443	58.94	145.70	59.20			
750212	30-Aug-83	2308	300.00	187,743	15.67	44.00	214.70			
901420	30-Aug-83	2010	750.00	188,493	200.34	510.10	0.00			
STS008-A	30-Aug-83	2017	527.98	189,021	433.12	0.00	0.00			
STS008-B	30-Aug-83	2015	528.11	189,549	432.98	0.00	0.00			
STS008-C	30-Aug-83	2012	528.19	190,077	432.78	0.00	0.00			
902316	31-Aug-83	2109	4.24	190,081	0.09	0.00	0.00			
750213	10-Sep-83	2308	320.00	190,401	12.62	240.20	0.00			
750214	22-Sep-83	2308	300.00	190,701	79.16	115.60	59.20			
901421	25-Sep-83	2010	148.49	190,850	5.54	138.59	0.00			
750215	27-Sep-83	2308	300.00	191,150	15.78	43.90	214.80			
901422	28-Sep-83	2010	50.00	191,200	45.64	0.00	0.00			
901423	1-Oct-83	2010	50.00	191,250	35.56	0.00	0.00			
750216	5-Oct-83	2308	70.00	191,320	15.80	40.10	0.00			
902317	9-Oct-83	2109	1.50	191,321	0.00	0.00	0.00			
750217	11-Oct-83	2308	300.00	191,621	285.45	0.00	0.00			
901424	13-Oct-83	2010	50.00	191,671	36.16	9.70	0.00			
902318	14-Oct-83	2109	190.00	191,861	96.47	79.70	0.00			
901425	17-Oct-83	2010	510.00	192,371	18.52	390.20	0.00			
750218	18-Oct-83	2308	300.00	192,671	15.60	270.10	0.00			

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902319	18-Oct-83	2109	510.00	193,181	18.35	392.20	0.00			
750219	24-Oct-83	2308	300.00	193,481	15.67	270.10	0.00			
901426	24-Oct-83	2010	6.61	193,488	2.33	0.00	0.00			
750220	1-Nov-83	2308	15.00	193,503	5.64	0.00	0.00			
901427	2-Nov-83	2010	510.00	194,013	18.42	390.20	0.00			
902320	4-Nov-83	2020	1.50	194,014	0.00	0.00	0.00			
902321	9-Nov-83	2020	1.50	194,016	0.00	0.00	0.00			
750221	10-Nov-83	2308	320.00	194,336	12.85	240.20	0.00			
902322	11-Nov-83	2020	190.00	194,526	96.37	79.70	0.00			
750222	15-Nov-83	2308	320.00	194,846	12.80	240.20	0.00			
901428	18-Nov-83	2010	510.00	195,356	18.44	390.20	0.00			
902323	19-Nov-83	2020	510.00	195,866	18.15	383.90	0.00			
901429	23-Nov-83	2010	595.00	196,461	5.70	585.10	0.00			
STS009-A	28-Nov-83	2011	515.52	196,976	11.17	406.20	0.00			
STS009-B	28-Nov-83	2018	515.65	197,492	11.32	406.25	0.00			
STS009-C	28-Nov-83	2019	515.78	198,008	11.52	406.45	0.00			
902324	1-Dec-83	2021	1.50	198,009	0.00	0.00	0.00			
902325	5-Dec-83	2021	190.00	198,199	96.48	79.70	0.00			
750223	6-Dec 83	2308	1.80	198,201	0.00	0.00	0.00			
901430	7-Dec 83	2017	510.00	198,711	18.52	390.20	0.00			
750224	10-Dec-83	2308	50.00	198,761	20.24	0.00	0.00			
902326	10-Dec-83	2021	510.00	199,271	18.22	384.10	0.00			
750225	15-Dec-83	2308	300.00	199,571	78.45	171.90	3.00			
750226	22-Dec-83	2308	150.00	199,721	39.56	55.10	29.60			
750227	28-Dec-83	2308	300.00	200,021	15.44	135.10	123.60			
901431	29-Dec-83	0108	1.50	200,022	0.00	0.00	0.00			
901432	4-Jan-84	0108	190.00	200,212	96.55	79.70	0.00			
750228	9-Jan-84	2308	5.18	200,218	0.90	0.00	0.00			
902327	10-Jan-84	2010	6.42	200,224	2.30	0.00	0.00			
750229	13-Jan-84	2308	300.00	200,524	79.33	115.70	59.20			
902328	15-Jan-84	2010	510.00	201,034	18.40	384.10	0.00			
750230	19-Jan-84	2308	300.00	201,334	16.08	44.20	214.80			
901433	21-Jan-84	0108	700.00	202,034	5.67	301.50	379.60			
901434	24-Jan-84	0108	700.00	202,734	5.66	1.00	680.10			

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902329	25-Jan-84	2010	510.00	203,244	18.54	384.00	0.00			
750231	30-Jan-84	2308	315.00	203,559	89.20	120.20	59.20			
STS011-A	3-Feb-84	2109	527.79	204,087	438.04	0.00	0.00			
STS011-B	3-Feb-84	2015	527.89	204,615	437.77	0.00	0.00		X	
STS011-C	3-Feb-84	2012	528.01	205,143	437.27	0.00	0.00			
902330	4-Feb-84	2010	1.74	205,144	0.00	0.00	0.00			
750232	6-Feb-84	2308	300.00	205,444	15.40	64.10	194.60			
901435	8-Feb-84	0108	60.00	205,504	11.82	8.70	15.10			
902331	13-Feb-84	2010	510.00	206,014	18.48	390.20	0.00			
901436	14-Feb-84	0108	611.06	206,626	5.32	0.50	601.16	X		
902332	13-Mar-84	2010	60.00	206,686	6.89	20.30	0.00			
902333	21-Mar-84	2010	60.00	206,746	6.14	8.70	0.00			
901437	22-Mar-84	2019	60.00	206,806	6.93	20.20	0.00			
901438	27-Mar-84	2019	510.00	207,316	18.47	390.20	0.00			
750233	6-Apr-84	2308	50.00	207,366	20.52	0.00	0.00			
901439	6-Apr-84	2019	250.00	207,616	35.71	190.10	0.00			
STS013-A	6-Apr-84	2109	517.14	208,133	13.44	410.34	0.00			
STS013-B	6-Apr-84	2020	517.25	208,650	13.60	410.05	0.00			
STS013-C	6-Apr-84	2012	517.40	209,167	14.36	409.31	0.00			
902334	7-Apr-84	2022	1.50	209,169	0.00	0.00	0.00			
901440	11-Apr-84	2019	250.00	209,419	35.66	190.10	0.00			
902335	12-Apr-84	2022	250.00	209,669	86.41	149.70	0.00			
750234	19-Apr-84	2308	100.00	209,769	16.60	15.50	30.10			
901441	2-May-84	0207	1.50	209,770	0.00	0.00	0.00			
901442	8-May-84	0207	100.00	209,870	76.59	9.70	0.00			
902336	10-May-84	2022	250.00	210,120	86.50	149.70	0.00			
901443	14-May-84	0207	110.00	210,230	76.56	14.20	6.00			
750235	19-May-84	2308	47.44	210,278	4.40	38.04	0.00			
901444	19-May-84	0207	160.00	210,438	96.65	15.60	14.60			
902337	22-May-84	2022	510.00	210,948	18.52	384.00	0.00			
FRF004-A	2-Jun-84	2021	17.60	210,965	13.30	0.00	0.00			
FRF004-B	2-Jun-84	2018	19.60	210,985	15.24	0.00	0.00			
FRF004-C	2-Jun-84	2017	19.72	211,005	15.44	0.00	0.00			
902338	8-Jun-84	2023	1.50	211,006	0.00	0.00	0.00			

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901445	9-Jun-84	0207	100.00	211,106	17.24	15.50	30.10			
902339	13-Jun-84	2023	250.00	211,356	48.79	149.70	0.00			
750236	15-Jun-84	2308	100.00	211,456	14.60	15.50	30.10			
901446	15-Jun-84	0207	91.30	211,547	40.22	26.00	0.00			
750237	20-Jun-84	2308	300.00	211,847	78.80	115.70	59.20			
902340	21-Jun-84	2023	250.00	212,097	86.50	149.70	0.00			
750238	26-Jun-84	2308	300.00	212,397	16.20	53.10	205.60			
STSA14-A	26-Jun-84	2109	0.00	212,397	0.00	0.00	0.00			
STSA14-B	26-Jun-84	2018	2.00	212,399	0.00	0.00	0.00			
STSA14-C	26-Jun-84	2017	0.22	212,400	0.00	0.00	0.00			
901447	27-Jun-84	0207	100.00	212,500	17.26	15.50	30.10			
750239	30-Jun-84	2308	300.00	212,800	16.64	15.50	208.10			
902341	30-Jun-84	2023	510.00	213,310	18.47	390.20	0.00			
750240	9-Jul-84	2308	310.64	213,620	5.04	15.50	235.10			
901448	10-Jul-84	0207	500.00	214,120	18.08	16.50	380.10			
901449	14-Jul-84	0207	500.00	214,620	17.96	16.50	380.10			
750241	18-Jul-84	2308	100.00	214,720	16.97	15.50	30.10			
902342	19-Jul-84	2014	1.50	214,722	0.00	0.00	0.00			
902343	21-Jul-84	2014	250.00	214,972	48.82	149.70	0.00			
901450	26-Jul-84	0207	124.34	215,096	5.22	4.84	110.10			
750242	27-Jul-84	2308	100.00	215,196	16.95	15.50	30.10			
750243	7-Aug-84	2308	312.65	215,509	5.94	1.00	249.60			
902344	7-Aug-84	2014	250.00	215,759	48.87	149.70	0.00			
901451	9-Aug-84	0207	10.96	215,770	5.20	0.50	1.06			
902345	12-Aug-84	2014	250.00	216,020	86.46	149.70	0.00			
750244	15-Aug-84	2308	318.88	216,339	5.59	1.00	249.90			
902346	20-Aug-84	2014	250.00	216,589	86.49	149.70	0.00			
901452	21-Aug-84	0207	100.00	216,689	17.32	15.50	30.10			
750245	23-Aug-84	2308	25.61	216,714	4.97	0.50	15.61			
STS014-A	30-Aug-84	2109	521.53	217,236	13.74	401.50	0.00			
STS014-B	30-Aug-84	2018	521.67	217,757	13.34	401.70	0.00			
STS014-C	30-Aug-84	2021	521.78	218,279	13.75	401.60	0.00			
901453	31-Aug-84	0207	300.00	218,579	79.43	115.70	59.20			
901454	12-Sep-84	0207	100.00	218,679	17.26	15.50	30.10			

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902347	13-Sep-84	2014	250.00	218,929	48.84	149.70	0.00			
901455	21-Sep-84	0207	500.00	219,429	99.01	16.50	380.20			
901456	25-Sep-84	0207	595.05	220,024	5.16	0.50	585.15			
902348	28-Sep-84	2014	249.94	220,274	58.41	149.70	0.00			
901457	29-Sep-84	0207	499.92	220,774	5.04	0.50	490.02			
901458	5-Oct-84	0207	500.00	221,274	5.11	0.50	490.10			
STS017-A	5-Oct-84	2023	536.69	221,811	429.82	0.00	0.00			
STS017-B	5-Oct-84	2020	536.83	222,348	429.70	0.00	0.00			
STS017-C	5-Oct-84	2021	536.95	222,885	429.78	0.00	0.00			
902349	10-Oct-84	2014	250.00	223,135	58.49	149.70	0.00			
750246	11-Oct-84	2308	1.50	223,136	0.00	0.00	0.00			
750247	15-Oct-84	2308	1.50	223,138	0.00	0.00	0.00			
902350	16-Oct-84	2014	250.00	223,388	58.55	149.70	0.00			
750248	18-Oct-84	2308	10.27	223,398	5.24	0.48	0.00			
750249	22-Oct-84	2308	69.96	223,468	19.92	17.36	28.20			
902351	24-Oct-84	2014	250.00	223,718	58.16	149.64	0.00			
901459	26-Oct-84	0207	193.36	223,911	5.12	0.50	183.46			
902352	2-Nov-84	2014	250.00	224,161	58.16	149.72	0.00			
STS019-A	8-Nov-84	2109	519.53	224,681	21.20	387.30	0.00			
STS019-B	8-Nov-84	2018	519.67	225,200	21.24	387.10	0.00			
STS019-C	8-Nov-84	2012	519.79	225,720	21.36	387.10	0.00			
901460	12-Nov-84	0207	500.80	226,221	5.80	1.68	488.84			
902353	28-Nov-84	2014	4.52	226,226	0.29	0.00	0.00			
902354	1-Dec-84	2014	250.00	226,476	58.40	149.36	0.00			
901461	28-Dec-84	0207	90.00	226,566	39.76	16.32	29.36			
901462	5-Jan-85	0207	90.00	226,656	40.16	16.16	29.36			
901463	14-Jan-85	0207	250.04	226,906	80.16	15.80	149.68			
901464	17-Jan-85	0207	283.75	227,189	25.36	1.20	252.80			
750250	18-Jan-85	2308	70.01	227,259	20.04	16.40	29.16			
901465	19-Jan-85	0207	32.95	227,292	25.28	1.60	1.60			
901466	24-Jan-85	0207	500.08	227,792	59.60	1.84	434.28			
STS020-A	24-Jan-85	2109	517.02	228,309	24.08	389.50	0.00			
STS020-B	24-Jan-85	2018	517.15	228,827	23.72	389.62	0.00			
STS020-C	24-Jan-85	2012	517.27	229,344	24.20	389.30	0.00			

SSME Chronological Experience with Power Levels

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901467	30-Jan-85	0207	586.82	229,931	26.32	2.12	554.00			
750251	1-Feb-85	2308	340.00	230,271	20.40	23.88	82.08			
901468	4-Feb-85	0207	203.86	230,474	25.32	1.20	172.92			
902355	6-Feb-85	2015	1.55	230,476	0.00	0.00	0.00			
750252	9-Feb-85	2308	340.01	230,816	21.08	24.08	81.80			
902356	11-Feb-85	2015	250.00	231,066	96.48	149.28	0.00			
750253	19-Feb-85	2308	177.32	231,243	5.36	1.56	166.00			
902357	19-Feb-85	2015	510.04	231,753	85.24	383.32	0.00			
750254	22-Feb-85	2308	300.00	232,053	6.44	279.40	0.00			
901469	23-Feb-85	2105	1.50	232,055	0.00	0.00	0.00			
750255	25-Feb-85	2308	300.00	232,355	6.20	141.00	139.20			
901470	25-Feb-85	2105	250.06	232,605	75.44	20.76	149.64			
901471	27-Feb-85	2105	503.00	233,108	107.24	11.32	380.20			
750256	1-Mar-85	2308	300.00	233,408	5.28	2.52	268.60			
901472	4-Mar-85	2105	520.00	233,928	99.84	415.88	0.00			
902358	5-Mar-85	2014	250.04	234,178	96.24	149.60	0.00			
750257	6-Mar-85	2308	300.00	234,478	5.12	22.00	249.08			
901473	6-Mar-85	2105	503.02	234,981	107.44	11.08	380.28			
902359	13-Mar-85	2014	250.04	235,231	96.44	149.40	0.00			
902360	16-Mar-85	2014	250.00	235,481	96.12	149.64	0.00			
901474	22-Mar-85	2105	503.06	235,984	107.20	11.72	379.76			
750258	23-Mar-85	2308	70.00	236,054	20.00	16.48	29.20			
902361	26-Mar-85	2014	250.08	236,304	58.60	149.48	0.00			
750259	27-Mar-85	2308	101.56	236,406	5.36	1.70	90.12	X		
STS023-A	12-Apr-85	2109	538.23	236,944	421.74	0.00	0.00			
STS023-B	12-Apr-85	2018	538.33	237,482	422.02	0.00	0.00			
STS023-C	12-Apr-85	2012	538.47	238,021	422.02	0.00	0.00			
901475	17-Apr-85	2105	520.03	238,541	100.04	415.56	0.00			
902362	22-Apr-85	2024	1.50	238,542	0.00	0.00	0.00			
902363	24-Apr-85	2024	250.05	238,792	58.60	149.72	0.00			
STS024-A	29-Apr-85	2023	521.63	239,314	27.04	338.06	0.00			
STS024-B	29-Apr-85	2020	521.46	239,835	27.28	387.78	0.00			
STS024-C	29-Apr-85	2021	521.57	240,357	27.32	387.98	0.00			
902364	3-May-85	2024	250.00	240,607	58.64	149.64	0.00			

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Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
902365	13-May-85	2024	380.41	240,987	7.28	331.60	0.00			
901476	21-May-85	2105	70.00	241,057	20.08	16.12	29.44			
901477	24-May-85	2105	250.00	241,307	75.44	20.60	149.64			
901478	1-Jun-85	2105	503.00	241,810	107.20	11.64	379.84			
901479	5-Jun-85	2105	503.00	242,313	107.20	11.48	379.96			
901480	7-Jun-85	2105	503.00	242,816	107.20	11.56	379.88			
901481	10-Jun-85	2105	520.06	243,336	99.84	415.84	0.00			
902366	17-Jun-85	2024	250.06	243,587	58.04	149.64	0.00			
STS025-A	17-Jun-85	2109	522.12	244,109	13.28	397.54	0.00			
STS025-B	17-Jun-85	2018	522.24	244,631	13.72	397.22	0.00			
STS025-C	17-Jun-85	2012	522.36	245,153	13.96	397.14	0.00			
902367	29-Jun-85	2024	250.00	245,403	57.92	149.44	0.00			
902368	2-Jul-85	2024	60.04	245,463	17.96	0.00	0.00			
901482	9-Jul-85	2105	520.00	245,983	99.88	415.80	0.00			
STSA26-A	12-Jul-85	2023	3.52	245,987	0.00	0.00	0.00			
STSA26-B	12-Jul-85	2020	1.74	245,989	0.00	0.00	0.00			
STSA26-C	12-Jul-85	2021	3.76	245,992	0.00	0.00	0.00			
901483	13-Jul-85	2105	520.00	246,512	100.04	415.64	0.00			
902369	17-Jul-85	2024	250.00	246,762	58.32	149.72	0.00			
901484	19-Jul-85	2105	603.06	247,365	12.28	1.40	585.00			
901485	24-Jul-85	2105	28.53	247,394	12.32	1.36	10.52			
STS026-A	29-Jul-85	2023	349.75	247,744	7.88	298.13	0.00			
STS026-B	29-Jul-85	2020	587.73	248,331	8.08	530.63	0.00			
STS026-C	29-Jul-85	2021	587.85	248,919	9.12	529.67	0.00			
901486	30-Jul-85	2105	520.00	249,439	99.68	416.00	0.00			
902370	31-Jul-85	2116	1.55	249,441	0.00	0.00	0.00			
902371	3-Aug-85	2116	249.84	249,691	38.52	20.88	149.32			
901487	4-Aug-85	2105	503.03	250,194	35.04	133.92	329.76			
901488	7-Aug-85	2105	502.96	250,697	103.24	10.20	385.24			
902372	9-Aug-85	2116	503.02	251,200	19.88	11.60	379.76			
901489	12-Aug-85	2105	302.04	251,502	20.96	276.76	0.00			
902373	13-Aug-85	2116	520.04	252,022	15.12	415.32	0.00			
902374	17-Aug-85	2116	225.54	252,247	8.32	186.44	0.00			
STS027-A	27-Aug-85	2109	513.92	252,761	12.64	412.82	0.00			

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Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
STS027-B	27-Aug-85	2018	514.04	253,275	13.84	411.82	0.00			
STS027-C	27-Aug-85	2012	514.16	253,789	13.48	412.14	0.00			
901490	31-Aug-85	2105	503.06	254,292	107.40	11.72	379.68			
902375	6-Sep-85	2116	466.03	254,758	38.96	120.36	19.48			
750260	7-Sep-85	2025	1.52	254,760	0.00	0.00	0.00			
901491	7-Sep-85	2105	503.05	255,263	107.40	11.32	380.04			
750261	12-Sep-85	2025	249.95	255,513	58.16	149.68	0.00			
902376	12-Sep-85	2116	466.08	255,979	38.56	120.68	19.36			
FRF005-A	12-Sep-85	2011	19.20	255,998	14.92	0.00	0.00			
FRF005-B	12-Sep-85	2019	20.50	256,019	16.20	0.00	0.00			
FRF005-C	12-Sep-85	2017	21.96	256,041	17.76	0.00	0.00			
902377	17-Sep-85	2116	503.06	256,544	19.92	11.48	379.84			
901492	19-Sep-85	2105	503.06	257,047	107.28	11.60	379.88			
902378	20-Sep-85	2116	761.08	257,808	205.60	1.64	511.44			
901493	24-Sep-85	2105	350.06	258,158	291.40	45.36	8.96			
902379	25-Sep-85	2116	503.04	258,661	19.56	10.32	385.24			
STS028-A	3-Oct-85	2011	518.28	259,179	11.80	416.74	0.00			
STS028-B	3-Oct-85	2019	518.40	259,698	11.44	417.18	0.00			
STS028-C	3-Oct-85	2017	518.52	260,216	11.64	417.02	0.00			
902380	7-Oct-85	2116	503.06	260,719	19.76	11.56	379.76			
750262	11-Oct-85	2025	250.00	260,969	56.72	1.68	149.44			
902381	14-Oct-85	2116	603.04	261,572	12.36	1.36	584.96			
901494	18-Oct-85	2026	1.50	261,574	0.00	0.00	0.00			
902382	19-Oct-85	2116	503.00	262,077	19.48	10.36	385.16			
901495	22-Oct-85	2026	250.04	262,327	38.88	207.04	0.00			
902383	26-Oct-85	2116	275.03	262,602	48.44	184.04	0.00			
STS030-A	30-Oct-85	2023	521.32	263,123	24.76	389.94	0.00			
STS030-B	30-Oct-85	2020	521.46	263,645	25.32	389.74	0.00			
STS030-C	30-Oct-85	2021	521.58	264,166	25.24	389.98	0.00			
902384	5-Nov-85	2116	250.03	264,416	58.32	149.16	0.00			
902385	20-Nov-85	2116	250.00	264,666	38.52	20.60	149.68			
STS031-A	26-Nov-85	2011	517.65	265,184	13.20	413.86	0.00			
STS031-B	26-Nov-85	2019	517.77	265,702	13.20	413.82	0.00			
STS031-C	26-Nov-85	2017	517.88	266,220	13.36	413.78	0.00			

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902386	11-Dec-85	2026	18.21	266,238	12.32	1.60	0.00			
902387	20-Dec-85	2026	503.06	266,741	20.24	31.72	349.88			
902388	23-Dec-85	2026	200.00	266,941	85.52	9.48	100.84			
STS032-A	12-Jan-86	2015	508.00	267,449	12.24	410.14	0.00			
STS032-B	12-Jan-86	2018	508.12	267,957	12.04	410.50	0.00			
STS032-C	12-Jan-86	2109	508.26	268,465	12.24	410.14	0.00			
902389	17-Jan-86	2022	250.00	268,715	38.64	20.48	149.84			
STS033-A	28-Jan-86	2023	79.40	268,795	8.00	31.92	0.00			
STS033-B	28-Jan-86	2020	79.56	268,874	8.16	31.92	0.00			
STS033-C	28-Jan-86	2021	79.62	268,954	8.24	32.00	0.00			
750263	11-Jun-86	2025	1.50	268,955	0.00	0.00	0.00			
750264	24-Jun-86	2025	40.00	268,995	12.12	23.72	0.00			
902390	26-Jun-86	2106	1.50	268,997	0.00	0.00	0.00			
902391	16-Jul-86	2106	250.00	269,247	95.84	149.96	0.00			
902392	25-Jul-86	2106	520.00	269,767	14.76	404.92	0.00			
902393	23-Aug-86	2106	520.00	270,287	14.80	415.88	0.00			
901496	13-Sep-86	2105	1.50	270,288	0.00	0.00	0.00			
901497	4-Oct-86	2105	520.00	270,808	16.08	499.76	0.00			
750265	8-Oct-86	2025	10.04	270,818	5.80	0.00	0.00			
901498	14-Oct-86	2105	520.00	271,338	16.00	499.72	0.00			
750266	16-Oct-86	2025	6.00	271,344	1.76	0.00	0.00			
901499	18-Oct-86	2105	520.00	271,864	15.96	499.76	0.00			
901500	25-Oct-86	2105	520.00	272,384	15.88	499.88	0.00			
901501	6-Nov-86	2105	519.12	272,903	15.04	499.88	0.00			
902394	11-Nov-86	2106	1.50	272,905	0.00	0.00	0.00			
902395	15-Nov-86	2106	1.50	272,906	0.00	0.00	0.00			
750267	24-Nov-86	2012	80.00	272,986	17.28	58.52	0.00			
902396	24-Nov-86	2106	1.50	272,988	0.00	0.00	0.00			
901502	26-Nov-86	2105	520.00	273,508	16.04	499.68	0.00			
901503	3-Dec-86	2105	520.03	274,028	99.72	416.00	0.00			
750268	6-Dec-86	2012	213.00	274,241	42.04	13.72	0.00			
901504	6-Dec-86	2105	520.00	274,761	99.96	415.72	0.00			
902397	7-Dec-86	2106	520.00	275,281	14.76	415.92	0.00			
901505	9-Dec-86	2105	520.00	275,801	99.92	415.72	0.00			

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902398	11-Dec-86	2106	520.00	276,321	16.24	499.56	0.00			
750269	12-Dec-86	2012	5.00	276,326	0.68	0.00	0.00			
901506	12-Dec-86	2105	520.00	276,846	99.68	416.00	0.00			
902399	15-Dec-86	2106	600.00	277,446	16.04	579.72	0.00			
901507	16-Dec-86	2105	590.06	278,036	100.00	485.80	0.00			
750270	18-Dec-86	2012	321.00	278,357	38.68	38.84	35.96			
902400	18-Dec-86	2106	520.00	278,877	11.08	504.72	0.00			
750271	23-Dec-86	2012	250.00	279,127	28.76	15.72	3.00			
901508	30-Dec-86	2105	520.00	279,647	15.88	499.80	0.00			
902401	2-Jan-87	2106	520.00	280,167	16.12	499.68	0.00			
901509	5-Jan-87	2105	520.00	280,687	15.88	499.76	0.00			
902402	10-Jan-87	2106	520.00	281,207	16.08	499.68	0.00			
750272	12-Jan-87	2012	300.00	281,507	38.64	133.60	0.00			
901510	12-Jan-87	2105	520.00	282,027	16.00	499.64	0.00			
902403	13-Jan-87	2106	520.00	282,547	16.12	499.64	0.00			
901511	15-Jan-87	2105	520.00	283,067	15.88	499.76	0.00			
902404	16-Jan-87	2106	520.00	283,587	7.64	499.64	0.00			
750273	17-Jan-87	2012	300.00	283,887	81.08	139.64	0.00			
750274	23-Jan-87	2012	300.00	284,187	16.48	279.28	0.00			
901512	27-Jan-87	2105	5.06	284,192	0.80	0.00	0.00			
901513	30-Jan-87	2105	520.00	284,712	99.84	415.88	0.00			
750275	31-Jan-87	2012	300.00	285,012	16.12	279.64	0.00			
902405	31-Jan-87	2106	200.00	285,212	7.64	179.68	0.00			
902406	3-Feb-87	2106	200.00	285,412	7.44	179.72	0.00			
902407	6-Feb-87	2106	200.00	285,612	7.60	179.68	0.00			
901514	11-Feb-87	2105	520.00	286,132	99.68	416.04	0.00			
901515	14-Feb-87	2105	503.00	286,635	107.28	11.16	380.28			
902408	14-Feb-87	2106	200.00	286,835	7.64	179.60	0.00			
901516	17-Feb-87	2105	761.00	287,596	243.56	2.24	510.92			
902409	19-Feb-87	2106	200.00	287,796	7.52	179.64	0.00			
901517	24-Feb-87	2105	603.00	288,399	12.51	1.25	584.96			
750276	2-Mar-87	0210	1.50	288,401	0.00	0.00	0.00			
901518	2-Mar-87	2105	520.00	288,921	99.97	415.71	0.00			
902410	2-Mar-87	2106	520.00	289,441	15.20	415.64	0.00			

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902411	11-Mar-87	2106	520.00	289,961	15.08	415.60	0.00			
750277	12-Mar-87	0210	200.00	290,161	11.92	183.92	0.00			
902412	13-Mar-87	2106	520.00	290,681	15.24	415.44	0.00			
901519	14-Mar-87	2011	1.50	290,682	0.00	0.00	0.00			
750278	16-Mar-87	0210	200.00	290,882	12.00	183.84	0.00			
902413	17-Mar-87	2106	503.00	291,385	20.04	11.28	380.16			
750279	19-Mar-87	0210	200.00	291,585	12.00	183.80	0.00			
901520	19-Mar-87	2011	200.00	291,785	16.28	129.92	49.36			
902414	23-Mar-87	2106	567.00	292,352	12.48	1.08	549.24			
750280	26-Mar-87	0210	200.00	292,552	11.96	183.80	0.00			
902415	31-Mar-87	2106	520.00	293,072	15.36	415.28	0.00			
750281	2-Apr-87	0210	200.00	293,272	11.84	183.96	0.00			
901521	4-Apr-87	2011	320.00	293,592	96.04	210.00	9.64			
750282	6-Apr-87	0210	200.00	293,792	12.00	183.76	0.00			
902416	9-Apr-87	2106	520.00	294,312	15.04	415.64	0.00			
902417	21-Apr-87	2106	797.00	295,109	206.00	1.60	547.48			
750283	22-Apr-87	0210	300.00	295,409	12.00	283.72	0.00			
901522	24-Apr-87	2105	520.00	295,929	99.72	415.92	0.00			
902418	28-Apr-87	2106	750.00	296,679	177.96	491.96	0.00			
750284	29-Apr-87	0210	300.00	296,979	11.92	283.84	0.00			
901523	30-Apr-87	2105	520.00	297,499	218.12	297.52	0.00			
902419	1-May-87	2106	90.38	297,590	8.20	51.68	0.00			
901524	9-May-87	2105	850.00	298,440	299.68	545.96	0.00			
901525	14-May-87	2105	250.00	298,690	34.52	211.08	0.00			
902420	18-May-87	2106	520.00	299,210	11.76	477.74	0.00			
901526	20-May-87	2105	520.00	299,730	137.52	378.08	0.00			
750285	21-May-87	0210	223.56	299,953	6.64	1.16	211.96			
902421	26-May-87	2106	680.00	300,633	7.24	668.60	0.00			
902422	29-May-87	2106	503.06	301,136	20.04	11.16	380.24			
901527	30-May-87	2105	700.00	301,836	94.44	601.12	0.00			
902423	3-Jun-87	2106	520.00	302,356	195.44	294.00	0.00			
901528	4-Jun-87	2105	503.00	302,859	107.28	11.28	380.04			
902424	6-Jun-87	2106	275.00	303,134	7.24	263.56	0.00			
901529	8-Jun-87	2105	603.00	303,737	12.28	1.28	585.00			

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901530	11-Jun-87	2105	503.00	304,240	107.28	11.32	380.04			
902425	11-Jun-87	2106	520.00	304,760	14.76	415.92	0.00			
901531	13-Jun-87	2105	520.05	305,280	100.12	415.48	0.00			
750286	16-Jun-87	0210	300.00	305,580	11.84	283.72	0.00			
901532	17-Jun-87	2105	520.00	306,100	41.56	474.06	0.00			
750287	19-Jun-87	0210	300.00	306,400	12.88	265.24	0.00			
902426	23-Jun-87	2106	1000.00	307,400	307.08	668.68	0.00			
750288	25-Jun-87	0210	4.40	307,405	0.00	0.00	0.00			
901533	25-Jun-87	2105	520.00	307,925	99.92	415.64	0.00			
902427	26-Jun-87	2106	138.36	308,063	59.72	74.36	0.00	X	X	X
902428	1-Jul-87	2106	204.12	308,267	82.88	114.06	0.00	X	X	X
750289	6-Jul-87	0210	300.00	308,567	11.92	283.68	0.00			
901534	6-Jul-87	2105	520.00	309,087	224.72	290.92	0.00			
750290	9-Jul-87	0210	300.00	309,387	11.96	283.64	0.00			
750291	16-Jul-87	0210	300.00	309,687	12.04	283.56	0.00			
901535	18-Jul-87	2105	761.00	310,448	213.08	32.04	511.44			
750292	23-Jul-87	0210	100.00	310,548	11.88	83.68	0.00			
750293	28-Jul-87	0210	100.00	310,648	11.88	83.76	0.00			
750294	31-Jul-87	0210	100.00	310,748	11.80	83.84	0.00			
750295	4-Aug-87	0210	99.96	310,848	11.80	83.80	0.00			
901536	6-Aug-87	2105	520.00	311,368	99.92	415.66	0.00			
750296	7-Aug-87	0210	99.96	311,468	12.00	83.60	0.00			
902429	11-Aug-87	2027	1.50	311,469	0.00	0.00	0.00			
750297	12-Aug-87	0210	100.00	311,569	11.84	83.76	0.00			
901537	12-Aug-87	2105	656.66	312,226	454.92	197.36	0.00			
750298	1-Sep-87	0210	149.96	312,376	12.08	133.64	0.00			
750299	4-Sep-87	0210	210	312,586	12.04	193.68	0.00			
901538	4-Sep-87	0211	1.5	312,588	0.00	0.00	0.00			
901539	12-Sep-87	0211	300	312,888	16.00	279.68	0.00			
901540	15-Sep-87	0211	300.00	313,188	16.04	279.56	0.00			
902430	16-Sep-87	2027	250.00	313,438	29.92	144.76	19.52			
750300	17-Sep-87	0210	6.00	313,444	1.72	0.00	0.00			
901541	17-Sep-87	0211	300.00	313,744	15.96	279.68	0.00			
901542	19-Sep-87	0211	300.00	314,044	15.92	279.68	0.00			

SSME Chronological Experience with Power Levels

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901543	21-Sep-87	0211	300.00	314,344	15.96	279.68	0.00			
901544	23-Sep-87	0211	300.00	314,644	15.92	279.68	0.00			
901545	26-Sep-87	0211	210.00	314,854	18.12	187.60	0.00			
901546	30-Sep-87	0211	250.00	315,104	30.60	165.84	49.20			
901547	3-Oct-87	0211	135.00	315,239	16.00	114.60	0.00			
901548	5-Oct-87	0211	250.00	315,489	16.00	229.68	0.00			
902431	10-Oct-87	2027	520.00	316,009	21.24	348.92	51.44			
902432	28-Oct-87	2022	1.50	316,010	0.00	0.00	0.00			
902433	6-Nov-87	2022	250.00	316,260	29.92	144.88	19.52			
750301	8-Nov-87	2105	280.00	316,540	11.92	263.72	0.00			
901549	10-Nov-87	2019	1.50	316,542	0.00	0.00	0.00			
750302	12-Nov-87	2105	280.00	316,822	16.56	1.84	257.24			
750303	17-Nov-87	2105	280.00	317,102	12.00	263.64	0.00			
750304	21-Nov-87	2105	280.00	317,382	12.00	263.64	0.00			
902434	21-Nov-87	2022	520.00	317,902	20.92	348.88	51.56			
901550	22-Nov-87	2019	250.00	318,152	67.12	144.88	19.72			
901551	28-Nov-87	2019	520.00	318,672	54.40	352.68	51.52			
750305	4-Dec-87	2105	280.00	318,952	12.04	263.60	0.00			
750306	8-Dec-87	2105	250.00	319,202	16.56	1.84	227.28			
902435	10-Dec-87	2028	1.50	319,203	0.00	0.00	0.00			
902436	15-Dec-87	2028	250.00	319,453	29.76	114.32	50.20			
750307	19-Dec-87	2105	280.00	319,733	46.52	1.88	227.24			
750308	23-Dec-87	2105	280.00	320,013	42.04	233.56	0.00			
902437	23-Dec-87	2028	520.00	320,533	20.72	349.00	51.72			
901552	29-Dec-87	2027	754.00	321,287	7.72	468.52	0.00			
750309	15-Jan-88	2105	0.50	321,288	0.00	0.00	0.00			
901553	22-Jan-88	0211	520.00	321,808	102.68	360.40	52.60			
750310	23-Jan-88	2105	10.12	321,818	5.72	0.00	0.00			
902438	24-Jan-88	2029	1.50	321,819	0.00	0.00	0.00			
901554	27-Jan-88	0211	520.00	322,339	100.04	415.68	0.00			
750311	29-Jan-88	2105	300.00	322,639	11.40	264.96	19.20			
901555	3-Feb-88	0211	519.96	323,159	99.68	415.80	0.00			
902439	9-Feb-88	2029	250.00	323,409	29.84	109.64	51.84			
750312	10-Feb-88	2105	9.96	323,419	5.24	0.00	0.00			

SSME Chronological Experience with Power Levels

Test/Flt Number	Date	Engn	Duratn per test (sec)	Program Exprnc cumulatv (sec)	Power Level Exposure (%) 100-103 per test (sec)	104-108 per test (sec)	109+ per test (sec)	Considered by this Study: Catastrophic Failures	Applicable Major Incidents	Applicable Catastrophic Failures
901556	10-Feb-88	0211	519.88	323,939	99.52	415.72	0.00			
901557	14-Feb-88	0211	502.96	324,442	107.08	11.16	380.28			
901558	18-Feb-88	0211	503.00	324,945	106.84	11.20	380.40			
902440	19-Feb-88	2029	519.96	325,465	21.00	348.20	52.32			
901559	20-Feb-88	0211	602.96	326,068	32.04	3.12	563.28			
901560	25-Feb-88	0211	572.96	326,641	99.64	468.76	0.00			
902441	4-Mar-88	2029	250.00	326,891	21.80	147.12	51.36			
901561	5-Mar-88	0211	519.96	327,411	99.76	415.60	0.00			
901562	10-Mar-88	0211	519.96	327,931	99.84	415.48	0.00			
750313	21-Mar-88	0208	1.50	327,932	0.00	0.00	0.00			
901563	21-Mar-88	0211	20.00	327,952	7.00	8.40	0.00			
902442	23-Mar-88	2030	1.55	327,954	0.00	0.00	0.00			
750314	25-Mar-88	0208	10.00	327,964	5.68	0.00	0.00			
902443	28-Mar-88	2030	300.00	328,264	29.88	109.92	51.68			
901564	29-Mar-88	0211	519.94	328,784	488.52	26.66	0.00			
904001	30-Mar-88	2206	1.50	328,785	0.00	0.00	0.00			
750315	31-Mar-88	0208	140.96	328,926	95.84	40.88	0.00			
901565	5-Apr-88	0211	622.96	329,549	34.68	580.28	0.00			
901566	8-Apr-88	0211	520.00	330,069	99.56	415.76	0.00			
904002	9-Apr-88	2206	25.00	330,094	20.24	0.00	0.00			
902444	10-Apr-88	2030	520.00	330,614	20.96	348.76	51.76			
901567	16-Apr-88	0211	519.96	331,134	100.04	415.28	0.00			
901568	19-Apr-88	0211	502.96	331,637	107.00	11.04	380.28			
904003	20-Apr-88	2206	220.00	331,857	15.96	199.40	0.00			

Appendix A.2

A Quick Calculation of the Effect of Failure Correlation Factor vs. Engine Out Capability

A.2 CORRELATION vs ENGINE OUT CAPABILITY

A preliminary trade off study of single large liquid rocket engines vs "clustering" with reliability as the driver follows. Weight and cost as well as engine out capability is also considered but not calculated.

Let,

R1 = rocket engine reliability excluding plumbing to tanks.

R2 = reliability of plumbing.

Assume a single engine plumbing reliability of R2 = 0.999 and that increases in numbers of rockets produce directly proportional increases in plumbing complexity.
Since reliability decreases with increasing complexity then if,

n := 1 ..16 the total number of rocket engines

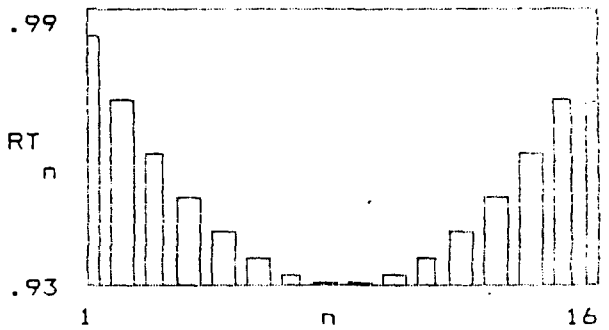
$R2_n := \exp(n \cdot \ln(0.999))$

Since smaller "state of the art" engines are more mature thus possibly more reliable then R1 increases as n (the no. of engines) increases. This is because the more engines there are, the smaller they are.

R1 := n

n	R1 n	R2 n
.985		
.986	0.985	0.999
.987	0.972196	0.998001
.988	0.9615048	0.997003
.989	0.9528571	0.996006
.99	0.9461968	0.99501
.991	0.9414801	0.994015
.992	0.9386757	0.993021
.993	0.9377636	0.9920279
.994	0.9387355	0.9910359
.995	0.9415944	0.9900449
.996	0.9463546	0.9890548
.997	0.953042	0.9880658
.998	0.9616943	0.9870777
.999	0.9723611	0.9860906
.9991	0.9851045	0.9851045
	0.9856968	0.9841194

$RT_n := R2_n \cdot R1_n$



$RT_8 = 0.9302877$ minimum reliability with 8 engines and NO engine out capability.

Consider now engine out capability:

if the number of engines varies from 4 to 16,

m = the total no. of engines

k = the maximum engine out capability

RS = total reliability with engine out capability

C := 1.0 cost

W := 1.0 weight

$m := 4$

$R1_m :=$

.985
.986
.987
.988
.989
.99
.991
.992
.993
.994
.995
.996
.997
.998
.999
.9991

$R2_m := \exp(m \ln(0.999))$

Now let.

$k := 3 ..4$ engines required for success

$$RE_k := \sum_k \left[\frac{m!}{(m-k)!\,k!}\right] {R1_m}^k \left[1 - R1_m\right]^{m-k}$$

$RS_k := W\ C\ RE_k\ R2_m \qquad RS_4 = 0.9946881$

Let REC = reliability with correlated failures

$j := 1 ..7$ = the number of correlated failures

$$REC_j := \left[1 - \frac{j}{1000}\right]^4$$,for four engines

REC_j
0.996006
0.992024
0.9880539
0.9840957
0.9801495
0.9762151
0.9722926

Thus 4 engines are no better than 1 if the correlation factor is between 20 and 30% as shown below.

$RT_j := REC_j\ RS_4$

RT_j
0.9907153
0.9867545
0.9828055
0.9788684
0.9749431
0.9710296
0.9671279

Not only are four engines no better than one under the above conditions, three or two engines are also no better. In fact the correlation factor drives the results and begins to do so at about 15%.

Time did not allow a thorough study of the effects of cost or weight. In fact the entire subject is complex enough to warrant a separate study.

One could easily envision that an increase in the number of engines, plumbing and detection apparatus would increase weight thus reduce payload and might quickly render a clustered system uneconomical.

The purpose of this brief set of calculations is not to draw conclusions but that correlation factors of about 15% are definitely a "red flag" that warrants further study. It appears that liquid engine manufacturers are overly optimistic about correlation factors.

Appendix A.3

Reliability Analysis of Current US Launch Vehicles

Yu Shen
SAIC, Division 265, New York

December 21, 1988

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SUMMARY

This report contains reliability data for the following families of United States launch vehicles: Thor/ Delta, Titan, Atlas, the Saturn "Family", the Scout "Family", and the Space Shuttle.

The reliability data was obtained through the statistical models and procedures described in Section 2.0 as applied to the "Launch Vehicle Failure History Data Base" compiled by C.T. Clague of the Aerospace Corporation and other data sources given in the bibliography. The results of the analysis are summarized in the following table.

The statistical model and algorithm contained in this report is unique and is the only technique except for D. Lloyd's model that has been developed expressly for launch vehicles. It provides conservative reliability estimates during the "early launch" period of development. It also converges to the same value obtained by D. Lloyd when a sufficiently large number of launches and or tests have been attained. Unlike D. Lloyd's method, it does not require judgement as to whether or not a failure has been corrected nor does it require that component failure mode be known.

OBJECTIVE AND BACKGROUND

The objective of this report is to produce a statistical model and algorithm which can estimate launch vehicle reliability based solely on attribute data that presently exists. In addition, the methodology is to serve as a means of estimating stage and system reliability. A secondary objective is to use the model as a means of predicting the reliability of new systems.

Presently existing methodologies do not meet the objectives cited above.

By way of background, the first attempts to measure launch system reliability were made in order to either ascertain what level of reliability had been attained at a given point especially prior to customer "buy off" or acceptance.

In the 1960's the most widely accepted approach was to assume that each test or launch was independent of all others. Using this assumption, one could easily calculate the reliability at any given level of confidence using the Binomial distribution. It became obvious, however, that reliability and confidence levels above 90% would require an inordinately large number of tests. In the early 70's Bayesian analysis was introduced. However, due to the subjective nature of prior distributions which rely on expert judgement rather than direct results from experiments and tests, the Bayesian approach did not receive wide acceptance in the aerospace industry.

In recent years D. Lloyd of TRW began developing a methodology that does require judgement, but the judgement is based solely on evidence that the propensity for certain failure modes to occur has been reduced by redesign and retest.

Dr. D. Lloyd's method appears to be the most recent attempt made to estimate reliability or developmental environment which includes Reliability Growth until now.

The methodology developed for this study is discussed in Section 2.0 of this report and is an approach which has some attractive features not found in other methods. This methodology was applied to the historical data obtained during the course of the study to produce the tables of reliability data which follow. A summary of all the results is given in Table A.2 and results for individual launch vehicle failures are indicated in Tables A.2a through A.2f.

TABLE A.2: RELIABILITY COMPARISON OF U.S. LAUNCH VEHICLE FAMILIES

	Vehicle Name / Data Collection Period	Thor / Delta			Titan					Atlas										
		Thor	Delta	Combine	Titan I	Titan II	Titan III	Titan 34D	Combine	Atlas A	Atlas B	Atlas C	Atlas D	Atlas E	Atlas F	Atlas SLV	Atlas G	Atlas H	Atlas/ Centaur	Combine
		57-83	60-87	57-87	59-65	62-76	64-87	82-87	59-87	57-58	58-59	58-59	59-67	60-86	61-81	87-83	64-87	83-87	62-87	57-88
	Success Ratio: Mean	0.8662	0.9402	0.9192	0.8427	0.8884	0.9408	0.7355	0.8013	0.4219	0.5556	0.5833	0.8401	0.7426	0.8863	0.9445	no failure	no failure	0.9089	0.7863
	5%	0.8750	0.9110	0.8788	0.5586	0.6323	0.9088	0.4878	0.8075	0.1827	0.3010	0.2642	0.8015	0.6454	0.8359	0.8736	0.6313	0.6313	0.8450	0.4781
	95%	0.9181	0.9815	0.9551	0.7202	0.9272	0.9651	0.8080	0.9546	0.6877	0.7896	0.8565	0.8734	0.8240	0.9276	0.9852			0.9489	0.9053
STAGE NO.	Stage 0	0.9965	0.9950				0.9946	0.8578												
	Stage 1/2													0.8713	0.9573	0.9861			0.9814	
	Stage 1	0.9346	0.9850		0.8214	0.9574		0.8476						0.8523	0.9279	0.9719			0.9810	
	Stage 2	0.9764	0.9746		0.7825	0.9258	0.9783									0.9856			0.9420	
	Stage 3	0.9877	0.9843				0.9867													
	Stage 4																			
SYSTEM	Propulsion	0.9568	0.9701		0.8725	0.9290	0.9622	0.7355		0.8844	0.8667			0.8713	0.9212	0.9824			0.9535	
	Guidance	0.9830	0.9880			0.9929	0.9862							0.9571	0.9869					
	Flight Control	0.9907	0.9851			0.9858	0.9946			0.7886	0.8669			0.9428	0.9869	0.9824			0.9907	
	Structure	0.9969			0.9702		0.9946			0.7886				0.9857					0.9814	
	Electrical	0.9815	0.9950			0.9929								0.9857		0.9824			0.9907	
	Separation	0.9969	0.9950			0.9858										0.9824			0.9907	
	Other or (UK)	0.9923													0.9934					

	Vehicle Name / Data Collection Period	Saturn "Family"						Scout "Family"			STS
		Jupiter	Juno	Saturn I	Saturn IB	Saturn V	Combine	Vanguard	Scout	Combine	Space Shuttle
		58-58	58-61	62-65	66-75	67-73	58-75	57-59	60-88	57-88	81-88
	Success Ratio: Mean	0.3811	0.4300	no failure	no failure	0.9832	0.7547	0.3368	0.9420	0.8404	0.9275
	5%	0.1028	0.2135	0.7943	0.7743	0.8180	0.2852	0.1558	0.9023	0.1821	0.8147
	95%	0.6879	0.6743			0.9997	0.9035	0.5723	0.9883	0.9744	0.9808
STAGE NO.	Stage 0										
	Stage 1/2										
	Stage 1		0.8575					0.8347	0.9917		0.9275
	Stage 2	0.5741	0.7009			0.9822		0.5049	0.9875		
	Stage 3		0.7829			0.9822		0.8038	0.9746		
	Stage 4	0.6290	0.9378						0.9870		
SYSTEM	Propulsion	0.7870						0.7521	0.9793		0.9275
	Guidance							0.9174	0.9917		
	Flight Control							0.8347	0.9917		
	Structure										
	Electrical								0.9876		
	Separation	0.5741							0.9959		
	Other or (UK)							0.8347	0.9959		

TABLE A.2a: RELIABILITY OF THE THOR/DELTA FAMILY

Vehicle Name Data Collection Period		Thor / Delta		
		Thor 57-83	Delta 60-87	Combine 57-87
Success Ratio: Mean 5% 95%		0.8982 0.8750 0.9181	0.9402 0.9110 0.9615	0.9192 0.8789 0.9551
STAGE NO.	Stage 0	0.9965	0.9950	
	Stage 1/2			
	Stage 1	0.9346	0.9850	
	Stage 2	0.9764	0.9746	
	Stage 3	0.9877	0.9843	
	Stage 4			
SYSTEM	Propulsion	0.9568	0.9701	
	Guidance	0.9830	0.9950	
	Flight Control	0.9907	0.9851	
	Structure	0.9969		
	Electrical	0.9815	0.9950	
	Separation	0.9969	0.9950	
	Other or (UK)	0.9923		

TABLE A.2b: RELIABILITY OF THE TITAN FAMILY

Vehicle Name Data Collection Period		Titan				
		Titan I 59-65	Titan II 62-76	Titan III 64-87	Titan 34D 82-87	Combine 59-87
Success Ratio:	Mean	0.6427	0.8864	0.9406	0.7355	0.8013
	5%	0.5585	0.8323	0.9055	0.4978	0.6075
	95%	0.7202	0.9272	0.9651	0.8990	0.9546
STAGE NO.	Stage 0			0.9946	0.8678	
	Stage 1/2					
	Stage 1	0.8214	0.9574		0.8476	
	Stage 2	0.7825	0.9258	0.9783		
	Stage 3			0.9667		
	Stage 4					
SYSTEM	Propulsion	0.6725	0.9290	0.9622	0.7355	
	Guidance		0.9929	0.9892		
	Flight Control		0.9858	0.9946		
	Structure	0.9702		0.9946		
	Electrical		0.9929			
	Separation		0.9858			
	Other or (UK)					

TABLE A.2c: RELIABILITY OF THE ATLAS FAMILY

Vehicle Name / Data Collection Period		Atlas										
		Atlas A 57-58	Atlas B 58-59	Atlas C 58-59	Atlas D 59-67	Atlas E 60-88	Atlas F 61-81	Atlas SLV 67-83	Atlas G 84-87	Atlas H 83-87	Atlas/ Centaur 62-87	Combine 57-88
Success Ratio:	Mean	0.4219	0.5558	0.5833	0.8401	0.7426	0.8883	0.9445	no failure	no failure	0.9069	0.7883
	5%	0.1827	0 3010	0.2642	0.8015	0.6454	0.8359	0.8736	0.6313	0.6313	0.8450	0.4761
	95%	0.6977	0.7896	0.8585	0.8734	0.8240	0.9276	0.9652			0.9489	0.9953
STAGE NO.	Stage 0											
	Stage 1/2					0.8713	0.9573	0.9861			0.9814	
	Stage 1					0.8523	0.9279	0.9719			0.9810	
	Stage 2							0.9856			0.9420	
	Stage 3											
	Stage 4											
SYSTEM	Propulsion	0.8844	0.6667			0.8713	0.9212	0.9824			0.9535	
	Guidance					0.9571	0.9869					
	Flight Control	0.7688	0.8889			0.9428	0.9869	0.9824			0.9907	
	Structure	0.7688				0.9857					0.9814	
	Electrical					0.9857		0.9824			0.9907	
	Separation							0.9824			0.9907	
	Other or (UK)						0.9934					

TABLE A.2d: RELIABILITY OF THE SATURN FAMILY

Vehicle Name Data Collection Period		Saturn "Family"					
		Jupiter 58-58	Juno 58-61	Saturn I 62-65	Saturn IB 66-75	Saturn V 67-73	Combine 58-75
Success Ratio: Mean 5% 95%		0.3611 0.1026 0.6879	0.4300 0.2135 0.6743	no failure 0.7943	no failure 0.7743	0.9822 0.8180 0.9997	0.7547 0.2652 0.9935
STAGE NO.	Stage 0						
	Stage 1/2						
	Stage 1		0.8575				
	Stage 2	0.5741	0.7009			0.9822	
	Stage 3		0.7629			0.9822	
	Stage 4	0.6290	0.9378				
SYSTEM	Propulsion	0.7870					
	Guidance						
	Flight Control						
	Structure						
	Electrical						
	Separation	0.5741					
	Other or (UK)						

TABLE A.2e: RELIABILITY OF THE SCOUT FAMILY

Vehicle Name Data Collection Period		Scout "Family"		
		Vanguard 57-59	Scout 60-88	Combine 57-88
Success Ratio: Mean 5% 95%		0.3388 0.1555 0.5723	0.9420 0.9023 0.9683	0.6404 0.1821 0.9744
STAGE NO.	Stage 0			
	Stage 1/2			
	Stage 1	0.8347	0.9917	
	Stage 2	0.5049	0.9875	
	Stage 3	0.8039	0.9746	
	Stage 4		0.9870	
SYSTEM	Propulsion	0.7521	0.9793	
	Guidance	0.9174	0.9917	
	Flight Control	0.8347	0.9917	
	Structure			
	Electrical		0.9876	
	Separation		0.9959	
	Other or (UK)	0.8347	0.9959	

TABLE A.2f: RELIABILITY OF THE SPACE SHUTTLE

Vehicle Name Data Collection Period		STS Space Shuttle 81-88
Success Ratio: Mean 5% 95%		0.9275 0.8147 0.9806
STAGE NO.	Stage 0	
	Stage 1/2	
	Stage 1	0.9275
	Stage 2	
	Stage 3	
	Stage 4	
SYSTEM	Propulsion	0.9275
	Guidance	
	Flight Control	
	Structure	
	Electrical	
	Separation	
	Other or (UK)	

1.0 EXISTING METHODOLOGIES

For the purposes of this report, the following existing methodologies will be briefly discussed.

- Binomial
- Polynomial Curve Fitting
- Bayesian
- D. Lloyd's Method

1.1 The Binomial Method

The "traditional," or classical, approach to reliability demonstration in a go/no-go type environment is the Binomial distribution shown below. In addition to the obvious constraints of the assumptions listed below, it is interesting to note, for example, that it would require 45 launches with no failures to demonstrate 0.95 reliability at 90% confidence. Since trials are assumed to be independent, the growth effect (a type of dependency) cannot be evaluated.

Stated mathematically the Binomial Distribution is as follows:

$$\sum_{X=S}^{N} \binom{N}{N-X} R^{X} (1-R)^{N-X} = 1 - C, \quad \text{if } N \leq S \leq 0$$

where;

S = number of successful start tests
N = number of trials
R = reliability
C = confidence level

where it is assumed that

- Trials or tests are independent
- Each trial results in success or failure
- The reliability (probability of success) of each system is the same on each trial
- The number of tests is fixed in advance of the demonstration test

1.2 Polynomial Curve Fitting

Polynomial trends are of the form

$$Y = A + BX + CX^2 + DX^3 + \ldots JX^k$$

The straight line is a special case having only the first two terms on the right hand side of the equation. Generally speaking, it is unwise to fit a high-degree polynomial to the data because of the possibility of mixing trend and cycle. The polynomial can be forced to fit data quite closely by just adding enough terms. This, however, does not contribute any information about trend. In fact, 1 degree of freedom for error is lost for every parameter that is estimated from data. Thus, if there are n observations and n degrees of freedom are lost in fitting a polynomial of degree n-1 item, there are 0 degrees of freedom left for error!

1.3 Bayesian Analysis

For the purposes of this report, Bayesian analysis can be divided into two categories:

1. Reduction of the number of tests or flights to demonstrate that a given level of reliability has been achieved.

2. The Beta-Binomial Model

If it is desired to reduce the numbers of tests or flights required to demonstrate a given level of reliability, then Bayesian analysis can be useful. If the following equation, taken from reference 1, is solved for n at R=0.95, r=0, P=0.50 and C=90% confidence is desired, then it can be concluded that only 14 launches would be required.

$$C = \frac{1}{1 + \dfrac{(1-P)(1-R)^2 \displaystyle\int_0^R p^{n-r+1} q^r \, dp}{(P)(R)^2 \displaystyle\int_R^1 p^{n-r} q^{r+1} \, dp}}$$

where;

n = number of launches
r = number of failures
R = reliability
C = confidence level
P = Bayesian Prior

The Beta-Binomial Bayesian model is used for Bayesian estimation when information is available about components of similar design and application. In this model, several similar components are treated as a single class. The probability p of each component in the class is assumed to be constant, but will have different values from component to component. If the Binomial distribution is used to obtain the probability of K failures in n trials, then the conjugate distribution g(p) for the class is the Beta distribution. This model weights the reliability growth effect and can be applied to forecast the reliabilities of launch vehicles. The detailed theoretica' analysis can be found in reference 2. The disadvantage of this model is that it is very difficult to separate the total sample data into several similar components unless there is detailed engineering analysis concerning each failure mode during the different periods of launch vehicle development history.

Bayesian approaches are highly sensitive to the prior distributions used. If no meaningful estimate of the prior probability of success can be made, none of the above conclusions apply. Particularly, one must be wary of consistent optimism or pessimism when records of success do not support the prior probabilities.

1.4 D. Lloyd's Method

In Lloyd's model, the rationale is that when engineering corrective action for a failure is implemented, the probability of recurrence of that failure is reduced; therefore, such failures should not be carried as

full failures in subsequent reliability estimates. The failure value for each failure model is assumed to be

$$f = 1-(1-\gamma)^{1/n}$$

where γ is the confidence level and n is the number of successful tests after corrective action.

Based on a detailed engineering analysis for each failure mode, the result of each failure for each failure mode can be obtained by solving the above equation. The final result of the reliability estimation is $R = 1- \sum f/N$ where $\sum f$ is the cumulative failure number of all failure modes and N = the test number.

This model weights the growth effect and can be extended to forecast the reliability, the failure mode and the launch number at which the failure mode occured as well as the launch number at which it was corrected. The confidence level γ is directly related to the final results and requires subjective judgement as to what value is to be used.

2.0 A NEW STATISTICAL MODEL

The developmental history of any launch vehicle can be considered as two time periods - the early testing period and the performance period. Generally, during the early testing period the unreliability of a launch vehicle is high and unstable. After a "failure, analysis, and fix" process, in conjunction with technical and design improvements, the unreliability of a launch vehicle decreases and stabilizes in the performance period.

A statistical model which weights the reliabilities of these two periods has been developed. The detailed descriptions of the materials for reliability analysis of vehicles, stages, systems, and engines (or motors) are introduced in the following sections.

2.1 Estimation of Launch Vechicle Reliability

The easiest way to estimate the average unreliability of a launch vehicle is:

$$U_e = F/L \qquad (1)$$

where U_e is the estimated average unreliability, and F and L are the cumulative failure and launch numbers.

As was mentioned before, the reliability growth effect must be considered to get a more realistic estimation of the unreliability. In the present model, the average unreliability is defined as

$$U = U_e - \Delta U \qquad (2)$$

where ΔU is the change in reliability caused by reliability growth and can be explained as

$$\Delta U = \Delta F/L$$

or

$$\Delta F = \Delta U \cdot L \qquad (3)$$

where ΔF is the cumulative failure correction number.

Averaging both sides of equation (3) results in

$$\overline{\Delta F} = \Delta U \cdot \frac{L}{2}$$

or

$$\Delta U = \frac{2}{L} \cdot \overline{\Delta F} \qquad (4)$$

Substitute equation (1) and equation (4) into equation (2)

$$U = \frac{F}{L} - \frac{2}{L} \cdot \overline{\Delta F} \qquad (5)$$

The estimation of the unreliability of the launch vehicle at the n^{th} launch can then be approximated as

$$U_n = \frac{F_n}{L_n} - \frac{2}{L_n} \cdot \frac{\sum_{i=1}^{N} \left(F_i - \frac{F_n}{L_n} \cdot L_i \right)}{N} \qquad (6)$$

where L_i is the i^{th} launch number, and F_i is the cumulative failure number at the i^{th} launch.

The reliability R_n at the n^{th} launch is

$$R_n = 1 - U_n = 1 - \left[\frac{F_n}{L_n} - \frac{2}{L_n} \cdot \frac{\sum_{i=1}^{N} \left(F_i - \frac{F_n}{L_n} \cdot L_i \right)}{N} \right] \qquad (7)$$

The concepts of confidence levels based on the value of average reliability from equation (7) are now illustrated as the following.

Let N be the launch number, then $X = N \cdot R_n$ is the success number

5th confidence -

$$R_{005} = \frac{x}{x + (n - x + 1) F_{095}(2n - 2x + 2, 2x)} \qquad (8)$$

95th confidence -

$$R_{095} = \frac{(x+1) F_{095}(2x+2, 2n-2x)}{(n-x) + (x+1) F_{095}(2x+2, 2n-2x)} \qquad (9)$$

where $F_r(n_1, n_2)$ is the 100 r^{th} percentile of F-distribution with n_1 numerator and n_2 denominator degrees of freedom.

This completes the formulation of the launch vehicle reliability calculations. The example which applies this model is given in section 5.

2.2 Estimation of Stage Reliability

The basic method of estimating the stage reliability of a launch vehicle in the present study is based on the following assumptions:

1. The failure of the launch vehicle must occur in one of its stages.

2. The starting operation time for each stage is followed by the order of stage number. In other words, the first stage should begin operating before the second stage.

The following formulation has been developed to perform the reliability estimation for the i^{th} stage

$$R_{si} = 1 - \frac{F_{si} \cdot U_v}{F_v - \left(\sum_{j=1, j \le i-1}^{i-1} F_{si} \right) \cdot U_v} \qquad (10)$$

where R_{si} is the reliability of the i^{th} stage, F_{si} is the cumulative failure number of the i^{th} stage, F_v is the cumulative failure number of the launch vehicle, U_v is the unreliability of the launch vehicle from equation (6).

For example, the reliability for

First stage: $R_{s1} = 1 - \frac{F_{s1} \cdot U_v}{F_v}$

Second stage: $R_{s2} = 1 - \frac{F_{s2} \cdot U_v}{F_v - F_{s1} \cdot U_v}$

Third stage: $R_{s3} = 1 - \frac{F_{s3} \cdot U_v}{F_v - (F_{s1} + F_{s2}) \cdot U_v}$

Since the value of U_v in equation (10) has been weighted, the estimation of reliability for each stage R_i is also a weighted average.

2.3 Estimation of System Reliability

The basic assumption for the method of estimating system relaibility in the present study is that the failure of the launch vehicle must occur in one of its systems.

The average reliability of each system of the launch vehicle can be formulated as

$$R_{sys\,i} = 1 - U_v \cdot F_{sys\,i} / F_v \qquad (11)$$

where R_{sysi} is the reliability of the i^{th} system, F_{sysi} is the cumulative failure number of the i^{th} system, U_v is the unreliability of the launch vehicle, F_v is the cumulative failure number of the launch vehicle.

2.4 Estimation of Engine (or Motor) Reliability

The basic assumption of the method for estimating engine (or motor) reliability is if any of the engines (or motors) in a stage fails, then the entire stage has failed. Since the failure of a stage can be caused by either engine (or motor) failure or other failures, the cumulative failure number of engine (or motor) in this stage needs to be known. The model for estimating engine (or motor) reliability is described as

$$R_{ei} = (1 - U_{si} \cdot F_{ei} / F_{si})^{1/N_{ei}}$$

where

R_{ei} is the reliability of the engine (or motor) in the i^{th} stage.

U_{si} is the unreliability of the i^{th} stage which can be obtained by $1-R_{si}$ from equation (10).

F_{ei} is the engine (or motor) cumulative failure number in the i^{th} stage.

F_{si} is the cumulative failure number of the i^{th} stage.

N_{ei} is the number of engines (or motors) in the i^{th} stage.

3.0 DATA COLLECTION

Based on the analysis of section 2, the following table for data collection of each launch vehicle was developed.

Vehicle Name _____

Data Collection from _____ Yr to _____ Yr

Total Launch Number _____

Total Failure Number _____

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Descrptn	Engine or Failure Y/N

Table A.3

In this table,

Date: the date when the launch vehicle failed
Failure Launch: the launch number at which the launch failed
Success Run: the number of successful launches between two failures
Failure Stage: failure stage number
Failure System: one of the following systems failed: propulsion, separation, flight control, structure, electrical, guidance, etc...
Failure Description: failure mode
Engine or Motor Failure Y/N: Y = engine or motor failure;
N = no engine or motor failure.

This table template was then applied to the history of all US Launch Vehicle Families according to given cut-off dates. The cut-off dates and the resulting historical tabulations are given in the supplement to this appendix.

4.0 ALGORITHM

The general solution procedures of launch vehicle reliability analysis can be described by the following steps.

1. Use Table A.3 to collect the data for each launch vehicle.

2. From the date of "Failure Launch" listed in Table A.3, the launch vehicle reliability can be estimated by applying equation (7) in section 2.1. The corresponding 95th and 5th confidence levels can be obtained by solving equations (8) and (9) in section 2.1.

3. From the data of "Failure Stage" listed in Table A.3 and the launch reliability obtained in step 2, the reliability of each stage of the launch vehicle can be calculated by using equation (10) in section 2.2.

4. The date of "Failure System" together with the results of step 2 provide the information to obtain the reliability of each system in the launch vehicle by applying equation (11) in section 2.3.

5. From the data of "Engine (or Motor) Failure Y/N" listed in Table A.3 and the result of step 3, the reliabilities of each engine (or motor) can be obtained by solving equation (12).

5.0 EXAMPLE

Consider the "Atlas/Centaur" as an example. The general information about the "Atlas/Centaur" is illustrated in the following figure which is taken from the report "Hazard Analysis of Commercial Space Transportation", Volume I, May 1988, published by the U.S. Department of Transportation.

Following the solution procedures described in section 4:

1. Table A.4 lists all the failure data on the "Atlas/Centaur", The data collection period is from 1962 to 1987. The launch number of the "Atlas/Centaur" during this period is 67, and the corresponding failure number is 11. In this example, the failure data was collected from the "Launch Vehicle Failure History Data Base," which was compiled by Cindy Thatcher Clague of the Aerospace Corporation (reference 4).

The March 26, 1987 failure, shown in Table A.4, which was caused by a lightning strike is considered as an externally caused failure. This failure is eliminated in the present reliability analysis otherwise all failures are included.

2. Based on the data in Table A.4, we used equation (7) in Section 2.1 to estimate the launch vehicle reliability. The estimation of the reliability for n=67 is

$$R_n = 0.9069$$

The corresponding 95th and 5th confidence levels, obtained by solving equations (8) and (9), are

$$R_{0.05} = 0.8450$$
$$R_{0.95} = 0.9489$$

3. From the "Stage Failure" data in Table A.4

The first stage is stage 1/2 and has the failure number $F_{1/2} = 2$.
The second stage is stage 1 and has the failure number $F_1 = 2$.
The third stage is stage 2 and has the failure number $F_2 = 6$.

The reliability of each stage can be obtained by solving equation (10). In this example, the unreliability of the vehicle is $U_v = 1-R_v = 0.0931$, and the cumulative failure number of the vehicle is $F_v = 10$. Substituting these values into equation (10), we get

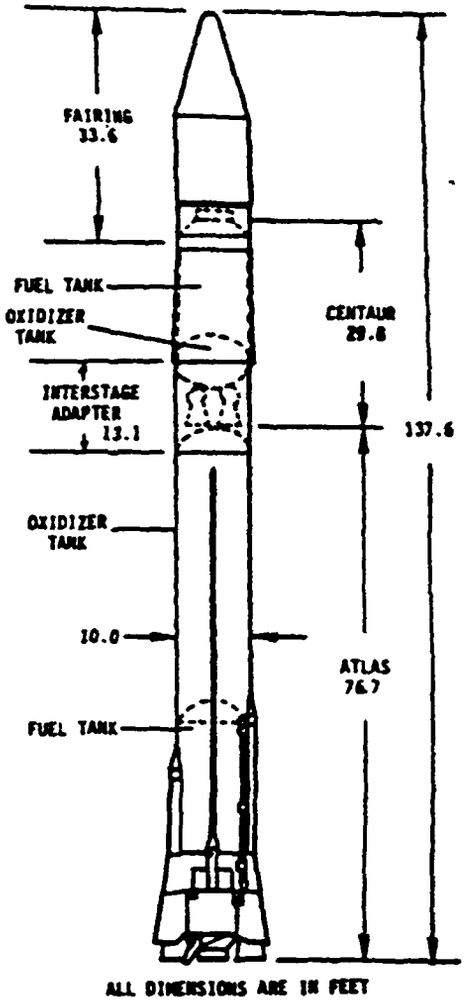
$R_{s1} = 0.9814$ for stage 1/2.
$R_{s2} = 0.9810$ for stage 1.
$R_{s3} = 0.9420$ for stage 2.

4. From the "System Failure" data in Table A.4

The failure number of the propulsion is 5.
The failure number of the structure is 2.
The failure number of the separation is 1.
The failure number of the flight control is 1.
The failure number of the electrical is 1.

General Dynamics

General Stage Data
Atlas Centaur Launch Vehicle



	Stage 1/2	Stage 1	Stage 2
Stage Data			
Designation		Atlas G	Centaur D-1A
Stage Mass, klbm		320.675	38.777
Usable Propellant, klbm		300.632	29.734
Stage Length, ft		76.7	29.8
Stage Diameter, ft		10	10
Number of Engines	2	1	2
Guidance Data			
Manufacturer			Honeywell
Type			Four Gimbal Inertial
Engine Data			
Manufacturer	Rocketdyne	Rocketdyne	Pratt and Whitney
Designation	YLR-89-NA-7	YLR-105-NA-7	RL-10A-3-3A
Number of Starts Possible	1	1	2
Fuel	RP-1	RP-1	LN_2
Oxidizer	LOX	LOX	LOX
Mixture Ratio, O/F	2.25	2.22	5.0
Average Thrust per Engine, lbf			
Sea Level	180,750	60,500	—
Vacuum	—	—	16,500
Average Chamber Pressure, psia	650	733	474
Specific Impulse, sec			
Sea Level	259	220	
Vacuum	292	312	446.4
Total Burn Time, sec	153	283	404
Nozzle Expansion Ratio	8	25	61
Nozzle Exit Area, ft^2	11.24	11.56	8.22
Engine Cant Angle, deg	0	0	0
Thrust Vector Control	Gimballed Engines and Verniers		Gimballed Engine

Figure A.1. Atlas/Centaur launch vehicle configuration and data.

TABLE A.4: FAILURE HISTORY DATA OF ATLAS/CENTAUR

Vehicle Name: Atlas/Centaur
Data Collection from: 62 to 87
Total Launch Number: 67
Total Failure Number: 11

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
05/08/62	1	0	2	Structure	Centaur upper stage structure failure	N
06/30/64	3	1	2	Propulsion	Centaur hydraulic failure, Loss of C_2 hydraulic power	N
03/02/65	5	1	1/2	Propulsion	Loss of Atlas thrust during liftoff, due to fuel starvation of booster engines stemming from closure of fuel prevelue	Y
04/07/66	7	1	2	Propulsion	Centaur restart sequence failure, engine ignition occurred but not sustained due to fuel deplation	N
08/10/68	16	8	2	Propulsion	Failure of boost pump H_2O_2 supply system centaur didn't achieve its second main engine start	N
11/30/70	21	4	1	Separation	Nose fairing failed to jettison properly	N
05/08/71	23	1	2	Flight Control	Centaur pitch control lost	N
02/20/75	34	10	1	Electrical	Atlas booster section electrical disconnect failed during booster jettison	N
09/29/77	42	7	1/2	Propulsion	Atlas booster engine hot gas leak failed mission	Y
06/09/84	62	19	2	Propulsion	Failure occurred at A/C Separation a liquid oxygen tank crack	N
03/26/87	67	4	---	other	Lightning strike failed mission	N

By solving equation (11), the reliability of each system can be obtained

$$R_{propulsion} = 0.9535$$
$$R_{structure} = 0.9814$$
$$R_{separation} = 0.9907$$
$$R_{flight\ control} = 0.9907$$
$$R_{electrical} = 0.9907$$

5. There are two engines (YLR-89-NA-7) in stage 1/2, one engine (YLR-105-NA-7) in stage 1, and two engines (RL-10A-3-3A) in stage 2. From Table A.4, the failure number of engine YLR-89-NA-7 is 2. The failure number of engine YLR-105-NA-7 is 1, and the failure number of engine RL-10A-3-3A is 0. By solving equation (12) together with results of stage reliabilities, the reliabilities of each engine can be obtained.

$$R_{YLR\text{-}89\text{-}NA\text{-}7} = 0.9907$$
$$R_{YYLR\text{-}105\text{-}NA\text{-}7} = 0.9905$$
$$R_{RL\text{-}10A\text{-}3\text{-}3A} = \text{No Failure}$$

The results of the reliability analysis for the "Atlas/Centaur" are summarized as

ATLAS/CENTAUR	RELIABILITY
Vehicle	
Mean	0.9069
5%	0.8450
95%	0.9489
Stages	
Stage 1/2	0.9814
Stage 1	0.9810
Stage 2	0.9420
System	
Propulsion	0.9535
Structure	0.9814
Separation	0.9907
Flight Control	0.9907
Electrical	0.9907
Engines	
YLR-89-NA-7	0.9907
YLR-105-NA-7	0.9905
RL-10A-3-3A	No Failure

The reliability estimation of "Atlas/Centaur" based on equation (7) at each launch is described in the following figure, A.2.

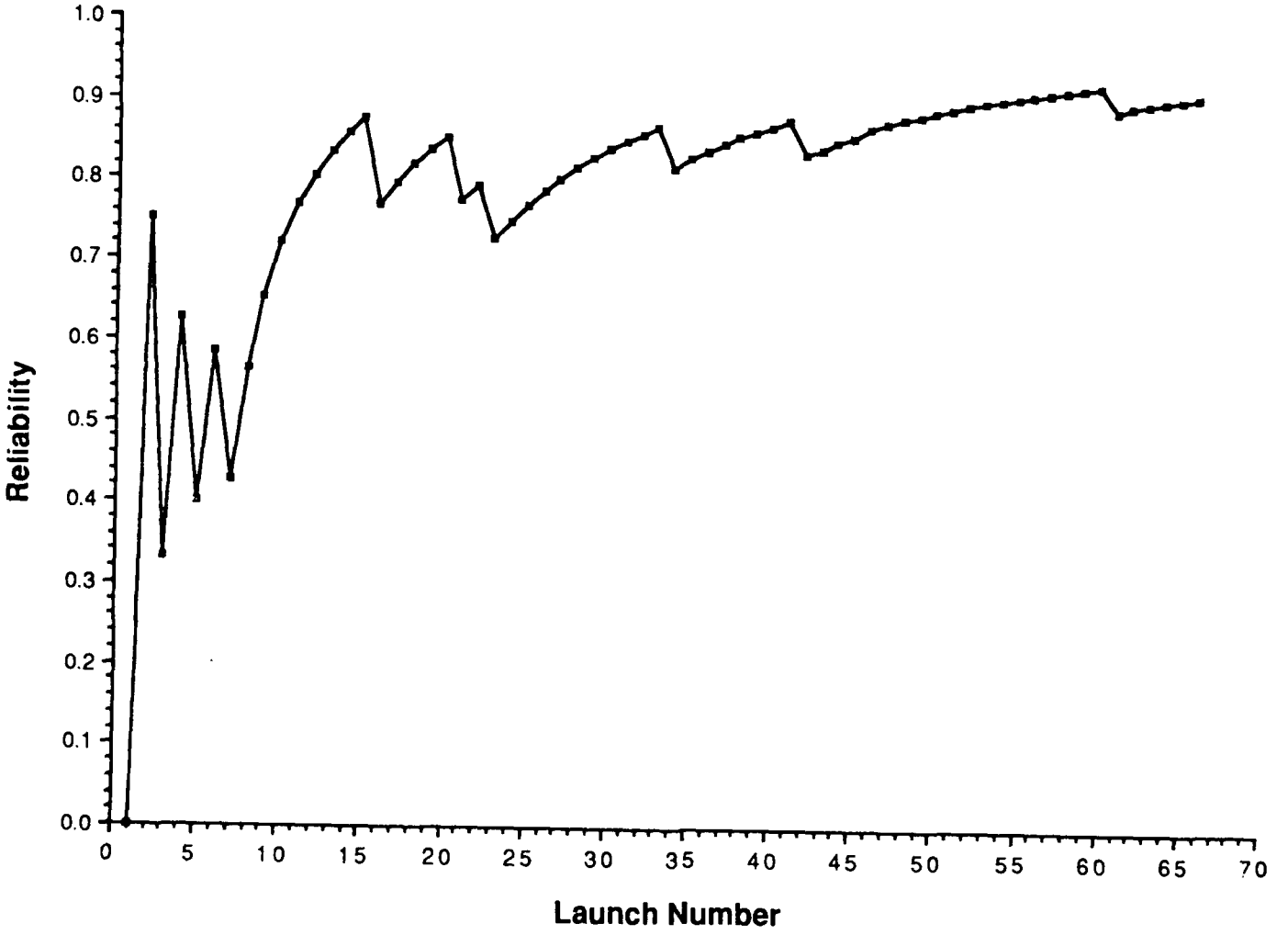


Figure A.2. Reliability estimation of Atlas/Centaur.

6.0 RESULTS

The statistical model (section 2) and the data collection method (section 3) following the solution procedures (section 4) have been applied to twenty-four U.S. launch vehicles. The results are listed in Table A.5.

In Table A.5, launch vehicles are separated into six groups based on their developmental histories. The results of the "Combine" in Table A.5 are the reliability estimates for each group. The following formulations, based on Bayesian reliability analysis, have been applied to perform the calculation for each group.

$$\mu = \frac{1}{N}\sum_{i=1}^{N} R_i$$

where N is the vehicle number in the group, R_i is the reliability of the i^{th} vehicle, μ is the mean reliability of the group.

$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(R_i - \mu)^2$$

where σ^2 is the variance.

Let

$$a = \frac{\mu^2}{\sigma^2}(1-\mu) - \mu$$

$$b = \frac{\mu}{\sigma^2}(1-\mu) + \mu - 1$$

Then the mean of the group is

$$\mu = a/(a+b)$$

The 5% confidence level is

$$R_{05} = \frac{a}{a + b \cdot F_{095}(2b, 2a)}$$

The 95% confidence level is

$$R_{095} = \frac{a \cdot F_{095}(2a, 2b)}{b + a \cdot F_{095}(2a, 2b)}$$

The reliability estimations for each engine of the launch vehicles are not listed in Table A.5. They are partially listed in the matrices which are for engine reliability analysis.

TABLE A.5: RELIABILITY COMPARISON OF U.S. LAUNCH VEHICLE FAMILIES

Vehicle Name / Data Collection Period		Thor / Delta			Titan					Atlas											Saturn "Family"						Scout "Family"			STS
		Thor	Delta	Combine	Titan I	Titan II	Titan III	Titan 34D	Combine	Atlas A	Atlas B	Atlas C	Atlas D	Atlas E	Atlas F	Atlas SLV	Atlas G	Atlas H	Atlas/ Centaur	Combine	Jupiter	Juno	Saturn I	Saturn IB	Saturn V	Combine	Vanguard	Scout	Combine	Space Shuttle
		57-83	60-87	57-87	59-65	62-76	64-87	82-87	59-87	57-58	58-59	58-59	59-87	60-88	61-81	87-83	84-87	83-87	82-87	57-88	58-58	58-61	62-65	66-75	67-73	58-75	57-59	60-88	57-88	81 88
Success Rate: Mean		0.8982	0.9402	0.9192	0.6427	0.8884	0.9408	0.7355	0.8013	0.4219	0.5556	0.5833	0.8401	0.7428	0.8863	0.9445	no failure	no failure	0.9089	0.7863	0.3811	0.4300	no failure	no failure	0.9822	0.7547	0.3388	0.9420	0.6404	0.9275
	5%	0.8750	0.9110	0.8789	0.5565	0.8323	0.9056	0.4978	0.8075	0.1827	0.3010	0.2642	0.8015	0.6454	0.8359	0.8738	0.6313	0.6313	0.8450	0.4761	0.1028	0.2135	0.7943	0.7743	0.8180	0.2652	0.1555	0.9023	0.1521	0.8147
	95%	0.9181	0.9615	0.9551	0.7202	0.9272	0.9651	0.8990	0.9546	0.6977	0.7898	0.8565	0.8734	0.8340	0.9276	0.9652			0.9488	0.9953	0.8879	0.6743			0.9997	0.9835	0.5723	0.9683	0.9744	0.9806
STAGE NO.	Stage 0	0.9965	0.9850				0.9946	0.8678																						
	Stage 1/2													0.8713	0.9573	0.9861			0.9814											
	Stage 1	0.9348	0.9850		0.8214	0.9574		0.8478						0.8523	0.9279	0.9719			0.9810			0.8575					0.8347	0.9917		0.9275
	Stage 2	0.9764	0.9746		0.7825	0.9258	0.9783									0.9856			0.9420		0.5741	0.7009			0.9822		0.5049	0.9875		
	Stage 3	0.9877	0.9843				0.9867															0.7829			0.9822		0.8039	0.9746		
	Stage 4																				0.6290	0.9378						0.9870		
SYSTEM	Propulsion	0.9568	0.9701		0.8725	0.9290	0.9822	0.7355		0.8844	0.9687			0.8713	0.9212	0.9824			0.9535		0.7870						0.7521	0.9703		0.9275
	Guidance	0.9830	0.9850			0.9929	0.9892							0.9571	0.9889												0.9174	0.9917		
	Flight Control	0.9907	0.9851			0.9858	0.9946			0.7868	0.8689			0.9428	0.9889	0.9824			0.9907								0.8347	0.9917		
	Structure	0.9969			0.9702		0.9946			0.7868				0.9857					0.9814											
	Electrical	0.9815	0.9850			0.9929								0.9857		0.9824			0.9907									0.9876		
	Separation	0.9969	0.9850			0.9858										0.9824			0.9907		0.5741							0.9956		
	Other or (UK)	0.9923													0.9934												0.8347	0.9956		

7.0 CONCLUSIONS

A new model has been developed which has the following advantages:

1. This model weights the reliability growth effect. Since the reliability of a launch vehicle can be estimated from each past launch, the extension of this model should be able to predict the future reliability of the launch vehicle.

2. The formulations of the model are simple and easy to apply. A computer program is being developed for future applications.

3. The results of the calculations are only dependent on the data collection.

4. The reliability estimations of vehicles, stages, systems, and engines are separated, which reduces the restrictions to the data collection.

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Appendix A.4

History
of
US Launch Vehicles

Cut-off dates for launch vehicle reliability data

Launch vehicle	Cut-off date	Failure No.	Launch No.
Thor/Delta			
Thor	01/25/57 - 08/05/83	66	369
Delta	05/13/60 - 03/20/87	12	181
Titan			
Titan I	02/06/59 - 03/05/65	24	68
Titan II	03/16/62 - 06/27/76	16	94
Titan III	09/01/64 - 02/11/87	11	137
Titan 34D	10/30/82 - 11/28/87	2	11
Atlas			
Atlas A	06/11/57 - 06/03/58	5	8
Atlas B	07/19/58 - 02/04/59	4	9
Atlas C	12/23/58 - 08/24/59	3	6
Atlas D	04/14/59 - 11/07/67	42	197
Atlas E	10/11/60 - 02/03/88	18	49
Atlas F	08/08/61 - 06/23/81	17	96
Atlas SLV	02/02/67 - 05/19/83	4	73
Atlas G	06/09/84 - 03/26/87	0	5
Atlas H	02/09/83 - 05/15/87	0	5
Atlas/Centaur	05/08/62 - 03/26/87	10	67
Saturn "Family"			
Jupiter	07/26/58 - 10/23/58	3	6
Juno	12/06/58 - 05/24/61	5	10
Saturn I	10/27/62 - 07/30/65	0	10
Saturn IB	02/26/66 - 07/15/75	0	9
Saturn V	11/09/67 - 05/14/73	1	13
Scout "Family"			
Vanguard	12/06/57 - 09/18/59	8	11
Scout	07/01/60 - 03/25/88	14	110
STS			
Space Shuttle	04/12/81 - 09/29/88	1	26

Vehicle Name: Thor
Data Collection from: 57 to 83
Total Launch Number: 369
Total Failure Number: 66

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
01/25/57	1	0	1	Propulsion	Missile fell back on launcher, oxygen start tank fill and check valve malfunction	Y
04/19/57	2	0	1	Human	Erroneously destroyed by RSU	N
05/21/57	3	0	2	Structure	Fuel tank ruptured	N
08/30/57	4	0	1	Propulsion	Propellant valve pneumatic line failure	Y
10/03/57	6	1	1	Electrical	Microswitch failure in MFV delayed signal to gas generator valve opening	N
10/11/57	7	0	1	Propulsion	Possible turbopump failure	Y
12/07/57	9	1	1	Electrical	Electrical systems malfunction, no main engine cutoff	N
01/28/58	11	1	1	Guidance	Excessive trajectory dispersion after 95 sec. terminated by RSO	N
02/28/58	12	0	1	Propulsion	Premature shutdown, failure of gas generator LRRP or liquid ox line	Y
04/19/58	13	0	1	Propulsion	Fell back on launcher due to fuel system malfunction	Y
04/23/58	14	0	1	Propulsion	Turbopump failure	Y
07/13/58	18	3	1	Electrical	Main engine cutoff failed to get through circuit problem	N
07/26/58	20	1	1	Structure	Pneumatic line failure caused MLV closure missile broke up due to aerodynamic forces	N
08/17/58	22	1	1	Propulsion	First stage malfunction, Turbopump failure	Y
11/05/58	24	1	1	Guidance	Autopilot malfunction	N

Vehicle Name: Thor
Data Collection from: 57 to 83
Total Launch Number: 369
Total Failure Number: 66

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
11/08/58	25	0	3	Propulsion	3rd stage failed to ignite	Y
12/05/58	27	1	1	Propulsion	Liquid oxygen tank pressurization malfunction	N
12/30/58	30	2	1	Guidance	Guidance malfunction at liftoff	N
01/21/59	31	0	1	Propulsion	Exploded on pad. A malfunction during countdown	N
01/23/59	32	0	2	Electrical	Electrical malfunction prevented cutoff and 2nd stage Ignition	N
01/30/59	33	0	1	Propulsion	Liquid oxygen tank pressurization problem	N
06/03/59	47	14	3	Propulsion	Premature engine burnout due to fuel exhaustion, Insufficient velocity was gained for orbital attainment	Y
06/16/59	49	1	1	Guidance	Autopilot did not program possibly liftoff switch didnot extract	N
06/25/59	51	1	2	Electrical	A diode failure in the D-timer brake circuit caused the Agena engine to burn to fuel exhaustion	N
06/29/59	52	0	1	Electrical	Electrical malfunction R/V did not separate retro-rockets did not fine	N
07/21/59	53	0	1	Flight Control	Flight controller did not program; Launcher arm did not extract liftoff pin	N
08/14/59	60	6	1	Propulsion	Fuel depletion, fuel underload, leak or engine miscalibration	Y
09/17/59	65	4	2	Separation	2nd stage retro device failed, 3rd stage did not ignite	N
12/01/59	77	11	1	Propulsion	Main engine cutoff occurred 6 sec. early. Possibly main liquid oxygen valve closed prematurely	Y
12/14/59	79	1	1	Flight Control	Control failure, Missile stability lost	N

Vehicle Name: Thor
Data Collection from: 57 to 83
Total Launch Number: 369
Total Failure Number: 66

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
02/04/60	83	3	1	Electrical	Failure of the fuel injector pressure switches or a short around them	N
02/19/60	86	2	1	Guidance	Autopilot component failure	N
06/29/60	94	7	2	Guidance	2nd stage attitude instability	N
08/18/60	97	2	1	Propulsion	Failure of the first stage hydraulic system	Y
10/26/60	101	3	2	Separation	2nd stage failed to separate	N
11/30/60	103	1	1	Electrical	Main engine shutdown from a premature MECO signal	N
03/30/61	111	7	3	Propulsion	A hydraulic system failure resulted in lose of attitute control	Y
06/08/61	113	1	3	Propulsion	Fuel line leak, Engine failed to provide thrust	Y
07/21/61	118	4	1	Flight Control	Control system instability	N
08/03/61	119	0	2	Flight Control	A failure occurred in the hydraulic system which provides the power for engine gimballing	N
10/23/61	125	5	1	Propulsion	Hydraulic failure and a failure in the engine actuating system	Y
11/05/61	126	0	3	Guidance	Apogee was higher than predicted as a result of excess velocity	N
01/13/62	131	4	2	Electrical	Blew a fuse in the line to the gyro guidance packages	N
01/24/62	133	1	2	Propulsion	2nd stage misfired, An acutator lug on the 2nd stage thrust chamber was broken	Y
02/21/62	134	0	1	Propulsion	The fuel vent valve stuck open during first burn	Y

Vehicle Name: Thor
Data Collection from: 57 to 83
Total Launch Number: 369
Total Failure Number: 66

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
03/19/62	136	1	1	Guidance	Pitch HIG gyro malfunction	N
05/10/62	140	3	1	Electrical	Failure of the 1st and 2nd stages to separate which was caused by 1st stage electrical malfunction	N
06/20/62	147	6	1	Propulsion	High temps weakened the load-carrying capabilit of the Thor engine section	N
07/25/62	153	5	1	Propulsion	The main oxidizer valve only partially opened	N
10/15/62	162	8	1	Propulsion	The actuator potentionmeter voltage show a continuing loss of power	Y
02/28/63	174	11	0	Propulsion	Solid motor failure	Y
03/18/63	175	0	2	Electrical	Electrical short circuit in the safe-arm junction box	N
04/26/63	177	1	3	Guidance	Failure in horizon sensors	N
06/12/63	179	1	1	Propulsion	During 1st engine operation a power short condition developed, igniters were set off by radiated heat from the nozzle	Y
11/09/63	191	11	1	Propulsion	overheating of the boattail section	Y
11/10/63	192	0	1	Flight Control	Unstable and premature termination of powered flight	N
03/24/64	203	10	2	Electrical	Electrical short circuit, loss of guidance and control	N
04/21/64	204	0	UK	Flight Control	Failure of flight control	N
04/27/64	206	1	UK	UK	UK	UK
05/28/64	207	0	UK	UK	UK	UK

Vehicle Name: Thor
Data Collection from: 57 to 83
Total Launch Number: 369
Total Failure Number: 66

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
09/02/65	250	42	UK	Guidance	Guidance failure, destroyed by RSO	N
01/06/66	260	9	2	UK	Failed to orbit	UK
05/03/66	269	8	2	Propulsion	Fire in thrust section due to leakages	Y
05/18/68	301	31	1	Guidance	Gyro failure, Booster guidance malfunction	N
02/17/71	335	33	1	Propulsion	Exploded after 40 sec.	UK
02/18/76	354	18	UK	UK	UK	UK

Vehicle Name: *Delta*
Data Collection from: 60 to 87
Total Launch Number: 181
Total Failure Number: 12

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
05/13/60	1	0	2	Flight Control	2nd stage attitude control malfunction, No 3rd stage ignition	N
03/19/64	24	22	3	Propulsion	Loss of 3rd stage halfway thru burn	Y
08/25/65	33	8	3	Propulsion	3rd stage ignition before separation, Did not achieve orbit	N
09/18/68	59	25	1	Guidance	1st stage control system (rate gyro)	N
07/25/69	71	11	3	Propulsion	3rd stage (AKM) thrust dropped during burn possibly nozzle blown off	Y
08/27/69	73	1	1	Propulsion	1st stage hydraulic system failure	Y
10/21/71	86	12	2	Flight Control	2nd stage control gas oxidizer vent valve failure, leak	N
07/16/73	96	9	2	Propulsion	2nd stage hydraulic system pump motor failure	Y
01/19/74	100	3	2	Flight Control	2nd stage electronics failure	N
04/20/77	130	29	2	Separation	Clamp band released early	N
09/13/77	134	3	0	Propulsion	SRM (Castor IV) burn-through	Y
05/03/86	178	43	1	Electrical	1st stage electrical short in relay box (main engine shutdown)	N

Vehicle Name: Titan I
Data Collection from: 59 to 65
Total Launch Number: 68
Total Failure Number: 24

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
08/14/59	5	4	1	Structure	Vibration fired holddown bolts: 1B1E pulled causing shutdown	N
12/12/59	6	0	1	Propulsion	Failure on pad: destruct system	UK
02/05/60	8	1	1	Structure	Failure at T+43 sec.	N
03/08/60	10	1	UK	UK	UK	UK
04/08/60	12	1	UK	UK	UK	UK
07/01/60	18	5	1	Propulsion	Failure at stage I hydraulics	Y
07/28/60	19	0	1	Propulsion	Stage I premature shutdown	UK
08/10/60	20	0	UK	UK	UK	UK
09/29/60	23	2	UK	UK	UK	UK
12/03/60	26	2	1	UK	Vehicle destroyed	UK
12/20/60	27	0	2	Propulsion	No stage II ignition	UK
01/20/61	28	0	2	Propulsion	No stage II ignition	UK
03/02/61	31	2	2	UK	Premature stage II shutdown	UK
03/31/61	33	1	1	UK	Premature stage I shutdown	UK
06/23/61	36	2	2	UK	Premature stage II shutdown	UK

Vehicle Name: Titan I
Data Collection from: 59 to 65
Total Launch Number: 68
Total Failure Number: 24

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
12/15/61	49	12	2	Propulsion	No stage II ignition	UK
01/20/62	50	0	2	Propulsion	No stage II ignition	UK
02/23/62	52	1	2	Propulsion	No stage II ignition	UK
05/01/63	60	7	1	Propulsion	Failure at liftoff	UK
07/16/63	61	0	2	Propulsion	No stage II ignition	UK
08/30/63	63	1	1	Propulsion	Gas generator shutdown	Y
12/08/64	66	2	2	UK	Stage II prel. shutdown	UK
01/14/65	67	0	2	Propulsion	No stage II ignition	UK
03/05/65	68	0	1	Propulsion	Propellant depletion	Y

Vehicle Name: Titan II
Data Collection from: 62 to 76
Total Launch Number: 94
Total Failure Number: 16

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
06/07/62	2	1	2	Propulsion	Stage II gas generator oxidizer injection blocked	Y
07/25/62	4	1	2	Propulsion	Stage II fuel pump leak downstream of TCV failure due to combustion instability	Y
12/06/62	8	3	2	Propulsion	Stage II oxidizer bootstrap line failure	Y
01/10/63	10	1	2	Propulsion	Gas generator oxidizer injector blocked	Y
02/16/63	13	2	1	Separation	Umbilicals failed to disconnect properly	N
04/19/63	15	1	2	Propulsion	Bootstrap premature shutdown	Y
05/09/63	17	1	2	Propulsion	OX leak, Premature shutdown of stage II 10% loss of stage II oxidizer during S II flight	N
05/29/63	20	2	1	Propulsion	Subassembly 1 thrust chamber fuel valve leak occurred at engine ignition	Y
06/20/63	21	0	2	Propulsion	Gas generator oxidizer injector clogging	Y
04/30/65	45	23	1	Propulsion	Subassembly / shutdown abruptly and vehicle flight continued erratically, Turbopump failure	Y
06/14/65	48	2	1	Flight Control	Loss of vernier nozzle	N
09/21/65	54	5	2	Electrical	Premature shutdown of stage II, bad connector coupled with a surge in the AOS power	N
11/30/65	57	2	1	Propulsion	Fuel leak, possibly at cross-over manifold with resultant thrust vectoring	Y
12/22/65	60	2	2	Human (Guidance)	Control of record stage lost following staging Probably due to technician reading wrong scale	N
05/24/66	67	6	1	Separation	No r/v Separation	N

Vehicle Name: Titan II
Data Collection from: 62 to 76
Total Launch Number: 94
Total Failure Number: 16

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
04/12/67	69	1	2	Flight Control	Stage II yaw rate gyro	N

Vehicle Name: Titan III
Data Collection from: 64 to 87
Total Launch Number: 137
Total Failure Number: 11

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
09/01/64	1	0	3	Propulsion	Premature transtage cutoff, Pressure system failure	Y
10/15/65	6	4	3	Propulsion	Propellant freezing in stage III engine bi-prop valve engine failed to shutdown	Y
12/21/65	7	0	3	Flight Control	ACS engines failed to shutdown after vernier burn loss of attitude control	N
08/26/66	10	3	0	Structure	P/L fairing failure during SRM flight	Y
04/26/67	16	5	2	Propulsion	Stage II engine thrust dropped to 1/2 nominal gross contamination on Martin side of interface	Y
11/06/70	48	31	3	Guidance	IGS-IMU failure, The electronic suspension of the IMU shorted out	N
02/11/74	75	26	3	Propulsion	Centaur stage failed to start after separation, failure of LO_2 boost pump	N
05/20/75	85	9	3	Guidance	IMU failed, Internally shorted transistor	N
09/15/76	99	13	2	Propulsion	Engine failed to shutdown on command burned to completion, hard contaminant in fuel valve	Y
09/05/77	106	6	2	Propulsion	Low velocity at stage II shutdown	Y
03/25/78	110	3	2	Propulsion	Turbine drive hydraulic pump failure after ignition	Y

Vehicle Name: Titan 34D
Data Collection from: 82 to 87
Total Launch Number: 11
Total Failure Number: 2

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
08/28/85	8	7	1	Propulsion	Stage I engine shutdown prematurely-massive leak shortly after ignition	Y
04/18/86	9	0	0	Propulsion	Insulation/case debond vehicle disintegrated at T+8.764 the first explosive flash was noted	Y

Vehicle Name: Atlas A
Data Collection from: 57 to 58
Total Launch Number: 8
Total Failure Number: 5

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
06/11/57	1	0		Structure		
09/25/57	2	0		Structure		
02/07/58	5	2		Flight Control		
02/20/58	6	0		Flight Control		
04/05/58	7	0		Propulsion		

Vehicle Name: Atlas B
Data Collection from: 58 to 59
Total Launch Number: 9
Total Failure Number: 4

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
07/19/58	1	0		Flight Control		
09/18/58	5	3		Propulsion		
11/17/58	6	0		Propulsion		
01/15/58	8	1		Propulsion		

Vehicle Name: Atlas C
Data Collection from: 58 to 59
Total Launch Number: 6
Total Failure Number: 3

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
01/27/59	2	1		Guidance		
02/20/59	3	0		Propulsion		
03/18/59	4	0		Propulsion		

Vehicle Name: Atlas D
Data Collection from: 59 to 67
Total Launch Number: 197
Total Failure Number: 42

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
04/14/59	1	0		Propulsion		
05/18/59	2	0		Propulsion		
06/06/59	3	0		Propulsion		
09/09/59	6	2	1/2	Electrical	Electrical signal to initiate separation did not reach the pyrotechnic cartridges	N
09/16/59	8	1		Propulsion	Hydraulic failure	
01/26/60	19	10		Guidance		
03/10/60	23	3		Propulsion		
04/07/60	24	0		Propulsion		
05/06/60	26	1		Flight Control		
06/22/60	30	3		Electrical		
07/02/60	32	1		Electrical		
07/22/60	33	0		Flight Control		
07/29/60	34	0		Structure	Static or dynamic loads, higer than could be predected, rupture of LOX tank	N
09/12/60	37	2		Propulsion		
09/29/60	41	0		Electrical		

Vehicle Name: Atlas D
Data Collection from: 59 to 67
Total Launch Number: 197
Total Failure Number: 42

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
10/12/60	43	1		Propulsion		
12/15/60	47	3	1	Structure	Rupture in the missile LOX tank	Y
04/25/61	52	4	1/2	Flight Control	Unsatisfactory due to a failure in the flight control system	N
09/09/61	57	4	1/2	Electrical	Failure of the ground power umbilical to eject normally at liftoff	N
10/21/61	59	1	1/2	Guidance	roll control was lost	N
11/22/61	61	1	1/2	Flight Control	Booster pitch control lost	N
12/22/61	65	3	2	Flight Control	Sustainer engine failed to cutoff	N
01/26/62	68	2	1/2	Guidance	Failure of Mod III G Guidance system	N
02/21/62	71	2		Propulsion		
04/09/62	74	2	2	Electrical	Electrical failure, excess altitude and under-velocity condition	N
07/22/62	87	12	2	Guidance	Failure of engine burning time	N
10/02/62	92	4		Electrical		
12/17/62	98	5	1	Propulsion	Thrust chamber oscillation	Y
01/25/63	100	1		Structure		
03/09/63	104	3		Flight Control		

Vehicle Name: Atlas D
Data Collection from: 59 to 67
Total Launch Number: 197
Total Failure Number: 42

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
03/15/63	106	1		Propulsion	Hydraulic failure	
03/16/63	107	0		Flight Control		
06/12/63	111	3	1/2	Propulsion	Booster hydraulic accumulater failure, Exploded just after launch	Y
09/06/63	117	5		Propulsion	Hydraulic failure	
09/11/63	118	0		Propulsion		
10/07/63	119	0		Propulsion		
11/13/63	123	3		Propulsion	Hydraulic failure	
01/21/65	149	25		Propulsion	Injection failure, no separation	Y
03/02/65	153	3	1/2	Propulsion	Stage failed due to loss of thrust	Y
05/27/65	159	5	1/2	Propulsion	Booster exploded	Y
03/04/66	175	15	1/2	Flight Control	Failure of sustainer low pressure hydraulic system at booster jettison	N
05/03/66	179	3	UK	UK	UK	UK

Vehicle Name: Atlas E
Data Collection from: 60 to 88
Total Launch Number: 49
Total Failure Number: 18

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
10/11/60	1	0	1/2	Guidance	Nitrogen control-gas was broken off, causing control-gas depletion	N
11/29/60	2	0	1	Propulsion	Loss of sustainer engine hydraulic pressure	Y
01/24/61	3	0	1	Flight Control	Lost vehicle stability	N
03/13/61	5	1	1	Flight Control	Premature shutdown of the sustainer engine due to fuel depletion	N
03/24/61	6	0	1/2	Flight Control	Control bottle helium was depleted during boost phase and the booster package was not jettisoned	N
06/07/61	9	2	1/2	Propulsion	Combustion instability in B1 thrust chamber	Y
06/22/61	10	0	1/2	Flight Control	Excessive pitchover rate during boost phase	N
09/08/61	13	2	1	Propulsion	Sustainer engine shutdown shortly after jettison of the booster section	Y
11/10/61	16	2	1	Propulsion	Sustainer engine shutdown during main stage transition	Y
02/28/62	20	3	UK	Structure	UK	UK
07/13/62	21	0	1	Propulsion	LOX leak during flight, failure of slow-closing propellant valve	Y
12/18/62	22	0	1/2	Propulsion	Booster engine shutdown due to loss of lube oil	Y
07/26/63	26	3	1	Electrical	Spurious voltage transients on range safey cutoff circuitry	N
09/25/63	29	2	1	Propulsion	Sustainer hydraulic system failed at staging	Y
02/12/64	30	0	1	Guidance	Guidance failure in premature engine cutoffs	N

Vehicle Name: Atlas E
Data Collection from: 60 to 88
Total Launch Number: 49
Total Failure Number: 18

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
08/27/64	32	1	UK	Guidance	Radial impact error BB NM short, GD/A did not perform an analysis	N
12/08/80	36	3	1/2	Propulsion	Booster engine nol 2 shutdown prematurely, due to loss of oil	Y
12/18/81	37	0	1/2	Propulsion	Propulsion B1 GG burn through	Y

Vehicle Name: Atlas F
Data Collection from: 61 to 81
Total Launch Number: 96
Total Failure Number: 17

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
12/12/61	3	2	1	Guidance	The ARMA guidance system computer malfunctioned. Engine cutoff 4 sec early	N
12/20/61	4	0	1	Propulsion	Loss of sustainer hydraulic pump iniet pressure	Y
04/09/62	5	0	1	Propulsion	The sustainer lox turbopump was destroyed by an internal overpressure	Y
08/10/62	7	1	1	Flight Control	Missile failed to roll to the planned target azimuth	N
11/14/62	12	4	1	Guidance	Guidance computer malfunctioned	N
03/23/63	17	4	UK	UK	Missle self-destructed at 91 sec.	UK
10/03/63	19	1	1/2	Propulsion	B1 Main fuel valve failed to open	Y
10/28/63	20	0	1	Propulsion	Sustainer hydraulic return system failed	Y
04/03/64	23	2	1/2	Propulsion	Thrust imbalance due to B1 main fuel valve sticking	Y
08/08/66	29	5	1/2	Propulsion	Abnormal operation of B2 engine caused high fuel and iow LOX usage, partial blockage of the B2 LOX high pressure system	Y
10/11/66	30	0	1/2	Propulsion	Fuel starvation of B1 engine due to malfunction of B1 engine fuel prevalve	Y
10/27/67	39	8	1/2	Propulsion	Loss of vehicle stability caused by small leak in booster hydraulic high pressure system	Y
05/03/68	45	5	1	Flight Control	Divergent oscillations of booster pitch control	N
11/06/68	52	6	1	Propulsion	Vernier engine hydraulic pressure lost after SECO	Y
10/10/69	58	5	1	Propulsion	Sustainer and vernier engines shutdown prematurely	Y

Vehicle Name: Atlas F
Data Collection from: 61 to 81
Total Launch Number: 96
Total Failure Number: 17

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
04/12/75	80	21	1	Propulsion	Damaged thrust section allowed overheating and premature shutdown of the sustainer and vernier engines	Y
05/29/80	95	14	1/2	Propulsion	B1 engine performance was 79% of nominal and injection time was late	Y

Vehicle Name: Atlas SLV
Data Collection from: 67 to 83
Total Launch Number: 73
Total Failure Number: 4

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
11/30/70	26	25	2	Separation	Nose fairing failure to jettison	N
12/04/71	30	3	1	Flight Control	Lost attitude control E pack	N
02/20/75	42	11	1	Electrical	Electrical disconnect failure during Atlas boost separation	N
09/29/77	52	9	1/2	Propulsion	Hot gas leak in the booster gas generator	Y

Vehicle Name: Atlas G
Data Collection from: 84 to 87
Total Launch Number: 6
Total Failure Number: 1

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
03/26/87	6	5		Other	Lightning struck vehicle	N

Vehicle Name: Atlas H
Data Collection from: 83 to 87
Total Launch Number: 5
Total Failure Number: 0

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N

Vehicle Name: Atlas/Centaur
Data Collection from: 62 to 87
Total Launch Number: 67
Total Failure Number: 11

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
05/08/62	1	0	2	Structure	Centaur upper stage structure failure	N
06/30/64	3	1	2	Propulsion	Centaur hydraulic failure, Loss of C_2 hydraulic power	N
03/02/65	5	1	1/2	Propulsion	Loss of Atlas thrust during liftoff, due to fuel starvation of booster engines stemming from closure of fuel prevelue	Y
04/07/66	7	1	2	Propulsion	Centaur restart sequence failure, engine ignition occurred but not sustained due to fuel deplation	N
08/10/68	16	8	2	Propulsion	Failure of boost pump H_2O_2 supply system centaur didn't achieve its second main engine start	N
11/30/70	21	4	1	Separation	Nose fairing failed to jettison properly	N
05/08/71	23	1	2	Flight Control	Centaur pitch control lost	N
02/20/75	34	10	1	Electrical	Atlas booster section electrical disconnect failed during booster jettison	N
09/29/77	42	7	1/2	Propulsion	Atlas booster engine hot gas leak failed mission	Y
06/09/84	62	19	2	Propulsion	Failure occurred at A/C Separation a liquid oxygen tank crack	N
03/26/87	67	4	---	other	Lightning strike failed mission	N

Vehicle Name: Jupiter
Data Collection from: 58 to 58
Total Launch Number: 6
Total Failure Number: 3

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
03/05/58	2	1	4	Propulsion	4th stage failed to ignite	Y
08/28/58	5	2	2	Separation	Booster burned into remaining stage upper stage fired in wrong direction	N
10/23/58	6	0	2	Separation	2nd stage failed to fire premature separation	N

Vehicle Name: Juno
Data Collection from: 58 to 61
Total Launch Number: 10
Total Failure Number: 5

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
07/16/59	3	2	UK	Guidance	Guidance failed, destroyed by RSO	N
08/14/59	4	0	1	Propulsion	Booster fuel depletion	Y
03/23/60	6	1	3	UK	Ignition malfunction	UK
02/24/61	8	1	2	UK	2nd stage malfunction	UK
05/24/61	10	1	2	UK	2nd stage failed to ignite	UK

Vehicle Name: Saturn I
Data Collection from: 62 to 65
Total Launch Number: 10
Total Failure Number: 0

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N

Vehicle Name: Saturn IB
Data Collection from: 66 to 75
Total Launch Number: 9
Total Failure Number: 0

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N

Vehicle Name: Saturn V
Data Collection from: 67 to 73
Total Launch Number: 13
Total Failure Number: 1

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
04/04/68	2	1	2 3	Propulsion	Second stage engine malfunction Third stage failure to restart	Y

Vehicle Name: Vanguard
Data Collection from: 57 to 59
Total Launch Number: 11
Total Failure Number: 8

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
12/06/57	1	0	1	Propulsion	First stage lost thrust, exploded after 2 second	Y
02/05/58	2	0	1	Flight Control	First stage control system malfunction after 57 sec	N
04/28/58	4	1	2	Propulsion	Bad 2nd stage shutdown preventing 3rd stage firing	Y
05/27/58	5	0	3	Flight Control	Improper 3rd stage trajectory loss of attitude control	N
06/26/58	6	0	2	UK	Early 2nd stage shutdown prevented 3rd stage firing	UK
09/26/58	7	0	2	UK	Below minimum 2nd stage performance prevented orbit	UK
04/14/59	9	1	2	Guidance	Loss of 2nd stage pitch control	N
06/22/59	10	0	2	Propulsion	Low tank pressures after 2nd stage ignition caused instability	Y

Vehicle Name: Scout
Data Collection from: 60 to 88
Total Launch Number: 110
Total Failure Number: 14

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
12/04/60	3	2	2	Electrical	Failed to ignite: Caused by wire break or disconnected power input	N
06/30/61	5	1	3	Propulsion	Improper venting causing ignition leads to be severed	Y
08/25/61	6	0	4	Separation	Diaphragm separation system failure	N
11/01/61	8	1	1	Guidance	Guidance failure destroyed by RSO after 30 sec	N
04/26/62	11	2	3	Guidance	Control was lost due to H_2O_2 not being available	N
05/23/62	12	0	2	UK	2nd stage shock input all three axes 0.29 sec after ignition	UK
04/05/63	18	5	3	Flight Control	3rd stage reaction control system failure	N
04/26/63	19	0	3	Electrical	short circuit in the destruct system, attitude control was lost	N
07/20/63	23	3	1	Propulsion	stage I engine nozzle failure	Y
09/27/63	24	0	4	Flight control	Pitch motor failure, loss of vehicle control	N
06/25/64	28	3	2	Electrical	Linear shaped destruct charge was ignited by an unplanned electrical input	N
01/31/67	51	22	4	Propulsion	Motor graphite nozzle insert resulted in rupture of the motor case	Y
05/29/67	56	4	3	Propulsion	Failure of motor caused by unstable chumber pressure	Y
12/05/75	94	37	3	Propulsion	3rd stage nozzle failure	Y

Vehicle Name: Space Shuttle
Data Collection from: 81 to 88
Total Launch Number: 26
Total Failure Number: 1

Date	Failure Launch	Success Run	Failure Stage	Failure System	Failure Description	Engine/Motor Failure Y/N
01/28/86	25	24	0	Propulsion	Vehicle exploded 73 sec. after launch-SRM *O-ring failure*	Y