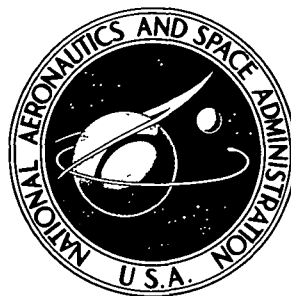NASA TECHNICAL NOTE

NASA TN D-8272

NASA TN D-8272

U. S. AIR FORCE

FAILURE RATE ANALYSIS OF GODDARD SPACE FLIGHT CENTER SPACECRAFT PERFORMANCE DURING ORBITAL LIFE

H. P. Norris and A. R. Timmins

Goddard Space Flight Center
Greenbelt, Md. 20771

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1976

Page intentionally left blank

Page intentionally left blank

CONTENTS

FAILURE RATE ANALYSIS OF GODDARD SPACE FLIGHT CENTER SPACECRAFT PERFORMANCE DURING ORBITAL LIFE

H. P. Norris and A. R. Timmins
Goddard Space Flight Center
Greenbelt, Maryland

INTRODUCTION

The space performance of Goddard Space Flight Center spacecraft launched in the 1960-1970 decade has been tabulated by type and criticality of defects, contribution of redundancy to space performance, comparison of defect population in the system test program with that in space, and by the time distribution of malfunctions in space (References 1, 2, and 3). These data have been used in the present study which· presents results of analyses using both Duane (Reference 4) and Weibull (Reference 5) growth models, provides failure rate values which may be useful for estimating future space performance, and for comparing past, present, and future space performance; and examines the failure rate data from the thermal-vacuum system tests and relates these rates to those experienced in space.

Reliability predictions of space performance based on the number and failure rates of piece parts in a spacecraft have not been adequate in the past and, in general, led to predictions which were unduly pessimistic. These assessments generally have used an exponential distribution with a constant failure rate for calculating space reliability. Also, experience has shown that the majority of space malfunctions are not catastrophic to the mission, nor even to the component (such as an instrument or a transmitter).

Piece parts are not used as the basis of the study reported here. Some of the results are on the basis of failures per spacecraft, and show a consistent decrease in failure rate with time in space. However, most of the results are on the basis of failures per component per day. A component as used in this study performs a definable function. Examples of spacecraft components are: transmitter, tape recorder, experiments, etc. The use of components as a base of reference makes the results more useful in comparing the performance of an individual spacecraft with computed average performance. Moreover, the results can be used to estimate future performance for spacecraft of differing complexities.

Results were presented in 1968 of a comprehensive survey (Reference 6) and study of the space performance from 225 launches (prior to 1967) which included both NASA and military programs [Additional data were compiled in 1971 (Reference 7) and 1972 (Reference 8)].

One part of these studies provides failure rate estimates for piece parts, components, and sub-systems. These estimates are usable as the constant failure rates needed when calculating reliability, assuming an exponential relationship. The present study deals only with component failure rates. The failure rates are averages of all the components of a spacecraft and are presented as a function of time.

DATA BASE

The data for this study are taken from the performance of 57 unmanned spacecraft developed under GSFC management. The spacecraft included four meteorological spacecraft, six applications technology spacecraft, twelve operational weather spacecraft, two astronomical observatories, six geophysical observatories, six solar observatories, seven interplanetary monitoring platforms, and fourteen miscellaneous scientific missions.

The experiments and subsystems for these spacecraft have been provided by various organizations, including GSFC, other government agencies, universities, and aerospace companies. Eighteen of the spacecraft received a full system test at GSFC, and the remaining 39 received a full system test at the contractor's facility

The terms "malfunction" and "failure" are frequently encountered when discussing spacecraft performance. A malfunction is defined as any performance outside specified limits and can be either a failure or a problem. A failure is the loss of operation of any function, part, component, or subsystem, whether or not redundancy permitted a recovery of operation. A problem is any substandard performance or partial loss of function which is believed to be temporary or not of sufficient gravity to be classed a failure.

TIME DISTRIBUTION OF MALFUNCTIONS

Figure 1 shows the time distribution (in 30-day increments) of the malfunctions and failures documented for the 57 GSFC spacecraft (Reference 1). Figure 2 presents the space malfunctions (and, separately, the space failures) in a cumulative fashion for the first 3 years in space. The total number of malfunctions for the 3 years was 438, of which 239 were classified as failures. Only 11 malfunctions were documented beyond 3 years. The analyses reported herein are based on the data up to 3 years.

LIMITATIONS ON DATA

The data base for this report is comprehensive and representative, but some limitations need to be kept in mind when assessing or using the results. The data are necessarily based on reported malfunctions. Some differences between reported and actual malfunctions can be expected, based on the wide spectrum of individuals responsible for reporting a malfunction. Although there is no way to quantify the difference, it is thought to be small. For instance, the number of documented first-day space malfunctions for the spacecraft of this study has increased about 15 percent since the 1971 analysis (Reference 3) was published. This situation emphasizes the fact that some malfunction data may be subjective and undergo change with later documentation.
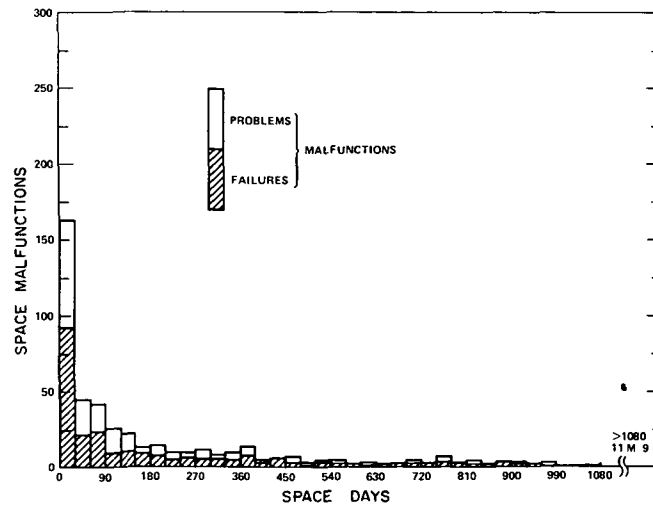
2

Figure 1. Time distribution of space malfunctions from 57 GSFC spacecraft.

The cases of radio frequency interference, including spurious commands, have been omitted from this study This specialized problem has varied widely between satellites, orbits, location and power of ground-based energy sources, and command systems. The omission is not intended to minimize the importance of this type of malfunction. For instance, an early spacecraft had 400 anomalous command states during the first year in space Inclusion of such data would have obscured the findings of this study. Because of continuing problems in this field, radio frequency interference testing of spacecraft before launch is as important now as it was in the early days of the space program.
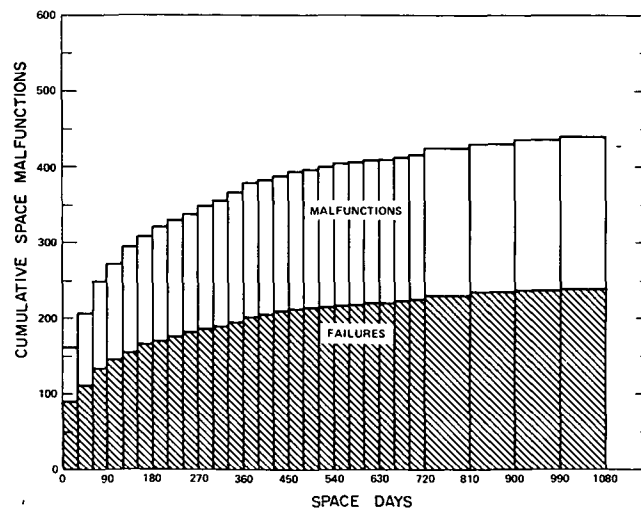

Figure 2. Relationship of space malfunctions and time

3

Ground station problems comprise another category not included in this study, since in the main, these are temporary equipment- or personnel-related events. When a malfunction was definitely ascribed to a spacecraft, it was then included as part of this study.

DUANE GROWTH MODEL

The Duane growth model (Reference 4) was shown to fit failure data taken during a reliability improvement program. It has been used for controlling and predicting reliability of diverse kinds of electrical and mechanical devices. Duane observed that the cumulative operating hours on a log-log plot gave a straight line with the relationship given by

$$\lambda_\Sigma \equiv \frac{F}{T} = KT^\alpha \tag{1}$$

where λ_Σ = cumulative failure rate, K = a constant given by the Y intercept at T = 1, T = total test hours, F = failures during T, and α = slope of the line or growth rate

The cumulative failure rate for the space data was determined using the above relationship where F was the cumulative failures, and T was the cumulative spacecraft days. A log-log plot of the cumulative failure rate versus time in space is shown in Figure 3. The two equations shown fit the observed data very well for the time period of 1 to 30 days and 31 to 300 days. The cumulative failure rate is in units of failures per spacecraft per day. It is significant to note that most of the failures did not result in the loss of a spacecraft. No attempt is made at this point to account for the comparative complexity of a spacecraft.

The Duane growth equation(1) was modified to improve the utility of the data by including the average number of components per spacecraft. This was done by letting $K = NK_o$, where
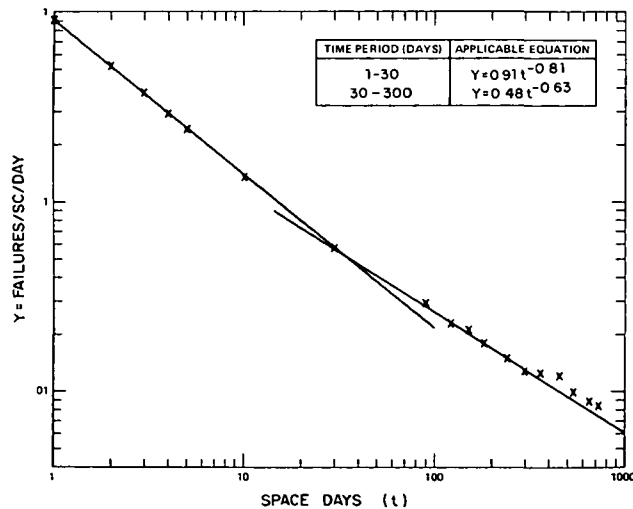

TIME PERIOD (DAYS)	APPLICABLE EQUATION
1-30	$Y = 0.91 t^{-0.81}$
30 – 300	$Y = 0.48 t^{-0.63}$

Figure 3   Cumulative failure rates in space.

4

N is the average number of components per spacecraft, and K_o is equal to a unit constant. Stated in other words, $K_o = K/N$. Thus,

$$\lambda_\Sigma \equiv \frac{F}{T} = NK_o T^{\alpha}$$

and finally

$$\lambda_\Sigma \equiv \frac{F}{NT} = K_o T^{\alpha} \tag{2}$$

where λ now becomes a failure rate with respect to components, rather than to the spacecraft.

One other change is made to the equation by replacing T with $(T + \gamma)$, where γ has the same function as the "location parameter" customarily used to fit a Weibull function to disparate data. Essentially, this parameter adjusts the data time base to coincide with the "aging time" of the reliability growth model. The final equation then, in a more general form, becomes

$$\lambda_\Sigma \equiv \frac{F}{N(T + \gamma)} = K_o (T + \gamma)^{-\alpha} \tag{3}$$

To be consistent with the units of the reported space failures or malfunctions, N was chosen to be the average number of components per spacecraft As previously defined, a "component" is a unit within a spacecraft that performs a function, such as a transmitter, receiver, voltage converter, etc. A component count was made, or where necessary, the number was estimated for each of the 57 spacecraft in the sample. This resulted in a number of components per spacecraft ranging from 30 to 114, with an average of 65. This average value was subsequently used to normalize the failure data, and for determining average failure rates.

The cumulative failure rate was again computed using first, equation 2, and again, equation 3. The results are plotted in figure 4. The upper plot exhibits the same apparent double slope as seen previously in figure 3; however, the lower plot, using a location parameter, γ, equal to 3, shows the log-log relationship of λ_Σ with total time to be essentially linear. The slope, α, is the same for both plots for large values of time T. The solid line through the corrected plot is a least squares fit, yielding the following estimates for the parameters in equation 3

$$\hat{K}_o = 0.00918$$
$$\gamma \text{ (est.)} = 3 \text{ days}$$
$$\hat{\alpha} = 0.689 \text{ (scalar)}$$

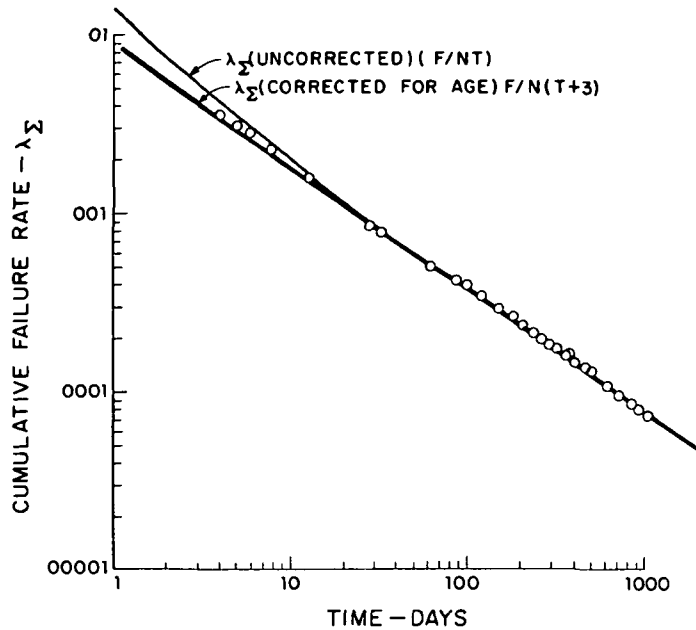The caret ($\wedge$) denotes a least squares estimated value.

Figure 4. Cumulative failure rate versus time in space for GSFC spacecraft components

WEIBULL RELIABILITY ANALYSIS

Crow (Reference 5) has shown that the Weibull failure rate, $\lambda\beta\,T^{\beta-1}$, is equivalent to the failure rate, $(1-\alpha)\,\lambda_\Sigma$, developed for the Duane growth model. This equivalence is useful in that it gives two independent techniques for computing the parameters in the failure rate function, particularly with respect to the slope, α, which is related to β by $\beta = 1 - \alpha$.

The total component count per spacecraft is not necessary in the Duane growth analysis for the determination of α, as evidenced by figures 3 and 4. For the graphic solution of the Weibull parameters, β and λ, however, the sample size, N, is necessary and is used to plot the log of (N/N-F) versus time on log-log paper as shown in figure 5. The basic plot shows an initial curvature that is corrected to a linear relationship by adding a location parameter, γ, equal to 3, to the space time base, as was done previously to the modified Duane plot. The corrected data points fitted with a least squares solution for the straight line yield

$$\hat{K}_o = 0.00917$$
$$\hat{\beta} = 0.316$$
$$\hat{\alpha} = 1 - \hat{\beta} = 0.684 \text{ (scalar)}$$
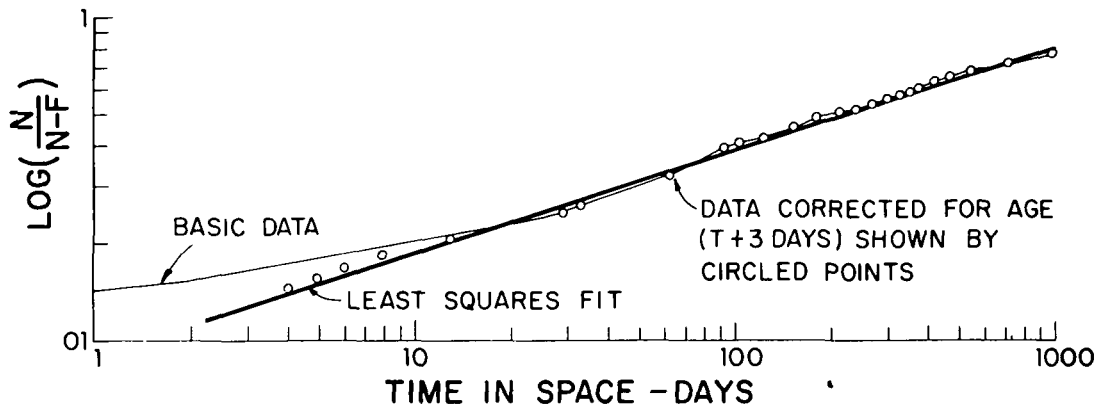$$\gamma \text{ (est.)} = 3 \text{ days}$$

6

Figure 5. GSFC spacecraft component failure analysis (space data).

The agreement between these values and those from the Duane model indicate the close relationship between the two models, and also confirms that the component count average per spacecraft (65) is compatible with the space failure data

Figure 6 is a plot of the cumulative component failure distribution, with the actual space failure count shown by the data points. The solid line represents either the modified Duane growth or the Weibull model (differences in the two models are not distinguishable). The solid line shows a good fit with the data for about 2 years in space Beyond this time, the
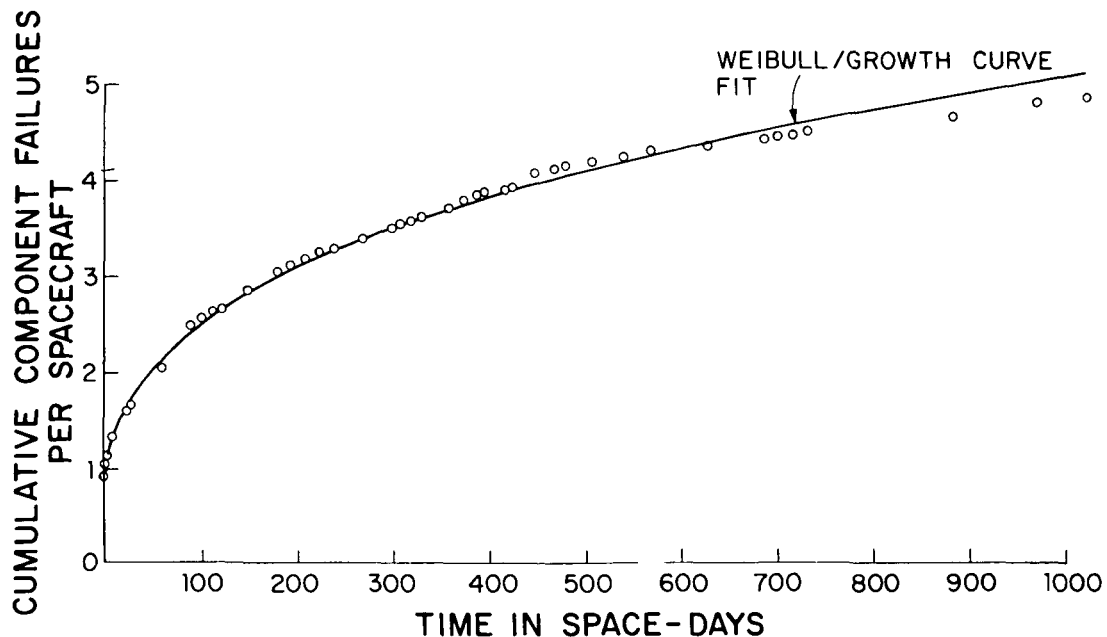

Figure 6 Time history of GSFC spacecraft component failures.

model projects a greater accumulation of failures than has been recorded. This difference is also reflected in figure 7, where $\lambda_i = K\hat{\beta} (T + \gamma)^{\beta-1}$, the Weibull instantaneous failure rate function is superimposed on the computed averages of the instantaneous failure rates, λ_i, derived from the data. The average failure rate, λ_i, from 540 to 1000 days is consistently lower than the Weibull function in this range, although the trend appears to be converging at the end. Figure 7 demonstrates that the instantaneous failure rate is not constant, but decreases with time in space. A plausible explanation for this decreasing trend is that the data sample includes a wide variety of components with a range of failure rates as depicted. This, of course, is the situation that prevails in any complex system.
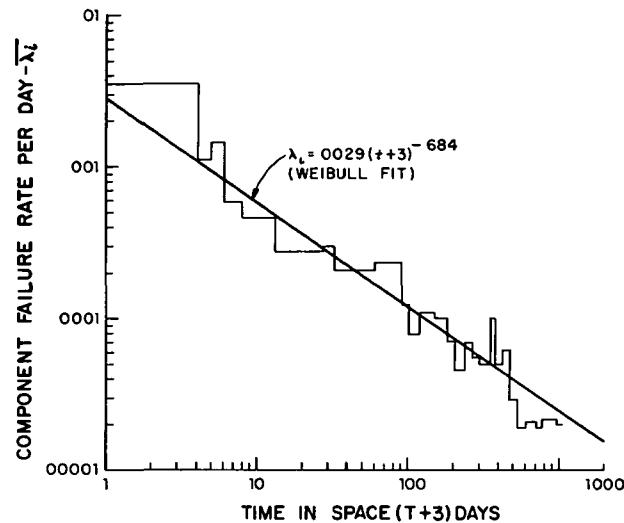

Figure 7. GSFC spacecraft component instantaneous failure rate.

Fortunately, all component failures do not result in a loss of the total spacecraft; and further, their effect on carrying out the spacecraft mission varies in significance from a minor to a major degree (References 1 and 6). One study (Reference 1) indicates that only about 10 percent of the component failures are critical to the spacecraft mission. Another study (Reference 6) appears to confirm this conclusion and presents a rather comprehensive analysis of the severity of each failure. The authors identify failure rates of each class of components without regard to aging effects (constant failure rates). The approach in the present study has been to show an average component failure rate for a composite spacecraft as a function of time. It is interesting to note that the range of failure rates in both cases are comparable.

With a location parameter, $\gamma = 3$, the mathematical model generates a first-day failure rate equal to one-fourth the average failure rate derived from the actual first-day data. This implies that the total of first-day failures was higher than normally expected by a factor of four,

8

assuming an environmental stress equivalent to that experienced in space beyond the first day. Since some spacecraft components are not turned on immediately after the launch phase, it is not possible to account for all failures until at least a day has passed. Accordingly, it would appear more appropriate, at least for the unmanned spacecraft programs, to measure the intensity of the launch environment as a function of its effect on the first day cumulative failure rate, instead of the usual consideration where a K-factor is used only for the time interval of launch vehicle operation. With respect to this analysis, then, it may be concluded that a K-factor of four is representative of the intensity of the launch environment averaged over the first day in space

SPACE VERSUS TEST FAILURE

A relationship between spacecraft performance during the test phase, and its performance during orbital life would be helpful in the evaluation of environmental test effectiveness. It could be helpful in refining the test philosophy that has been developed for more than a decade

Thermal-vacuum system test data from 39 spacecraft were evaluated in the same manner as that used for the 57 spacecraft in space. After the data were normalized to account for time
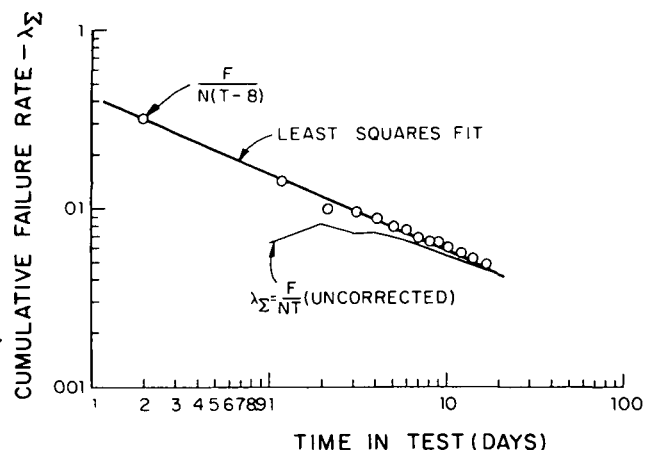

Figure 8. GSFC spacecraft component failure rate during thermal-vacuum tests.

truncated tests (failed units were replaced, and all units operated when testing was complete) the cumulative failure rate was plotted as before (figure 8). A time correction factor, γ, of minus 0.8 days was applied, and a reasonable least squares fit was obtained yielding the following parameters

$$\gamma \text{ (est.)} = -0.8 \text{ days}$$
$$\hat{K}_o = 0.01552$$
$$\hat{\alpha} = 0.434$$

The reliability growth slope, α, is still present, but at a reduced rate in comparison to that experienced in space. The ratio of α_{test} to α_{space} was 0.43/0.69, or approximately 0.62.

Having obtained the parameters for the cumulative failure rate function, the next step was to compute the instantaneous failure rate for comparison with that in space. Here again the Weibull function, $\lambda_i = K\beta (T + \gamma)^{\beta-1}$, was used. However, for a more graphic presentation, the inverse of λ_i was computed, thus yielding the mean time between failures (MTBF), which when plotted, shows the reliability growth trend of the spacecraft during the test phase. This is shown in figure 9, along with the MTBF derived from the Weibull function, λ_i, from space data. The MTBF at the end of the test program was compared to the space model at T = 1 day. This would approximate the condition somewhere during or immediately after the launch phase in real time. At this point, the instantaneous MTBF appears to be in reasonable agreement with the terminal value developed from test.
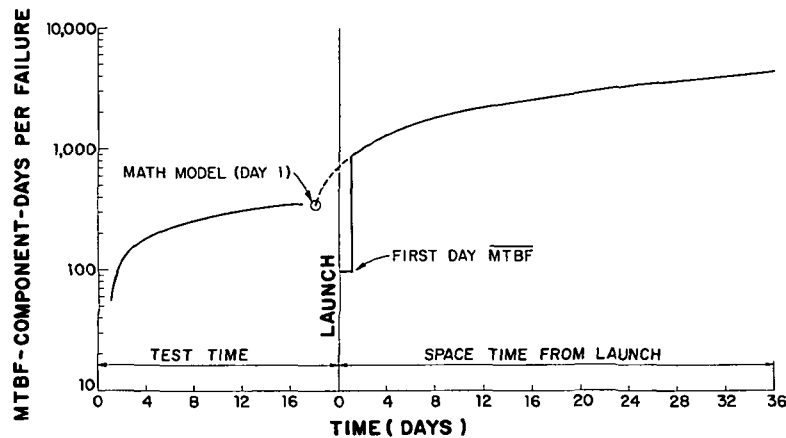

Figure 9   Comparison of component MTBF during thermal-vacuum test and first 36 days in space.

COMPONENT RELIABILITY

The average component reliability for 3 years in space is shown in figure 10. The reliability was computed using Weibull reliability function

$$R(t) = e^{\dfrac{-\lambda_i}{\beta}(T+3)^{\beta}}$$

The terminal value of the component failure rate (λ_i = 0.00285) from the thermal-vacuum test, and the value of β (β = 0.311) derived from space data, were used in this solution. The resulting curve is coincident with the plot from the actual space data. The reliability that would have resulted if the terminal component failure rate (0.00285) in test had remained constant in space, and the exponential relationship of $R(t) = e^{-\lambda t}$ used are shown in figure 10. Reliability values in this case are dramatically lower than the reliability values from the actual space data.
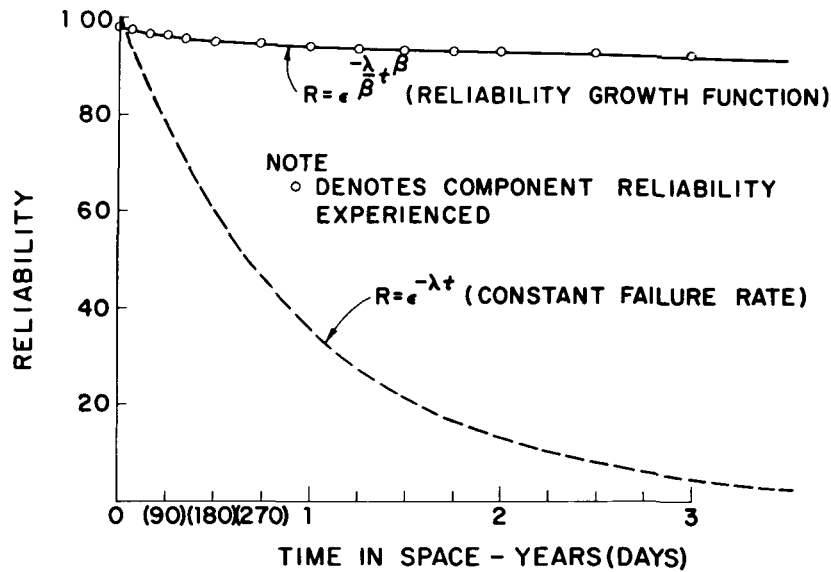
10

$$R = \epsilon^{-\frac{\lambda}{\beta}t^{\beta}} \text{ (RELIABILITY GROWTH FUNCTION)}$$

NOTE
o DENOTES COMPONENT RELIABILITY
  EXPERIENCED

$$R = \epsilon^{-\lambda t} \text{ (CONSTANT FAILURE RATE)}$$

Figure 10. GSFC component reliability in space.

CONCLUSIONS

The results of this study, in addition to the corollary studies of references 1 and 2, form the basis for the following conclusions on the space performance of GSFC spacecraft for the era of 1960 through 1970.

- The average component failure rate in space decreases with time for the entire three-year period covered by this study. This trend can be represented with acceptable accuracy by either the Weibull distribution or the Duane Growth models.

- First-day failure rates are higher than would be indicated by either the Duane or Weibull growth curve by a ratio of 4·1.

- The average component failure rate during spacecraft thermal-vacuum testing exhibits a reliability growth trend The termination failure rate is generally similar to initial failure rates experienced in orbit, although the first day failure rate may be as much as four times greater due to the increased severity of the launch environment.

- Early component failures do not usually result in the loss of a spacecraft.

11

Page Intentionally Left Blank

REFERENCES

1. Timmins, A. R., *A Study of Total Space Life Performance of Goddard Space Flight Center Spacecraft,* NASA TN D-8017, July 1975.

2. Timmins, A. R., *A Study of First Month Space Malfunctions,* NASA TN D-7750, October 1974.

3. Timmins, A. R. and R. E. Heuser, *A Study of First-Day Space Malfunctions,* NASA TN D-6474, September 1971.

4. Codier, E. O., "Reliability Growth in Real Life," Fifteenth Annual Symposium on Reliability, January 1968.

5. Crow, L H., "On Tracking Reliability Growth," Proceedings Reliability and Maintainability Symposium, 1975.

6. Bean, E. E. and C. E. Bloomquist, "Reliability Data from In-flight Spacecraft," Fifteenth Annual Symposium on Reliability, January 1968, pp. 271-279.

7. Planning Research Corporation, *Reliability Data From In-flight Spacecraft 1958-1970,* Report PRC-1453, 1971.

8. Planning Research Corporation, *Addendum to Reliability Data from In-flight Spacecraft· 1958-1970,* Report PRC-D-1864, 1972.

1. Report No. NASA TN D-8272 b	2. Government Accession No	3. Recipient's Catalog No		
4. Title and Subtitle Failure Rate Analysis of Goddard Space Flight Center Spacecraft Performance During Orbital Life		5. Report Date JULY 1976		
		6. Performing Organization Code 326		
7. Author(s) H. P. Norris and A. R. Timmins		8. Performing Organization Report No G-7681		
9. Performing Organization Name and Address Goddard Space Flight Center, NASA Greenbelt, Maryland 20771		10. Work Unit No 506-17-31		
		11. Contract or Grant No.		
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note		
		14. Sponsoring Agency Code		
15. Supplementary Notes				

16. Abstract

Space life performance data on 57 Goddard Space Flight Center spacecraft have been analyzed from the standpoint of determining an appropriate reliability model and the associated reliability parameters. Data from published NASA reports, which cover the space performance of GSFC spacecraft launched in the 1960-1970 decade, form the basis of the analyses. The results of the analyses show that the time distribution of 449 malfunctions, of which 248 were classified as failures (not necessarily catastrophic), follow a reliability growth pattern that can be described with either the Duane model (represented by the accumulated failure rate, $\lambda_\Sigma = F/NT = KT^{-\alpha}$), or a Weibull distribution. The advantages of both mathematical models are used in order to. identify space failure rates, observe chronological trends, and compare failure rates with those experienced during the prelaunch environmental tests of the flight model spacecraft.

[handwritten notes] Space vehicles - Design & testing
Aerospace vehicles
Space vehicles - Life cycle

17. Key Words (Selected by Author(s)) Aerospace, Failure rates, Performance, Spacecraft		18. Distribution Statement Unclassified—Unlimited CAT. 18		
19. Security Classif (of this report) Unclassified	20. Security Classif (of this page) Unclassified		21. No of Pages 13	22. Price $3.25

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . to the expansion of human knowledge of phenomena in the atmosphere and space The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."
—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge

TECHNICAL NOTES· Information less broad in scope but nevertheless of importance as a contribution to existing knowledge

TECHNICAL MEMORANDUMS Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge

TECHNICAL TRANSLATIONS Information published in a foreign language considered to merit NASA distribution in English

SPECIAL PUBLICATIONS Information derived from or of value to NASA activities Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies

TECHNOLOGY UTILIZATION PUBLICATIONS. Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546