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Lakehurst, New Jersey
08733

NATF-EN-1101

RELIABILITY OF THE MARK 7 MOD 3 ARRESTING GEAR
(23 October 1966 to 15 April 1968)

Final Report
19 December 1968

by

Willi K. Kraut
Computer Division
and
Henry J. Swiencinski
Recovery Division

Prepared under Naval Air Systems Command
Air Task A05-537-007/204/1/W4503-05

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Naval Air Test Facility
(Ship Installation)
Naval Air Station
Lakehurst, New Jersey 08733

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ABSTRACT

Failure data obtained during tests with the Mark 7 Mod 3 arresting-gear system was used to determine reliability by two methods:

First, by finding an empirical relationship between total number of failures and service life and then deriving the functional relationship of reliability to service life and mission size. Reliability thus obtained was independent of service life and decreased for increasing mission size.

Next, reliability was determined by applying the failure data to the geometric failure distribution. Using this failure distribution, 95-percent confidence interval curves for reliability were calculated.

FORWORD

The reliability analysis presented in this report was prepared by Mr. W. Kraut of the Computer Division, from information submitted by Mr. H. Swiencinski of the Recovery Division

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I INTRODUCTION

A. This report presents the results obtained for a reliability analysis of the Mark 7 Mod 3 arresting gear system. Tests were authorized by reference (a) and conducted at the Runway Arrested Landing Site (RALS), Naval Air Test Facility (Ship Installations), Lakehurst, New Jersey during the period of 23 October 1966 through 15 April 1968.

II GLOSSARY OF SYMBOLS

Term	Explanation
a	Least squares constant coefficient
b	Least squares slope for linear regression
c	Constant
d	Constant
f(n)	Density function for the geometric distribution
F	Total number of failures
F(X)	Representation of F as a function of X
k	Constant
n	Number of arrestments before a failure
N	Total number of observed failures
Nm	Number of aircraft arrestments in a mission
NS	Total number of arrestments which did not result in a failure
p	Constant probability of no failure after each arrestment
P(n)	Failure distribution function
P_L	Lower 95-percent confidence limit of p
P_U	Upper 95-percent confidence limit of p
q	Constant probability of failure after each arrestment
R	Reliability
R(n)	Representation of R as a function of n
X	Arrestment or event number
Yi	Number of arrestments between failures

III RELIABILITY ANALYSIS

A. Failure Data

1. The failure data used in this report was obtained during a 1,854-event test program with the Mark 7 Mod 3 arresting gear and is tabulated in Appendix A. Reference (a) requested that reliability of the arresting gear tested at NATF(SI) (Naval Air Test Facility (Ship Installations)) be calculated from this data.

2. A total of 21 failures occurred in the test program, but most of these were of the nuisance variety and did not require repair before further arrestments could be made. Failures listed in Appendix A are classified into one of the following three categories:

Type I - Must-stop-to-fix or repair

Type II - Continue to run, but monitor failed component

Type III - Failure is not serious; run and defer repair or replacement

Of the three categories, Type I is the most serious because a Type I failure renders the arresting gear immediately inoperable. In this analysis, only Type I failures are considered pertinent to the determination of reliability.

3. Seven Type I failures occurred, but three were caused by the sheave-damper tailpiece. It is to be noted that the tailpiece configuration installed at the RALS (Runway Arrested Landing Site) is not representative of a typical Fleet installation. The long fluid-charging lines necessary to connect the accumulators to the sheave dampers are peculiar to the RALS installation and failures in these lines--probably resulting from vibration--should not occur as frequently in the Fleet. Because of this, only the first tailpiece failure which occurred was considered in the determination of reliability.

4. The five Type I failures included in this reliability analysis are listed below, along with: X (arrestment on which the failure occured), F (total number of Type I failures up to and including arrestment X), and Yi (number of arrestments between failures).

Type I Failures

Failed Component	X	F	Yi
	0	0	0
Fluid-indicator drive rod, and air-oil separator	528	1	528
Sheave-damper tailpiece	1,142	2	614
Purchase cable	1,202	3	60
Fluid-indicator O-rings	1,208	4	6
Port anchor damper	1,514	5	306

5. Results of this analysis are entirely dependent on the small sample of failure data given above. Because of the small number of failures which occurred, reliability estimates given have large variances and could be extrapolated for other Mark 7 Mod 3 arresting gear systems only if these were operated in the same manner as the tested gear. In order to project results of this analysis to other Mark 7 Mod 3 arresting-gear systems, it must be assumed that the tested gear is typical of the universe of all existing and contemplated Mark 7 Mod 3 arresting gears. In this report, stated results will apply only to the arresting gear tested at NATF(SI).

6. Throughout the test period, the arresting gear was under development which meant that failed components were not only repaired but, in many cases, were replaced by parts not susceptible to similar types of failures. Consequently, these modifications should increase the reliability of the arresting gear in its later service life, but the extent of this improvement could not be estimated because the test program was terminated, for economic reasons, with the arresting gear still in its development stage.

B. Reliability and Service Life

1. Various empirical relationships between F and X were considered, that is, linear, quadratic, exponential, logarithmic, etc., and the one which fit the data best was F as a linear function of X, or

$$F = a + bX$$

where a and b are constants. Least-squares estimates of a and b, using data of F and X from the table of Type I failures were:

$$a = -0.383$$

$$b = 0.00309$$

Ninety-five-percent confidence limits for b were $0.00132 < b < 0.00487$. These confidence limits are wide because of the limited amount of data available to calculate b. Failure data, the least-squares line, and upper and lower 95-percent confidence lines are plotted in Figure 1. If the lines were extended to X = 10,000, the 95-percent confidence interval for F would be $13 \leq F \leq 48$.

2. Mathematically, reliability (R) is defined as 1 minus the probability that the arresting gear will fail after 1 or 2 or 3 ... or Nm aircraft arrestments. Nm will be referred to as the mission size. Reliability is thus a function of mission size and is the probability that a failure will not occur after 1 or 2 or 3 ... or Nm arrestments. It should be noted that one arrestment can always be made, but that reliability for a mission of one equals 1 minus the probability of a failure after the first arrestment, and this is a number less than 1. Reliability thus differs from the probability that a mission of size Nm can be arrested. In fact, the probability that a mission of size Nm can be arrested before an arresting-gear failure equals

$$R(Nm-1)$$

where

$$R(0) = 1.$$

In this report, reliability is calculated for various mission sizes rather than the probability that the mission of size Nm can be arrested.

3. Empirically, F as a function of X can be expressed by F(X). If at any service-life X it is assumed that the probability of a failure after arrestment 1 equals that after arrestment 2 ... equals that after arrestment Nm, then the total number of failures expected during the mission Nm is

$$F(X + Nm) - F(X).$$

Consequently, the probability of a failure after each arrestment equals

$$\frac{F(X + Nm) - F(X)}{Nm}$$

and the probability of no failure after each arrestment is

$$1 - \frac{(F(X + Nm) - F(X))}{Nm}$$

Finally, reliability for Nm arrestments is

$$R(Nm) = \left[1 - \frac{(F(X + Nm) - F(X))}{Nm}\right]^{Nm} .$$

For the fitting function

$$F(X) = a + bX$$

$$R(Nm) = (1 - b)^{Nm}$$

so that the reliability for the Mark 7 Mod 3 arresting gear is independent of service life but decreases sharply for increasing mission size. Another way of saying the same thing, is that the failure rate for the arresting gear is constant and equals b.

4. Reliability $(1 - b)^{Nm}$ is plotted as a function of mission size along with the upper and lower 95-percent confidence interval curves $(1 - 0.00132)^{Nm}$ and $(1 - 0.00486)^{Nm}$ in Figure 2. The probability of arresting 50 aircraft without an arresting gear failure is 0.857, while if the objective is to arrest 200 aircraft, reliability decreases to 0.538. As a point of interest and for comparison purposes, using the criteria that the probability of completing 7,000 arrestments without a failure is 0.97, reliability equals 0.999785 and 0.999140 for 50 and 200 aircraft. This criteria was developed in reference (c), but refers to critical failures and not to Type I failures. Confidence interval estimates for arresting 50 and 200 aircraft are:

$$0.784 \leq R \leq 0.936$$

$$0.377 \leq R \leq 0.768.$$

Sampling variation accounted for the wide confidence interval spread for b and consequently the spreads of the reliability intervals. The following intuitive reasoning clarifies the interpretation of the confidence intervals given: If the NATF(SI) test program had been run identically and halted each time after five Type I failures, 95 percent of the estimates for b would be expected to fall within the interval $0.00132 < b < 0.00486$. Resulting confidence intervals would then also be expected to lie within those given 95 percent of the time. Confidence intervals given indicate regions in which reliability estimates are expected to lie but the best estimates are those given from the function $(1 - b)^{Nm}$.

5. Results of this section are entirely dependent upon the form of the fitting function F(X) and whether this function will adequately describe failure occurrences at later service life. Only extensive testing well beyond the total service life of X = 1,854 would reveal the exact form of the function F(X), but this approach would be quite expensive and could even verify that the fitting function chosen a + bX was the proper one for all service-life X. A general fitting function would be of the form $F(X) = c + dX^k$ where c, d, and k are constants. Insertion of this function within the expression for reliability yields:

$$R(Nm) = 1 - \frac{b((X + Nm)^k - X^k))^{Nm}}{Nm} .$$

For K = 1, $R(Nm) = (1 - b)^{Nm}$ and this corresponds to a constant failure rate of b with the function

$$F(X) = a + bX.$$

For k = 0, R(Nm) = 1 for all service-life X, and for $k > 1$, R(Nm) decreases as service-life X increases. For $0 < k < 1$, R(Nm) increases as service life X increases. The parameter k in the general fitting function F(X) thus determines the direction of reliability as service life increases. If failures begin to occur less frequently as service life increases, then $0 < k < 1$ and if failures occur more often as service life increases, then $k > 1$. Determination of k is thus of utmost importance in the determination of reliability. It may occur that k is not a constant and that k is really a function of service-life X. In these cases, it would be necessary to determine the form of the function k(X) in order to detremine reliability from the function

$$R(Nm) = (1 - \frac{b\ ((X + Nm)^{k(X)} - X^{k(X)})}{Nm})^{Nm} .$$

This latter type of investigation has not been considered in this report.

C. Failure Distribution Function

1. If failures are essentially chance occurrences, if service life does not appreciably alter the performance of the arresting gear, and if arresting-gear modifications do not affect the failure rate, a probability failure distribution can be considered. Again, to either accept or refute these assumptions an extensive test program, which would not be feasible, is required. Accepting these assumptions, the failure distribution is geometric. Usage of the fitting function F(X) = a + bX in section B of this report is equivalent to accepting the above assumption.

2. Using the notation in reference (d), let

p = constant probability of no failure after each arrestment,

q = probability of failure after each arrestment (q = 1 -p), and

n = a random variable which is defined to be the number of arrestments before a failure (n = 1, 2, 3, ...).

The density function for the geometric distribution is thus

$$f(n) = qp^{n-1} \quad n = 1, 2, \ldots,$$

the failure distribution function is

$$P(n) = \sum_{i=1}^{n} q\, p^{n-1}$$

and reliability is

$$R(n) = 1 - \sum_{i=1}^{n} q\, p^{n-1}$$

Note that R(n) is equivalent in meaning to that of R(Nm) of section B. The maximum liklihood estimates of p (see reference (e)) is

$$\frac{\sum_{i=1}^{N} Yi - N}{\sum_{i=1}^{N} Yi} = \frac{1514 - 5}{1514} = 0.9967$$

and N is the total number of observed failures and equals 5. R(n) as a function of n or mission size if plotted in Figure 3 and is the middle curve. As expected, results of Figures 2 and 3 are in excellent agreement. For example, the probability of arresting 50 aircraft without an arresting-gear failure is 0.86 compared with 0.857, while for 200 aircraft it is 0.52 compared with 0.538.

3. Upper and lower 95-percent confidence limits for p (P_U and P_L) were calculated according to the procedures on pages 7 to 9 of reference (d), where

NS (the total number of arrestments which did not result in a failure) was 1,509.

Results were $P_U = 0.9989$

and $P_L = 0.9930$.

The confidence limit curves

$$1 - \sum_{i=1}^{n} Q_U P_U^{n-1}$$

and

$$1 - \sum_{i=1}^{n} Q_L P_L^{n-1}$$

are plotted in Figure 3. Confidence limits for 50 and 200 arrestments are $0.71 \leq R \leq 0.95$, and $0.24 \leq R \leq 0.81$. These results do not compare favorably with those of Section B of this report, but it should be pointed out that the procedures for establishing the confidence intervals in these two sections are vastly different. In fact the method used in section B of this report includes the failure data point $F = 0$, $X = 0$ for the purpose of getting a better curve fit, whereas the method used in this Section does not consider this point. The method used in this Section has a strong theoretical base, while that of Section B is not as adequately based. As with the results of Section B, the confidence interval bands obtained are wide because of the small number of observed failures.

IV CONCLUSIONS

1. Reliability obtained from results of the limited test program was found to be independent of service life and equal to 0.86 and 0.54 when 50 and 200 aircraft are arrested. As a point of interest, the idealized critical failure criteria set forth in reference (c) results in reliability numbers of 0.999785 and 0.999140 for 50 and 200 aircraft. (Paragraphs III.B.3 and III.B.4)

2. Arresting gears, intended for use in gathering failure data to use for reliability analysis, should have physical configurations identical in every way to fleet systems, in order to make proper simulation. The test program demonstrated that test systems should closely simulate its shipboard counterpart and this would tend to insure the collection of meaningful data. (Paragraphs III.A.3 and III.A.5)

V RECOMMENDATIONS

1. Reliability of arresting gears for Fleet use should be determined under actual or closely-simulated Fleet-operation conditions where many arrestments are made in relatively small intervals of time and where operations are not interrupted to test and evaluate new equipment.

2. Development, to improve items disclosed to be marginal in these tests, should be continued in order to obtain a significant improvement in the reliability of the Mark 7 Mod 3 arresting-gear system.

3. The Mark 7 Mod 3 arresting-gear system at NATF(SI) should continue to be monitored so that results of this report can be updated as new Type I failures occur.

VI REFERENCES

(a) Naval Air Systems Command Air Task No. A05-537-007/204/1/W4503-05
(b) NATF(SI) Report NATF(SI)-E-1074 of 18 March 1965, by N. P. Ivanovic: The Applicability of Certain Distributions to Ship Installations Reliability and Maintainability Evaluations
(c) NAVAIRSYSCOM ltr AIR-5373A/54:RBC of 12 July 1968: Technical Development Plan (TDP) W45-25X, Shipboard Arresting Gear; distribution of
(d) NATF(SI) Report NATF(SI)-E-1077 of 7 April 1966, by W. K. Kraut: Probabilistic Derivation of Optimal Maintenance Schedules for Cyclical Equipment
(e) Mood, "Introduction to the Theory of Statistics", McGraw-Hill, 1950

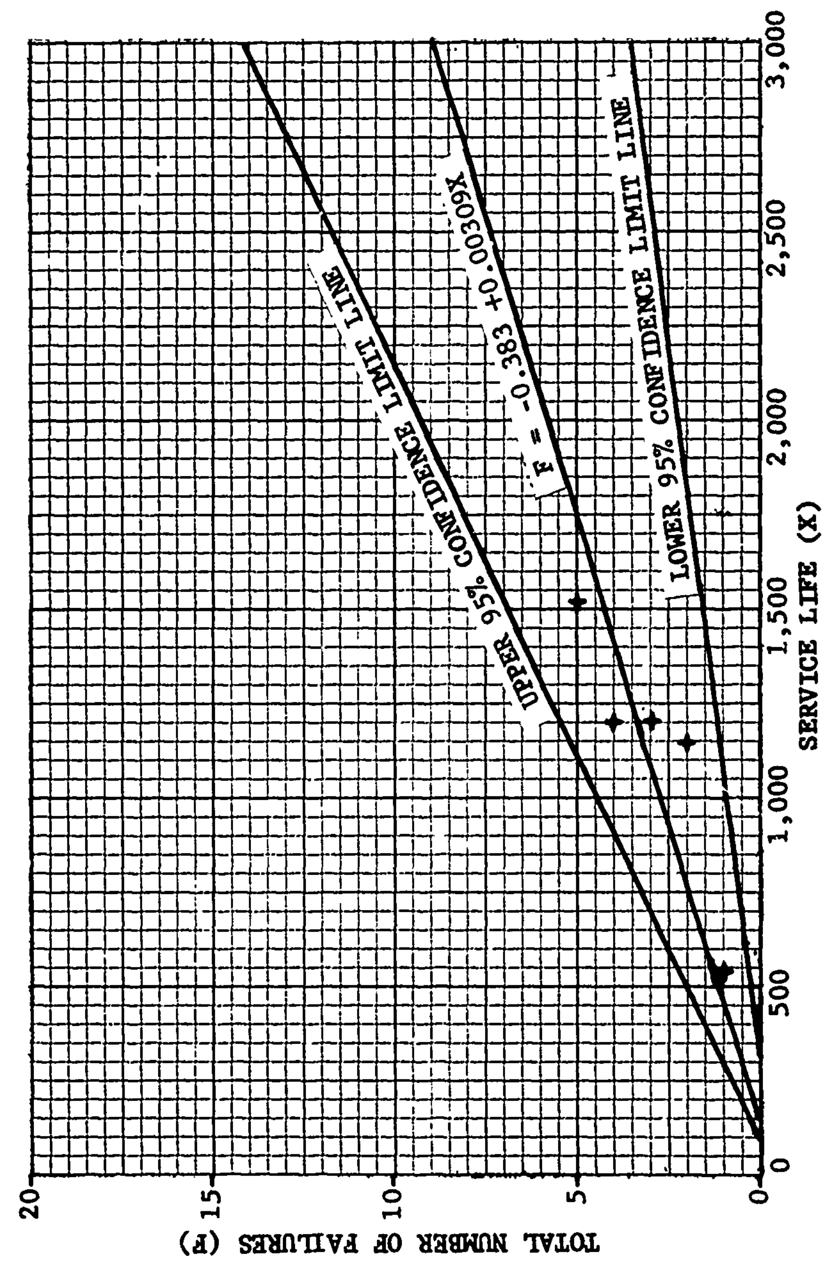

Figure 1 - Total Number of Failures versus Service Life - Mark 7 Mod 3 Arresting Gear at NATF(SI)

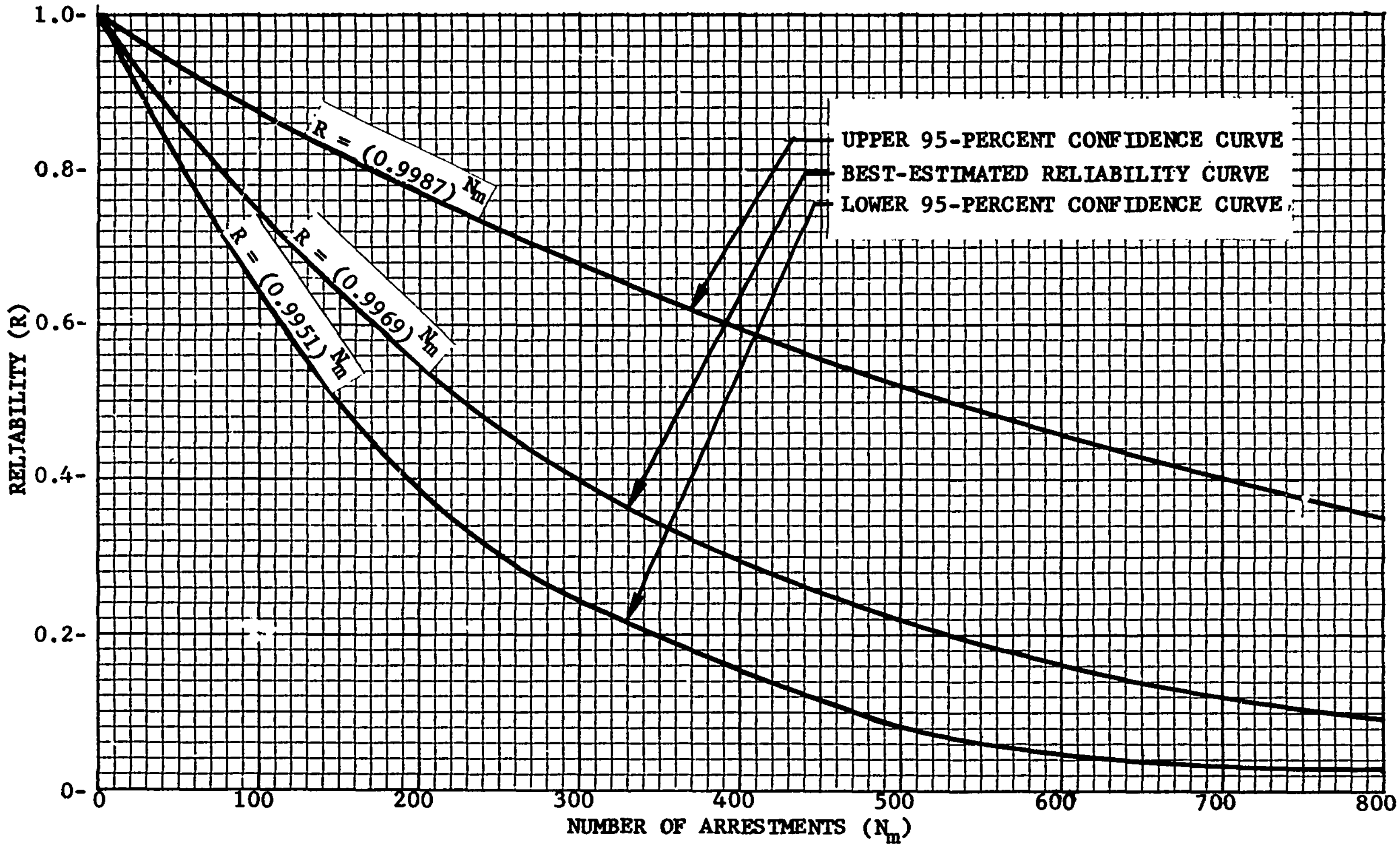

Figure 2 - Reliability versus Mission Size - Mark 7 Mod 3 Arresting Gear at NATF(SI) (Section B Method)

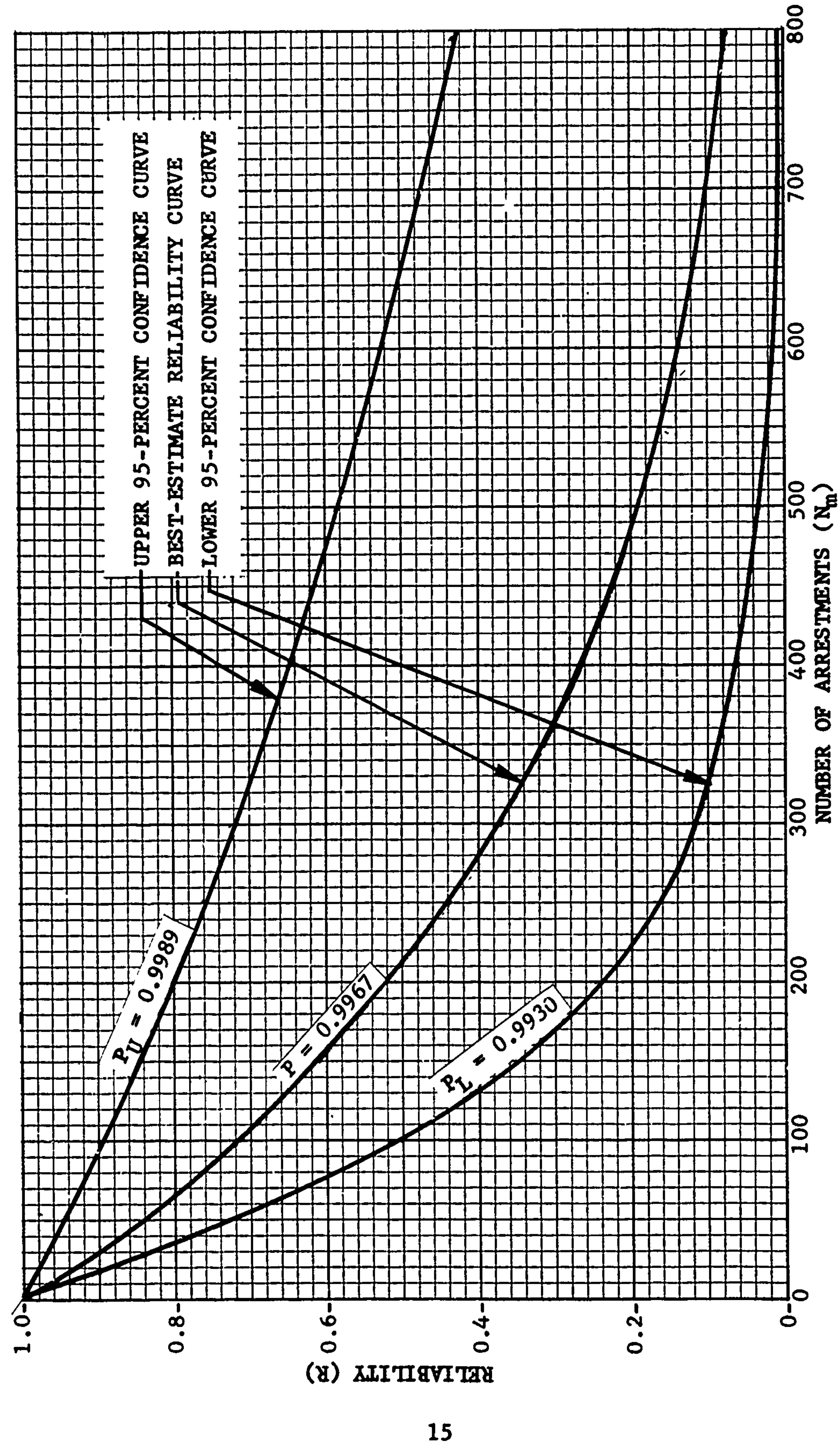

Figure 3 - Reliability versus Mission Size - Mark 7 Mod 3 Arresting Gear at NATF(SI) (Section C Method)

MARK 7 MOD 3 ARRESTING-GEAR COMPONENT FAILURES

NOTES:

Arrestment Number: The number of the arrestment during which the component failed.

Type of Failure: The failures are classified as one of the following categories:
Type I - Must-stop-to-fix or repair
Type II - Continue to run, but monitor failed component
Type III - Failure is not serious; run and defer repair or replacement

Date	Arrestment Number	Type of Failure	Description	Part No. Replaced	Man-Hours to Repair
10/28/66	138	III	Packed air/oil separator	F87772-12 AN6227-56	72
11/23/66	150	III	Replaced liquid sight indicator	318534	1
12/2/66	528	I	Replaced fluid indicator drive rod Packed air/oil separator	54-31461-1 F87772-12 E87889-2 H87890-14	468 62
			Installed Service Change No. 227		
1/26/67	707	II	Cropped purchased cable; rotated deck sheaves end for end		35
1/30/67	713	III	Packed air/oil separator	F87772-12 AN6227-56	75
			Replaced O-rings on fluid-level indicator	AN6227-19 AN6227-31	
2/27/67	852	II	Cropped purchase cable		16

Date	Arrestment Number	Type of Failure	Description	Part No. Replaced	Man-Hours to Repair
3/1/67	872	III	Replaced port anchor damper cylinder and cushioning piston Packed anchor damper	506311-1 410409-1 H87772-22 410294-10 AN6227-67 MS28782-67	192
5/18/67	945	III	Packed main engine cylinder	52-3535-1 E87772-23	80
6/27/67	1,047	II	Reeved purchased cable		160
8/11/67	1,142	I	Repaired sheave-damper tailpiece	A316379-2	
8/28/67	1,202	I	Reeved purchase cable		160
9/25/67	1,208	I	Replaced fluid-indicator O-rings	AN6227-19 AN6231-9	16
9/28/67	1,286	I	Repaired sheave-damper tailpiece	A316379-2	
10/4/67	1,304	II	Honed ram to remove score marks Replaced wiper ring and retainer	52-32524-1 52-42283-1	320
10/17/67	1,342	II	Replaced deck-sheave spacer	71-40212-2	12
10/26/67	1,426	I	Repaired sheave-damper tailpiece	A316379-2	4
11/16/67	1,514	I	Packed port anchor damper	AN6227-67	16

Date	Arrestment Number	Type of Failure	Description	Part No. Replaced	Man-Hours to Repair
1/12/68	1,706	III	Packed port anchor damper; Replaced starboard anchor-damper piston and packing	410294-3 410295-1 410294-3	24
		II	Reeved purchase cable Installed Service Change No. 248		170
2/2/68	1,718	II	Packed anchor dampers	410294-3 AN6227-67	16
3/5/68	1,838	II	Cropped purchase cable		32
3/15/68	1,854	III	Packed main engine cylinder Packed air/oil separator Replaced slipper cage	52-3535-1 F87772-12 54-41435-1	218

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13. ABSTRACT

Failure data obtained during tests with the Mark 7 Mod 3 arresting-gear system was used to determine reliability by two methods:

First, by finding an empirical relationship between total number of failures and service life and then deriving the functional relationship of reliability to service life and mission size. Reliability thus obtained was independent of service life and decreased for increasing mission size.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Mark 7 Mod 3 Arresting Gear						
Arresting Gear						
Recovery System						
Reliability						