Title

FAILURE DATA ANALYSIS OF THE SUPERHILAC RADIO FREQUENCY SUBSYSTEM

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FAILURE DATA ANALYSIS OF THE SUPERHILAC RADIO FREQUENCY SUBSYSTEM

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MASTER

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ABSTRACT

This report is a follow-up of the study done by Liang [1], [2] in 1977 to investigate new techniques for analyzing SuperHILAC system availability. Recent and more accurate data are used and emphasis is on the Radio Frequency (RF) subsystem and its components. Time Series Analysis and Total Time on Test plots are the main tools used in the analysis. Recommendations for the improvement of RF availability, general SuperHILAC performance, and the data collecting process are given. The primary result suggests that the RF operating period should be extended.

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CHAPTER 1

INTRODUCTION AND SUMMARY OF RESULTS

1.1 The Report

This report is a continuation of an earlier report by Liang [2] with emphasis now on the Radio Frequency subsystem and its components, using current and improved data. It was stated in Liang's report that improvement in overall SuperHILAC availability, which must be very high for medical purposes, is best made by improving subsystems that are needed in all modes of operation. Two such subsystems were *Radio Frequency* (RF) and *Other*, with relatively low availabilities of .96 and .93 respectively. Since subsystem *Other* is not well defined, the RF became the object of this investigation. It was hoped that the components of the RF would show properties that were obscured at the higher level. The analytic procedure of this report is essentially identical to that in the earlier report, except that an operating period analysis is added.

1.2 The SuperHILAC and the RF

A block diagram of the Super Heavy Ion Linear Accelerat r, showing the 14 subsystems analyzed by Liang, is given in Figure 1.1. Some of these subsystems have since been redefined somewhat.

For a given mode of operation, the SuperHILAC is a *series* system in terms of the subsystems being used. The *mode* of the SuperHILAC depends on the injector(s) being used, the beam line, and time-sharing in particular. Generally, Mode 1 indicates that the Adam injector is providing the ions; Mode 2 indicates Eve is being used; and Mode 3,

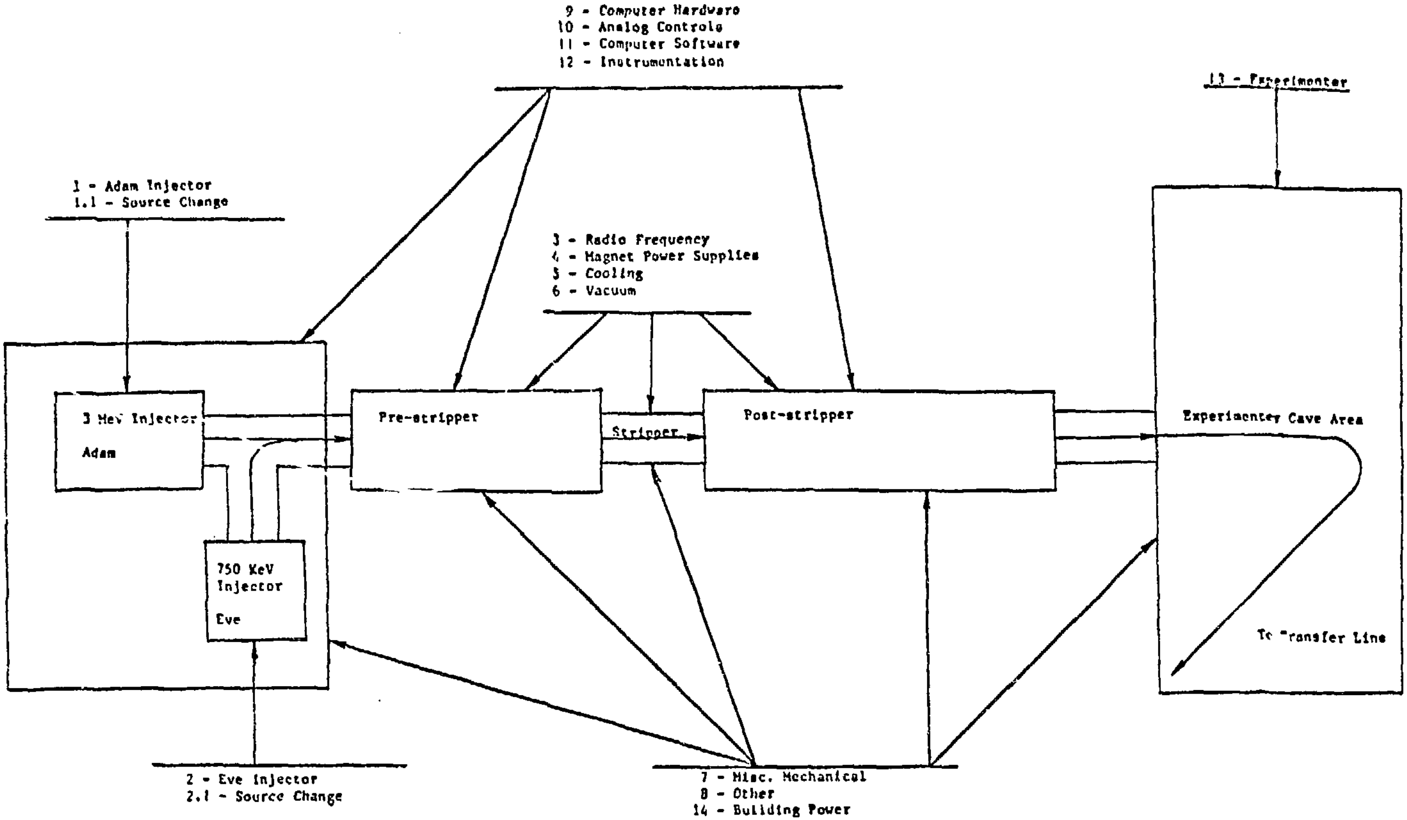

FIGURE 1.1

SUBSYSTEMS OF THE SUPERHILAC

the parasitic mode, indicates that the ion beam of either Adam or Eve is time-shared with another experimenter.*

Different ion beams from different modes may be accelerated independently and concurrently through the SuperHILAC by time-sharing. This computer controlled process splits a second into 36 pulses and allocates a number of pulses to each mode. For each pulse the electromagnetic field is tuned automatically and instantaneously to the specified level by adjusting the RF gradient, frequency, and phase. A fault tree, constructed by Besse, for the RF subsystem is shown in Figure 1.2. The RF is also a series system, and although there are spares for the driver and final amplifiers, they are very seldom used.

Available computerized data can trace a SuperHILAC failure to the failed subsystem (but see No. 12 in Conclusion). However, identification of the subsystem component responsible requires careful reexamination of logbook records. In some cases it was difficult to pinpoint the basic event responsible and the failure was attributed to an intermediate event. This caused missing data in some component failure records.** A new and entirely different categorization procedure is being developed but has not been put to use yet.

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*The descriptions of Modes 1 and 2 given here are consistent with Liang's report and are the ones used by Besse [3]. However, the definitions are reversed in other SuperHILAC documents.

**For convenience, we shall often refer to an event in the RF fault tree as a RF "component." It should be clear that occurrence of an event is caused by some component failures.

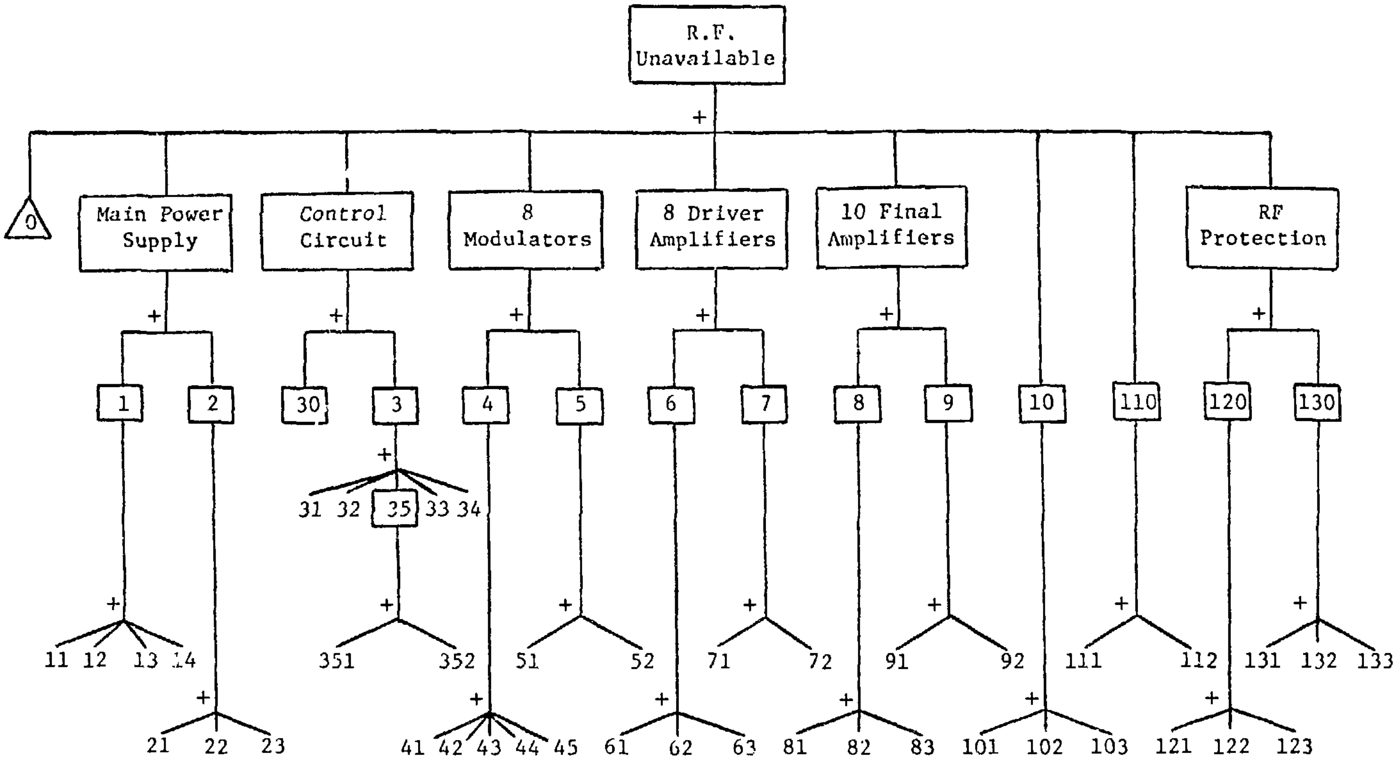

FIGURE 1.2

FAULT TREE FOR THE RF SUBSYSTEM

All intersections contain OR gates (+).
Component failure/unavailability event descriptions are given in Table 1.1.

TABLE 1.1

COMPONENT DESCRIPTION

Event/Component No.	Description
0	OTHERS
1	POWER FAILURE
11	Rectifier
12	Firing Circuit
13	Switch Gear
14	Capacitor Bank
2	OTHER MAIN POWER SUPPLY SHUTDOWN
21	D. C. Crowbar
22	Switched Off
23	Circuit Breaker
30	IMPROPER SETTING
3	ACTUAL CONTROL CIRCUIT FAILURE
31	Frequency
32	Gradient
33*	70W Amplifiers
34	Phase
35	MASTER CONTROLLER FAILURE
351*	Crystal
352	Master Pulser
4	MODULATOR FAILURE
41*	8641
42	2KV & 5KV Power Supply
43*	Preamp
44	Machlett
45*	Driver
5	OTHER MODULATOR SHUTDOWN
51*	Noise
52*	Breaker
6	DRIVER FAILURE
61*	LCW 25K
62*	Screen Modulator
63	RF Preamp: 250W, 400W, 2000W
7	OTHER DRIVER AMP SHUTDOWN
71	Flow Switch
72*	Breaker
8	FINAL AMP FAILURE
81*	6949 Tube
82	Filament Transformer
83*	Plate Choke
9	OTHER FINAL AMP SHUTDOWN
91	Flow Switch
92*	Breaker

TABLE 1.1 (continued)

COMPONENT DESCRIPTION

Event/Component No.	Description
10	DRIVE LINE FAILURE
101*	Loop Motor
102*	Insulator
103*	Drive Line
110	MONITORING FAILURE
111*	Phase
112*	Gradient
120	COMPONENT FAILURE
121*	Relays
122	Boards
123	Other
130	OTHER RF PROTECTION SHUTDOWN
131	Spark
132	Computer
133	Other

*Basic event with no failure record.

1.3 The Data

Operations data, recorded by the SuperHILAC crew in logbooks, have been edited and transferred onto a computer file by Besse. With the use of program HILAC [3], information such as uptimes, downtimes,* and subsystems at fault are easily obtained.

The logbook records go back for many years, but Liang used only the computerized data existing at the time. That covered the 26 months period from January 1974 to February 1976, where the recording units were .5 hours. The present study covers the subsequent 24 months from March 1976 to February 1978, with recording units of .25 hours.

On comparison, the computerized data contained many omissions and mistakes. Having corrected the discrepancies, we ran the data through a program that picks out those entries essential for a specified subsystem analysis (see Appendix A for program listing). The selection was made with respect to the subsystem alone and disregarded the operating mode. It was felt that the separate mode analytic approach used by Liang is highly questionable when applied to subsystems, like the RF, which are essential in all modes of operation. Although the load on such subsystems may be different for each mode, the major stress comes during periods of time-sharing, which are most frequent, and thus failures cannot be easily assigned as just due to one single mode.** This fact is verified by the multiple entries in the logbooks for such failures and the similarities of the availabilities, obtained by Liang, of such subsystems for different modes. This problem was not unknown to Liang; he called it *Coupling of Type 1.*

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*Downtime and repair time will be used interchangeably.

**We wish also to point out that the schematic diagram used by Liang for Mode 3 is incorrect.

Close examination of the failure data of the RF subsystem revealed a large number of records each consisting of a succession of short uptimes and downtimes terminating with a relatively long repair time. Such a sequence of entries is actually due to one single failing component and represents the instability before the final crash. Since the univariate life distributions we will be using cannot account for this characteristic, such a sequence was compressed into a single entry with downtime equaling the sum of the separate downtimes. Figure 1.3 illustrates the procedure.

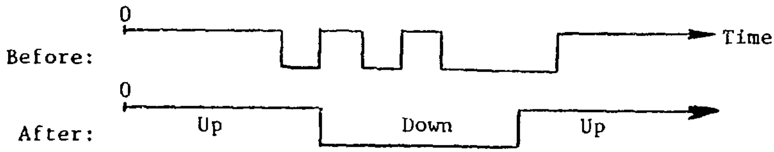

FIGURE 1.3

REMOVAL OF INSTABILITIES

Another necessary adjustment to data before analysis can proceed is the removal of discontinuities caused by shutdowns, and, for part of the analysis, those caused by maintenance breaks as well. For a shutdown or maintenance break flanked by an uptime *and* a downtime, the discontinuity was simply deleted, yielding a pair of *incomplete* data points. For a shutdown or maintenance break flanked by a *pair* of uptimes or downtimes, *suspended animation* was assumed and the pair was merged into a single point. There are no justifications for these two steps, but they are the least drastic. Although real time scale will be changed after such an operation, the data and the analytic techniques turn out to be insensitive to this change. Figure 1.4 illustrates the procedure.

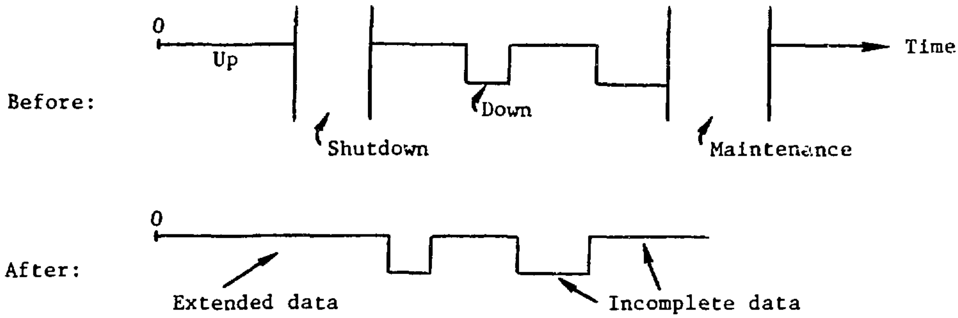

FIGURE 1.4

REMOVAL OF SHUTDOWN AND MAINTENANCE BREAKS

We did not remove or reduce any outlying data points. There were only a couple of them in each series and their effects were obvious and easily compensated.

1.4 Summary of Results

The following is a list of the main results of the study. Some were also found by Liang and none contradicts those given in his report. More general comments may be found in the Conclusion.

1. RF and Computer subsystems' maintenance records show that the failure processes may have Decreasing Failure Rate (DFR) distributions, implying that the *operating period should be extended.* Maintenance records for RF events *Final Amp Failure* and *Filament Transformer* display the Increasing Failure Rate (IFR) property, while all other RF components have operating periods with exponential failure distributions.

2. Downtimes are likely to have DFR distributions. RF and most component uptimes are also DFR. Fault tree branch *Actual Control Circuit Failure* and its components are the only ones possibly having exponential uptimes.

3. Among the intermediate events, *Actual Control Circuit Failures* and *Other RF Protection Shutdowns* are most frequent. They in turn are caused mainly by failures of basic components *Phase* (No. 34) and *Other* (No. 133) respectively.

4. There does not appear to be a seasonal pattern in the RF failures.

5. Refinement of the recording unit reduced RF mean time to fail (MTTF) to 31.00 hours, however the RF availability remained at .96.

6. There are no serial autocorrelations within, and no cross-correlations between, the uptime and downtime series of the RF and Computer subsystems, and of three RF components.

7. Downtime distributions are concentrated over rather short intervals. RF subsystem has a mean time to repair (MTTR) of 1.14 hours with half of the downtimes caused by "trip-offs" of .25 hour.

CHAPTER 2

TOTAL TIME ON TEST PLOTS OF UPTIME AND DOWNTIME SERIES

2.1 Introduction

Total time on test (TTT) plots [4] provide information about *local behavior of* the failure rate function $r(t)$, which is of chief interest in our failure data analysis. If the failure rate is constant or decreasing, no replacement or maintenance should be planned since the present unit is actually "better" than a new or an overhauled one.

If unit failures are observed at ordered ages $X_{(1)} \leq X_{(2)} \leq \cdots \leq X_{(N)}$, then

$$T(X_{(i)}) = NX_{(1)} + (N-1)[X_{(2)} - X_{(1)}] + \cdots + (N-i+1)[X_{(i)} - X_{(i-1)}] \qquad (2.1)$$

is the total time on test to age $X_{(i)}$, and $T(X_{(i)})/T(X_{(N)})$ is the *scaled total time on test* at age $X_{(i)}$. A plot of $T(X_{(i)})/T(X_{(N)})$ versus $\frac{i}{N}$ for $i = 1,2, \ldots, N$ as in Figure 2.1 provides information about $r(t)$. If the plot is strongly concave, it is very likely that $r(t)$ is increasing (IFR). If the plot is strongly convex, then $r(t)$ is probably decreasing (DFR). See Appendix C for a listing of programs to calculate and plot TTT.

The *cumulative total time on test statistic* [9: page 267]

$$V_N = \sum_{i=1}^{N-1} T(X_{(i)})/T(X_{(N)}) \qquad (2.2)$$

is useful in testing H_0 : exponentiality versus H_1 : DFR and not exponential. Under H_0, V_N is stochastically equivalent to a sum of $N - 1$ independent uniform random variables on $[0,1]$. It can be shown that under H_0, the distribution of $Z_N = \sqrt{12(N - 1}\left[\frac{V_N}{N - 1} - \frac{1}{2}\right]$ converges to that of a $N(0,1)$ random variable. The corresponding test rejects H_0 in favor of IFR at significance level α if $Z_N \geq c_\alpha$ where $P[Z_N \geq c_\alpha \mid \text{Exponentiality}] = \alpha$. For $N \geq 10$, Z_N is approximately $N(0,1)$. If $Z_N \geq 2$ (i.e., Z_N is greater than 2 standard deviations) then this is evidence in favor of IFR. If $Z_N \leq -2$, then this is evidence in favor of DFR.

2.2 TTT Plots of RF Failure Data

TTT plots of the uptime and downtime series, obtained with program RF (Appendix B), of the RF, two intermediate and three basic RF components are given in Figures 2.1 - 2.12. These 12 series have shorter MTTF than others.

The initial long flat portions of the downtime plots are due to round-offs of .25 hour and/or a near degenerate distribution. They should not be interpreted as exhibiting the IFR property. Liang had hoped that improved accuracy would be able to remove such features. However, it now appears that *in practice* the downtime distributions can be regarded as discrete with only a few assumed values.

Most uptime and downtime plots shown here have noticeable convexities, indicating that the underlying distributions are likely to be DFR. TTT plots for the other RF components, obtained with smaller samples $(11 \leq N \leq 30)$, and for the Computer subsystem, show a similar property. This could mean given that the subsystem or component has been up (or down) for time x, the probability of its remaining in the current state is higher, the larger x is. In other words, replacement of a functioning unit is undesirable. There are other interpretations. It could be that given a collection of uptimes (downtimes), the "bad" ("less drastic") ones were seen to have failed (be repaired) quickly, causing the rest to have relatively longer records.

Since most basic component downtimes are DFR, the downtimes of the intermediate components and of the RF should also be DFR, as they are. It could be shown that a *mixture*, as in the case for downtimes of a series system, of DFR distributions is also DFR [5: Chapter 4.4].

On the other hand, the uptimes of a complicated series system are often exponential (see SuperHILAC uptimes in [2]). It is known that a *superposition* of a large number of different renewal processes often produces a Poisson process [5: Chapter 8.4]. However, our RF uptime series cannot be exponential since the number of diagonal crossings is insufficient.* One explanation for this is that different designs were often used to replace failed equipment and we are probably seeing the effect of a mixture of different distributions that existed at various times.

Among the components, Nos. 3 (*Actual Failure*), 31, 32, and 34 are the only ones most likely to have exponential uptimes from our TTT results. This indicates that the *Actual Failure* branch of the RF fault tree may be much more complicated than the rest.

It must be pointed out that the results presented here are only valid when the uptimes, and downtimes, are *independent* drawings from some distribution. This assumption is supported by our time series analysis results in Chapter 5.

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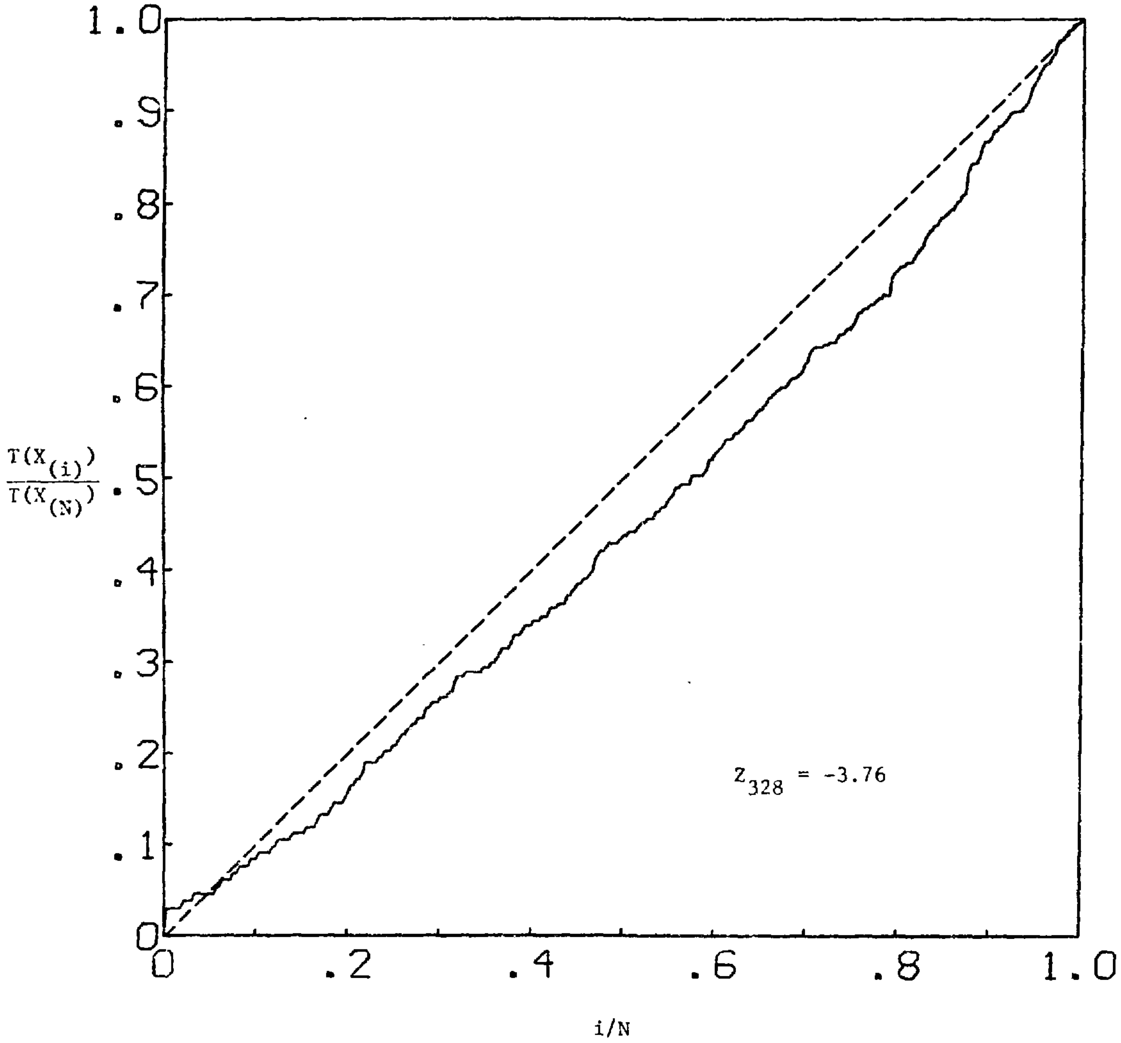
*The distribution of the number of crossings under exponentiality depends on sample size. For $N = 20$, the mean number of crossings is just under 3. The expected number of crossings under exponentiality is of order $e^{-1}\sqrt{2\pi n}$ as $n \to \infty$.



TOTAL TIME ON TEST PLOT

FIGURE 2.1

RF UPTIME

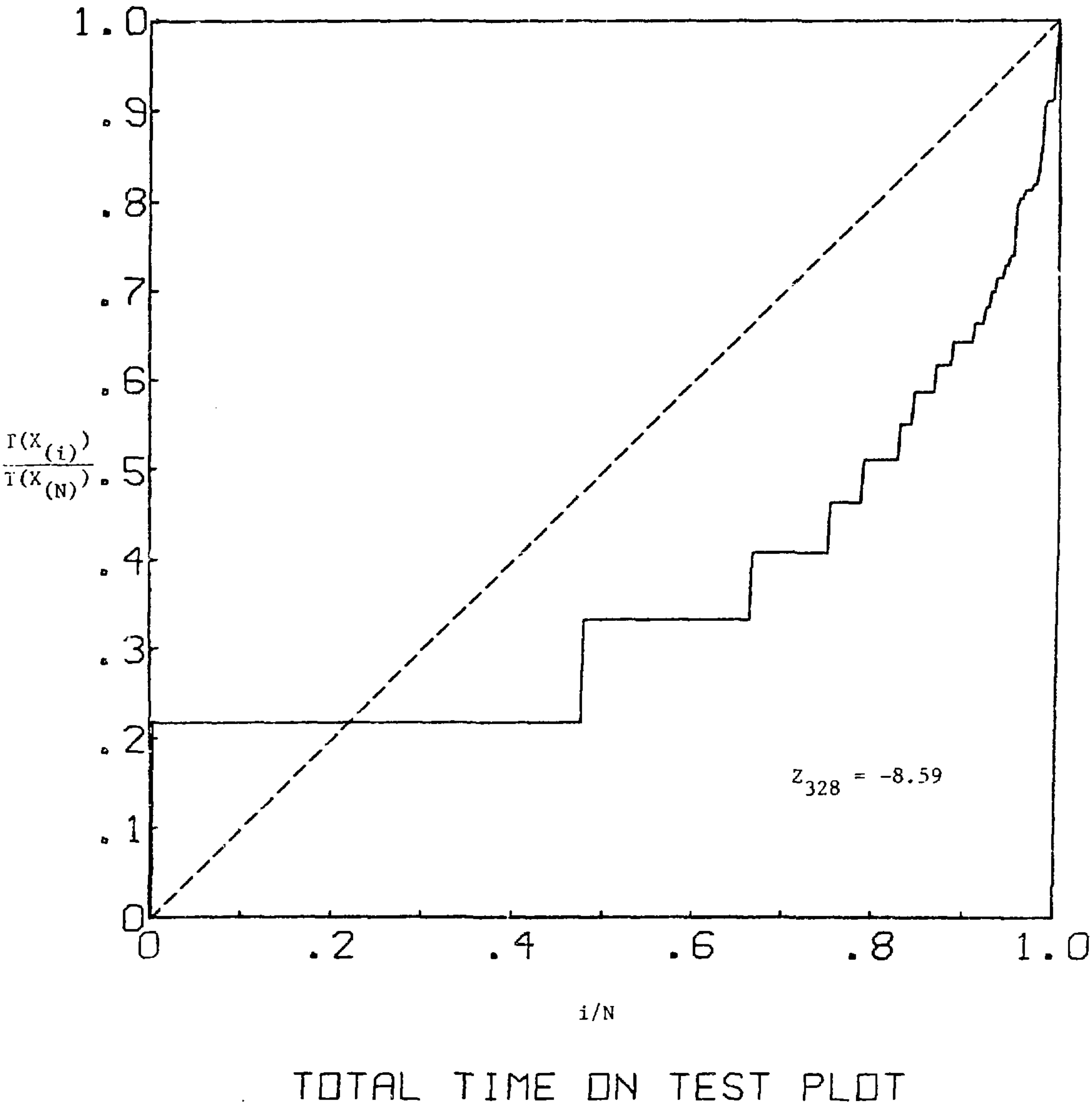


FIGURE 2.2

RF DOWNTIME

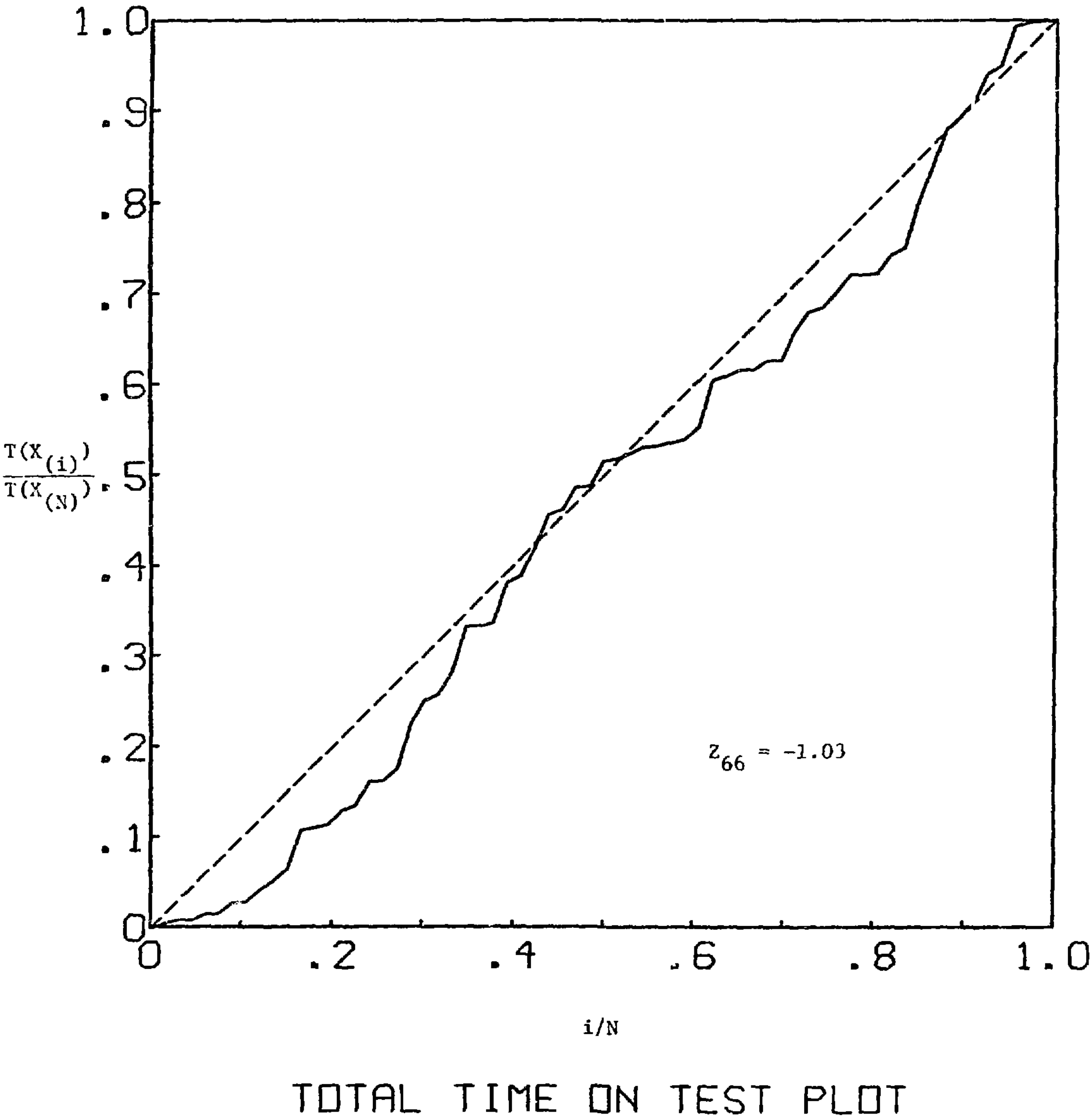


FIGURE 2.3

UPTIME: ACTUAL CONTROL CIRCUIT FAILURE (NO. 3)

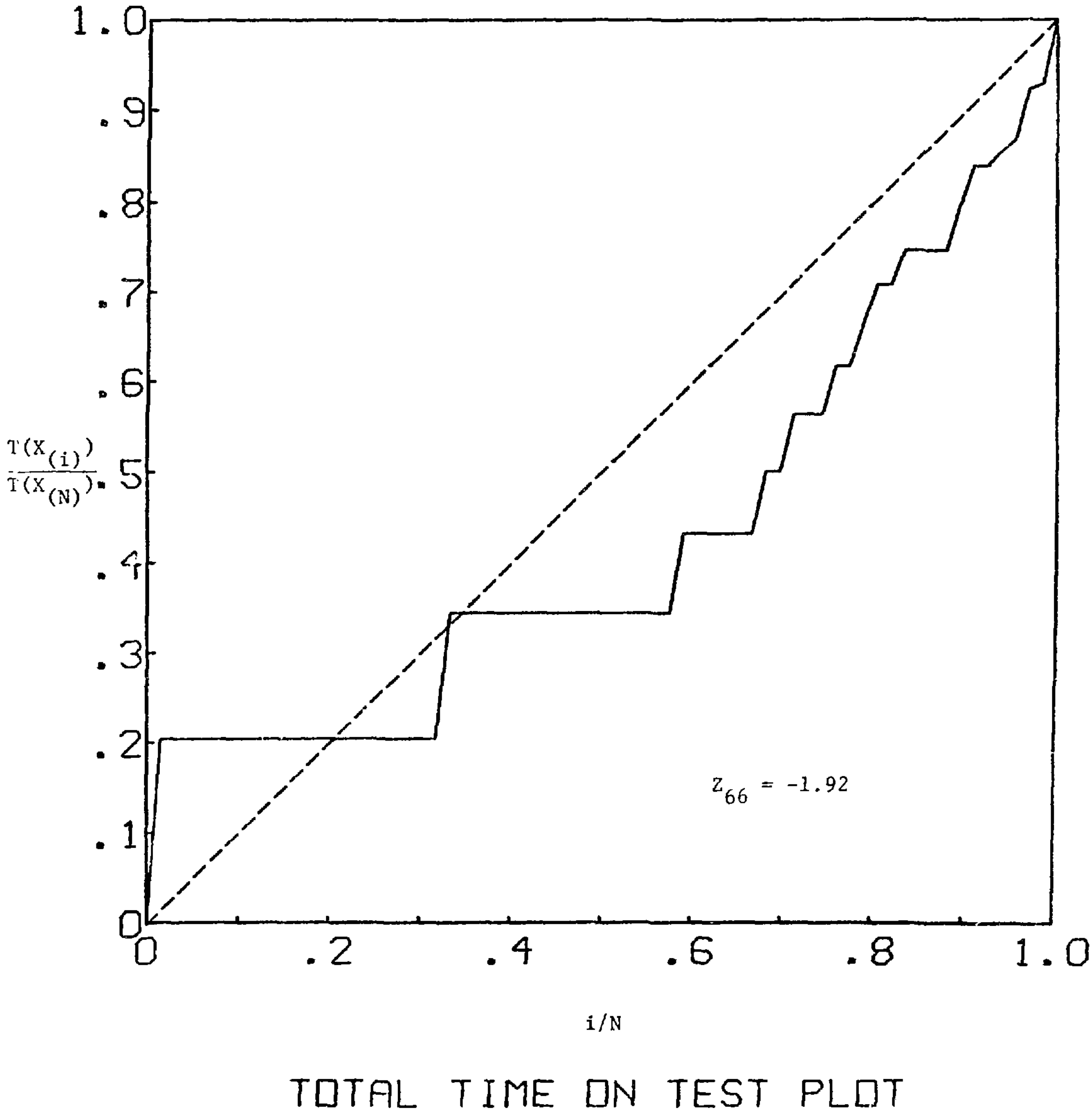


FIGURE 2.4

DOWNTIME: ACTUAL CONTROL CIRCUIT FAILURE (NO. 3)

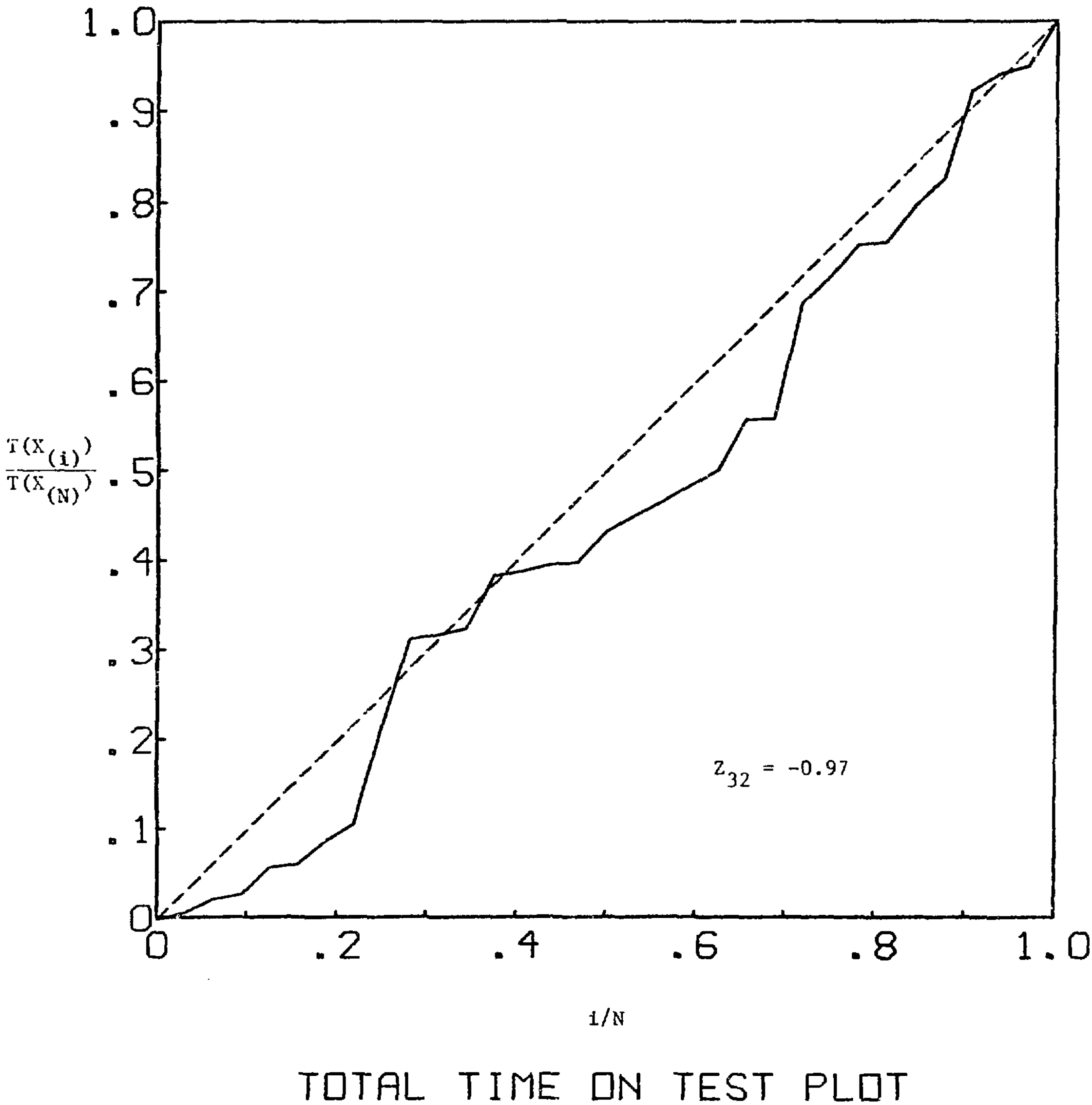


FIGURE 2.5

PHASE (NO. 34) UPTIME

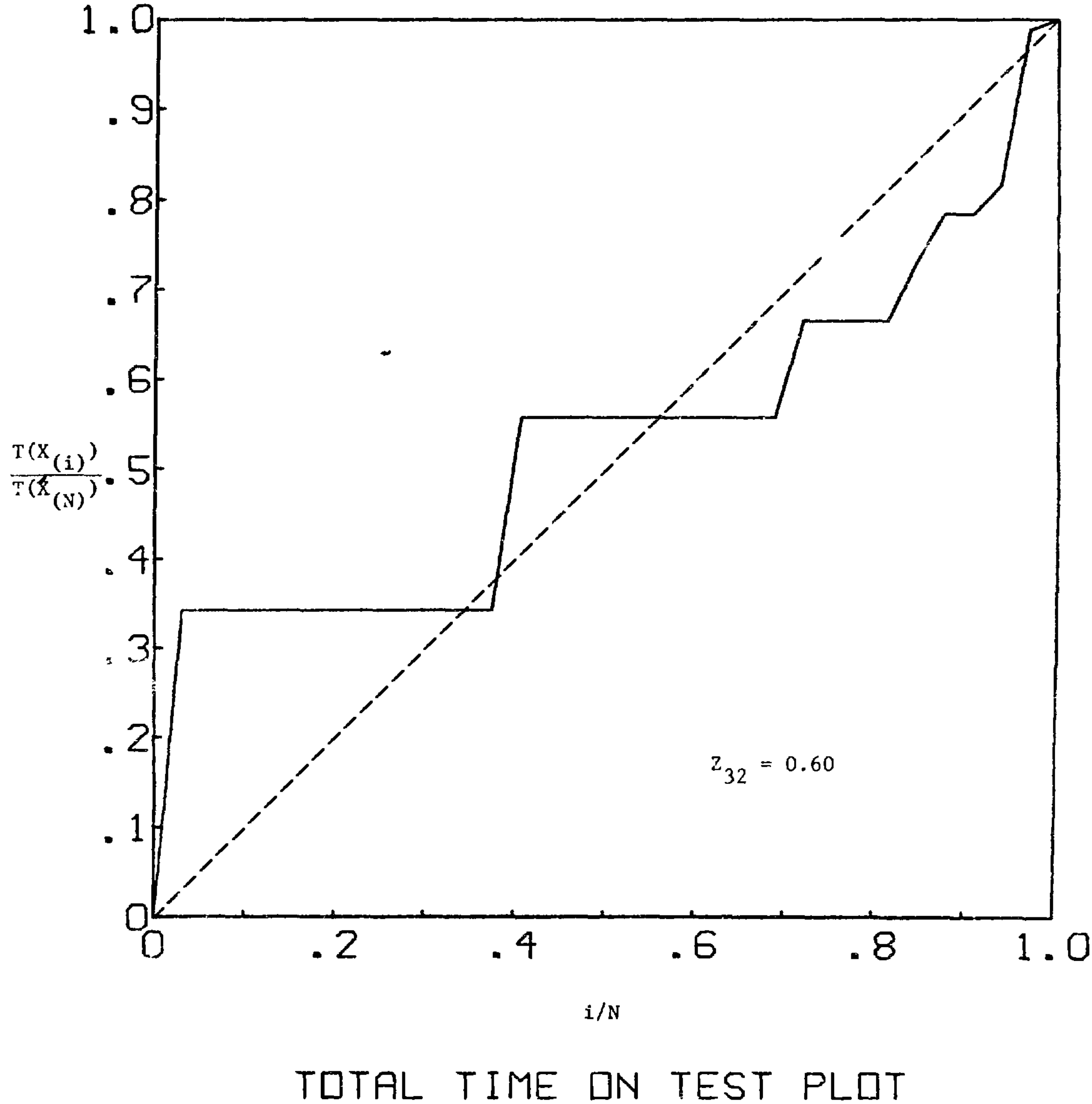


FIGURE 2.6

PHASE (NO. 34) DOWNTIME

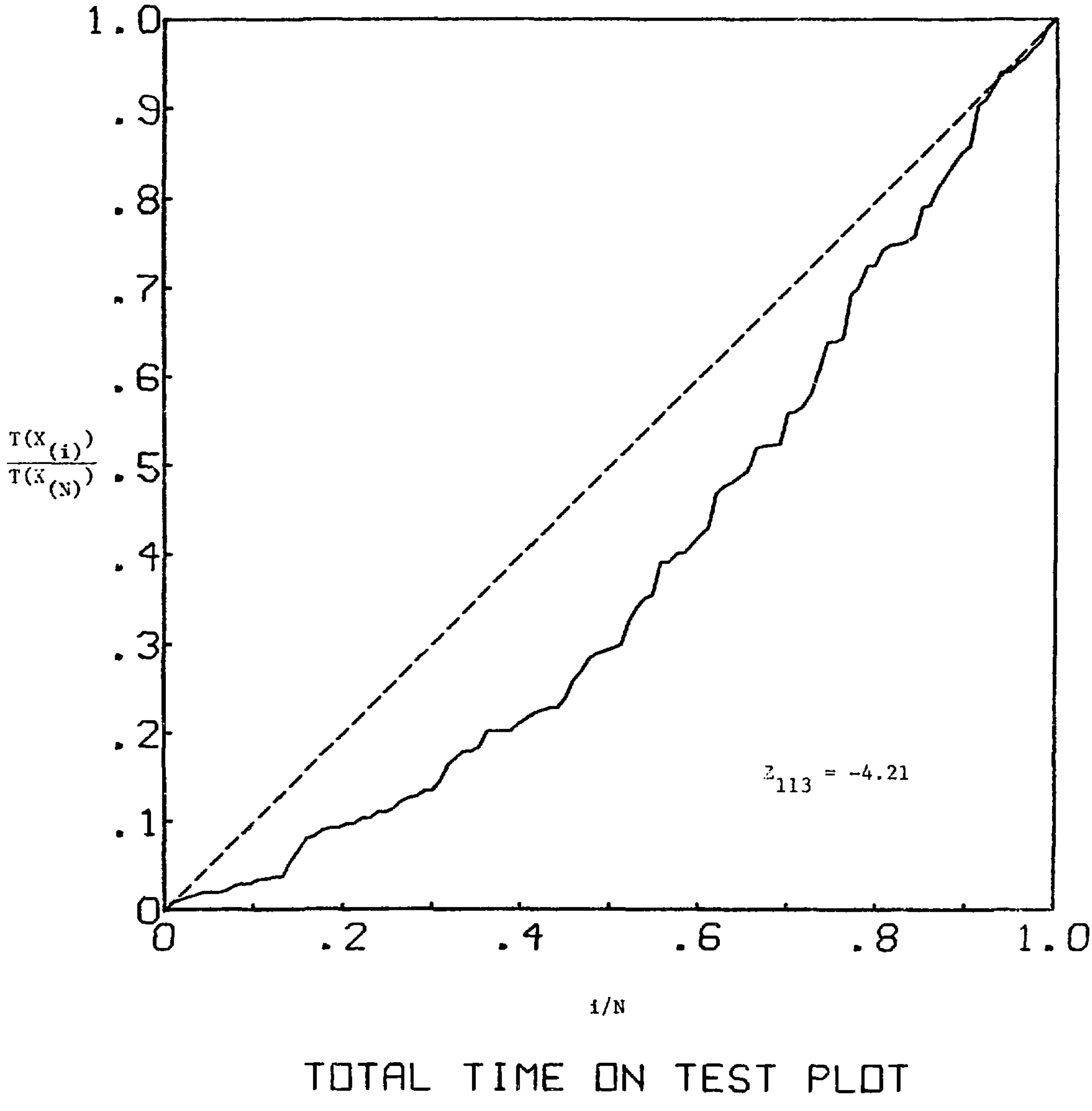


FIGURE 2.7

UPTIME: OTHER RF PROTECTION SHUTDOWN (NO. 130)

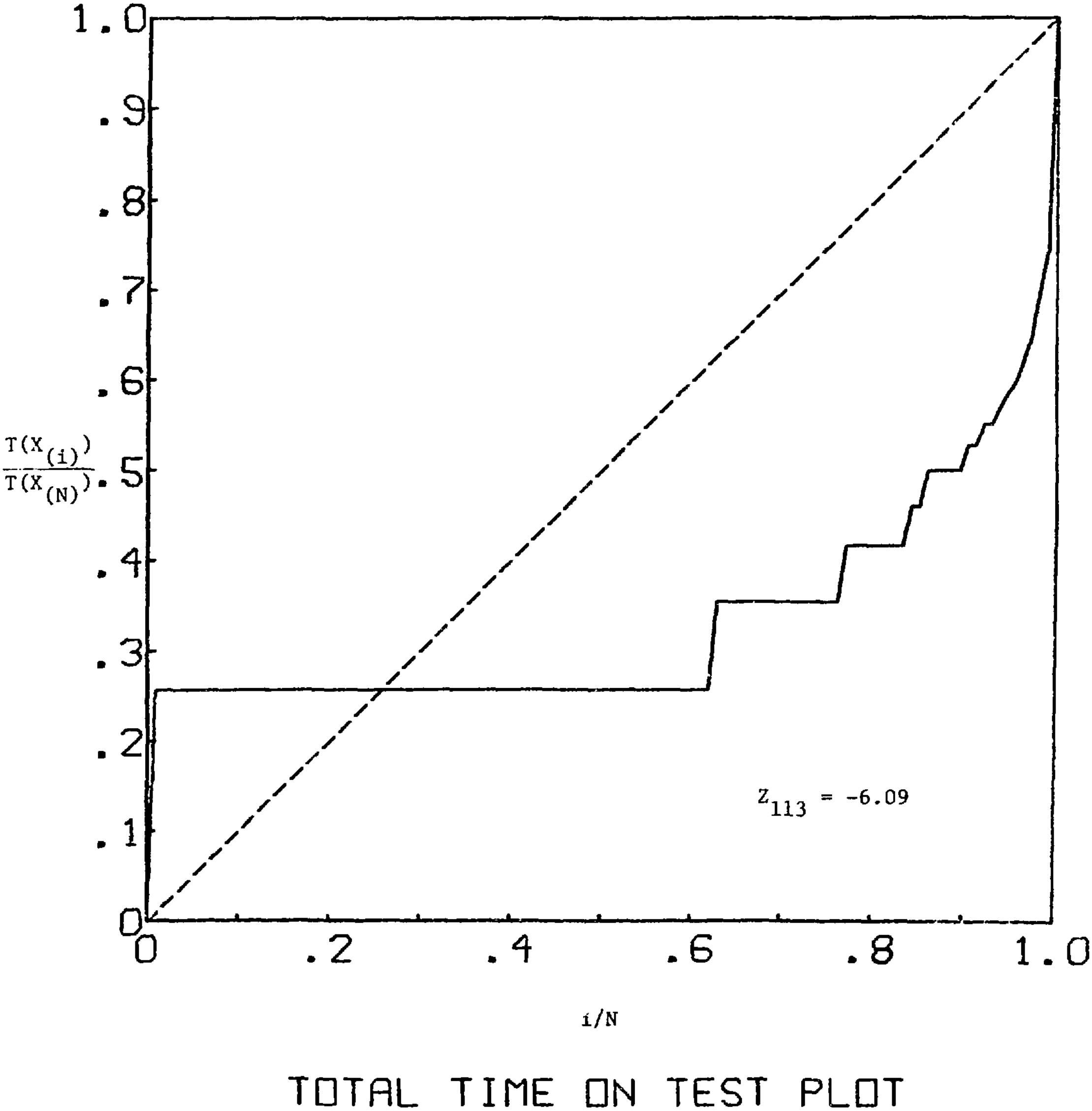


FIGURE 2.8

DOWNTIME: OTHER RF PROTECTION SHUTDOWN (NO. 130)

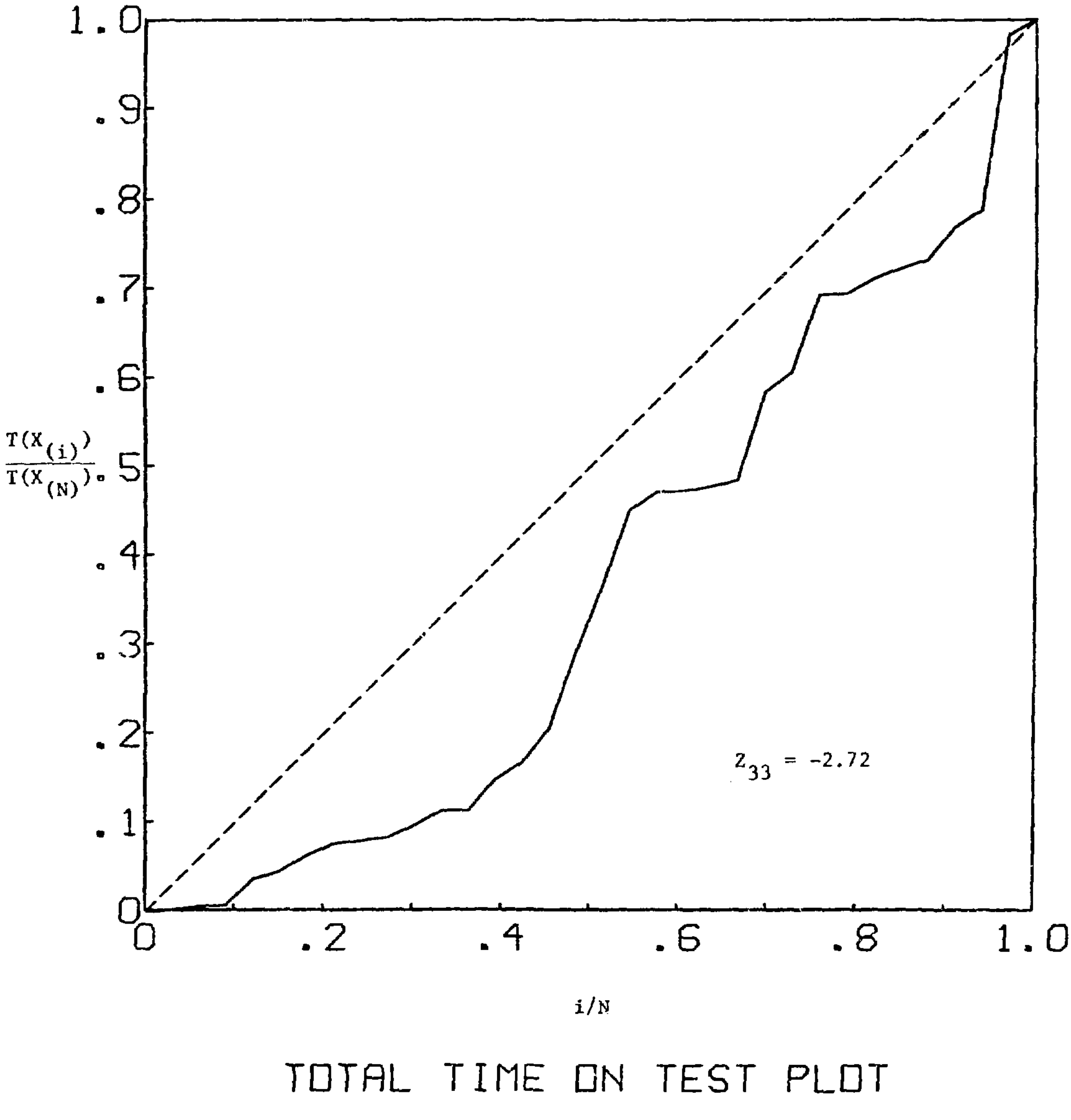


FIGURE 2.9

SPARK (NO. 131) UPTIME

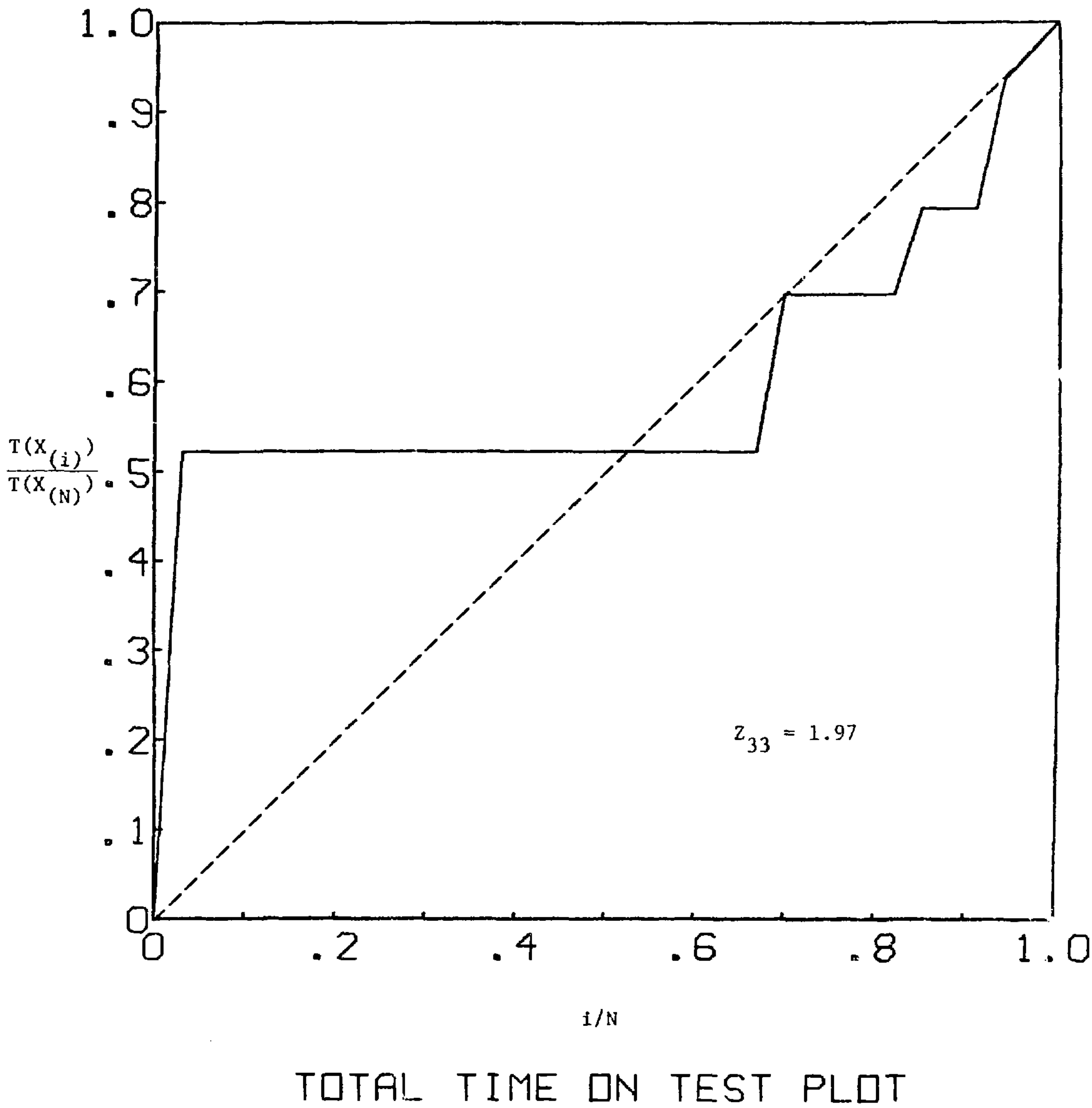


FIGURE 2.10

SPARK (NO. 131) DOWNTIME

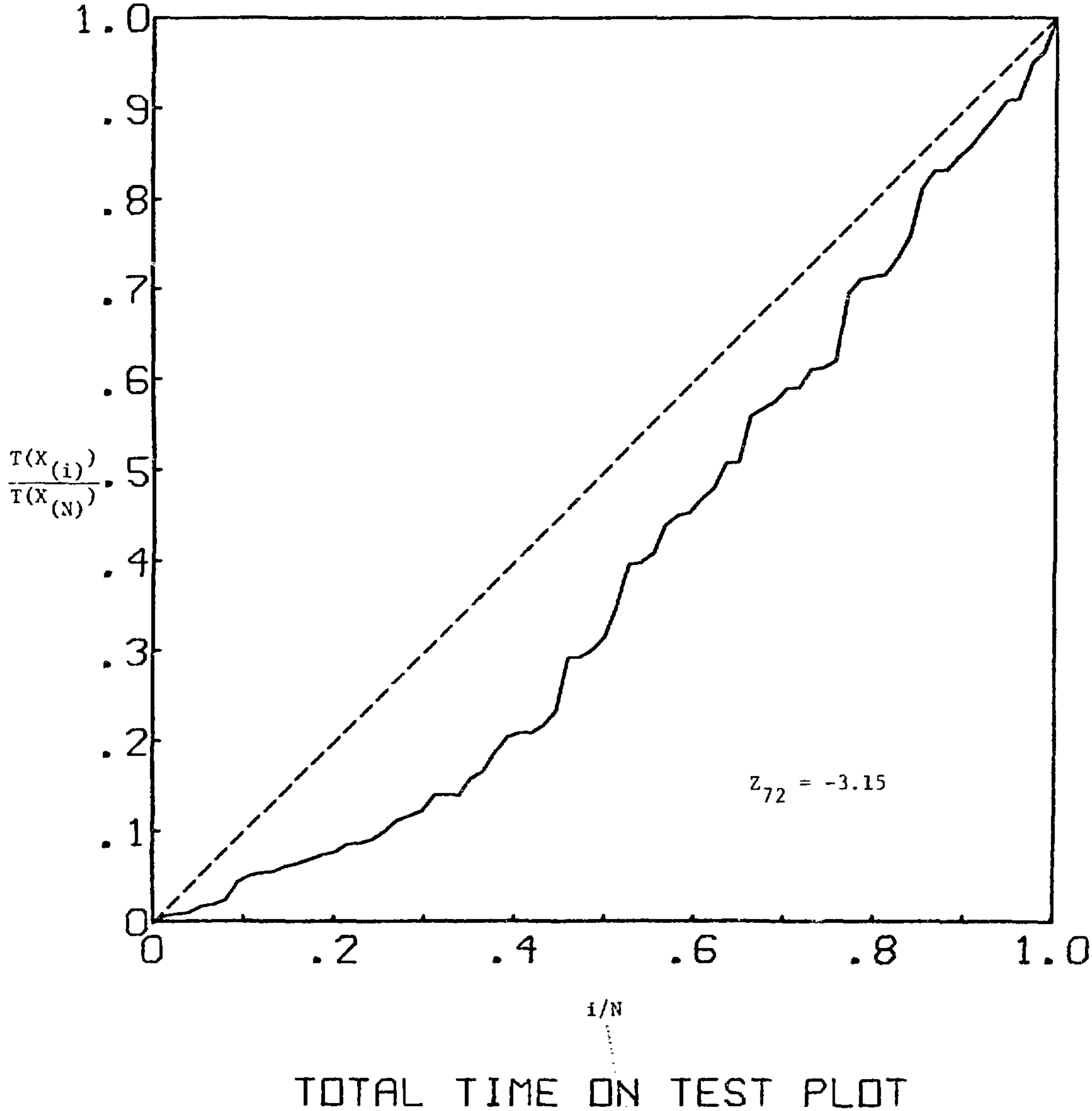


FIGURE 2.11

OTHER (NO. 133) UPTIME

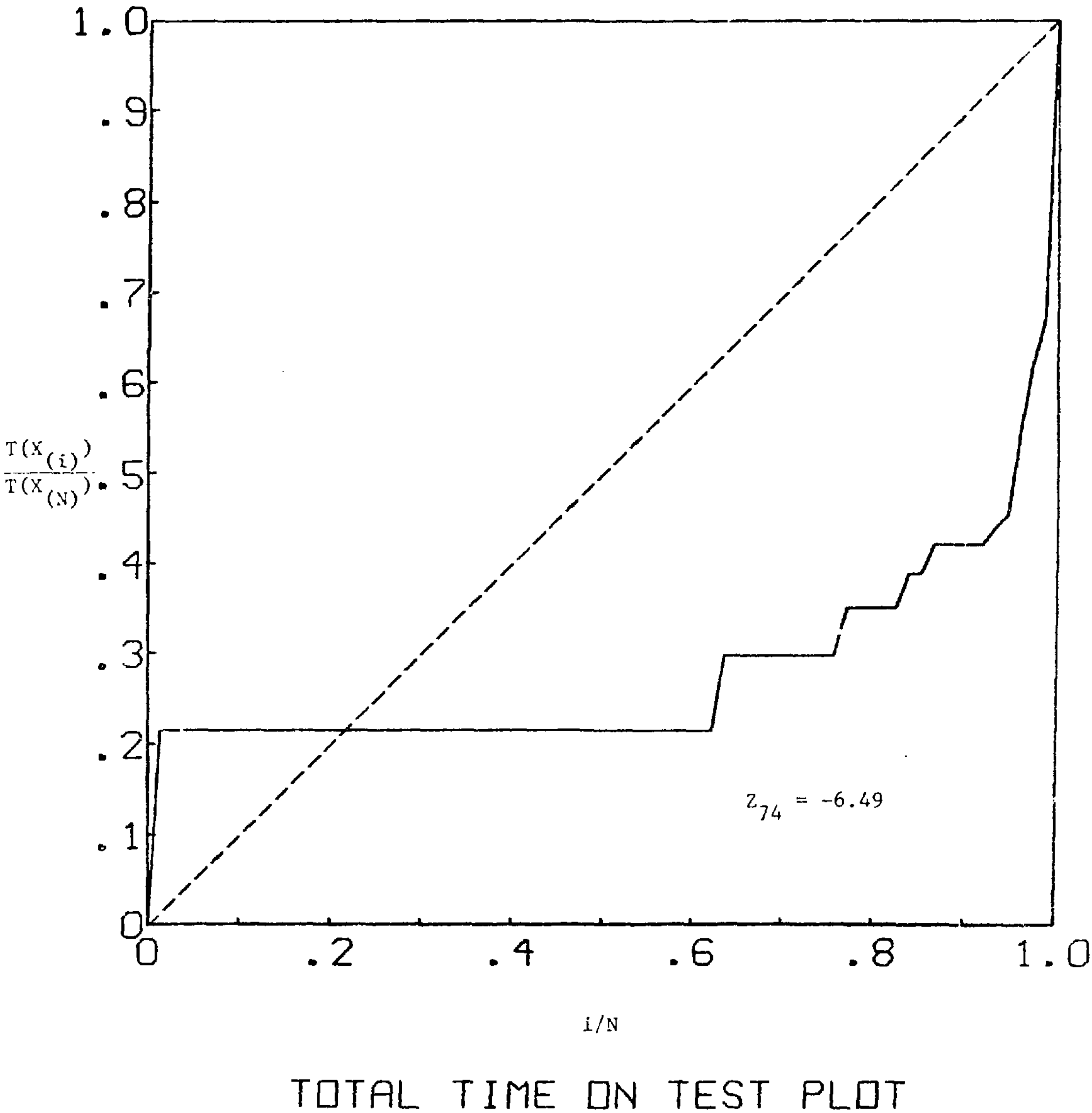


FIGURE 2.12

OTHER (NO. 133) DOWNTIME

CHAPTER 3

ANALYSIS OF OPERATING PERIOD

3.1 Introduction

According to the experiences of the SuperHILAC crew, more failures exist in the early portion of an operating period.

The operating period between general maintenance shutdowns is usually 12 days long.* To test this hypothesis on the RF, all 38 operating periods, shown in Figure 3.2, were superimposed together as in Figure 3.1. Note that the lengths of the downtimes have been ignored. This is because (1) it makes the analysis simpler, (2) a bivariate analysis seems fruitless since the uptimes are uncorrelated with the downtimes (Chapter 5), and (3) the downtimes are insignificant relative to the much longer uptimes.

Treating the failure in each operating period as a truncated point process, a scaled total time on test can be defined for the *processes* (see [6], [7]). Let $n(u)$ be the number of operating periods under observation at operating age u. Let $Z_{(1)} \leq Z_{(2)} \leq \cdots \leq Z_{(N)}$ be the ordered failure epochs in the pooled process. Plot

$$\frac{\int_0^{Z_{(i)}} n(u)du}{\int_0^{Z_{(N)}} n(u)du} \quad \text{versus} \quad \frac{i}{N} \qquad i = 1,2, \ldots, N .$$

*Very short operating periods are associated with holidays. Long operating periods are anomalies.

Assuming the failures in each operating period can be modeled as a nonhomogeneous Poisson point process with intensity function $\lambda(t)$ (analogous to the failure rate), a convex TTT plot indicates $\lambda(t)$ is decreasing while a concave TTT plot indicates $\lambda(t)$ is increasing [6]. If $\lambda(t)$ is decreasing, we expect more failures in the startup phase of the operating period. As in the last chapter, we can use the cumulative TTT statistic to test for a constant intensity function.

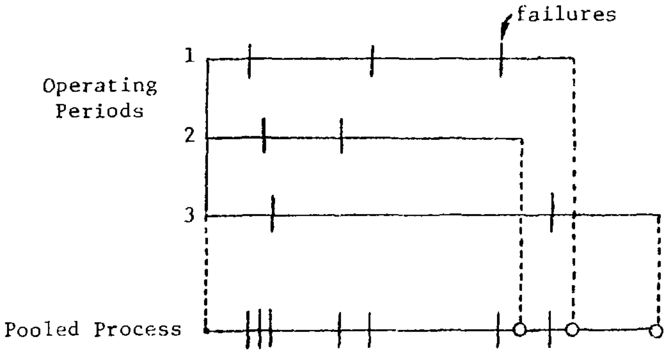


FIGURE 3.1

POOLING OF OPERATING PERIOD UPTIMES

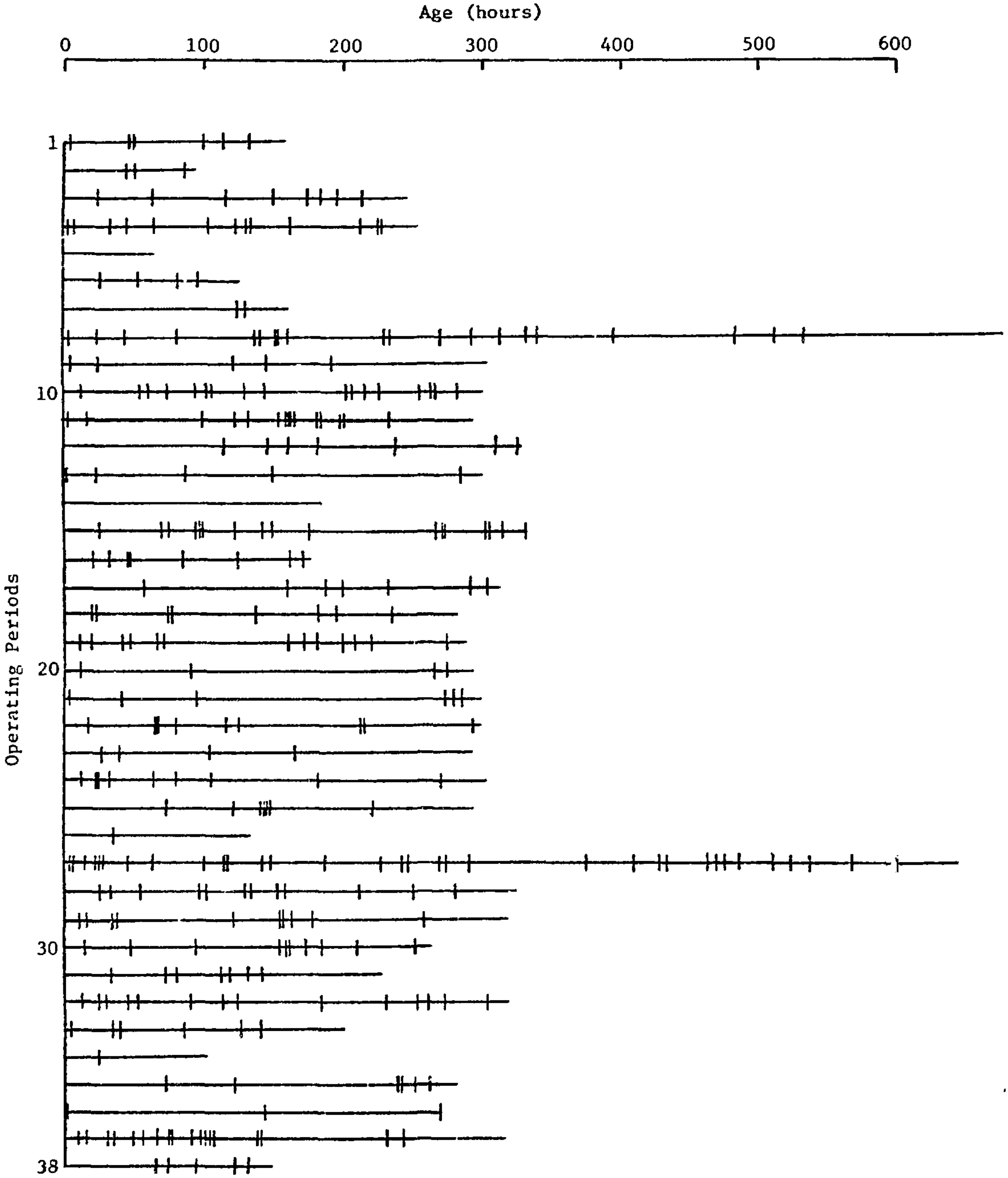


FIGURE 3.2

OPERATING PERIODS

Each vertical line denotes a failure event.

3.2 TTT Plots of Pooled Operating Period Uptimes

TTT plots of the pooled operating period uptimes of the RF, two intermediate and three basic RF components are given in Figures 3.3 - 3.8.

The plot for the RF is near exponential, but is predominantly below the diagonal. A plot for the Computer subsystem, not shown here, displays slightly stronger DFR behavior. This suggests that the RF and Computer subsystems' operating periods ought to be extended.

Among the RF components, all except those associated with *Final Amp Failure* show signs of being exponential and therefore operating periods for these components should be lengthened also. The *Final Amp Failure* branch of the fault tree exhibits IFR properties. Hence it may be desirable to overhaul its associated components more frequently, particularly the Filament Transformer.

Since most RF components are exponential and since we are dealing with superposition, the RF plot is expected to be exponential. The fact that it is not as exponential as we wish suggests that our description of the component-RF relationship may have slight deficiencies. Nevertheless, the reasoning for extending the operating period remains valid.

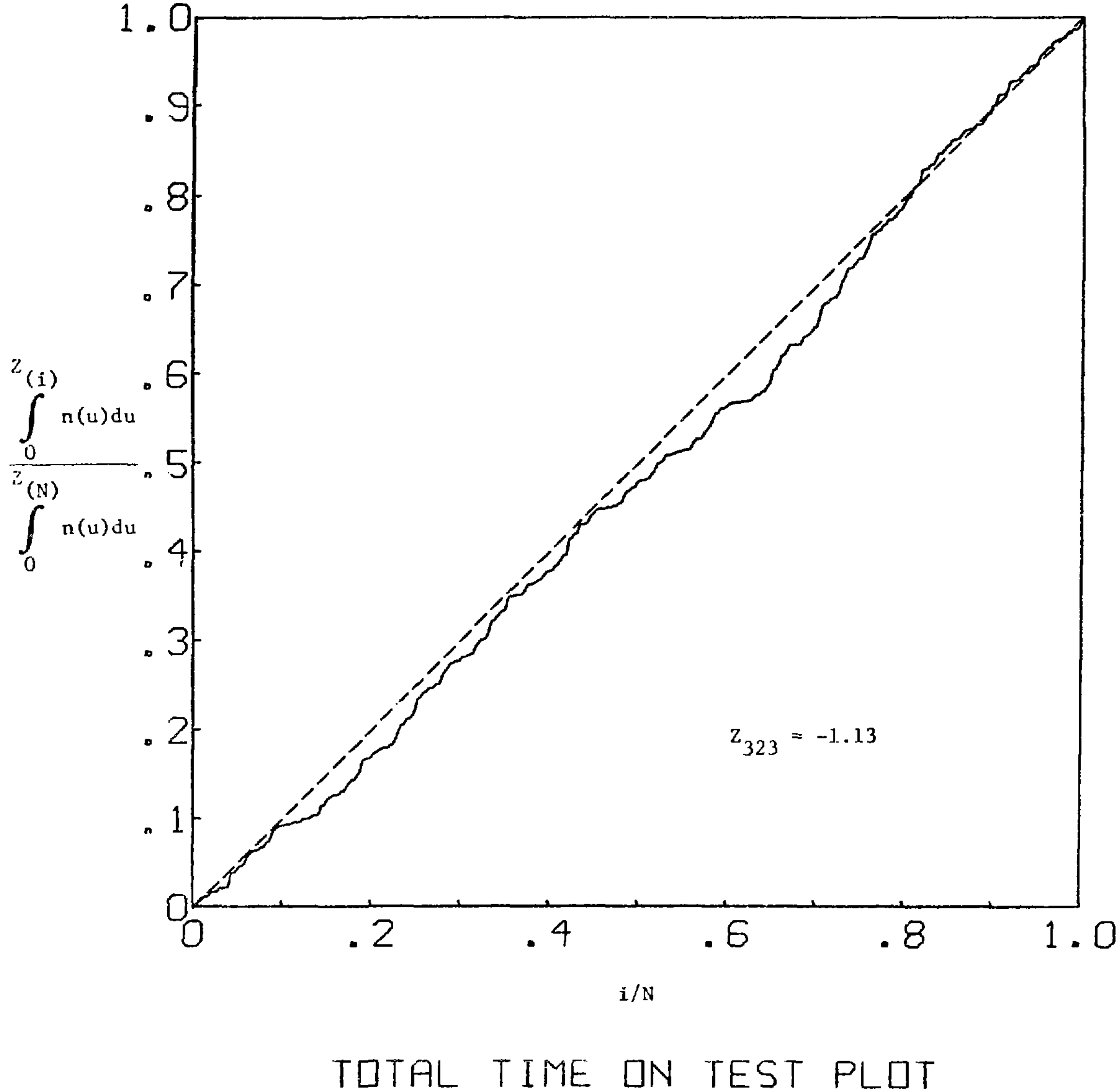


FIGURE 3.3

RF OPERATING PERIOD ANALYSIS

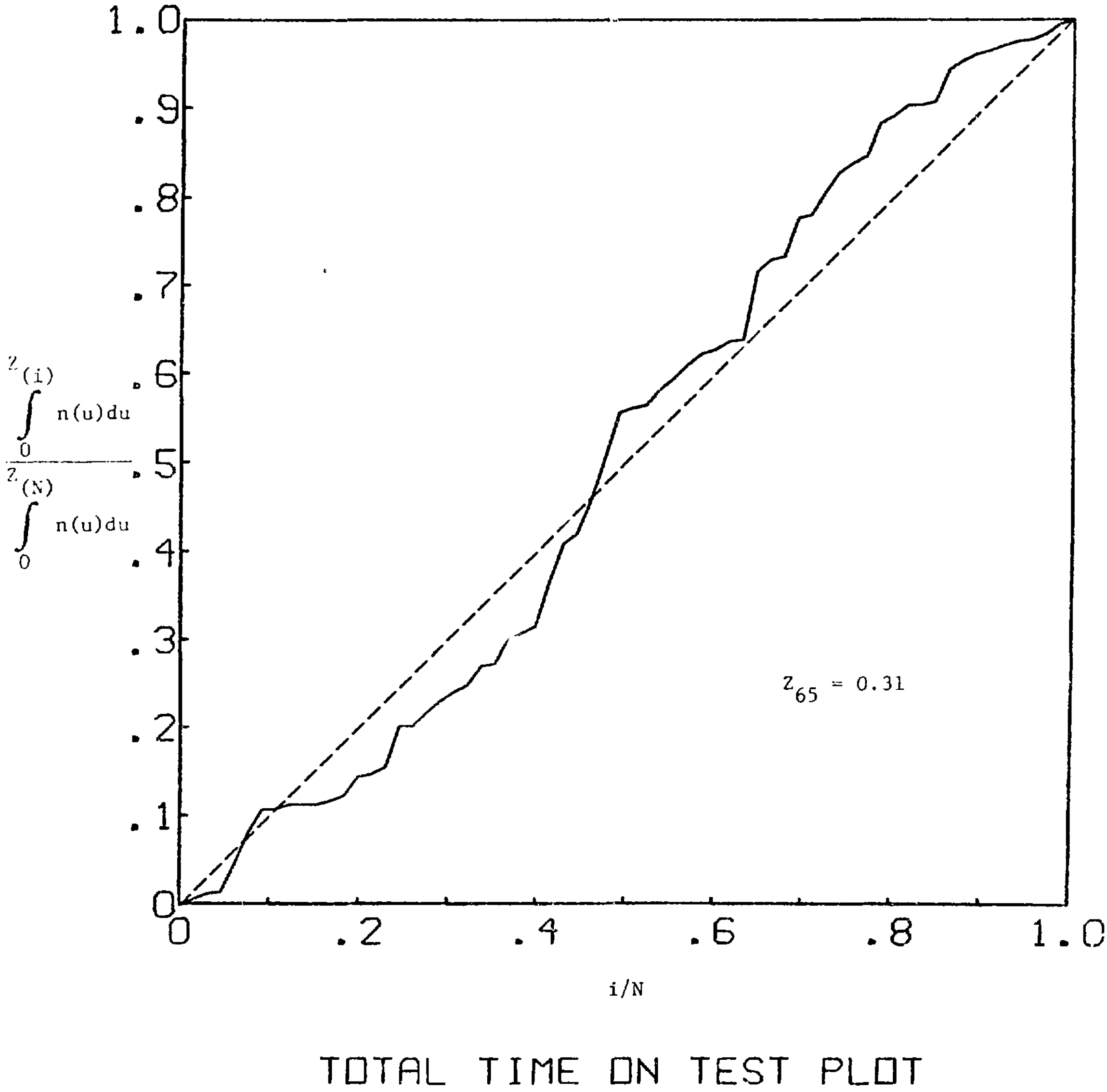


FIGURE 3.4

OPERATING PERIOD ANALYSIS: ACTUAL CONTROL CIRCUIT FAILURE (NO. 3)

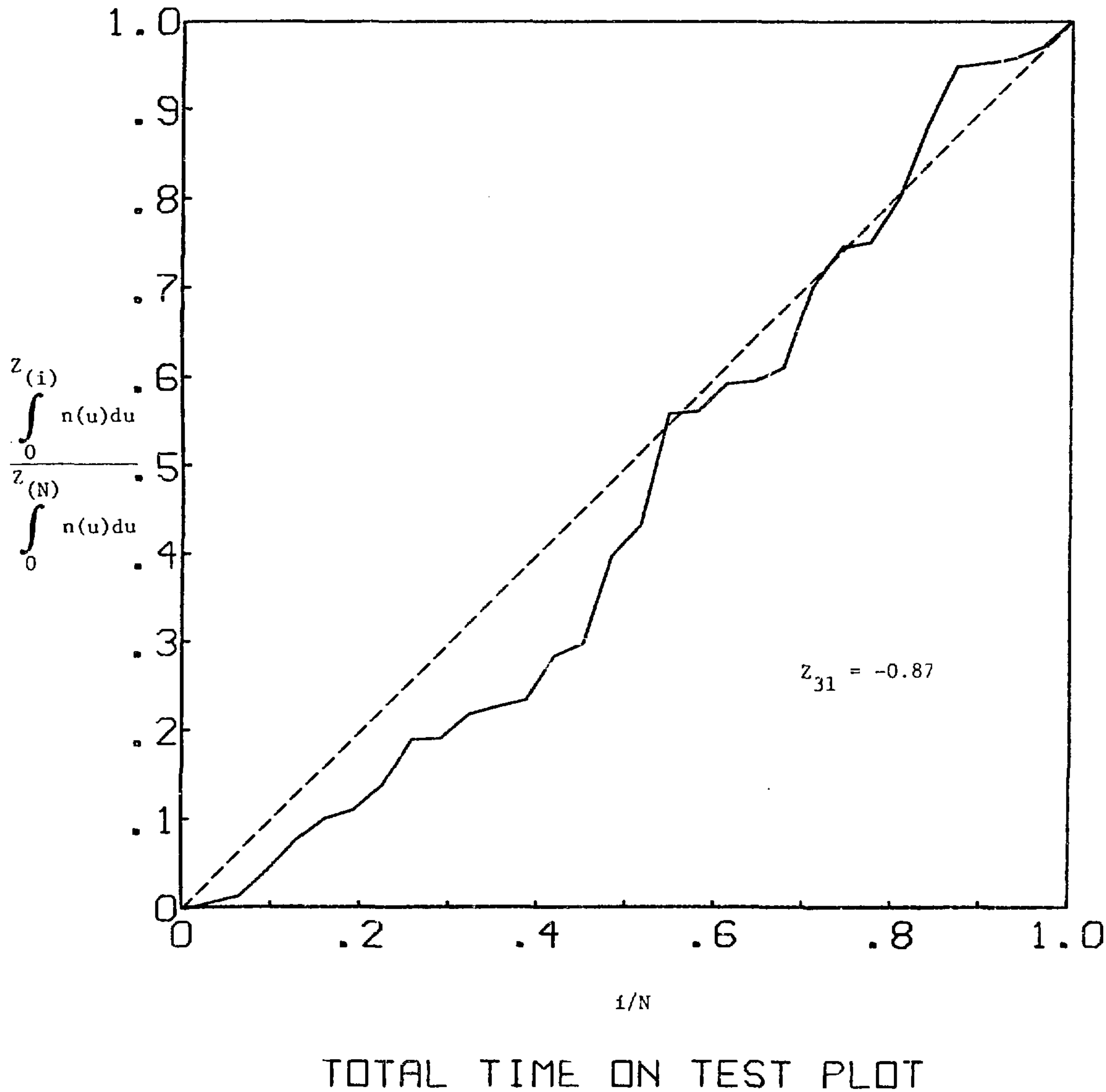


FIGURE 3.5

OPERATING PERIOD ANALYSIS: PHASE (NO. 34)

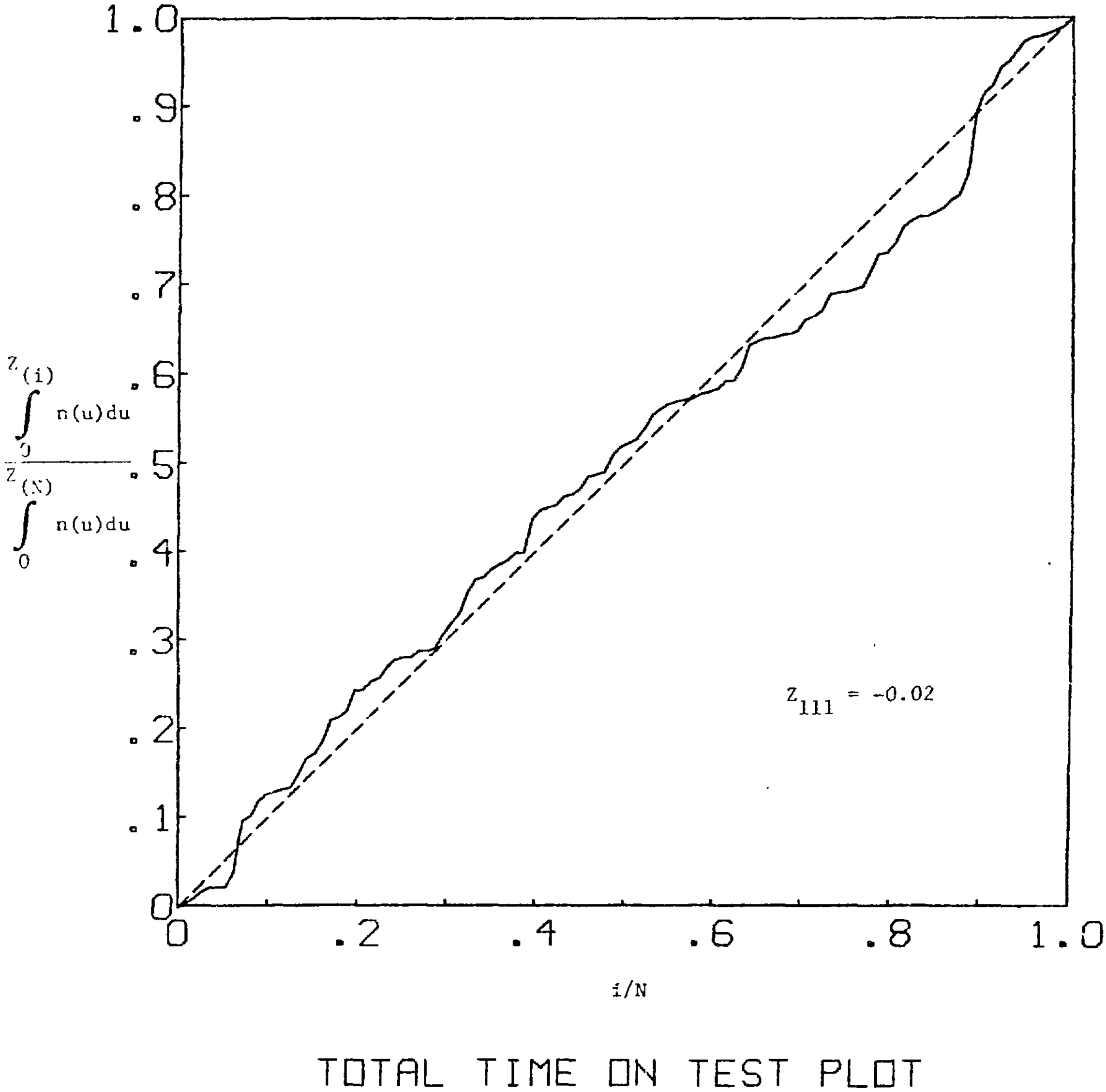


FIGURE 3.6

OPERATING PERIOD ANALYSIS: OTHER RF PROTECTION SHUTDOWN (NO. 130)

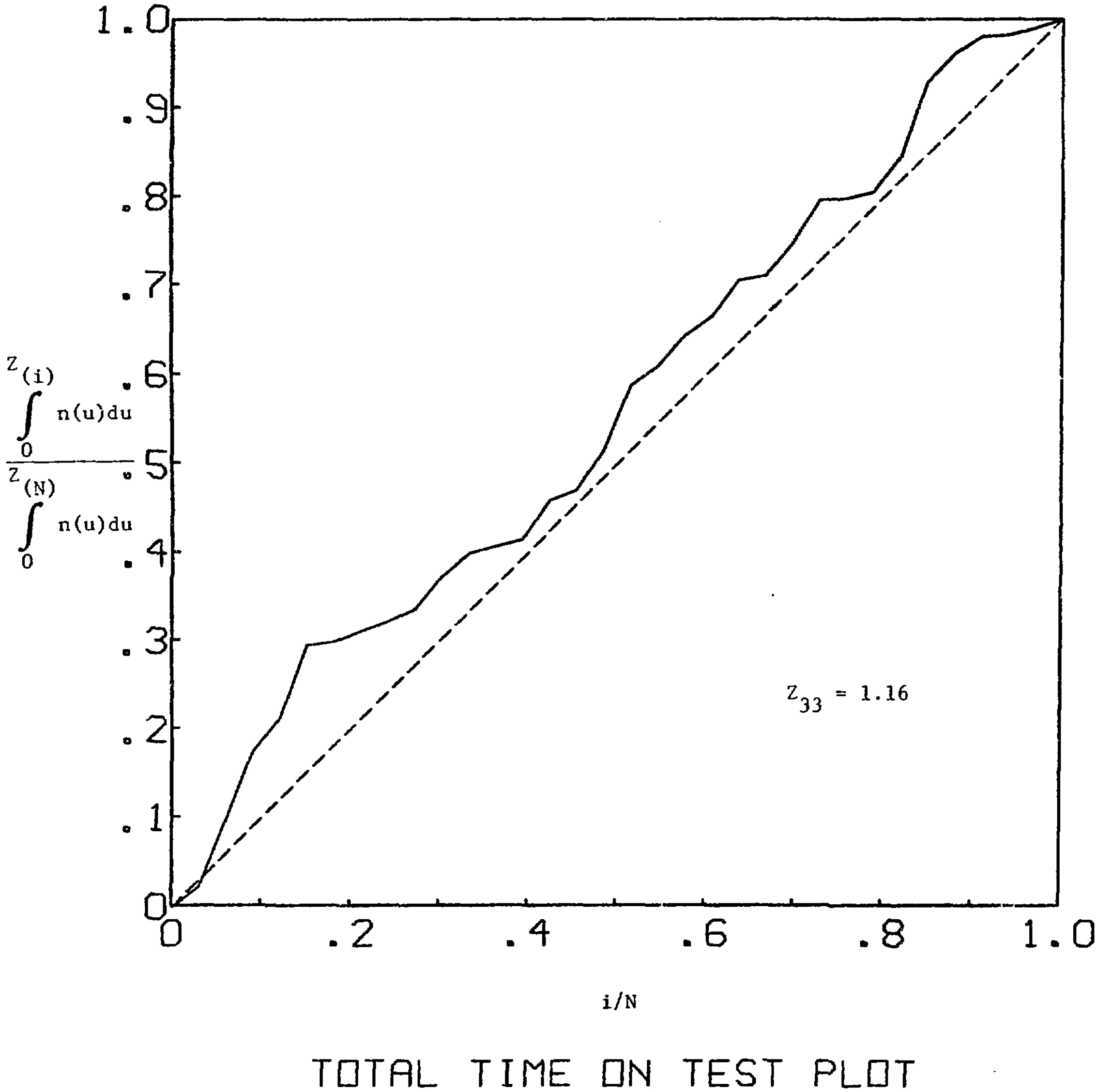


FIGURE 3.7

OPERATING PERIOD ANALYSIS: SPARK (NO. 131)

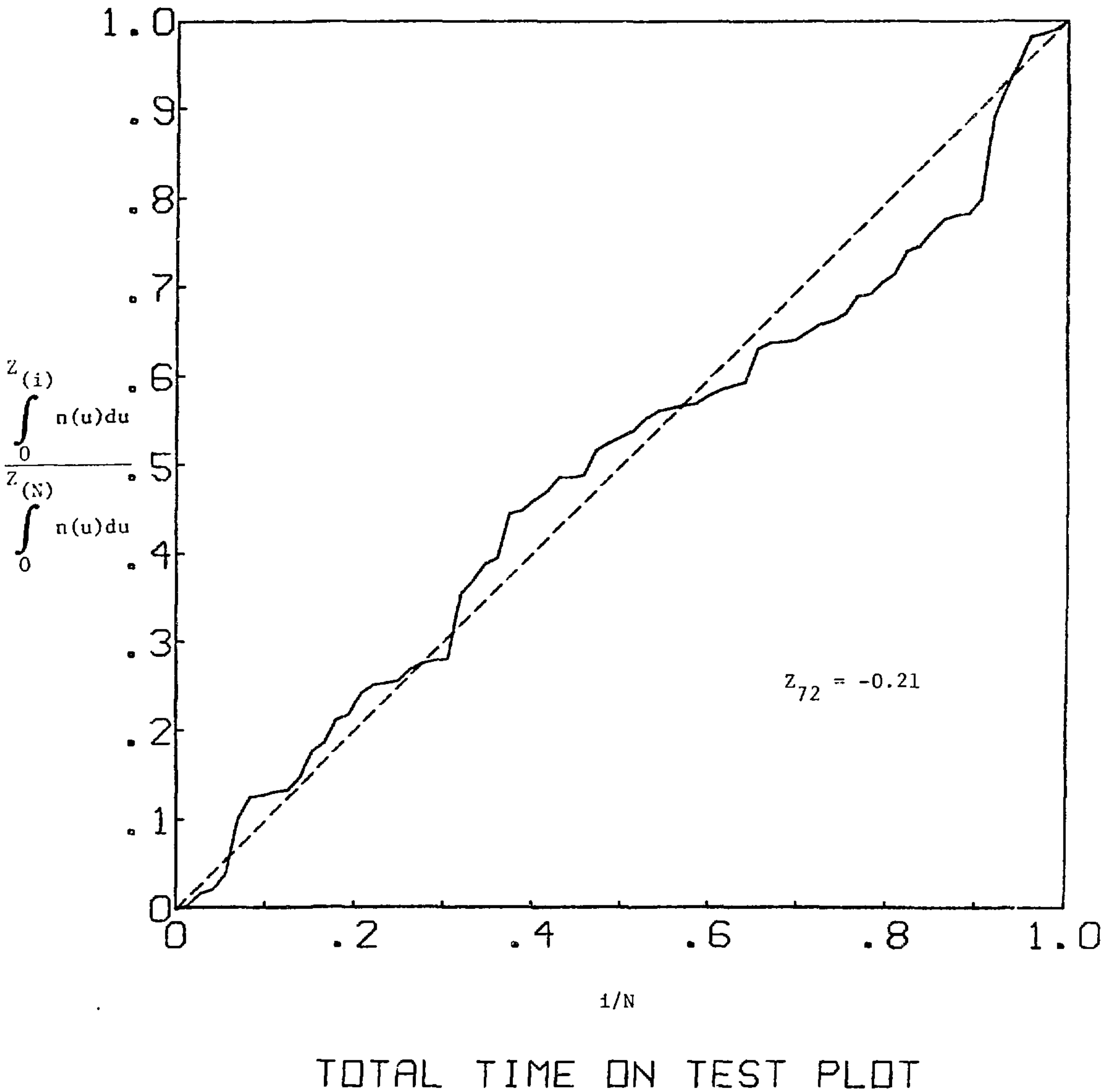


FIGURE 3.8

OPERATING PERIOD ANALYSIS: OTHER (NO. 133)

CHAPTER 4

SUMMARY STATISTICS

In Table 4.1 several summary statistics are given. The first column entries are the SuperHILAC units, subdivided into subsystems, RF intermediate and basic components. RF components not listed have no failure records. The other columns are:

1. Mean time to fail (MTTF) = $\sum_{i=1}^{N+1} U_i/N$ where

   N = number of failures

   U_i $(i = 1, \ldots, N)$ = uptime prior to i^{th} failure

   U_{N+1} = incomplete uptime prior to shutdown.
2. Mean time to repair (MTTR) = $\bar{D}$.
3. Availability (A) = $\frac{\text{MTTF}}{\text{MTTF + MTTR}}$.
4. Number of failures (N) .
5. Coefficient of variation (CV) for uptimes = $\frac{s_U}{\bar{U}}$.
6. CV for downtimes.

The estimates of MTTF, MTTR, and A are defined in accordance with common engineering practice. They are in fact only valid under statistical independence and identically distributed uptimes (downtimes). Our time series analysis will show independence to be a valid assumption. These crude estimates are useful for comparison purposes. The validity of our comments may be weighted by the sample size and the coefficients of variations given. For small samples, the CV is not calculated.

On inspection, the table shows two points: (1) availability is not a good measure of performance here since uptime dominates downtime, and (2) on the basis of MTTF, RF intermediate events *Actual Control Circuit Failure* and *Other RF Protection Shutdown* caused the most failures as expected. A partial ranking of RF components in terms of failure rate $\left(\frac{1}{\text{MTTF}}\right)$ is given in Figure 5.1. 95% confidence intervals are also plotted.

In Figure 4.2 the RF failure rates within the 38 maintenance intervals are plotted chronologically. Based on this small sample, there does not appear to be a seasonal pattern in the RF failures, although component failures may be seasonal. According to SuperHILAC personnel, there should be different SuperHILAC failures in the summer and winter when temperature varies. However, this question was not pursued further.

TABLE 4.1

SUMMARY STATISTICS

Group	Unit	MTTF (hrs)	MTTR (hrs)	A	N	CV (UP)	CV (DOWN)
	Computer	32.49	1.18	.97	313	1.37	1.75
	RF	31.00	1.14	.96	328	1.15	2.36
RF intermediate events	0	340.23	.83	1.00	30	1.59	1.30
	1	421.24	1.70	1.00	24	1.31	2.26
	2	340.36	.68	1.00	30	1.18	1.31
	30	3523.25	1.00	1.00	2		
	3	156.59	1.21	.99	66	1.04	1.39
	4	404.29	2.41	.99	25	1.07	1.40
	6	1173.14	1.69	1.00	8		
	7	1761.25	.85	1.00	5		
	8	479.89	.68	1.00	21	1.34	1.71
	9	1778.21	.50	1.00	5		
	120	2642.75	.25	1.00	3		
	130	91.78	.97	.99	113	1.26	3.56
RF basic components	11	1761.50	.55	1.00	5		
	12	1509.86	.46	1.00	6		
	13	2641.69	1.67	1.00	4		
	14	3521.92	3.00	1.00	2		
	21	363.86	.71	1.00	28	1.13	1.30
	22	5285.63	.50	1.00	1		
	23	5285.76	.25	1.00	1		
	31	620.41	1.55	1.00	16	.94	1.65
	32	879.19	1.95	1.00	11	1.05	.95
	34	319.65	.73	1.00	32	1.07	1.12
	35 (352)	3521.92	3.00	1.00	2		
	42	1320.41	1.21	1.00	7		
	44	3522.16	2.63	1.00	2		
	63	2642.19	1.00	1.00	3		
	71	2113.55	1.00	1.00	4		
	82	621.46	.44	1.00	16	1.50	.62
	91	3523.50	.63	1.00	2		
	122	3523.75	.25	1.00	2		
	123	5285.76	.25	1.00	1		
	131	310.47	.48	1.00	33	1.38	.98
	132	1760.55	1.21	1.00	7		
	133	139.82	1.15	.99	74	1.29	3.67

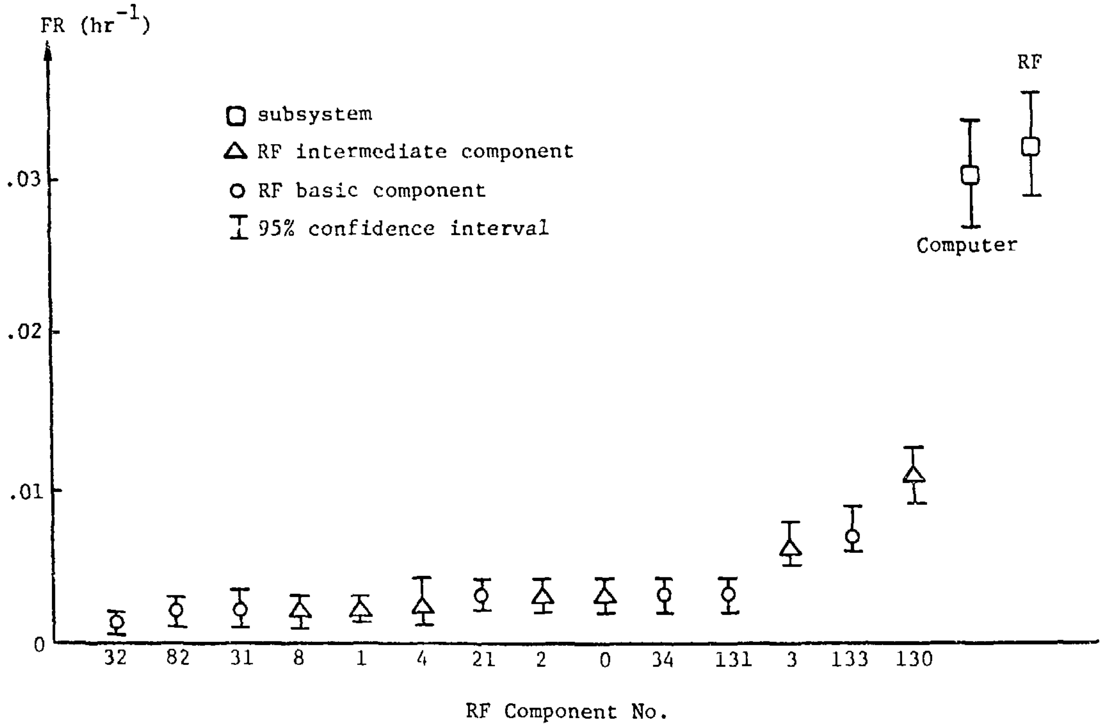


FIGURE 4.1

RF COMPONENT FAILURE RATE

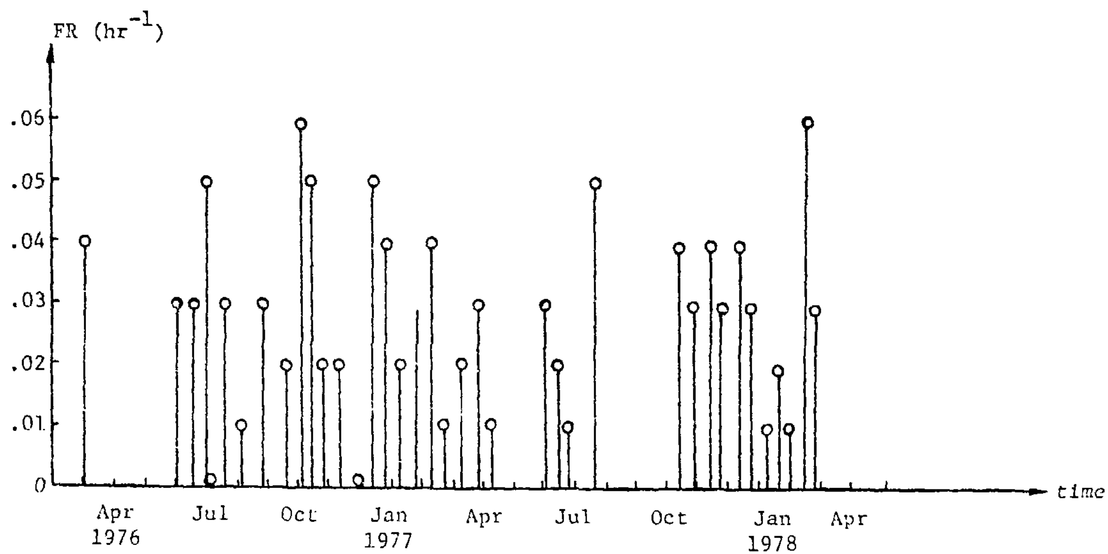


FIGURE 4.2

CHRONOLOGICAL RF FAILURE RATE

CHAPTER 5

TIME SERIES ANALYSIS OF UPTIME AND DOWNTIME SERIES

By using time series analysis techniques, we hope to reveal some underlying structures of operation and failure processes in order to *predict* RF status with past history. The ability to predict accurately is important in scheduling medical usage. The structures we wish to identify belong to the class of Autoregressive Integrated Moving Average (ARIMA) processes. We refer the reader to the book by Box and Jenkins [8] for a complete description of the ARIMA model.

5.1 Univariate Analysis of Serial Data

One modelling attempt is to fit univariate ARIMA models to the uptime and to the downtime series. Serial plots of RF uptimes and downtimes are given in Figures 5.1 and 5.2. The question we wish to address is: given past history of the lengths of the uptimes (downtimes), what can we say about the next uptime (downtime)? In simple mathematical terms, we may wish to find the values of the parameters p , q , ϕ_i $(i = 1,2, \ldots, p)$, θ_j $(j = 1,2, \ldots, q)$, μ , and σ_a^2 in the equation

$$\phi(B)(z_k - \mu) = \theta(B)a_k \tag{5.1}$$

where

$\phi(B) = 1 - \phi_1 B - \cdots - \phi_p B^p$

$\theta(B) = 1 - \theta_1 B - \cdots - \theta_p B^q$

$B^i z_k = z_{k-i}$

z_k = length of the k^{th} uptime (downtime)

μ = mean time to fail (repair)

a_k = independent random shock during the k^{th} uptime (downtime) with mean zero and variance σ_a^2 .

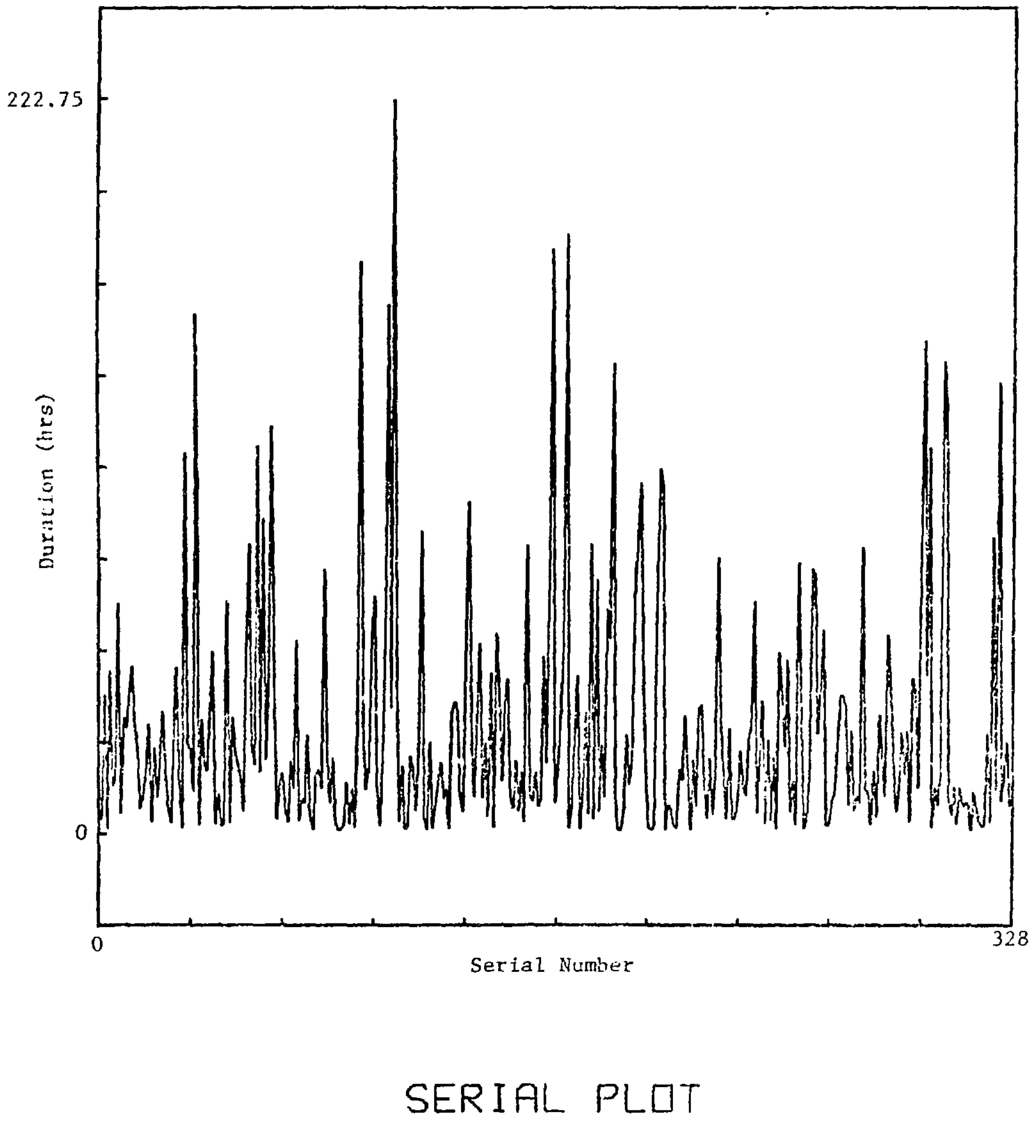


FIGURE 5.1

RF UPTIMES

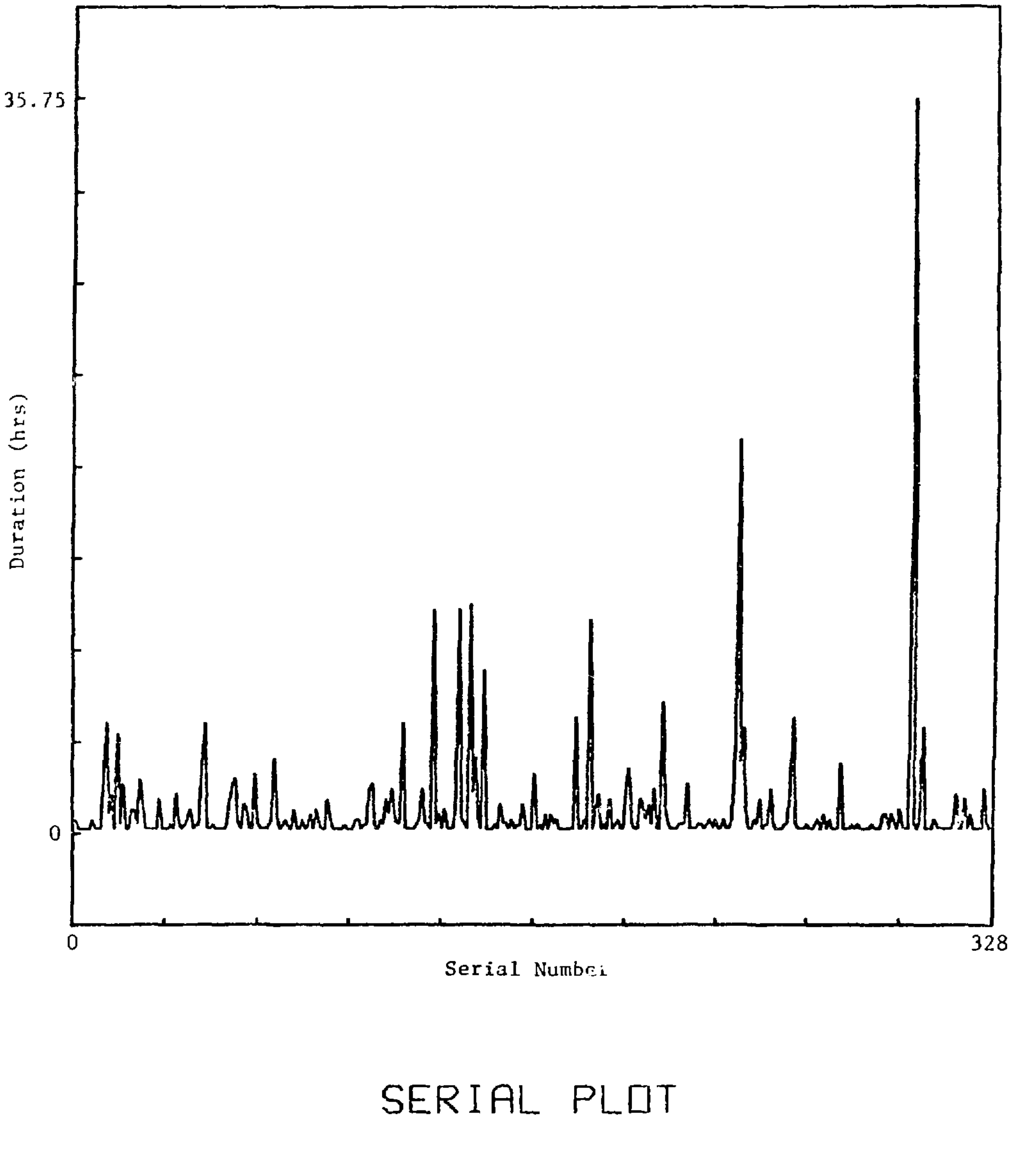


FIGURE 5.2

RF DOWNTIMES

The estimated values of the above parameters depend on the sample autocorrelations r_i :

(5.2) $$r_i = \frac{\sum_{k=1}^{N-i} (z_k - \bar{z})(z_{k+i} - \bar{z})}{\sum_{k=1}^{N} (z_k - \bar{z})^2} \qquad i = 0,1, \ldots$$

where $\bar{z}$ = mean of the series.

The first 5 sample serial autocorrelations for the RF and three of its components are given in Table 5.1.

TABLE 5.1

SAMPLE SERIAL AUTOCORRELATIONS

	RF		Component No.					
			3		130		133	
i	Up	Down	Up	Down	Up	Down	Up	Down
1	.12	.02	-.04	-.10	.07	-.03	-.12	-.01
2	.06	.00	.13	-.06	-.02	-.00	.04	-.03
3	-.05	-.03	.04	.16	.05	-.03	-.03	-.02
4	-.05	.10	-.15	-.02	-.06	-.00	-.07	-.04
5	.01	.01	-.17	-.05	.01	-.03	-.07	-.04
N	328		66		113		74	

Under Normality, which unfortunately is not true here, the standard error of r_i is usually $> 1/\sqrt{N}$. Nevertheless, the autocorrelations are small, and other tests indicate that the uptimes and downtimes of the RF and component Nos. 3, 130, and 133 are each uncorrelated random variables: $z_k = \mu + a_k$.

Of the above three components, Nos. 3 and 130 are intermediate events and No. 133 is a basic event. No other basic event has enough data for a reliable analysis. Based on the above experience, similar analysis with other intermediate events was not attempted.

Examination of uptime and downtime histograms* (Figures 5.3 and 5.4) indicates a logarithmic transformation might be able to produce Normality and brings along more powerful testing procedures. Some trials in this direction resulted in slightly larger and *positive* autocorrelations for small lags. However, sample autocorrelations are known to be correlated, and the values were not large enough to reject our earlier hypothesis.

The preceding analysis has been applied to the SuperHILAC Computer subsystem (No. 9) and identical results were obtained.

5.2 Transfer Function Analysis of Serial Data

Since there are no autocorrelations within each uptime and downtime series, let us see whether something might be said about the next downtime, say, given the past history of the *uptimes*. In simple mathematical terms, we may wish to seek the values of the parameters b , r , s , δ_i $(i = 1,2, \ldots, r)$, ω_j $(j = 0,1, \ldots, s)$, μ_x , μ_y , and σ_n^2 in the equation

$$(y_k - \mu_y) = \delta^{-1}(B)\omega(B)(x_{k-b} - \mu_x) + n_k \tag{5.3}$$

where

*Note the near degenerate downtime distribution.

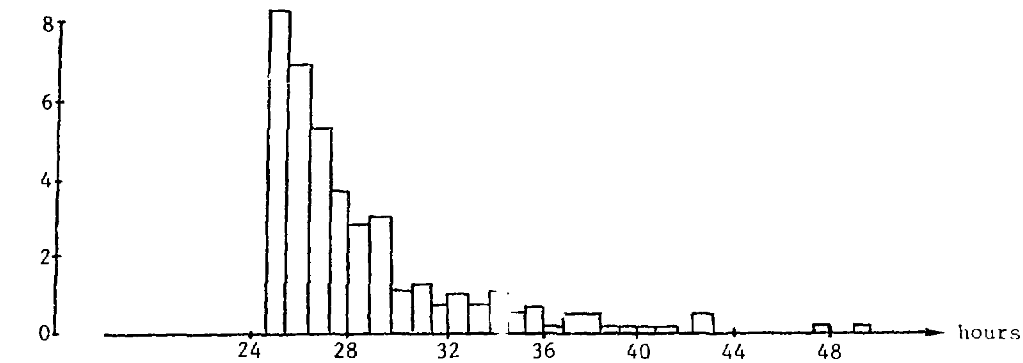


FIGURE 5.3

RF UPTIMES: ORIGINAL DATA

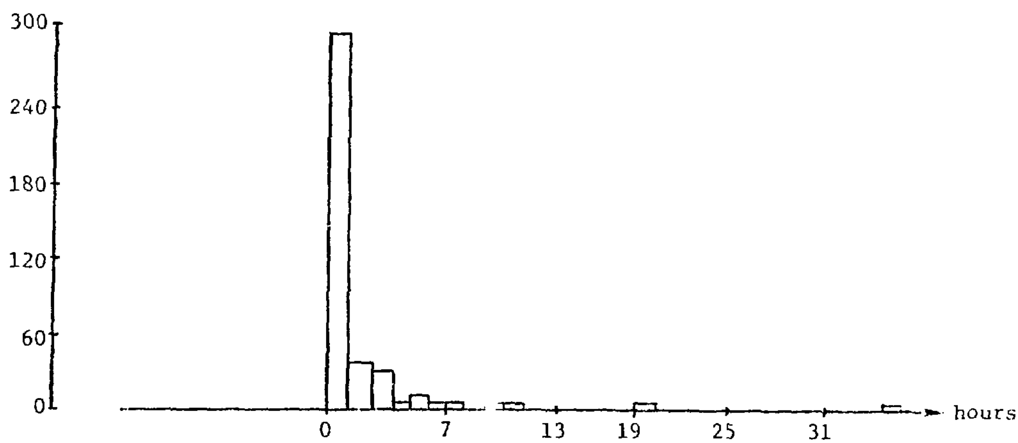


FIGURE 5.4

RF DOWNTIMES: ORIGINAL DATA

$\delta(B) = 1 - \delta_1 B - \cdots - \delta_r B^r$

$\omega(B) = \omega_0 - \omega_1 B - \cdots - \omega_s B^s$

y_k = k^{th} downtime

x_k = k^{th} uptime

n_k = k^{th} noise at the output.

The estimated values of the above parameters depend on the sample cross correlations $r_{xy}(i)$:

$$r_{xy}(i) = \frac{c_{xy}(i)}{\sqrt{c_{xx}(0) \cdot c_{yy}(0)}} \qquad i = 0, \pm 1, \ldots \tag{5.4}$$

where

$$c_{xy}(i) = \begin{cases} \frac{1}{N} \sum_{k=1}^{N-i} (x_k - \bar{x})(y_{k+i} - \bar{y}) & i = 0,1, \ldots \\ \frac{i}{N} \sum_{k=1}^{N+i} (x_{k-i} - \bar{x})(y_k - \bar{y}) & i = 0,-1, \ldots . \end{cases} \tag{5.5}$$

The 11 central sample cross correlations for the RF and three RF components are given in Table 5.2.

Under Normality, standard error of $r_{xy}(i)$ is usually $> 1/\sqrt{N}$. Again the values are small considering the sample sizes, indicating that the uptimes and downtimes are *mutually* uncorrelated random variables.

The preceding analysis was repeated with the Computer subsystem and identical results were obtained.

TABLE 5.2

SAMPLE CROSS CORRELATIONS

i	RF	Component No. 3	130	133
-5	.08	-.15	-.07	-.10
-4	.10	-.04	-.10	.09
-3	-.00	.06	-.05	-.07
-2	-.09	-.13	-.06	-.09
-1	-.03	.03	.18	.10
0	.01	-.09	-.11	-.01
1	.12	.10	.06	.12
2	.05	-.01	.23	-.07
3	.13	-.04	-.07	.27
4	.04	.32	.0[illegible]	-.11
5	-.01	-.06	.18	-.06
N	328	66	113	74

5.3 Problems in Real Time Analysis

One approach used by Liang [1], but was not repeated here, involves real time variables like bimonthly mean failure rate (MFR) and mean repair rate (MRR). These data are:

1. Discontinuous because of the existence of several idle months. Liang had to "invent" data points to fill the gaps.
2. Few in numbers. Bimonthly data for our 2 years period give at most a 48 points time series, just barely enough for a reliable analysis. Shorter interval yields more missing data points.
3. Not very reliable. Some bimonthly MFR and MRR would have to be obtained from averages of only a few uptimes and downtimes.
4. Difficult to interpret, since they would cut across maintenance periods.

Because of the above, real time analysis with MFR and MRR was not attempted.

CHAPTER 6

CONCLUSION

In Chapter 1 we gave a list of raw results obtained from analyses described in preceding chapters. In this conclusion we offer interpretations of results and recommendations for the improvement of SuperHILAC performance.

1. Information in the stored data files contains too many discrepancies with logbook data. These errors were incurred during coding and key punching. We expect that by having the SuperHILAC crew doing the coding directly, in addition to keeping a log, data handling errors will be minimized.
2. Logbook entries are not well designed for categorization into the 14 subsystems. Furthermore, descriptions are not detailed enough to trace RF failures to the components responsible. Future logbook format, component definitions, and descriptions of fault tree events should be linked without ambiguities.
3. There is a conflict of interests concerning information provided by the logbooks. Summary statistics favored by SuperHILAC personnel and bookkeeping usage use a different set of information than a statistical life testing model. In particular, our study needed to know (1) actual termination time of a maintenance break instead of the scheduled time, and (2) actual component responsible for failure and the effective downtime instead of a history of the trial-and-error search process and the instability before the final crash. Although not much can be done since different analyses require different data, we felt it is appropriate to point out this fact.

4. Refinement of the recording unit produced no changes in the time series analysis or TTT plots. The .25 hr unit did manage to bring out more failures and therefore reduced RF MTTF and MTTR from 51.70 and 2.00 hrs to 31.00 and 1.14 hrs respectively. However, the availability remained at .96. The Computer MTTF and MTTR were reduced from 146.50 and 2.14 hrs to 32.49 and 1.18 hrs respectively, with a drop of availability from .99 to .97. Further refinement of unit is always welcomed, but we feel it is unnecessary for our purposes unless "trip-offs" of less than 7.5 minutes are considered significant.

5. As (4) has shown, the interpretation of MTTF and MTTR depend on what is considered as a failure. Many SuperHILAC failures considered by Liang were not actual failures - e.g., Source Element Change, Set-Up, Stripper Foil Change - but were necessary steps prior to an experiment. Removal of such nonfailures, particualrly in *Adam*, *Eve*, and *Other* subsystems' records, would yield higher MTTF. Likewise, the definition of the availability of the SuperHILAC needs reexamining. Availability of .95 was somehow set to be a desirable level of operation. We wish to point out such a goal is unreachable even if RF were made perfect. Experimental set-ups have already slashed *Adam*, *Eve*, and *Other* subsystems' availability down to .82, .94, and .93 respectively. For our purposes, we feel that if tuning and *Experimenter's* downtimes (subsystem 14) were not considered

as actual failures, neither should set-ups. In any case, improvement in SuperHILAC availability rests more on the efficiency of set-up procedures than on reliability of the RF.

6. Partially because of (5), we feel availability is not a good measure of desirable SuperHILAC performance. The RF downtimes are so short compared with the uptimes that a 50% decrease in MTTF would cause no appreciable decrease in availability. Since scheduling periods of continuous use is important, MTTF, and hence reliability, would be a better measure.
7. Another point in the interpretation of availability concerns the parasitic mode. Availability of the parasitic mode was found by Liang to be larger than those of the other modes when we expected lower availability, since the parasitic beam puts more stress on the system. It seems that the higher availability came about because the parasitic beam was never turned on until the system had been operating satisfactorily for some time.
8. Although only basic time series analytic techniques were used, we are convinced that the RF and the SuperHILAC are too unstable, in terms of their constituents, and their workloads are too random to sustain any ARIMA structures. Besides sample information like mean and variances, there may not exist any reliable predictions of uptimes and downtimes. Further time series analysis is unwarranted unless more stable data could be obtained or some physical model is to be tested.

9. The uptimes of the RF and its components are found to be either exponential or DFR. This suggests that no replacement or overhaul of units should be made until the unit goes down. For the RF and most components, this is impossible since scheduled maintenance dictates that service be done at a given time, whether the unit is up or down.

10. The maintenance records of the RF, and all but one RF component, are found to be either exponential or DFR. This means the RF operating period should be extended, perhaps to a month. Only the Filament Transformer shows IFR property and suggests more frequent maintenance on this unit is desirable.

11. Liang has shown earlier that subsystem *Other* with availability of .93 and MTTF of 18.15 hrs is the worst subsystem. This study found that RF basic component number 133 (*Other*) is the worst among its peers. Together with RF intermediate component number 0 (*Others*) and basic component number 123 (*Other*) they comprise 36% of the total number of failures and 40% of the total downtimes. Clearly a great deal of effort must be put in constructing better fault trees for the SuperHILAC and the RF if we are to identify and correct the weaknesses of the system.

12. The RF failure records did not show any seasonal patterns. Inspection of the Computer subystem data also failed to turn up seasonal patterns. If summer temperatures are the cause of more failures, the Cooling subsystem data should reveal it.

However, Cooling was found by Liang to have a MTTF of 1479.64 hrs and availability of 1.00, and hence cannot account for much of anything. This indicates that current records do not identify actual causes of RF failures, but only indicate components that needed immediate attention.

13. If our MTTFs were not so much larger than our MTTRs, and we have accurate information about the shut-off relationships among the components (i.e., the status of a component when another component is down), then we can test the accuracy of our RF fault tree by comparing actual RF availability with derived RF availability from component data. But since MTTF >> MTTR, availabilities are insensitive to shut-off relationships [2]. Liang has therefore put unnecessary emphasis on the importance of these relationships.
All our component uptimes were obtained under assumption of functional independence, i.e., failure of one component will not shut off another. Our derived RF availability $A_{\cdot\cdot} = \prod_i A_i = .964$ is $\leq$ actual RF availability of .965, which agrees with theory. The contrary result $(A_{\cdot\cdot} > A)$ that Liang got is probably due to data error.

14. We have not made too many assumptions in our analysis. The most obvious being suspended animation during maintenance in order to join uptimes and downtimes. This is of course incorrect since all kinds of testings are being made, but it may be unimportant considering these uptimes and downtimes are truncated random data.

APPENDIX A

SUBROUTINE FOR SUPERHILAC SUBSYSTEM DATA RETRIEVAL

Subroutine RADIO and the accompanying two sets of program HILAC updates, listed here, are used to select from a stored data file the relevant information for a SuperHILAC subsystem analysis. Subroutine RADIO utilizes the input and output features of program HILAC but avoids all its other subroutines.

Subroutine RADIO serves two functions. One is to produce detailed output similar to program HILAC but for one specified subsystem and without SuperHILAC operating mode considerations. Another is to rearrange and condense this output into a table as input to program RF (Appendix B). Update statements titled TABLE need to be inserted for the second function.

Besides deleting irrelevant information concerning other subystems and recalculating uptimes between failures and shut-downs, subroutine RADIO also edits maintenance breaks and orders events with respect to time to adjust for having ignored operating modes. An example of maintenance break editing is shown in Figure A1.1.

RF Subsystem Data

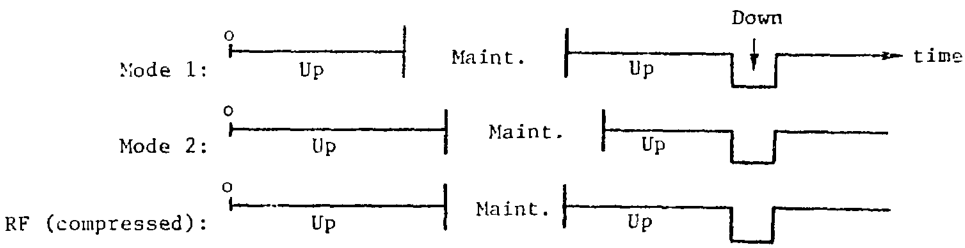


FIGURE A1.1

COMPRESSION OF MAINTENANCE BREAKS

```
*IDENT RADIO
*D HILAC.2
*B HILAC.3
      PROGRAM HILAC(INPUT,OUTPUT,PUNCH)
*I HILAC.6
      DIMENSION RFDATA(500,5),INDEX(40)
      INDEX(1)=0
      JINDEX=1
*I HILAC.45
      GO TO 1
*I HILAC.62
    1 CALL RADIO(RFDATA,INDEX,JINDEX)
*INSERT HILAC.65
      SUBROUTINE RADIO(RFDATA,INDEX,JINDEX)
      COMMON/A/AD,AF,AFA,AT,AU,AUT,A1(750,10),B(60),ED,EF,EFA,ET,EU,EUT,
     1EVENT(2),EVT(750,2),EXE,IM,IX,G(14),U(10),L8,LV,M,PD,PF,PFA,PT,PU
     2,QD,QF,QFA,QT,QU,QUT,RD,RF,RFA,RT,RU,RUT,SD,SF,SFA,ST,SU,SUT,UD,UF
     3,UFA,UT,UU,UUT,VD,VF,VFA,VT,VU,VUT,WD,WF,WFA,WT,WU,WUT
     4,ID,IF,IFA,IT,IU,IUT,PUT,V(10),EA,PA,AA
      DIMENSION RFDATA(500,5),INDEX(40),Z(80,2)
C
C          COMPRESS MAINTENANCE INTERVALS
C
      IM1=IM+1
      A1(IM1,1)=0
      DO 5 I=1,IM
      IF(A1(I,7).NE.3)GO TO 5
      K=I+1
      DO 6 J=K,IM1
      IF((A1(J,7).NE.3).OR.(A1(J,1).EQ.0))GO TO 52
    6 CONTINUE
   52 LL=J-1
      IF(LL.EQ.I)GO TO 5
      BIG=24*(A1(I,1)-1)+A1(I,2)
      SMALL=BIG+A1(I,4)
      DO 4 LP=K,LL
      BIG1=24*(A1(LP,1)-1)+A1(LP,2)
      BIG=AMAX1(BIG,BIG1)
      SMALL1=BIG1+A1(LP,4)
    4 SMALL=AMIN1(SMALL,SMALL1)
      A1(I,1)=1+AINT(BIG/24)
      A1(I,2)=BIG-24*(A1(I,1)-1)
      A1(I,4)=SMALL-BIG
      DO 43 LP=K,LL
   43 A1(LP,7)=2
    5 CONTINUE
C
C          DELETE IRRELEVANT INFORMATION
C
      IT=0
      DO 1 I=1,IM
      IF(A1(I,7).EQ.2)GO TO 1
      IF((A1(I,7).EQ.5).OR.(A1(I,7).EQ.4).OR.(A1(I,7).EQ.3).OR.(A1(I,6).
```

```
     1EQ.9))GO TO 2
      GO TO 1
    2 IT=IT+1
      Z(IT,1)=I
      Z(IT,2)=24*(A1(I,1)-1)+A1(I,2)
    1 CONTINUE
C
C          SORT Z WITH RESPECT TO TIME
C
      I=1
   15 IF(Z(I,2).LE.Z(I+1,2))GO TO 20
      X=Z(I,1)
      Y=Z(I,2)
      Z(I,1)=Z(I+1,1)
      Z(I,2)=Z(I+1,2)
      Z(I+1,1)=X
      Z(I+1,2)=Y
      I=MAX0(I-1,0)
      GO TO 15
   20 I=I+1
      IF(I.NE.IT)GO TO 15
C
C          OUTPUT AND UPTIME CALCULATION
C
      DO 7 IL=1,IT
      IP=Z(IL,1)
      IF(A1(IP,7).NE.5)GO TO 8
    3 K=IP
      UPTIME=0
C           FOR TABLE, INSERT  -  GO TO 33
      PRINT 100,(EVT(IP,L),L=1,2),(A1(IP,L),L=1,7)
      GO TO 7
    8 IF((A1(IP,7).EQ.3).AND.(A1(K,7).EQ.4))GO TO 3
    9 UPTIME=24*(A1(IP,1)-1)+A1(IP,2)-(24*(A1(K,1)-1)+A1(K,2)+A1(K,4))
      K=IP
C           FOR TABLE, INSERT  -  GO TO 33
      PRINT 100,(EVT(IP,L),L=1,2),(A1(IP,L),L=1,4),UPTIME,(A1(IP,L),L=6,
     17)
  100 FORMAT(1X,2A10,7F7.2)
   33 I=500-(IT-INDEX(JINDEX)+IL)
      RFDATA(I,1)=A1(IP,1)
      RFDATA(I,2)=A1(IP,2)
      RFDATA(I,3)=A1(IP,4)
      RFDATA(I,4)=UPTIME
      RFDATA(I,5)=A1(IP,7)
    7 CONTINUE
      JINDEX=JINDEX+1
      INDEX(JINDEX)=IT+INDEX(JINDEX-1)
      RETURN
      END
```

```
*IDENT TABLE
*I HILAC.10
      DATA XAY/10HMAY       /,SEPT/10HSEPTEMBER /,APRIL/10HAPRIL     /
      IF((HEADER.EQ.XAY).AND.(IYEAR.EQ.1978))GO TO 33
      IF((HEADER.EQ.SEPT).AND.(IYEAR.EQ.1977))GO TO 33
      IF(((HEADER.EQ.XAY).OR.(HEADER.EQ.APRIL)).AND.(IYEAR.EQ.1976))GO T
     1O 33
      DATA FEB/10HFEBRUARY  /
      IF((HEADER.EQ.FEB).AND.(IYEAR.EQ.1976))GO TO 149
*D HILAC.11
*D HILAC.14
*I HILAC.63
   33 READ 101,(EVENT(I),I=1,2),(B(I),I=1,24)
      GO TO 50
  149 PRINT 777
  777 FORMAT(1H1,/)
      PRINT 150,((RFDATA(I,J),J=1,5),I=1,500)
  150 FORMAT(5F8.2)
```

APPENDIX B

PROGRAM FOR SUPERHILAC SUBSYSTEM COMPONENT UPTIME AND DOWNTIME EDITING

Program RF and its four supporting subroutines, listed here, are used to obtain (1) the uptime and downtime series, and (2) the pooled maintenance information from the output of subroutine RADIO.

For uptimes and downtimes, program RF (1) merges consecutive downtimes, (2) joins time segments separated by shutdown/maintenance, (3) discards downtimes which lead an operating period, and (4) gives useful statistics and other information. For the maintenace analysis, program RF does the above for each operating period and then pools the uptime information into a vector. Details of the above procedures were given in Chapters 1, 3, and 5.

Note: There is a problem with the initial value of the uptime series.

```
      PROGRAM RF(INPUT,OUTPUT,PUNCH)
      COMMON /A/IK,RFDATA(500,5)
      DIMENSION UPTIME(500),OFF(500)
      DIMENSION UPMAX(50),MAXI(50),UPOOL(500)
C           IK = AMOUNT OF RFDATA
C           RFDATA = INPUT DATA (DAY,TIME,DOWN,UP,OPTION)
      IK=0
      DO 2 J=1,500
    2 UPTIME(J)=0.
  110 IK=IK+1
      READ 112,(RFDATA(IK,J),J=1,5)
  112 FORMAT(5F8.?)
      IF(RFDATA(IK,5).NE.8.)GO TO 110
      IK=IK-1
      PRINT 1
    1 FORMAT(1H1)
      PRINT 111,IK
  111 FORMAT(16I5)
  123 FORMAT(10F8.2)
C           MERGE CONSECUTIVE DOWNTIMES (0-OCARDS)
      CALL MERGE
C           JJ = AMOUNT OF UP-DOWN PAIRS
C           KPP,IKK = DATA SEGMENT TO BE ANALYZED
C           UPTIME,OFF = UP-DOWN PAIRS
      KPP=1
      IKK=IK+1
C
C           ANALYSIS OF MAINTENANCE SEGMENTS 1
C           INSERT FOLLOWING 12 CARDS FOR MAINT ANALYSIS
      IFLAG=KZ=0
      GO TO 99
   98 KPP=IKK
   99 DO 510 KP=KPP,IK
      IF((RFDATA(KP,5).NE.3.).AND.(KP.NE.IK))GO TO 510
      IKK=KP+1
      R3=RFDATA(IKK,3)
      R4=RFDATA(IKK,4)
      R5=RFDATA(IKK,5)
      GO TO 96
  510 CONTINUE
   96 CONTINUE
C
      RFDATA(IKK,4)=.001
      RFDATA(IKK,3)=RFDATA(IKK,5)=0
C           JOIN TIME SEGMENTS SEPERATED BY SHUTDOWNS/MAINTENANCE
      CALL JOIN(UPTIME,OFF,KPP,IKK,JJ)
C           IGNORE STARTING DOWNTIME
      K=1
      IF(UPTIME(1).EQ.0)K=2
C           IGNORE ENDING ZERO UPTIME
      IF(UPTIME(JJ).EQ.0.001)JJ=JJ-1
      PRINT 663
  663 FORMAT(16H    DOWN      UP)
      PRINT 664,(OFF(I),UPTIME(I),I=K,JJ)
  664 FORMAT(2F8.2)
C           AVAILABILITY STATISTICS
      CALL STAT(UPTIME,OFF,K,JJ,PERIOD)
```

```
C
C          ANALYSIS OF MAINTENANCE SEGMENTS 2
C          INSERT FOLLOWING 41 CARDS FOR MAINT ANALYSIS
      IF(PERIOD.LE.0.001)GO TO 14
      CALL MAINT(UPTIME,K,JJ,J1,IFLAG,UPOOL,UPMAX,KZ)
   14 IF((IKK-1).EQ.IK)GO TO 10
      RFDATA(IKK,3)=R3
      RFDATA(IKK,4)=R4
      RFDATA(IKK,5)=R5
      GO TO 98
   10 PRINT 11
   11 FORMAT(/,1X,14HPOOLED MAINT =)
      PRINT 123,(UPOOL(I),I=1,J1)
C          ORDER UPMAX
      DO 16 L=1,KZ
      J=L
      XMIN=UPMAX(L)
      DO 15 I=L,KZ
      IF(UPMAX(I).GE.XMIN)GO TO 15
      XMIN=UPMAX(I)
      J=I
   15 CONTINUE
      UPMAX(J)=UPMAX(L)
   16 UPMAX(L)=XMIN
C          FIND INDICES
      UPOOL(J1+1)=1000.
      KY=1
      I=1
    5 IJ=0
      DO 4 II=KY,KZ
      IF(UPMAX(II).NE.UPMAX(KY))GO TO 3
    4 IJ=IJ+1
    3 IF(UPOOL(I).LE.UPMAX(KY))GO TO 6
      I=I-IJ
      MAXI(KY)=I
      IF(KY.EQ.KZ)GO TO 7
      KY=KY+1
    6 I=I+1
      IF(I.LE.(J1+1))GO TO 5
    7 PRINT 12,KY
   12 FORMAT(1X,33HTOTAL NUMBER OF MAINT INTERVALS =,I5)
      PRINT 13
   13 FORMAT(1X,32HINDICES OF MAINT ENDING POINTS =)
      PRINT 111,(MAXI(I),I=1,KY)
C
      JJ=JJ-1
      END
```

```
      SUBROUTINE MERGE
      COMMON /A/IK,RFDATA(500,5)
C          MERGE CONSECUTIVE DOWNTIMES (0-0 CARDS)
C          J = NUMBER OF 0-0 CARDS
C          JJ = END LOCATION
C          KK = START LOCATION
C          LK = FLAG VARIABLE FOR ADJUSTMENT TO KK
      J=1
      LK=0
      DO 7 I=1,IK
C          TEST FOR 0-0 CARD
      IF((RFDATA(I,4).NE.0).OR.(RFDATA(I,5).NE.0))GO TO 7
      IF(RFDATA(I-1,5).NE.0)LK=1
C          COUNT NUMBER OF 0-0 CARDS
    8 IF((RFDATA(I+J,4).NE.0).OR.(RFDATA(I+J,5).NE.0))GO TO 11
      J=J+1
      GO TO 8
   11 JJ=I+J-1
      KK=I-1+LK
      IF(JJ.EQ.KK)GO TO 13
      DOWN=0
      UP=RFDATA(KK,4)
C          MERGE
      DO 12 L=KK,JJ
      DOWN=DOWN+RFDATA(L,3)
      RFDATA(L,3)=RFDATA(L,4)=0
   12 RFDATA(L,5)=8.
C          RESET
      RFDATA(JJ,3)=DOWN
      RFDATA(JJ,4)=UP
      RFDATA(JJ,5)=0
      J=1
   13 LK=0
    7 IF(RFDATA(I,5).EQ.3.)RFDATA(I,3)=0.
      RETURN
      END
```

```
      SUBROUTINE JOIN(UPTIME,OFF,KPP,IKK,JJ)
      COMMON /A/IK,RFDATA(500,5)
      DIMENSION UPTIME(IKK),OFF(IKK)
C         JOIN TIME SEGMENTS SEPERATED BY SHUTDOWNS/MAINTENANCE
C         J = NUMBER OF SHUTDOWNS/MAINT CARDS TO SKIP
      JJ=0
C         ADJUST STARTING POINT
      KPPP=KPP
      DO 1 I=KPPP,IKK
      IF((RFDATA(I,3).NE.0.).OR.(RFDATA(I,4).NE.0.))GO TO 2
    1 KPP=KPP+1
    2 DO 77 I=KPP,IKK
      IF(RFDATA(I,5).EQ.8)GO TO 77
      J=1
      UP=DOWN=0
      JJ=JJ+1
C         RECORD IF FAILURE CARD
      IF(RFDATA(I,5).NE.0)GO TO 70
      UPTIME(JJ)=RFDATA(I,4)
      OFF(JJ)=RFDATA(I,3)
      GO TO 77
C         TEST FOR ZERO PREVIOUS UPTIME
   70 IF(RFDATA(I,4).NE.0)GO TO 60
C         SEARCH FOR NEXT FAILURE CARD
   72 IF(RFDATA(I+J,5).EQ.0)GO TO 71
      J=J+1
      GO TO 72
C         TEST FOR DOWN-DOWN
   71 IF(RFDATA(I+J,4).NE.0)GO TO 78
      KK=I-1
      LK=I+J
C         JOIN DOWN-DOWN
      DO 94 L=KK,LK
      DOWN=DOWN+RFDATA(L,3)
      UP=UP+RFDATA(L,4)
      RFDATA(L,3)=RFDATA(L,4)=0.
   94 RFDATA(L,5)=8.
C         RESET
      RFDATA(LK,5)=0
      RFDATA(LK,3)=DOWN
      RFDATA(LK,4)=UP
      JJ=JJ-2
      IF(JJ.LT.0)JJ=0
      GO TO 77
C         DOWN-UP
   78 LK=I+J-1
      DO 79 L=I,LK
   79 RFDATA(L,5)=8
      GO TO 76
C         SEARCH FOR NEXT FAILURE CARD
   60 IF(RFDATA(I+J,5).EQ.0)GO TO 91
      J=J+1
      GO TO 60
C         JOIN UP-UP/DOWN
   91 LK=I+J
      DO 93 L=I,LK
      UP=UP+RFDATA(L,4)
```

```
      RFDATA(L,5)=8
   93 RFDATA(L,4)=0.
C          RESET
      RFDATA(LK,5)=0
      RFDATA(LK,4)=UP
   76 JJ=JJ-1
   77 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STAT(UPTIME,OFF,K,JJ,PERIOD)
      DIMENSION UPTIME(JJ),OFF(JJ)
C          AVAILABILITY STATISTICS
      J1=JJ
      UP=DOWN=0.
      DO 10 I=K,JJ
      UP=UP+UPTIME(I)
   10 DOWN=DOWN+OFF(I)
      PRINT 11,UP
   11 FORMAT(1X,15HTOTAL UPTIMES =,F12.2)
      PERIOD=UP+DOWN
      PRINT 15,PERIOD
   15 FORMAT(1X,8HPERIOD =,F19.2)
      IF(PERIOD.LE.0.001)GO TO 60
      AVAIL=UP/PERIOD
      UP=UP/(JJ-K   )
      IF((OFF(JJ).EQ.0.).AND.(JJ.NE.K))J1=JJ-1
      DOWN=DOWN/(J1-K+1)
      PRINT 20,UP
   20 FORMAT(1X,19HMEAN TIME TO FAIL =,F8.2)
      UP=1/UP
      PRINT 30,UP
   30 FORMAT(1X,19HMEAN FAILURE RATE =,F8.2)
      PRINT 40,DOWN
   40 FORMAT(1X,21HMEAN TIME TO REPAIR =,F6.2)
      PRINT 50,AVAIL
   50 FORMAT(1X,14HAVAILABILITY =,F13.2)
   60 RETURN
      END
```

```
      SUBROUTINE MAINT(UPTIME,K,JJ,J1.IFLAG,UPOOL,UPMAX,KZ)
      DIMENSION UPTIME(JJ)
      DIMENSION UPOOL(500),UPMAX(50),UPTIM(50)
C          J1 = SIZE OF UPOOL
C          J2 = SIZE OF UPTIM
C          UPMAX = ENDING POINTS OF MAINT INTERVALS
C          IFLAG = 1 AFTER CALL MAINT
C          UPOOL = POOLED MAINT
C          KZ = SIZE OF UPMAX
C          UPTIM = TEMPORARY STORAGE OF INDIVIDUAL MAINT
C          LB = LOWER INDEX FOR UPOOL
      IF(IFLAG.NE.0)GO TO 625
      IFLAG=1
      UPOOL(1)=UPTIME(K)
      J1=JJ-K+1
      IF(J1.LT.2)GO TO 627
      DO 626 I=2,J1
  626 UPOOL(I)=UPOOL(I-1)+UPTIME(I+K-1)
  627 KZ=KZ+1
      UPMAX(KZ)=UPOOL(J1)
      GO TO 2
C          ACCUMULATE UPTIME
  625 UPTIM(1)=UPTIME(K)
      J2=JJ-K+1
      DO 601 I=2,J2
  601 UPTIM(I)=UPTIM(I-1)+UPTIME(I+K-1)
      KZ=KZ+1
      UPMAX(KZ)=UPTIM(J2)
      LB=1
      DO 602 I=1,J2
      IF(UPTIM(I).LT.UPOOL(LB))GO TO 607
      IF(UPOOL(J1).LT.UPTIM(I))GO TO 608
      DO 603 J=LB,J1
      IF(J.EQ.J1)GO TO 608
      IF((UPOOL(J).LE.UPTIM(I)).AND.(UPOOL(J+1).GE.UPTIM(I)))GO TO 604
  603 CONTINUE
  604 J1=J1+1
      LB=J+2
      UPT=UPOOL(J+1)
      UPOOL(J+1)=UPTIM(I)
      GO TO 606
  607 J1=J1+1
      LB=LB+1
      UPT=UPOOL(LB-1)
      UPOOL(LB-1)=UPTIM(I)
C          SHIFT
  606 DO 605 L=LB,J1
      IF(L.EQ.J1)GO TO 628
      UPT1=UPOOL(L)
  628 UPOOL(L)=UPT
  605 UPT=UPT1
  602 CONTINUE
      GO TO 2
C          ATTACH
  608 K21=J1+1
      J1=J1+J2-I+1
      DO 609 J=K21,J1
      UPOOL(J)=UPTIM(I)
  609 I=I+1
    2 RETURN
      END
```

APPENDIX C

PROGRAM FOR CALCULATING TOTAL TIME ON TEST

Program TTTPLOT and its six supporting subroutines, listed here, are used to calculate and plot the total time on test transform for (1) uptimes or downtimes, and (2) pooled operating period uptimes. The input to program TTTPLOT is the output of program RF. Details of the total time on test plot were given in Chapters 2 and 3.

```
      PROGRAM TTTPLOT(INPUT,OUTPUT,TAPE99,TAPE8=INPUT)
      COMMON /A/Z(400)/B/KY,MAXI(50)
      DIMENSION X(400),N(400),NS(400),NN(400)
      DIMENSION X1(400),Y1(400),X2(401),Y2(401),SPECS(30)
      EQUIVALENCE(X1(1),X2(2)),(Y1(1),Y2(2))
C          Z = INPUT DATA
C          X = ORDERED DISTINCT VALUES OF Z
C          N = REMAINING NUMBER OF ITEMS ON TEST
C          NF = NUMBER OF DISTINCT VALUES OF Z
C          NS = COUNTS OF THE REPETITION OF VALUES OF X
C          X1,2 = NORMALIZED X-AXIS
C          Y1,2 = NORMALIZED TTT
C          SPECS = PLOT SPECIFICATIONS
C
C          INSERT THE FOLLOWING 10 CARDS FOR MAINT RUN
C          KY = TOTAL NUMBER OF MAINT INTERVALS
C          MAXI = INDICES OF ENDING POINTS FOR THE MAINT INTERVALS
C          NN = REMAINING NUMBER OF MAINT INTERVALS ON TEST
      READ(8,300)KY,(MAXI(I),I=1,KY)
  300 FORMAT(16I5)
      PRINT 10,KY
   10 FORMAT(1X,34HTOTAL NUMBER OF MAINT INTERVALS = ,I5)
      PRINT 20
   20 FORMAT(1X,32HINDICES OF MAINT ENDING POINTS =)
      PRINT 300,(MAXI(I),I=1,KY)
C
 222  READ(8,35)Z
      IF(EOF(5LINPUT))2,222
    2 PRINT 30
   30 FORMAT(1X,12HINPUT DATA =)
      PRINT 35,Z
   35 FORMAT(10F8.2)
      CALL SORT(X,N,NF,NS)
C          FOR MAINT RUN, INSERT  -  CALL SORT1(NN,NS,NF)
C          FOR MAINT RUN, REMOVE THE FOLLOWING CARD  -  CALL SOVERA
      CALL SOVERA(NF,X,NS)
C          FOR MAINT RUN, REPLACE BY  -  CALL TTT1(NF,NN,N,X,X1,Y1)
      CALL TTT(NF,N,X,X1,Y1)
      NOS=N(1)
C          FOR MAINT RUN, INSERT  -  CALL FIX1(NOS,X1,Y1)
      PRINT 40
   40 FORMAT(/,1X,27HTOTAL TIME ON TEST VALUES =)
      PRINT 35,(Y1(I),I=1,NOS)
C          PLOT
      X2(1)=0.
      Y2(1)=0.
      SPECS(1)=1.2
      SPECS(2)=3.
      SPECS(7)=6.
      SPECS(8)=6.
      SPECS(9)=1.0
      SPECS(10)=1.0
      SPECS(11)=1.0
      SPECS(12)=99.0
```

```
      CALL GDLILI(SPECS)
      SPECS(9)=10.
      SPECS(10)=10.
      CALL AXLILI(SPECS)
      SPECS(3)=1.0
      SPECS(4)=0.0
      SPECS(5)=1.0
      SPECS(6)=0.0
      SPECS(17)=.12
      SPECS(18)=.10
      SPECS(19)=0.0
      SPECS(20)=0.
      SPECS(21)=2.0
      SPECS(24)=0.0
      SPECS(26)=0.0
      SPECS(28)=1.0
      CALL NODLIL(SPECS)
      CALL NODLIB(SPECS)
      SPECS(24)=1.
      CALL TITLES(23HTOTAL TIME ON TEST PLOT,SPECS)
      SPECS(13)=NOS+1.
      SPECS(14)=1.0
      SPECS(15)=1.0
      CALL SLLILI(X2,Y2,SPECS)
      X2(2)=1.
      Y2(2)=1.
      SPECS(13)=2.
      DASH = .1
      SPACE = .05
      CALL DLLILI(X2,Y2,DASH,SPACE,SPECS)
      CALL COSEND(SPECS)
      END
```

```
      SUBROUTINE SORT(X,N,NF,NS)
      COMMON /AZZ/Z(400)
      DIMENSION X(400),N(400),NS(400)
C          K = AMOUNT OF DATA IN Z
C          Z IS BUTCHERED AFTER EXECUTION
      K=1
      ZMAX=Z(1)
      DO 10 I=2,400
      IF(Z(I).GT.ZMAX)ZMAX=Z(I)
   10 IF(Z(I).GT.0.)K=K+1
      DO 20 I=1,K
   20 NS(I)=0
      NF=1
   30 XMIN=Z(1)
      DO 40 I=2,K
   40 IF(Z(I).LT.XMIN)XMIN=Z(I)
      IF(XMIN.EQ.ZMAX+1)GO TO 60
      X(NF)=XMIN
      DO 50 I=1,K
      IF(Z(I).EQ.XMIN)NS(NF)=NS(NF)+1
   50 IF(Z(I).EQ.XMIN)Z(I)=ZMAX+1
      NF=NF+1
      GO TO 30
   60 NF=NF-1
      N(1)=K
      DO 70 I=2,NF
   70 N(I)=N(I-1)-NS(I-1)
      RETURN
      END
```

```
      SUBROUTINE SORT1(NN,NS,NF)
      DIMENSION NS(NF),NN(NF)
      COMMON /L/KY,MAXI(50)
C          LI = AMOUNT OF DATA IN Z
C          LJ = NF+1
      LI=0
      LJ=1
      KYY=KY
      DO 31 LK=1,KY
   32 LI=LI+NS(LJ)
      LL=LI
      NN(LJ)=KYY
      LJ=LJ+1
      IF(LI.EQ.MAXI(LK))GO TO 22
      IF(LI.GT.MAXI(LK))GO TO 9
      GO TO 32
    9 LKK=LK
   10 LL=LL-1
      KYY=KYY-1
      LK=LK+1
      IF(LL.EQ.MAXI(LKK))GO TO 22
      GO TO 10
   22 KYY=KYY-1
   31 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SCVERA(NF,X,NS)
      DIMENSION X(NF),NS(NF)
C           A = ESTIMATED MEAN
C           S2 = ESTIMATED VARIANCE
C           CV = ESTIMATED COEFFICIENT OF VARIATION
      N=0
      A=0.
      S2=0.
      DO 10 I=1,NF
      N=N+NS(I)
      A=A+X(I)*NS(I)
   10 S2=S2+NS(I)*X(I)**2
      A=A/N
      S2=S2/N-A**2
      CV=SQRT(S2)/A
      PRINT 20,CV
   20 FORMAT(1X,22HCOEFF. OF VARIATION = ,F5.2)
      RETURN
      END
```

```
      SUBROUTINE FIX1(NOS,X1,Y1)
      COMMON /E/KY,MAXI(50)
      DIMENSION TEMP(400),X1(NOS),Y1(NOS)
      J=1
      K=1
      DO 10 I=1,NOS
      IF(I.EQ.MAXI(K))GO TO 5
      TEMP(J)=Y1(I)
      J=J+1
      GO TO 10
    5 K=K+1
   10 CONTINUE
      NOS=NOS-KY
      DO 20 I=1,NOS
      X1(I)=FLOAT(I)/NOS
   20 Y1(I)=TEMP(I)/TEMP(NOS)
      RETURN
      END
```

```
      SUBROUTINE TTT(NF,N,X,X1,Y1)
      DIMENSION X(NF),N(NF),X1(400),Y1(400),TEMP(400)
C           TEMP = DISTINCT CUMULATIVE TTT
C           NOS = TOTAL NUMBER OF ITEMS TESTED
      NOS=N(1)
      DO 10 I=1,NOS
   10 X1(I)=FLOAT(I)/NOS
      TEMP(1)=X(1)*NOS
      DO 20 I=2,NF
   20 TEMP(I)=(X(I)-X(I-1))*N(I)+TEMP(I-1)
      N2=1
      N1=NF-1
      DO 40 J=1,N1
      N3=N2+N(J)-N(J+1)-1
      DO 30 I=N2,N3
   30 Y1(I)=TEMP(J)
   40 N2=N3+1
      N3=N2+N(NF)-1
      DO 50 I=N2,N3
   50 Y1(I)=TEMP(NF)
      DO 60 I=1,N3
   60 Y1(I)=Y1(I)/Y1(N3)
      RETURN
      END
```

```
      SUBROUTINE TTT1(NF,NN,N,X,X1,Y1)
      DIMENSION NN(NF),X(NF),X1(400),Y1(400),TEMP(400),N(NF)
C           LI = AMOUNT OF DATA IN Z
C           TEMP = DISTINCT CUMULATIVE TTT
      LI=N(1)
      DO 1 I=1,LI
    1 X1(I)=FLOAT(I)/LI
      TEMP(1)=X(1)*NN(1)
      DO 2 I=2,NF
    2 TEMP(I)=TEMP(I-1)+(X(I)-X(I-1))*NN(I)
      N2=1
      N1=NF-1
      DO 3 I=1,N1
      N3=N2+N(I)-N(I+1)-1
      DO 4 J=N2,N3
    4 Y1(J)=TEMP(I)
    3 N2=N3+1
      N3=N2+N(NF)-1
      DO 5 J=N2,N3
    5 Y1(J)=TEMP(NF)
      DO 6 I=1,N3
    6 Y1(I)=Y1(I)/Y1(N3)
      RETURN
      END
```

REFERENCES

[1] Liang, T. Y., "Time Series and Reliability," Working Paper, (1977).

[2] Barlow, R. E. and T. Y. Liang, "Availability Analysis of the SuperHILAC Accelerator," ORC 77-11, Operations Research Center, University of California, Berkeley, (1977).

[3] Besse, L., "Program HILAC," LBL document, (1976).

[4] Barlow, R. E. and R. A. Campo, "Total Time on Test Processes and Applications to Failure Data Analysis," in RELIABILITY AND FAULT TREE ANALYSIS, SIAM, 1975.

[5] Barlow, R. E. and F. Proschan, STATISTICAL THEORY OF RELIABILITY AND LIFE TESTING, Holt, Rinehart and Winston, 1975.

[6] Barlow, R. E. and B. Davis, "Analysis of Times Between Failures for Repairable Components," in NUCLEAR SYSTEMS RELIABILITY ENGINEERING AND RISK ASSESSMENT, SIAM, 1977.

[7] Barlow, R. E., "Analysis of Retrospective Failure Data Using Computer Graphics," Annual Reliability and Maintainability Symposium Proceedings, IEEE, (1978).

[8] Box, G. E. P. and G. M. Jenkins, TIME SERIES ANALYSIS: FORECASTING AND CONTROL, Revised Edition, Holden-Day, 1976.

[9] Barlow, R. E., D. J. Bartholomew, J. M. Bremner and H. D. Brunk, STATISTICAL INFERENCE UNDER ORDER RESTRICTIONS, Wiley, 1972.