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RELIABILITY ANALYSIS OF HEAVY WATER EXTRACTION EQUIPMENT

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INTRODUCTION

To optimally design and operate any chemical system, the reliability of the system, as well as its actual performance, should be determined. Several techniques to analyze reliability are available - statistics and probability are particularly effective. Statistics and probability use the history of equipment failure to determine the mathematical distribution of equipment lifetimes. These mathematical distributions can serve as a basis for optimal system designs and maintenance policies.

A continuing research project is attempting to develop mathematical models of equipment reliability. Preliminary models for pumps and blowers are given and are accurate enough to provide some information about preventive maintenance and the parameters of the lifetime distributions.

SUMMARY AND RECOMMENDATIONS

Enough data are available to permit multiple parameter models to be fitted with accuracy. These preliminary models can identify equipment requiring further mechanical analysis and can determine preventive maintenance policies.

The most useful mathematical model for failure rate in this study is the two region Weibull[1] model:

$$Z(t) = R_1 \, t^{(R_1 - 1)/S_1} \qquad \text{when } t < 100 \text{ days}$$

$$Z(t) = R_2 \, (t - 100)^{(R_2 - 1)/S_2} \qquad \text{when } t > 100 \text{ days}$$

where $Z(t)$ = Failure rate,
R = Shape parameter,
S = Scale parameter, and
t = Time

This model is applied to the pump in the heavy water extraction units and has the shape parameter values shown in Table 1. The model is also used for gas blowers (Table II) and for auxiliary pumps (Table III). The parameters that describe failure rates are defined in the discussion.

TABLE I

Pump Parameters for Regions I and II

	Region I		Region II	
Pump	Shape	Probability of failure in First 100 Days	Shape	MTTF*
CTP-1	.44	.108	.88	1140
MUP-1	1.12	.031	1.12	1167
CTP-2A	.92	.128	1.08	924
CTP-2B	.55	.179	1.12	945
BPP-2	.38	.088	1.43	983
HTP-1	.93	.061	1.06	532
HP-1	1.29	.025	1.29	996
CCP-1	.32	.066	2.20	1082
CCP-2	.69	.123	1.56	1085
HTP-2A	1.46	.039	1.59	580
HTP-2B	.37	.073	1.65	590

*MTTF - mean time to failure in days

TABLE II

Blower Parameters for Regions I and II

	Region I		Region II	
Blower	Shape	Probability of failure in First 100 Days	Shape	MTTF
GB-1	.30	.095	.84	1088
GB-2	.40	.20	1.83	908

TABLE III

Auxiliary Pumps Parameters

Pump	Shape	MTTF
Silicone Pump	1.09	12.5
RP-2 & -2A	.76	58
PP-3	2.10	32.6
PP-2	1.46	385.
PTP-1	1.27	398.

The Weibull model is useful in describing general trends and in locating equipment weaknesses; however, bias is introduced by the method of maximum likelihood (p 12) used to fit the parameters. Bias particularly effects extrapolating the failure rate to greater service time, but does not greatly affect comparison of failure rates for similar pieces of equipment.

The shape and scale parameters found for the pumps are useful in determining equipment weaknesses; weaknesses are now being studied by a mechanical design group. During the first 100 days of service, failure rate decreases. The higher short term failure rate is believed to be caused by difficulty in installing and starting-up the equipment. The average probability of failing during the first 100 days is 6%. During the second 100 days the probability of failure is 3%.

The differences in the distributions of failure rates of the pumps under varying conditions are also investigated. Most of the pump failures during the first 100 days are caused by packing and bearing failures. Some failures are caused by random events or wear-out. Failure rates for equipment serviced during unit overhaul are lower than those for other pump replacements. This result suggests that the method for starting up the pump should be investigated to determine the causative stress which appears to be associated with replacement. Lower pressures during the first few hours of operation after a unit overhaul are recommended to allow better seating of the packing.

A pump run-in facility, such as proposed in Figure 1, should also be investigated. The casings should be put on-line with a tank of water and a cooler, as shown.

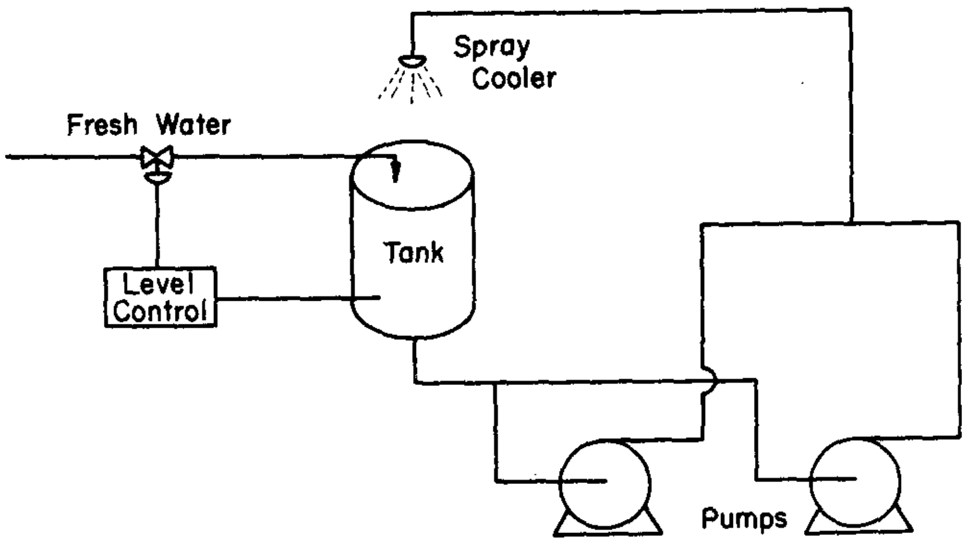

FIG. 1 PUMP RUN-IN FACILITY

The failure rate distributions are useful for scheduling preventive maintenance. Second stage hot tower pumps are now operated into the wear-out period before they are overhauled. The probability of not failing during the two years between overhauls is now 0.23. This could be increased to 0.41 if these pumps were replaced at the end of the first year.

The degree of pump wear-out (p. 9) is also measured. The second-stage hot-tower pumps has the greatest wear-out; the CCP-1, CCP-2, BPP-2, HTP-1, HP-1, and CTP-2B has some wear-out; and the CTP-1, MUP-1 and CTP-2A has little or no wear-out, i.e., they were still within the useful life region. Thus, extending the replacement time for the last group of pumps may be possible. Also, using a sleeve wear-detector on the by-pass and condensate pumps on alternate overhauls is recommended.

Less data on failure rates for the auxiliary pumps are available. PTP-1 and PP-2 had mean times to fail (MTTF) of about one year. The silicone pump, with a MTTF of about a week, should be replaced by a more suitable pump. PP-3 has a MTTF of about one month which seems to be caused by wear-out which applies statistically as a high shape parameter. The two RP pumps which are in parallel, are operating at maximum throughput. If more pumps were brought on-line in parallel with these two pumps, then the stress on the pumps could be reduced. A plan for adding these RP pumps is presented in Figure 2. This plan would provide a low cose method of reducing the failure rate because the major pieces of pipe and the pumps are already in place in Building 413-D.

Further studies are needed to: (1) build better models of the failure rates to permit simpler analysis, (2) extend the method to more equipment, and (3) relate the statistical analysis more closely to the mechanical analysis of the equipment's performance.

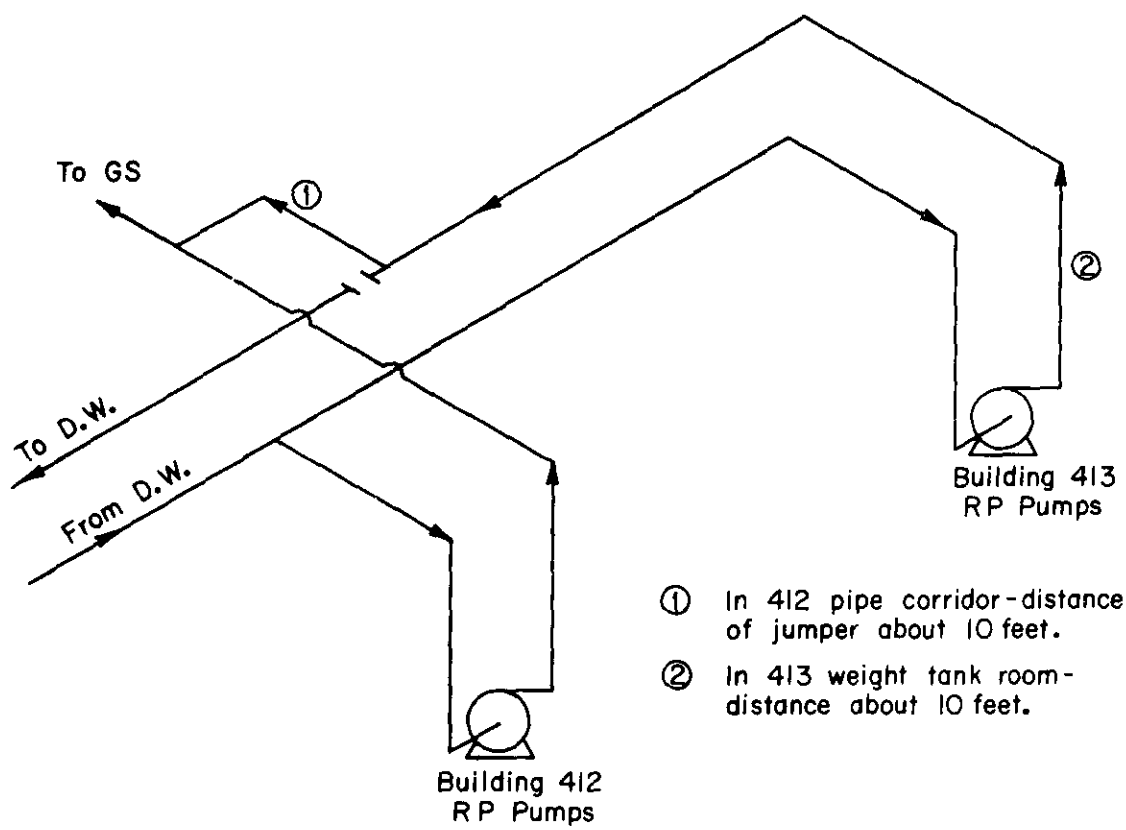

FIG. 2 MODIFICATION TO RP SYSTEM

DISCUSSION

The mathematical methods of arriving at these conclusions are discussed in the following three sections. The first section considers the nature of reliability, the second section discusses the proposed reliability models, and in the third section the parameters are applied to actual data.

NATURE OF RELIABILITY

The mathematical theory of reliability results from application of probability methods to the failure of equipment.[2-4] These theories are necessary because deterministic techniques of equipment design failed to predict adequately equipment lifetimes. Three reasons for this failure are: 1) only ideal cases are considered, with imperfections ignored, 2) all variables are not considered and often major variables are ignored, and 3) only a mean value of those variables is considered and their fluctuation is ignored.

The life of many pieces of equipment cannot be predicted with accuracy; rather the lifetimes have a probability distribution. This probability distribution as a function of time shows the probability that the equipment will have a given lifetime. The shape of this distribution will change for different pieces of equipment and for different operating conditions.

The failure rate of the equipment is defined as the number of failures per unit time per unit of equipment which survives up to a given time. A general failure rate curve is shown in Figure 3. Three regions are present on this curve. First, a period of decreasing failure rate is caused by errors in manufacture and assembly which cause early failure. The middle region of constant failure rate is caused by random events which overstress some component in the equipment. The third region is a wear-out period characterized by age and degradation of equipment parts.

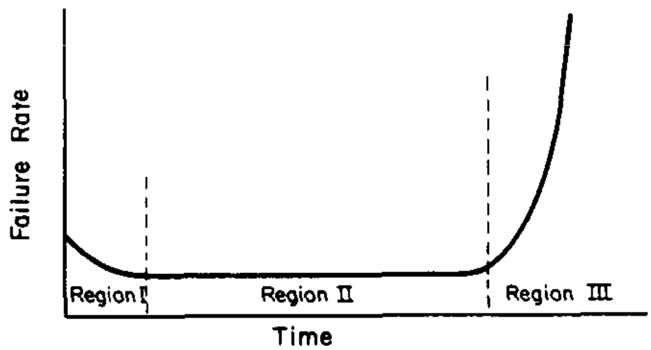

FIG. 3 GENERAL FAILURE RATE CURVE

Reliability is the probability that the system will perform satisfactorily from time zero to time t under stated environmental conditions. This definition is similar to that of failure rate, but reliability predicts future performance and failure rate describes present tendencies. Reliability and failure rate are related by the following equation:

$$\frac{-dG(t)}{dt} = Z(t)\, G(t)$$

or

$$G(t) = \exp\left(-\int_0^t Z(x)dx\right)$$

where $G(t)$ = Reliability
$Z(t)$ = Failure rate, and
x = Vector of observed failure and truncation times

BUILDING AN EMPIRICAL MODEL

Mathematical models of failure rate are given and generally consist of two parts: 1) a mathematical description of failure rate as a function of time, and 2) a set of characteristics which relate the model to actual equipment. The following characteristics must be determined before any accurate mathematical model can be proposed:

- What is a single piece of equipment
- What constitutes a failure
- What renews a piece of equipment
- What is the condition of the equipment after other repairs
- How can similar pieces of equipment be grouped
- What are normal operating conditions

Only a few of the many possible answers to these questions are considered.

A single piece of equipment is defined in three alternative ways: 1) as an entire processing unit, 2) as an individual pump or blower, or 3) as individual components within the pump or blower. Two definitions of failure were investigated: 1) a failure whose repair removes the equipment from service when operating, and 2) one whose repair would have removed the equipment from service if it had been operating. This second category includes the repairs on one component while the unit was shut down for repairs on another component. Two types of renewal are investigated: 1) an overhaul which restores equipment to original conditions, and 2) replacement of the equipment (the pump or blower seal).

Repairs which did not renew equipment are assumed to leave it with the same failure rate as before the failure. Similar pieces of equipment are grouped two ways: 1) those in which the environment in each unit caused the failure rates to be the same for each of the pumps (or blowers), and 2) those in which the environment for each type of pump were the same regardless of the unit in which the individual pump was located. Normal operating conditions are assumed to be any performance, including minor maintenance tasks, not regarded as failure repairs.

Two mathematical models using parameters fitted to these characteristics are given. At this time, the effects of temperature, pressure, and component over-design have not been incorporated into the model.

The first mathematical model describing equipment failure probability is the Weibull function:

$$Z(t) = Rt^{[(R - 1)/S]}$$

$$G(t) = \exp(-t^{R/S})$$

This function has a major disadvantage in that the two parameters (R and S) in the failure rate can give only an increasing failure rate (if $R > 1$) or a decreasing failure rate (if $R < 1$). Because the failure rate curve (Figure 3) is constant in the middle region, this method will not fit the entire curve.

A second model has been proposed (p 5) for failure rate and reliability which gives more accurate parameters. To allow the entire curve to be fitted closely, at least three parameters must be present in the equation for failure rate. This second model, built from two Weibull functions, has four parameters and describes the entire curve more accurately than the simple function; but the parameter values have more uncertainty than in the Weibull distribution. The time scale is divided into two regions: from renewal to 100 days and from 100 days until next renewal.

The first failure rate region has the same shape as the Weibull distribution. The second contains the time displaced to a new origin in the time scale. Thus, the second is a conditional probability, independent of the first. This second region is the probability of surviving to a certain age, given that it has survived through the first 100 days.

The maximum likelihood method is the best method for evaluating the parameters in these models. A general discussion of maximum likelihood is given in Guttman and Wilkes.[5] Maximum likelihood uses all information contained in the sample; however, this method introduces bias into the data. The bias factor approaches 1.0 (zero bias) as the sample size increases, and the variance of the estimates approaches zero.

The expected value of the biased parameter estimates is a constant times the true value of the parameter. Although the study of the bias factor is not complete, preliminary analysis indicates that the bias can be ignored for samples of 25 points and more. For samples less than ten, the mean time to fail has an extremely high variance. Thus for small sample sizes, the mean time to fail should be ignored and the shape parameter should simply be multiplied by 3/4 to get the best estimate of the parameter.

There are other methods by which both shape and scale parameters can be estimated; however, they are not as accurate for small sample sizes. There are insufficient data to use least-square estimates to fit the failure rate curve. The existence of truncation points invalidates the moment methods. And, there are too many data points to use nonparameter methods.

The equations necessary for fitting the Weibull distribution by maximum likelihood are derived by Cohen.[1] These equations are based on the likelihood function, ℓ:

$$\ell(\theta|x) = \prod_{i-1}^{n} f(x_i|\theta) \prod_{g=1}^{nn} G(x_j|\theta)$$

In determining the maximum value of this function, it is somewhat easier to use the logarithm of the likelihood, L. The log likelihood is differentiated with respect to the parameters and set equal to zero, then the equations are solved simultaneously.

When this procedure is carried out for the Weibull model the resulting equations are:

$$S = \sum_{j=1}^{nn} x_j^R / n$$

$$\sum_{i=1}^{n} \ell n \; x_i = \frac{\sum_{j=1}^{nn} x_j^R \; \ell n \; x_j}{S} - \frac{n}{R}$$

where j and nn are the truncation times at which equipment which was still operational was removed from service; a total of nn events having occurred.

The algorithm used in this study for solving these equations is a combination of Newton-Raphson and Gauss-Seidel.[6] An initial value of R is assumed. In the first step, the value of S is calculated. In the second step, this value of S is used to improve the value of R in the Newton-Raphson manner. This two step procedure is repeated until the estimate of R changed less than 0.01% between successive estimates. With this method, the estimated values of R and S converged linearly from either side of the true value. With the above criteria for convergence, the difference in the estimates from the opposite sides is in the fourth decimal, much less than the standard deviation of the estimates of the parameters. In any routine work, the matrix form of the Newton-Raphson method should give more satisfactory results.

In estimating the parameters for the two region model, the same equations are used. The definition of this model is such that the parameters in each region are independent of the parameters in the other region. In the first region, all equipment which fails after the first 100 days should be considered to have their service truncated at 100 days. In the second region, the values of failure time should have the initial 100 days subtracted from them.

With the two parameters estimated, the mean time to fail may be calculated as:

$$MTTF = \Gamma \left(\frac{R + 1}{R}\right) S^{1/R}$$

where Γ is the gamma function.

Further questions to be resolved are the bias in the estimates and the variance of the estimates of the parameters. As the number of recorded failures becomes infinite, the variance of the parameters approaches the limit:

$$\lim_{n\to\infty} \text{Var } \Theta_i = -\left(\frac{\partial^2 L}{\partial \Theta_i^2}\right)^{-1}$$

This gives the lower boundary of the potential variance of the estimate.

To find the true variance and the bias associated with the estimates, different data sets were randomly generated and the corresponding estimates were compared to the known parameters (Table IV). The procedure for finding these estimates is first generating failure times with the inverse Weibull function operating on numbers from a unit rectangular distribution. The appropriate sample size is taken and the estimates found for fifty of these samples. The bias and variance of these fifty estimates were then found.

TABLE IV

TEST OF VARIANCE AND BIAS IN ESTIMATES
(50 Simulations)

Bias in Shape Parameter, R

True	5 failures		10 failures		25 failures		35 failures	
Value	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
.50	.80	.51	.61	.16	.55	.07	.55	.06
.75	1.08	.49	.90	.26	.83	.12	.81	.11
1.00	1.33	.58	1.13	.30	1.06	.17	1.06	.13
1.25	1.70	1.08	1.44	.36	1.30	.22	1.34	.19
1.50	1.99	.71	1.97	.87	1.56	.25	1.59	.19

Bias in MTTF for Scale Parameters, S =1.0

Shape	True	5 failures		10 failures		35 failures	
R	MTTF	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
.50	2.00	2.08	2.06	1.94	1.19	1.78	.59
.75	1.19	1.19	.57	1.13	.52	1.18	.26
1.00	1.00	.88	.36	1.07	.31	1.02	.17
1.25	.93	.92	.34	.91	.22	.94	.14
1.50	.90	.91	.27	.95	.18	.93	.10

Truncation of observations also causes the parameter estimates to be biased. Truncation occurs when equipment is removed from service when still operational, or when failures prior to a certain time are ignored. These must be included in the parameter estimates because they contain necessary information. Further studies will determine the effect of truncation on parameter estimates using simulations.

These considerations will provide sufficient information for interpreting the parameters fitted to data. Bias factors will cause some difficulty in properly interpreting the data, but general trends will still be evident.

DATA AND FITTED PARAMETERS

SOURCE OF DATA

The data used in this study was compiled from the last six years of operation of Building 412-D, Heavy Water Extraction. The data is summarized in the Appendix. The sources of the data were:

1. Production Shift Supervisors' Log (1968-1969)
2. Maintenance Department Daily Reports (1965-1969)
3. Production's Unit Shutdown Log (1963-1969)
4. Separations Technology Reports and Data Records (1963-1969)
5. Inspection Schedules (1963-1969)

Although this study was concerned with pumps and blowers, data were also collected on the failure of heat exchangers (work to be continued later). Other components are not sufficiently documented to give a clear picture of their history. Data previous to 1963 does not appear to be of sufficient quality to provide information for fitting the parameters.

DATA CHARACTERISTICS

What is a Single Piece of Equipment

An entire unit is first considered a single component and any unplanned shutdown is considered a failure (Figure 4). After the distribution was fitted with the two models, it had a Weibull shape parameter of 1.09 and a MTTF of 422 days. In the first part of the two region model, the shape is 0.79 and the probability of failing in the first 100 days is 0.20. In the second part, the shape is 1.39 and the MTTF 494 days. Thus, there is a definite wear-in period and a slightly increasing failure rate after the 100 days. There is a slightly higher failure period around 500 days and then a drop-off at 600 days.

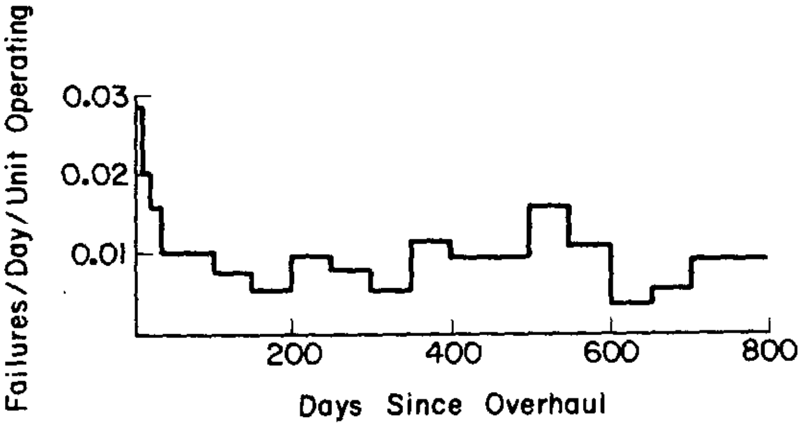

FIG. 4 UNPLANNED SHUTDOWN FREQUENCY

Although this 500 day period occurs in the winter, the increased failure rate cannot be attributed to seasonal freezing because the failure rate does not increase during the 100 to 180 day period. Rather, the increase may indicate a wear-out tendency. The lower failure rate at 600 days may be caused by deferring needed repairs until the scheduled overhaul. The cause of the higher failure rate is difficult to determine because the definition of components is too broad.

Components are also defined as separate pumps. The best set of parameters for this definition is shown in Table 1. Using these parameters, the failure rate may be found as a function of time. Some components in the unit begin to enter the wear-out period around 500 days. Other components, such as heat exchangers and valves, can also be contributing to this failure.

The definition is then narrowed further so that the effect of different components on the pump's failure rates can be specified.

There are too few data to draw many conclusions, but general trends can be observed. Packing failures have the same effect as the overall pump failures. The shape parameter in the distributions is slightly closer to 1.0 than for the general pump, indicating that the failures are more nearly random. Bearings tend to fail early in the life of the pump. The shape parameter is 0.20 to 0.40 (bias removed), indicating a very strong dependence on the manner of installing and running-in the pump. On the other hand, couplings tend to fail more randomly. Motor failures appear to be caused by wear-out in the second-stage hot-tower pumps. The MTTF is about three and a half years. Data are not sufficient to distinguish the other motor failures from a completely random type of failure.

What Constitutes a Failure

The major difference between the two definitions of failure which were proposed is that one is the distribution of major repairs and the other is the distribution of the unexpected catastrophic failures which forced the equipment to be removed from service. The parameters representing the distribution for major repairs is shown in Table 1, the one for catastrophic failure in Table V. Fewer data are used in the determination of the parameters for the catastrophic failure model and the parameters have more uncertainty. The higher shape parameters for the second region indicate that the equipment is operated further into the wear-out region. Thus these represent those pumps for which more of the life is being extracted.

TABLE V

Parameters for Catastrophic Failures

	Region I		Region II	
Pump	Shape	Probability of failure in First 100 days	Shape	MTTF
CTP-1	.45	.127	.85	3756
MUP-1	-	-	1.28	1535
CTP-2A	1.75	.100	1.75	1105
CTP-2B	.48	.156	.95	2193
BPP-B	.39	.103	2.05	1658
HTP-1	1.16	.041	1.16	1265
HP-1	-	-	3.46	1002
CCP-1	.32	.068	3.87	979
CCP-2	.62	.117	3.09	1415
HTP-2A	1.46	.048	2.45	1240
HTP-2B	.32	.068	1.59	2096

In Figure 5, the shape for the second region of the repair distribution and the ratio of the mean time to fail to the mean time between major repairs is plotted. For two of the general temperature ranges in which the pumps are operated, longer times between repairs tend to cause an increase in shape parameter.

In the general model in the report, a component fails when it is repaired either because of failure or preventive maintenance similar to a failure repair. Shape parameters can be compared, and the fraction of life extracted from the equipment can be determined.

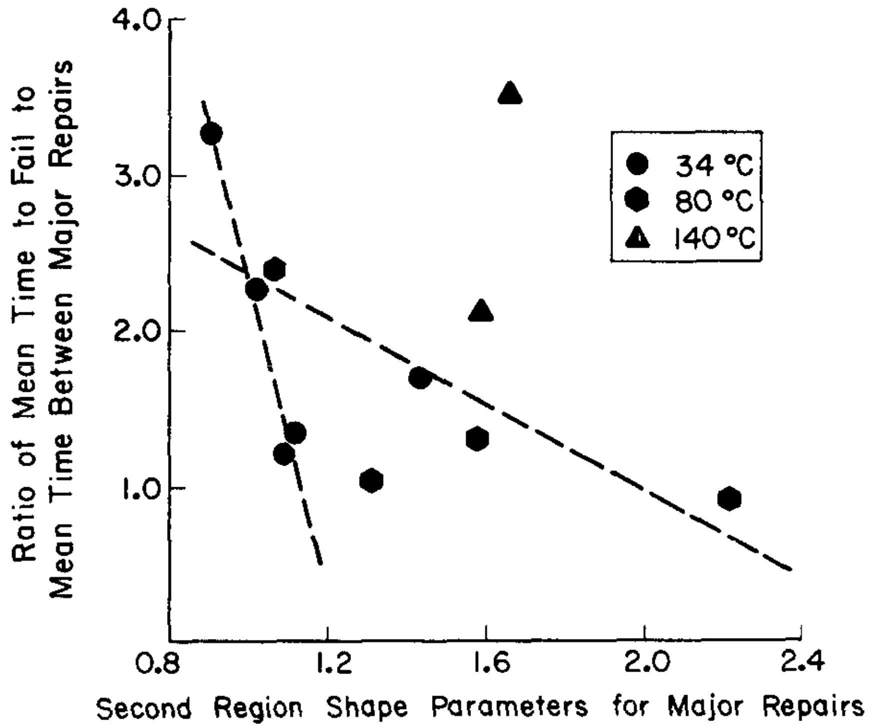

FIG. 5 EFFECT OF TRUNCATION ON SHAPE PARAMETER ESTIMATES

What Constitutes Renewal

The effect of the two different types of renewal (p 10) with all other assumptions held constant is considered. It is assumed that the stress within the units is the same for each pump type and that the pump types have different failure rates. A component is considered an individual pump. The probabilities (Table VI) show only the effect of renewal during the first 100 days (wear-in) of the two region model. The wear-out region is not affected by the difference in the definition of renewal. Thus, the general shape of the wear-in period is the same for all pumps; however, there is a higher probability of a failure after non-overhaul replacement when there is a decreasing failure rate. This increased probability suggests that the extra stress on the pumps during the first 100 days is higher because the method of starting up from the shutdown is different during overhaul than during the other startups. If the decreasing failure period were due to some trouble in the rebuilding of the pumps, then the failure probabilities during the first 100 days should be the same. In a general model, however, the renewal is assumed to be equivalent to pump replacement.

TABLE VI

Renewal Effectiveness Comparison

Pump	Region I Shape	Probability of failure in first 100 days: Overhaul	Replacement
CTP-1	.45	.087	.108
MUP-1	1.32	.028	.031
CTP-2A	.94	.130	.128
CTP-2B	.52	.141	.179
BPP-B	.40	.059	.088
HTP-1	.80	.032	.061
HP-1	1.70	.026	.025
CCP-1	-	-	-
CCP-2	.72	.104	.123
HTP-2A	1.47	.040	.039
HTP-2B	.35	.059	.073
Average		.070	.086

To test different units, the pumps are grouped together within the unit and the overall form of the failure distribution is found for each unit. The estimates of the MTTF and the confidence regions for each of these estimates is shown in Table VII. Because of the size of the uncertainty in the estimates of the MTTF, the apparent difference in the units is insignificant.

TABLE VII

MTTF in Different Units

		Confidence Interval	
Unit	MTTF	Lower	Upper
21	826	540	1120
22	636	480	800
23	955	630	1290
24	854	550	1150
25	1110	740	1480
26	729	510	950
27	755	490	1030
28	618	440	800
Average	810	548	1078

APPENDIX

DATA USED IN STUDY

The failure modes and repair modes are coded as follows:

FAILURE MODES

CATS	Catastrophic failure
PRVN	Preventative replacement during other repair
OVHL	Overhaul
LNGS	During long shutdowns for sandblasting, etc.

REPAIR MODES

REPL	Replace pump
PACK	Pack pump
HDGS	Replace pump headgasket
COUP	Replace pump coupling
MOTR	Replace pump motor or blower motor
BEAR	Replace pump after bearing failure, or for blower
ELEC	Repair electrical failure in pump or blower circuit
NOTN	No action
SEAL	Replace blower seal
LBRN	Replace blower labyrinth seal
IMPL	Replace blower impeller
CASE	Replace blower case
LUBE	Repair or replace some element in lubrication system
SLHS	Replace seal housing
SHFT	Replace blower shaft

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