Reliability Concepts in Injection Unit Pumping

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Many steps are taken in the design of injection facilities that are intended to result in better performance, less maintenance and a greater degree of "on stream time." These steps might be collectively described as a conservative application and, among others, include derating both speed and loading of prime movers and pumps, design of piping to eliminate undesirable frequencies of pulsations, provision of adequate suction conditions for the pumps employed and utilization of standby or alternate systems. The desirable result of such design is a station of high reliability that can be obtained with an optimum investment of capital and will result in a minimum operating cost over the life of the installation. Of paramount importance in obtaining such an installation is the reliability of the components employed **and** the reliability of the resultant system.

At this point it may be desirable to define, for the purposes of this paper, reliability. One commonly accepted definition is: Reliability is the probability that a component will satisfactorily perform its function for the period of time intended under the operating conditions encountered.

Reliability, then, is a function of both time and environment. With these constraints one might logically expect that many years of observations of failures might be required to assign a reasonable estimate of reliability to a given component or piece of equipment. Actually, in the past few years great strides have been made in the development of techniques to increase the confidence level that can be placed on reliability estimates derived from reasonable periods of failure observations.

To illustrate the means by which statistical methods have been applied to obtain useful reliability estimates, let us examine the plot of the failure rate of a theoretical component versus time; failure rate being the number of failures per unit of time. (Fig. 1)

Observation of this plot reveals that this theoretical curve can be divided into three practical and distinct regions labeled I, II and III. Explanations follow:

Region I has an initial high failure rate that decreases with time. This region correlates with failures experienced during start-up and "de-bugging" periods. It is generally termed the "region of early failures."

Region II is the region of random failures and the failure rate is essentially constant.

Region III is the region of wear-out failures where the failure rate increases as the useful life is reached.

Reliability is concerned with all three of these regions; however, with reasonable quality and proper design Region I can be reduced to a quite short duration and Region III can be postponed past the period of interest by proper maintenance. Thus, the mathematical determination of reliability is normally concerned with Region II, that of essentially constant failure rate.

While the derivation of the mathematical relationship for the reliability of a component for a period of time, t, is beyond the scope of this paper, this relationship can be expressed as follows:

$$R_t = e^{-\lambda t}$$

where: R_t is the reliability of the component for the period of time, t.
e is the base of natural logarithms
λ is the failure rate or reciprocal of mean time between failures
t is a specified period of time.

This relationship is termed the exponential failure distribution.[1]

The use of this relationship is proper only when dealing with Region II, that of constant failure rate, and when the failures that do occur are both random and independent. It is realized that seldom are these prerequisites exactly met. However, much evidence exists to show that these prerequisites are approximated closely enough in actual operation to justify the use

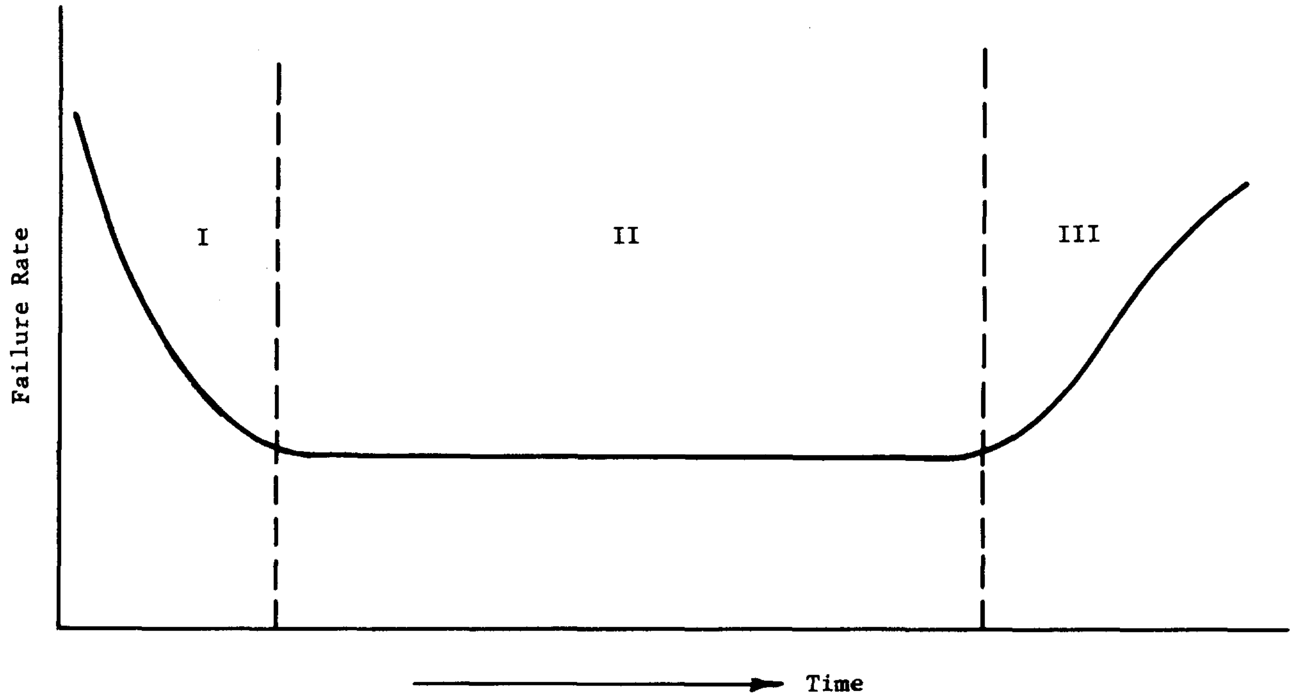

FIG. 1

of this relationship in many instances.

Reliability estimates for the components of any system can be made by proper observations of the components in the same environment and recording the time between failures. These data can be taken from components in actual service, or from testing programs.

Table I presents a hypothetical record of a component and the resulting mean time between failures. Note that the estimate is based on the data at hand and should improve as more components are observed over longer periods of time. In the interest of brevity this table is limited to an approximate one-year operating time. As indiacted, the mean time between failure is 633 hours with a resultant value of λ of 1/633.

Failure	Time	$\triangle$T	Failure	Time	$\triangle$T
1	400	400	9	5400	200
2	600	200	10	6100	700
3	1300	700	11	7400	1300
4	1900	600	12	8000	600
5	2800	900	13	8400	400
6	3200	400	14	8800	400
7	4000	800	15	9500	700
8	5200	1200			
					9500

TABLE I

From Table I: Mean Time Between Failures =

$$\frac{9500}{15} = 633 \text{ hours}$$

$$\lambda = 1/\text{MTBF} = \frac{1}{633}$$

With these data Tables II shows a comparison of the probabilities for failure-free periods of time developed by both empirical probability and the relationship $e^{-\lambda t}$. Note that these probabilities are in relatively close agreement even though we have used only 15 failure observations.

t	Probability of Failure-Free Period Longer Than t	$e^{-\lambda t}$
0	15/15 = 1.00	1.00
200	13/15 = 0.87	0.73
400	9/15 = 0.60	0.53
600	7/15 = 0.47	0.39
800	3/15 = 0.20	0.28
1000	2/15 = 0.13	0.21
1200	1/15 = 0.07	0.15
1400	0/15 = 0.00	0.10
1600	0/15 = 0.00	0.08

TABLE II

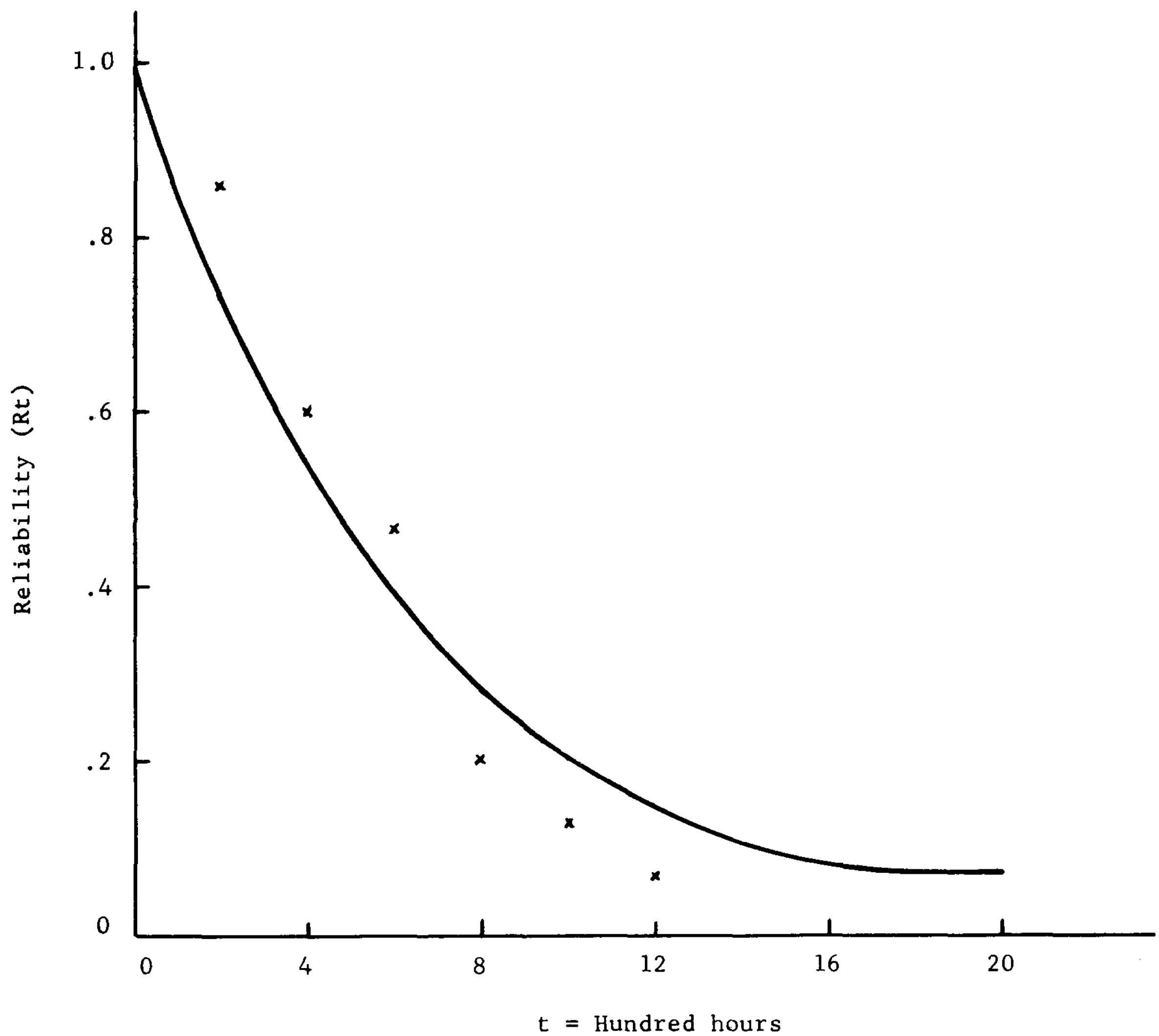

FIG. 2

This relationship is shown graphically in Fig. 2. From this one might, based on the limited observations, assign a reliability estimate of 0.50 for a failure-free period of operation of 500 hours. As more observations are recorded, an even closer fit to the exponential failure distribution might be expected. These reliability estimates are useful in component comparison as well as in evaluating the need for standby systems where continuity of operation must be maintained. (Fig. 2)

In most instances we are more concerned with the expected "on stream" time than with the probability of a set period of failure-free operation. Using the data in the previous example and arbitrarily assigning ten hours' downtime for each failure, we might determine an expected average operating time for this component as follows:

MTFB = 633 hours or 15 failures in 9500 hours

$$\frac{15x10}{9500} = 0.016$$ not operational or 0.984 expected average operating time

In practice the mean time to repair can be determined and used in this estimate of expected average operating time. The mean time to repair can become quite significant and should be properly evaluated in the comparison of alternate designs.

EXAMPLE OF INJECTION UNIT EVALUATION

In this example total required design volume is 12,000 BPD and the selection appears to be one of the following alternates:

	Expected Average Operating Time/Unit	Rated Volume/Unit
A. One large unit	0.92	13,300
B. Two medium units	0.85	7,000
C. Four small units	0.80	3,500

The expected average volume for Alternate is 12,200 BPD, a volume slightly greater than required. In making this same determination for Alternates B and C the binominal distribution becomes a useful tool. In general terms this expression is: $(O + D)^n = 1$

where O = expected average unit operating time
D = expected average unit downtime
n = number of units involved

For Alternate B, expansion of this distribution becomes $O^2 + 2OD + D^2$

These three terms correspond to the following:

O^2 — Both units operating $(.85)^2 = 0.722$

2OD — Two combinations of one operating and one down $2(.85)(.15) = 0.255$

D^2 — Both units down $(.15)^2 = 0.023$

Using these percentages and the volume capability associated with each, the expected average volume becomes:
0.722(14,000) + 0.255(7000) = 11,980 BPD

Similarly for Alternate C:

$(O + D)^4 = O^4 + 4O^3D + 6O^2D^2 + 4OD^3 + D^4$

Four units operating $= (0.80)^4 = 0.410$

Three units operating $= 4(.80)^3(.20) = 0.410$

Two units operating $= 6(.80)^2(.20)^2 = 0.154$

One unit operating $= 4(.80)(.20)^3 = 0.025$

No units operating $= (.20)^4 = 0.001$

Expected average volume

= 0.41 (14,000 + 10,500) + 0.154(7000) + 0.025(3500) = 11,200 BPD

The results of the evaluation are summarized below.

Alternate	Expected Average Volume	Expected Station Downtime
A	12,200	0.080
B	11,980	0.023
C	11,200	0.001

With these estimates completed, an economic analysis can be performed to give proper weight to investments, operating costs, tax considerations and resultant income associated with each alternate. Also, compatibility of the alternates with requirements of the injection pattern can be evaluated. It should be pointed out that the above example for illustrative purposes was kept quite simple and straightforward. In all cases consideration must be given to failure of systems that are common to the injection units, such as fuel systems, electrical distribution systems, etc. In some cases a combination of different units may better fit design requirements. As an example of the latter, suppose design volume in the above case is modified by the requirements of a very high probability of maintaining a minimum rate of 6000 BPD. In this case a fourth alternate might offer advantages. This could involve use of one highly reliable medium unit and three small units as below.

	Expected Average Operating Time/Unit	Rated Volume/Unit
One medium unit	0.92	7000
Three small units	0.80	3500

This alternate is identified "D" and determination of expected average volume follows.

Four units operating $= 0.92(.80)^3 = 0.471$

Three units operating $= 3(.92)(.80)^2(.20) = 0.353$
$(.08)(.80)^3 = 0.041$

Two units operating $= 3(.92)(.80)(.20)^2 = 0.088$
$3(.08)(.80)^2(.20)^2 = 0.031$

One unit operating $= (.92)(.20)^3 = 0.007$
$3(.08)(.20)^2(.80) = 0.008$

No units operating $= (0.08)(.20)^3 = 0.0006$

Expected average volume then becomes

0.471	(17,500) =	8,250
0.353	(14,000) =	4,940
0.041	(10,500) =	431
0.088	(10,500) =	924
0.031	(7,000) =	217
0.007	(7,000) =	49
0.008	(3,500) =	28
		14,389 BPD

Summarized, Alternate "D" then offers 14,-839 BPD expected average volume with an expected station downtime of .06 of 1 per cent. The comparison of all four alternates for maintaining an expected minimum rate of 6000 BPD follows:

A. .92 B. .977 C. .974 D. .9914

By this alternate, significant improvement is obtained in both expected station downtime and expected operation above the minimum rate of 6000 BPD. Further refinement will allow reduction of the volume capability of the medium unit in Alternate "D" without sacrifice of design requirements. With this refinement an optimum selection is indicated.

CONCLUSION

It is felt that reliability concepts provide a useful tool for those concerned with evaluation and selection of equipment for applications of this nature. The techniques are readily adaptable to mechanization with resultant economy in data assimilation and offer a means of objectively forecasting performance.

REFERENCES

1. Roberts, N. H., Mathematical Methods in Reliability Engineering, 1st edition, McGraw-Hill Book Company, pp 45-57, 1964.

2. Bazovsky, Igor, Reliability Theory and Practice, Prentice-Hall, Inc., 1961.

3. Calabro, S. R., Reliability, Principles and Practices, McGraw-Hill, 1962.