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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

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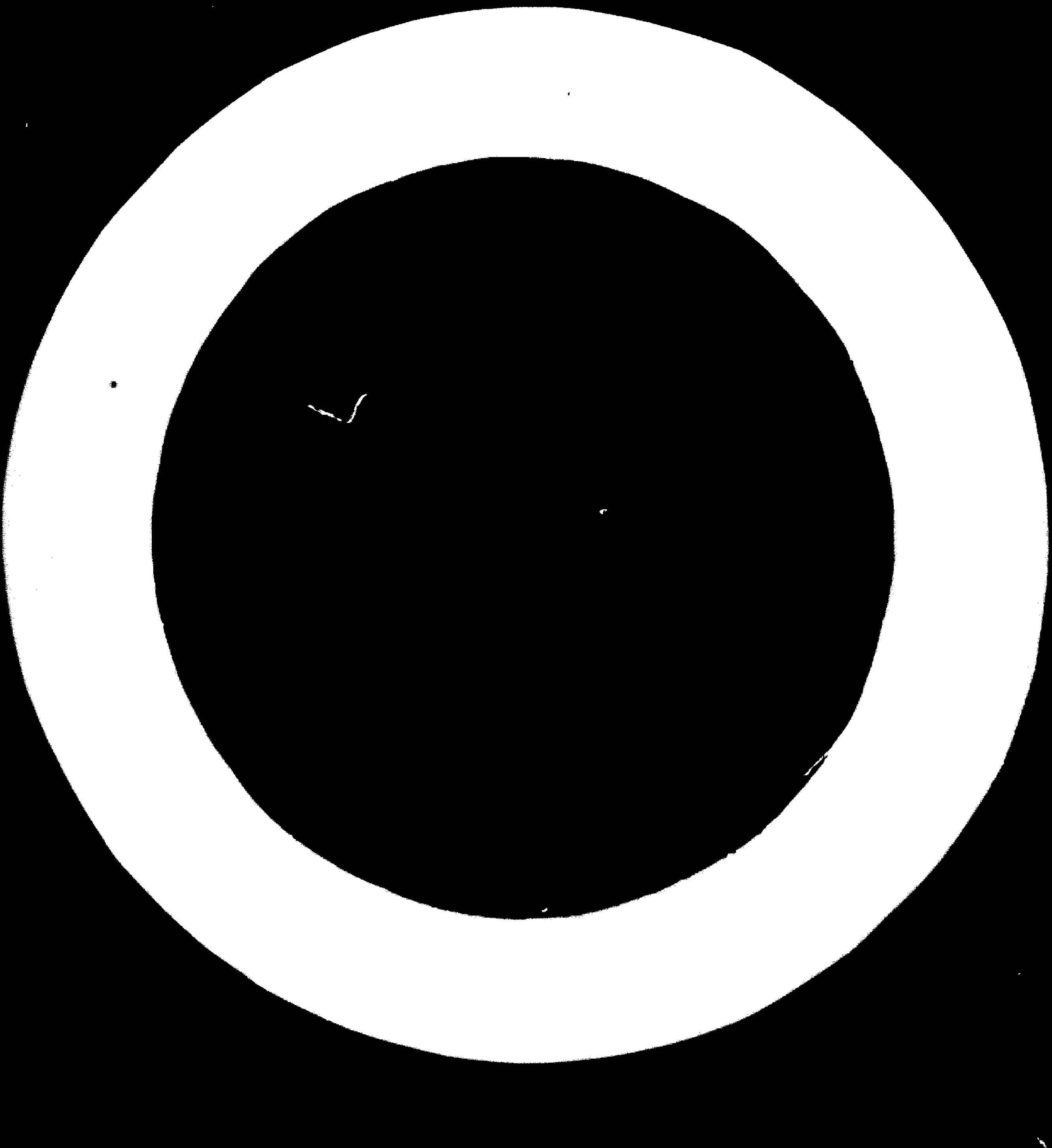
MAINTAINABILITY

by

B. W. Jenney
University of Birmingham

Organised in co-operation with the Government of Japan and the Japan Management Association (JMA).



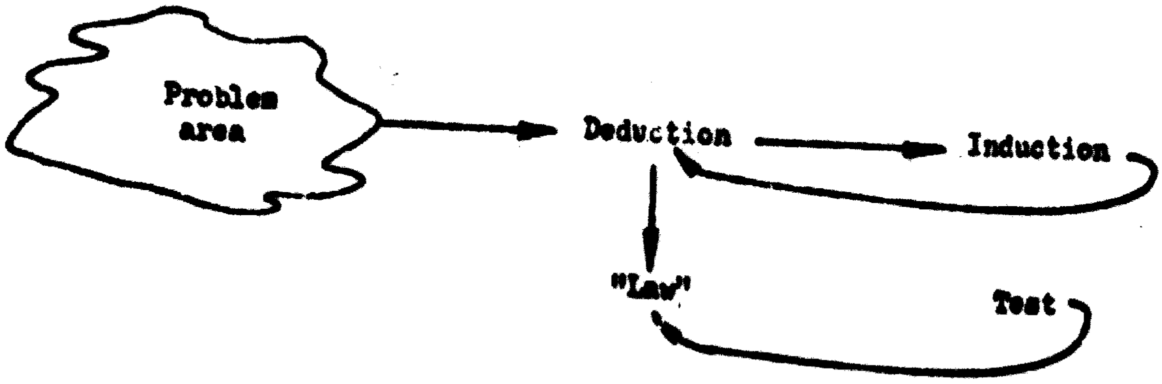
Both the words 'theory' and 'theatre' come from the Greek θεα which means to see or to understand, and this precisely is the aim of any theoretical approach. Our ability to explain any situation, to predict what will happen and thereby be in a position to control illustrates the fact that we evolve theories so that they can be used to practical advantage. Any theory has three elements:

a. Parameters, which are outside the analytical framework,

b. Variables, the magnitudes of which are to be determined within the theory, and

c. Postulates, or behavioural assumptions, which define the set of operations by which the values of the variables are found.

In actual research work we progress along two paths, theoretical analysis (or deduction) and empirical investigation (or induction), as follows:

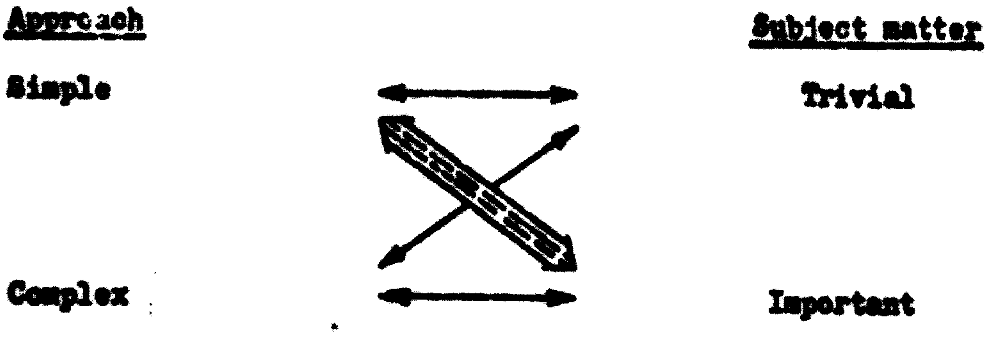


Theory does not equal practice, although the nearer it equates them the better is that theory. Essentially theory is much more simple than practice and it enables us to cast wider and to see the principles rather than the details. In this paper we shall start by developing approaches concerning statistical methodology, finance and human factors.

Theory and Practice

It is a constant aggravation to have to counter the charge of "that is alright in theory but what about practice?". The very best engineers have almost invariably been those who had a sound grounding in the mathematical sciences and who have used these skills in the construction and testing of theories. Mathematics are not a set of theories, of course, especially as it would spoil one's definition that theories are simplifications, or approximations, to practice. A favourite stricture is to listen to people who use theories but to be very wary if you think these people actually believe the theories they are promulgating. Indeed, it is one of the tasks of all of us, especially if we work in a university, to challenge existing theories and to try to get better ones; that is, ones which relate more closely to the observations in practice. Thus are theory and practice complementary and in no manner the antithesis of each other.

In the particular field of communication and endeavour called education, it is useful to identify the extremes of approach and subject matter as follows:

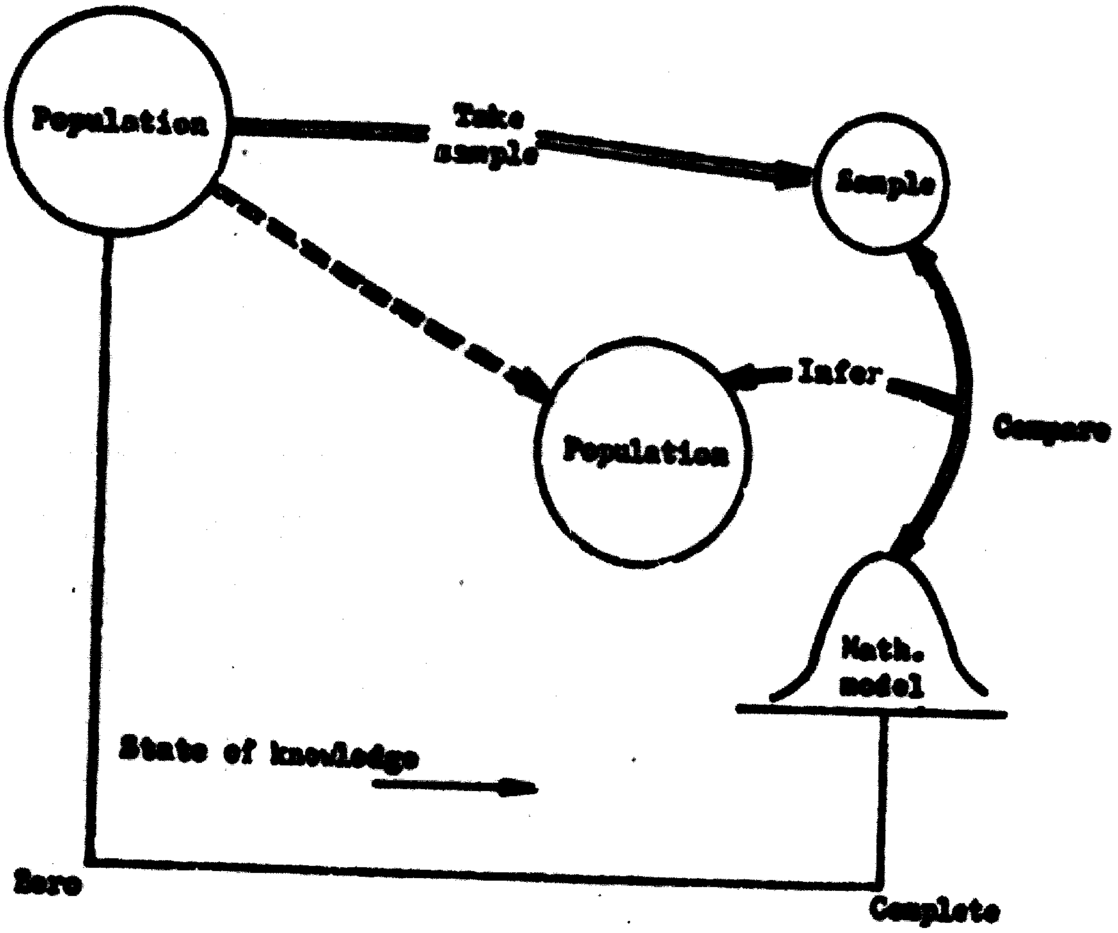


It is all too easy to assume only a horizontal relationship, yet one may presume that many have suffered from complex triviality. However, the subject is eminently suitable for a diagonally opposite viewing.

The aim of this paper is to develop models which we can use in the field of maintenance management and so we can relate them to the basic inputs. Firstly, we must say something about the handling of the data which leads us directly to the fairly familiar field of statistics.

Statistical approaches

A very important part of statistics concerns samples and this enables us to make comments upon, and even decisions about, a situation where we have incomplete data. In a case where we have reasonable full information, such as the Census of Population, it is still useful to take samples because we can speed things up this way.



One way indicating the principles behind statements of confidence level and the methods of statistical inference can be shown by the above diagram. The first use of sampling to make comment upon a larger number related to data about human beings, and to this day we talk of 'populations'. To maintain our scientific objectivity, we presume that we know nothing about the parent population as well as taking the sample without bias, or 'at random' as it is often called. The next step is to measure the sample characteristic in which we are interested and to note how many comply or, more usefully, how its variability is spread throughout the sample. Then a comparison is made of the distribution of the measure and a mathematical model, about whose properties everything is known, which enables us to infer something about the original populatio from which the sample was drawn. Skill is required in all such steps and we make probabilistic statements of how nearly the sample number allows it to be indicative of the population, and also of what significanc are the differences between the sample and the model. Thus all our inferences have this 'double probability' about them, even though we wish to be in the position of making a single decision.

Thus we are seeking mathematical models which fit our set of data to enable us to predict the performance in life. Most familiar in use is the Normal, or Gaussian, distribution, but the experimentally-derived Weibull distribution is of particular importance in maintenance predictio This is because of the flexibility allowed in altering the shaping, scali and locating parameters. Warnings must be restated concerning the way in which the failure data were derived; for instance, accelerated life testing may cause failure modes other than those of real service conditio

Further, we must be sure of the way in which our model is working - for instance, with respect to truncations, replacement and so on. On a more optimistic note, we can hope to apply prior knowledge within the manipulation of our mathematical models, and thereby make more positive statements than those possible from starting at 'zero knowledge'.

Estimation

Within a population the variable (usually called a variate and, in this case, time) will be distributed in a certain way. In practice, there tends to be a relatively small number of standard patterns to which most distributions approximate. Each distribution is defined by a frequency function, or in the case of a continuous variate a probability density function, in which the population parameters appear. Samples also have their distributions incorporating the sample statistics and the latter may be used to estimate the corresponding values of the population parameters, i.e. as Point Estimators. Estimators may be unbiassed, e.g. the mean, or biassed, e.g. variance, the latter needing correction to give a 'best' estimate. Best estimates of population parameters are indicated by a 'hat' symbol, e.g. $\widehat{\mathrm{mttf}}$ (mean time to failure), $\widehat{\mathrm{mttr}}$ (mean time to repair) and so on.

Interpretation of Life Characteristic Functions

Experience has shown that certain statistical distributions appear to have a rational relationship to the shapes of certain hazard rate curves found in analysis of maintainability records and identification of these shapes is therefore important. Individual distributions are considered later but they may be grouped initially under the three phases of biological life, described colloquially in engineering applications by the 'bath-tub' curve:

Early life failure. These are identified by having a decreasing hazard rate as the equipment logs up operating hours. Stabilisation, bedding down, undetected assembly errors are all examples of this initial period.

Random failure. Are associated with a Poisson process since they occur randomly in time and their incidence is independent of accumulated life. They are sometimes called "memory-less failures". With random failure the hazard rate is constant and unrelated to any prior pattern and the corresponding failure density function is exponential in form. While academically a true 'constant' failure rate is most unlikely to exist, constant hazard rate models may be appropriate in such circumstances as:

a. Complex mature electro-mechoanical or mechanical systems in the middle ranges of life where many different failure patterns combine and where, because of repair by replacement, the average age of the system is falling.
This arrests the normal increase of Hazard Rate with age and a stable state of random failure can result. Depending on the extent of renewal at overhauls an effectively constant failure rate can continue for some time, and the relevance to many types of engineering is clear.

b. Electronic systems such as computers, where again a large number of different components is combined.

c. Short time intervals where it may be convenient to assume constant hazard rates for analytical purposes. Care should be taken not to extrapolate such assumed values over longer life periods.

Perhaps we can add here a few words that the correct maintenance strategy here is to leave well alone, although it took years of arguing in certain airlines to replace certain flying instruments 'on condition' and not according to some preventive maintenance strategy.

<u>Wearout failure</u>. When exhaustion of some property or properties related to life is occurring the hazard rate increases. This may be due to metallic wear, the cumulative effects of vibration or of overheating, or to chemical changes, etc. Since the numbers in the original population are also failing the failures will tend to bunch about some limiting, or wear out, value and the frequency distribution function will typically be of the Rayleigh or normal shape, or Weibull with shaping factor of, say, two or more.

An increasing hazard rate in early life may also indicate some uncorrected cumulative design deficiency.

<u>Key to identification</u>. The crucial differences which it is important to identify as soon as possible are whether failures are:

a. Life Dependent, and if so whether the hazard rate is Increasing (Wear-out) or Decreasing (Burn-in);

or

b. Independent of Life History, i.e. Random.

The transition from one phase to another may not be well defined. Early life failures are often distinctive, but in complex equipment which is maintained by replacement policies and where withdrawal from service may arise from technical obsolescence a true 'wear-out' phase may not be reached. The conclusions drawn as to the trend of Failure Rate should have a direct impact on the Planned Maintenance strategy adopted since if failures continue random, no overhaul is indicated.

Some Useful Distributions

a. **Negative Exponential:** A poisson distribution of failures in equal intervals of time will give rise to an exponential distribution of failure density with time and a corresponding constant hazard rate. As well as its legitimate application in situations such as mentioned above the mathematical simplicity of the exponential function has led to its use in cases where it may be unjustified, or often by default when the true distribution is unknown.

The Negative Exponential is almost universally called an 'Exponential' and is typically of the form

$$f(t) = e^{-\lambda t}$$

b. **Normal:** The majority of Reliability statistical models are skew but in some wear-out cases the symmetrical and well-known normal or near-normal distribution is appropriate. A classic case is the failure pattern of a large family of like objects, e.g. electric light lamps.

c. **Log Normal:** This positively skewed distribution in which the logarithms of the random variable form a normal distribution has been in use for some twenty-five years and, before the development of the Weibull distribution, proved a useful model for many repair time distributions. These involve situations where due to the need for diagnosis and to initial administrative time no repairs actually take zero time but the subsequent pattern of times tends to cluster about a mean, with a relatively few jobs taking much longer. It has also been used to describe the pattern of early life design and manufacturing failures, i.e. before they are corrected by modifications, and provides a reasonable basis of explanation for certain physics of failure modes, e.g. in transistors. The greater flexibility and mathematical simplicity of the Weibull distribution makes it, however, more generally attractive and study of repair times suggests that the latter should in future be adopted for analysis of Repairability wherever possible.

d. Extreme Value: This is a derivative of the negative exponential and is descriptive of the physical situation of breaking strength, e.g. weakest link in the chain structures.

e. Gamma: This adaptable distribution is of the basic form:

$$f(t) = K.t^{c-1}.e^{-t}$$

and can be seen to contain two interacting terms in t:

- the first in which t is raised to a power
- a second decreasing exponentially with t.

It can therefore be representative of a physical situation where a constant force combined with a second effect inversely proportional to age and has been used, e.g. to model an item failing on being subjected to a series of repeated shocks. It becomes a negative exponential when c = 1.

f. Weibull: The Weibull distribution has no special theoretical justification but was developed in 1951 as an empirical means of describing certain sets of data connected with the breaking strengths of materials. It is linked to the Gamma distribution as can be seen from the probability distribution function:

$$f(t) = \frac{\beta}{\alpha} \cdot \left(\frac{t - \gamma}{\alpha}\right)^{\beta - 1} \cdot e^{-\left(\frac{t - \gamma}{\alpha}\right)^{\beta}}$$

where -

α is a scaling factor (scale parameter) defining the point in time where 63.2% of the population have failed, i.e. it is the Characteristic Life.

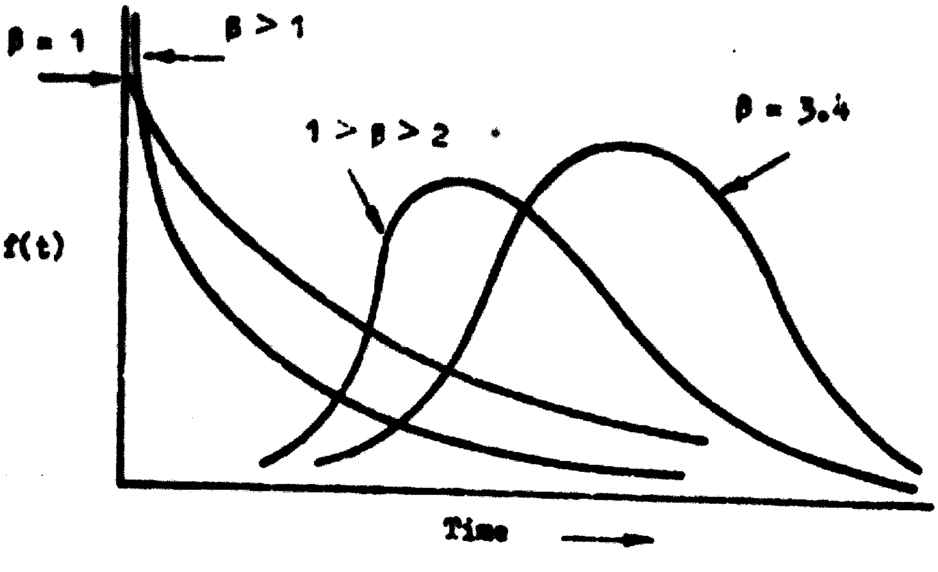
β is a shape parameter controlling the rate of interaction of the two terms containing the random variable, and therefore the shape of the distribution.

γ is a location parameter defining the origin.

when $\beta = 1$ the distribution again becomes exponential

$(\beta - 1 = 0)$

<u>Application of Weibull Distribution to Life Assessment:</u> This is being increasingly applied to Reliability and Maintainability problems. Its importance lies in the fact that variation of the three parameters leads to the adoption of a wide variety of shapes of which certain other well known distributions are special cases. This is illustrated in the figure below and the case of the negative exponential has already been indicated.



<u>Effect of Variation of Shape Parameter on Weibull Probability Density Function</u>

Notes: 1 If $\gamma = 0$, failures start when equipment is put into use. They may start later and even in some cases, e.g. batteries which deteriorate in store, sooner.

2 β will be found to be the slope of the Cumulative Distribution Function when plotted on Weibull probability paper - see below.

Numerical techniques for deriving estimators exist, e.g. by maximum likelihood or moment methods or by order statistics, but are tedious and that offering most attraction for immediate applications is the use of graphical data plotting. This is simple and effective and enables parameter estimates to be easily obtained to accuracies which are satisfactory and often as good as numerical methods.

In addition they give a complete and easily visualised picture of the data, enable theoretical distribution to be conveniently fitted by eye and goodness of fit to be gauged (though not quantified) and allow sample data to be evaluated and smoothed. Confidence limits can also be readily estimated.

Graphical Methods of Parameter Estimation

In all cases this involves plotting the Cumulative Distribution, i.e. the Failure or Maintainability Function, against the random variable.

Probability paper has been designed for a variety of distributions, typically:

a. Exponential and Normal

b. Log Normal

c. Weibull

Exponential and Normal: In these papers the abscissa is linear but the ordinate scale is so arranged that if exponential and normal cumulative distributions respectively are plotted, the curved extremities are appropriately 'stretched' so that straight lines result when data corresponding to the parent distribution are plotted.

Data whose cumulative function plots as a straight line on exponential paper (usually logarithmic paper inverted) must therefore represent random failure and this is a valuable test. A wear-out situation would ideally plot a straight line on Normal - more usually called Arithmetic-probability paper.

Log Normal: This is arithmetic probability paper on which a logarithmic scale is used for the abscissa and which therefore inherently carries out the necessary log normal to normal transformation of the variate.

Weibull: It will be recalled that the Weibull distribution incorporates an expression with a double exponent, e to a power of t, to the power of β . If double natural logarithms are taken the function will reduce to an expression linear in t and of the form $y = a t + b$. It can as result be shown that any distribution which is describable by the Weibull function will plot as a straight line on probability paper whose abscissa is a single natural log scale of the random variable and whose ordinate is a double natural log scale containing the proportion failing. If a straight line does not appear it must be because either the origin is incorrect or because the data are multi-modal, and both situations can readily be investigated. Since the Weibull function can cover such a variety of shapes this provides a technique of versatility and power.

Weibull probability paper has been developed incorporating also simple nomograms from which the empirical parameters and mean of the distribution can be read directly. It is also necessary to have Median Rank tables available, as well as those suitable for the plotting of confidence limits should these be required.

Plotted Example: To demonstrate the efficacy of graphical methods a simplified example is given. The recorded TTF (time to failure, although they could be any other measure in which we are interested such as TTR, time to repair) for an equipment, in hours, is as follows:

190 120 240 80 155

The first step is to rank these and then ascribe plotting points.

TTF (hours)	Percentage Plotting Points	
	Prob. and Log Prob.	Weibull
80	10	13.0
120	30	31.5
155	50	50.0
190	70	68.8
240	90	87.1

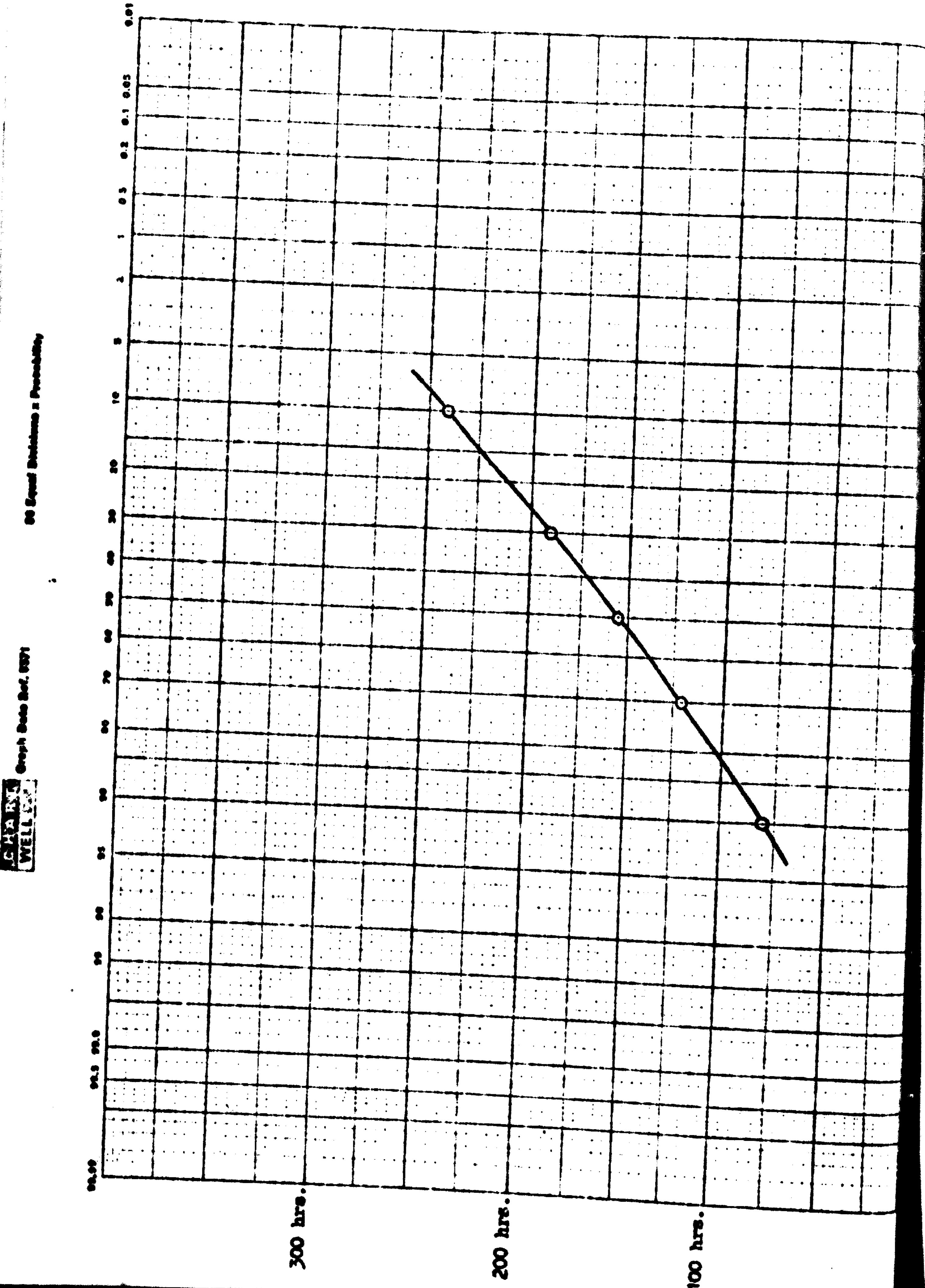
The formulae for the two sets of percentage plotting points is

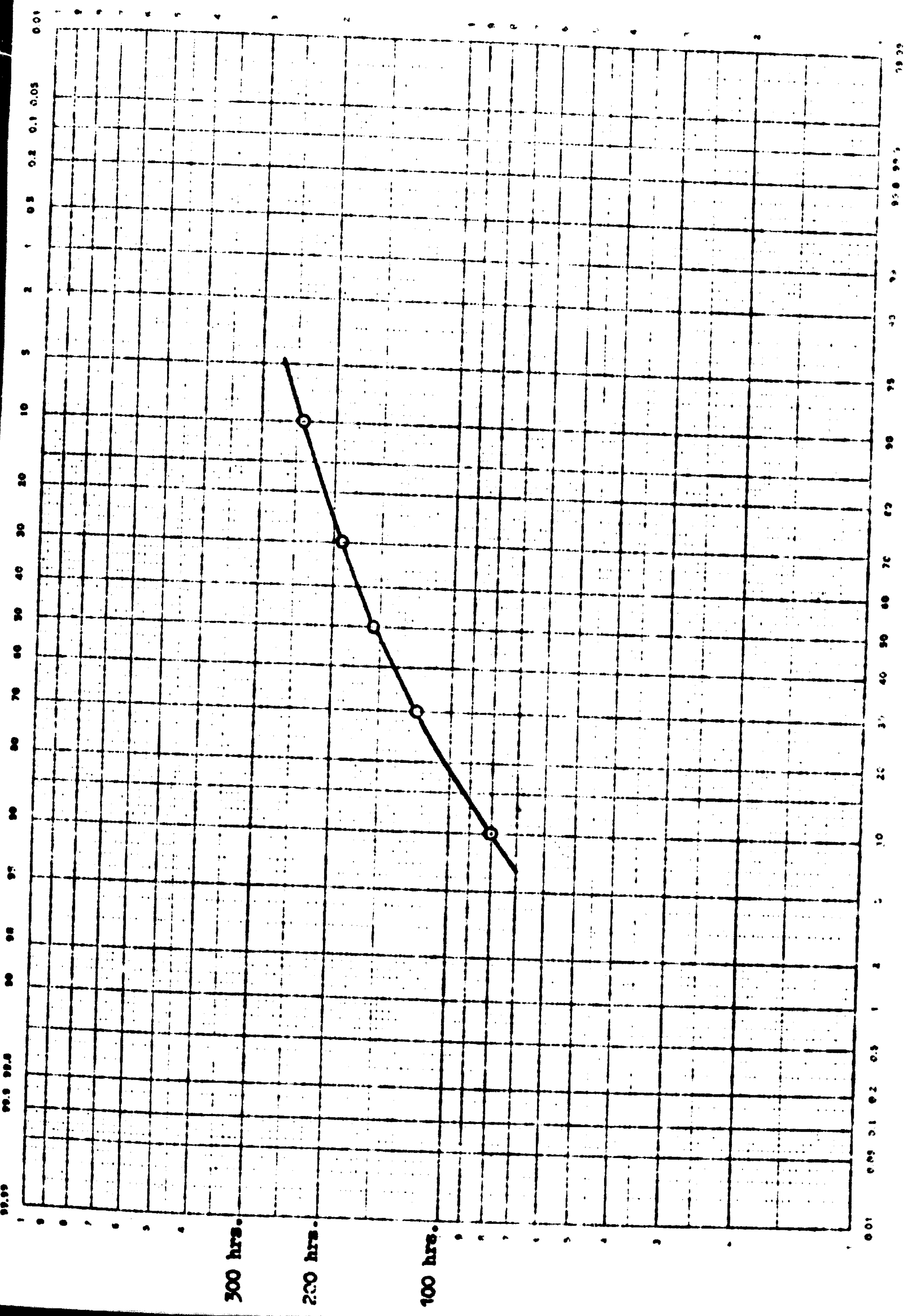
$$\frac{100\,(i - \frac{1}{2})}{n} \quad \text{and} \quad \frac{100\,(i - 0.3)}{n + 0.4} \quad \text{respectively}$$

The Weibull plot also shows the 90% Confidence interval as the area enclosed by the broken lines and an example of the construction necessary is included. The entry points for our sample size of five are as follows:

Weibull Percentage Plotting Points		
5% Rank	Median Rank	95% Rank
1.0	13.0	45
7.8	31.5	66
19	50.0	81
34	68.8	92
55	87.1	99

At this point we can leave statistical methodology for the time being and look at a different (and this time determinate) model concerning money.


CHARTWELL Graph Data Ref. 5571
Equal Divisions x Probability
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
300 hrs.
200 hrs.
100 hrs.


0.01
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99.8
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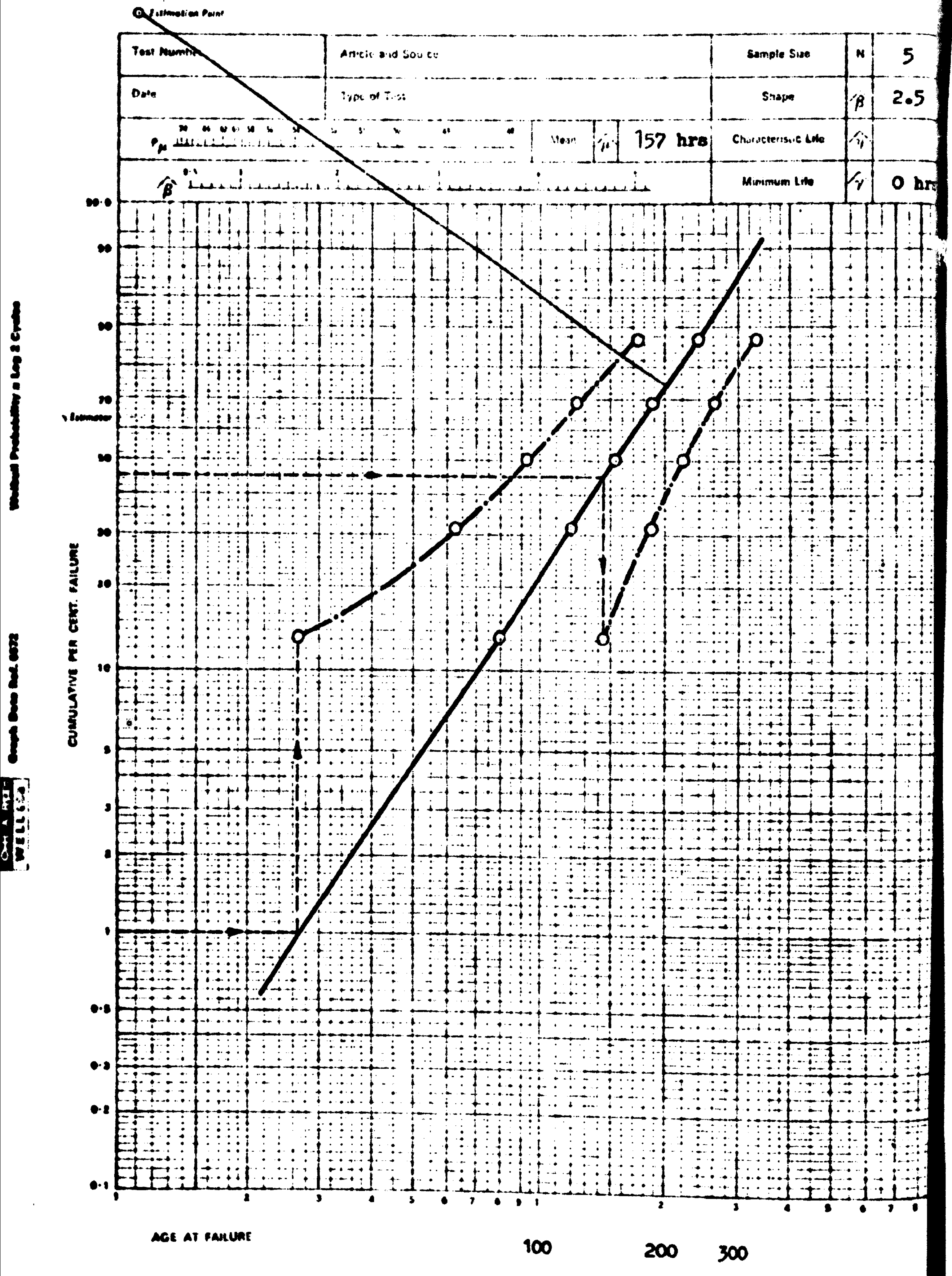
99.99
300 hrs.
200 hrs.
100 hrs.



Test Number

Article and Source

Sample Size N 5

Date

Type of Test

Shape $\hat{\beta}$ 2.5

Mean $\hat{\mu}$ 157 hrs

Characteristic Life $\hat{\eta}$

Minimum Life $\hat{\gamma}$ 0 hrs

Sample Size = n																				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Rank Order Number
50.0	29.3	20.7	16.0	13.0	11.0	9.5	8.3	7.5	6.8	6.2	5.7	5.2	4.9	4.6	4.3	4.0	3.8	3.6	3.5	1
	70.8	50.0	38.7	31.5	26.6	23.0	20.3	18.1	16.4	14.9	13.7	12.7	11.8	11.1	10.4	9.8	9.3	8.5	8.4	2
		79.4	61.4	50.0	42.2	36.5	32.2	28.8	26.0	23.7	21.8	20.2	18.8	17.6	16.5	15.5	14.7	13.9	13.3	3
			84.1	68.8	57.9	50.0	44.1	39.4	35.6	32.5	29.9	27.6	25.7	24.1	22.6	21.3	20.1	19.1	18.2	4
				87.1	73.5	63.6	56.0	50.0	45.2	41.3	37.9	35.1	32.7	30.6	28.7	27.0	25.6	24.3	23.1	5
					89.1	77.1	67.9	60.7	54.9	50.0	46.0	42.6	39.6	37.0	34.8	32.8	31.0	29.4	28.0	6
						90.6	79.8	71.3	64.5	58.8	54.1	50.0	46.6	43.5	40.9	38.5	36.5	34.6	32.9	7
							91.7	82.0	74.1	67.6	62.2	57.5	53.5	50.0	47.0	44.3	41.9	39.7	37.8	8
								92.6	83.7	76.4	70.2	65.0	60.5	56.5	53.1	50.0	47.3	44.9	42.7	9
									93.3	85.2	78.3	72.4	67.4	63.0	59.2	55.8	52.8	50.0	47.6	10
										93.9	86.4	79.9	74.4	69.5	65.3	61.5	58.2	55.2	52.5	11
											94.4	87.4	81.3	76.0	71.4	67.3	63.6	60.4	57.4	12
												94.9	88.3	82.5	77.5	73.0	69.1	65.5	62.3	13
													95.2	89.0	83.6	78.9	74.5	70.7	67.2	14
														95.5	39.7	84.5	80.0	75.8	72.1	15
															95.8	90.3	85.4	81.0	77.0	16
																96.0	90.8	86.1	81.9	17
																	96.3	91.3	86.8	18
																		96.5	91.7	19
																			96.6	20

MEDIAN RANKS (PER CENT)

SAMPLE SIZE

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
5.0	2.5	1.6	1.2	1.0	0.8	0.7	0.6	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2
	22	14	10	7.8	6.2	5.3	4.6	4.1	3.6	3.3	3.0	2.8	2.6	2.4	2.2	2.1	2.0	1.9	1.8
		37	25	19	15	13	11	10	8.7	7.8	7.1	6.6	6.1	5.6	5.3	4.9	4.7	4.4	4.2
			47	34	27	23	19	17	15	14	12	11	10	9.6	9.0	8.4	7.9	7.5	7.1
				55	42	34	29	25	22	20	18	17	15	14	13	12	12	11	10
					61	48	40	34	30	27	25	22	21	19	18	17	16	15	14
						65	53	45	39	35	32	29	26	24	23	21	20	19	18
							69	57	49	44	39	35	33	30	28	26	24	23	22
								72	61	53	47	43	39	36	33	31	29	27	26
									74	64	56	51	46	42	39	36	34	32	30
										76	66	59	53	49	45	42	39	37	35
											78	69	61	56	52	48	45	42	39
												79	70	64	58	54	50	47	44
													81	72	66	60	56	52	49
														82	74	67	62	58	54
															83	75	69	64	60
																84	76	70	66
																	85	77	72
																		85	78
																			86

5% RANKS

95% RANKS

99.7																			
98	99.7																		
96	98	99.7																	
93	96	98	99.6																
90	92	95	98	99.6															
86	89	92	95	98	99.6														
82	85	88	92	95	98	99.6													
78	81	84	88	91	94	97	99.6												
74	77	80	83	87	90	94	97	99.5											
70	73	76	79	82	86	90	93	97	99.5										
65	68	71	74	77	81	85	89	93	97	99.4									
61	63	66	69	72	76	79	83	88	92	96	99.4								
56	58	61	64	67	70	74	78	82	86	91	96	99.3							
51	53	55	58	61	64	67	71	75	80	85	90	95	99.2						
46	48	50	52	55	58	61	65	68	73	78	83	89	95	99.1					
40	42	44	46	48	51	54	57	61	65	70	75	81	87	94	99				
34	36	38	40	42	44	47	49	53	56	61	66	71	77	85	92	99			
28	30	31	33	34	36	39	41	44	47	51	55	60	66	73	81	90	98		
22	23	24	25	26	28	30	32	34	36	39	43	47	52	58	66	75	86	97	
14	15	15	16	17	18	19	21	22	24	26	28	31	35	39	45	53	63	78	95
20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1

SAMPLE SIZE

Financial Factors

In maintenance decision making we often have to consider spending money now in order to save money in the future, or, conversely, deciding not to spend now knowing that it will cost us more to repair in the future. Whilst the models we use are deterministic (indeed, they only employ variations on the compound interest formula) the estimates which we manipulate may be fraught with under- or over-optimism, modified by inflation and so on. Thus we must always guard against modelling elegance being a substitute for engineering experience.

The way which is frequently recommended for any large investment, because it gives a more accurate picture over the life of an asset than any of the averaging or approximating methods, is to discount the cash flow. This considers the cash flowing in from an investment for each succeeding year ahead. From these expected amounts the amount which would have to be invested today to achieve this amount is calculated. That is, there are no assumptions about regular, or continuous or equal amounts of return. This is where discount tables come in.

n	Present Worth Factor pwf_{sp}
	$\frac{1}{(1+i)^{n}}$
1	0.9434
2	0.8900
3	0.8396
4	0.7921
5	0.7473
6	0.7050
	£491.74

i.e. an investment of £492 today will yield £600 over 6 years, or
the promise to pay £100 p.a. for 6 years is worth £492 today.

A slightly more complex example, and more realistic, is where an investment does not earn a constant stream.

Values given assume that payments are made at the end of each year:

Year No.	Annual Saving Expected	i = 10%
1	0	-
2	0	-
3	200	150
4	150	102
5	150	93
6	133	75
7	100	51
8	100	47
	£833	£518

Thus we are getting a 10% rate of return on our £518 but it is not £518 invested at 10% for 8 years

which is $518 \times (1 + 0.10)^8$

$= \quad \times \ \text{caf}_{sp} \quad = \ 2.144$

$= 518 \times 2.144 \quad = 1113 \neq 833$

£518; what is happening?

Asset value at beginning of year	10%	Asset value at end of year	Drawings	10% to end of period	End of period value
518	52	570			
570	57	627			
627	63	690	200	122	322
490	49	539	150	69	219
389	39	428	150	51	201
278	28	306	133	28	161
173	17	190	100	10	110
90	9	99	100	0	100
			£833		£1,113

Thus we are getting a 10% return on our investment but only in a very special way. This latter is less serious an objection than we might think because the enterprises for which we work have a constant stream of decisions like this going on from year to year and the savings enjoyed can be regarded as part of the flow of money which acts as the blood stream of any company. A set of typical single payment and uniform series multiplying factors is given for one of the many interest rates which could be employed.

Annual Cost Method

Using the ideas developed by considering the time value of money, one of the most simple extensions of this concept enables us to consider the relative merits of overhaul, replacement or leaving the facility alone. The inputs of information necessary are current and salvage values of the equipment, operating costs (which include maintenance) and a definition of what value we put on money. This latter enables us to calculate the crf_{US} (capital recovery factor for a uniform series, which is like a mortgage repayment). We then use the formula:

Annual Cost = (Initial value - Salvage) x crf + (Salvage value x i) + Operating costs

Example.

A company is considering the replacement or renovation of a vertical borer. The existing machine has a secondhand value of £4,000, which is expected to decrease to nil in ten years' time, and has an operating cost of £8,000 per annum. To renovate would cost £3,000, but it is estimated that £1,000 of this would be recoverable at the end of ten years; in addition, the annual operating costs would be reduced by £750. The new machine would cost £6,000 per annum to run but the net capital outlay would

20% COMPOUND INTEREST FACTORS

n	Single Payment		Uniform Series				n
	Compound Amount Factor caf	Present Worth Factor pwf	Sinking Fund Factor sff	Capital Recovery Factor crf	Compound Amount Factor caf	Present Worth Factor pwf	
	Given P To find S $(1+i)^n$	Given S To find P $\frac{1}{(1+i)^n}$	Given S To find P $\frac{i}{(1+i)^n-1}$	Given P To find R $\frac{i}{(1+i)^n-1}$	Given R To find S $\frac{(1+i)^n-1}{i}$	Given R To find P $\frac{(1+i)^n-1}{i\ (1+i)^n}$	
1	1.200	0.8333	1.00000	1.20000	1.000	0.833	1
2	1.440	0.6944	0.45455	0.65455	2.200	1.528	2
3	1.728	0.5787	0.27473	0.47473	3.640	2.106	3
4	2.074	0.4823	0.18629	0.38629	5.368	2.589	4
5	2.488	0.4019	0.13438	0.33438	7.442	2.991	5
6	2.986	0.3349	0.10071	0.30071	9.930	3.326	6
7	3.583	0.2791	0.07742	0.27742	12.916	3.605	7
8	4.300	0.2326	0.06061	0.26061	16.499	3.837	8
9	5.160	0.1938	0.04808	0.24808	20.799	4.031	9
10	6.192	0.1615	0.03852	0.23852	25.959	4.192	10
15	15.407	0.0649	0.01388	0.21388	72.035	4.675	15
20	38.338	0.0261	0.00536	0.20536	186.688	4.870	20
25	95.396	0.0105	0.00212	0.20212	471.981	4.948	25
50	9100.427	0.0001	0.00002	0.20002	45497.1	4.999	50

be £13,000, only £3,000 of which is recoverable at the end of ten years. With a minimum required rate of return of 20%, make an annual cost estimate. Using the basic 1-year test we use the formula for annual cost.

A C = (Initial - Salvage) x crf at required rate over n years of life
+ Salvage value x required rate + operating disbursements.

New Machine

$$A\ C = £(10{,}000 \times 0.23852) + (3{,}000 \times 0.2) + 6000$$

$$= £2{,}385 + 600 + 6000 \qquad = \underline{£8{,}985}$$

Existing Machine

$$A\ C = £(4{,}000 \times 0.23852) + 8000$$

$$= 954.08 + 8000 \qquad = \underline{£8{,}954}$$

Existing Machine, re-conditioned

$$A\ C = £(6{,}000 \times 0.23852) + (1{,}000 \times 0.2) + 7{,}250$$

$$= 1{,}431 + 200 + 7{,}250 \qquad = \underline{£8{,}881}$$

Thus it would appear that the renovation of the existing machine should be recommended.

It might also be apposite to remember that these calculations are only as good as the estimates which were given in the first place. However, we shall leave the accuracy of the decimal place and look at the third of our basic approaches wherein it is very difficult to develop anything like a mathematical model.

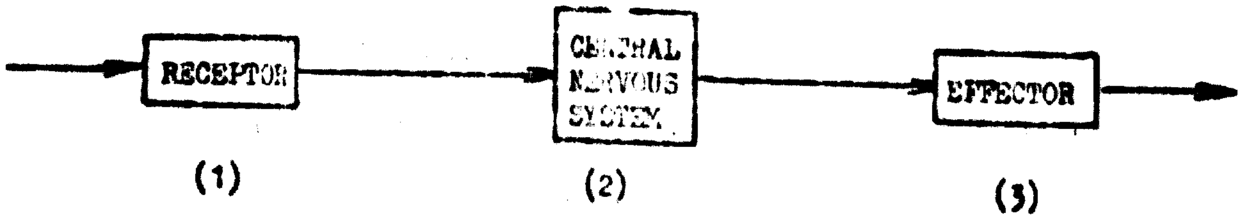
Human Factors

The most important, difficult and fascinating input to any maintenance situation is the human one. It both dominates and limits. It is the key factor to all activity relating to the design; that is, making decisions what, how, when even if, anything should be done. This factor is also vital when we want to monitor, or control, what is being done. So important is this factor of control that management, the most highly paid part of the production complex, (sic highly skilled) does little else but control.

Engineering (if not most of human history) can be written in terms of our controlling our environment, existing forms of power (other than human) to help select, control and make decisions. We have used machines as far as possible to take the drudgery out of life. However, we cannot eliminate the human factor because we shall always need to make decisions about <u>which</u> decisions to make. Many people hope that automatic inspection will eventually replace that particular part of the maintenance function. Certainly a machine is more efficient in '100 per cent' checking of a continuous flow of products for one or two faults. But whenever control is complex and conditions are variable a man has certain decided advantages over a machine as a detector. It is difficult to find a machine that can match human powers of examining for numbers of different faults at once over a wide range of possibilities, or take note of a rare, perhaps unspecified, fault. The human may be 'reprogrammed' by management more rapidly than any machine, and he is capable of acting on instructions with discretion. He is unsurpassed where discrimination is required between a large number of faults, where classification and diagnosis are needed, and where eliminating the fault involves liaison work. His performance and his value to a firm do not depreciate but tend to increase with time and experience.

Technical progress is creating new demands for the maintenance factor. In some of the more advanced industries the total number of maintenance men has actually risen in spite of an overall reduction in the labour force.

In fact, this is very much an area of Ergonomics, where we have to discover what physiology and psychology say about our problem area. We rig ourselves up with aids, metrology, 'non-destructive testing', but we rely on our in-built detectors to supply the most important answers. What are these? How do we use them? What do we know about them? The simplest possible model is:-



whereby: (1) We perceive signals through our sensory organs:-

electromagnetic	e.g.	eyes
mechanical	e.g.	touch
chemical	e.g.	taste

(2) We store, process and act upon these signals through our mental processes, though all our brains receive is a series of clicks from the nerves, and the 'best theory' at the moment postulates single channel.

(3) These mental processes are effected through our physiological make-up (we can only move muscles) which is affected by the physical and social environment, and subject to error.

Throughout the recorded history of man we have been observing, and theorising, about how we work. The traditional modesty of the scientist is not a smoke screen, it is very humbling to realise how little we know about this fantastic component in the field of maintenance.

Electron miscroscopes have enabled us to develop better theories about how we work in a physical sense, but these are only approximations towards a real answer which (one can be reasonably confident in saying) we shall never achieve.

Essentially, we are looking at the nervous system in this communications problem within the human body. We have many observable facts and we have many more theories about the explanation of these, starting in the early 1950s with an ingenious theory; e.g. it was only in 1963 that Professors A.F. Huxley and A.L. Hodgkin shared the Nobel Prize for Medicine - their discoveries concerning nerve transmission, with Sir J.C. Eccles (Austr.) supplementing their work later. This relates only to the 'input/output' side of our 3-step model. "We cannot even prove the existence of a mental life".

But even if we do not know the nature of the mind, we know quite a lot about this mechanism, or the nervous system. Simply, the job of receiving and reacting to stimuli is given to this system. Consisting of the brain, the spinal chord and a complex network of nerves. Nerves can be split into sensory (to the brain) or motor (from the brain). Some systems are conscious. others sub-conscious; e.g. the viscera, which is the name given to the various organs filling the chest and abdominal cavities.

The transmission of information via our electro-chemical (hence the Ionic title) nervous system is sent at speeds varying from 2 - 200 m.p.h.

The 10,000, (10^{10}) nerve cells of the brain forming the bumpy knot of 'grey matter' can be divided, crudely, in terms of anatomical entities related to different functions.

BRAIN STEM (spinal cord) and CEREBELLUM work below the level of consciousness. They are responsible for MUSCULAR CO-ORDINATION and modify unrealistic demands on them.

THALAMAS (and CORTEX) working together INTEGRATE MESSAGES from the sense organs which are received via the thalamas.

CEREBRAL CORTEX is where sensations are registered and voluntary actions initiated. Higher THOUGHT PROCESSES occur and MEMORY is stored.

LIMBIC system contributes to the EMOTIONS.

Perception

Is concerned with the sensory nerves and we can identify several channels through which the brain receives relevant signals, though we are particularly concerned with the conscious system only:-

1. Vision
2. Hearing
3. Smell
4. Touch
5. Taste
6. Balance, rotation
7. Vibration
8. Pressure
9. Temperature
10. Acceleration

Fairly obviously, we are very much in the area of theories or 'best explanations' but we can be fairly confident in asserting that perception is not at a constant level and seems very much like a probabalistic concept. Highly relevant is the problem of sensitivity - absolute and relative - especially important is the latter in terms of our remarkable ability to detect signals against a noisy background. However, a background or reference can increase our sensitivity.

Our sensitive organs have a logarithmic response to excitation; also the perception of a change in environment depends upon its previous level. In the absolute sense, an eardrum can detect a movement equal to the size of one-tenth of the diamter of a hydrogen atom. The eye can detect a candle's light at the distance of one mile; it can also respond to a range varying from 1 quanta to 10^9 quanta.

The problem of discrimination is explained by levels of discernment with and without reference, e.g.

LIGHT stimulus
in isolation : 4 - 5 intensitise 12-13 discrete colours
with reference : 570 intensities 128 shades of white light

SOUND
in isolation : 3 - 5 intensities 3-5 pure tones
with reference : 325 intensities 1,800 notes

The problem of detection is best explained in terms of background noise and level of skill.

A signal comes in mixed with noise, and the level of the system noise varies in a fashion similar to Gaussian distribution so there will be a statistically-based decision, at the small levels, in order to detect the signal. When a stimulus is applied to the receptor organs, extra activity is produced from this source and it is added to the existing 'noise'. Whether this increase in activity is considered a random peak or a signal applied to the system will depend on the statistical criterion which is being employed by the 'decision centre' at that moment.

Still in the area of statistical analogy, we only ever use part of the information which is presented to us. With experience, we can perform a secondary task, apparently with little or no conscious effort. Similarly, we can identify by minimal information.

Human powers of discrimination and detection are quite remarkable but there are also snags, i.e. inconsistency, fatigue, susceptibility to external conditions (physical and social) also there are problems with short term/long term memory.

Certainly,perception is related to the learning process. Physical abilities with regard to different perceptions alter between persons but this may be a reflection of training. Certainly physical characteristics between perceotions in one person show marked differences.

Physical Environment

Undoubtedly, physical conditions have a primary influence in the perception, for they affect directly the Detection stage. But once we have the satisfactory physical conditions the psychological and social conditions will be preponderant, for they affect directly the Judgement and Decision Stages. The relevant conditions of particular importance to us are:

1. Temperature (and humidity)
2. Vibration
3. Noise
4. Visual Environment

Extreme environmental conditions can have an effect on the individual in maintenance in three ways. Firstly, they can be detrimental to health and possibly cause permanent damage; secondly, they can cause discomfort with resulting distraction from the job; and thirdly, they can reduce working efficiency. The last two ways are particularly significant to our task. We shall not consider general environmental effects but deal more specifically with conditions affecting the task of subjective assessment.

Social Environment

Many people today consider that a man goes to work solely to earn money. This concept is only partly true; the other part is that the man goes for the social benefits that he can derive from working with others.

Within a factory there are two types of organisations, the formal and informal. The formal organisation, or group as we shall call it, consists of management and workers working together to produce an article. The informal group, although it has the title 'informal', has its own rules, regulations and standards. It is through this group that a man can be influenced more than by management.

It therefore follows that if the standards are to be raised then we must tackle them with the group as a whole and not with individuals. The group must be made to feel that it does something for the final product (and the way to start to do this is to show them where the particular task they are doing fits in, and how important it is to maintain the standard). Secondly, we must keep them informed because an informed man is an interested one. A constant supply of the right type of information about performance shows our man that if the one above him, e.g. the foreman, is interested in the job, then the job is important, and, consequently, the standard will be maintained.

Maintainability

In general terms maintainability relates to the ease or difficulty with which an item can be repaired when it fails. Maintainability is a design factor which competes with other requirements such as low initial cost, good performance and reliability. For example, it may improve the maintainability of an aircraft to have an access plate in a certain spot, but this will also increase the cost and reduce the performance because of increased weight. Similarly, the maintainability of an electronic device may be improved by making it in the form of detachable boards joined by plugs. The plugs, however, may have low reliability when compared with soldered joints. Here there is usually a trade-off between maintainability and reliability.

Maintainability can be defined as the probability that an item which has failed will be repaired within a stated time. The stated time is known as the maintenance time constraint, and is dictated by operational circumstances, e.g. aircraft turn around time.

Maintainability relates normally to active repair time, and not to time waiting for spares, etc. It may be related to repair <u>time</u> or repair man hours depending on the application. This definition implies that the time to repair is a random variable, and defines maintainability M for time constraint tc as

$$M = R(tc)$$

where function R is the cumulative distribution function of the repair time.

Availability

Availability is the proportion of time for which a machine is available for use. The overall objective in most maintenance and replacement problems is to minimise the cost per unit service. This is related to the availability as follows:-

$$\text{Cost per unit service} = \frac{\text{Cost per unit time}}{\text{Availability}}$$

Since availability appears as a denominator in this equation, it is clear that a low value of availability will result in a very high cost per unit service. In many public service applications it may be taken as an actual constraint that the availability should exceed some lower limit. For these reasons it is generally a requirement in most practical cases that availability should be 90% or higher.

Much of the study of problems of availability has been inspired by what is called the machine interference problem. This arises from the practical problem of determining the optimum number of machines per operative in textile mills. Some typical problems are as follows:

A single machine is maintained by a single repair crew. The MTBF of the machine is Ta and the MTTR is Ts. Suppose that the size of the repair crew is variable and that the cost per unit time of providing a repair crew which can achieve a MTTR of Ts is C/Ts where C is a constant. Let B be the profit per unit time for which the machine operates. Determine the optimum MTTR (and hence the optimum crew size).

$$\text{Availability} = \frac{Ta}{Ta + Ts}$$

$$\text{Profit per unit time} = \frac{B \cdot Ta}{Ta + Ts} - \frac{C}{Ts}$$

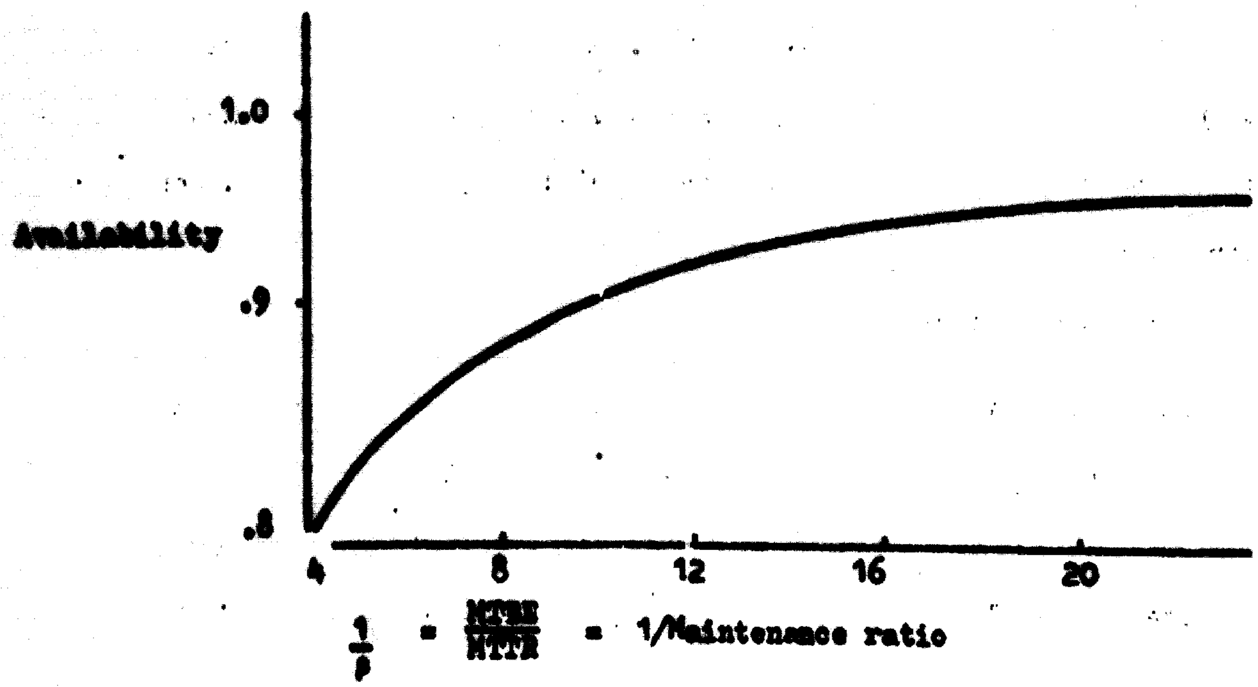
This has a maximum when:

$$Ts = T_a \; (B\,Ta/C)^{\frac{1}{2}} - 1)^{-1}$$

The availability is then:

$$A = 1 - (C/B\,Ta)^{\frac{1}{2}}$$

We may just require the availability to achieve a certain level. A plot of this equation reveals the difficulty of achieving high availability.



Availability and Maintenance Ratio

Repair Pools

Problems of determining the optimum number of repair men to maintain N machines when the profit per machine hour and the cost per repair man is known can be tackled by queueing theory. Typically the results appear in the form of tables.

However, in the repair pool situation, where items undergoing repair are offset by drawing on a repair pool, some simple analyses can be given provided that we assume that the repair pool is rarely completely empty. The overall failure rate can then be regarded as constant, say λ. With a single repair crew with MTTR $= 1/\mu$ the mean number of machines broken down is:

$$\frac{\lambda}{\mu - \lambda}$$

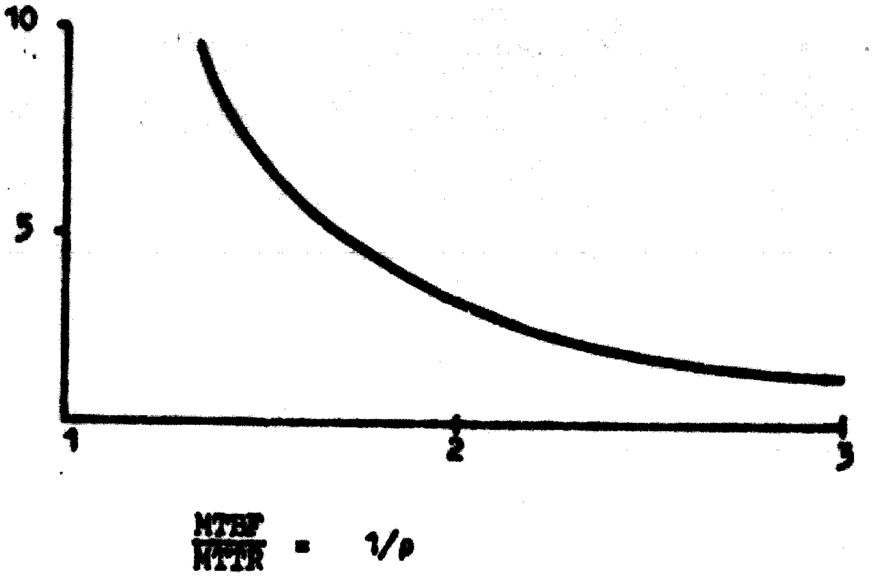
and the s.d. of the number of machines broken down is:

$$\frac{\sqrt{\lambda\mu}}{\mu - \lambda}$$

If we base the repair pool size on mean + 2s.d.,

$$\text{Repair Pool} = \frac{\lambda + 2\sqrt{\lambda\mu}}{\mu - \lambda}$$

$$= \frac{\rho + 2\sqrt{\rho}}{1 - \rho} = \frac{1 + 2\sqrt{\frac{1}{\rho}}}{\frac{1}{\rho} - 1}$$



Repair Pool Optimisation

Replacement

Most equipment deteriorates in use. Thus anyone who wishes to use equipment over anything but the very short term must operate a replacement policy - whether deliberately or by default. The aim of a replacement policy is to balance the costs associated with equipment provision and maintenance in the most favourable way. The following factors should ideally be considered:

Acquisition cost

Repair costs

Value of the service or production

Availability

Obsolescence

Safety requirements

Ease of application

Tax

Rate of interest

Scrap or second-hand value

Planning horizon

Alternative forms of investment

Two main replacement areas could be considered. The first relates to the replacement of components which may suddenly fail in use and which are always replaced by new components of the same type. The second main area is equipment replacement; that is the replacement of items which deteriorate gradually and which require repairs from time to time prior to replacement.

The Problem of Data Collection

To re-introduce that most complex of all the inputs and consideratio relevant to a preliminary discussion on maintainability let us consider the collection of data. Ideally we are attempting:

a. to measure the operation Availability level;

b. to provide (quick response) failure data for post design;

c. to build up a data bank for the benefit of future designers in order to:

   (i) minimise repetition of known design weaknesses

   (ii) give design groups a realistic base for the design and testing of new equipments;

d. to provide management control data.

The success of any study depends on good planning and a sound experimental design must precede any kind of life characteristic or data gathering exercise. The technical objectives must first be explicitly defined and the data gathering programme then planned to realise them.

The aim must be to collect a sufficient quantity of data from actual service conditions to enable conclusions to be drawn with the stipulated confidence. No more data than is necessary for this purpose should be amassed. Motivation is an important factor in ensuring accuracy of returns and the knowledge that redundant data will not be sought must assist in improving it. As well as being accurate the data must be representative of the true operational and maintenance environment. Equipment modification state, level of maintenance expertise, logistic support available, etc., may normally be representative but possible exceptional circumstances should be identified.

The following questions should be considered:

What data are required?

How will the data be analysed?

How accurately are the results to be stated?

How much data are needed to achieve this?

Who will use the results?

How will they be used and for what?

The more background information available the more exactly the circumstances surrounding any technical event can be reconstructed. While voluminous records are unnecessary, brief notes on the following should be available for each relevant event:

Equipment identification to level required.

Event - failure, defect, adjustment, trial, modification, maintenance, etc. It is important to record trials consciously undertaken, since mishaps may occur during tests which it would be misleading to attribute to normal operation.

State of equipment at time of event

Time of occurrence

Cumulative running hours, cycles, etc. to occurrence

Time taken for repair

Down Time

Reasons for failure if known

Environment at time particularly if unusual

Stores used in repair

Man hours and skills needed for repair

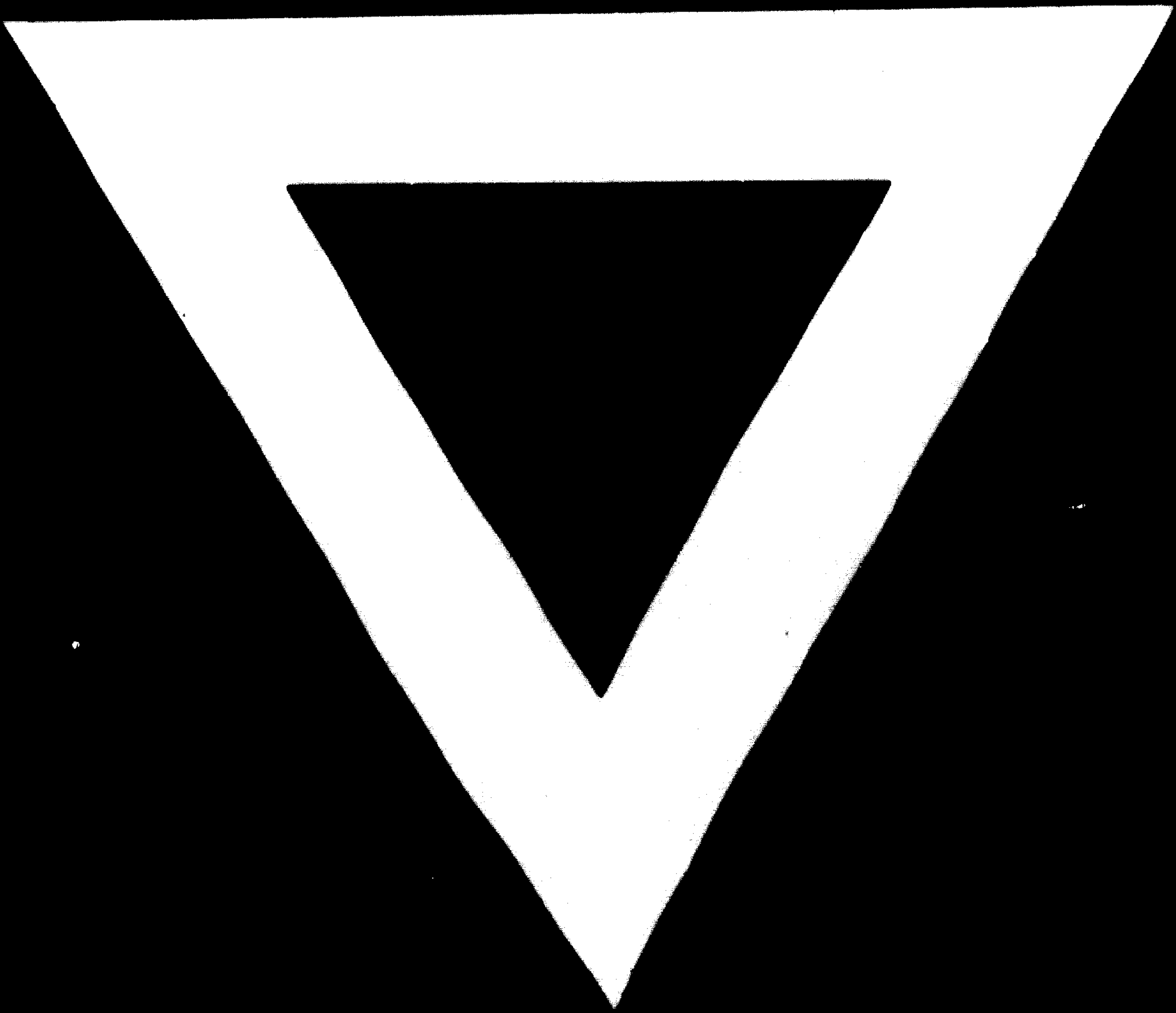
Reasons for any delay in repair or in return to operational state.

There is no easy way to the provision of accurate life characteristic data and broad brush, loosely monitored systems will be an expensive waste of time. A systematic approach with painstaking attention to all factors which may improve the quality and consistency of the data must be followed. This will involve detailed planning, specification, establishment of responsibilities, training, careful design of logs, supervision, motivation and informed engineering leadership over the possibly lengthy periods of time involved.

If this sounds a pedestrian and possibly depressing catalogue, it may encourage to repeat an opinion by two engineers of R.C.A.(Canada):

> "....it is safe to say that the ideal...or even a
> reasonably efficient method of field data acquisition
> has yet to be devised....!"

[redacted]



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