A DATA COLLECTION EXPERIMENT — MAINTAINABILITY

BY

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Introduction

The systematic pursuit of greater cost effectiveness in the design, production and operation of the Fleet inevitably calls for the estimation and measurement of that quantity. Cost effectiveness can be defined as:

$$Ec = \frac{\text{Value}}{\text{Cost}} = \frac{Es}{Ct} = \frac{f\,(P, U, Ed, D)}{Ca + Co}$$

Where:

- Ec = Cost effectiveness
- Es = System effectiveness
- Ct = Total cost
- P = Performance capability
- U = Utilization of performance capability
- Ed = Effectiveness of system delivery programme
- D = System dependability
- Ca = Acquisition cost
- Co = Ownership cost.

System dependability is a function of the reliability, maintainability and availability of the system. Maintainability has also a direct effect on ownership cost and its improvement a direct effect on acquisition cost. Thus it is an important element of cost effectiveness.

To control maintainability in the design and production phases it is necessary to be able to specify, predict and demonstrate it. This involves expressing it in a quantitative manner. An essential tool is knowledge of the nature of the frequency distributions of upkeep job times and upkeep job efforts. A subsidiary aim of the data collection experiment in H.M.S. *London* was to test the hypothesis that upkeep job times and efforts are distributed lognormally. The purpose of this article is to present the evidence gathered and to show that marine engineering ships staff work was distributed in this way in 95 per cent of the cases examined. It is accordingly argued that the lognormal distribution can be used with confidence as a working hypothesis for ships staff work; and that its use to cover fleet maintenance unit and dockyard work as well would involve little risk, though a separate test of the validity of this extension is desirable.

The frequency distribution plots used to establish the validity of the hypothesis can also be used to provide data for immediate use provided the limitations of the data source are remembered. To make this possible, without the need to reproduce in this article all the plots, the parameter values and certain additional values are given. From this information individual plots can be reconstructed when required.

Possible Job Time Distributions

A job time frequency distribution is the result of plotting the number of jobs whose length coincides with each successive equal small interval of time against time. In a general sense frequency distributions of many kinds occur in nature. They are classified by the mathematical expressions which describe the curves. By usage, they have acquired names associated with those expressions or with their discoverers.

Three of those distributions have particular interest as possible approximations to the upkeep job time distribution. The Exponential and Poisson distributions are illustrated in FIG. 1. These can each be described by relatively simple mathematical expressions containing one variable. A specific example of either distribution can be identified by the value of the variable, or parameter, a mean. The Lognormal, however, requires two parameters to identify it, the mean (μ) and the standard deviation (σ) of the logarithms of the variate. As each parameter can vary independently the variety of individual shapes which may appear is considerable. Three examples from the relatively restricted range of standard deviation covered by the data from H.M.S. *London* are shown in FIG. 2.

Maintainability—Background

Maintainability is a young quantity. Until very recently interest in this attribute of equipments and systems has been purely qualitative. As far as the author has been able to discover, Calabro (1) published the first text to discuss maintainability in terms of job time distributions as recently as 1962. He used the Poisson distribution to derive an expression for maintainability. This was used to produce the appropriate curves in (2).

The United States Air Force in (3) specified a maintainability demonstration procedure based on a lognormal job time distribution, though the possibility of other distributions occurring was recognized. In (4) and (5), the superseding documents, though the lognormal is still evidently regarded as dominant more attention is paid to procedures to cater for other distributions. Shelley (6)

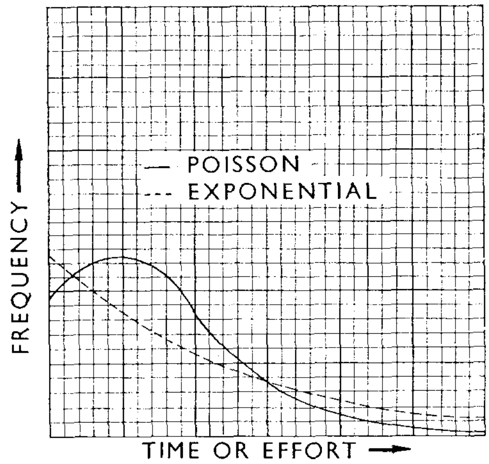

FIG. 1—EXPONENTIAL AND POISSON FREQUENCY DISTRIBUTIONS

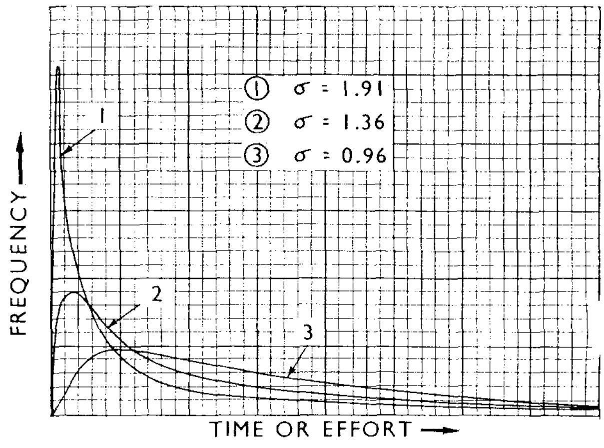

FIG. 2—LOGNORMAL FREQUENCY DISTRIBUTION

tested the job effort distribution for a group of five C–130E aircraft and concluded that agreement with the lognormal was sufficiently close to give a satisfactory accuracy when the procedures of (3) were used.

Goldman and Slattery (7) discuss the possible relevance of the exponential and lognormal distributions and conclude that, while cases where the former may be used occur, the latter is to be preferred on grounds of philosophy and experience.

The concensus of these views is that the lognormal has a general, but not universal application to job time distributions in electronic or predominantly electronic fields. Whether it is equally applicable in the marine mechanical field, for job efforts as well as job times, is the question which this article sets out to explore.

Test Method

The computation associated with the accepted methods of lognormal test and parameter estimation is extremely tedious if it has to be done by hand. Fortunately it is possible to establish graphically whether a given sample could come from a lognormal population by plotting job time against the cumulative frequency, or percentile, of jobs on logarithmic—probability paper. If the points fall on a straight line, the distribution is lognormal. This is not a rigorous test. Though valid in a perfect case it suffers from admitting of no method of assessing the significance of deviations from the straight line. Thus, whether the distribution is lognormal or not can be a matter of nice judgement.

For all such graphs it is as well to remember that what is being plotted is a sample of an infinite population. It is probably quite small and would not be expected to be perfectly lognormal itself even if drawn from a lognormal population. However, Aitchison and Brown (8) have provided the means for demonstrating the kind of deviation from exact lognormality which may be expected when using good samples. They generated a number of artificial samples in such a way that they are unbiassed samples from a lognormal population and they give the cumulative frequency data for five of them. FIG. 3 shows the data from two of them plotted on logarithmic-probability paper. The sizes (N) of the five samples range from 32 to 512. Broadly, sample size makes very little difference in the degree of deviation from the straight line. But because the curve, when placed on linear axes, is asymptotic to the x axis (see FIG. 2) the definition of the tail at high values of x is bound to lack precision when the data relate to discrete jobs, unless the sample is very large.

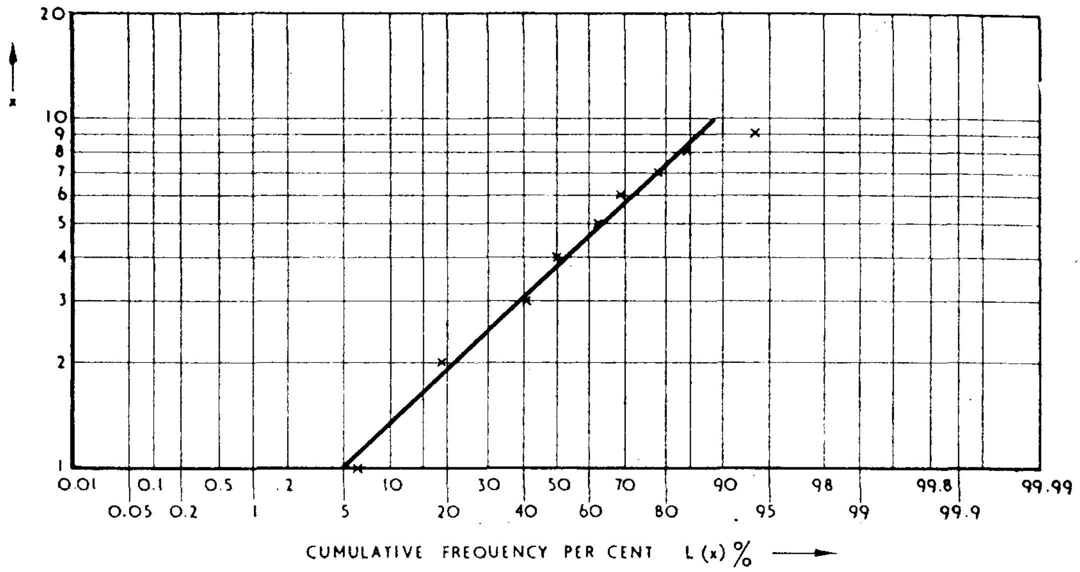

FIG. 3(*a*)—ARTIFICIAL LOGNORMAL SAMPLE—N = 32

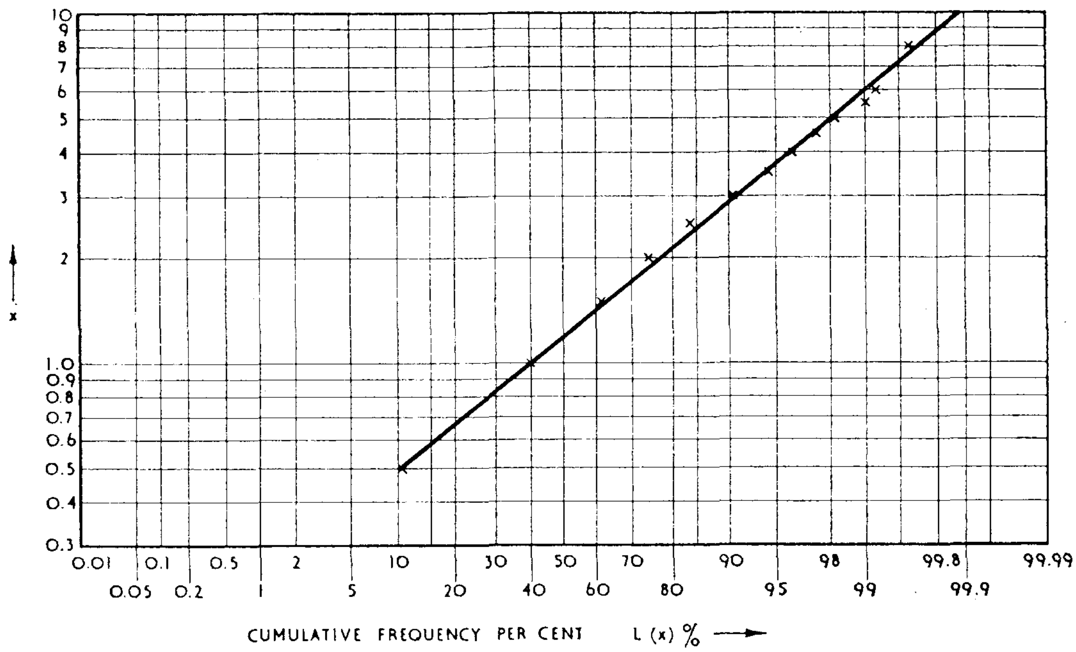

FIG. 3(*b*)—ARTIFICIAL LOGNORMAL SAMPLE—N = 512

Hence on logarithmic—probability axes the points representing high percentile values will become increasingly imprecise as sample size diminishes.

Sample Selection

Clearly, only those equipments having an adequate number of defects recorded would be suitable for investigation. The criterion is the number of defects for a specific equipment type regardless of the number of examples actually fitted. When assessed in this way some six equipments had over 50 defects recorded for them. With the knowledge that Aitchison and Brown had achieved a satisfactory plot with a sample as small as 32 these equipments were selected for study.

It seemed likely that groups of equipments having similar general characteristics would show similar results from a statistical treatment of the kind contemplated. Such a group has the advantage that it can contain a number of equipments whose defect numbers are too low for individual study. Five groups

TABLE I—*Section Machinery Responsibilities*

Steam End		*Gas End*		*Outside Machinery*
Main Boilers	2	G6 Gas Turbines	4	Steering Gear
Forced Draught Blowers	2	G6 Lub Oil Pumps	2	Stabilizers
Compound Turbine Sets	2	G6 Lub Oil Filters	2	Capstans
Condensers	2	G6 Dieso Boost Pumps	2	Air Conditioning Plant
Main Air Ejectors	2	Main Gearing	2 sets	Refrigerating Plant
Turbo Driven Extraction Pumps	2	Main Centrifugal Lub Oil Pumps	2	Galley Machinery
Motor Driven Extraction Pumps	2	Standby Lub Oil Pumps	2	Laundry Machinery
Harbour Service Feed Pump	1	Lub Oil Coolers	4	General Service Hydraulic Systems and Equipments
Deaerators	2	Lub Oil Filters	10	
Deaerator Extraction Pumps	2	Gearing Lub Oil System	2	LP Air System
Main Feed Pumps	3	Propellers	2	Syrens
FFO Pumps	3	Shafting and Fittings	2 sets	Domestic Steam Systems
FFO Heaters	3	Allens 450 kW GTAs	2	Chilled Water System
Pilot Burner Pumps	2	Ruston 750 kW GTA	1	Boat Engines
Main Circulators	2	HP Air Compressors	2	
Auxiliary Circulator	1	HP Air System up to HP/LP Reducers	1	
Servo Air Compressors	3	Diesel Air Compressor	1	
1000 kW Condensing TAs	2	Auxiliary Circulating Pumps	3	
Distilling Plant (Compound)	2	Lub Oil Separators	3	
Steam and Drain Systems		Dieso Transfer Pump	1	
FFO and Dieso Systems		Auxiliary Boilers	2	
Feed System				
Lub Oil System				
Gland Evacuation System				
Servo Air System				

TABLE II—*Equipment Groups—Details*

	Air Compressors			*Refrigerating and A.C. Plant*	
311u	H.P. Air Compressor	2	1611c	Galley R.U. Cupboard	1
314f	Servo Air Compressors	3	1611v	Main A.C. Plants	4
314p	Laundry Air Compressor	1	1611y	Main Refrigerator	2
314q	Diesel Air Compressor	1	3611b	Ice Cream Conservator	1
	Controls and Instrumentation		612a	D.A.R.s (7 cu ft)	2
			612b	D.A.R.s (2·7 cu ft)	7
911c	Boiler Steam Pressure and Combustion Control	2	612s	Wardroom R.U. Cupboard	1
			612t	Cold Counter (Galley)	1
912d	Main Engine L.O. Temp. Control	2	613c	Water Coolers	3
			616b	A.C.U. (9,000 BTU/hr)	1
912c	Separator L.O. Temp Control	3	616f	A.C.U. (12,000 BTU/hr)	2
913a	Exhaust Pressure Control	2	616g	A.C.U. (24,000 BTU/hr)	1
914g	Tank Contents Transmitters	14		*Steam, Exhaust and Drain Systems*	
914h	Temperature Transmitters	15			
915n	Mag. Flood and Spray—Remotes	10	510h	Steam Systems (General)	1
			515g	Domestic Steam System	1
915r	H.P. Air Compressor—Drains	2	516m	Main Engine Gland Evacuation	2
1915f	Gas Turbine Air Start (G6)	4	521e	H.P. and L.P. Drain System	1
2915b	Gas Turbine Throttles	4	522c	Thermodynamic Steam Traps	4
2915c	Main and Aux. Feed Checks	4			
2915d	Main Engine Throttles	4	522e	Ogden Pumping Trap	1
2915e	Main Circulator Nozzle Control	2		*Turbo Auxiliaries*	
			321r	Forced Draught Blowers	2
2915f	Feed Cross Connection	2	351u	Steam Turbo Generators	2
2915g	Stand-by Feed Pp. Range Valve	1	411m	Boiler Feed Pumps	3
2915h	Soot Blower Control System	2	413n	Extraction Pumps	2
2915j	FFO Supply Diverting and Spill Return Cocks	3	421n	Main Circulators	2
			431a	FFO Supply and Service Pumps	3
2915k	Make Up Feed Valves	2			
2915m	Manoeuvring Fluid Coupling	2		*Boilers and Boiler Mountings*	
2915n	Condensate Recirculating Valves	2	141u	Main Boilers	2
2915p	FFO Pp. Throttle Valves	3	150a	Boiler Mountings (General)	2
916c	Saturated Steam Pressure Control	2	151a	Safety Valves	6
			152f	Feed Regulators	2
916d	Evaporator Saturated Steam Control	2	153g	Retractable Soot Blowers	6
			153h	Non-Retractable Soot Blowers	12
917d	Standby FFO Heater	1			
917e	FFO Heater Control	2	154a	Water Level Indicators (Igema)	4
918d	Servo Air Induction Systems	1			
			154b	Gauge Glasses	4
	Distilling Plant		155b	Main Stops	2
222t	Distilling Plants	2	156d	Auxiliary Stop Valves	2
1422m	Water Service Pumps	2	157j	Feed Check Valves (Main)	2
426j	Brine Pumps	2	157k	Feed Check Valves (Aux.)	2
428c	Air Pumps	2			
1471k	Fresh Water Pumps	2			
415r	Element Drain Pumps	2			

were selected, each very different from the next, to cover the plant as completely as possible. On a higher level, the three maintenance sections and the whole plant were included.

There were nine possible paired combinations of degree of skill and type of work for each item to be studied, under the two heads of job effort and job time. This gives a total of 270 possibly interesting plots. The number was reduced to more manageable size by a succession of decisions. First by deciding not to examine the Other degree of skill alone, but to limit the degrees of skill to two, Skilled and All, the latter being Skilled + Other. In practice the number of Other defects are too small anyway for useful examination at any but the plant level. Secondly, by limiting to the whole plant the examination across all the remaining six combinations of skill and work type. Thirdly, by limiting the lower level plots for job effort to Skilled Upkeep as this was the combination of greatest interest. And lastly, by limiting the lower level plots of each job time to All Upkeep. Here also, this combination, with its availability significance, seemed the most important.

The whole array of plots carried out is shown in TABLE III where the existence of a plot is indicated by a letter in the appropriate square. The equipment covered by each management section is listed in TABLE I and the equipments included in each equipment group detailed in TABLE II.

Time and Effort Classes

Grouped frequency counts of job efforts and job times were carried out for the samples selected. To ensure that the fitting of the straight line was made as easy as possible and, therefore, by inference, most likely to be accurate, the data were grouped in classes which gave roughly equal point intervals on the plot. As a consequence the classes are unequal in time and effort terms.

Goodness of Fit

There is no rigorous method of establishing from a plot on logarithmic-probability paper the goodness of fit of the straight line and hence the goodness of fit of the lognormal distribution. A subjective assessment sufficient for the purpose of this investigation, however, can be made by comparing visually the individual plots with plots of the sample data given by Aitchison and Brown and judging the quality of fit. Three standards have been used; Good to describe a fit of the same or better quality than the control samples; Fair and Poor to describe fits of a less satisfactory nature. Examples of the three classes are shown in FIGS. 8–11 (Good), FIG. 4 (Fair) and FIG. 5 (Poor). Essentially these qualities of fit describe the amount of deviation of individual points from the straight line. Where the points suggest a curve rather than deviation from a straight line the plot suggests a different distribution. In such cases alternative distributions have been tried and in one an exponential distribution gives a marginally better fit.

The quality of fit for each plot is indicated in the appropriate square in TABLE III. Where the lack of fit makes it probable that a different distribution is involved the word none, or where it has been identified, the name of the appropriate distribution has been inserted.

Exceptions

Three examples reveal points which lie more nearly on a curve than in a straight line, two curving in a direction which suggests an exponential distribution. In fact, however, only one, H.P. Air Compressor Job Times, shows a marginally better fit to the exponential than to the lognormal. The difference in quality of fit is so small, however, that the use of the lognormal instead would introduce only a small error. The two plots are shown in FIGS. 6 and 7.

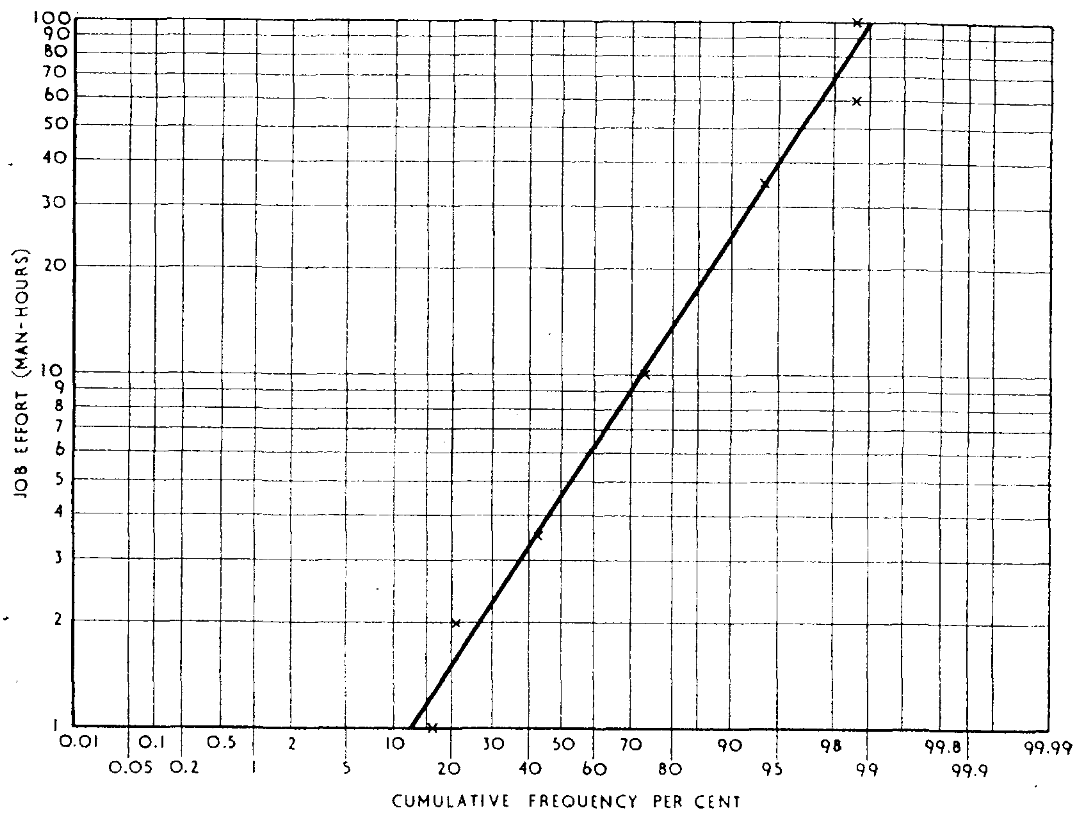

FIG. 4—EXAMPLE OF FAIR FIT—DISTILLING PLANTS—SKILLED UPKEEP JOB EFFORTS*

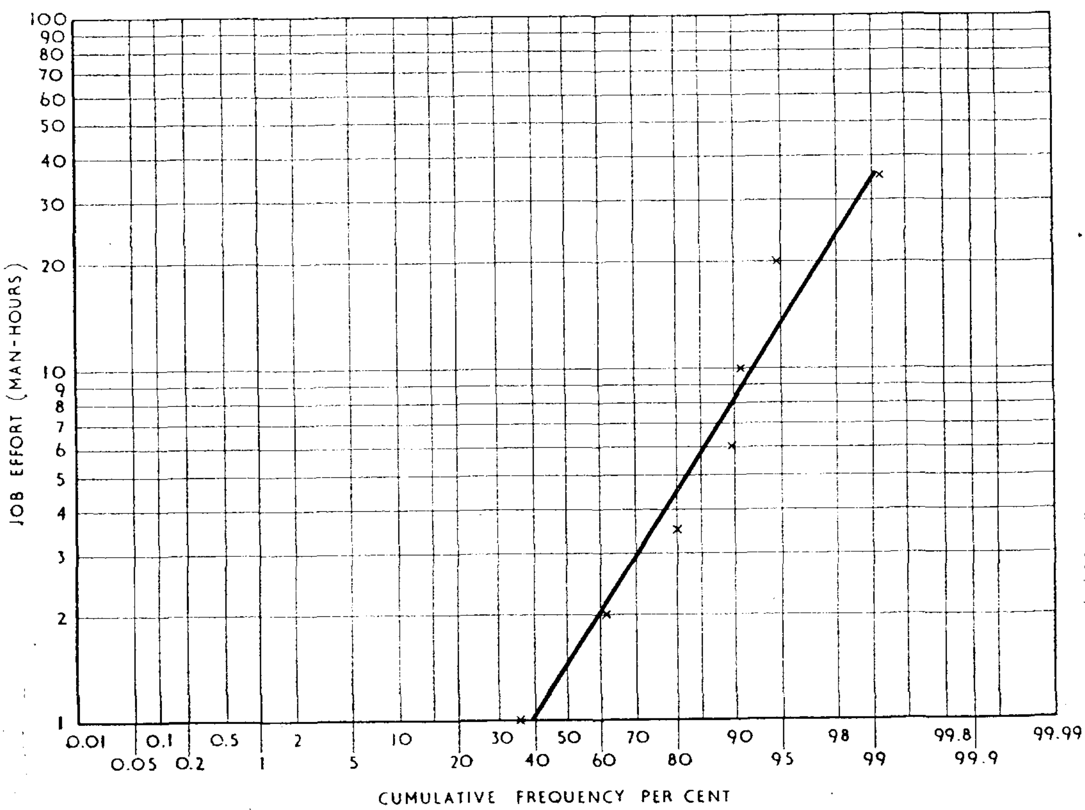

FIG. 5—EXAMPLE OF POOR FIT—REFRIGERATING AND AIR CONDITIONING PLANTS—SKILLED UPKEEP JOB EFFORTS

*Insert in Fig. 4 points 59.7/6 and 85/20

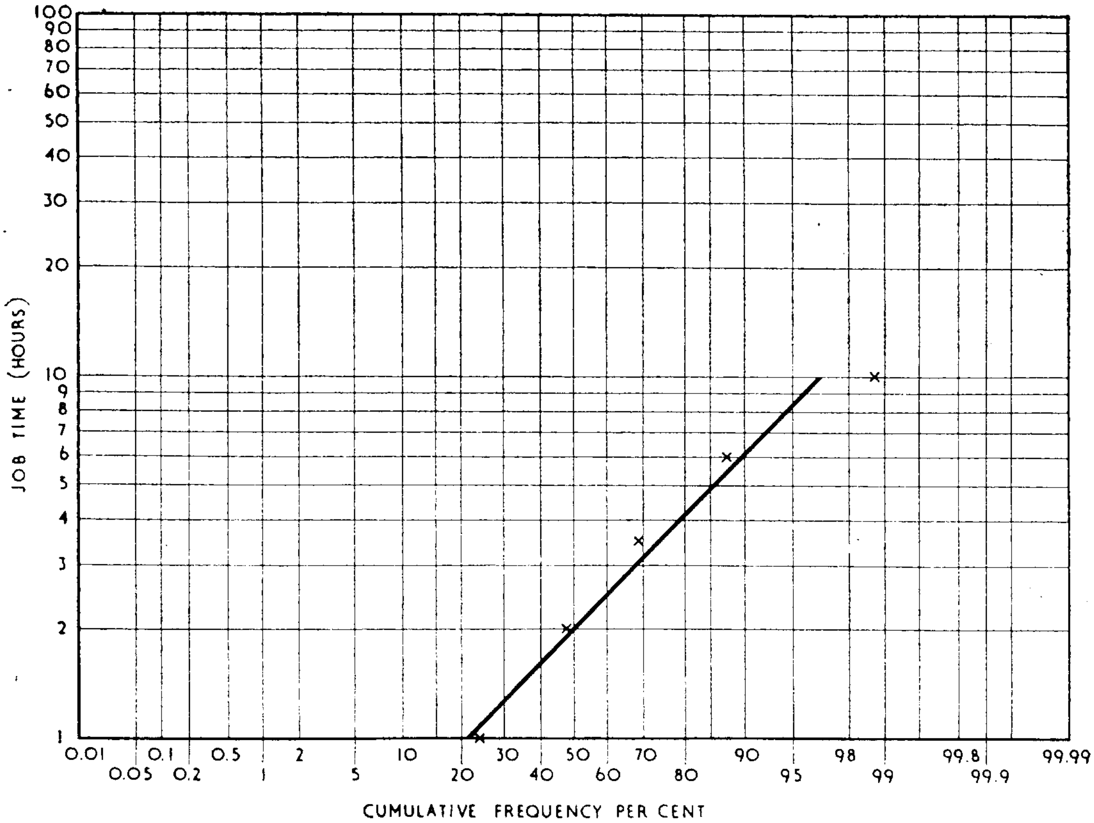

FIG. 6—HP. AIR COMPRESSOR LOGNORMAL—ALL UPKEEP JOB TIMES

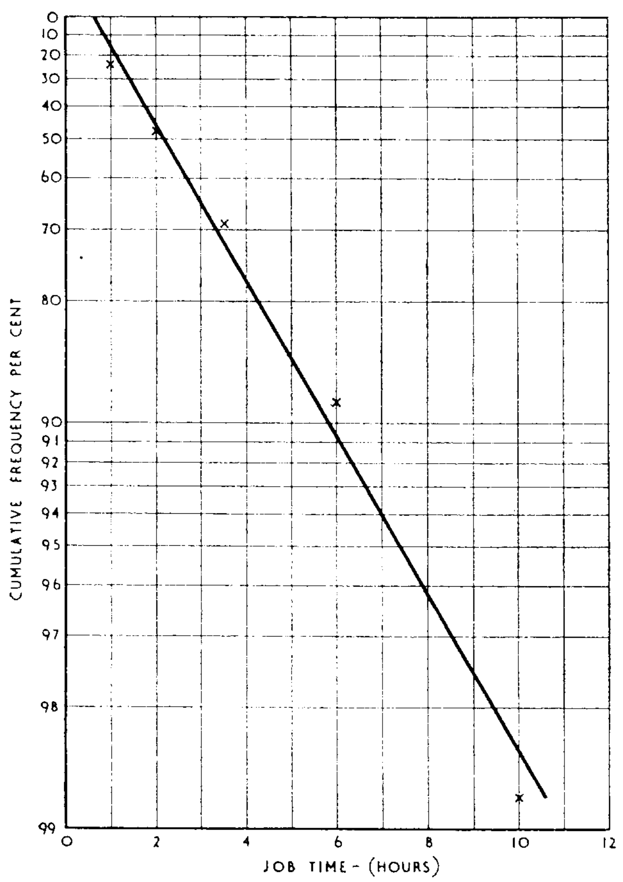

FIG. 7—HP. AIR COMPRESSOR EXPONENTIAL—
ALL JOB TIME

The other, Gas Turbine Main Engine Job Times, shows a fair fit to both distributions and thus either is useable in that case. Refrigerating and Air Conditioning Plant Job Times on the other hand fits neither the log-normal nor the exponential. The appropriate distribution has not been identified. Why this group should be exceptional is not understood, but it may be that the group of equipments concerned is not coherent as a group. It is noticeable that this group also produces the only poor fit among the skilled upkeep job efforts.

Goodness of Fit—Summary

A summary of the goodness of fit in the forty samples is shown in TABLES IV (*a*), (*b*) and (*c*). The first shows the number of samples achieving each standard of fit under the headings—Plant, Section, Group and Equipment. As might be expected the proportion of good

TABLE IV—*Summary of Goodness of Fit*

	Plant	*Sections*	*Groups*	*Equipments*
Good	11	4	4	3
Fair	1	2	3	8
Poor			2	
Exceptions			1 (None)	1 (Exp)

(a) All Plots

	Plant	*Sections*	*Groups*	*Equipments*
Good	5	2	3	2
Fair	1	1	1	4
Poor			1	
Exceptions				

(b) Job Effort Plots

	Plant	*Sections*	*Groups*	*Equipments*
Good	6	2	1	1
Fair		1	2	4
Poor			1	
Exceptions			1 (None)	1 (Exp)

(c) Job Time Plots

fits falls with sample size. It is noticeable that both poor fits and one of the two exceptions occur under the heading—Group. Since Equipment with smaller sample sizes performs better in this respect it is not inconceivable that the fault lies in the groups and their coherence or lack of it. Certainly this particular result cannot be regarded as invalidating the general conclusion resulting from the remainder, that the lognormal distribution of job efforts and job times is a valid working hypothesis, though it is not infallible.

TABLES IV (*b*) and (*c*) show the same information for the job efforts and job time samples respectively. The quality of fit achieved by the former is marginally better than that by the latter. The difference is small and probably not significant, but there is a difference in the bases which might explain it. For Sections, Groups and Equipments, the job effort samples were Skilled and the job time samples All. It is conceivable that the introduction of a small number of Other job times has a distorting effect. However, the distortion is insufficient to invalidate the general conclusion.

Distribution Parameters

The lognormal distribution has two parameters, the mean and the standard deviation of the logarithms of the variate. The mean can also be expressed in linear values as a function of the median, or halfway value, of the variate itself.

Table III—*Goodness Fit and Parameters*

		Skilled			*Skilled + Other = All*			*Number in Sample*	*Mean*	*Standard Deviation*	*Median (50%)*	*Maximum (95%)*	99%
		Defects	*Maint.*	*Upkeep*	*Defects*	*Maint.*	*Upkeep*						
	Job Efforts												
	Whole Plant												
1.	Steam, Gas and Outside Machinery Sections	G						1225	6·78	1·28	2·73	23·0	56
2.	,, ,, ,, ,, ,, ,,		F					640	3·13	1·66	0·79	12·5	40
3.	,, ,, ,, ,, ,, ,,			G				1865	4·82	1·39	1·90	19·8	53
4.	,, ,, ,, ,, ,, ,,				G			1316	7·06	1·34	2·87	27·0	70
5.	,, ,, ,, ,, ,, ,,					G		887	4·34	1·91	0·71	17·3	66
6.	,, ,, ,, ,, ,, ,,						G	2203	6·02	1·54	1·83	23·2	69
	Sections												
7.	Steam Section			G				933	5·97	1·47	2·05	24·0	67
8.	Gas Turbine Section			G				485	4·21	1·28	1·87	15·3	37
9.	Outside Machinery Section			F				446	4·07	1·36	1·62	15·5	40
	Equipment and System Groups												
10.	Air Compressors			G				143	3·79	1·19	1·88	13·7	—
11.	Controls and Instrumentation			G				130	5·43	1·77	1·12	22·3	—
12.	Refrigeration and Air Conditioning Plant			P				134	3·53	1·34	1·45	13·5	34·5
13.	Steam, Exhaust and Drain Systems			F				112	4·18	0·96	2·65	13·0	26
14.	Turbo Auxiliaries			G				267	6·97	1·70	1·65	27·0	89
	Equipments												
15.	Boilers and Boiler Mountings			F				127	8·17	1·78	1·68	33·0	113
16.	Distilling Plants (including Pumps)			F				80	10·65	1·30	4·55	40·0	100
17.	Gas Turbo Alternators (Allens 500 kW)			F				107	3·48	1·37	1·36	13·3	35
18.	Gas Turbine Main Engines (G6)			F				140	4·61	1·22	2·20	16·7	—
19.	H.P. Air Compressors			G				67	4·20	0·97	2·30	11·3	22
20.	Main Feed Pumps			G				76	8·12	1·57	2·35	32·0	97
	Job Times												
	Whole Plant												
21.	Steam, Gas and Outside Machinery Sections	G						1223	5·7	1·30	2·43	21·5	54
22.	,, ,, ,, ,, ,, ,,		G					660	3·41	1·76	0·73	13·5	47
23.	,, ,, ,, ,, ,, ,,			G				1883	4·90	1·44	1·75	19·3	53
24.	,, ,, ,, ,, ,, ,,				G			1293	5·40	1·25	2·5	20·0	48
25.	,, ,, ,, ,, ,, ,,					G		885	4·08	1·81	0·80	16·0	57
26.	,, ,, ,, ,, ,, ,,						G	2178	4·95	1·48	1·65	19·5	55
	Sections												
27.	Steam Section						G	1124	5·60	1·52	1·77	22·0	63
28.	Gas Turbine Section						G	562	3·67	1·29	1·60	13·7	34·5
29.	Outside Machinery Section						F	492	4·98	1·55	1·50	19·8	58
	Equipment and System Groups												
30.	Air Compressors						P	157	2·95	1·06	1·68	9·9	20·5
31.	Controls and Instrumentation						F	185	4·26	1·88	0·72	16·5	—
32.	Refrigeration and Air Conditioning Plant						N	134	—	—	—	—	—
33.	Steam, Exhaust and Drain Systems						F	133	3·91	0·92	2·55	11·8	22·5
34.	Turbo Auxiliaries						G	331	4·98	1·54	1·53	20·0	59
	Equipments												
35.	Boilers and Boiler Mountings						F	158	8·65	1·82	1·66	35·0	—
36.	Distilling Plants (including Pumps)						F	81	9·97	1·38	3·85	38·5	100
37.	Gas Turbine Alternator (Allens 500kW)						F	117	3·45	1·47	1·17	13·7	39
38.	Gas Turbine Main Engines (G6)						F	149	3·93	1·22	1·88	14·3	—
39.	H.P. Air Compressors						Exp	71	—	—	—	—	—
40.	Main Feed Pumps						G	87	5·65	1·42	2·08	22·0	60

G = Good F = Fair P = Poor N = Not lognormal Exp = Exponential

Mean Job Effort and Job Time

The arithmetic mean of the variate, or in the distribution discussed here, the mean job effort or job time, is a function of the median and the standard deviation. It is also a quantity of considerable practical interest for estimates of total task or total job time are readily made by multiplying failure rate, mission time and mean job effort or job time.

Examination of the means in TABLE III reveals some interesting patterns. The mean job effort for whole plant defects is significantly bigger than the mean job time. This is probably an indication of the amount of double manning which occurs in practice. The mean job effort for whole plant skilled maintenance was less than half that for whole plant skilled defects. The mean job effort for skilled upkeep in the steam plant was much larger than those of the gas and outside machinery sections. With the exception of the steam and drain system group all equipment groups and equipments in the steam end have mean skilled upkeep job efforts substantially larger than those of the other two sections.

For job times, differences similar in sense but smaller in magnitude occur in all these areas.

Standard Deviation

The standard deviation is a parameter of considerable importance. It is the root mean square deviation from the mean of the logarithm of the variate. It is also called the dispersion parameter and as such describes the way in which the distribution spreads about the mean. In terms of the logarithmic-probability plot the standard deviation describes the slope of the straight line and the median its vertical position.

For job time distributions the value of the standard deviation tends to fall into a particular pattern for electronic equipments. Goldman and Slattery quote values obtained experimentally for twelve different radar and communication equipments. They were equipments of diverse types fitted in aircraft, ships and ashore. The data are found to fall into two groups according to whether the standard deviation is low or high. The first group includes all the aircraft equipments and has an average standard deviation of 0·60. The second group includes all but one of the ground and ship equipments and has an average standard deviation of 1·40. It is argued that the two groups differ mainly in the type of upkeep performed on them, and that this is the reason for the difference in the standard deviations. The airborne equipment is primarily maintained by module replacement, whereas ground and shipborne equipment upkeep may also include the repair of faulty components and part replacements.

If this line of argument is pursued into the mechanical field it would be reasonable to expect marine engineering equipment to fall within the second group. A glance at the standard deviations in TABLE III will show that this is exactly what happens. The average standard deviation for all the job time distributions is 1·45 and for the job efforts 1·43, a remarkably close agreement with the complex electronic equipment.

Goldman and Slattery also show that two basically similar transmitters, both employed in ships, have widely different standard deviations. One manually tuned and simple has a value of 0·69 and the other, push-button tuned and relatively complex has a value of 1·41. Some evidence of a similar pattern can be seen in TABLE III. There are three standard deviation values below 1·0, all of which belong to situations in which diagnosis is easy and quick and repair straightforward, though not necessarily quick. At the other extreme lie controls and instrumentation, with its difficult diagnostic problems, turbo-auxiliaries and boilers and their mountings, all relatively complex. The rather low value for G6 main engines is noteworthy because, although it is a complex equipment, module replacement forms a significant part of the upkeep.

Just what this similarity in behaviour means is difficult to decide, but one thing it does suggest is that some of the features of electronic maintenance are not as different from those of marine engineering as we are apt to suppose. This is encouraging when the use of reliability design methods developed in the electronic field is contemplated for marine engineering work.

The Maximum

The maximum value of job time or job effort is a quantity of more than passing interest. Design situations are conceivable in which this could be important. For example, the minimum useful maintenance period must be related to the longest likely job.

The use of the 95 percentile value to describe the maximum is an established method of dealing with a distribution whose tail extends to infinity. It means that there is a 5 per cent probability of a given job costing more effort, or taking longer, than the maximum value. Whether this is the most convenient value to use depends very much on what it is being used for. One can envisage circumstances in which a chance of 1 in 20 of a job exceeding the declared maximum is too high and only a smaller chance could be tolerated. To meet such cases the 99 percentile values have been included in TABLE III where it appears from the plot that the degree of approximation involved is reasonable and, therefore, such values meaningful.

Going still further, the whole plant defect plot gives a meaningful 99·9 percentile point from which it can be argued that the chance of exceeding a ships staff job effort of 160 skilled man-hours, or a job time of 150 hours, in a situation similar to that which obtained in H.M.S. *London* is about 1 in 1,000.

Plot Reconstruction

It is clearly impracticable to reproduce in this article all the plots which were constructed during the investigation. Each one, however, has information which may be of immediate value for purposes other than establishing the form of the distribution. To make it accessible the most important whole plant plots are shown in FIGS. 8–11 and the median (50) and maximum (95) percentile values for each plot considered to be lognormal have been included in TABLE III From these two values the line representing the appropriate distribution can be readily reconstructed on logarithmic-probability paper.

The Skilled Upkeep plus Repair Distribution

So far the discussion has been based entirely on data gathered from ships staff work. While this leads to the conclusion that the lognormal distribution is generally applicable to marine engineering job efforts and job times, this has so far only been shown to be valid for ships staff work. Whether the addition of fleet maintenance unit, dockyard and contractor's work would so distort the distribution as to make the lognormal inappropriate is difficult to establish precisely as the appropriate data for fleet maintenance unit work is incomplete and there is none available for dockyard work. However, if the problem is considered as a whole it soon becomes apparent that the same distribution is almost certain to apply. Also, though the parameter values will change somewhat the change is unlikely to be very great.

Let us consider, for example, the main feed pumps. The fleet maintenance unit work upon them was of the same general type as the ships staff work. However, no really small jobs will have been done and the number of fleet maintenance unit jobs compared with those done by ships staff will be small.

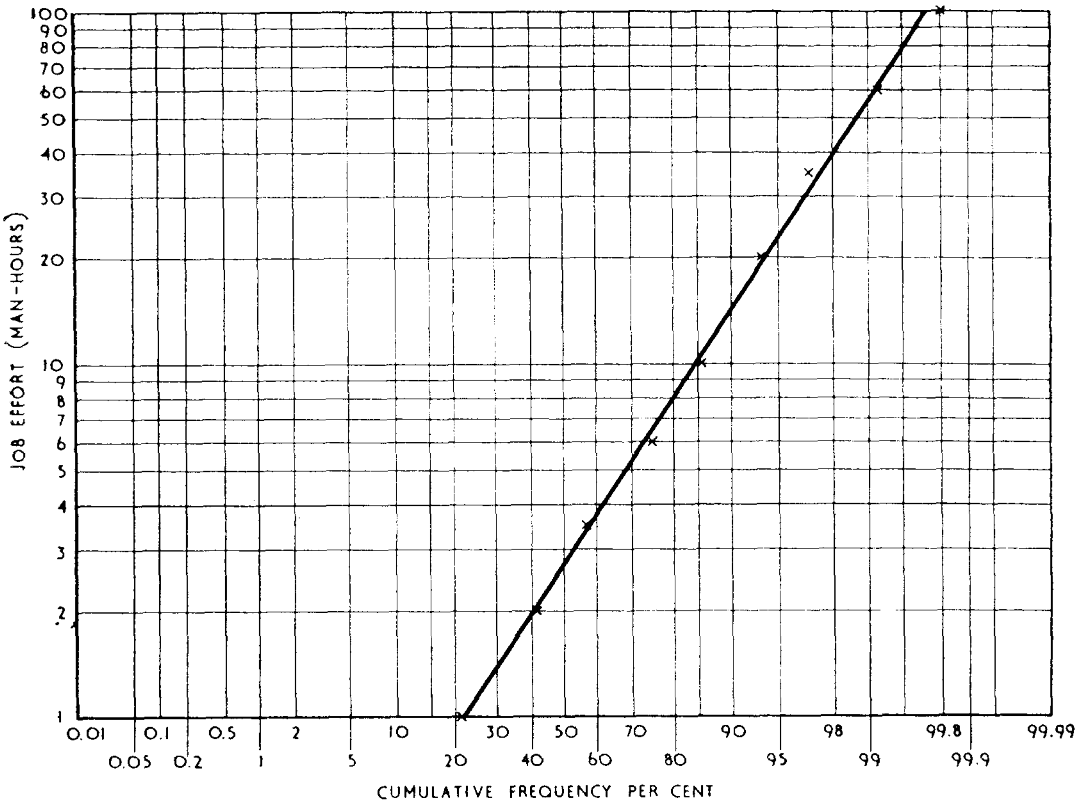

FIG. 8—WHOLE PLANT—DEFECTS—SKILLED JOB EFFORT

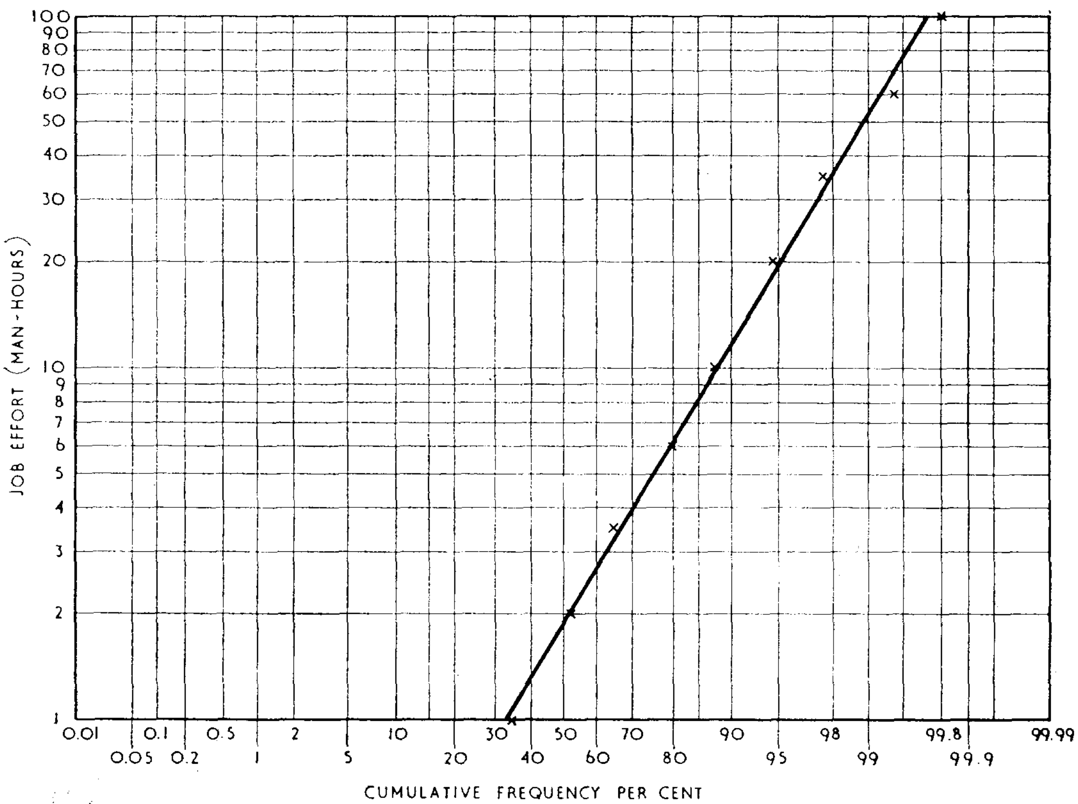

FIG. 9—WHOLE PLANT—UPKEEP—SKILLED JOB EFFORT

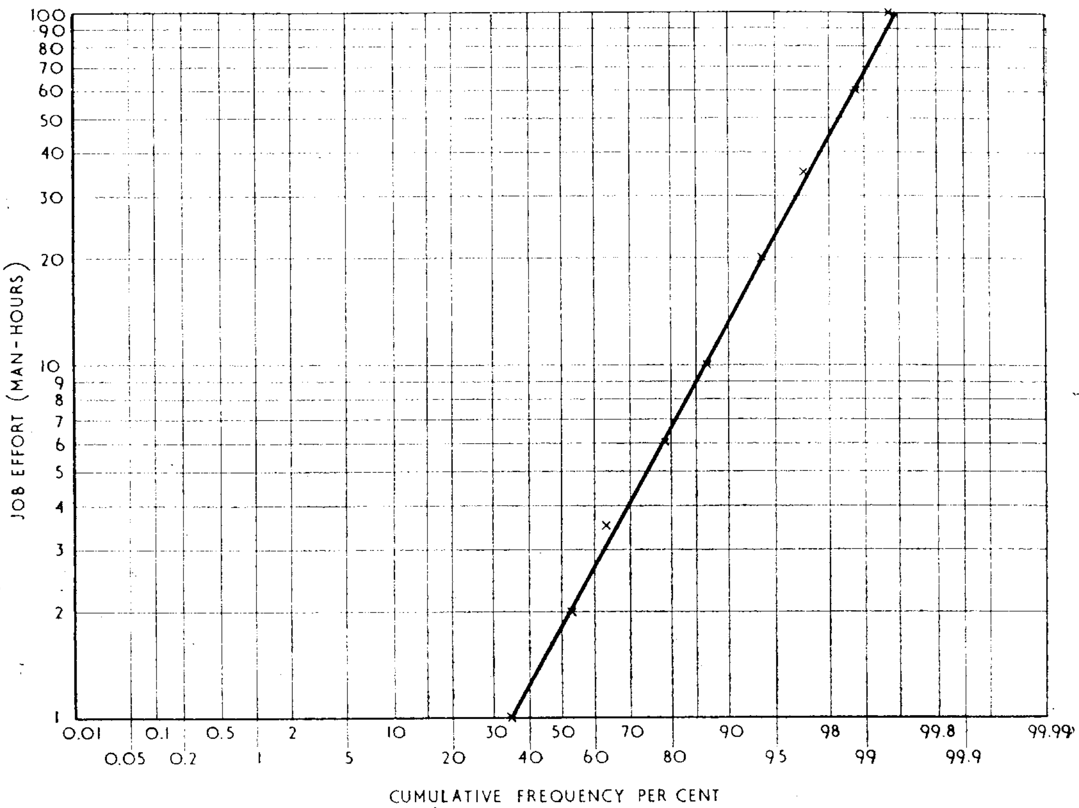

FIG. 10—WHOLE PLANT—UPKEEP—ALL RATINGS JOB EFFORTS

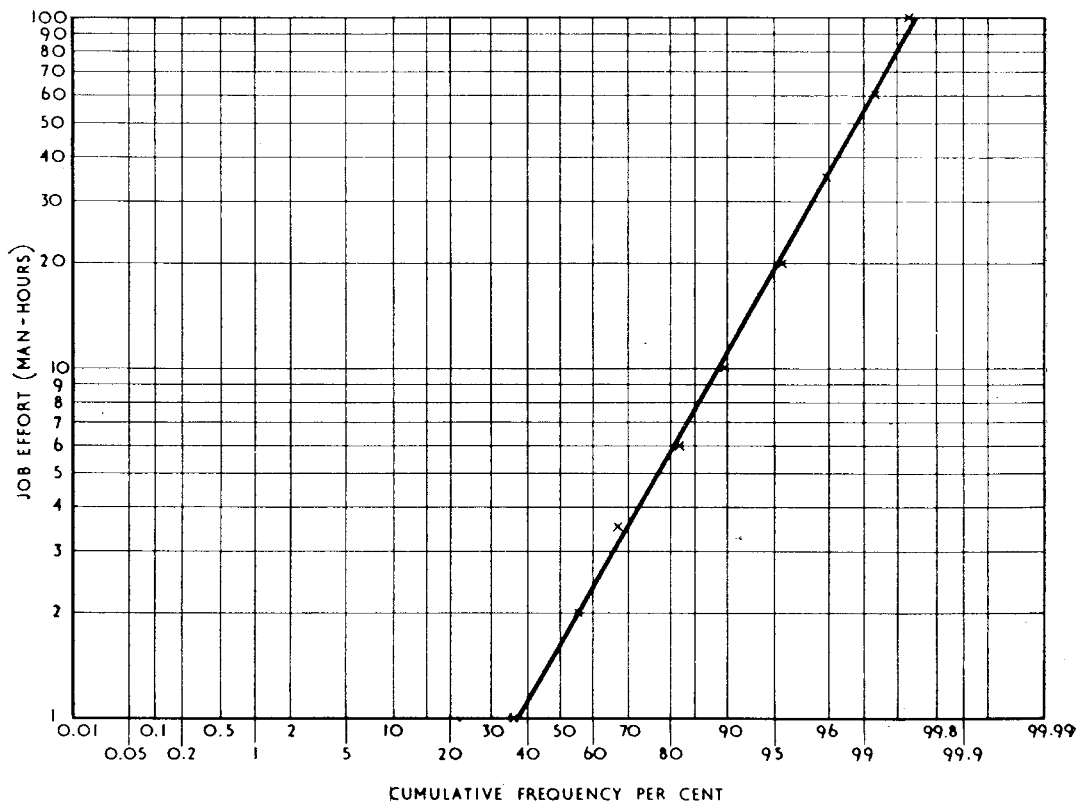

FIG. 11—WHOLE PLANT—UPKEEP—ALL RATINGS JOB TIMES

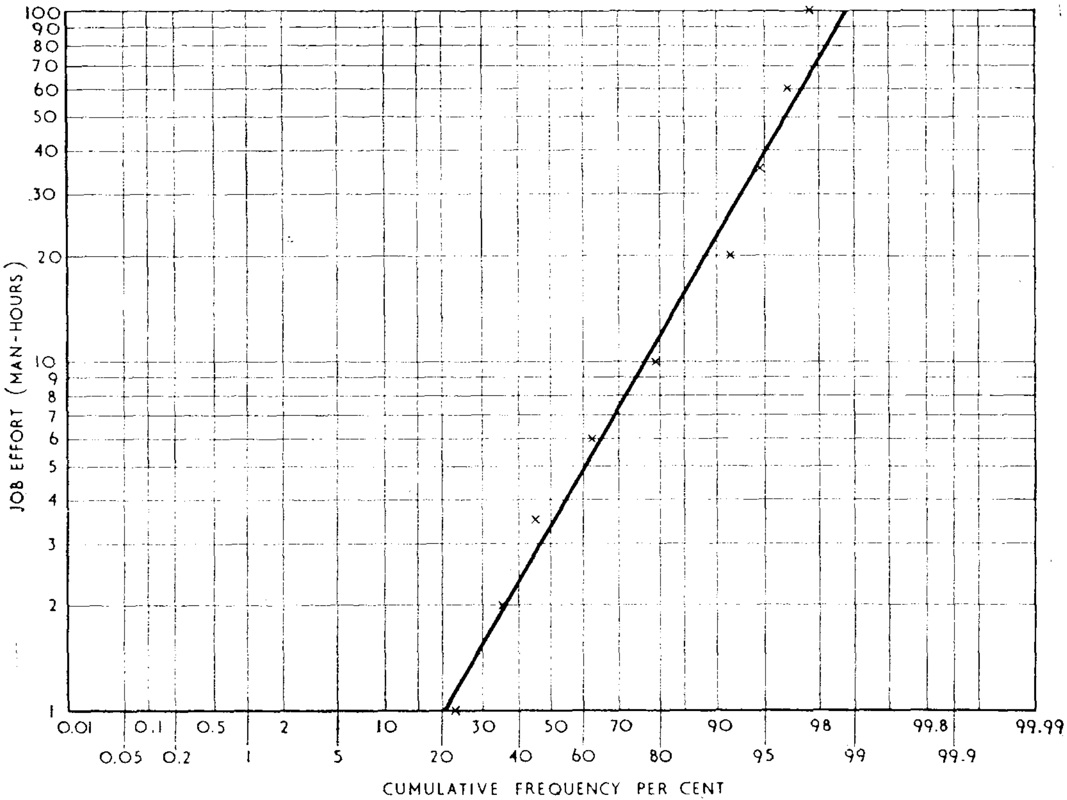

FIG. 12—MAIN FEED PUMPS—UPKEEP AND REPAIR—SKILLED JOB EFFORTS

In the period concerned, and this was representative, the fleet maintenance unit contribution was 9 per cent of the ships staff plus fleet maintenance work. While this proportion does not necessarily apply to a specific equipment, it does suggest that the Fleet Maintenance Unit is unlikely to have done more than a small proportion of the jobs on a given equipment. Where the Dockyard and the Contractors are concerned, their work consists of a small number of jobs which are, usually, of medium or large size, such as overhauls. Considered as a separate distribution the fleet maintenance unit, dockyard and contractors' jobs would also spread over a range of job efforts and job times, but because they tend to consist of longer jobs the mean would be higher.

In fact the ships staff upkeep distribution consists of a marriage of two distinct distributions, one having a substantially smaller mean than the other. They merge quite satisfactorily to give a lognormal upkeep distribution. It is most likely that the relatively small number of repair jobs will merge with the ships staff jobs in the same way, though the mean of the whole will almost certainly be higher.

Some support for the argument can be produced by constructing artificially a likely distribution for upkeep plus repair. FIGS. 12 and 13 show the total work skilled job effort distributions for main feed pumps and distilling plant respectively. The ships staff component of these plots was obtained by scaling up the quantities obtained from the *London* data to provide a whole commission estimate. The contractor and dockyard work list was prepared from a survey of representative defect lists and OPDEF histories and the job efforts estimated for each item. The fleet maintenance unit work data was gathered from a survey of some of their records.

As can be seen the lognormal distribution still fits, one example being good and the other fair. The mean of 9·83 man hours and standard deviation of

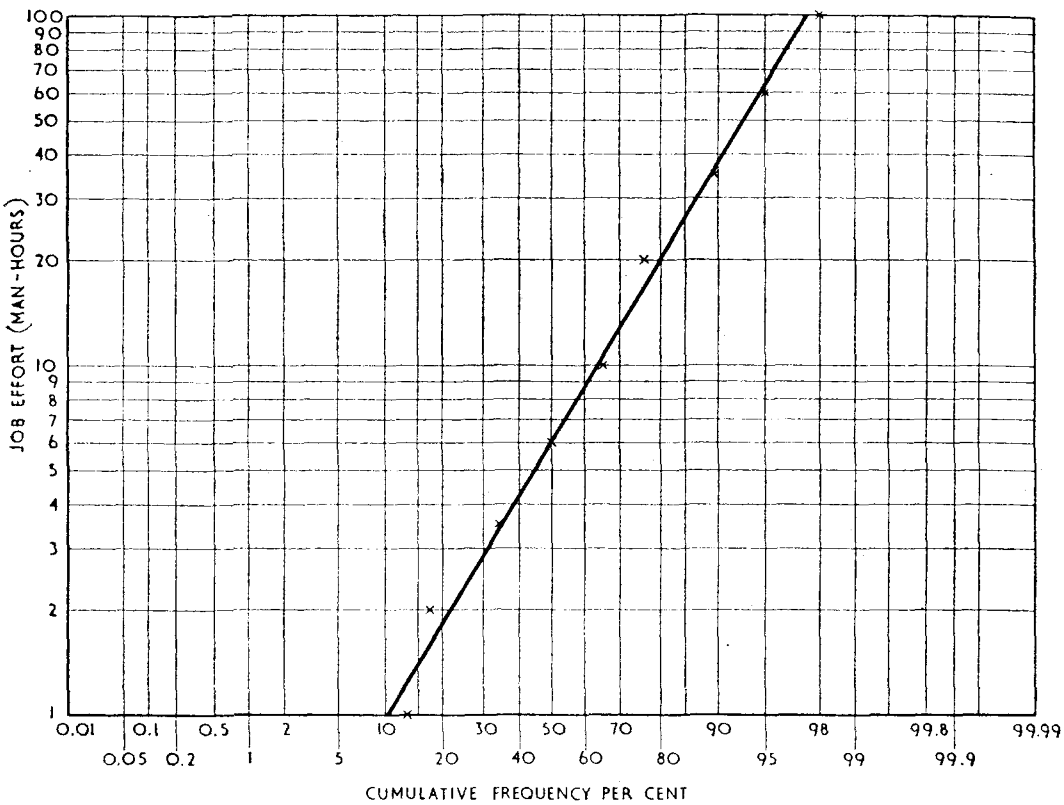

FIG. 13—DISTILLING PLANT—UPKEEP AND REPAIR—SKILLED JOB EFFORTS

1·46 for the feed pumps compares with ships staff values of 8·12 man hours and 1·57 respectively. For the distilling plant the total work values are 16·32 man-hours and 1·41 and the ships staff values 10·65 man-hours and 1·30. While both means are higher, one standard deviation moves up and the other down.

Though these two samples have been constructed in a very rough and ready manner, they go some way towards demonstrating that the total work distribution is of the same form as the ships staff one. A systematic examination of that hypothesis is desirable, and indeed necessary, before it can be used with complete confidence. However, it seems unlikely that any very great error would be introduced by using it in the interim.

Conclusions

It is concluded that:

(*a*) Ships staff job time and job effort distributions are almost always log-normal for marine engineering mechanical work.

(*b*) As 95 per cent of the distributions examined, and all the large sample ones, showed definite lognormal characteristics, that distribution may be used safely as a working hypothesis.

(*c*) The standard deviations encountered agree closely with those met in complex ground and ship's electronic equipment.

(*d*) The lognormal hypothesis can be used for distributions including dockyard, contractors' and fleet maintenance work with small risk of error. A more thorough investigation of this aspect is desirable.

(*e*) The mean of the total work distributions will almost certainly be somewhat higher than that for ships staff distributions.

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References

1. *Reliability Principles and Practices*—S. R. Calabro—McGraw Hill—1962.
2. 'Availability—A Methodical Approach'—Commander A. O. F. Venton, R.N.—*Journal of Naval Engineering*, Vol. 16, No. 1.
3. MIL—M—26512C (USAF)—13 December, 1963—'Maintainability Programme Requirements for Aerospace Systems and Equipments'.
4. MIL—STD—471—15 February, 1966—'Maintainability Demonstration'.
5. MIL—HDBK—472—24 May, 1966—'Maintainability Prediction'.
6. 'Maintenance Manhour Distributions—A Case Study'—B. F. Shelley—*Proceedings of I.E.E.E. Reliability Conference*, 1966.
7. *Maintainability*—A. S. Goldman and T. B. Slattery—Wiley—1964.
8. *The Lognormal Distribution*—J. Aitchison and J. A. C. Brown—Cambridge University Press—1957.