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RESPONSE TIMES OF OPERATORS IN A CONTROL ROOM

O. Platz, J. Rasmussen and P.Z. Skanborg

Abstract. A statistical analysis was made of operator response times recorded in the control room of a research reactor during the years 1972-1974. A homogeneity test revealed that the data consist of a mixture of populations. A small but statistically significant difference is found between day and night response times. Lognormal distributions are found to provide the best fit of the day and the night response times.

INIS Descriptors BEHAVIOR; CONTROL ROOMS; HUMAN FACTORS; REACTOR OPERATORS; STATISTICS.

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INDHOLDSFORTEGNELSE

INTRODUCTION

A research programme is being run at Riso concerning control room layout and communication between operator and instrumentation in large industrial plants. The objective is to find appropriate ways of presenting information for rapid and reliable communication.

An important information channel from the plant to the operator is the warning or alarm system by means of which a signal is given when a predetermined plant parameter level has been transgressed. The warning signal initiates operator action. The pattern of warning signals combined with the measured data and the general plant operating status is the basis for the operator's identification of his task. To study the role of the information carried by the warning signals under different plant conditions and operator tasks, a recording system was installed at the Danish research reactor DR3. This system records the time of arrival and clearance of warning signals, and the pattern of warning signals given on each occasion. The system also offers the possibility of analyzing operator response times.

Operator response times have been studied by Green et al., 1969, using equipment termed HORATIO (Human Operator Response Analyzer and Timer for Infrequent Occurrences). This equipment uses an alarm lamp that lights up at random time points and a reset button. Response times between lamp indication and reset action were recorded, and the distribution of response times was found to be approximately lognormal with a median response time around 1 second.

The HORATIO equipment was additional to the control room instrumentation, whereas our equipment HAMLET (Human Alertness Measuring and Logging Equipment) works on the instrumentation itself and thus adds no extra equipment to the console. It allows the collection of response time information comparable to the data obtained by Green et al., and the present paper presents a statistical analysis of the recorded response times.

ALARMS AND INCIDENT RECORDING

The test equipment was installed in the control room of the DR3 reactor. This reactor is supervised by some 120 alarm circuits connected to transducers eith r in the reactor circuits or in the different experiments. A large panel in front of the operator contains the alarm lamps which are identified by name. Whenever an alarm comes up, a warning bell rings. This bell can be reset with a push button in front of the operator. Another push button located lo cm away from the bell-reset button, is used to reset the alarm panel, i.e. to extinguish the alarm lamps relating to the alarm condition that has since disappeared. The alarm lamps thus remain activated - even if the alarm condition has ceased - until the alarm panel reset button is pressed. This means, the only information available to the operator from the alarm system indicating whether or not the cause of the alarm is still present, will be its response to his attempts to reset the light-panel.

(Figure 1 about here)

A normal sequence of events is alarm, i.e. bell resetting and later alarm panel light resetting. These events are named AL, BR and LR, respectively. The times for these events are recorded by the equipment and printed on tape in tenths of seconds. 100 milliseconds after a BR and an LR event, the alarm status is scanned and recorded. As disappearing alarms are not indicated directly, a sequence may include several LRs as a result of the operators tests of the alarm status.

SELECTION OF DATA

Operation of the research reactor alternates between running periods of approximately three weeks duration and one-week shut-down periods. The data used originate from the running periods only, starting with period no. 145 (P145), March 1972. The last period analyzed was P172, ending in June 1974. Periods P151 and P168 were not used in the analysis because of failure in the data collection equipment; neither are data from the first and the last days of the periods used, because these days were felt to be atypical due to the special demands on the operator in the start-up and shut-down phases.

The pool of operators consisted of 24 men working in a three--shift schedule; one shift from 23.00 to 7.00, another from 7.00 to 15.15, and a third from 15.15 to 23.00. Only a few changes took place in the pool of operators during the years considered here.

In the present paper, the time delay between alarm event (AL) and the acknowledging bell reset (BR) has been chosen for analysis. This action can be considered an automated response which is independent of features in the individual alarm event. The related time delay therefore can be taken as a measure of the general state of alertness of the operator. Furthermore, a large number of data is present to statistical analysis.

Preliminary attempts have been made to analyse the distribution of time delays between bell reset (BR) and the operator's attempts to reset alarm state (LR) since this time delay might be a measure of the operator's expectations of alarm cause disappearence, i.e. his process-feel.

This kind of analysis imply separate analysis of individual alarm channels and causes,and discarding of data from situations where LR action may relate to several simultaneous alarms present. The conclusion from such analysis has so far been, that data become too sparse for conclusive results.

ALARM ENVIRONMENT OF THE OPERATORS

In order to determine which factors could possibly influence the operators' bell reset response times, figure 2 and the following numbers give a number of gross characteristics of the alarm environment.

(Figure 2 about here)

Figure 2 shows the total number of AL's coming up within each hour of the day, summed over all periods used. The peaks in the morning and in the afternoon are caused by experiments made in connection with the reactors. The alarm rate - that is the average number of bell ringings per hour - varies between 0.9 for the time interval 23.00 - 24.00 and 2.2 for the time interval 9.00 - 10.00.

In 40% of the total time no alarm lamp is activated on the alarm panel in front of the operator; in 39%, one lamp is active; in 15% two lamps are active, and in 6% of the time more than two lamps are active. These numbers vary only slightly from day to night. The largest number of simultaneously active alarm lamps that has been recorded was 37.

HOMOGENEITY OF THE DATA MATERIAL

A preliminary analysis of data showed no sign of dependence between the bell-reset response times and the specific alarms coming up, nor was there any indication of dependence between the response times and the number of alarms coming up or the number of alarms already activated. Furthermore, there was no indication of a correlation between a response time and the immediate following response time. However, there was some indication of variation through the day, and some indication of variation through the 26 periods. It was therefore decided to divide the data into three groups corresponding to the three magnetic tapes containing the data. The first group, a, contained the periods P145-P153 with 7326 response times, the second group, b, contained P154-P165 with 7393 response times, and the third group, c, contained P166-P172 with 3582 response times. Within each group the data were subdivided into 6 half-shifts: 1) 23.00-3.00, 2) 3.00 - 7.00, 3) 7.00 - 11.00, 4) 11.00 - 15.15, 5) 15.15 - 19.15, 6) 19.15 - 23.00. In the following, these 18 subdivisions are denoted by a_1 .. a_6, b_1 .. b_6, c_1 .. c_6. Table 1 shows the grouping of the data and the number of response times in each of these 18 subdivisions.

(Table 1 about here)

For each of the 18 subdivisions the response times were grouped into 23 classes with equidistant class boundaries on a logarithmic (base 10) time scale. The data below logarithmic time 0.01 (1.02 seconds) constituted the first class and the data above 1.06 (11.48 seconds) the last class. The lowest number of data in any class was 1. A X^2-test for homogeneity was run for each of the $\binom{18}{2}$ = 153 possible pairs of frequency distributions.

The null hypothesis is that the two sets of frequencies originate from the same distribution. The upper 5% and 1% boundaries for the χ^2-variable with 22 degrees of freedom, d.f., are 33.9 and 40.3, respectively. The results of the test for pairwise comparison are given as a "similarity matrix" in figure 3. The row and column indices denote the subdivisions. A matrix element 1 means that the χ^2-value for the pair of subdivisions corresponding to the row and column indices lies below the 5% boundary; a matrix element 1 with a circle around, that the values lies between the 5% and the 1% boundaries; and a blank that the χ^2-value is above the 1% boundary. In other words, a blank means that we reject the null hypothesis at the 1% level, a 1 that we accept at the 5% level, and an encircled 1 that the null hypothesis is doubtful. In figure 4 the row and column indices have been rearranged to provide maximum clustering of non-zero elements. For symmetry reasons, only the part of the matrix above the diagonal is shown.

(Figures 3, 4 and 5 about here)

From figure 4 it is seen that there is a tendency for the frequency distributions to fall into two major groups, one containing the subdivisions (a_1, a_2, a_6, b_1, b_2, b_6, c_1, c_3, c_5, c_6) and another containing (a_3, a_4, a_5, b_3, b_4, b_5, c_4) whereas c_2 is unique. An overall test for homogeneity of the 10 subdivisions in the first group gave the χ^2-value 305. The upper 0.1% boundary at 198 degrees of freedom is 264. The hypothesis of homogeneity is therefore rejected. For the second group, the χ^2-value was 226. The 0.1% boundary at 132 degrees of freedom is 186. The hypothesis of homogeneity is also rejected here.

A closer investigation of the χ^2-test between pairs of subdivisions within each of the two groups revealed that the χ^2-contribution from the first 3 classes nearly always caused the null hypothesis to be rejected. These three classes containing the response times below 1.29 seconds correspond to about 5% of the total number of response times. The whole test was therefore redone, but this time with the first three classes omitted. For 19 degrees of freedom, the 5% and 1% χ^2 boundaries are 30.1 and 36.2, respectively. The result of the pairwise comparison is given in figure 5. The clustering of the subdivisions into two groups is now evident. An overall test for homogeneity of the ten members in group one gave the χ^2-value 189, which is below the 5% boundary for 171 degrees of freedom, 202. A corresponding test for group two gave the value 130. The 5% boundary at 114 degrees of freedom is 140. In either case there is no indication for rejecting the hypothesis of homogeneity. Pairwise chi-square tests between group 1, group 2 and c_2, with and without the first three classes included, all rejected the hypothesis of homogeneity at the 0.1% level.

The homogeneity test thus did not indicate that the operators' response times differ from the first part of the shifts to the last part, as might have been anticipated as a result of increasing tiredness. However, it indicated that the empirical distribution of the response times is a mixture of two or more distributions. The majority of the fast response times - below 1 second - presumably have other causes than those of the response times above 1 second. Furthermore, the test indicated that the response times above 1 second can be grouped into two major groups, one group containing the "day"-times and another group containing the "night"-times. The remaining response times belonging to group c_2 are slower than the response times in either of the two major groups.

COMPARISON BETWEEN DAY AND NIGHT RESPONSE TIMES

The 10013 "day" response times of groups a_3, a_4, a_5, b_3, b_4, b_5, c_4 were extracted from the raw data. The extract included the response times below 1 second. The mean value was found to be 3.3 seconds and the standard deviation was 2.5 seconds.

The 7836 "night" response times from groups a_1, a_2, a_6, b_1, b_2, b_6, c_1, c_3, c_5, c_6 had the mean 3.8 seconds and the standard deviation 3.4 seconds.

The 455 response times from group c_2 had a mean value of 8.5 seconds and a standard deviation of 78 seconds. This group contained a few very long response times that are presumably due to errors in the data collection equipment.

The two empirical distribution functions, for the day and the night response times, are plotted in figure 6 on normal probability paper with logarithmic abscissa. In this paper a lognormal distribution function will show up as a straight line. The deviations from lognormality of the two empirical distribution functions are most pronounced for the very short and the very long response times. The median of the day times is 2.9 seconds, and the median of the night times is 3.3 seconds.

(Figure 6 about here)

A FURTHER SUBDIVISION OF THE RESPONSE TIMES

For some alarms, the operator may know somehow or other, e.g. from showings of other instruments, that they are due to come up and this may influence his response times. An example of such an alarm is alarm no. 38 for high gamma-radiation. Most of the warnings from this alarm come from the pneumatic dispatch system.

The operator knows in advance that the alarm is coming up because the pneumatic dispatch is operated from the control room. If the operator himself controls the dispatch, he will presumably have a long bell-reset response time, whereas his response time may be short if he remains at the console and another operator controls the dispatch.

In order to determine the influence of the operators' advance awareness of alarms on the response times, two subgroups were extracted from each of the "day" and "night" groups of response times. The first subgroup, AW, contained the response times for alarms which the operators may be aware of in advance, that is alarms no. 16, 22, 23, 38, 41, 55 and 75. The second subgroup, UNAW, contained alarms which it is unlikely that the operators were aware of in advance. These alarms have numbers 11, 17, 21, 24, 40, 43, 45, 54, 61 and 62.

The four empirical distribution functions for these alarms are shown in figures 7-9. From these figures it is seen that the majority of the very small response times - below 1 second - belongs to the AW-subgroup. The difference between day and night times is seen to be pronounced for the AW as well as for UNAW subgroup. The response times below 1 second in the AW subgroup show no difference between day and night recordings.

(Figure 7 about here)

The plots of the two UNAW subgroups on lognormal probability paper, figures 8 and 9, show that they are both very close to straight lines. In order to test that the response times do belong to lognormal distributions, the parameters of an assumed lognormal distribution was estimated, using the minimum χ^2-method as this simultaneously gives a measure of how "consonant" the data are with the assumed distribution. The joint consideration of parameter estimation and goodness of fit test was emphasized by Easterling, 1976.

(Figures 8 and 9 about here)

The original classes of 1/10 of a second in which the data were recorded were used in the fitting. For the 4055 UNAW-day times the classes below 1.25 seconds were lumped into a single class containing 26 response times, and the data above 6.75 seconds were also lumped into a single class containing 140 response times in order to avoid working with classes containing too few response times. The lognormal fit was then performed by using a standard iterative program for nonlinear function minimization. The best minimum χ^2-fit was obtained by a lognormal distribution having a mean and a standard deviation - of the logarithm of the response times - at 0.499 (= 3.16 seconds) and 0.173 (= 1.49 seconds), respectively. The χ^2-value obtained was 77.9. For 54 degrees of freedom the probability that the χ^2 random variable exceeds this value is 1.8%. The hypothesis of a lognormal distribution is therefore doubtful.

A similar procedure was applied to the night times in figure 8. As before, the data below 1.25 seconds were lumped into one class containing 26 response times and the data above 7.65 seconds were lumped into a single class containing 104 response times. The best fit was obtained by a distribution having a mean and a standard deviation - of the logarithm to the response times - at 0.539 (= 3.46 seconds) and 0.181 (= 1.52 seconds), respectively. The minimum χ^2-value was 63.5. For 63 d.f., the probability that the chi-square random variable exceeds 63.5 is 46%.

It thus seems reasonable to assume that the night response times for the UNAW subgroup follow a lognormal distribution. A chi-square comparison between the two groups (day and night) showed that there was less than 0.01% probability that they both could result from a common distribution.

In order to determine if it was possible to fit the data to other models, a minimum chi-square fit with the same classes as before was tried for the two-parameter Weibull distribution.

$$F(t) = 1 - e^{-\lambda t^{\alpha}}$$

and the two-parameter gamma distribution with density

$$f_k(t) = \frac{\lambda^k \, t^{k-1} \, e^{-\lambda t}}{\Gamma(k)}$$

where $\Gamma(k)$ is the gamma-function. For the Weibull distribution, the lowest chi-square value obtained was 621 and 494 for the UNAW day- and night-times, respectively. For the gamma distribution, the values were 213 and 170, respectively, indicating very poor fits as compared to the values 78 and 64 obtained for the lognormal distribution.

The inverse Gaussian distribution is another possible two-parameter alternative to the lognormal distribution, as shown by Chhikara and Folks, 1977. Furthermore, it has a physical basis as the distribution of the first passage time of a Brownian motion with a drift term, a Wiener process. The distribution function is

$$F(t) = \Phi\left[\sqrt{\frac{\lambda}{t}}\left(\frac{t}{\mu} - 1\right)\right] + e^{2\lambda/\mu}\,\Phi\left[-\sqrt{\frac{\lambda}{t}}\left(1 + \frac{t}{\mu}\right)\right]$$

where Φ denotes the cumulative standard normal distribution function. With the same classes as before, the best minimum chi-square fit obtained for this distribution had the χ^2-value 312 for the UNAW day times. The corresponding minimum chi-square value obtained for the night times was 172. As in the case of the Weibull and the gamma distributions, these fits are very poor compared to the fits obtained by the lognormal distributions.

CONCLUSION

The analysis of the bell-reset response times thus showed that there is a small but statistically significant difference between day and night response times. There is no indication that the operators are slower during the last part of a shift than during the first part. With regard to the long time trends, the operators seem to react more slowly towards the end of the time period investigated here. The reason for this is unknown.

Most of the very short response times, those below one second, turned out to belong to alarms that the operator may have had knowledge of in advance.

The lognormal distribution provides a very good fit for the night response times for alarms that the operators did not have knowledge of in advance. In contrast, the lognormal distribution did not give a good fit for the corresponding day times. A closer investigation of the chi-square contributions from the various classes of the best lognormal fit for the day times showed that three classes only (the first class with response times below 1.25 seconds, the class corresponding to a response time of 2.0 seconds, and the last class with response times above 6.75 seconds) together contributed 20.4 to the total chi-square value of 77.9. This, together with the fact that other two-parameter distributions gave much higher chi-square values, makes us inclined to believe that the lognormal distribution is the proper distribution, also for the day times. The slightly too high chi--square value found in this case may be due to a slight contamination of a lognormal distribution with response times having different physical causes because of other activities taking place in the control room in the day time.

If it is taken for granted that the response times follow lognormal distributions, an interesting question arises about the physical or physiological reasons for this fact. As is well known, see e.g. Aitchison and Brown, 1969, the lognormal distribution occurs naturally when the underlying process proceeds in steps in such a way that the change in the variate at any step of the process is a random proportion of the previous value of the variate. (The law of proportionate effect). Unfortunately, we have not been able to relate the behavior of the operators to a model of this type. The possibilities for interpretation range from a fundamental physiological model for the reactions of man to a model that reflects the geometry of the control room.

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FIGURE AND TABLE CAPTIONS

Table 1:

Grouping of bell reset response times for test of homogeneity. The number of response times (N) in each group is shown together with the mean (μ) and the standard deviation (σ) of the logarithmic response times.

Figure 1:

Typical time sequence. True time is recorded for AL, BR and LRs with 100 ms resolution.

Figure 2:

Number of alarms (bell soundings) coming up for each hour of day. Summed over all running periods. Total = 18939 bell soundings.

Figure 3:

Similarity matrix for pairwise chi-square test for homogeneity among the groups shown in Table 1. 1: The two groups are homogeneous. 1: Homogeneity is uncertain. Blank: The two groups are inhomogeneous.

Figure 4:

Identical to Figure 3 with row and column indices rearranged to provide maximum clustering.

Figure 5:

Similarity matrix with the three first classes left out in the chi-square test.

Figure 6:

Empirical distribution functions for day and night response times plotted on lognormal probability paper. Crosses correspond to day times, dots to night times. The total number of day times is 10013. The total number of night times is 7836.

Figure 7:

Empirical distribution functions for 3342 day (crosses) and 2173 night (dots) response times for which the operators may know in advance that they are due to come up. Lognormal probability paper.

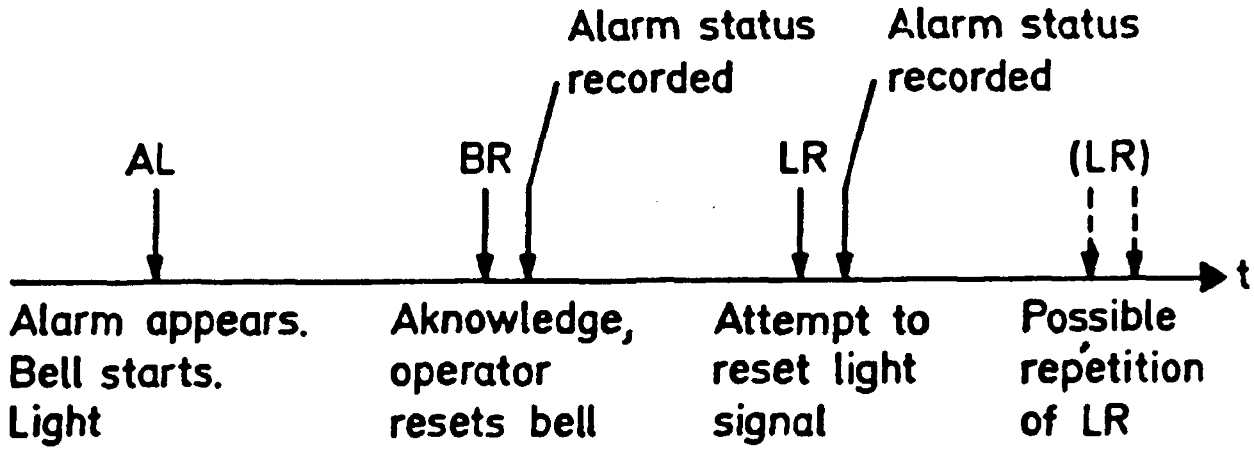
Figure 8:

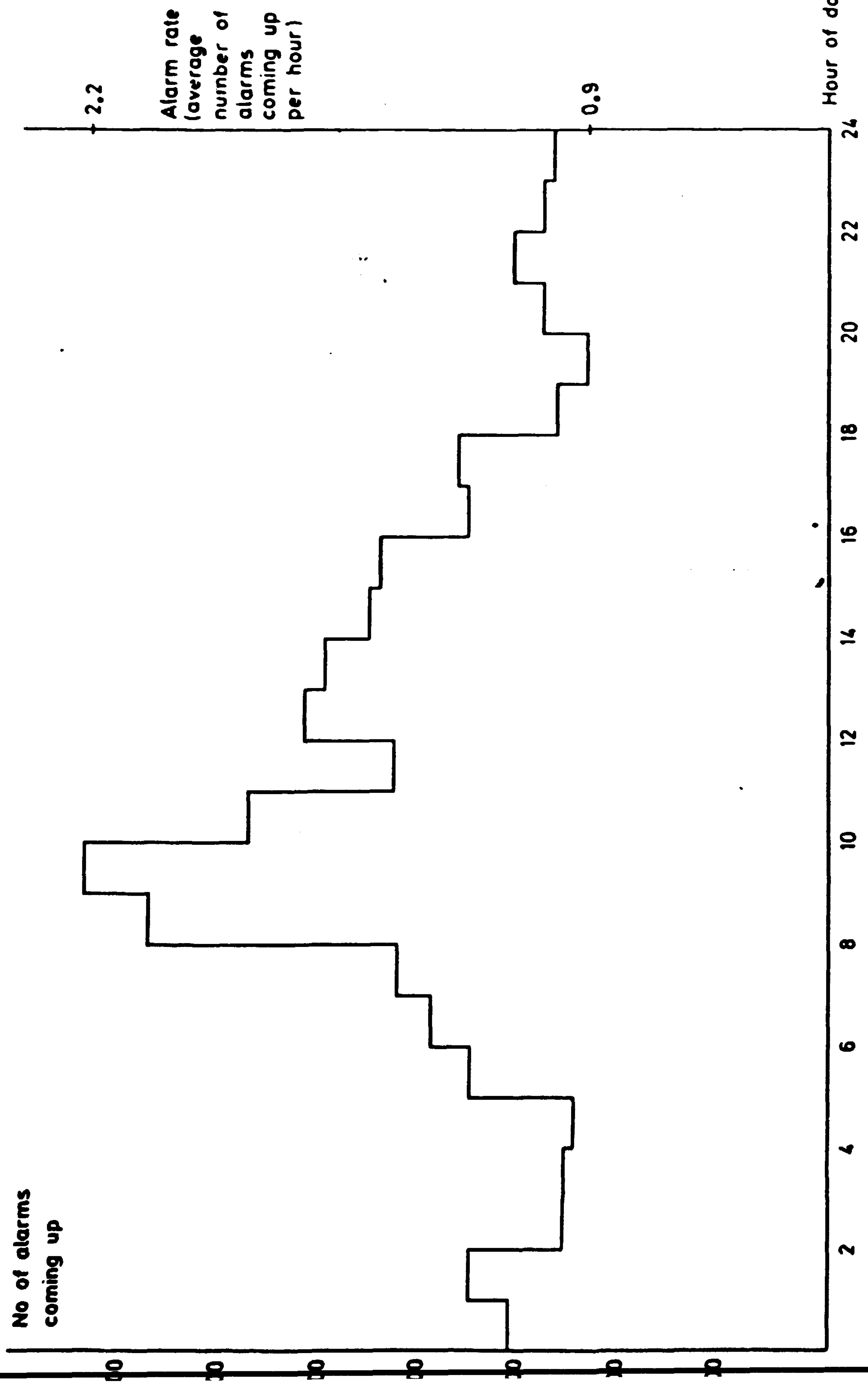
Empirical distribution function for 4055 day response times for alarms which it is unlikely that the operators were aware of in advance. Lognormal probability paper.

Figure 9:

Empirical distribution function for 3208 night response times for alarms which it is unlikely that the operators were aware of in advance. Lognormal probability paper.

hour \ period	P 145 – P 153			P 154 – P 165			P 166 – P 172		
$3^{\underline{00}}$ – $3^{\underline{00}}$	a_1	$\mu = 0.520$ $\sigma = 0.227$	N = 1049	b_1	$\mu = 0.487$ $\sigma = 0.261$	N = 897	c_1	$\mu = 0.508$ $\sigma = 0.296$	N = 416
$3^{\underline{00}}$ – $7^{\underline{00}}$	a_2	$\mu = 0.518$ $\sigma = 0.260$	N = 1027	b_2	$\mu = 0.493$ $\sigma = 0.280$	N = 901	c_2	$\mu = 0.560$ $\sigma = 0.350$	N = 455
$7^{\underline{00}}$ – $11^{\underline{00}}$	a_3	$\mu = 0.463$ $\sigma = 0.240$	N = 1784	b_3	$\mu = 0.451$ $\sigma = 0.273$	N = 1995	c_3	$\mu = 0.479$ $\sigma = 0.295$	N = 967
$11^{\underline{00}}$ – $15^{\underline{15}}$	a_4	$\mu = 0.458$ $\sigma = 0.245$	N = 1623	b_4	$\mu = 0.428$ $\sigma = 0.274$	N = 1561	c_4	$\mu = 0.434$ $\sigma = 0.316$	N = 834
$5^{\underline{15}}$ – $19^{\underline{15}}$	a_5	$\mu = 0.466$ $\sigma = 0.236$	N = 1028	b_5	$\mu = 0.457$ $\sigma = 0.250$	N = 1188	c_5	$\mu = 0.473$ $\sigma = 0.285$	N = 477
$9^{\underline{15}}$ – $23^{\underline{00}}$	a_6	$\mu = 0.512$ $\sigma = 0.208$	N = 815	b_6	$\mu = 0.511$ $\sigma = 0.244$	N = 851	c_6	$\mu = 0.498$ $\sigma = 0.251$	N = 433
Σ			7326			7393			3582

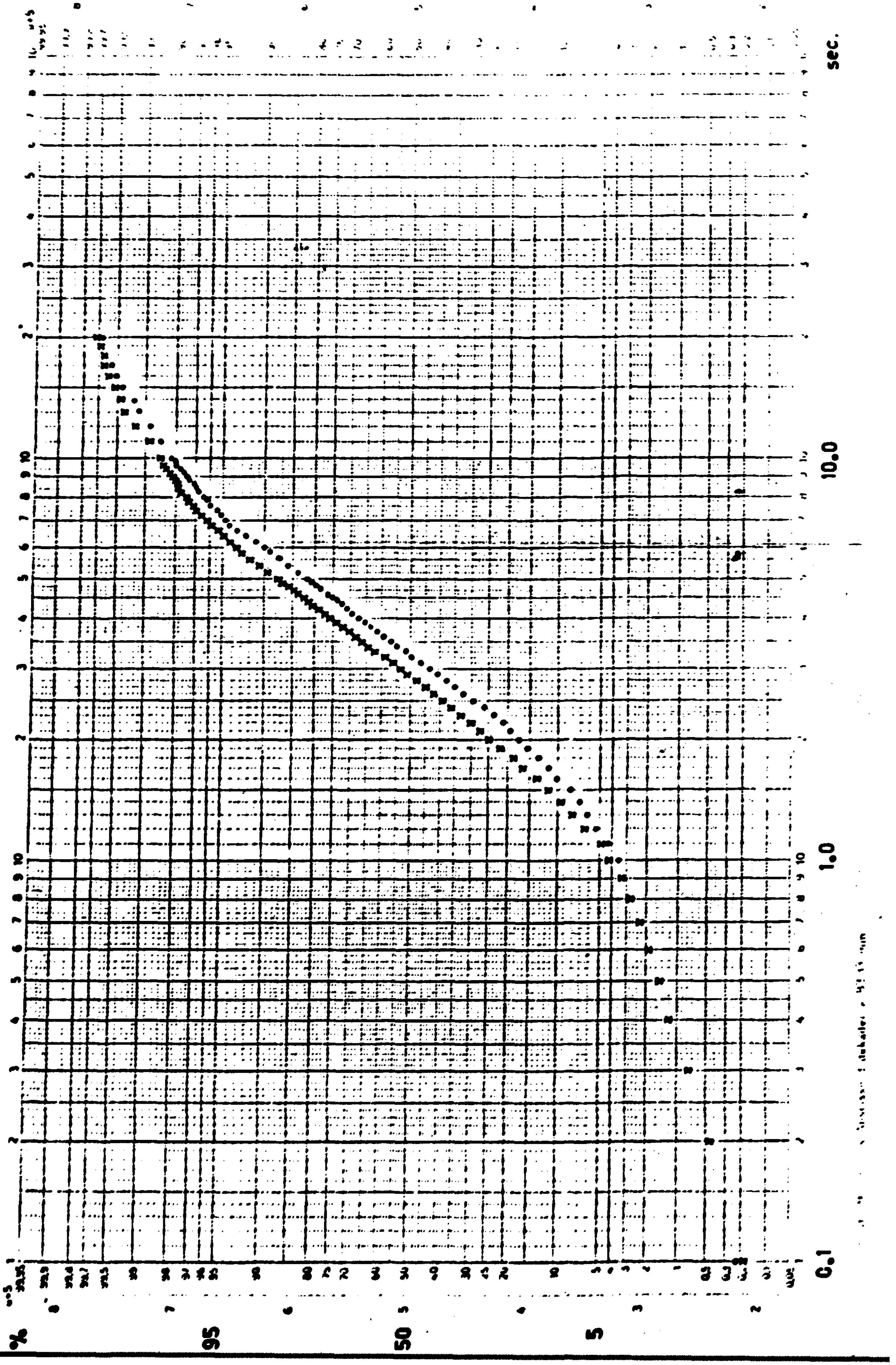

Alarm status
recorded
Alarm status
recorded
AL
BR
LR
(LR)
t
Alarm appears.
Bell starts.
Light
Aknowledge,
operator
resets bell
Attempt to
reset light
signal
Possible
repetition
of LR

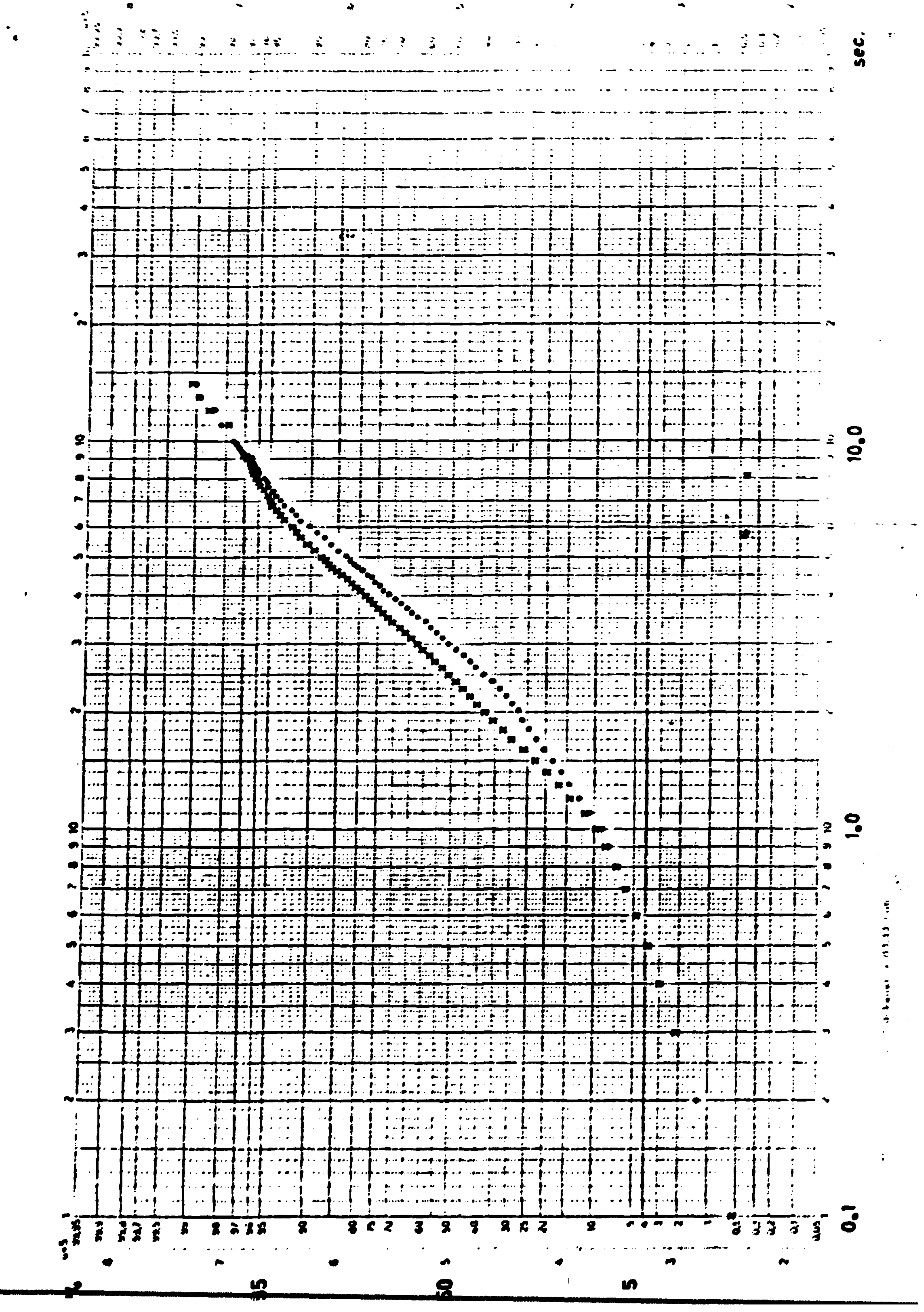

No of alarms
coming up
Alarm rate
(average
number of
alarms
coming up
per hour)
2.2
0.9
Hour of day
2
4
6
8
10
12
14
16
18
20
22
24

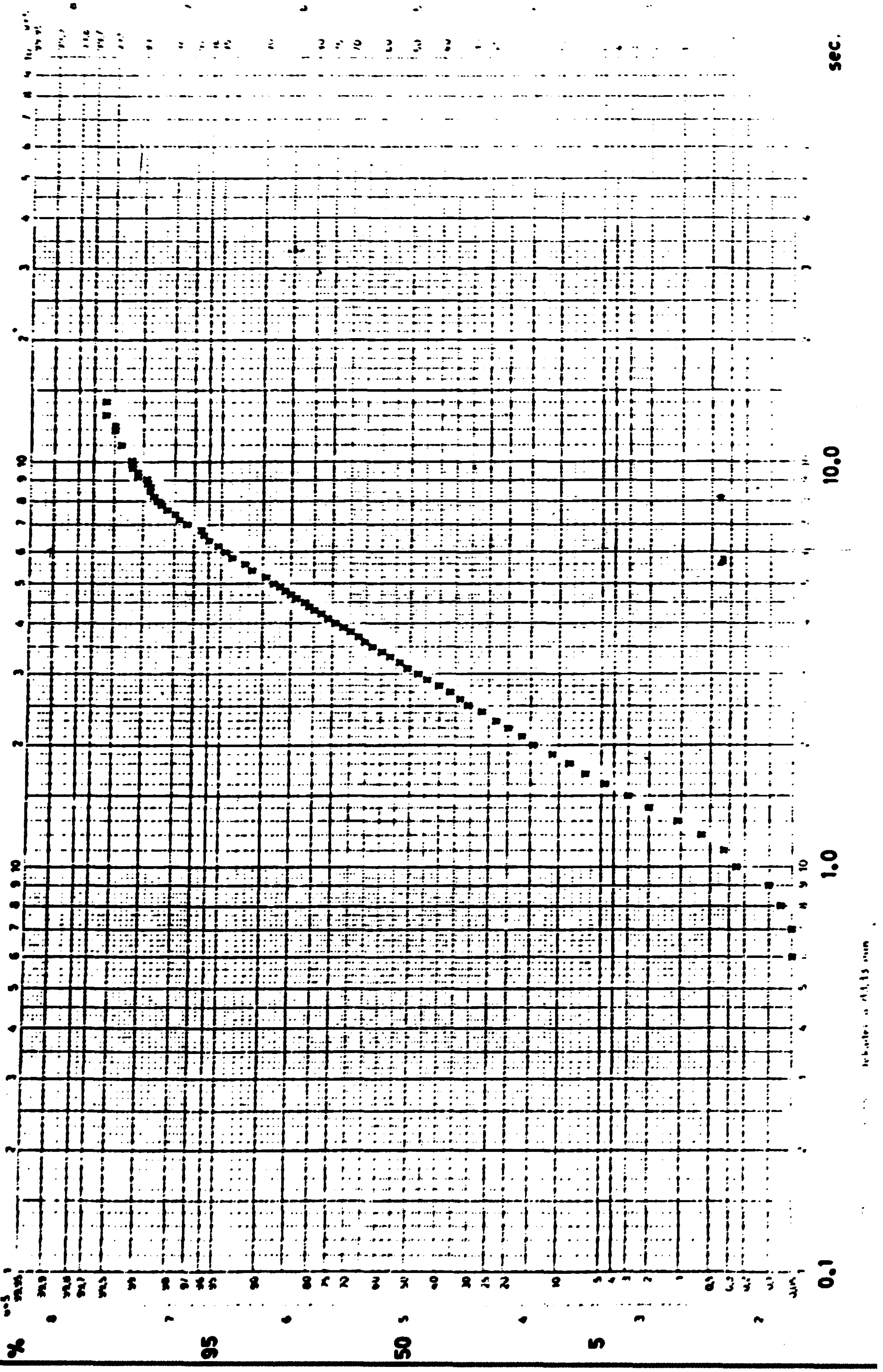
	a_2	a_3	a_4	a_5	a_6	b_1	b_2	b_3	b_4	b_5	b_6	c_1	c_2	c_3	c_4	c_5	c_6
a_1	1				1	1					1						1
a_2					1						1	1		1		1	1
a_3			1	1						1							
a_4								1	1	1							1
a_5								1		1							
a_6											1						1
b_1							1				1	1		1		1	1
b_2											1	1		1	1	1	1
b_3									1	1				1	1	1	
b_4										1					1		
b_5															1		1
b_6												1		1		1	1
c_1													1	1		1	1
c_2																	
c_3																1	1
c_4																1	1
c_5																	1

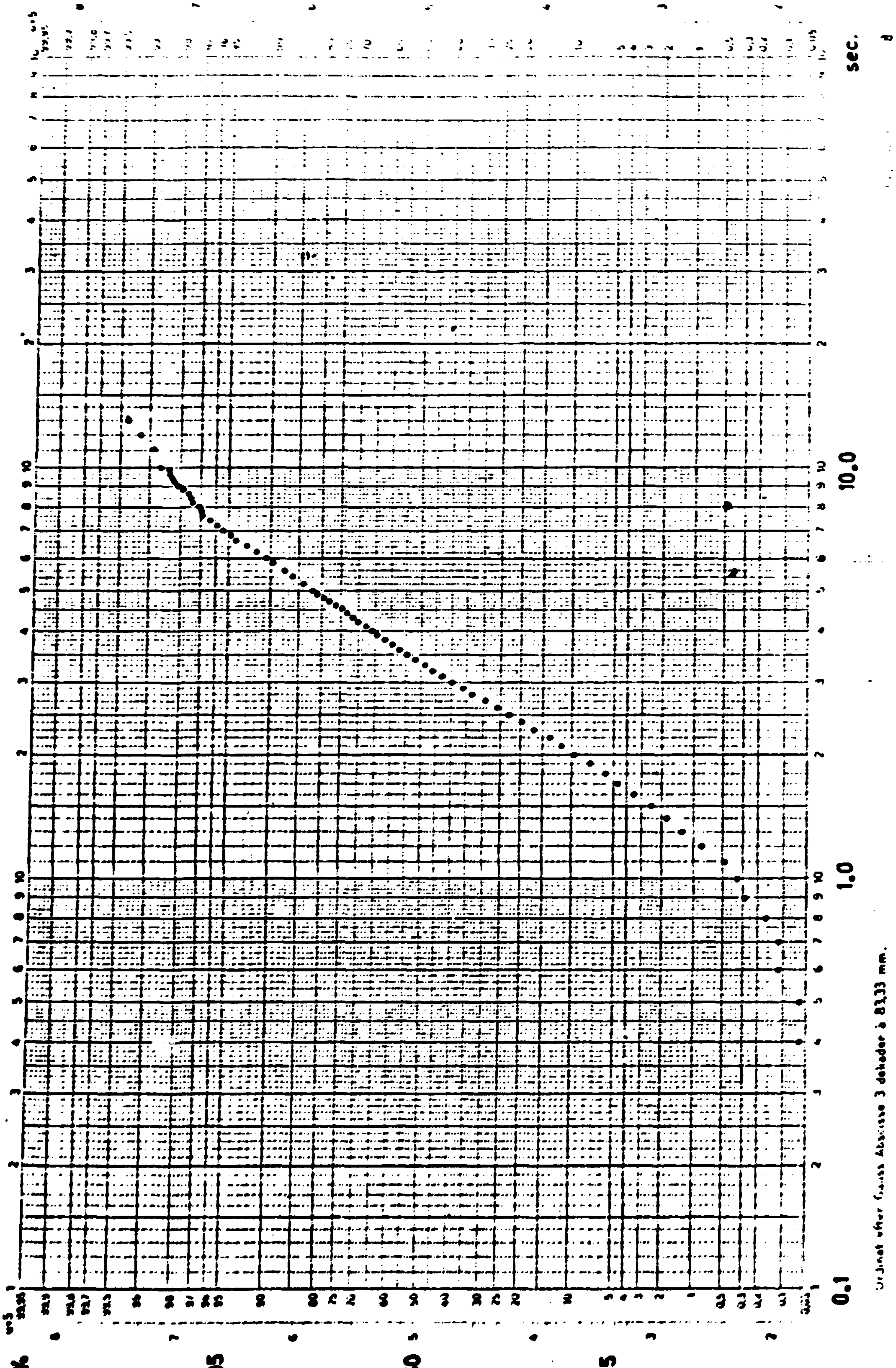
	a_2	a_6	b_1	b_2	b_6	c_1	c_3	c_5	c_6	a_3	a_4	a_5	b_3	b_4	b_5	c_4	c_2
a_1	1	1	1		1				1								
a_2		1			1	1	1	1	1								
a_6					1				1								
b_1				1	1	1	1	1	1								
b_2					1	1	1	1	1							1	
b_6						1	1	1	1								
c_1							1	1	1								1
c_3								1	1				1				
c_5									1				1			1	
c_6											1				1	1	
a_3											1	1			1		
a_4													1	1	1		
a_5													1		1		
b_3														1	1	1	
b_4															1	1	
b_5																1	
c_4																	

	a_2	a_6	b_1	b_2	b_6	c_1	c_3	c_5	c_6	a_3	a_4	a_5	b_3	b_4	b_5	c_4	c_2
a_1	1	1	1	1	1	1	1	1	1							1	
a_2		1	1	1	1	1	1	1	1								
a_6			1	1	1		1	1	1		1				1	1	
b_1				1	1	1	1	1	1								
b_2					1	1	1	1	1							1	
b_6						1	1	1	1						1	1	
c_1							1	1	1								1
c_3								1	1				1			1	
c_5									1		1					1	
c_6											1				1	1	
a_3											1	1	1	1	1	1	
a_4												1	1	1	1	1	
a_5													1	1	1	1	
b_3														1	1	1	
b_4															1	1	
b_5																1	
c_4																	


sec.
10.0
1.0
0.1
%
95
50
5


sec.
10.0
1.0
0.1


sec.
10.0
1.0
0.1
%
95
50
5


sec.
10.0
1.0
0.1
%
95
50
5
Ordinat efter Gauss Abscisse 3 dekader à 83,33 mm.

Risø National Laboratory **Risø - M - 2365**

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Title and author(s)	Date December 1982
Response Times of Operators in a Control Room O. Platz, J. Rasmussen and P.Z. Skanborg	Department or group Electronics
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Abstract

A statistical analysis was made of operator response times recorded in the control room of a research reactor during the years 1972-1974. A homogeneity test revealed that the data consist of a mixture of populations. A small but statistically significant difference is found between day and night response times. Lognormal distributions are found to provide the best fit of the day and the night response times.

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