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THE COLLEGE OF AERONAUTICS

CRANFIELD

MATERIALS HANDLING RESEARCH UNIT

IN-PROCESS STOCKS FOR AUTOMATIC TRANSFER LINES

BY

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FIGURES 1 - 18.

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1. INTRODUCTION

Automatic transfer lines are playing an increasingly important role in production. As production rates and capital investment increase, the cost of line stoppages also increases. A line stoppage of an automatic transfer line occurs everytime any of the machines stops, unless there is a sufficient buffer stock between each machine in the line. Thus there arises the question of how much buffer stock between each machine is required to optimise line operation in accordance with some criterion such as maximum output or minimum cost.

Though it is fairly easy to formulate this problem in mathematical terms, it has been shown (Ref.1) that an analytical solution is not possible. The problem can, however, be solved for each particular case by simulation.

This report describes one such solution for the case of an automatic bottling plant in a brewery. The work was carried out as a thesis project for the college's diploma, by Mr. A.C. Roberts, a student in the Statistics and Operational Research section, School of Management, during the Academic year 1967/68. Mr. E. Kay of the Materials Handling Research Unit acted as project supervisor.

As a bottling line is a prime example of an automatic transfer line, we believe that the method here described can be applied to all similar problems.

2. SUMMARY

The objectives of the study were to obtain the optimum layout of the bottling line, such that the breakdown of any one machine could be isolated from the other machines by the cushioning effect of the intermediate buffer stocks, thereby reducing the probability of a line stoppage and consequent loss of production. Owing to the complexity of a mathematical analysis the problem was approached by the technique of simulation. This technique - in which we formulate a model of the real system - is described in the main text.

The results obtained from the model indicated that the line efficiency could be considerably improved by enlarging the capacities of the intermediate conveyor lines, and so increasing the amount of buffer stock carried on them.

Two alternative modification schemes have been proposed. The first offers an increase in efficiency of some 12½% (equivalent to 1000 dozen bottles additional production per day) for an initial outlay of £300, covering the costs of doubling the capacities of two sections of conveyors. The alternative proposal shows a mean line efficiency of 86% (a 20% increase over the current line efficiency) and involves a more drastic enlargement of the conveyors, the installation costs for the new system being correspondingly higher (£3,000). No production costs are available with which to derive the most cost effective layout, but it is considered that the potential increases in production far outweigh the costs involved in modifying the system. In other cases where these costs may be significant a method of obtaining an optimum solution is outlined.

3. THE PROBLEM

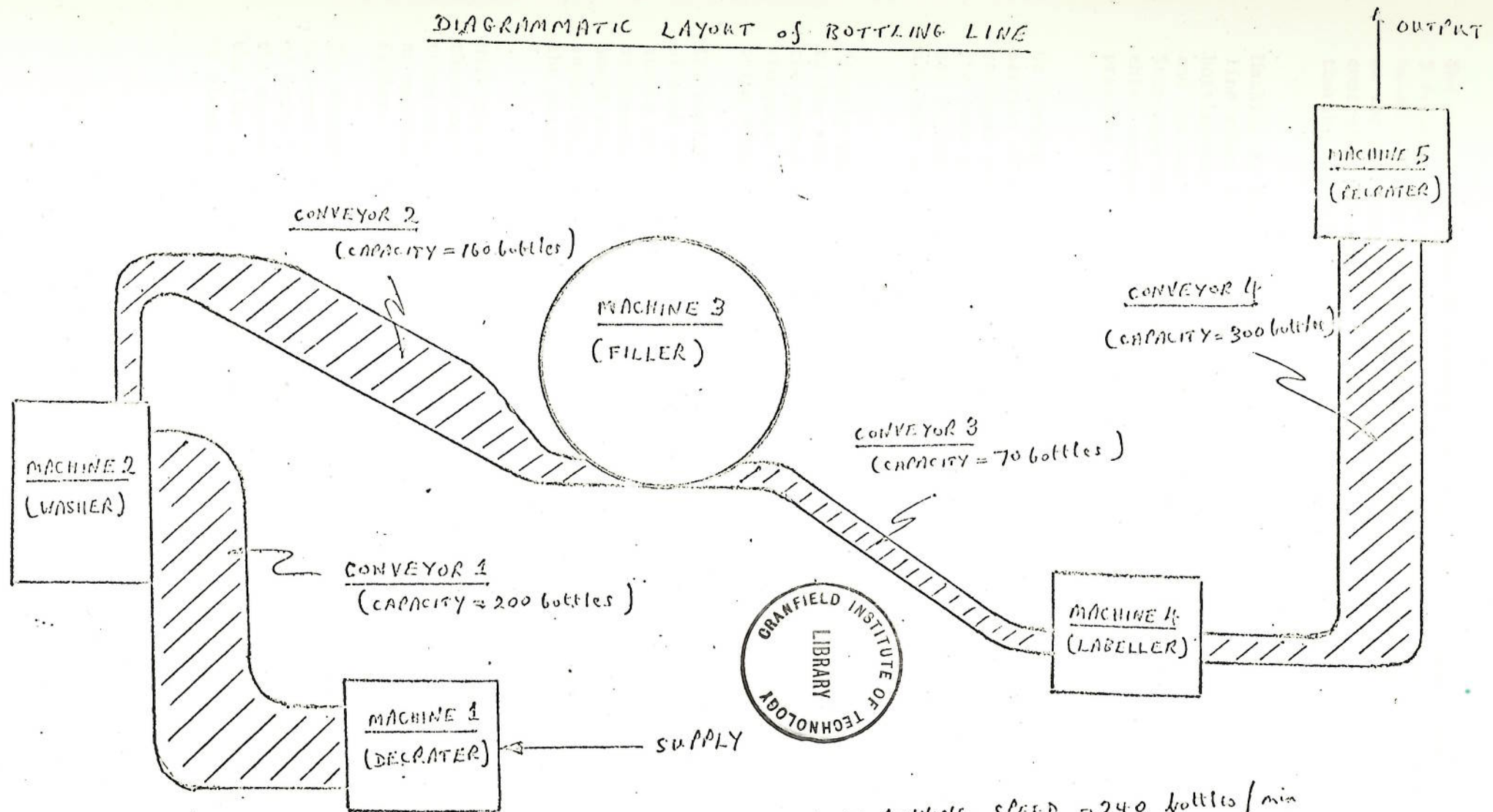
The automatic transfer line can be considered as a set of n machines connected in series so that the output of the i th machine is the input to the $(i + 1)$ th machine. ($i = 1, 2, \dots, n-1$). The machines operate at such rates that unless there is an intermediate buffer supply between each pair of machines, the stoppage of any machine will stop the entire set. If, however, such buffer stocks exist the effect of a breakdown of the i th machine is cushioned by machine $(i + 1)$ taking its supply automatically from the i th buffer until either the buffer becomes empty, when the line stops, or machine (i) is set operating again, whichever is the earlier. As soon as machine (i) is repaired it is restarted and operated at a speed $(1 + a_i)r$, where r is the mean running speed of the line. Thus the $(i + 1)$ th machine is able to take its input directly and the buffer stock is replenished at the rate $a_i r$.

In many practical cases the line running speed is governed by the running speed of the slowest machine. Hence a stoppage of this machine, for whatever reason, will automatically result in a loss of production as the machine is incapable of operating at an excess rate when restarted. The problem then becomes one of optimising the capacities of the intermediate buffers such that the bad running of any one machine does not result in adjacent machines having to be shut down, thereby initiating a chain reaction which results in the slowest machine being halted - with consequent loss of production. The optimising criterion may be purely one of maximising the output from the line, but more usually it will be to minimise the costs of production.

This report is concerned with a practical case, namely the bottling plant at a brewery. The bottling line consists of five machines connected by sections of conveyor belt, each machine performing a different process on the bottles, which then move along the conveyors to the next machine on the line. The layout of the plant is shown diagrammatically overleaf.

Machine 1, the decrater, picked the empty beer bottles out of the crates and placed them on the conveyor feed machine 2. Stoppages from this machine usually arose from the crates being broken or otherwise damaged, resulting in the bottles not being picked up cleanly. The decrater was capable of handling up to 20 crates a minute, representing a bottle supply to the washer of about 450 bottles/min., well in excess of the running speed of 240 bottles/min.

DIAGRAMMATIC LAYOUT of BOTTLING LINE



LINE RUNNING SPEED = 240 bottles / min

The washer (machine 2) produced 24 clean bottles once every 5 seconds - an output rate of 288 bottles/min. Stoppages were usually due to bottles toppling over as they were set down on the conveyor. Output from the washer could only be controlled by shutting the machine down for short periods, thereby reducing the average output.

Machine 3, the filler and crowner, was the key machine in the line since its running speed had to be kept constant (240 bottles/min.) in order that the bottles were completely filled, and the beer was at the same time adequately pasturised. Stoppages with this machine occurred for a variety of reasons, chief amongst these being a bottle exploding under the filling pressure.

On leaving the filler/crowner the bottles passed down a short section of conveyor to the labeller (machine 4). Since this conveyor was so short, the labeller was normally operated at the same speed as the filler- although it was capable of being set at faster speeds. Labeller stoppages were very infrequent and were usually caused by variation in the label gum viscosity.

Finally the finished stock was passed along further conveyors to the recrater (machine 5) where the bottles were picked off the conveyor belt and replaced in the crates. Recrater stoppages were again mainly due to damaged crates, this machine being similar to the decrater.

The buffer stocks consisted of the build-up of bottles in front of each machine. In this particular case therefore the buffer stocks were in fact the queues of bottles waiting to be processed, and if one conveyor became empty the following machine would stop. The maximum buffer capacities were of course the capacities of each conveyor, and when one conveyor became full the preceding machine had to be shut down.

With the exception of the filler and labeller, the other three machines ran intermittently - the operators running these machines in short bursts at their pre-set speeds, which as mentioned before are higher than the operating speed of the filler.

The average length of a bottling session was $1\frac{3}{4}$ hours. The conveyor between the decrater and washer was always left full of empty bottles so that the washer could be started immediately the session commenced. At the end of each session bottles on the line after the washer were run off to prevent contamination of clean bottles, and pilferage of those which had been filled.

All machines had efficiencies above 90% (measured as the ratio of mean breakdown time/mean running time) and the usual daily output was between 5500 and 6000 dozen bottles, representing an overall line efficiency of 65% - 70%.

4. OBJECTIVES AND METHOD OF SOLUTION

The primary objectives of the study were to investigate what effect the capacities of the conveyors had on the output from the bottling line. In particular we required to know to what extent the line efficiency could be increased by enlarging the capacities of the conveyor lines, and also to obtain the optimum arrangement regarding the costs of installing and operating any new system.

The analysis was performed using the technique of simulation. Essentially simulation is a technique for obtaining information about the performance of a system, in this case the bottling line, without actually putting that system into operation. A model in terms of a computer programme is constructed so that the results obtained by operating or modifying the model indicate the results to be expected when the corresponding real system is operated or modified. In particular the effect of many different approaches or configurations can be evaluated without implementing new systems or modifying those already in existence.

Expressed in simpler terms, the computer is programmed in such a way that it "Pretends" to be the bottling line. Since the computer, of course, never produces bottles - but numbers representing the bottle output over a period of time - it can simulate a month's production in about an hour. Furthermore in our computer model we can change the capacities of the conveyor belts and the machine running speeds quite simply by feeding new information into the computer.

The computer needs to know the characteristics of each machine, such as the breakdown frequency and average running and repair times. This information was obtained by a time study of the line lasting a fortnight, which was carried out during April, 1968.

5. RUN AND STOPPAGE CHARACTERISTICS OF THE MACHINES IN THE
BOTTLING LINE

The study was conducted over a period of two weeks with the object of obtaining the distributions of run and stoppage times for each of the five machines on the line. Stoppages were only recorded for a machine when the machine itself had broken down, and not in the cases where the machine had to be shut down through a lack of supply or when the following conveyor became full.

The machine breakdown times were measured with a stop-watch to an accuracy of 1/10th of a minute. Running times were observed by recording to the nearest minute the clocktime at which a breakdown occurred. Since the machine efficiencies were of the order of 90%, the distributions of breakdown and running times were thus obtained with approximately the same accuracy. Including machine halted (shutdown) time in the running time made no appreciable difference to the mean as the average halted time amounted to only 10% of the running time of each machine.

Characteristics of the observed distributions:

Figures 1 - 10 gives the histograms of breakdown and running times obtained in the study. All the distributions have shapes similar to negative exponential distributions, which suggests that the machine breakdowns are randomly occurring events, and the service, or repair time has a constant probability of being completed at any given instant.

However, on applying the χ^2 test of significance to the observed distributions, in many cases these were found to be significantly different from a negative exponential distribution having the same mean. In such cases the shape of the histogram departed from a negative exponential distribution in the manner illustrated below.

Such a shape suggests that the observed distribution is the result of two or more indepently occurring factors, giving a

probability density function of the form $\sum_{i=1}^n \mu_i e^{-\mu_i t}$ where μ_i is the average rate of occurrence of each factor.

Significantly better fits were obtained by using the χ^2 test against a hypothesis of a distribution containing two factors with parameters μ_1 and μ_2 . (For each new factor of course the number of degrees of freedom are reduced by one.)

Physically, these results may be explained in the following way. Let p_B be the probability of a machine breakdown being of duration t .

Then p_B may depend on (i) the operator correcting the jam herself
or (ii) the mechanic being immediately available to correct the fault
or (iii) the mechanic being sent for if the operator is unable to correct the defect.

If each type of repair service has a negative exponential distribution of service time, then the probability density function for the repair time will be given by,

$$\mu_{(i)} e^{-\mu_{(i)} t} + \mu_{(ii)} e^{-\mu_{(ii)} t} + \mu_{(iii)} e^{-\mu_{(iii)} t}$$

where $1/\mu_{(i)}$, $1/\mu_{(ii)}$ and $1/\mu_{(iii)}$ are the respective mean repair times for the three types of service.

Machine breakdowns are largely the result of bottles falling over or bursting inside the machines. It would therefore be reasonable to suppose that these bottles which cause any one machine to jam arrive at that machine in a Poisson stream, and thus the running time intervals would be distributed as a negative exponential distribution. However, the running times observed in the study also included the intervals during which the machines had been shut down, and so the observed distribution may be modified as,

$$\mu e^{-\mu t} + f_1(t) + f_2(t)$$

where $1/\mu$ is the average machine running time and f_1 and f_2 are time dependent functions describing the influence of the buffer stocks which cause the machine to be shut down.

The derived cumulative probability distributions:

For the purposes of using random numbers to sample running and breakdown times, the observed distributions were converted to cumulative probability distributions. These are shown in Figs. 6 - 10. In many cases the tails of these distributions had to be estimated owing to the lack of sufficient observations for the longer time intervals. However, the rate of change of the slope in these regions is very small and no significant errors are likely.

In the computer simulation programs, the sampling procedure requires that the cumulative probability distributions are given in an approximate form by a continuous set of straight line segments. (This approximation is also shown in Figs. 6-10.) In order to sample a time value from the distribution, a probability value is selected at random by means of a random number generator, and the corresponding time is found from the distribution, interpolating linearly where necessary.

RESULTS OF SIMULATION

The program was first run by using the present conveyor capacities and machine excess running speeds. The simulation was run for 100 sessions, each of 105 minutes duration - the average length of a bottling session.

The mean line efficiency was 67% and the production output was approximately normally distributed over a range of 66-78 minutes per session. This corresponds to a daily output of 5250-6000 dozen bottles, which is consistent with the production currently achieved in practice. Employing the χ^2 test of significance to the histograms of machine breakdown times showed good agreement with the observed histograms.

As indicated in Section 5 loss of production will occur if the filler (machine 3) is stopped, since this machine has to operate at a constant speed. Analysis of the filler stoppage times showed that out of an average total stoppage of 37 mins. per session, only 25% of this time was the result of the filler itself breaking down. Of the remainder, 50% was due to the preceding buffer (2) being exhausted, and 25% of the filler stoppage time was the result of the following conveyor (buffer 3) becoming full.

In order to investigate the effect of the buffer capacities on the line output, the simulation was re-run with the conveyor sizes increased proportionately by amounts 1.25, 1.5, 2.0, 3.0, 4.0, and 8.0 times their present capacities. The number of sessions simulated for each case was reduced to 10, thereby considerably reducing the computer running time. Although no sensible histograms of production output can be obtained from only 10 sample runs, the previous results for 100 sessions showed the distributions to be quite stable and have relatively small variances. Fig. 11 shows how the line efficiency is affected by the sizes of the intermediate buffer capacities. For moderate increments in conveyor size there is a drastic improvement in efficiency which then tails off as the capacities are enlarged still further.

The reasons for this are demonstrated in Figs. 12-15. We are primarily interested in reducing the effects of the bad running of the other machines on the performance of the filler. Thus the chief concern is the total filler stoppage time due to Buffer 2 being empty and Buffer 3 being full. To a lesser extent we also wish to reduce the stoppage time of machine 2 (when buffer 1 is empty), as there is a possibility that

buffer 2 may then become exhausted and so also stop the filler. Likewise, should buffer 4 become full and stop the labeller (Machine 4) this may in turn also cause the filler to stop as buffer 3 becomes full. Figs. 12 and 13 show the reduction in respective machine halted times as the conveyor sizes are enlarged. (Fig. 12 is plotted against the proportional increases in buffer capacity, and Fig. 13 with the buffer capacities expressed as the time such buffer stock would last at the depletion rate of 240 bottles/min. - the line running speed.)

These curves are akin to negative exponential shapes, and explain why the improvement in the line efficiency reduces for the larger buffer capacities, since filler stoppages are then mainly due to the machine itself breaking down. Figs. 14 and 15 show how the probability of the respective machines halting (due to the adjacent buffers being empty or full) is reduced by increasing the buffer capacities. The reliability of these results is of course reduced as the probabilities become small, since fewer observations are recorded in each run.

The above results were obtained by increasing all conveyor sizes proportionately and the individual effect of the buffers is not shown. Accordingly a series of runs were made with only the capacity of buffer 2 enlarged by amounts 1.25, 1.5 and 2.0 times its present size. The respective machine halted times are shown in Fig. 17. The filler stoppages due to buffer 2 being empty follow approximately the same curve as was obtained when all the conveyor sizes were increased, and with the exception of the washer (machine 2) there is little significant effect on the other machines. The washer appears to halt (due to buffer 1 becoming empty) more frequently, and this is to be expected since more stock is capable of being transferred to the larger conveyor between washer and filler.

Fig. 16 shows that the ratios of average buffer stock to buffer capacity remain practically constant as the capacities of the four conveyors are proportionately increased. When only conveyor 2 was enlarged (Fig. 15), the other buffer stocks remained at their existing mean values, while buffer 2 again increased in direct proportion to its maximum capacity.

These results indicate that the effect of enlarging any one conveyor is primarily limited to the buffer supply held on that conveyor, and the effect this then has on the machines at either end of it.

7. OPTIMISATION OF THE SYSTEM

If the only criterion is to maximise output from the lines, then obviously using the largest possible buffer capacities would provide a solution. However a more sensible method would be to enlarge each conveyor until machine stoppages due to the effect of adjacent buffer stocks were reduced to negligible proportions. Alternatively, the sizes of the conveyors could be increased until further increments offered little improvement in efficiency - as indicated by the flattening off of the curves in Figs. 12-15.)

Where the costs of installing and operating larger conveyors are significant compared with the cost benefits obtained from increased line efficiency then different techniques must be employed. One method is to employ the "hill climbing" technique. Using this the buffer giving the greatest potential improvement in efficiency is enlarged until the rate of improvement becomes less than that offered by increasing the size of another conveyor. This conveyor may then be enlarged up to the point when another alternative shows a greater potential improvement. The process continues until the cost of any further modification becomes greater than the extra benefit achieved.

Regarding the bottling line here considered, installation of 7" width conveyor track costs approximately £10 per foot and this can carry about 3 bottles/foot. Thus doubling the capacity of the conveyor between the washer and filler, and also between the filler and labeller (these buffers having the greatest influence on the running of the filler) would involve an initial outlay of £300. With this layout the program showed a mean line efficiency of 80%, representing an increased output of approximately 1000 dozen bottles per day. No production costs are available - but the cost of new conveyors is considered negligible in the light of the expected improvement in line efficiency.

Enlarging conveyors 1, 2 and 3 by 4.0, 4.0 and 8.0 times their present respective capacities gave a mean line efficiency of 87%. (The present conveyor between labeller and recrater is considered adequate). This is felt to be the "best" layout in terms of maximising the production output, as machine stoppages due to the bad running of other machines are then negligible. Installation costs for this system are in the region of £3,000.

6. CONCLUSIONS

The simulation programme has given an accurate representation of the bottling plant. Loss of production on the line will occur if the filler stops, as this machine cannot be speeded up when it is restarted. The filler may stop for one of three reasons:

- i) The machine itself breaks down
- ii) The supply of bottles to the machine becomes exhausted.
- iii) A stoppage further down the line causes a build up of bottles which eventually reach back to the filler, causing it to be shut down.

With the present layout of the line only 25% of the total filler stoppage time is the result of the filler itself breaking down.

By enlarging the size of the buffer capacities the simulation has shown that the remaining filler stoppages can be considerably reduced, as this machine is then cushioned from the effects of the bad running of the other machines.

Two alternative modification schemes are feasible. The first involves doubling the capacity of the conveyor between the washer and the filler, and also that between filler and labeller. With this layout the simulation has shown a mean line efficiency of 80%, an increase of some 12½% over the currently achieved efficiency - or, in terms of production, an increased daily output of about 1000 dozen bottles. Installation costs for this scheme are in the region of £300, and no significant extra running costs are anticipated.

The second proposal is that the capacities of conveyors 1,2 and 3 are increased by 4.0,4.0, and 3.0 times their present sizes - such a layout giving a mean efficiency of 86%, at which point filler stoppages are almost entirely caused by the machine itself. In all cases the variance in the production output is small enough to guarantee the mean line efficiency to $\pm 5\%$ with 95% confidence. The second scheme would involve an initial outlay of £3000. No production figures are available, but in the opinion of the company these installation costs are insignificant compared with the indicated additional output.

The above results apply only to the bottling line studied. They indicate, however, that simulation by computer is capable of increasing operating efficiency in similar situations.

The M.H.R.U. intends to carry out further studies aimed to produce more generally valid results.

It is by request of the company, in whose brewery the study described in this report was carried out, that the name of the brewery is withheld.

REFERENCES:

1. MORAN, P.A., THE THEORY OF STORAGE
2. TOCHER, K.D., THE ART OF SIMULATION.

FIG 1

MACHINE 1 (DECATER)

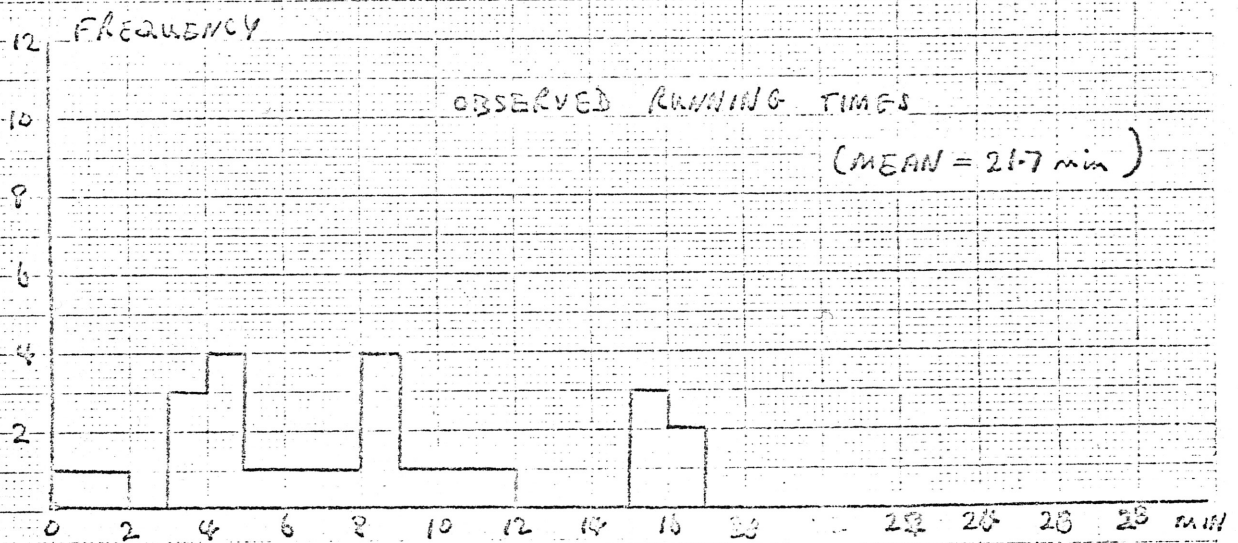
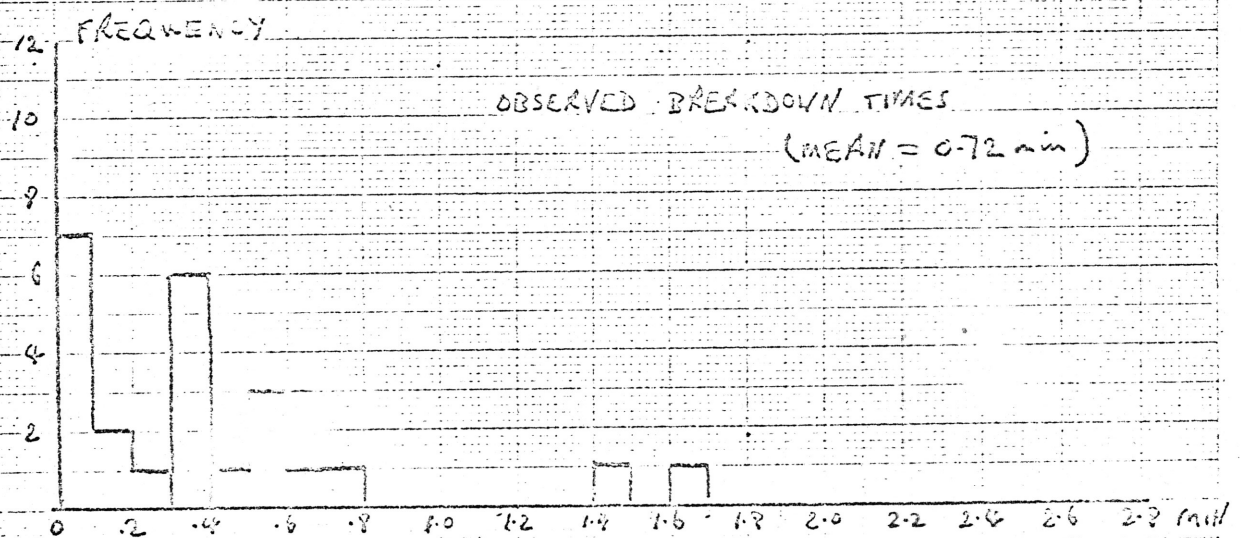


FIG 2

MACHINE 2 (WASHER)

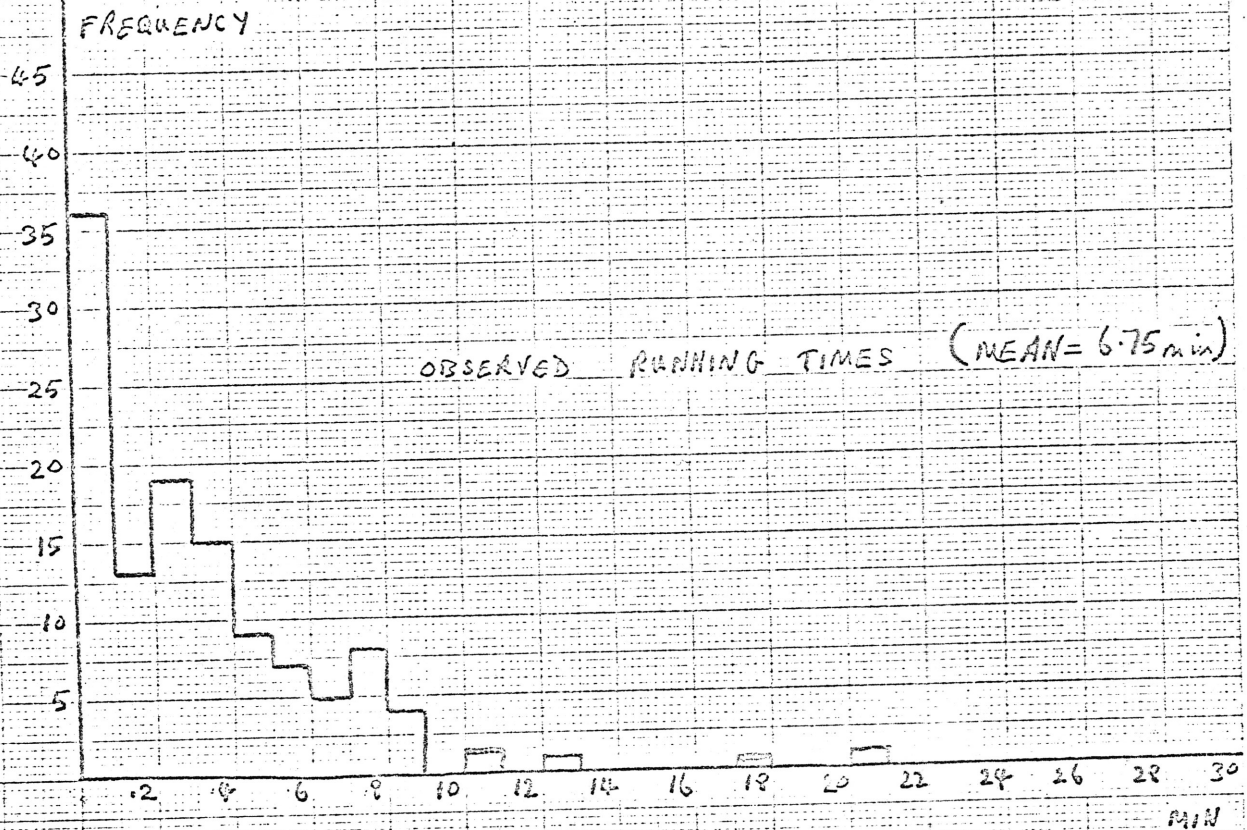
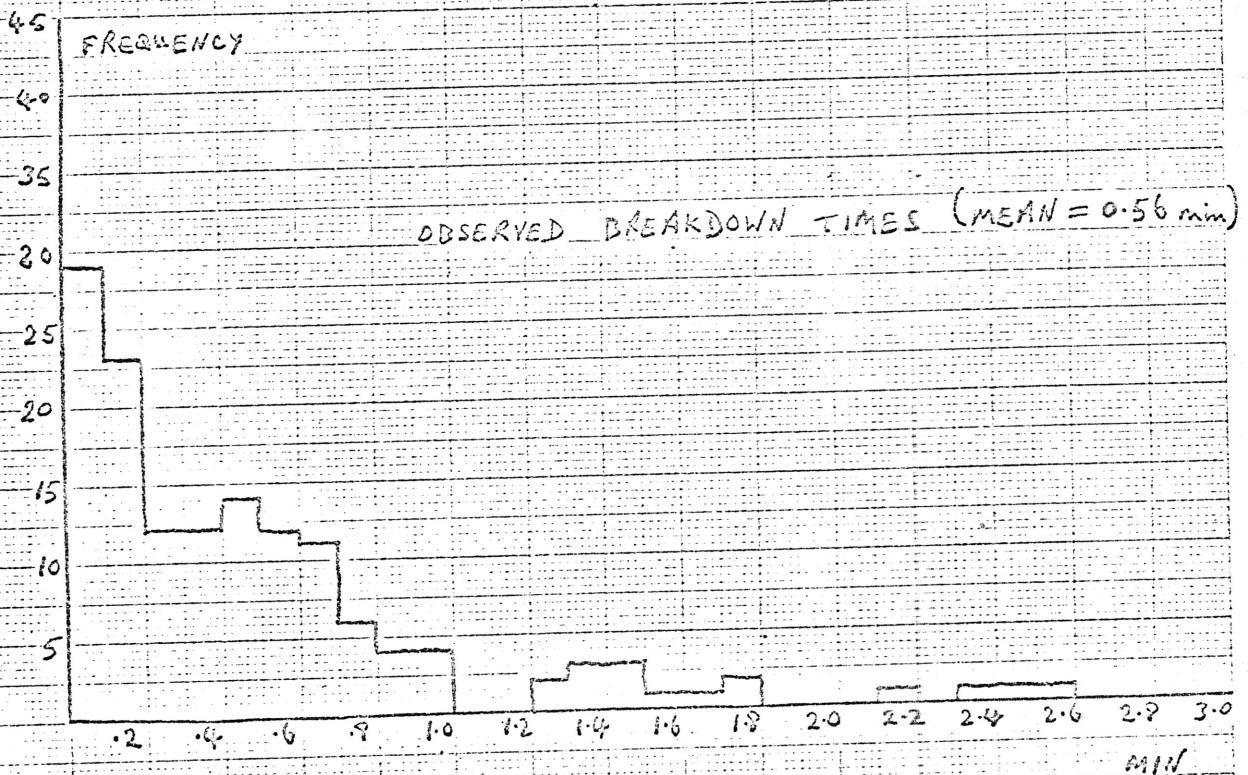


FIG 3

MACHINE 3 (FILLER)

FREQUENCY

200
180
160
140
120
100
80
60
40
20

OBSERVED RUNNING TIMES

(MEAN = 3.36 min)

2 4 6 8 10 12 14 16 18 20 22 24 26 28 MIN

FREQUENCY

200
180
160
140
120
100
80
60
40
20

OBSERVED BREAKDOWN TIMES

(MEAN = .25 min)

.2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 MIN

FIG 4

MACHINE 4 (LABELLER)

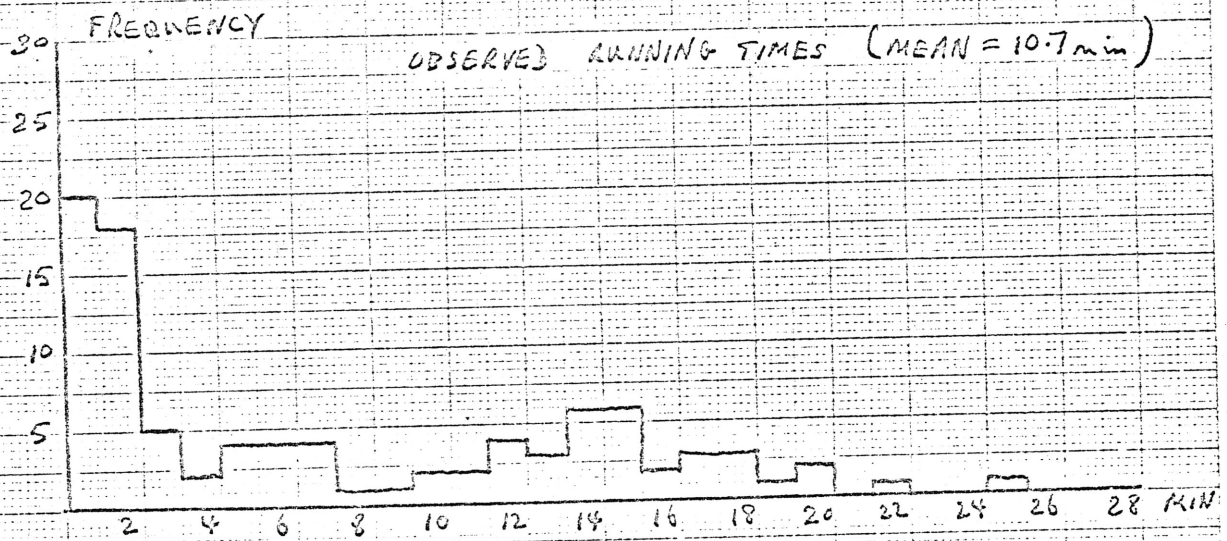
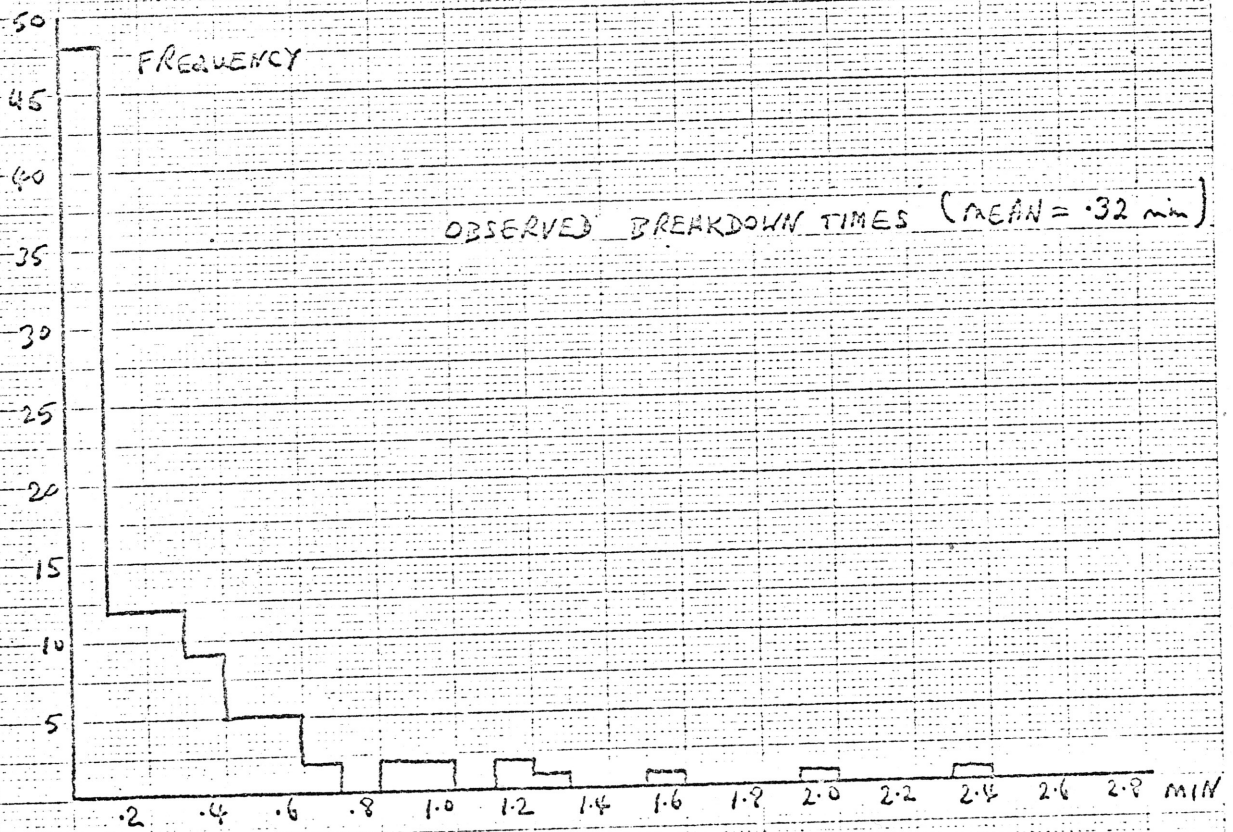
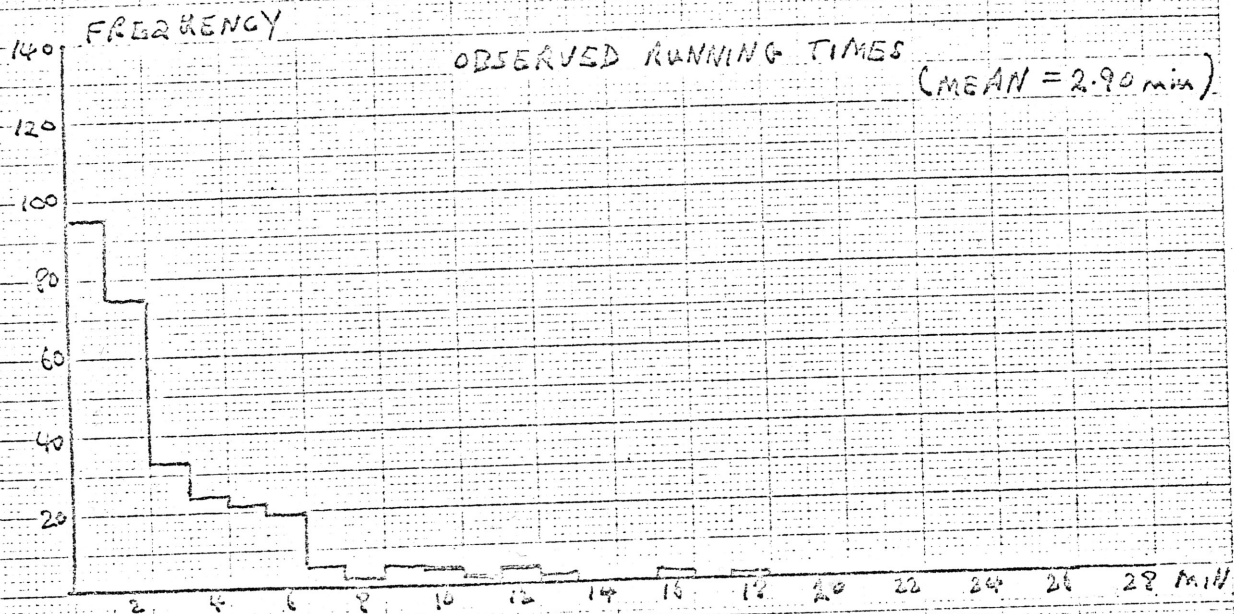
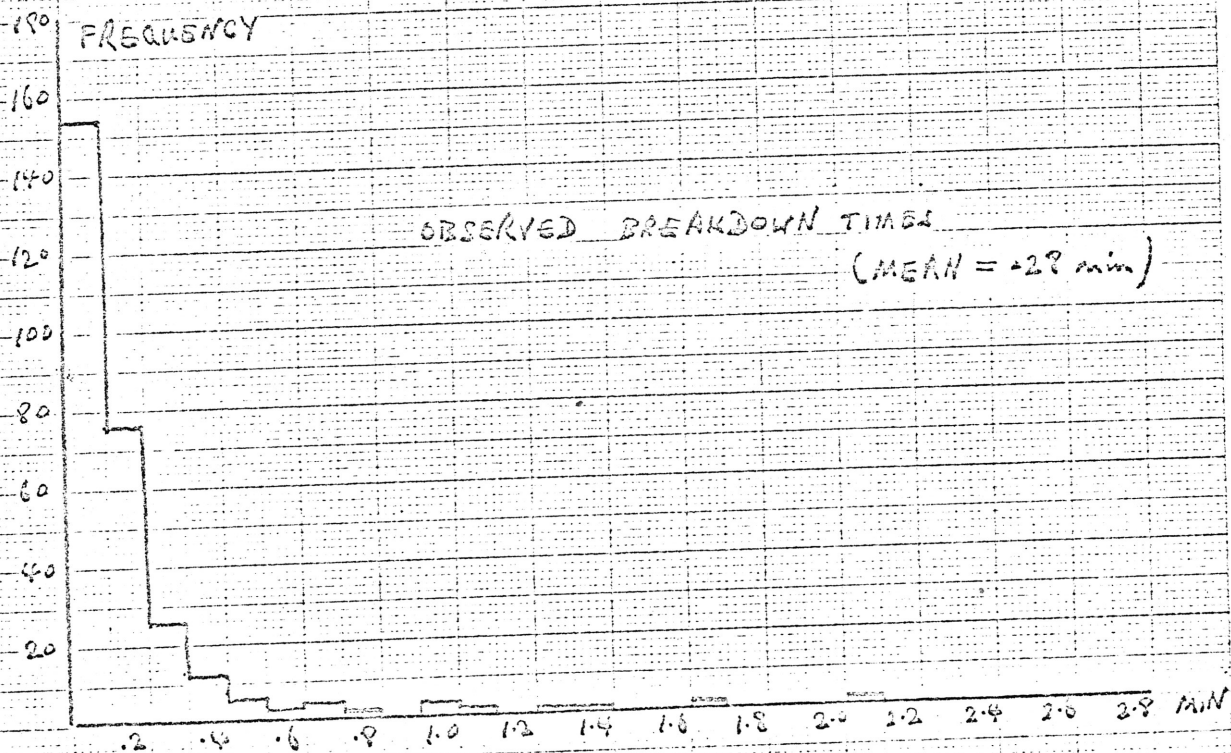


FIG 5

MACHINE 5 (REGRATER)



CUMULATIVE PROBABILITY DISTRIBUTIONSMACHINE 1 (DECRATER)

PROBABILITY

1.0

.9

.8

.7

.6

.5

.4

.3

.2

.1

0

RUNNING TIMES

2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 min

1.0

.9

.8

.7

.6

.5

.4

.3

.2

.1

0

BREAKDOWN TIMES

.2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 min

FIG 7

CUMULATIVE PROBABILITY DISTRIBUTIONS

MACHINE 2 (WASHER)

1.0 PROBABILITY

RUNNING TIMES

1.0 PROBABILITY

BREAKDOWN TIMES

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 min

0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 hr

FIG 8

CUMULATIVE PROBABILITY DISTRIBUTIONS

MACHINE 3 (FILLER)

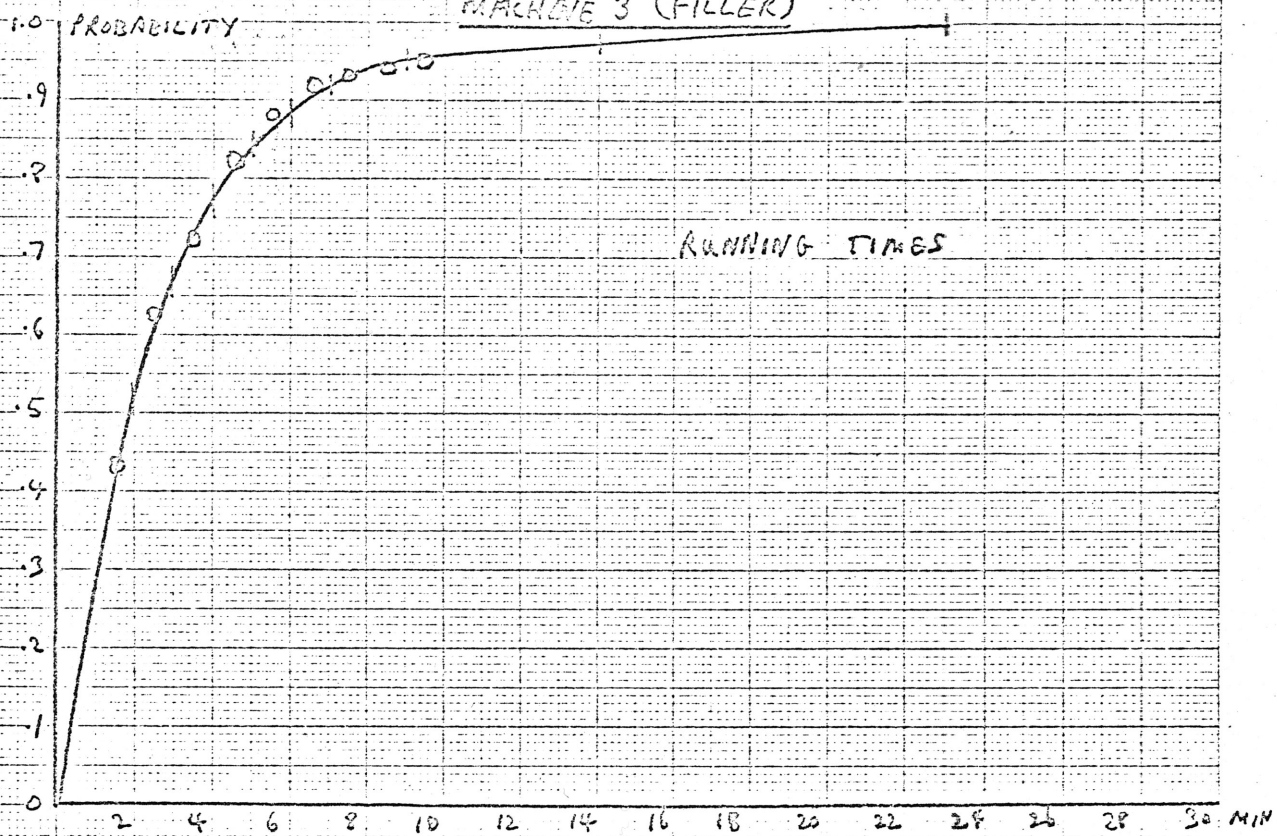
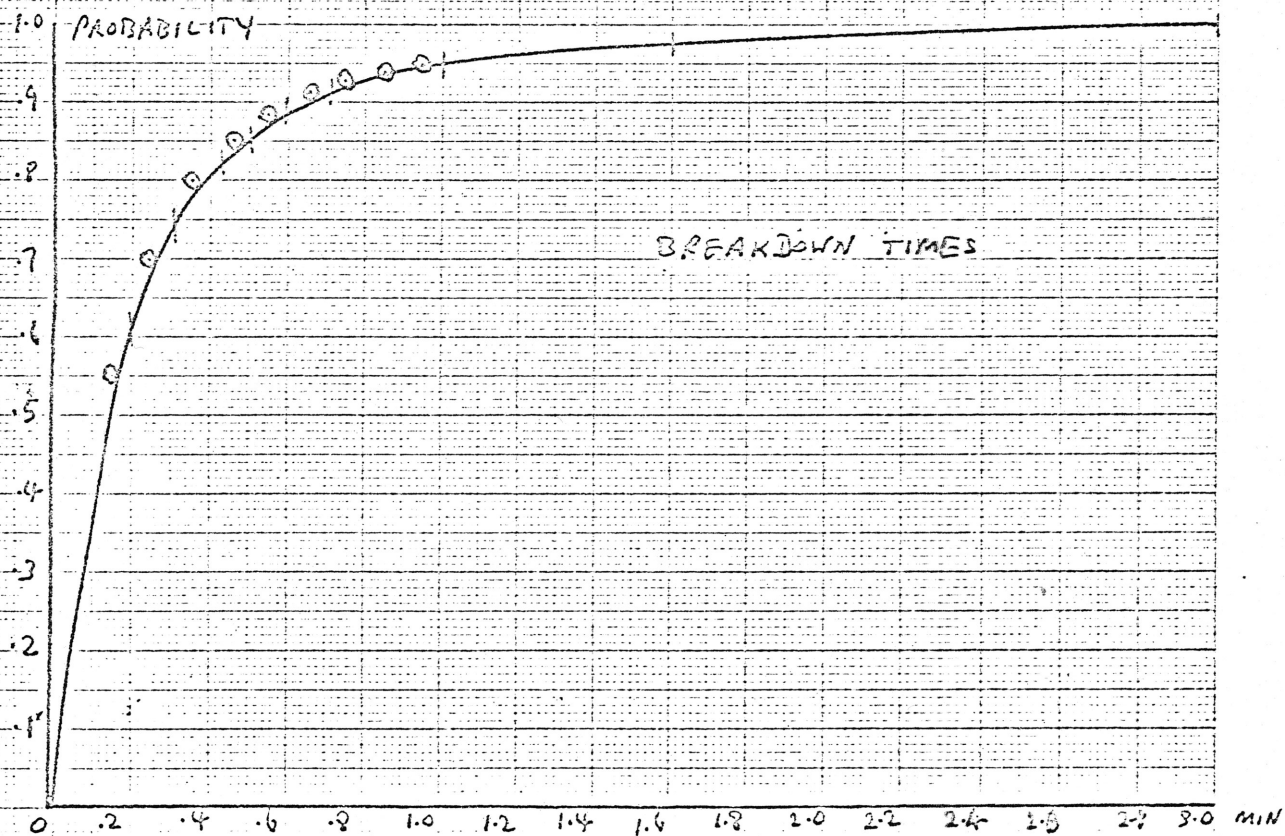


FIG 9

CUMULATIVE PROBABILITY DISTRIBUTIONS

MACHINE 4 (LABELLER)

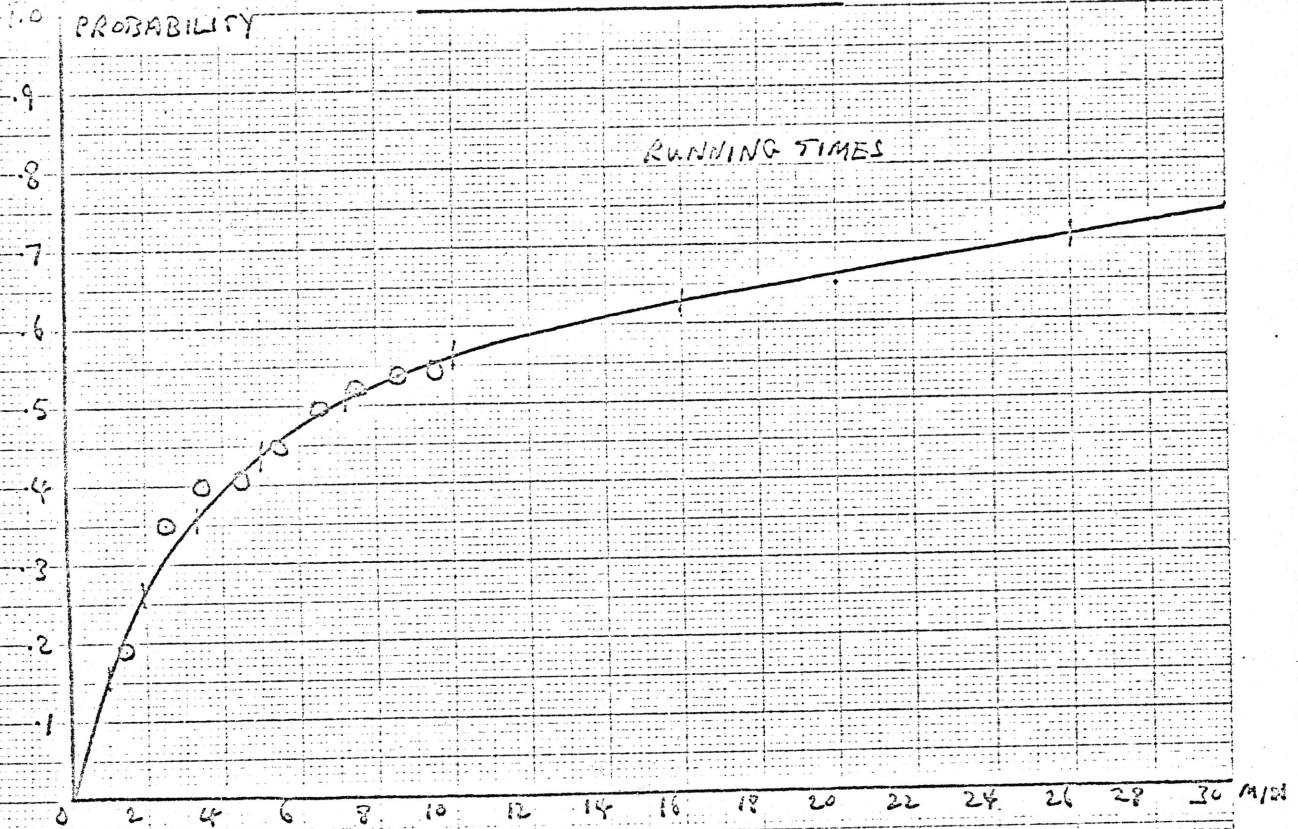
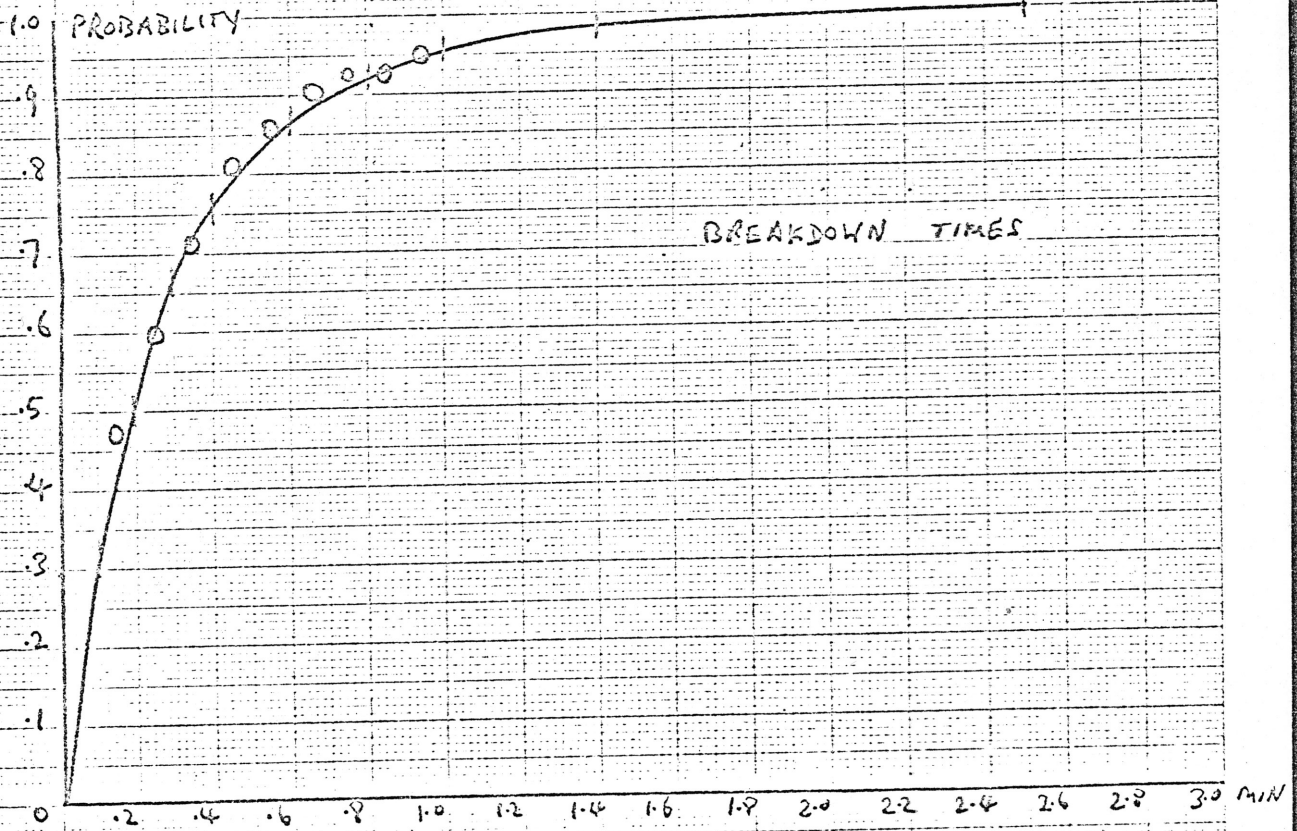


FIG 10

CUMULATIVE PROBABILITY DISTRIBUTIONS

MACHINE 5 (RECRATER)

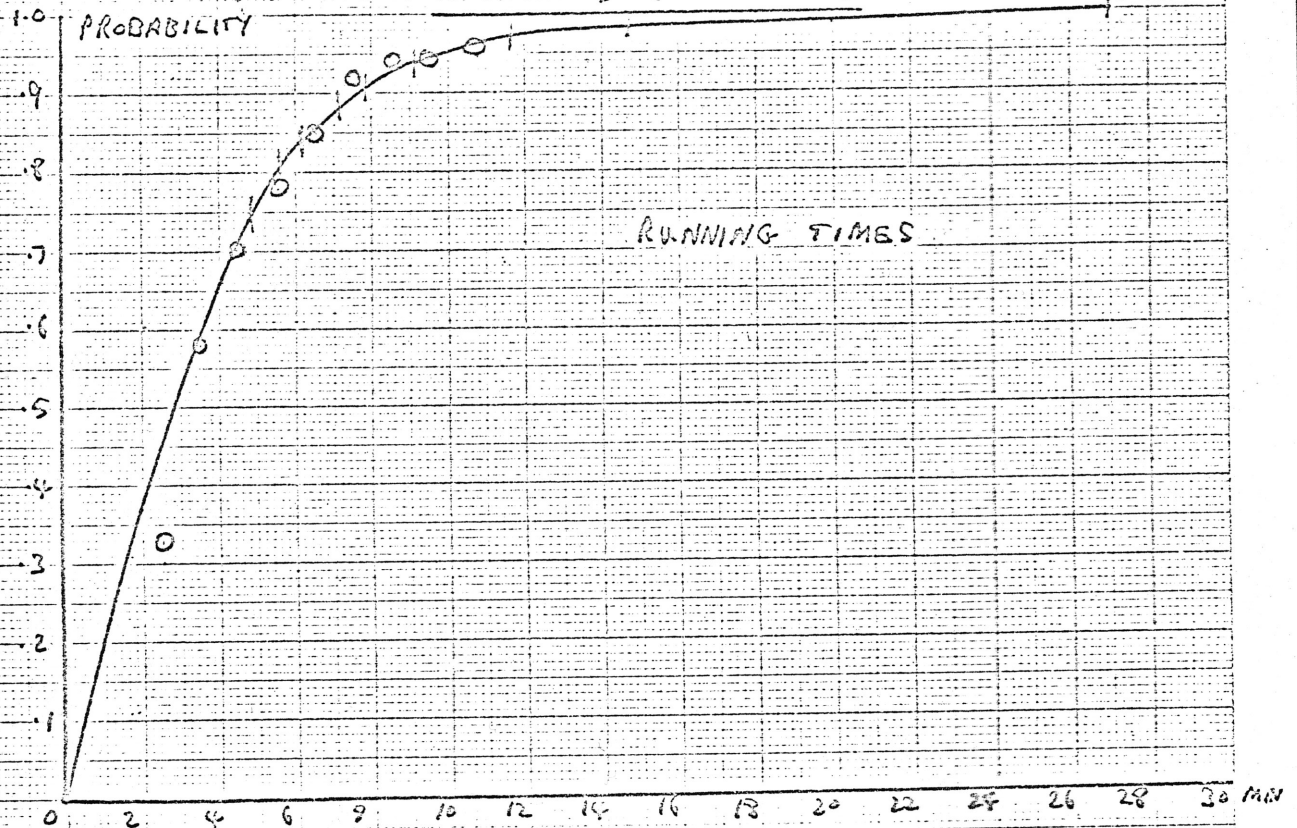
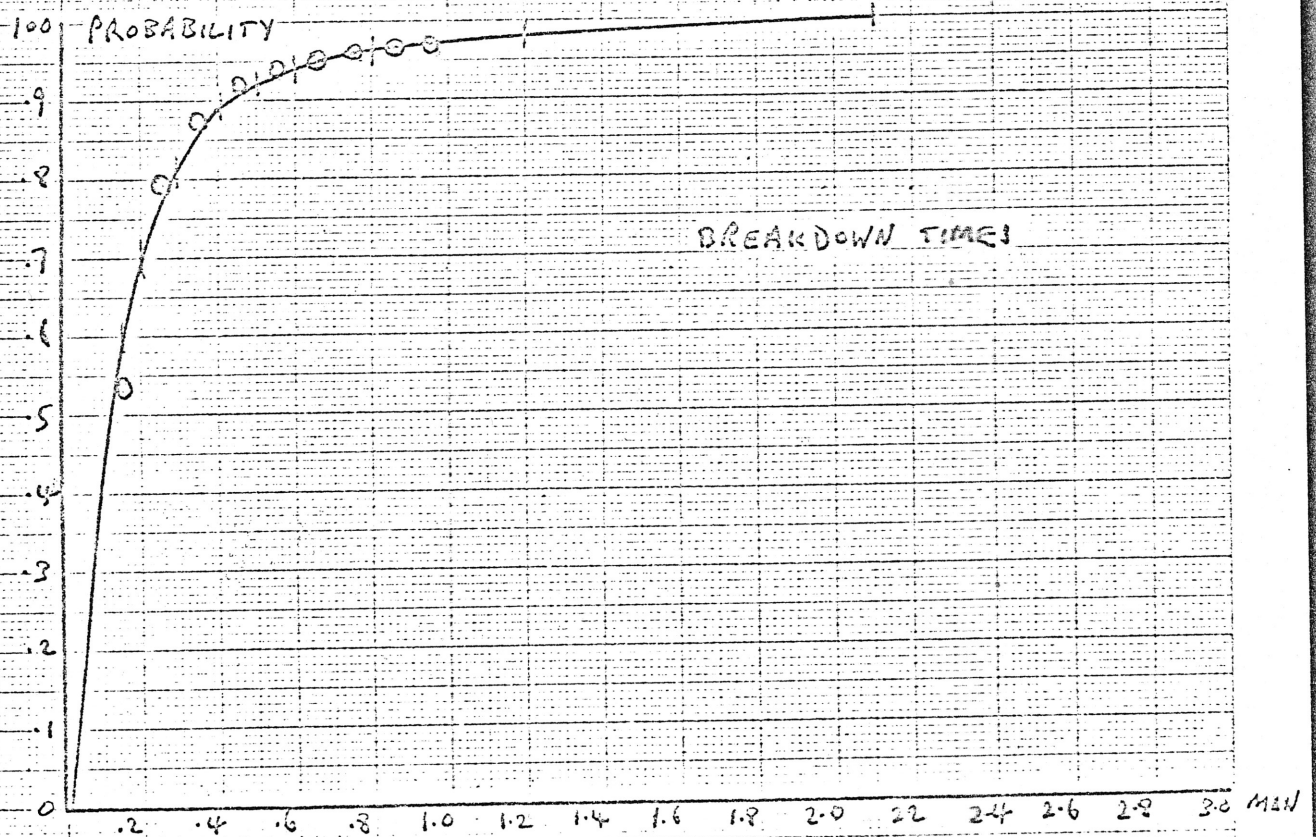


FIG. 11

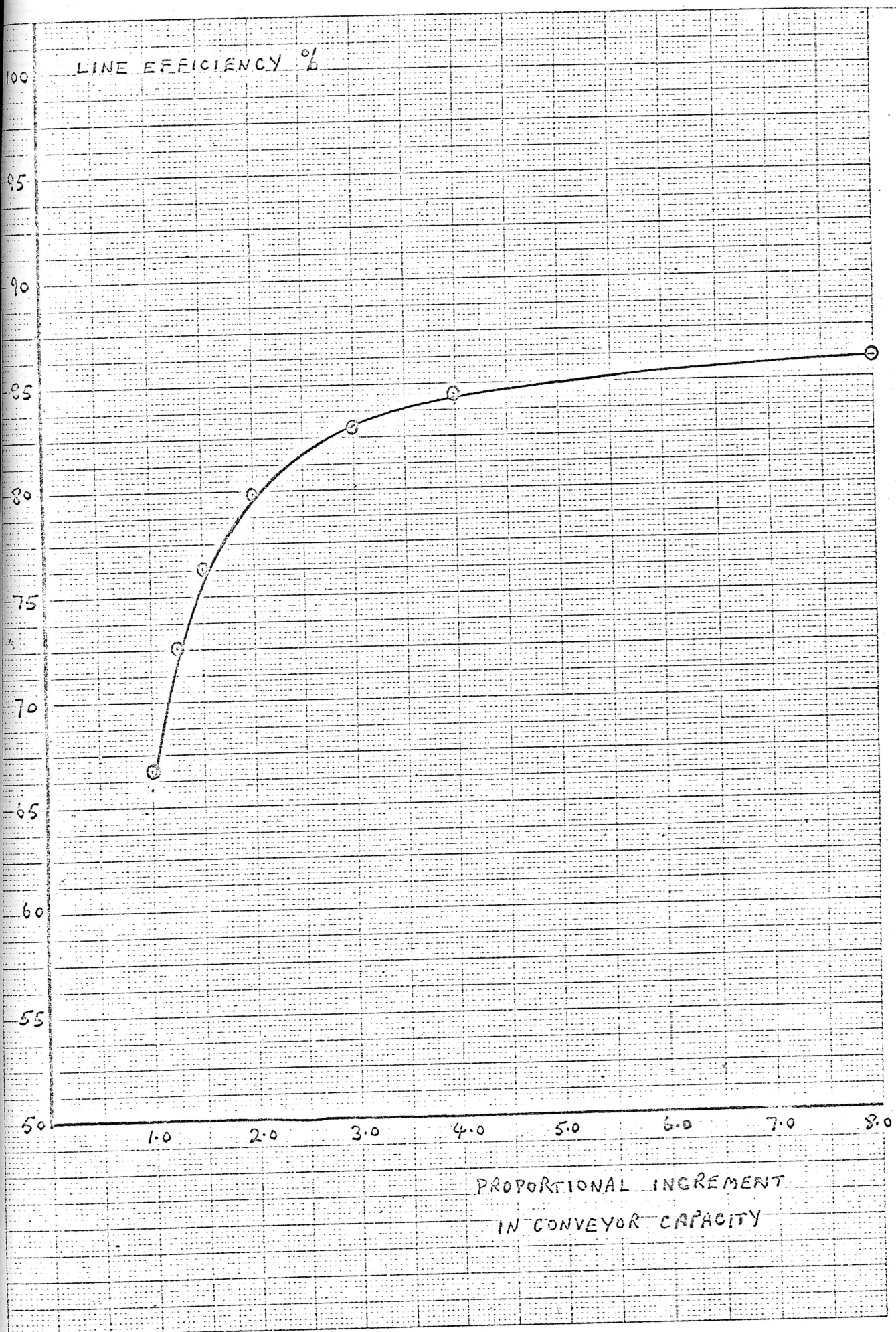


FIG. 12

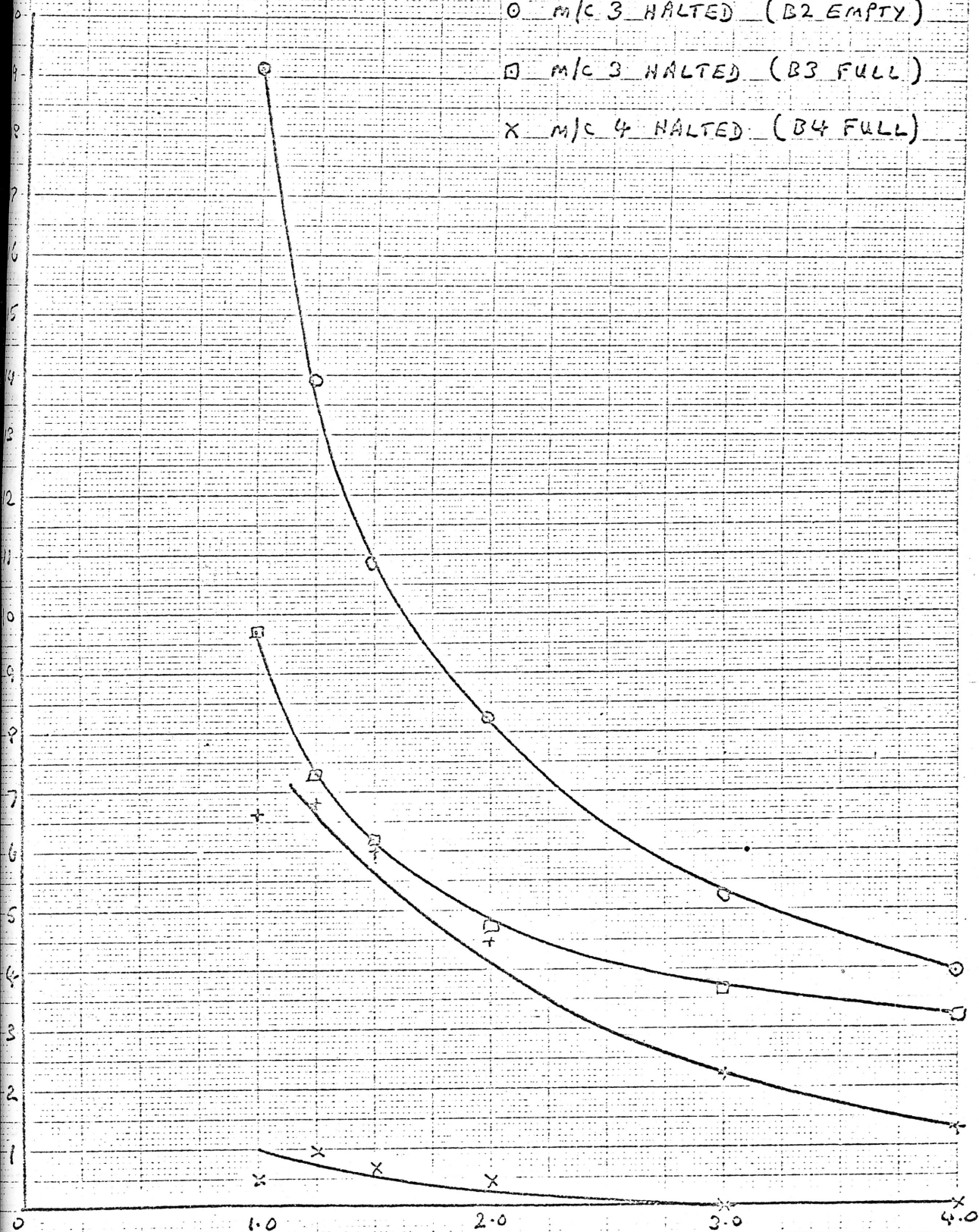
TIME HALTED (MINS)
PER SESSION

+ M/C 2 HALTED (B1 EMPTY)

O M/C 3 HALTED (B2 EMPTY)

□ M/C 3 HALTED (B3 FULL)

X M/C 4 HALTED (B4 FULL)



PROPORTIONAL INCREASE IN
CONVEYOR CAPACITY

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FIG. 13

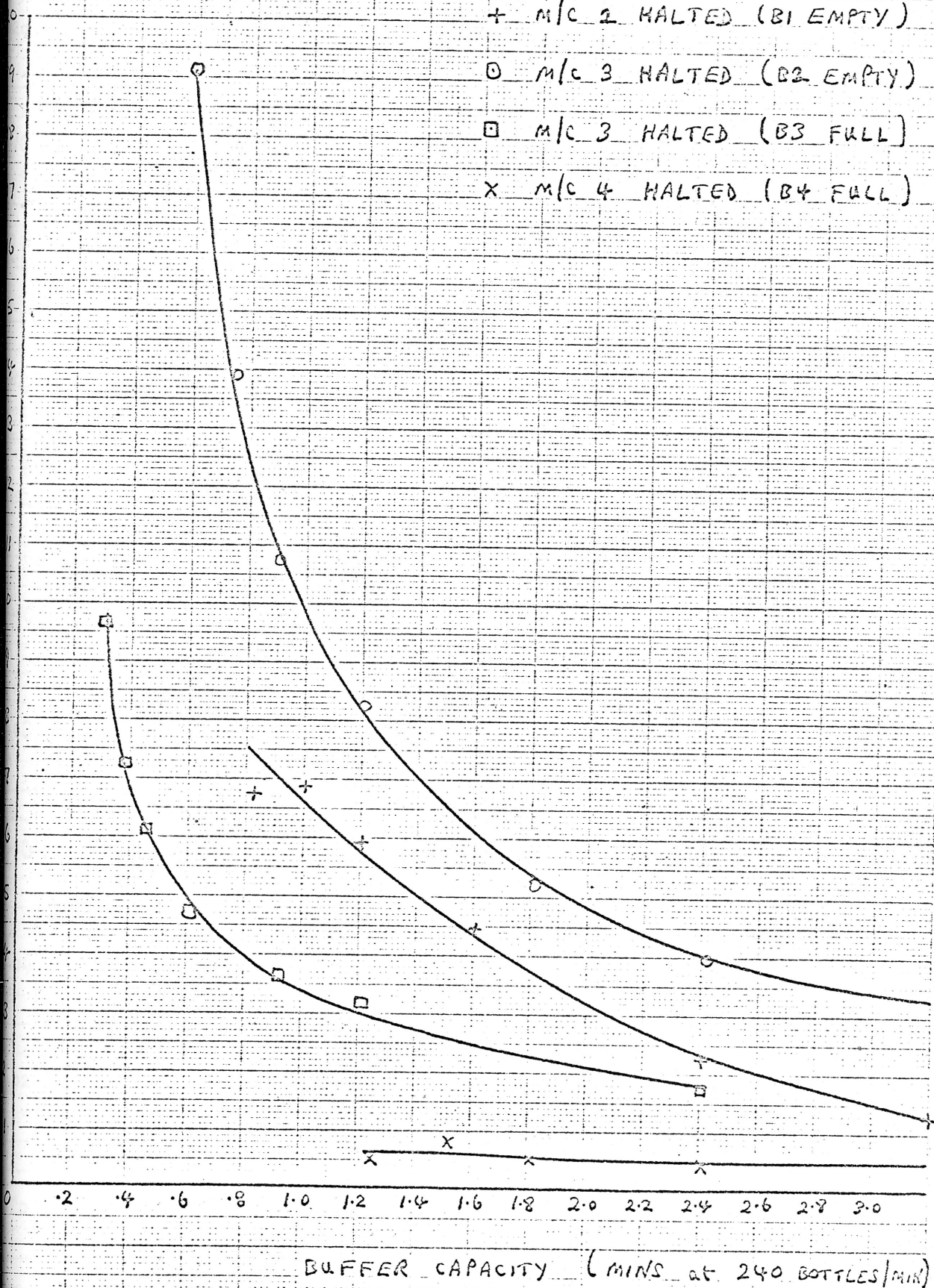
TIME HALTED (MINS)
PER SESSION

+ M/C 2 HALTED (B1 EMPTY)

○ M/C 3 HALTED (B2 EMPTY)

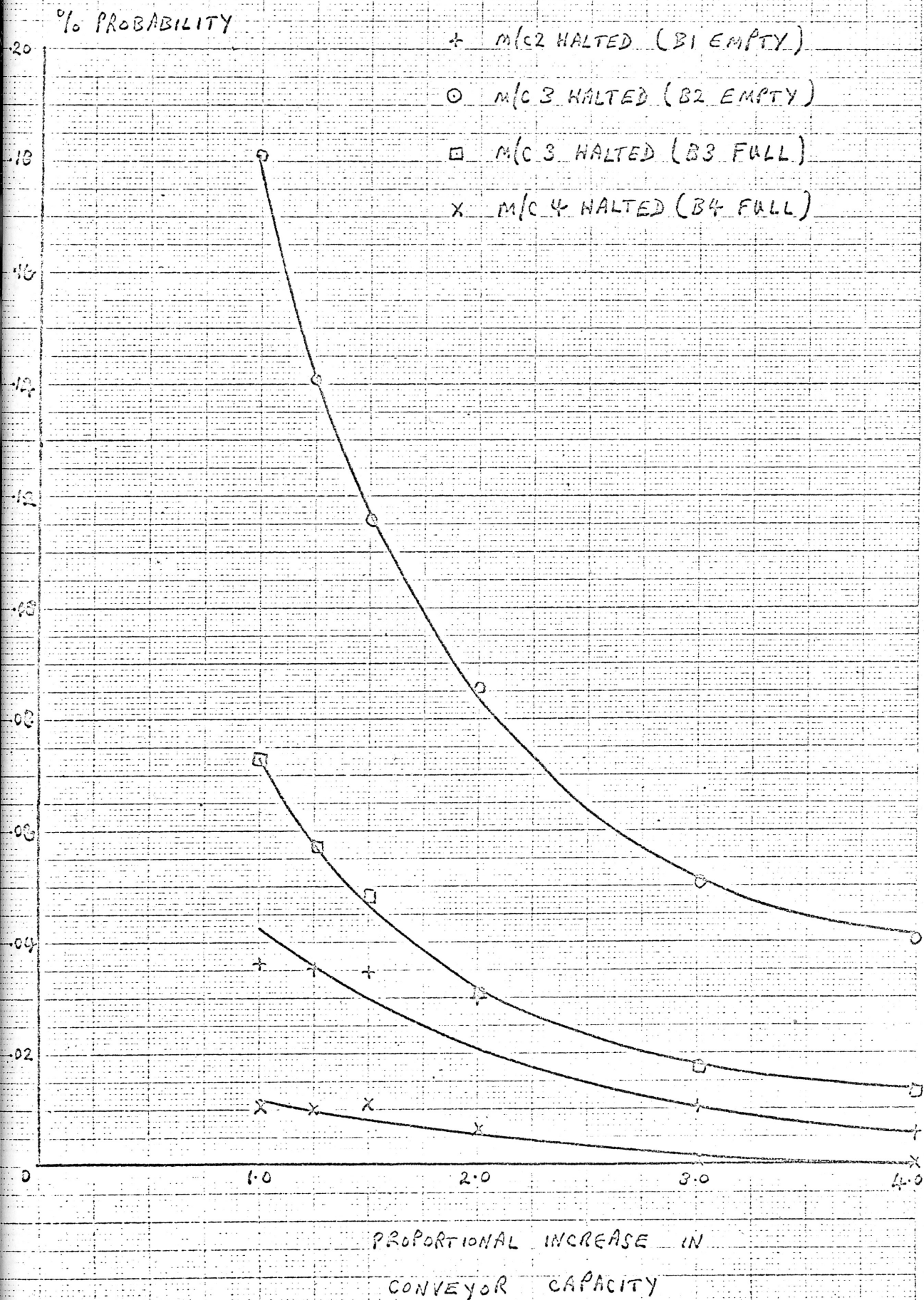
□ M/C 3 HALTED (B3 FULL)

x M/C 4 HALTED (B4 FULL)



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FIG. 14



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FIG. 15

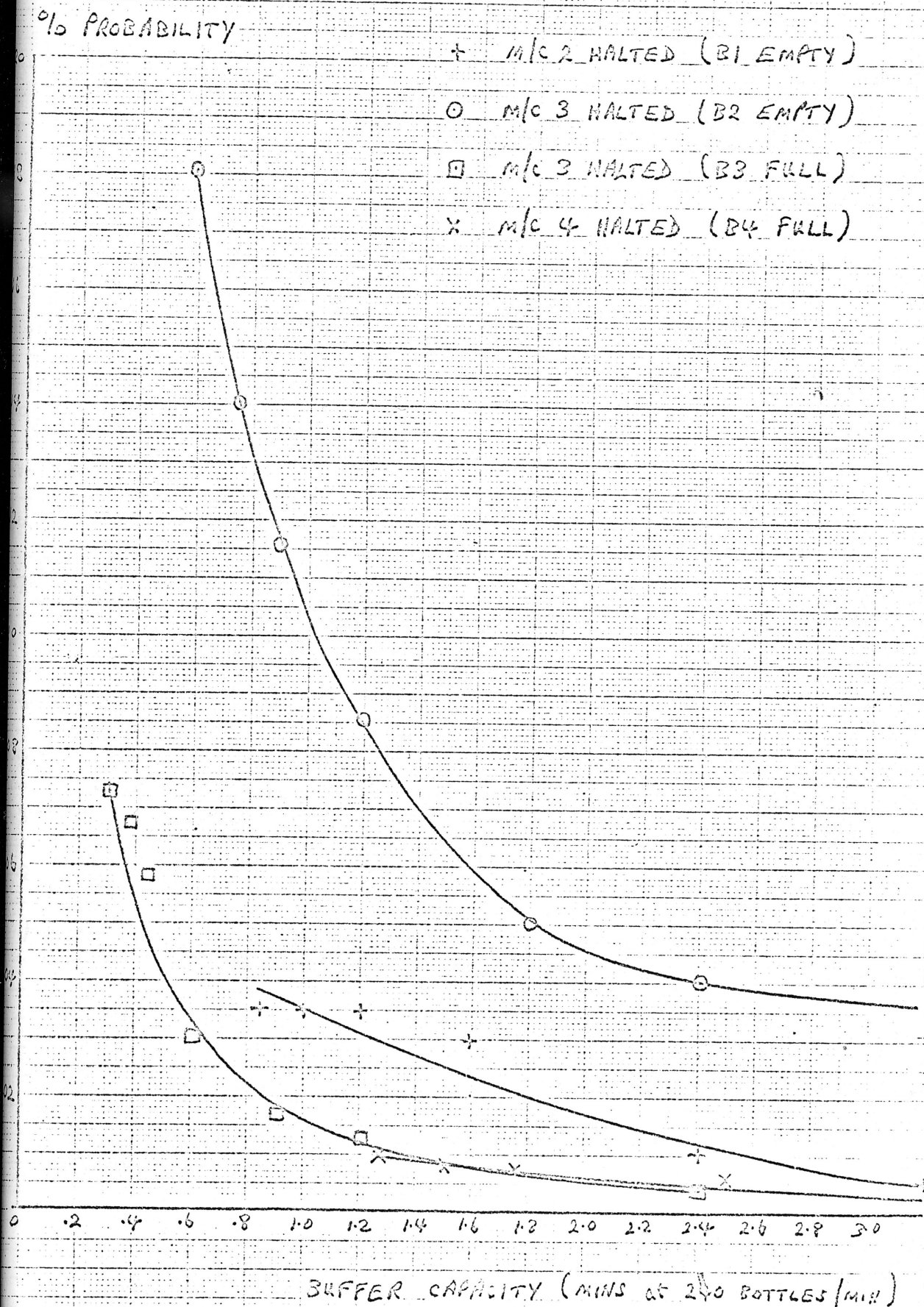
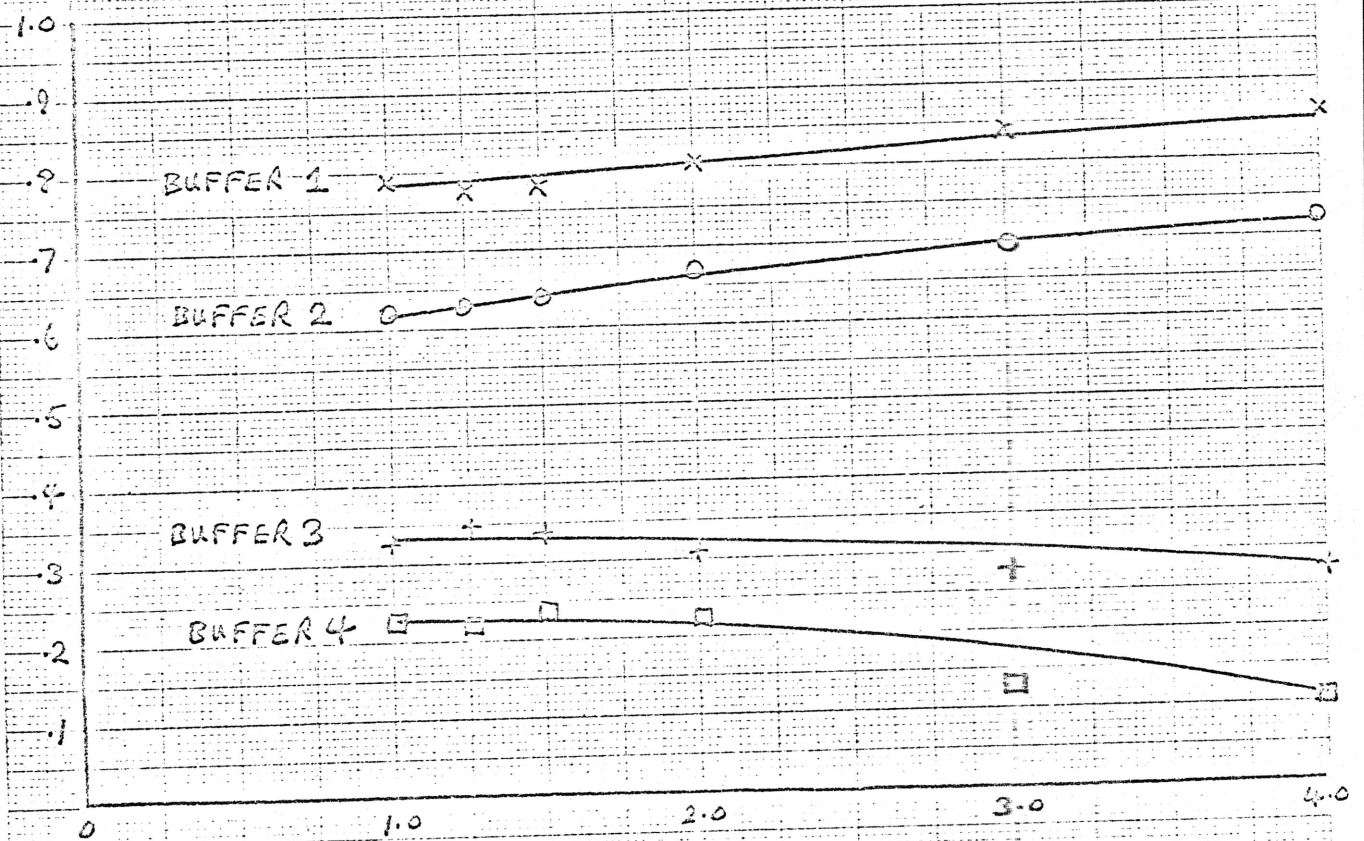


FIG. 16

AV. BUFFER / BUFFER CAPACITY



PROPORTIONAL INCREASE IN
CONVEYOR CAPACITY

TIME HALTED (MIN PER SESSION)

---+--- M/C 2 HALTED (B1 EMPTY)

---○--- M/C 3 HALTED (B2 EMPTY)

---□--- M/C 3 HALTED (B3 FULL)

---X--- M/C 4 HALTED (B4 FULL)

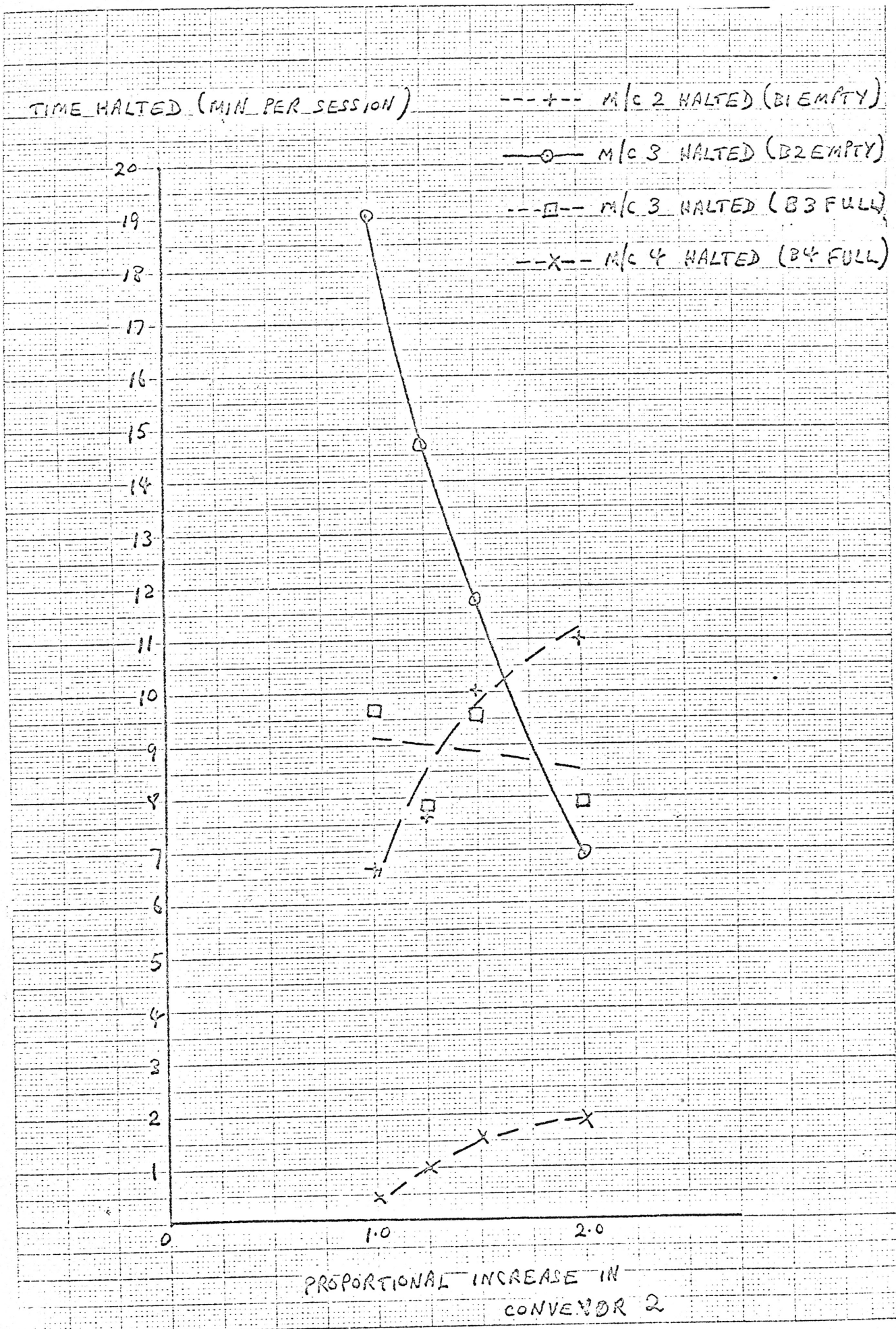
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

0

1.0

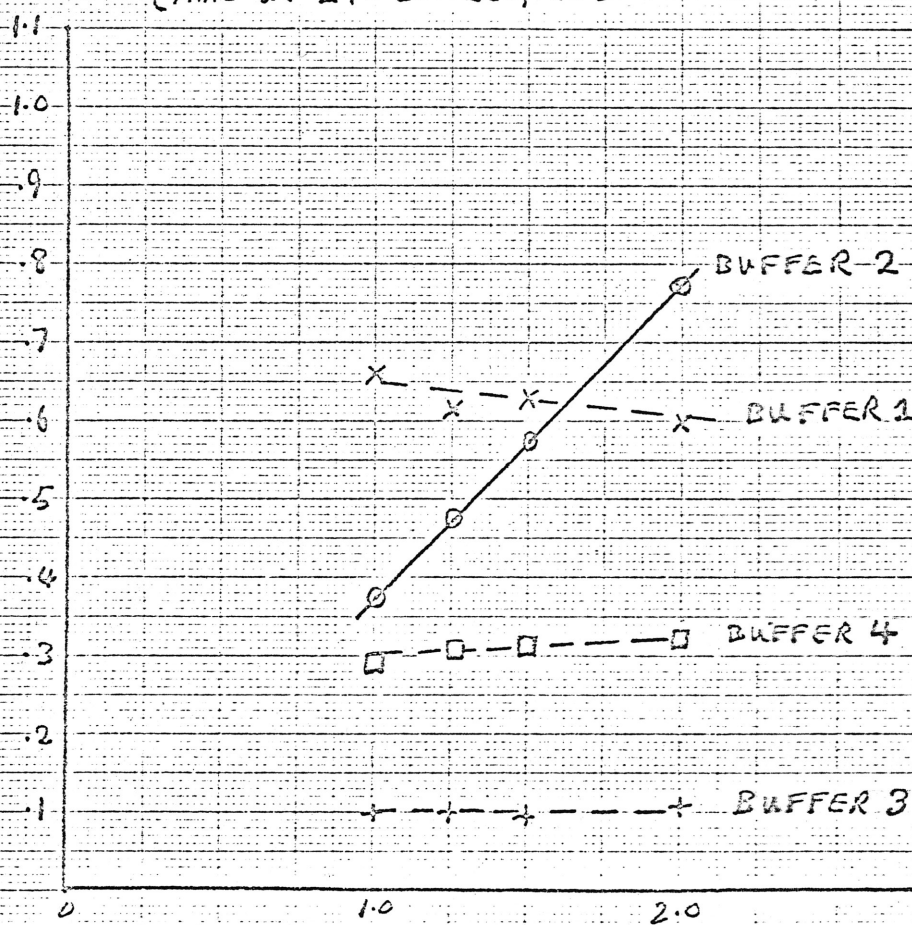
2.0

PROPORTIONAL INCREASE IN
CONVEYOR 2



AVERAGE BUFFER STOCK

(MINS. AT 240 BOTTLES/MIN)

PROPORTIONAL INCREASE IN
CONVEYOR 2