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# A Comparative Analysis of Loading Rules for Assembly Line Balancing

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THE LUBIN SCHOOLS
OF BUSINESS

PACE
UNIVERSITY

# A COMPARATIVE ANALYSIS OF LOADING RULES FOR ASSEMBLY LINE BALANCING

BY

JOHN C. CARTER Ph.D. AND FRED N. SILVERMAN Ph.D.

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## INTRODUCTION

The purpose of this paper is to compare the effectiveness of two loading rules for balancing paced assembly lines. Task times are assumed to be stochastic with known means and variances. The experiment utilizes an efficient line balancing algorithm which incorporates a comprehensive cost function. The operating assumption used here is that the line is stopped whenever a work station is unable to complete its assigned tasks in the cycle time. This remedial action is often appropriate in the production of heavy, complex products for which end of line repair would require major disassembly. The Toyota production system, for example, allows workers to temporarily stop the assembly line through the use of a series of lights.

The assembly line balancing problem has received considerable attention in the literature since its formulation by Bryton (1954). The problem is to assign the smallest feasible work elements to work stations so that all precedence and time constraints are satisfied and an objective function is optimized. This has been accomplished by a variety of methods including linear and dynamic programming as well as heuristic techniques. Because the computational complexity grows geometrically with the number of work elements, the heuristic techniques have been most popular for problems of real-world complexity.

A majority of the research has been concerned with improving the accuracy and efficiency of models for balancing assembly lines. Based on the assumption that task times are known, constant and independent of sequence, the primary objective has been the minimization of assembly man-hours utilized per unit. This is accomplished by minimizing the number of work stations, or equivalently, the total nonproductive time at all stations for a given cycle time. Little attention has been paid to explicitly considering costs other than those for man-hours utilized in balancing the line.

In practice, assembly lines are comprised of tasks whose completion times vary from unit to unit. This means that one or more work stations may not complete their assigned work within the cycle time. Studies of repetitive tasks have shown that completion times are well described by the normal distribution (Dudley 1963, Walker 1959). Like the other work on stochastic line balancing, this paper treats task times as independent, normally distributed random variables with known means and variances. It also assumes that (1) the assembly line is a single paced line with no paralleling, (2) precedence constraints are known and specified, (3) subject to precedence constraints, tasks can be completed in any order, (4) units produced are identical and (5) workers receive equal pay.

Line balancing methods which allow for uncompleted tasks have been of three major types. One approach commonly used in industry is to deterministically assign tasks to any station until the cumulative task time at that station is no more than a fixed percentage (often 90%) of the cycle time (Ingall 1965). A second approach is to assign tasks to any station until the probability of exceeding the cycle time is less than a fixed value (Brennecke 1968, Moodie and Young 1965, Ramsing and Downing 1970, Reeve and Thomas 1973). Although several of these papers mention the importance of balancing the labor and incompletion costs, none shows how to do so.

A third approach takes labor and incompletion costs into account in the process of designing an assembly line. For lines in which repairs are made off-line, Kottas and Lau (1973) developed a balancing heuristic which selects tasks from an updated "marginal desirability list" containing tasks for which expected labor cost equals or exceeds expected incompletion cost. Being an incremental approach, the procedure builds each station in turn without regard to the potential system's benefit of assigning a currently desirable task to a different station. In a second paper, the same authors (1976) presented a total cost model for evaluating any proposed design. The model is based on identifying all incompletion combinations, their probabilities and expected total costs. In their third paper, Kottas and Lau (1981) use a probabilistic procedure to generate many promising designs and select the best of these by applying the cost model in their second paper. This approach to assembly line balancing, when uncompleted tasks are prepared off-line, is similar to the one presented by Silverman and Carter.

In this paper the total costs of operating the assembly line are calculated for each candidate line design generated, so that a balance can be selected which directly minimizes these costs. This is accomplished by developing a stochastic cost function which represents the total cost of producing one unit and includes both the standard operating costs as utilized in the deterministic case and costs associated with not completing all assigned tasks at a station. A heuristic algorithm then assigns tasks to stations so as to approximately minimize these total costs.

## EVALUATING THE COST FUNCTION: THE LINE BALANCING ALGORITHM

This section of the paper describes an algorithm for obtaining a balance using stochastic work times and approximately minimizing the total cost function. This line balancing algorithm generates a large number of line layouts, each of which is evaluated by computing the value of the expected total cost.

Work done by Mastor in evaluating heuristic line balancing algorithms led to the modification of the Arcus technique for use in this research (Arcus 1963, 1966, Mastor 1970, Silverman and Carter 1984). The modified algorithm works by first generating a list of tasks whose precedence constraints have been satisfied (the precedence list). From this list, a fit list is generated to include all tasks that will fit into the station such that the conditions of the loading rule are not violated. Tasks are selected at random from the fit list for assignment to the station. After each task is assigned, the precedence list and fit list are updated. When the fit list is empty, a new station is started. After all tasks have been assigned, the total cost of the balance is calculated using the stochastic cost function. The procedure is repeated a predesignated number of times with various threshold levels used for calculation of the fit list. The lowest cost balance is retained as the "best."

## Research Question

The research question for this paper was whether the station loading rule had any effect on the ability of the line balancing algorithm to find an approximately lowest cost balance.

The first loading rule (the percent rule) disregards task time variance in determining tasks eligible to enter a station. A task is eligible if the station's cumulative mean (the sum of the means for assigned tasks) would be no more than some percentage of the cycle time. This means that if two tasks with the same means are being considered for a station, the choice will be made randomly, even if one has a much larger variance than the other. A line design produced by this rule could well have many stations which have a high probability of exceeding the cycle time, even if the station means are well balanced.

The second loading rule (the probability rule) utilizes both the task means and variances in determining which tasks are eligible to be included in the fit list. A task is eligible if the probability of the station completing all tasks, including the one under consideration, within the cycle time is greater than a specified value. Thus, high variance tasks would be less likely to be eligible than lower variance tasks with the same mean. Line designs with high probabilities of exceeding the cycle time are precluded. Therefore, more designs of a "higher quality" can be generated within a given number of trials. The consequence of evaluating variance in addition to mean times is to force a more uniform allocation of slack capacity. The probabilities of stations completing their assigned tasks are balanced rather than mean times being balanced. Such lines will be perceived by workers as being more equitable.

Each line generated has its cost evaluated. Given a finite number of lines generated (800 for the 70 task problem and 400 for the 45 task problem), many will be high-cost lines. By precluding these high cost lines, there will be more opportunities to evaluate other candidates and thus potentially find a better design.

The above reasoning suggests that the probability rule can be expected to perform better because it explicitly considers the task time variances in the generation of line design candidates. Furthermore, applying tighter constraint on the selection of tasks to be included in a work station should produce yet better results. In a given run, the algorithm has only a finite number of lines it can generate. If those lines are of the highest quality, then there is more chance of identifying a design which is closer to the true optimum.

The cost of adding a work station is a major cost in assembly line design. For a given number of stations, the best design is the one which minimizes the cost of exceeding the cycle time or probability.

Lowering the percent and probability thresholds increases the constraint on the allocation process. It becomes harder and harder to find tasks to fit into a station as this constraint increases. At some point it becomes necessary to add a new station to accommodate all tasks. At that point there is a large increase in total cost. Prior to reaching that point, however, the balance of tasks across stations is more and more uniform, thus tending to reduce the cost of exceeding the cycle time. So the tighter the constraint, the lower the expected total costs.

### Hypotheses

The above analysis gives rise to the following three hypotheses to be tested:

1. The probability rule will find a lower cost balance than the percent rule.

2. The tighter the constraint imposed by the percent threshold for a given number of stations, the lower the cost of the best design found.

3. The tighter the constraint imposed by the probability threshold for a given number of stations, the lower the cost of the best design found.

## EXPERIMENTAL DESIGN

The purpose of the experiment was to identify the lowest cost balance for a given set of parameters as efficiently as possible. A binary search procedure was utilized for the maximum-probability rule and for the percent-of-cycle-time rule to determine the number of iterations required to find the lowest cost balance. The minimum costs and number of iterations were compared for each rule.

In this experiment, the 70 task example of Tonge and the 45 task of Kilbridge and Wester were used. The 70 task problem was derived from an actual assembly line and reflects a large degree of flexibility in assigning tasks to stations. The lowest cost balance was found for each of 8 cases in the Tonge problem and for each of 12 cases in the Kilbridge and Wester problem in order to compare the procedures. On the average, 12 runs were required to create the minimum cost for each case.

The following parameters were used:

Rules

Maximum-probability rule.
Percent-of-cycle-time rule.

Overtime Repair Rates

1.5 times the standard labor rate - low overtime rate
2.0 times the standard labor rate - medium overtime rate

Coefficient of Variation

10% of Task Mean - low variance
25% of Task Mean - medium variance
50% of Task Mean - high variance

For each set of parameters, a binary search was utilized to determine the best probability value (p-value) or best percent of cycle time. The stochastic line balancing algorithm was used to balance the line and calculate the costs for each balance.

### Binary Search Procedure

The objective of the binary search procedure is to find the probability value or percent of cycle time which yields the lowest cost balance. The first step is to use a sample of five trials across the full range of reasonable values. These range from a low p-value of .50 which effectively ignores task variance to a high p-value of .999 which results in 99.9% chance of completing all tasks in a work station. The value associated with the lowest cost balance is selected as a starting point.

In general, the incremental cost of adding a station to the optimum number of stations as found in step 1 is higher than the savings obtained through the reduction in the probability of exceeding the cycle time. Thus, step 2 attempts to increase the p-value or decrease the percent of cycle time without increasing the number of stations. This is accomplished by averaging the values (p-value or percent of cycle time) for the lowest cost balance and the balance requiring the next higher number of stations.

Step 3 is to continue the process by averaging the p-values or percents of cycle times in such a way as to not allow the number of stations to increase. For the probability rule, the highest p-value for the selected number of stations is averaged with the lowest p-value for the next higher number of stations. For the percent rule, the lowest percent for the selected number of stations is averaged with the highest percent for the next higher number of stations. The entire process concludes when no improvement in cost can be obtained.

The entire process is illustrated in Example 1.

## RESULTS AND CONCLUSIONS

The first hypothesis was that the probability rule will find a lower cost balance than the percent rule. The results for the 45 task problem are shown in Table 1 and those for the 70 task problem are in Table 2. In the 45 task case, the probability rule arrived at a lower cost balance in both low variation (CV=0.1) cases and for the double time overtime rate in the high variation case (CV=0.5). In the other three cases, however, the percent rule prevailed. Of the four cases investigated for the 70 task problem, three supported the hypothesis. In all cases, the difference in lowest costs is very small, so both loading rules found comparably good balances. In conclusion, the first hypothesis has not been confirmed.

The second and third hypotheses tested in this research were that the tighter the constraint imposed by the two loading rules for a given number of stations, the lower will be the cost of the best balance. The graphs in Appendix I show the results for the 45 task problem. Total costs declined monotonically as constraint increased (i.e., the allowed percent decreased) in 5 out of the 6 cases. This did not happen in the high variation (CV=0.5), low overtime rate (1.50 x normal) case. The hypothesis is supported by these results but certainly not confirmed.

The results for the 45 task problem using the probability rule do not favor the hypothesis. As constraint increases (probability increases), costs fall monotonically in only one of the 6 cases.

The results for the 70 task problem shown by the graphs in Appendix II are not supportive of the hypothesis. In the four cases for both loading rules, costs first fall and then rise as constraint increases.

### Implications

The disappointing results of the experiment suggest that either the hypotheses are untrue or the experiment itself was flawed. The authors believe that the logic underlying the hypotheses is sound. Therefore, the next step will be to carefully validate the simulation model; in particular, to ensure the randomness of the process of selecting tasks from the "fit list." Another possible cause of the inconsistency between hypotheses and results is an inadequate run size. Perhaps 400 and 800 runs, respectively, in the 45 task and 70 task problems is insufficient to allow the outcomes expected under the hypotheses.

## Table 1

## Cost Comparisons for the 45 Task Problem

| | | Loading Rule | Overtime Rate | |
|---|---|---|---|---|
| | | | 1.5 | 2.0 |
| Coef of Var | .10 | % | 623.05 | 623.73 |
| | | p | 622.97 | 623.63 |
| | .25 | % | 692.61 | 716.48 |
| | | p | 692.72 | 716.63 |
| | .50 | % | 875.66 | 936.41 |
| | | p | 861.41 | 933.34 |

## Table 2

## Cost Comparisons for the 70 Task Problem

| | | Loading Rule | Overtime Rate | |
|---|---|---|---|---|
| | | | 1.5 | 2.0 |
| Coef of Var | .10 | % | 4207.5 | 4260.0 |
| | | p | 4195.0 | 4245.0 |
| | .25 | % | 5225.0 | 5600.0 |
| | | p | 5230.0 | 5550.0 |

# EXAMPLE 1

## MAXIMUM PROBABILITY THRESHOLD
## ILLUSTRATION OF
## BINARY SEARCH PROCEDURE

LOADING RULE: A TASK ENTERS THE FIT LIST IF ITS INCLUSION INTO THE WORK STATION WILL NOT CAUSE THE PROBABILITY OF EXCEEDING THE CYCLE TIME TO EXCEED A PREDETERMINED THRESHOLD.

Ie. $\mu_{STATION} = \Sigma t_i$ $\qquad \sigma_{STATION} = \sqrt{\Sigma \sigma^2_{tasks}}$

$THRESHOLD = 1 - P$

$\mu_{STATION} + z_p \sigma_{STATION} \leq C$

OBJECTIVE:
NEED THE HIGHEST P-VALUE WHICH WILL NOT INCREASE THE NUMBER OF STATIONS

STEP 1. FIND OPTIMAL BALANCES FOR WHICH IMPLY Z VALUES OF PRODUCES AND COSTS

| | | ① | ② | ③ | ④ | ⑤ |
|---|---|---|---|---|---|---|
| FIND OPTIMAL BALANCES FOR | P = | 0.5, | .625, | .75 | .875 | .999 |
| WHICH IMPLY Z VALUES OF | | 0 | .32 | .68 | 1.15 | 3.08 |
| PRODUCES | n: | 9 | 9 | 10 | 11 | 17 |
| AND COSTS | \$: | 985. | 942. | 937. | 953 | 1356. |
| | | | | * | ** | |

STEP 2. IDENTIFY P-VALUE FOR LOWEST COST BALANCE - AND THE # OF STATIONS. (*) FIND THE AVERAGE P-VALUE FOR THIS BALANCE AND THE BALANCE REQUIRING THE NEXT HIGHER # OF STATIONS (**)

⑥
$\overline{P\text{-VALUE}} = .8125$
$\Rightarrow z = .89$
n 11
\$ 958.

STEP 3 CONTINUE THIS PROCESS. AVERAGE THE HIGHEST P-VALUE FOR THE SELECTED # STATIONS (10) AND THE LOWEST P-VALUE FOR NEXT HIGHER # OF STATIONS (11)

③
.75 (.68)
10, 937

⑥
.8125 (.89)
11, 958

⑦
.7812 (.78)
10, 935

⑧
.7969 (.83)
11, 960

⑨
.7891 (.80)
10, 934

⑩
.7930 (.82)
11, 963

⑪
.7911 (.81)
10, 934

LOWEST COST BALANCE FOUND ⇒ 10, 934

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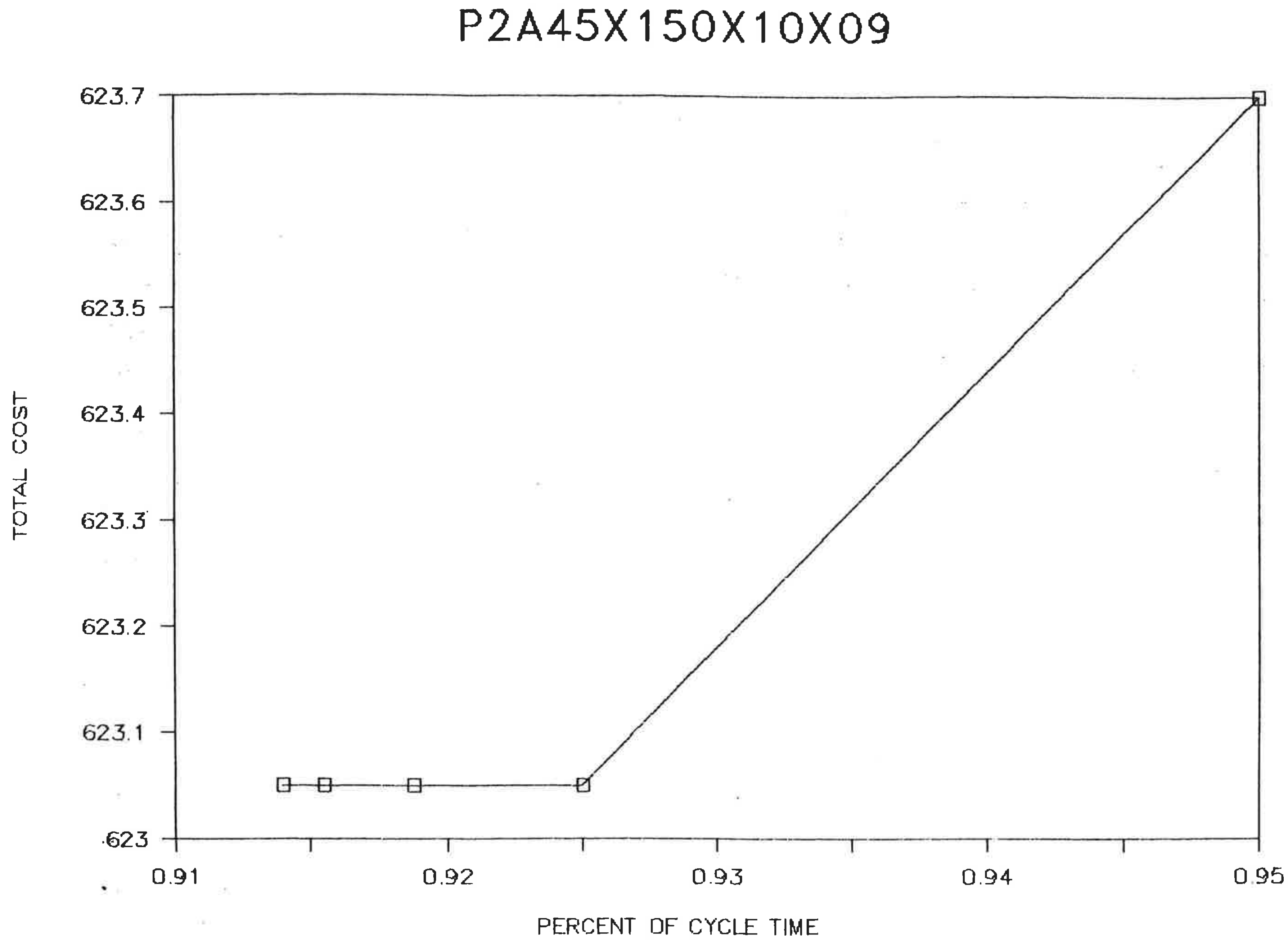
# APPENDIX I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623.7
623.6
623.5
623.4
623.3
623.2
623.1
623
0.91
0.92
0.93
0.94
0.95
PERCENT OF CYCLE TIME

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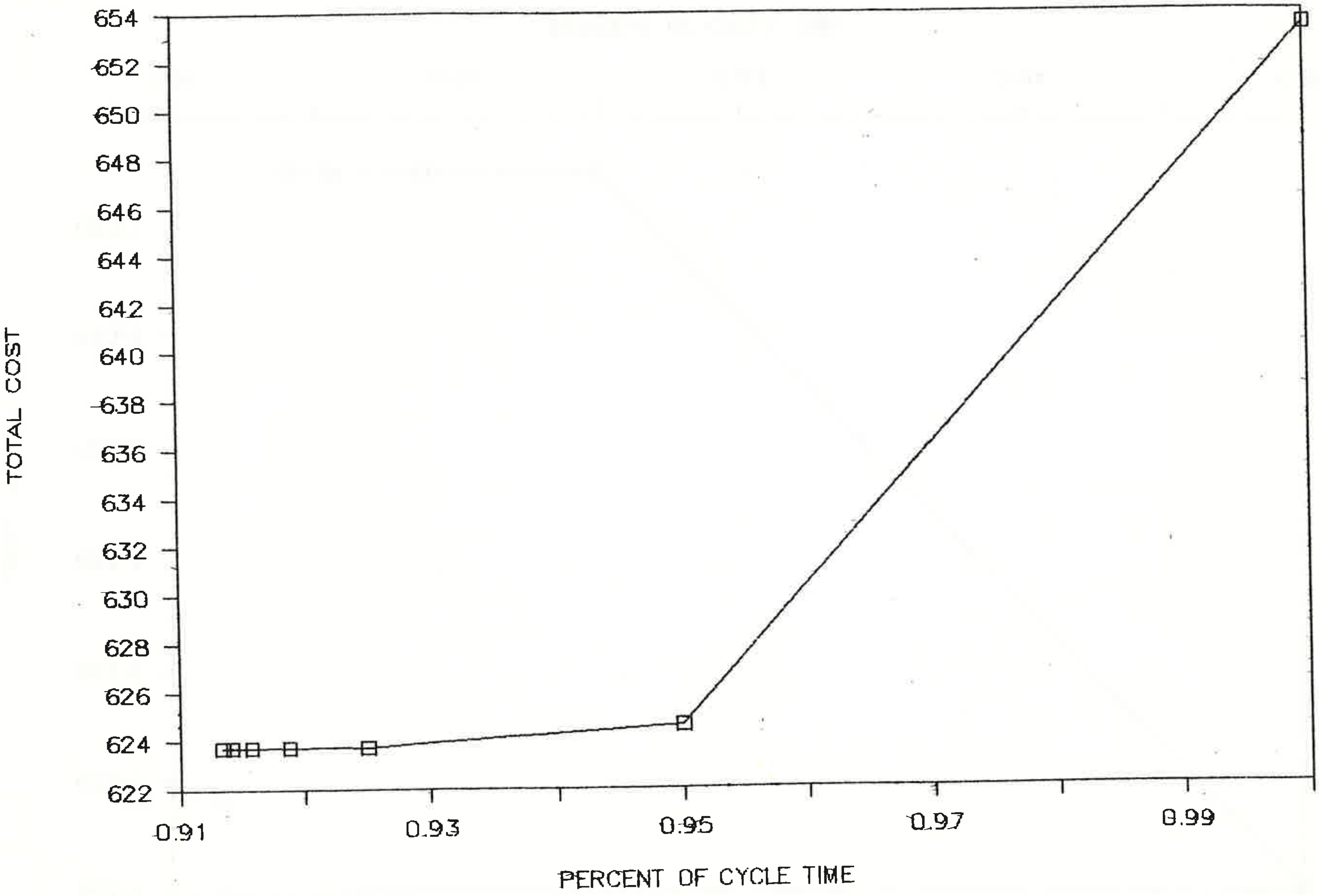

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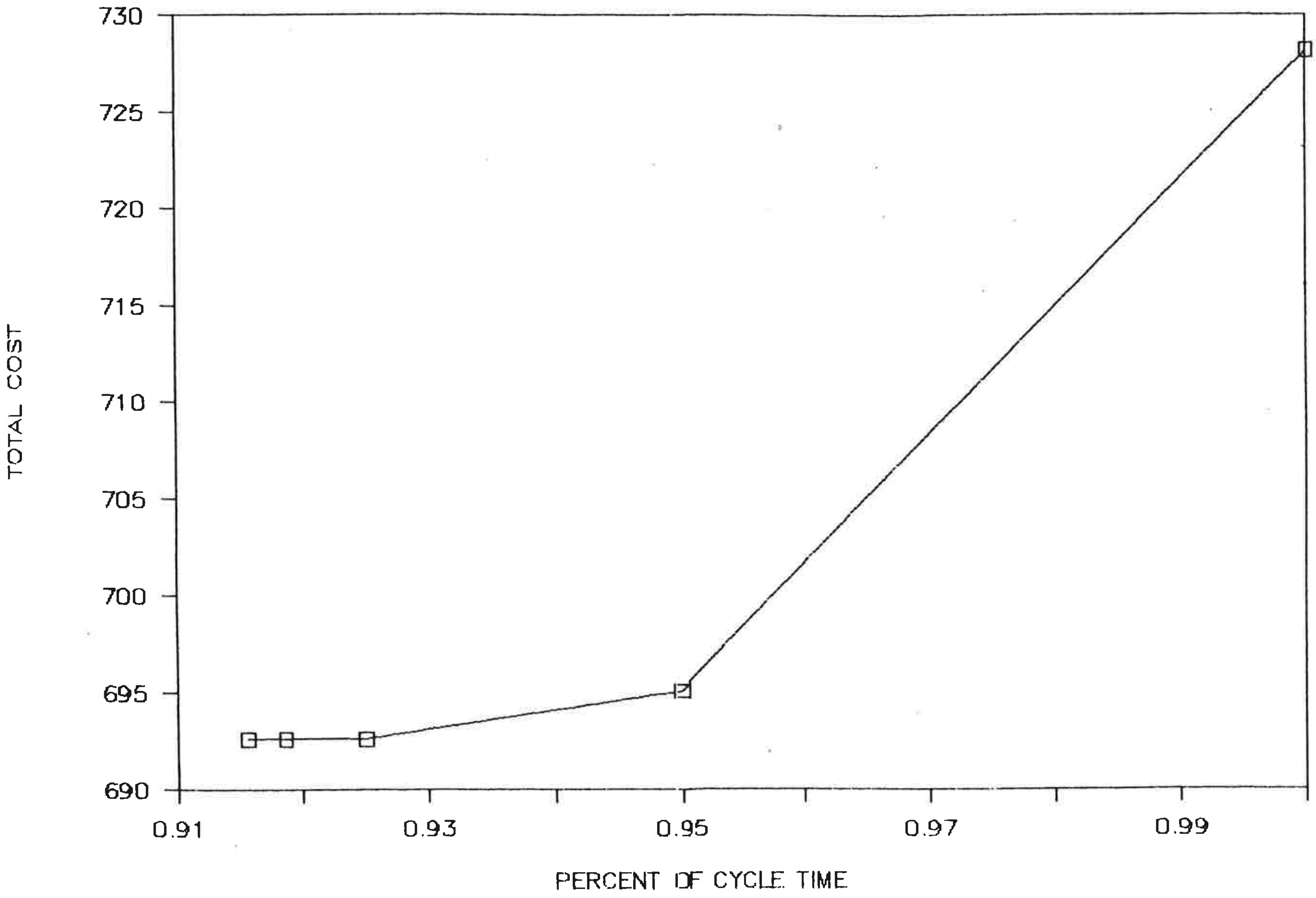

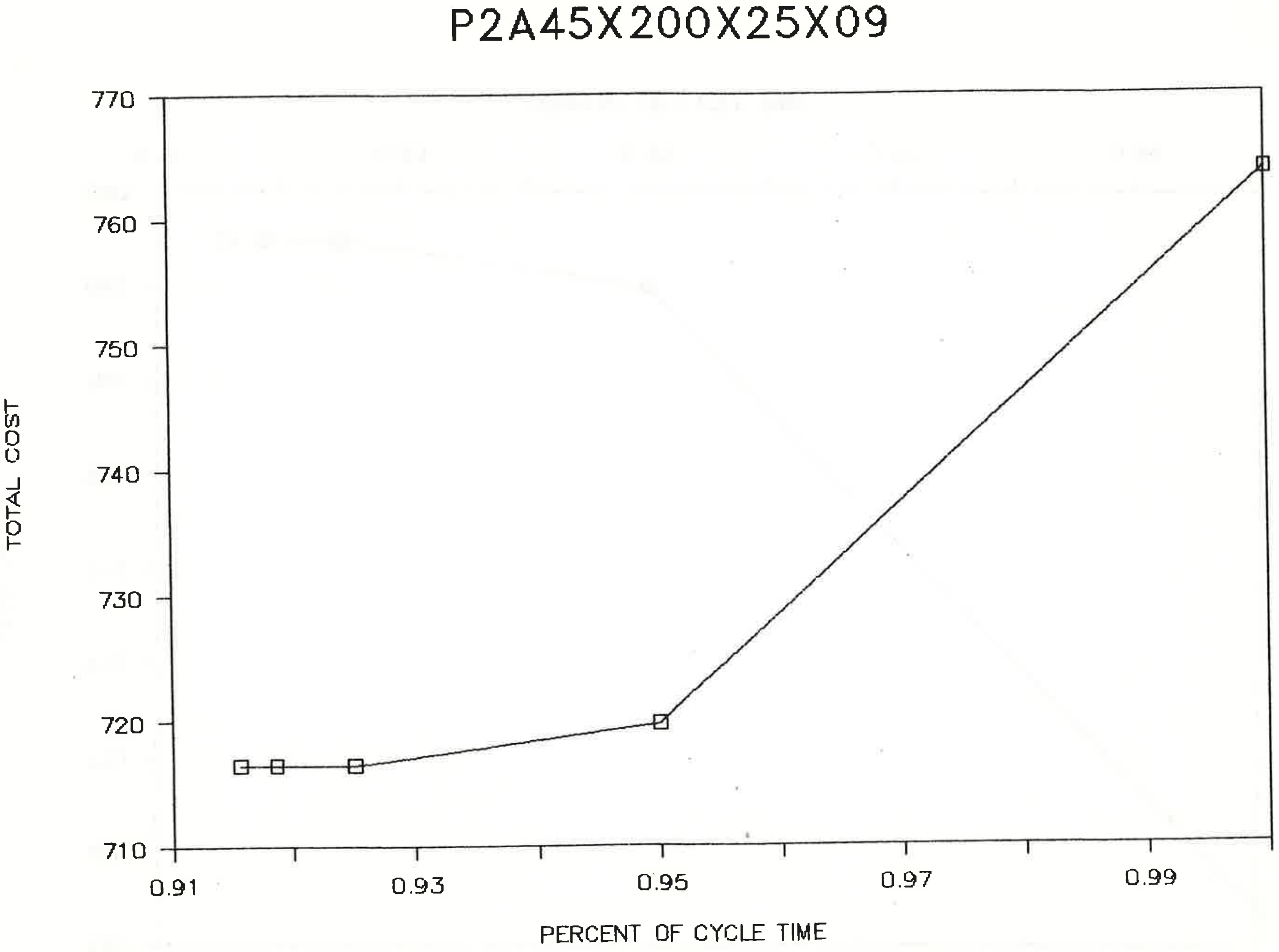
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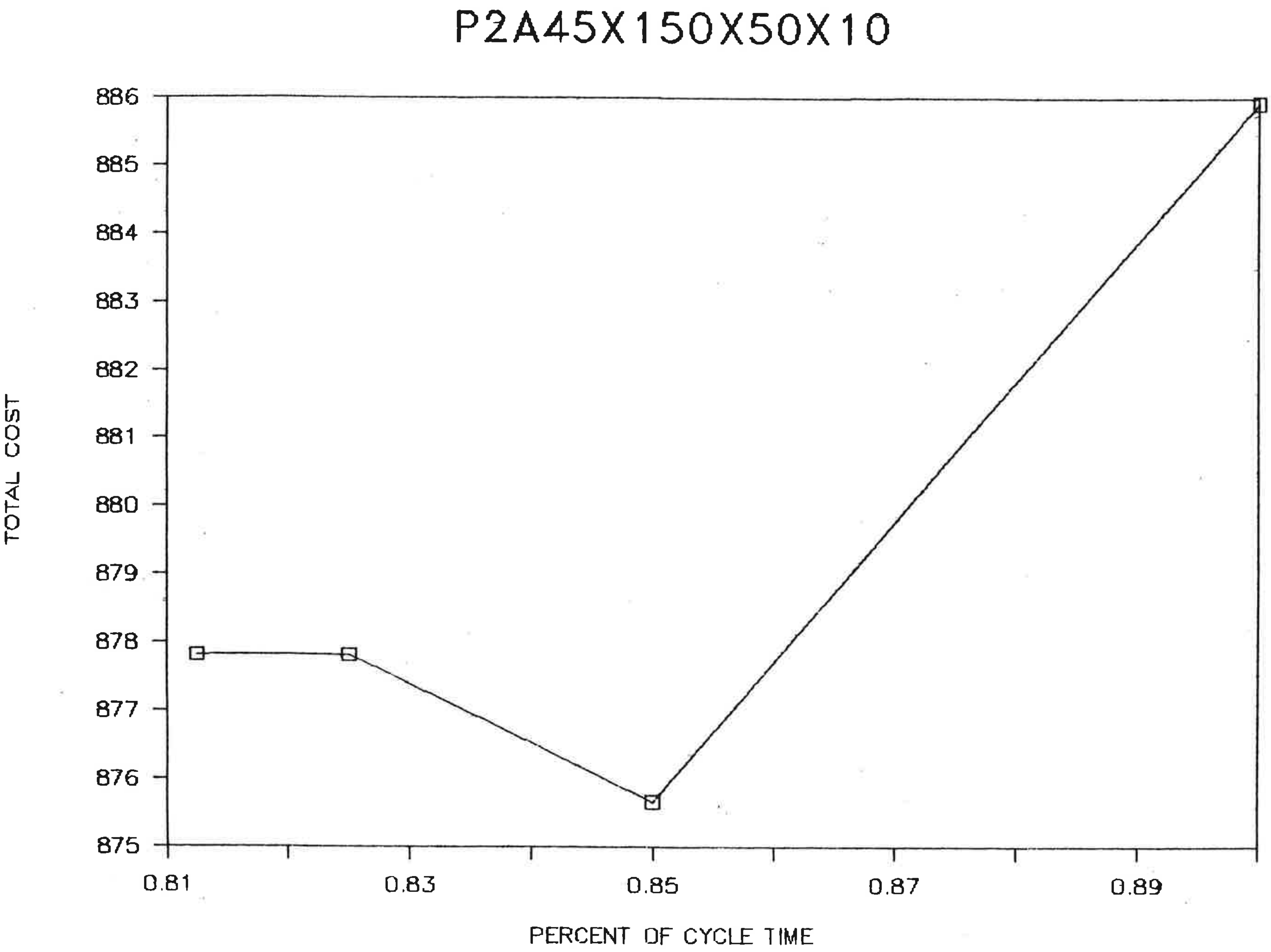
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885
884
883
882
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880
879
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877
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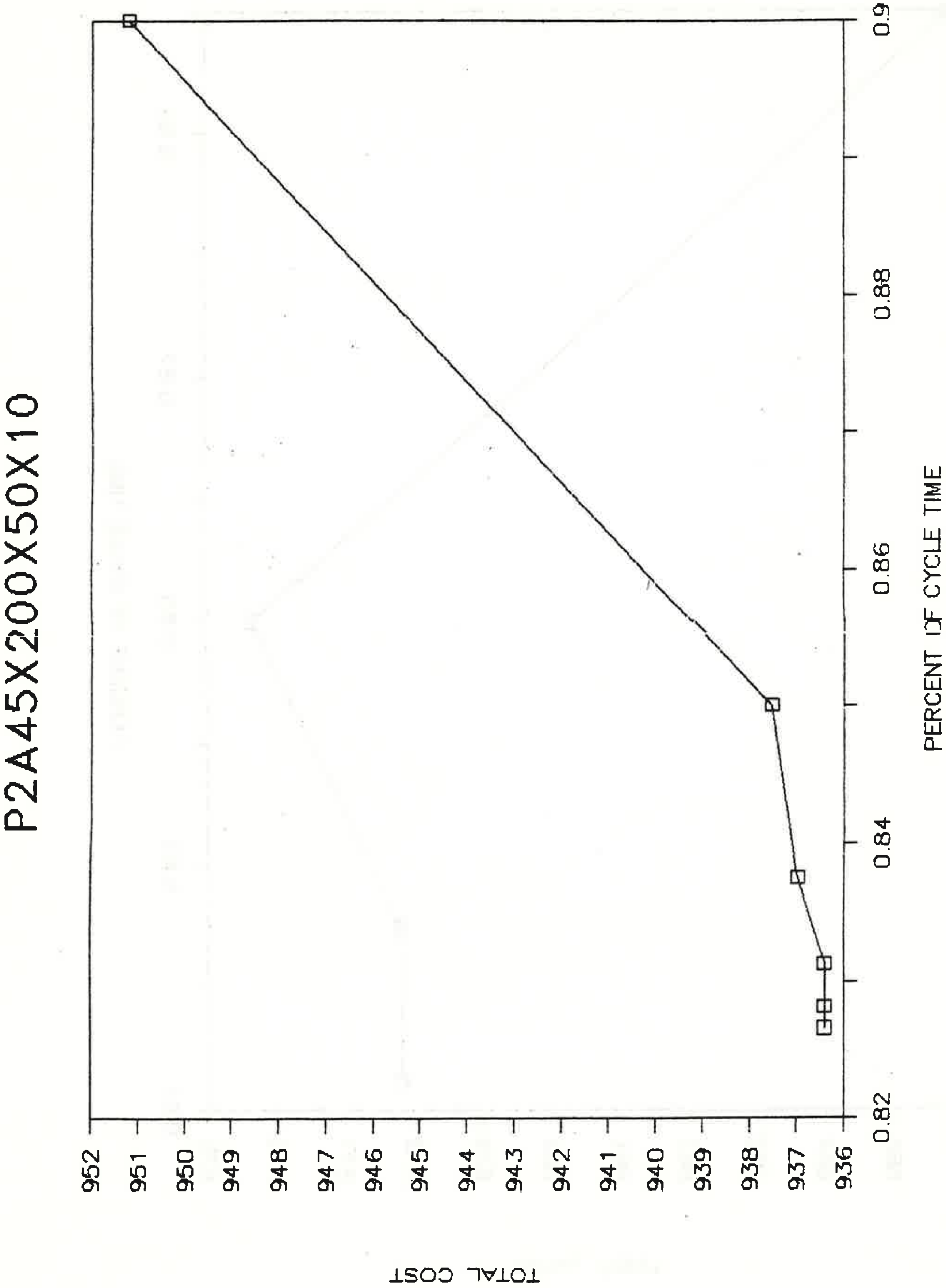
0.85
0.87
0.89
PERCENT OF CYCLE TIME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951
950
949
948
947
946
945
944
943
942
941
940
939
938
937
936
PERCENT OF CYCLE TIME
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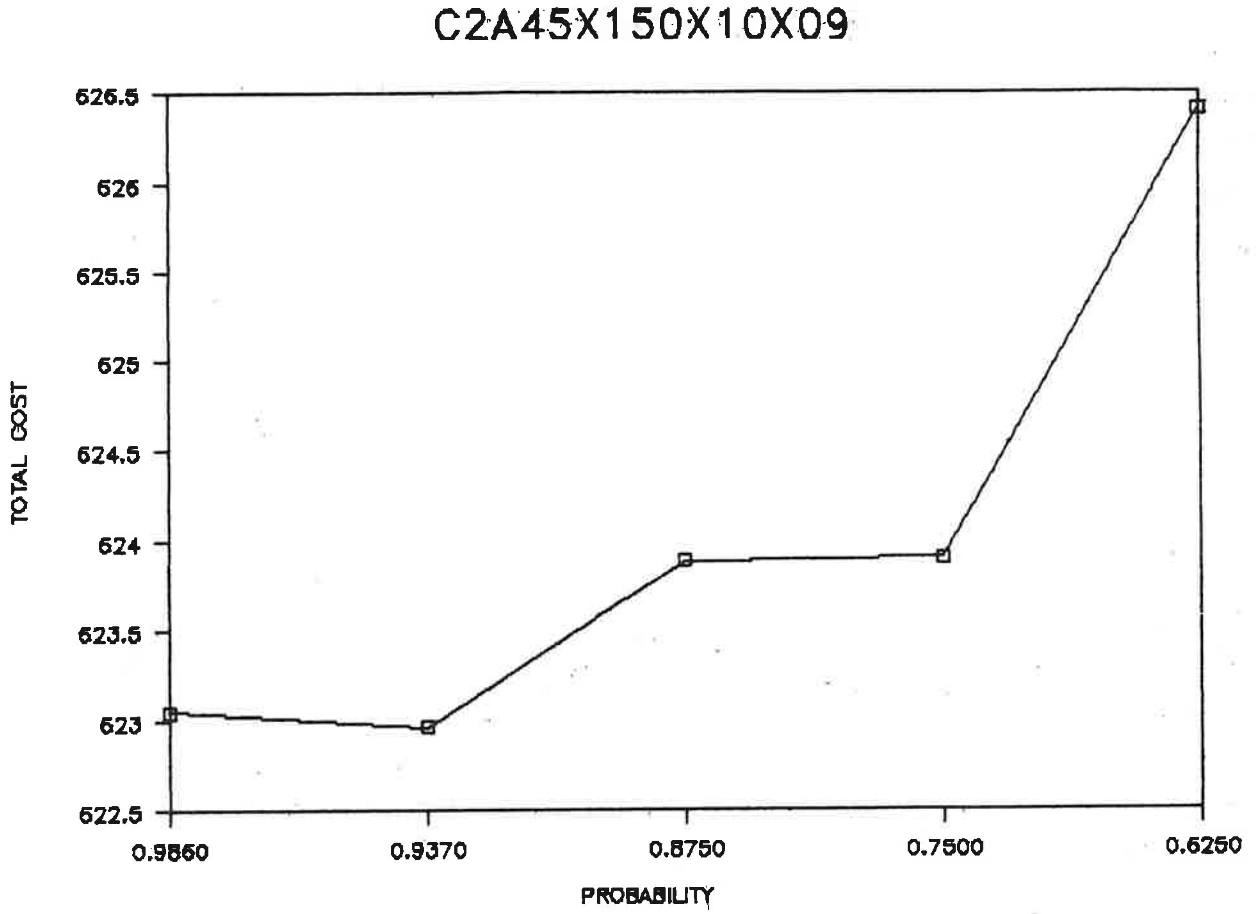
0.84
0.86
0.88
0.9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626
625.5
625
624.5
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623.5
623
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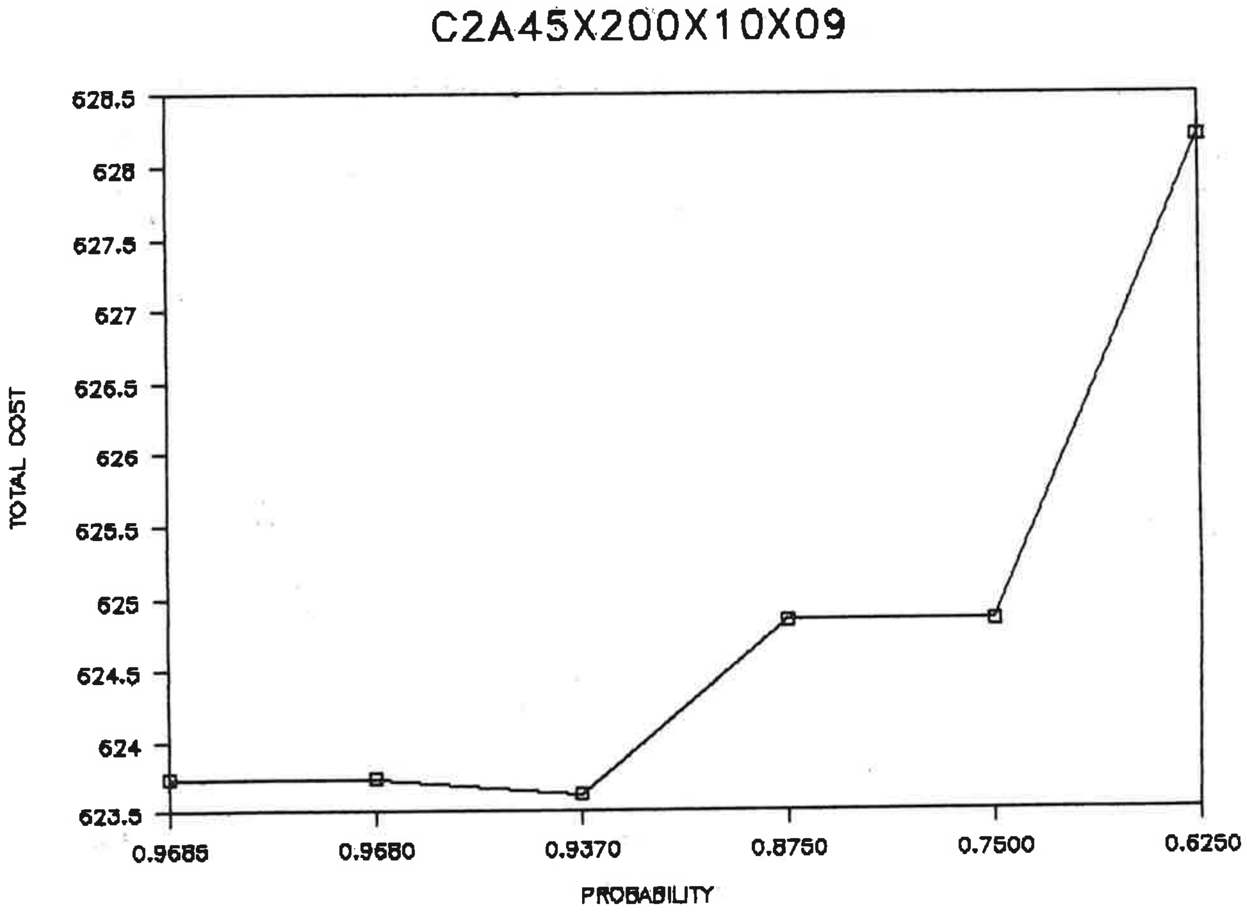
0.8750
0.7500
0.6250
PROBABILITY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628
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626.5
626
625.5
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623.5
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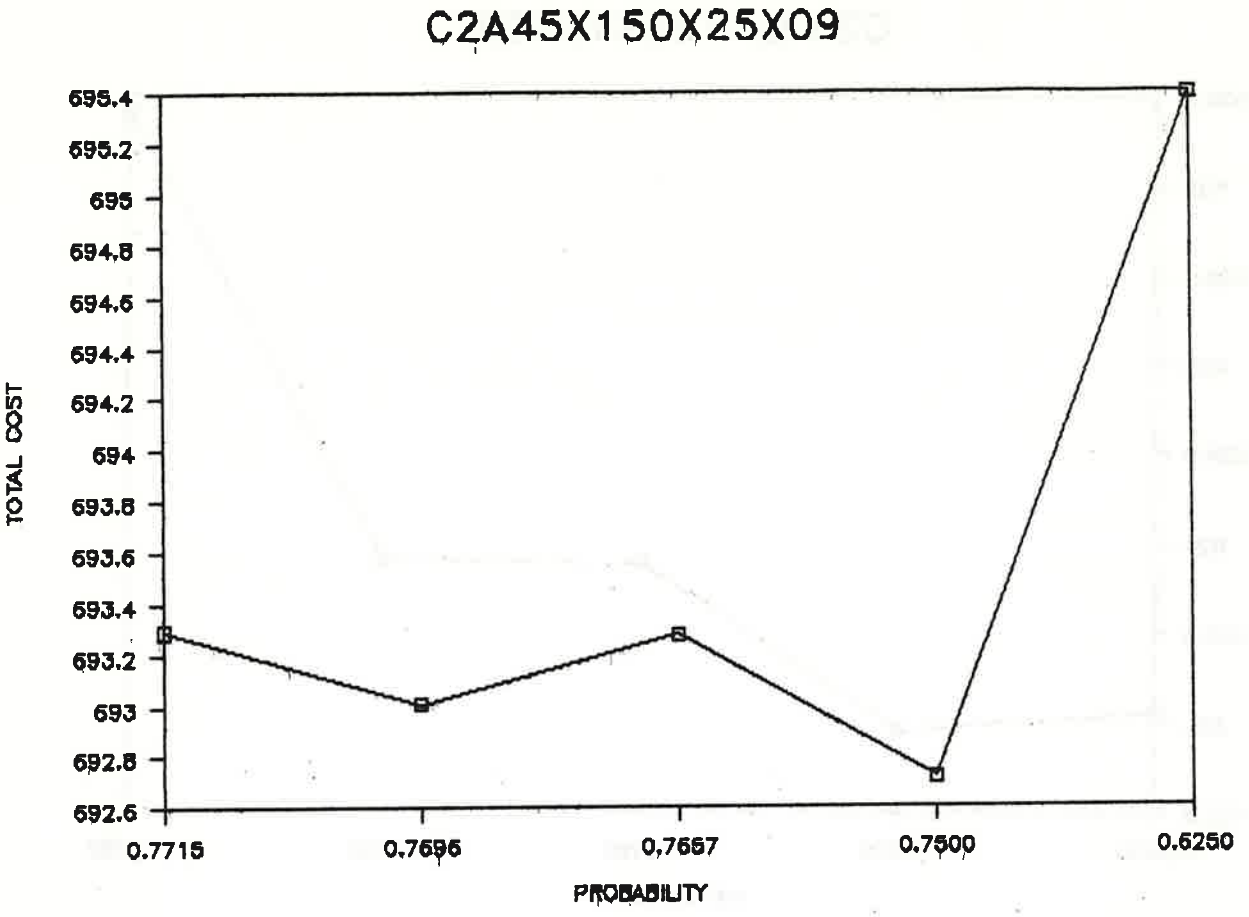
0.6250
PROBABILITY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695.2
695
694.8
694.6
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694.2
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693.6
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692.8
692.6
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0.7657
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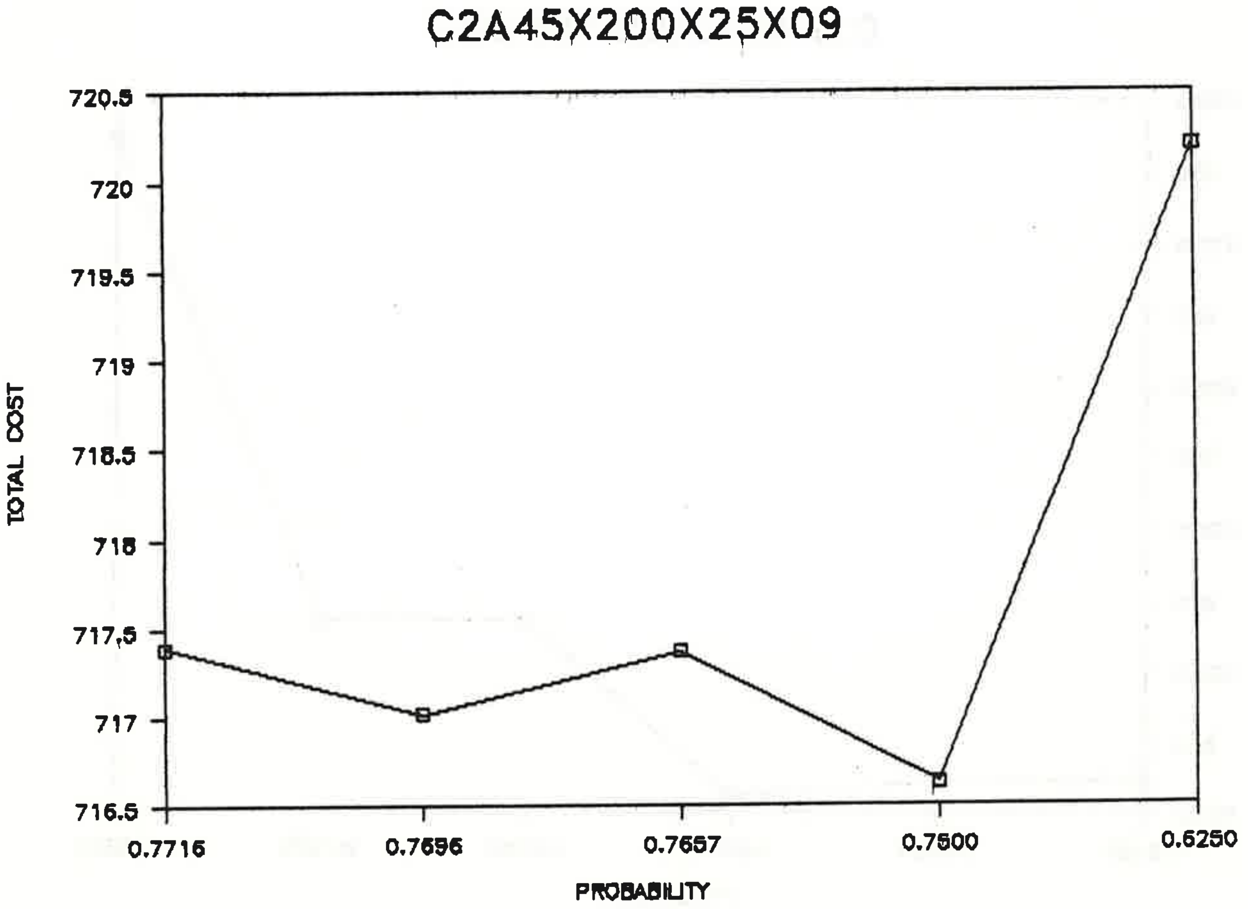
0.6250
PROBABILITY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720
719.5
719
718.5
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717.5
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0.7696
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PROBABILITY

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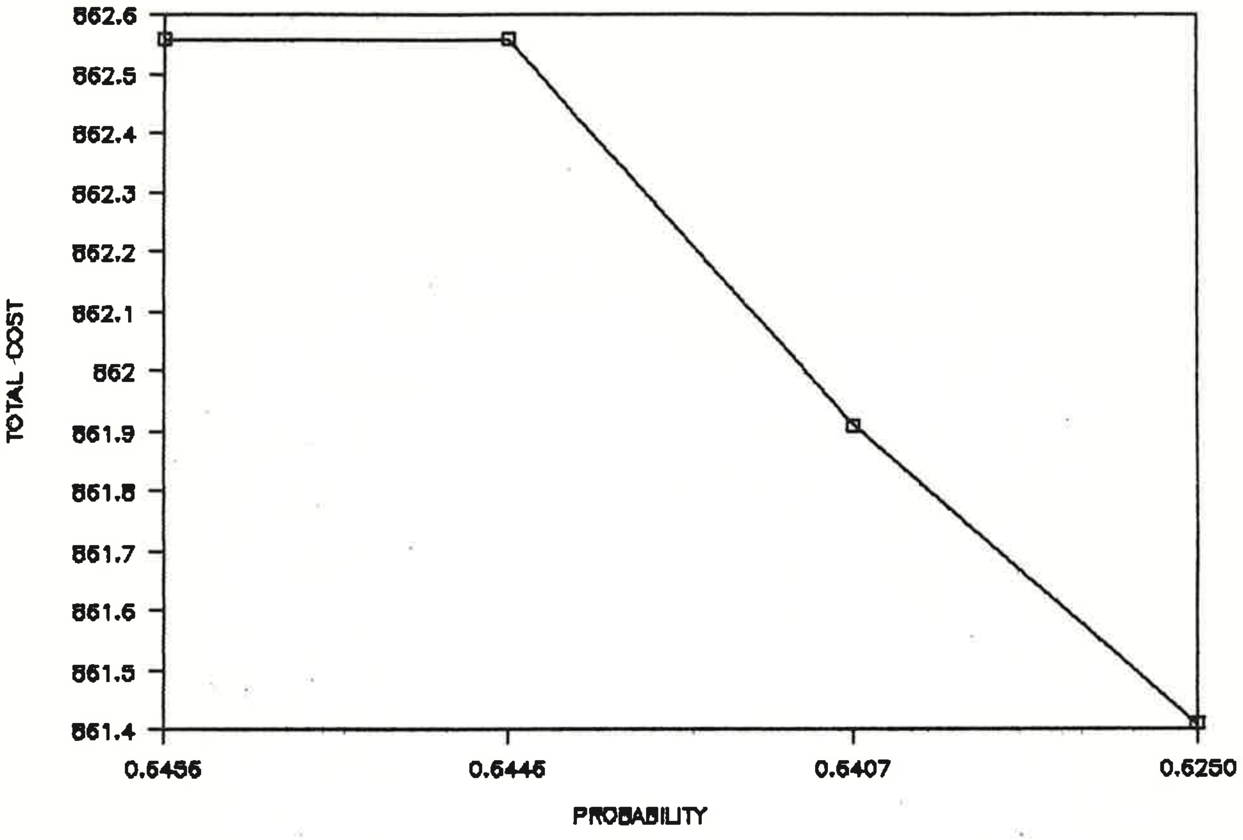

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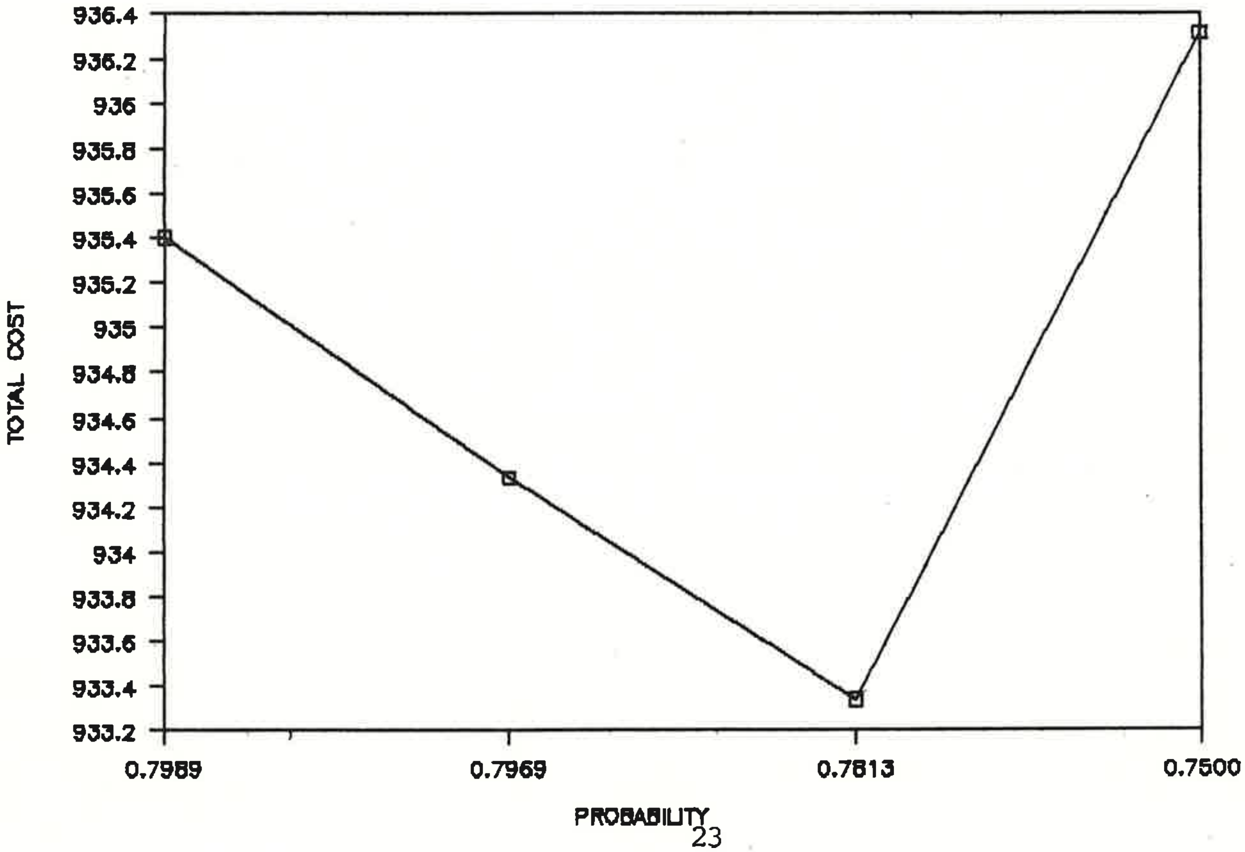

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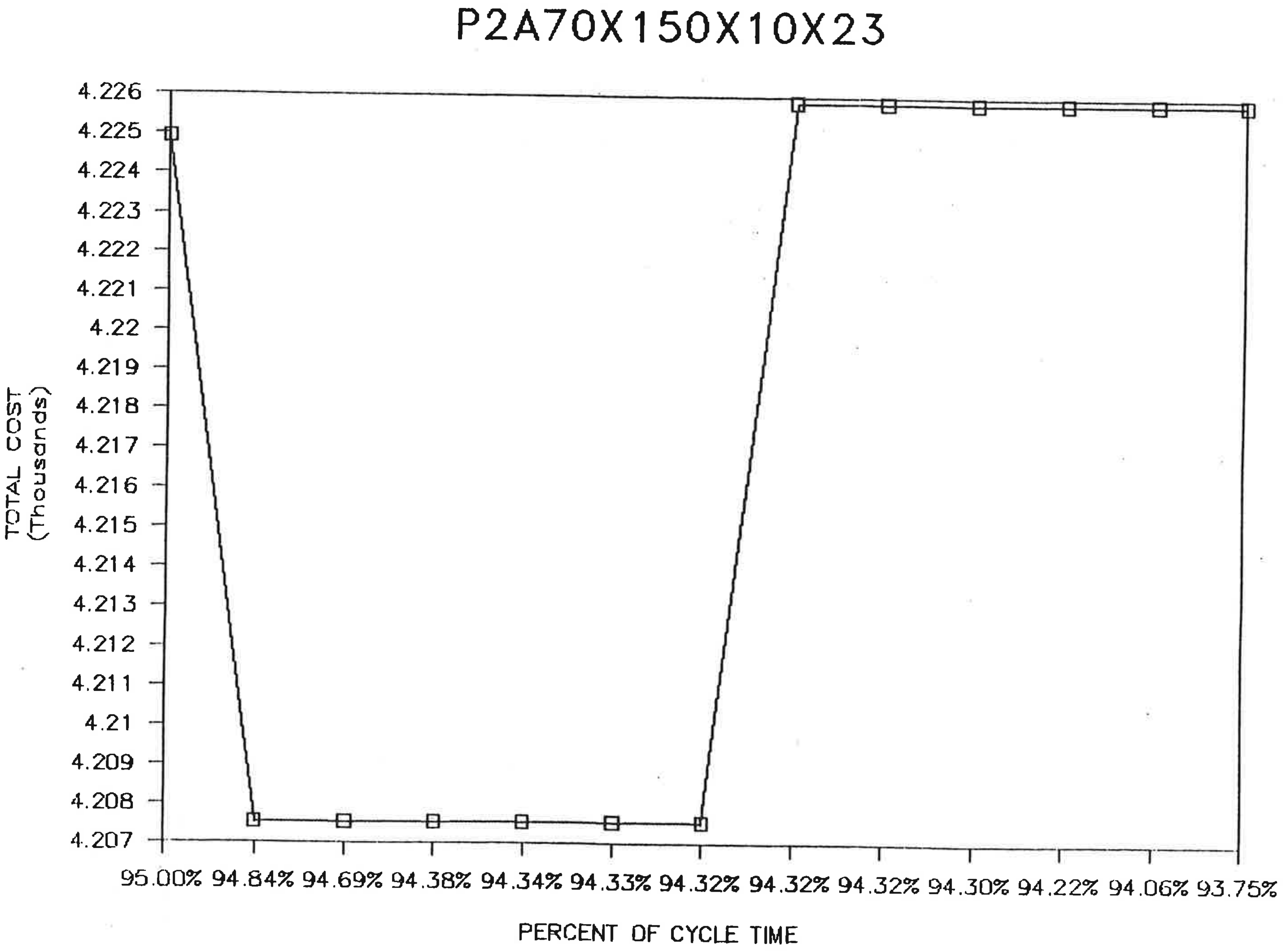
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TOTAL COST
(Thousands)
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4.225
4.224
4.223
4.222
4.221
4.22
4.219
4.218
4.217
4.216
4.215
4.214
4.213
4.212
4.211
4.21
4.209
4.208
4.207
95.00%
94.84%
94.69%
94.38%
94.34%
94.33%
94.32%
94.32%
94.32%
94.30%
94.22%
94.06%
93.75%
PERCENT OF CYCLE TIME

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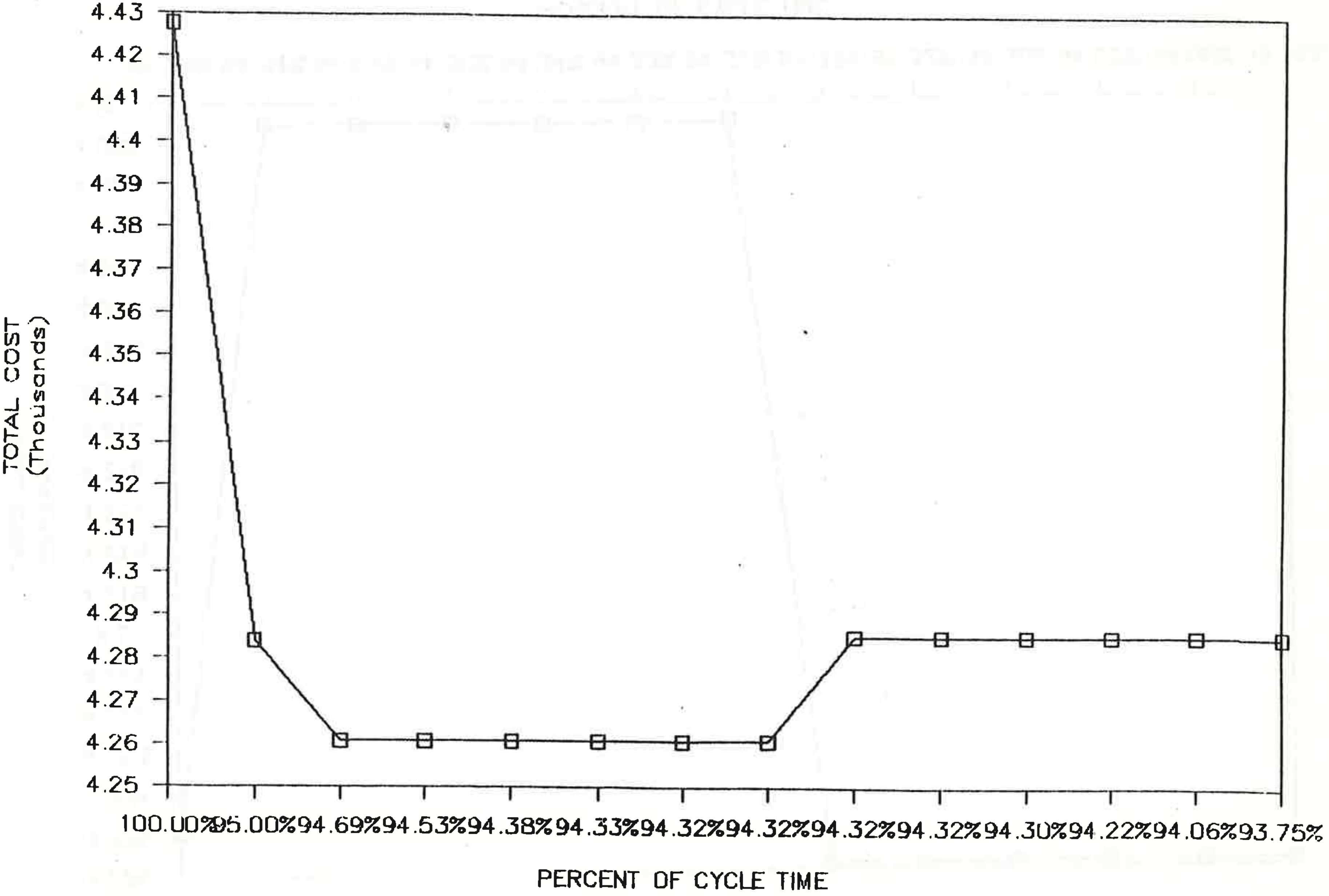

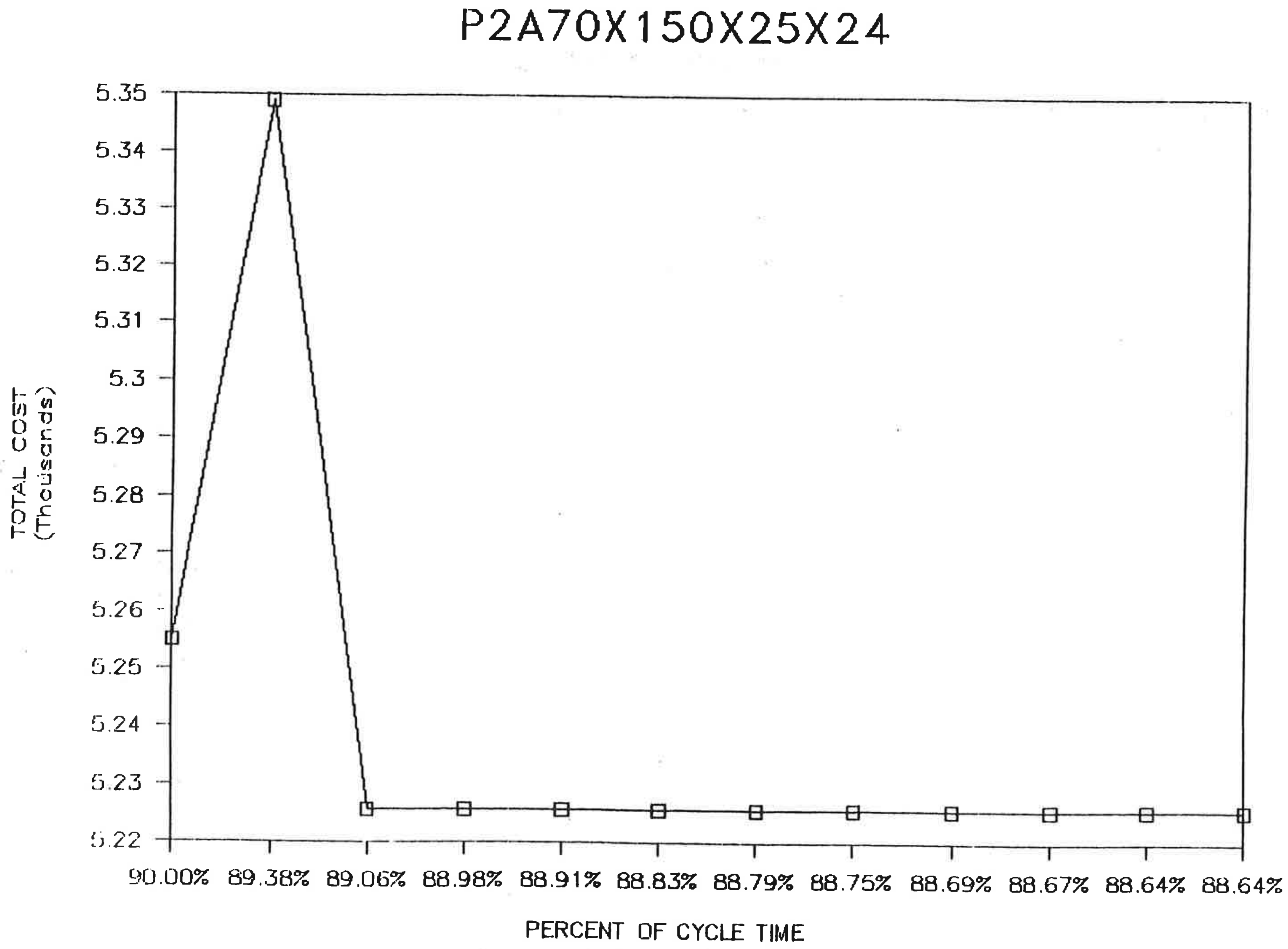
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(Thousands)
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5.33
5.32
5.31
5.3
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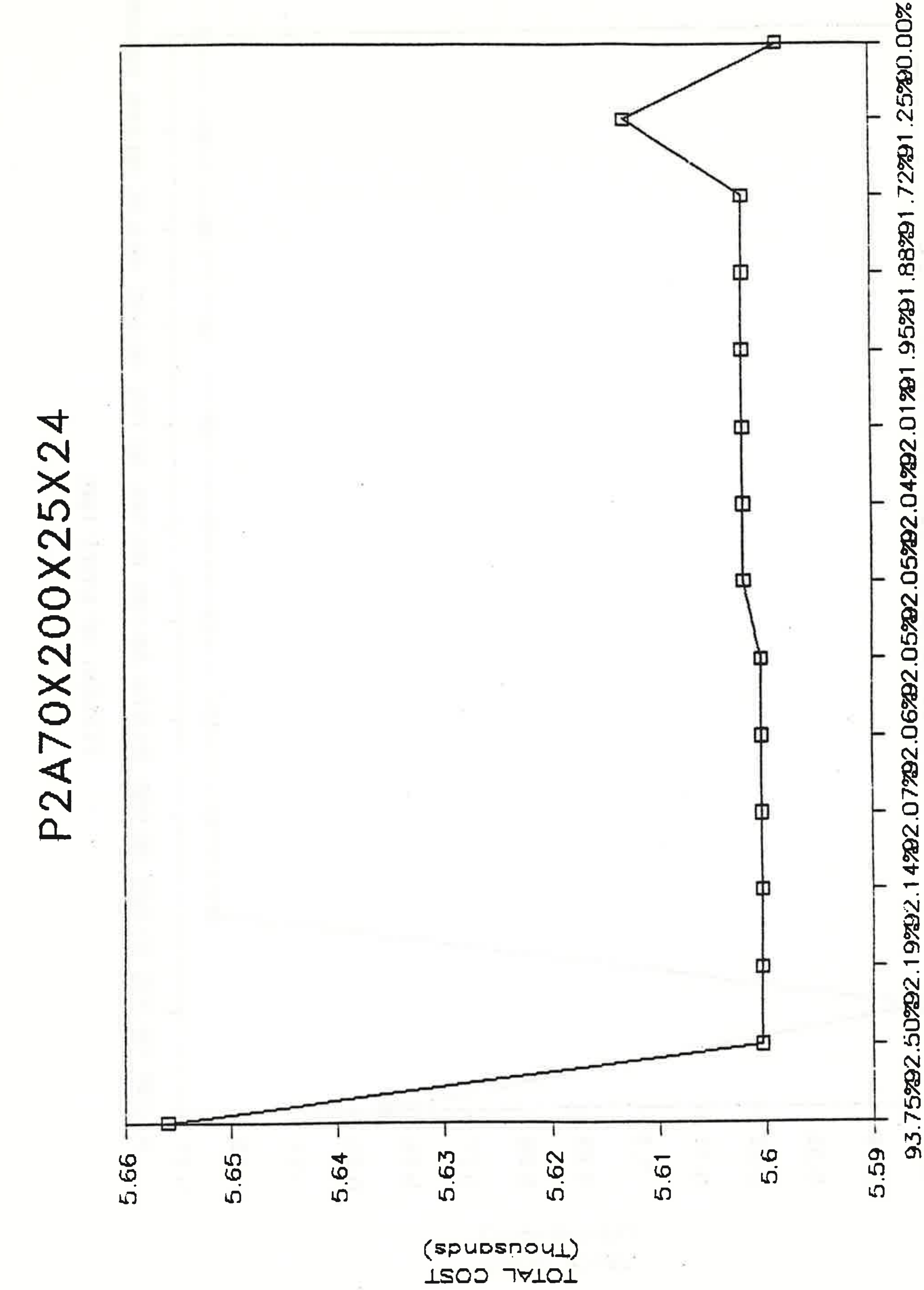
5.28
5.27
5.26
5.25
5.24
5.23
5.22
90.00%
89.38%
89.06%
88.98%
88.91%
88.83%
88.79%
88.75%
88.69%
88.67%
88.64%
88.64%
PERCENT OF CYCLE TIME

P2A70X200X25X24
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5.63
5.62
5.61
5.6
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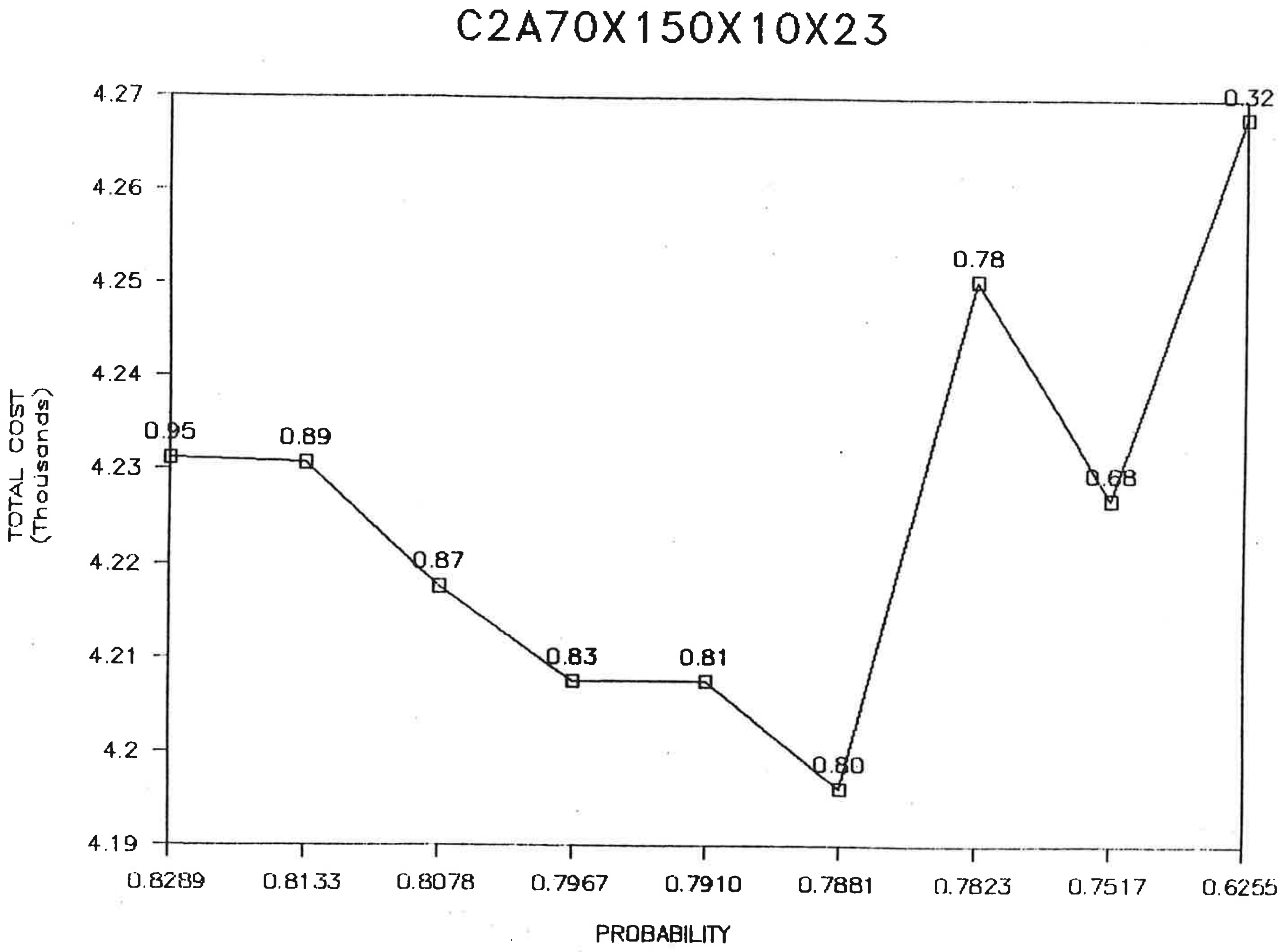
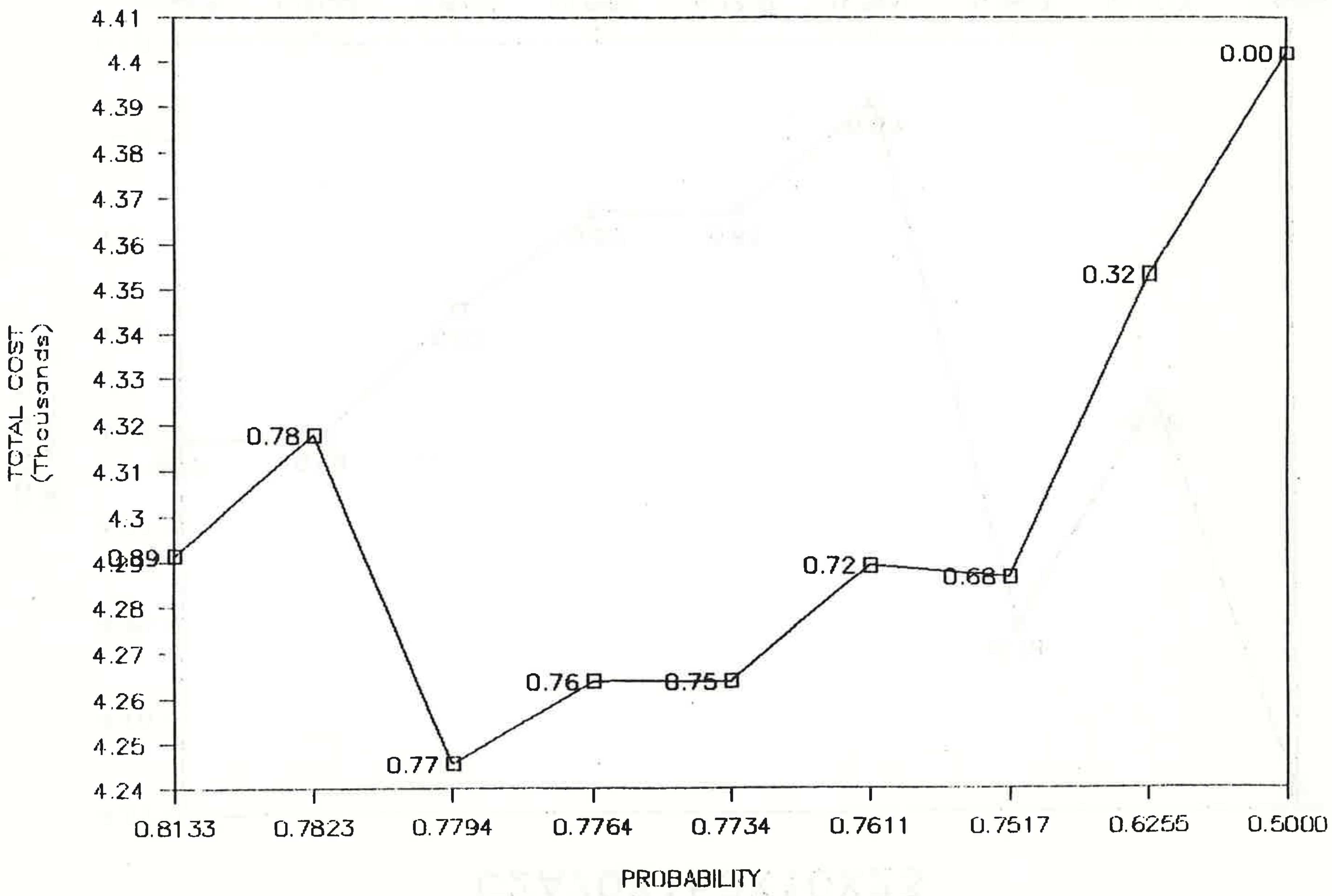
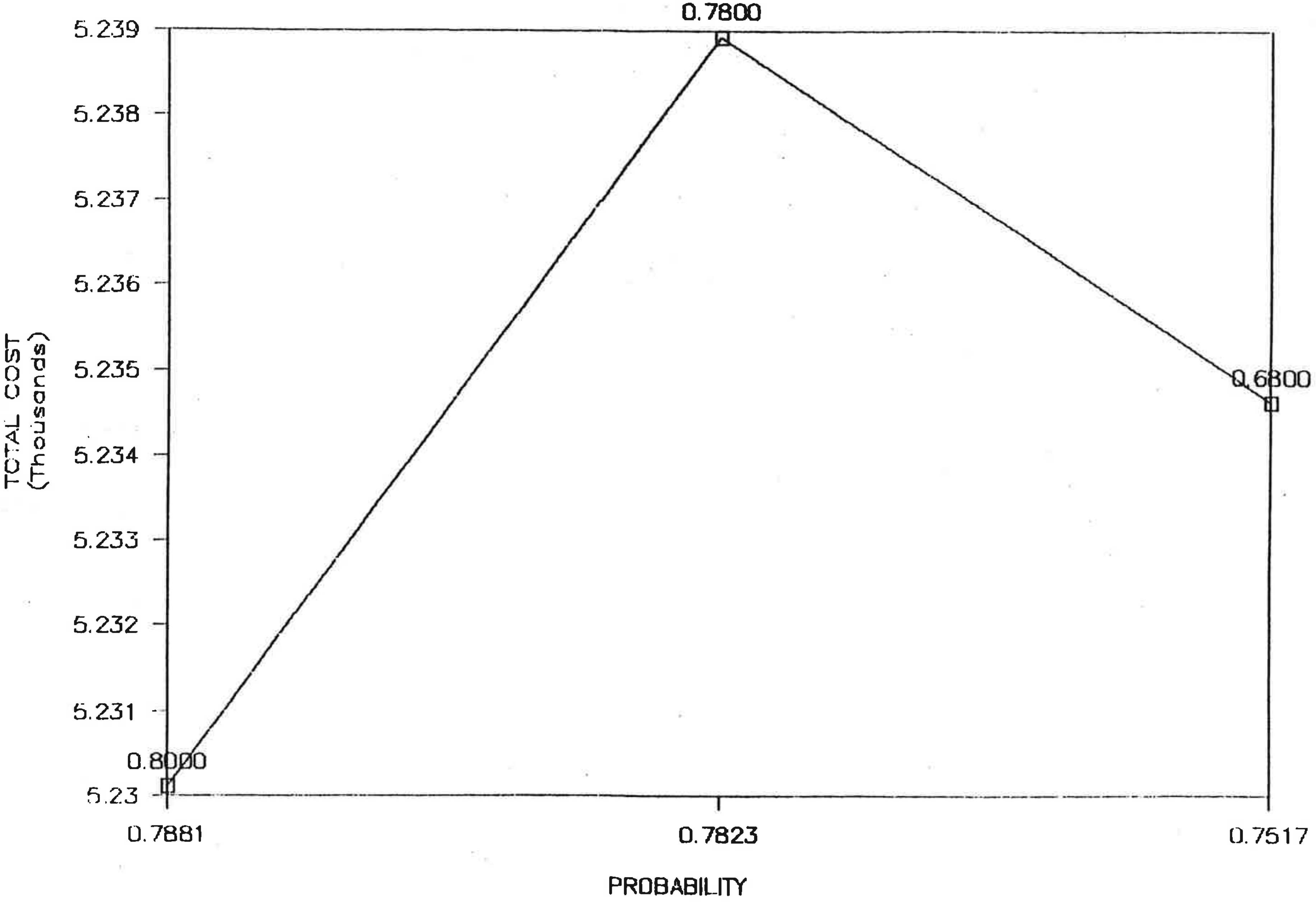
92.50%
92.19%
92.14%
92.07%
92.06%
92.05%
92.05%
92.04%
92.01%
91.95%
91.88%
91.72%
91.25%
90.00%
PERCENT OF CYCLE TIME

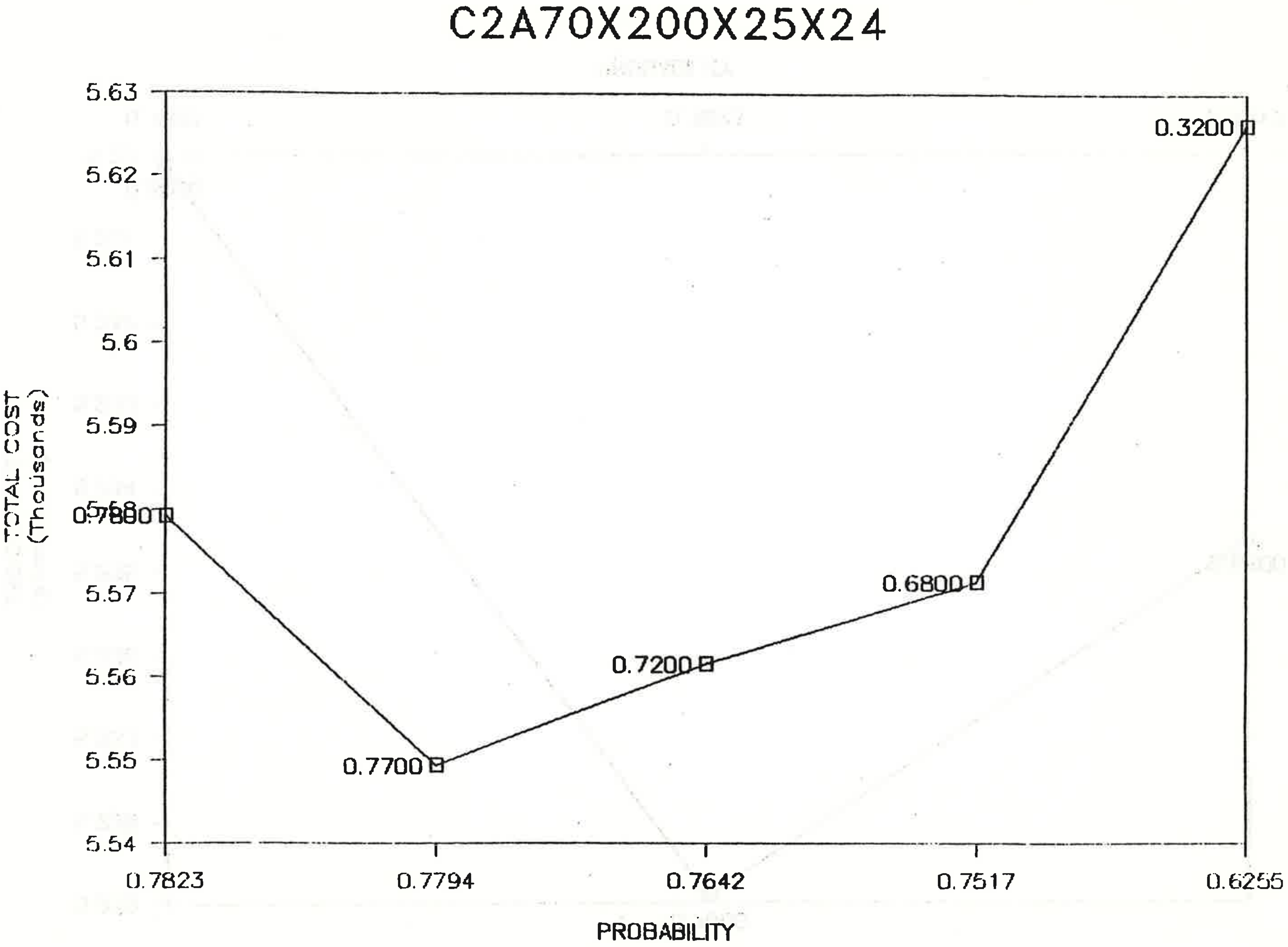

C2A70X150X10X23
TOTAL COST
(Thousands)
4.27
4.26
4.25
4.24
4.23
4.22
4.21
4.2
4.19
0.95
0.89
0.87
0.83
0.81
0.80
0.78
0.68
0.32
0.8289
0.8133
0.8078
0.7967
0.7910
0.7881
0.7823
0.7517
0.6255
PROBABILITY

# C2A70X200X10X23



C2A70X150X25X24




C2A70X200X25X24
TOTAL COST
(Thousands)
5.63
5.62
5.61
5.6
5.59
5.58
5.57
5.56
5.55
5.54
0.7800
0.7700
0.7200
0.6800
0.3200
0.7823
0.7794
0.7642
0.7517
0.6255
PROBABILITY

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