AN INVESTIGATION OF THE EFFECT OF
VARYING LOADS ON THE
TIME REQUIRED FOR CRANKING MOTIONS

by

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GRAPHS

I. INTRODUCTION

When at the turn of the century, Frederick W. Taylor introduced time study as one of the essentials to scientific management, he envisioned compilations of standard times for the fundamental elements necessary to perform work. These tables were to provide the measurements of the time required for any job in a particular trade or branch of a trade through analysis and identification of the elements of work involved.

At about the same time, Frank B. Gilbreth and Lillian M. Gilbreth were studying the motions used in performing work and found that only 17 "therbligs" or fundamental motions were involved in manual labor.

The integration of Taylor's time study and Gilbreth's motion study concepts raised the question of whether standard times could be determined for therbligs or combinations of therbligs which would apply throughout industry regardless of any particular trade, and thus provide a universal basis for measurements of the time required to perform work.

Many individuals have been working on this problem, using combinations of therbligs which were appropriate to the particular type of work in which they were interested and, in general, withholding the data and procedures on which their results were based. There appear to be two reasons for this secrecy; first, the proponent desired to retain the exclusive benefits of his work and, secondly, the results were so empirical, that the successful application required indoctrination in the particular method of derivation involved.

The first results for general application to be published in detail were given by Maynard, Stegemerten and Schwab (5) in 1948. The authors emphasized the "uncertainties and doubts which must accompany every search for new knowledge" and express "their expectation that there must be corrections, additions, and refinements before the task is finished."

The publication of this book gave impetus to much research work. One area of inadequate data, that of cranking motions, was selected by Horst (4) for further study. This study developed normal cranking times under average conditions and included recommendations for further investigation of the effect on those times of certain variables, one of which was various brake loads.

The present investigation was undertaken to determine what factors should be applied to normal cranking times to provide for the effect of increased resistance.

II. REVIEW OF LITERATURE

Raines and Rosenbloom (6) investigated the variation in angular velocity with change in braking force which an operator has to overcome, for the purpose of determining the ideal torque. A horizontal shaft with a hand wheel was mounted about "waist high" and a pulley carrying a rope tensioned by spring scales was used for braking force. The maximum rate of rotation in revolutions was measured by means of a tachometer generator and recording ink-writing galvonometer. The force to be overcome was varied from zero to as high as 30 pounds and the crank radii used ranged from three-quarters of an inch to three and three-quarters inches. The subject stood facing the crank and turned for approximately one second.

The subjects were asked to "decide upon the torque above which they would not want to rotate the hand wheel under practical conditions." There were wide individual differences, but the mean resistance selected was five and one-half pounds at all radii.

The only data on the effect of load on speed published was for the three-quarters of an inch radius. This data shows the maximum speed for any subject of 225 r.p.m. (.0044 min. per revolution) and a linear relationship between load and speed.

Sandberg and Lipschultz (8) investigated the variations in angular velocity with a one and one-half inch radius crank as the location of the crank was changed in a vertical plane parallel to the frontal plane of the subject's body. The subject was seated and resistance to turning the crank was reduced to a minimum. The work period or cycle was selected as approximately six seconds to minimize the effect of acceleration and deceleration in starting and stopping and to eliminate the effects of fatigue which has been found to become noticeable after 30 seconds. (5). Conclusions were drawn on the areas of best performance for each hand. No conclusive relationships were found between cranking performance and certain body dimensions of the subjects.

The data published in this report show a mean maximum performance for the right hand of 348.65 r.p.m. (.00286).

Reed (7), using maximal rate of rotation as the criterion of performance, investigated the variation of angular velocity with changes in crank radii for three different torques. The apparatus used consisted of a crank handle mounted on a vertical shaft which could be turned and set at any point on an arc 90° from the vertical. The vertical shaft was geared to a horizontal shaft which carried a brake drum and cam. The cam operated a Veeder counter through a lever and micro switch. Current through the counter was controlled by the experimenter by means of a telegraph key and a standard electric timer in the circuit. Torque was applied through a brake band connected to a lever by adjustable weights. Five seconds intervals were used for measurements and starting and stopping conditions were excluded. The effect of the following variables were studied:

(a) radius of crank handle from 1.5 cm. (0.59 ins.) to 24.0 cm. (9.45 ins.)

(b) brake loads of 0, 2500 gm.cm. (2.17 in. lbs.) and 5000 gm.cm.

(4.34 in. lbs.)

(c) orientation of the crank

(d) height of the crank

(e) preferred and non-preferred hand

(f) direction of rotation

(g) bodily position (sitting vs. standing), and

(h) fatigue.

Pertinent conclusions were:

(1) That only small influences may be attributed to such factors as the height and the orientation of the crank, the direction of rotation, the position of the subject, or the amount of practice at turning the crank;

(2) that increasing the braking force affects the smaller radii to a greater degree than the larger radii;

(3) that the highest rate may be obtained with the orientation of the crank such that motion takes place in a vertical plane parallel to the body.

In the investigation of the effects of load, the resistance was held constant and the radius of the crank varied from one and one-half centimeters to 24 centimeters. The force to be overcome therefore decreased with each increase in the radius. The maximum torque used would correspond to a force of about seven and one-third pounds at the minimum crank radius, and less than one-half pound at the maximum radius. The question of holding the force constant is dismissed as less directly practical. As might be expected, loads of less than one pound had no effect on performance.

The published data shows a time per turn of .0055 minutes with a 12 cm. (4.72 inches) crank and a load of less than one pound. This data applied to turning a crank in a horizontal plane.

Horst (4) investigated cranking motions with the object of substantiating the value given by Maynard, Stegemerten and Schwab (5) and establishing the limits of all the possible variables in cranking applications. The apparatus used consisted of an automobile differential mounted on a column and having the differential gears locked to give positive drive to both axles. A brake drum was attached to one axle with a brake band anchored to the housing. A thumb screw was used to tighten the brake band to the desired force on the crank. The axle opposite the brake was threaded. A pointer follower was actuated by the thread with the pointer traveling along a blank scale on which any desired point could be marked. The crank was mounted on the drive shaft.

Measurements were recorded by photographing the subject in the performance of the task, using an electric drive 8 mm. Measurement Cine-Kodak with a calibrated shutter speed. Analysis of the film permitted detailed study of the task at time intervals of 0.001 minutes or 0.00025 minutes depending on whether the shutter speed was 1000 frames per minutes or 4000 frames per minute.

Probably the most important departure from the technique of previous studies was the selection of the speed at which the subjects were to work. Throughout his experiment, the subjects were requested to exert what they considered "average effort". The general practice in determining capability is to require the subject to perform with maximum effort. This eliminates the subjective decision on the part of each individual on what level of effort constitutes "average performance". Barnes and Mundel (2) found that, for a simple repetitive linear movement, the time required exerting a subjective "moderate" effort was double the time required exerting maximum effort. The data showing this relationship is the mean of eight subjects and the variations between subjects is now shown.

The Horst investigation developed Standard Times for industrial applications for cranking under average conditions. It confirmed Reed's (7) findings (quoted above) that height and orientation of the crank were not significant and that the only variables requiring special consideration were the radius of the crank and the resistance to be overcome. It confirmed Maynard et al'(5) distinction between first turns and additional turns and added a distinction between these and the last turns including delays due to individual reactions. It showed that variability within additional revolutions was not significant.

Pertinent conclusion on brake loads were, that increased brake load increases the time for cranking motions and that the Standard Time can be applied if the force required to turn the crank does not exceed some value lying between four and 10 pounds. The times shown in the experimental data are subject to the individual operator's concept of average effort.

III. INTRODUCTORY SUMMARY

The purpose of this investigation was to determine the critical loadings at which normal time values for first, additional, and last turns should be changed, and the amount by which they should be changed.

The results of the investigation indicate that

1. An allowance of 0.00020 min. should be made for each pound of load below four pounds and above five pounds up to, and including, nine pounds.

2. For all practical purposes the same time allowances for the effect of load on additional turns may be used for first turns and last turns.

IV. THE INVESTIGATION

A. Method of Procedure

1. Apparatus.

The equipment used was the machine built for and described in detail by Horst: Investigation of Cranking Motions (4). This consisted of an automobile differential mounted on a column with the drive shaft horizontal at a height of 39 inches from the floor. This height was selected because it was an average of three and one-quarter inches below the height of the elbows of the subjects. A four and one-half inch radius, balanced, crank was mounted on the drive shaft. The differential gears were locked to give a positive drive to both axles, one of which carried a brake drum and the other actuated a pointer indicating numbers of turns. Resistance was introduced by tightening a brake band against a brake drum.

Measurements were recorded by photographing the subject in the performance of the task, using an electric drive 8 mm. Measurement Cine-Kodak with a calibrated shutter speed of 1000 frames per minute.

Applied loads were measured at the crank handle by means of a push-pull gage in the same manner as described by Horst.

2. Subjects.

The four mechanics from the Virginia Polytechnic Institute machine shop used by Horst in his investigation were selected for this study. Relative rather than absolute time values were being sought, so the consistency of performance obtainable from trained subjects was essential. The physical characteristics and Minnesota Rate of Manipulation Test Scores of these subjects are shown in Appendix A.

3. Speed.

The subjects were requested to crank at the maximum speed consistent with smooth performance. It would seem obvious that if the determination of speed of performance were left to the discretion of the individual operator, no matter how good his intentions, his psychological reaction would be to adjust his speed to the load. The ratios of the time values at the level of maximum effort would be valid to apply to any standard times adjusted to a level of average effort.

4. Loads.

A cardinal principle in Motion and Time Study is that, before an attempt is made to set or apply standard times, wasteful and fatiguing motions should be eliminated, efficient mechanical devices should be installed to reduce manual effort and the tools, equipment, and method used in performing the work should be standardized. In this process, excessive loads would be reduced mechanically so there would be no point in carrying the investigation into a region of unlikely loads.

Raines and Rosenbloom (6) report an average preferred load of five and one-half pounds on cranks up to three and three-quarters inches radius. The highest force used in Reed's (7) investigation was about seven and one-third pounds on a 0.59 inch radius crank. Experience and observation lead to the conclusion that a force of 10 pounds on average sized cranks is the maximum likely to be encountered in industry.

From these considerations, it was decided to investigate the effect of loads from zero to 10 pounds in two pound increments.

Two possible experimental causes of variation in the load were anticipated; first, the mechanical difficulty of setting to an exact load (see Horst (4) pp. 12 and 18) and, secondly, the heating of the brake band due to friction. To mitigate the former, the same setting was used for each operator at each load and, to preclude the latter, the operation of the machine was limited to periods short enough so that no heating was incurred.

5. Task.

It was felt that task should be identical for each cycle, not only with respect to the sequence and number of motions but also with respect to the stimuli and reactions of the operator. Preliminary investigation showed that, when counting turns, it was instinctive to make the tally when the hand passed the position at which the handle was first grasped and that the impulse was to stop the handle at this same point. At low loads, where the time for one revolution is less than the reaction time, this tendency introduced hesitation, over-run, reversal of over-run, and delay on the last turn. On the other hand, if the command to stop was given by voice by the experimenter, it was felt that a variable between cycles would be introduced by variations in tone and timing of the command and by the distraction of the operator anticipating a command. In order to make the cycle as automatic as possible, a gong was connected to the pointer on the machine so that both visual and auditory stimuli would signal the completion of the required number of turns.

The operator took position in front of and parallel to the plane of rotation of the crank with his hand at his side. At a voice signal to start, he raised his hand, grasped the handle of the crank, and turned the crank six revolutions until the pointer reached the line and the gong sounded and then brought the crank to rest in the shortest period of time regardless of the final stopping position. He then released his hold and moved his hand to the center of the crank.

B. Conduct of the Experiment

The experiment was divided into two parts, partly because two of the subjects were on vacation, and partly to permit changes in technique which might appear desirable after a preliminary analysis of data.

The first set of observations was taken with Operators Numbers One and Two. Observations were made using a camera speed of 1000 frames per minute on three cycles in succession at each load for each operator. Loads were applied in a uniformly increasing sequence. For mechanical reasons (see above under par. 4), and to offset any effect which might arise from practice, the observations were made at different times of the day over a period of a day and a half. Whenever cranking was interrupted for any appreciable length of time, each operator was given a practice run at zero load before proceeding with the recording of observations.

Analysis of the resulting film showed that it was quite difficult to read the position of the crank at low loads due to the blur occasioned by the speed and due to the offset of the camera position necessitated by the masking effect of the operator's body. To facilitate reading future film, a protractor scale was mounted behind the crank on the machine and calibrated from the perspective of the camera position.

The second set of observations was taken with Operators Numbers Three and Four in the same manner as the first set except that loads were applied in a uniformly decreasing sequence.

C. Film Analysis

The film for each cycle was projected onto a screen and the number of frames (each frame being equal to a time interval of one one thousandth of a minute) recorded for each of the following categories:

First turns, from the frame in which motion of the crank was first observed to the frame including the first 360° position.

Five additional turns, from the frame including the first 360° position.

Last turns, (after Horst) from the frame showing the first movement of the fingers in Release Load back to the frame including the previous 360° position.

D. Discussion of Variables

The data obtained from the film analysis (Appendix B) is plotted in Figures 1, 2 and 3. Each of the three plots disclose a consistent difference between the two sets of data.

The factors affecting the data were:

a. Mechanical - principally the accuracy and consistency of loading.

b. Physiological - the motor coordination and strength of the individual subject and his dimentional relationships with the machine.

c. Mental - the individual's interpretation of "maximum speed consistent with smooth performance".

d. Psychological - the transference by one individual of the observed speed and rhythm of another individual to his own speed of performance.

e. Practice - the improved rhythm and performance obtained by repetition of the task.

The difference in level between the two sets of data can only be explained by the mental and physiological factors. The physical characteristics of the four operators (Appendix A) indicate that similar performance might be expected from Operators #2 and #4, whereas Operator #3 might be superior and Operator #1 inferior. The curves do not confirm these expectations. Hence, it appears that the mental factor was the principle cause of the discrepancy.

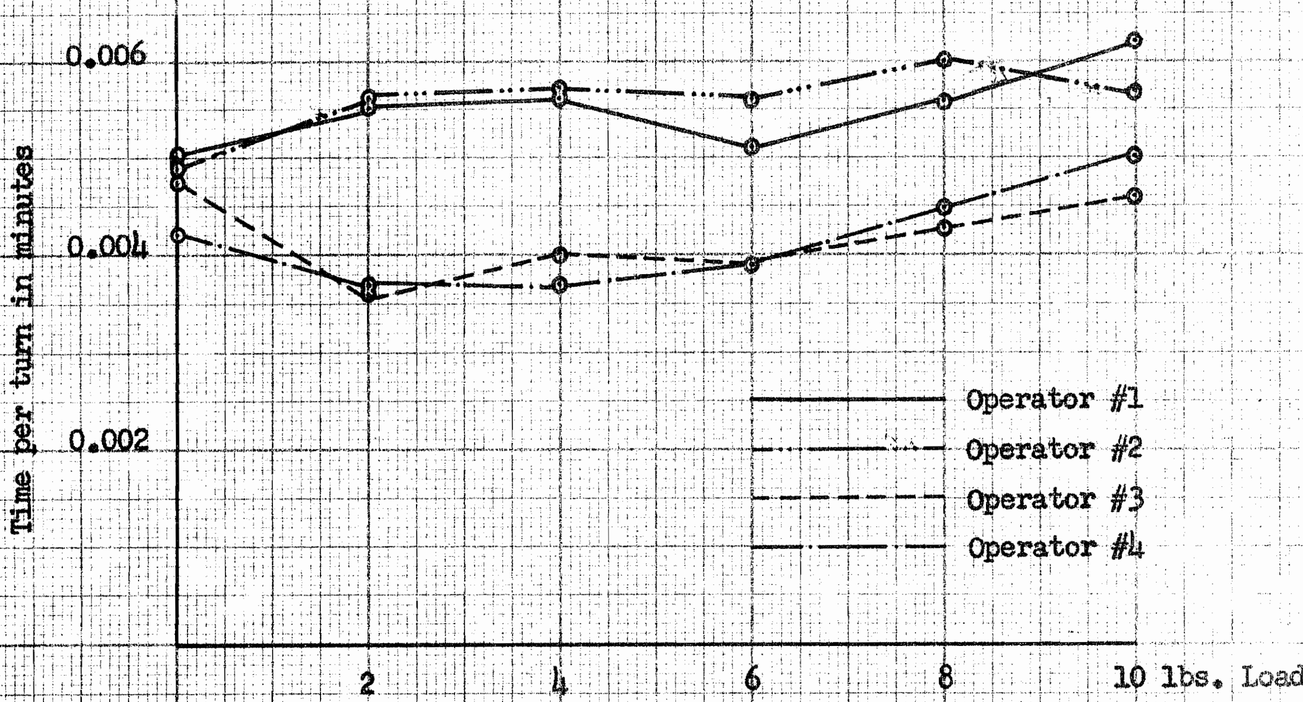

Figure 1. Load-Time Curve for Additional Turns

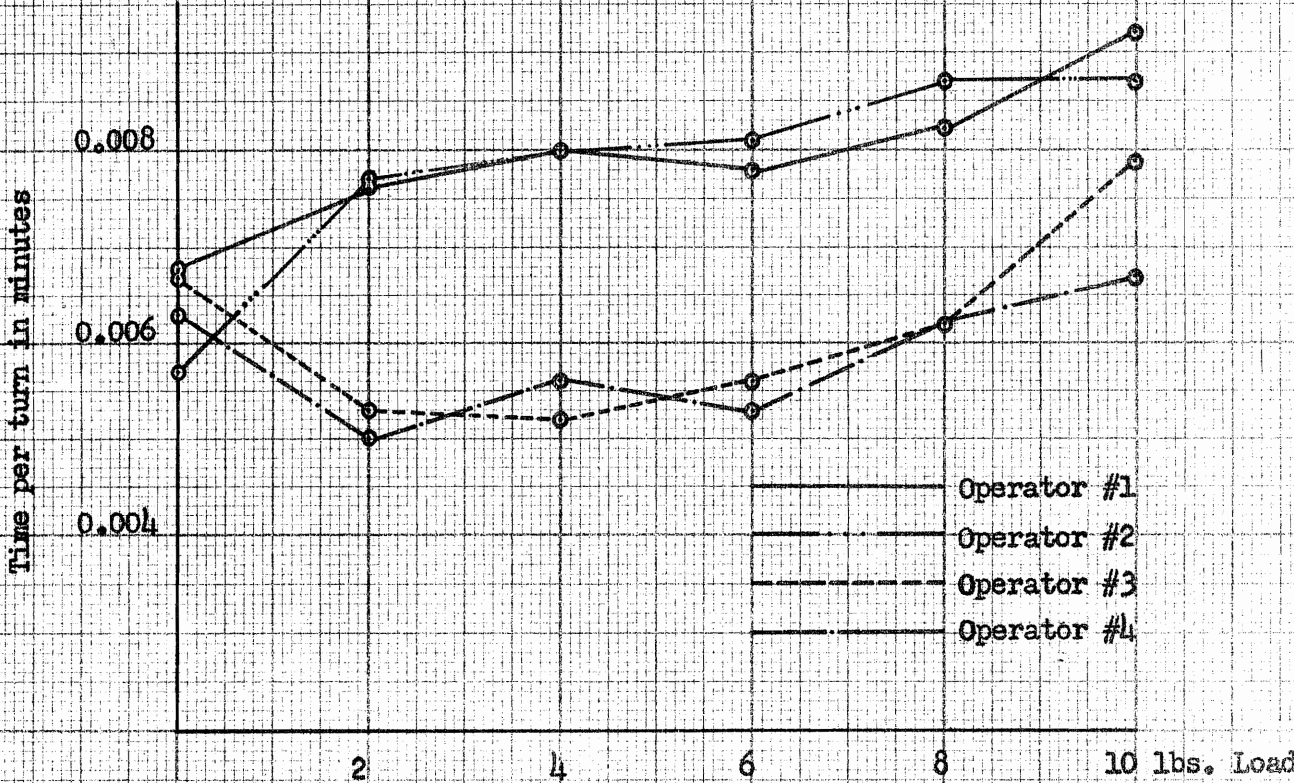

Figure 2. Load-Time Curve for First Turns

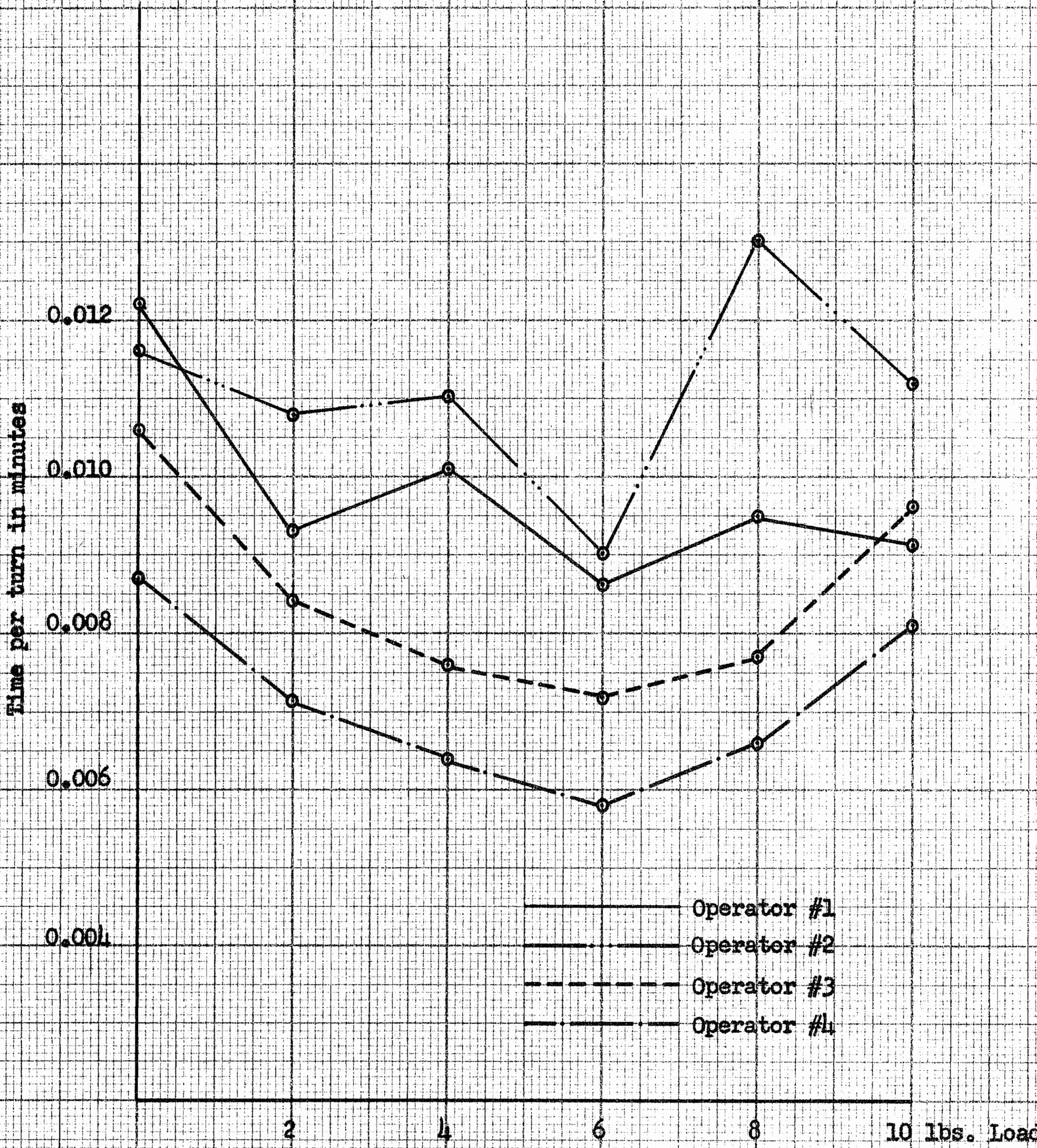

Figure 3. Load-Time Curve for Last Turns (including delays)

At the two pound and four pound loads in Fig. 1, where the observations on the two operators of both pairs were in closest agreement, the time per revolution for the first pair was approximately 40% longer than for the second pair. The magnitude of this difference is suggestive of the difference Barnes and Mundel (2) found between subjective average and maximum performance.

If the subjects were not exerting their maximum effort, it would be expected that there would be greater variability between them and that any effect of the load would be dampened so that the curve would approximate a straight line. The plotted data in Fig. 1 seem to confirm this conclusion in so far as additional turns are concerned.

For first and last turns only three observations for each operator at each load are available as compared with fifteen for additional turns. The much greater dispersion of points is, therefore, to be expected.

For first turns, the strength of the individual will have a definite effect on the time at higher loads. It was observed that acceleration was completed in the first half of the turn, hence the effect due to strength is diluted when the unit of measurement is taken as one full turn. This would lead to the expectation of a greater variability between individuals than with additional turns. The discrepancy between the level of performances of the two pairs (Fig. 2) is explainable by the same arguments developed above in connection with additional turns.

For last turns, another physiological factor, that of mental reaction and muscular coordination assumes importance. As the load increases the time required for deceleration should decrease sharply as it will approach the reaction time necessary to stop applying any force. However, the factor having more effect is indecision, leading to premature relaxation of the force or to an overrun of a preconceived position with correcting reversal of the crank or to simply holding on to the crank after it has stopped. These delays become more pronounced as the load approaches zero, more than offsetting any advantages obtained from the reduced mechanical resistance.

The shape of the curves for the two lots of data are similar only for last turns (Fig. 3). In both Fig. 1 and Fig. 2, the slopes are contradictory below the two pound load.

A plausible reason for the reversal of the slope below the two pound load in the second set of curves would be the change of direction of the dominant force. With no load on the crank, a centripetal force replaces the tangential force causing the operator to reduce his speed in order to maintain smooth performance. If this is true, the fact that the curves for the first two operators do not show this characteristic provides additional evidence that they were not working at the maximum level of performance.

The inter pair conformity of the curves indicates the influence of the psychological factor.

There is no evidence that either the mechanical or the practice factor affected the data appreciably.

By interpolating between zero and two pound loads to obtain conditions comparable with Reed's (7) experiment, the average time per turn for operators #1 and #2 was 0.00525 min. This is very close to the time obtained by Reed (0.0055 min.). The background of Reed's subjects is not given but it is reported that they were "trained for several days". It would be expected that the trained mechanics used in the current experiment would show appreciably better performance, especially in a region where motor coordination is most important. The average time for the four operators was 0.00466 min. and for operators #3 and #4 it was 0.00407 min.

E. Analysis of Data

The statistical analyses of variance for each of the classes of turns are shown below. Statistical significance at the 5% level is indicated by asterisks.

It will be noted that the variation between repetitions is not statistically significant at the 5% level for Additional Turns and for Last Turns but is significant for First Turns. We may therefore conclude that the data is representative for Additional and for Last Turns, but is not conclusive for First Turns.

Additional Turns (average of 5)

Variances	D/F	SS	S^2
Reps.	2	0.30	0.15
Operators	(3)	(33.04)	
Between Pairs	1	32.994	32.994 *
Between #1-#2	1	0.044	0.044
Between #3-#4	1	0.002	0.002
Loads	(5)	(6.10)	
Linear	1	3.945	3.945 *
Quadratic	1	1.635	1.635 *
Cubic	1	0.012	0.012
Quartic	1	0.073	0.073
Quintic	1	0.432	0.432
Oper. and Loads	15	6.10	0.41 *
Residue	46	7.50	0.16
Total	71	53.06	

The speed attainable will be a function of the strength and motor coordination of the individual. The inter pair variance is not statistically significant but the variance between pairs is highly significant. The variance between Operators #1 and #2 is much greater than the variance between #3 and #4. This leads to the inference that the level of performance of each operator was influenced by the performance of his partner and that the level of performance of the first pair was more subjective than that of the second pair.

As was brought out in the Discussion of Variables, the effect on performance of the subject not exerting maximum effort would be to distort the true load - time curve. Hence the shape of the load-time curve for the second pair will most nearly represent the true load-time curve.

The table of variance for Additional Turns for the second pair is shown below.

Additional Turns (average of 5)

Operators #3 and #4

Variances	D/F	SS	s^2
Reps.	2	0.62	0.31
Operators	1	0.003	0.003
Loads	(5)	(6.14)	
Linear	1	1.346	1.346 *
Quadratic	1	4.073	4.073 *
Cubic	1	0.447	0.447 *
Quartic	1	0.078	0.078
Quintic	1	0.196	0.196
Oper. and Loads	5	0.93	0.186
Residue	22	1.56	0.071
Total	35	9.25	

The only statistically significant variance appears to be that due to loads. This may be expressed by the mathematical equation $a+bx+cx^2+dx^3$.

First Turns

Variances	D/F	SS	S^2
Reps.	2	6.06	3.03 *
Operators	(3)	(62.95)	
Between pairs	1	62.16	62.16 *
Between #1-#2	1	0.15	0.15
Between #3-#4	1	0.64	0.64
Loads	(5)	(27.65)	
Linear	1	23.17	23.17 *
Quadratic	1	3.86	3.86 *
Cubic	1	0.33	0.33
Quartic	1	0.01	0.01
Quintic	1	0.28	0.28
Oper. and Loads	15	22.24	1.48 *
Residue	46	19.61	0.43
Total	71	138.51	

The speed attainable will be a function of the strength, motor coordination and nervous reaction of the individual. In the event that maximum effort is not being used, the reserve of power would tend to dampen the difference between individuals.

Here, again, the inter-pair variance is not significant, but the variance between pairs is highly significant. However, in the case, the position of the two pairs is reversed, with the first pair having a much lower variance.

The psychological factor of transferrence of level of performance is again evident. The probability of a level of performance below capacity by the first pair is again indicated by the seeming closer agreement of the data between them.

For the same reasons given for additional turns, the shape of the load-time curve for the second pair will most nearly represent the true load-curve.

The analysis of variance for the second pair is shown below.

<u>First Turns</u>

Operators #3 and #4

Variances	D/F	SS	S
Reps.	2	1.48	0.74
Operators	1	0.64	0.64
Loads	(5)	(20.38)	
Linear	1	4.74	4.74 *
Quadratic	1	14.50	14.50 *
Cubic	1	0.44	0.44
Quartic	1	0.45	0.45
Quintic	1	0.25	0.25
Oper. and Loads	5	1.89	0.38
Residue	22	7.46	
Total	35	31.85	

The only statistically significant variance appears to be that due to loads. This may be expressed by the mathematical equation $e+fx+gx^2$.

Last Turns

Variances	D/F	SS	S
Reps.	2	11.23	5.61
Operators	(3)	(159.31)	
Between pairs	1	125.88	125.88*
Between #1-#2	1	15.08	15.08*
Between #3-#4	1	18.35	18.35*
Loads	(5)	(63.14)	
Linear	1	7.47	7.47
Quadratic	1	45.01	45.01*
Cubic	1	0.99	0.99
Quartic	1	0.53	0.53
Quintic	1	9.14	9.14*
Oper. and Loads	15	30.97	2.06
Residue	46	155.95	3.39
Total	71	420.60	

The speed attainable will be a function of nervous and mental reaction of the individual. As might be expected, the variance between each of the operators is statistically significant and the interaction between operators and loads is not statistically significant.

The variance between loads is statistically significant and may be expressed by the equation $h+ix+kx^2+lx^5$.

Recapitulation

1. The data is representative for Additional and Last Turns, but is not conclusive for First Turns.

2. All the evidence points to a subjective level of performance by the first pair of subjects, resulting in a distortion of the load-time curve for Additional and First Turns, but not affecting the Last Turns.

3. Within the range of the loads studied, the interaction between operators and loads is not statistically significant.

4. The shape of the load-time curves may be represented by the following mathematical equations:

Additional Turns	$a+bx+cx^2+dx^3$
First Turns	$e+fx+gx^2$
Last Turns	$h+ix+kx^2+lx^5$

5. At levels of performance lower than the maximum, the effect due to load is less evident and is progressively absorbed by effects due to the physiological, mental and psychological characteristics of the individual.

V. APPLICATIONS OF RESULTS

The effect of load has been measured at the level of maximum performance. The application of any results of this study will be to levels of performance represented by normal* or standard times.

Horst's normal times for a corresponding experimental condition (four and one-half inch crank and four pound load) for Additional, First, and Last Turns were, respectively, 8.02, 10.70 and 11.39 thousandths of a minute. These times are 2.09, 1.99 and 1.29 times the corresponding means obtained in the present experiment. In other words the level of performance for normal times is about 50% of the maximum capability of the operators.

At this level the actual effect due to load will be much smaller or may be completely offset by the effects of variables other than load. However, if a time allowance is to be made, an amount equal to the measured difference at maximum performance may be added to the normal time. Such an adjustment will be fully as precise as the determination of the normal time itself.

This allowance is determined by plotting the curves from the data in Appendix B and Analyses of Variances by the method of least squares using orthagonal polynomials (8) and measuring the differences from the base used in the determination of normal times.

The plot for Additional Turns is shown in Fig. 4 and the values for the time allowances, using the four pound load as a base, are below.

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* for definition of normal times see Horst (2), page 31.

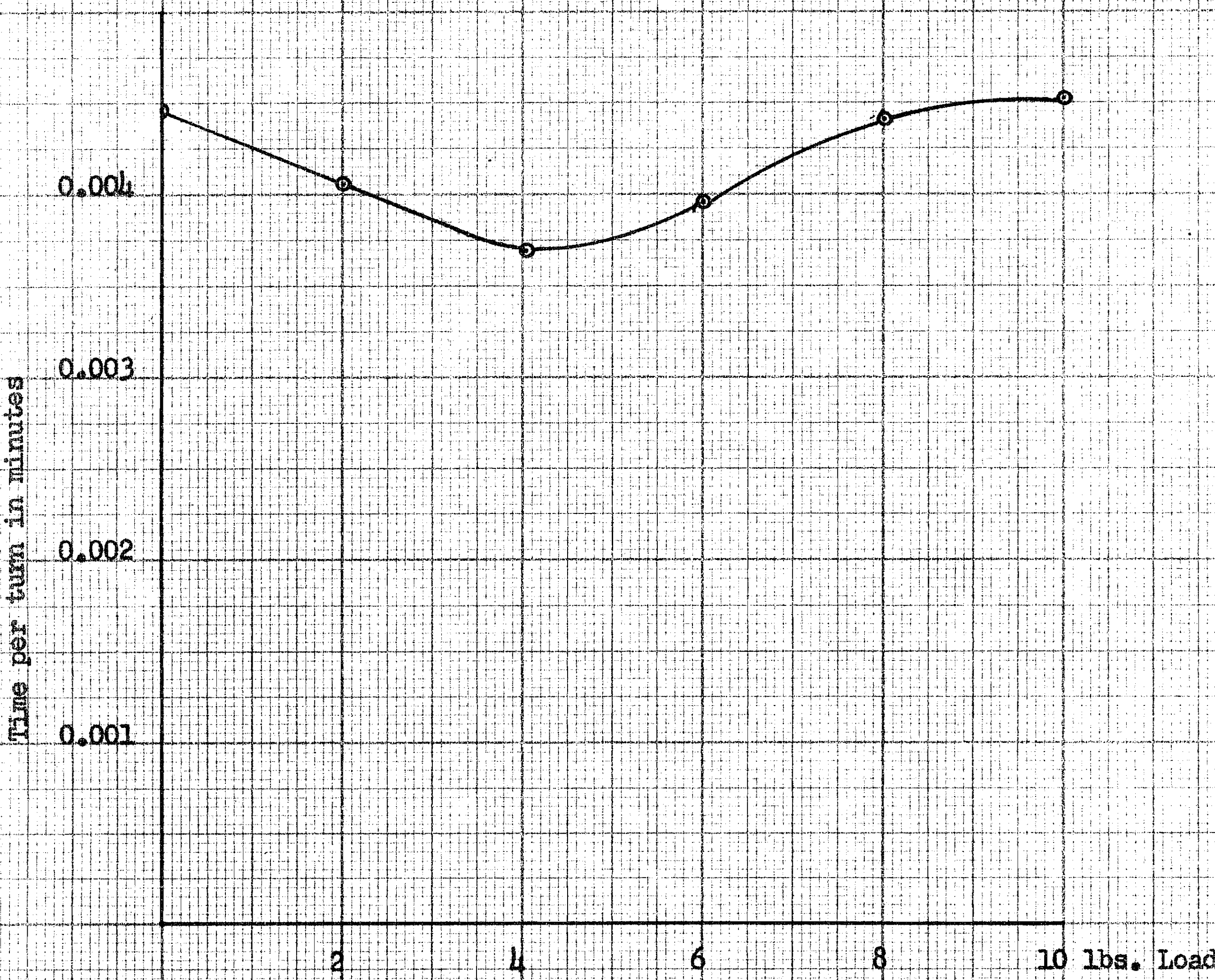

Figure 4. Load-Time Curve for Additional Turns

Plotted from the equation $Y=\bar{\bar{Y}}+ax+bx^2+cx^3$ by the method of least squares using orthagonal polynomials (8).

Additional Turns

Load in pounds	Time Allowance per turn in thousandths of a minute
0	0.77
1	0.56
2	0.37
3	0.15
4	0.00
5	0.05
6	0.28
7	0.53
8	0.72
9	0.82
10	0.85

Time allowances from a base load of four pounds

These differences may be simplified without exceeding the limitations of precision inherent in the determination of normal times by considering the curve below four pounds and above five pounds up to nine pounds as straight lines with a slope of 0.00020 minutes per pound of load.

First and Last Turns occur only once in each cycle. Neither the amount of data obtained nor the magnitude of the difference between the shapes of the curves justify the more precise determination of the allowances, particularly from the perspective of the approximation in application. The allowance for Additional Turns may be used for all turns.

VI. CONCLUSIONS

1. For the purpose of modifying a "normal" time per turn to take into account the effect of varying loads up to nine pounds, an allowance of 0.00020 minutes per pound of load below four pounds and above five pounds should be made.

2. No appreciable error will be involved if the same allowance is made for First and Last Turns as for Additional Turns.

3. The lowest time per turn was obtained under loads of four or five pounds. Raines and Rosenbloom (3) report a preference for five and one-half pounds at radii varying from three-quarters to three and three-quarters inches, indicating a wide range for the optimum load. Pending determination of limits, cranks should be designed to have a resistance of four or five pounds.

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VIII. VITA

The candidate was born in Tacoma, Washington on February 11, 1894. He was subject to instruction in the following schools and institutes: California Public Schools, Oundle (England), Asbury College (Canada), Johns Hopkins University (Baltimore), Alexander Hamilton Institute (New York), and The Massachusetts Institute of Technology (Cambridge) from which he received the degree of SB in Aeronautical Engineering. He has had 17 years of industrial experience, seven years of agricultural experience, over 30 years commissioned service in the United States Army and five years of teaching. He has held public office as Selectman and State Representative. He is a member of the following professional and honorary societies: American Association of University Professors, American Society for Engineering Education, American Institute of Industrial Engineers, and Alpha Pi Mu.

Jack V. Thomas.

APPENDICES

Appendix A

Physical Characteristics of Subjects

Operator #1

Age - 27 years Height - 5 ft. 8 ins. Weight - 175 lbs.

Height of elbow from floor - $41\frac{1}{2}$ ins.

Minnesota Rate of Manipulation Test: Score 231, 75th Percentile.

Operator #2

Age - 40 years Height - 5 ft. 10 ins. Weight - 165 lbs.

Height of elbow from floor - $42\frac{1}{2}$ ins.

Minnesota Rate of Manipulation Test: Score 225, 80th Percentile.

Operator #3

Age - 38 years Height - 5 ft. 7 ins. Weight - 122 lbs.

Height of elbow from floor - $40\frac{1}{4}$ ins.

Minnesota Rate of Manipulation Test: Score 211, 95th Percentile.

Operator #4

Age - 29 years Height - 5 ft. 11 ins. Weight - 200 lbs.

Height of elbow from floor - 44 3/4 ins.

Minnesota Rate of Manipulation Test: Score 228, 80th Percentile.

Appendix B

Cranking Against Various Loads

Times per revolution in .001 min.

Load in lbs.	First Turns Operator 1	2	3	4	Additional Turns (Ave. first 5) Operator 1	2	3	4	Last Turns (including delays) Operator 1	2	3	4
	6.5	6.7	6.5	6.8	4.68	5.40	4.38	5.20	13.0	15.4	13.5	9.6
Zero	6.8	5.0	7.6	6.3	5.20	4.40	4.16	5.02	12.0	8.7	9.6	9.1
	7.0	5.4	5.9	5.8	5.06	4.82	4.12	4.04	11.7	10.7	8.8	7.4
	7.3	9.0	5.7	5.3	5.52	5.60	3.96	3.68	9.6	11.0	8.7	7.5
2	7.4	6.6	5.5	4.5	5.60	5.60	3.60	3.75	9.5	11.5	8.0	6.7
	8.2	7.4	4.7	5.2	5.52	5.60	3.54	3.44	8.8	10.0	8.6	7.0
	8.0	9.0	4.4	6.6	5.88	5.70	3.52	4.52	9.0	12.0	8.1	7.0
4	7.9	6.9	5.5	5.0	5.36	5.56	3.90	3.75	10.7	10.0	7.0	6.2
	8.0	8.0	5.6	5.1	5.50	5.72	3.76	3.62	10.7	11.0	7.7	5.9
	9.0	10.0	5.9	5.5	4.92	5.36	3.78	3.97	8.5	9.5	8.3	6.7
6	6.7	6.7	5.3	5.2	4.76	5.60	4.00	3.65	8.3	9.2	6.2	5.2
	7.6	7.6	5.7	5.3	5.54	5.80	4.02	3.94	9.0	8.4	7.1	5.5
	8.1	8.7	6.3	7.4	5.60	6.30	4.98	4.52	7.7	8.8	7.8	6.8
8	8.3	8.6	6.0	5.3	5.64	5.84	4.30	4.00	12.3	20.9	8.2	6.5
	8.2	8.7	6.2	6.0	5.68	5.92	4.30	4.30	8.5	9.2	7.1	6.5
	9.3	9.0	7.8	7.0	5.90	5.68	4.98	4.80	10.0	11.4	10.8	8.3
10	8.9	8.0	8.0	7.3	6.16	5.60	5.20	4.60	7.7	12.0	8.5	8.7
	9.4	9.0	7.8	6.0	6.60	5.80	4.98	4.40	9.7	10.3	9.6	7.3