A PROCEDURE FOR THE EVALUATION
OF START-UP EFFECT IN MANUAL
INDUSTRIAL OPERATIONS

By

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PREFACE

"Of all the faculties of the mind, memory is the first that flourishes and the first that dies" - this quotation by Colton emphasizes the importance of memory and the phenomena of learning. Industry has recently recognized the effect of learning inherent in manufacturing. This effect is evident in many phases of production. However, this paper will deal with only one area of interest, learning theory applied to a wage incentive system. This study is one more effort toward the ultimate goal of a wage incentive plan with equal potential for all workers regardless of assignment.

I would like to express my gratitude to the following people:

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CHAPTER I

INTRODUCTION

Objective

The study described in this report has as its ultimate goal:

1. The development of a practical and economical tool for the prediction or estimation of the time required to learn a manual operation.
2. The use of this tool in establishing allowances to be applied in a wage incentive system. This will permit the adequate compensation of experienced operators when they are assigned new work although of the same type they have previously worked upon.
3. To enable an allowance to be calculated and applied by either manual or computer methods.

The data collected in this investigation is from a less mechanized part of industry, specifically, the manufacture of wired telephone switching equipment. Although the conclusions drawn are based on the electronics industry, the basic concepts of the study should be valid in many related types of industry.

Conclusions

The conclusions are discussed in detail in the last chapter; therefore, it will suffice at this point to say that the objectives, within the limitations of this paper, are attained.

CHAPTER II

HISTORY

Systematic experimental study of human learning dates from 1885 when Ebbinhaus stated some of the fundamental problems, devised methods for studying these problems and, in many ways, set the pattern for later research. Edward L. Thorndike, Edwin R. Guthrie and others have made extensive contributions to learning theory, with many facets of the subject being investigated. These psychologists have immeasurably contributed to the field of learning by their experiments and theoretical formulations.

The import of this work to practical problems was not realized until 1925 when McDill conducted the original investigations with the manufacturing progress curve. However, it was not until 1936 that Wright published the first paper on the "Aircraft Progress Function" and this concept found wide use in the aircraft industry.[1] It was about this same time that the Western Electric Company, using empirical data obtained in laboratory studies in conjunction

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[1]T. P. Wright, "Factors Affecting the Cost of Airplanes," Journal of Aeronautical Sciences, Vol. 3, February, 1936, pp. 122-128.

with a plan outlined in an undergraduate thesis by a student at Lafayette University, came up with a plan known as the "Piece Rate Plan for Small Lot Allowances."[2] Under this plan, work is classified according to dexterity and intelligence. The resulting small lot allowance is then adjusted by factors for "similarity," "lapse," "automaticity" and "repetition," the first two always, and the latter two if necessary. These factors will be discussed more fully later in the paper, but at this point it is necessary only to say that their use in the Western Electric Plan required so much judgment that the results had very little consistency.

In general, the affect of small lots on the time allowed the worker to perform a job has not been considered to any great extent by the majority of companies who have instituted incentive systems in their factories, although one exception is the comparatively widespread use of "set-ups" usually allowed each time that a job is run by an operator. Granted, that "set-up" or preparation time required prior to the start of actual production plays an extremely important part in the small lot problem, but there are a number of basic factors which cannot be correctly included in "set-ups" in the majority of jobs. Operations are studied and standards set for conditions of

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[2]K. D. Snyder, "Small Lot Allowances for Incentive Systems," (an undergraduate thesis at Lafayette University) 1928-1930.

high production, as a rule. These are sadly inadequate under small lot conditions.

It should be mentioned that Industrial Engineers and Psychologists are not the only professions who have delved into this field. During the past 20 years, Economists have become increasingly interested in the subject. Much of the early impetus to its investigation by Economists was given by the United States Air Force, which for quite some time had recognized that the direct labor input per air frame declined substantially as cumulative air frame output went up. The Stanford Research Institute and the Rand Corporation initiated extensive studies in the late forties, and the early conclusions were that insofar as World War II Air Frame Data were concerned, doubling cumulative air frame output was accompanied by an average reduction in direct labor requirements of about 20 per cent. This was referred to by the aircraft industry as an "80% Curve." While the Economist thinks of the progress function in terms of average labor requirements, the basic theory is the same as our utilization of the curve in operator learning theory.

CHAPTER III

DEFINITION

It is a common experience in industry for trained operators, familiar with a certain type of work, to lose efficiency when switching to an operation in the same general category but not done by them previously. The same is also true if the time lag between operations exceeds some length of time. When observing an operator who starts to work on an operation which he or she has not done previously, hesitations are seen. These hesitations are due primarily to sub-standard physical and mental co-ordination occasioned only in part by the change in motion pattern brought about by the new layout. The operator has to learn where the parts are, and subsequently, where he has to position them. After these initial "get" and "place" locations are learned, the initial hesitation is less discernible but it is still present; now the hesitation is due to the poor degree of neural and kinesthetic co-ordination. The loss in efficiency, therefore, may be hypothesized to two factors: (1) the function of what is accepted to be the conscious memory, and (2) the degree of neural (mental) and kinesthetic (physical) co-ordination which is the co-ordination between the nerve system and muscular activity.

Obviously, the same factors cause the poor efficiency when an employee is newly hired for manual operations or is transferred from one type of work to another. However, the degree of loss in efficiency is different. An operator skilled in the general type of work has experienced visual, and tactile sensations similar to those encountered in the new job; he has bits of information stored in his nervous system for unconscious comparison; therefore, he acquires nervous and kinesthetic co-ordination faster than his untrained counterpart.

Much has been done throughout industry in the area of learning curves to determine expected output of newly hired or transferred employees; this will take these unskilled employees through the "learning" phase in which they acquire the basic skills. Skilled operators, however, who lose efficiency through frequent changes, long-time lag between jobs and new jobs, require some sort of allowance to compensate for this loss, particularly when they are participating in an incentive plan. Elemental Time Standards are developed for operators who have acquired a relatively high degree of neural and kinesthetic co-ordination. For example, two operators using the same method with equal effort and with the same basic skill in performing an operation, would not necessarily produce the same amount of work. The fully co-ordinated operator will perform faster than his counterpart who is newly assigned or is starting a job which he has not done for a long time. This time difference is Start-Up-Loss or Small-Lot effect.

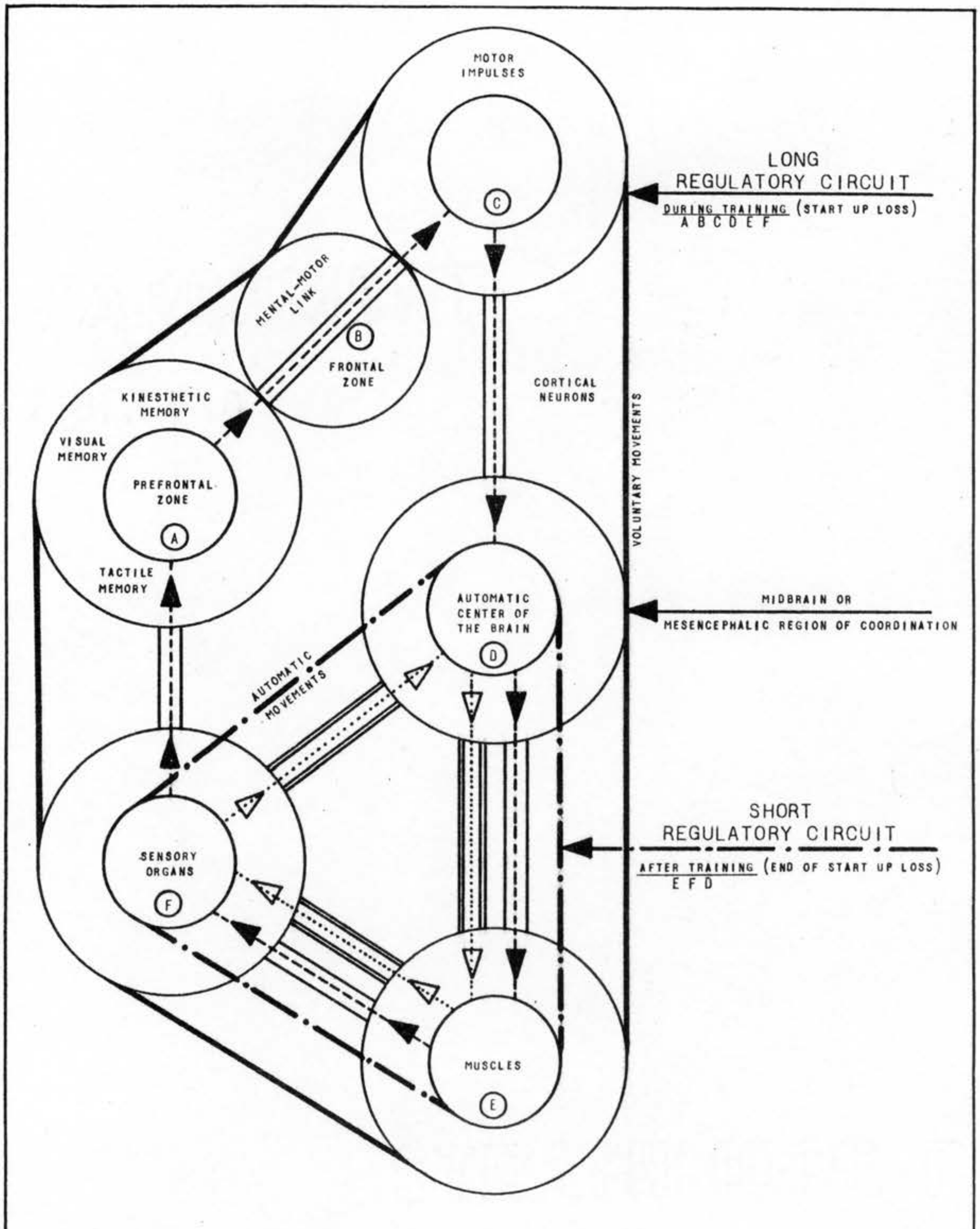
CHAPTER IV

FACTORS INFLUENCING START-UP-LOSS

Physiological

Psychology divides movements into two categories. They are: voluntary and automatic movements. The voluntary movements are cortical, originating from the outer periphery of the brain; while the automatic movements originate from the central gray mesencephalic, region of the brain. In effect, all movements pass through the voluntary stage. When a child learns to walk or to reach for an object, he has to interpret sensations originating from his senses and execute corrections knowingly. When the neural-muscular mechanism has been controlled a few times, however, it can be utilized without conscious effort. The child will walk and reach without hesitation. In the course of ones life, several simple movements become automatic; neural-muscular co-ordination has been acquired for these simple movements.

The nerve path utilized to perform automatic movements may be called the "Short Regulatory Circuit," as opposed to the "Long Regulatory Circuit" which is used to execute voluntary movements. (Figure 1 is a graphical



CIRCUITS OF VOLUNTARY AND AUTOMATIC MOVEMENTS

FIG. A

FROM "LA MESURE DE L'ACCOUTUMANCE"; BY CLAUDE CATELAS, LES EDITIONS D'ORGANISATION, PARIS, 1960.

Figure 1. Circuits of Voluntary and Automatic Movements

presentation of the two circuits.)

When industrial work is performed, the sensory organs collect information from the surroundings and the specific conditions of the work; this is done primarily by sight, but also by touch. Through practice, the tactile information more and more replaces the visual information. Tactile information also serves to control the path of movements. This is readily apparent in experienced relay assemblers who perform the assembly operations with remarkable speed and ease while talking to a co-worker. Sense of touch is thought of commonly as a unit, but is composed of different organs with different functions. They are:

1. <u>Touch and Pressure Sensing</u>

   Organ: Pressure sensitive bodies in the skin.

   Stimulus Required: Tangential stress of the skin.

2. <u>Stress and Pressure Sensing (also called Kinesthetic Sensing)</u>

   Organ: Spindle-formed bodies in muscles and cartilages of the joints.

   Stimulus Required: Stress.

3. <u>Sense of Temperature</u>

   Organ: Temperature sensitive bodies in skin.

   Stimulus Required: Mainly temperature differences.

4. <u>Sense of Pain</u> (Rarely participating in sense of touch)

   Organ: Free ends of nerves, anatomically indefinable.

Stimulus Required: Chemical changes in tissues.

Objectives (targets) are reached with reasonable accuracy when reaching for an object with closed eyes if the position of the object was previously established by sight. The object has formed an image in the brain and impulses originating from this image guide the muscular activity. Constant reports keep coming in from the measuring units, the spindle-formed bodies in the muscles and cartilages, to the nerve center, the brain. These reports ascertain instantaneously and successfully the relationship of the hands to the target. If correction is required, a control process sets in which requires approximately 0.0008 of a minute and is automatic. The Short Regulatory Circuit is followed.

A miss of the target is noticed by the sense of touch and is followed by a re-grasp. In this process, the Long Regulatory Circuit takes over. It has a functioning time of approximately 0.0033 of a minute including the muscle contraction. The processes of the Long Regulatory Circuit are more conscious than those of the Short Circuit. Corrections based on the informations obtained by the sense of touch adjust the movements until the imagined relationship is obtained. The visual information collected during the movement also exercise their control effect, through the Long Regulatory Circuit, but they are lagging behind. The visual information may be effective up to 0.0033 of a minute before the end of the movement.

The time difference between the functioning of the two Regulatory Circuits is of major importance in reducing the difficulty of industrial operations and is the basis for the difference in efficiency between an operator who has acquired nervous-Kinesthetic co-ordination and one who has not. This is a major factor causing "Start-Up-Loss."

Factors Influencing Its Measurement

There has been previous discussion of the basic reasons causing "Start-Up-Loss," that is learning what to do, the function of the memory; and learning how to do it, acquiring muscular co-ordination. Now, the discussion will be concerned with the factors in the nature of a productive unit; a shop, a group, or an individual operator which influence the amount of Start-Up-Loss.

Some factors influencing Start-Up-Loss may be found in the operation itself, (A), and others are related to the character of the operating unit, (B). The factors to be found in the operation are as follows:

A. Factors in the operation

1. The difficulty of the job.
2. The number of simultaneous operations in job.
3. The number of different operations.
4. The cycle time.
5. Similarity of elements within the cycle.
6. Uniformity of the product.

7. The amount of machine time.

8. The intelligence required.

B. Factors relating to the character of operating unit.

1. Similarity between jobs.

2. Number of cycles run at a time.

3. Lapse time between assignments.

4. How well job was engineered.

5. Supervision.

Each of the above are defined as follows:

A. (1) The Difficulty of the Job.

Did you ever try to sew a seam by hand keeping your seam straight, your stitches parallel and uniformly distributed? How long would it take you to learn to do it rhythmically? But now, compare this with the time it would take you to learn to load boxes onto a conveyor. These are two extremes, but they illustrate what is meant by difficulty. The former job requires a high degree of co-ordination while the latter is composed of movements one is co-ordinated to do since childhood.

Catelas, has divided the M.T.M. movements into three categories.[1] Movements which may be

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[1]Claude Catelas, "La Mesure De L'Accoutumance," Les Editions D'Organisation, Paris, 1960.

performed unconsciously and without using the eye, those which have to be performed consciously <u>or</u> for the performance of which the eye is necessary, and movements which must be performed consciously <u>and</u> the use of the eye is also required. He found that it took approximately 50, 1,600 and 20,000 cycles in each category respectively to reach M.T.M. level. The difference in number of cycles is startling.

It is reasonable to assume that, aside from those factors which influence the time to learn what to do (memory), all other factors, whether inherent to the job or related to the character of the operating unit, either aid in acquiring co-ordination for the difficult elements or extend the time required to overcome the difficulty. They do this mainly by either reducing the time interval between performing the same difficult motion element and, thereby, accelerate the rate of acquiring co-ordination, or by prolonging the time interval and, thereby, reducing the rate of acquiring co-ordination.

A. (2) <u>The Number of Simultaneous Operations in Job</u>.

Every day experience tells us that it takes more time to learn to pick up a part with each hand simultaneously than to learn to pick up a part with one hand only. However, in order to explain the cuase and estimate the difference, one has to return to physiological factors.

It is known that impulses, while training, pass through the conscious mind which is a composition of the centers A, B, and C on Figure 1, page 10. It is also known, or at least has been experienced by many, that the function of the mind manifests itself as an entity. Only one thing can be concentrated on at a time; either on the right hand or on the left hand. When performing simo-movements, therefore, the mind works like a flip-flop; it directs impulses to the automatic center successively and not simultaneously. It follows that, all other operations being equal, it should take twice as long to learn a two-handed operation than a one-handed operation. However, when simple movements are performed, where co-ordination has been acquired since childhood, no learning time should be required even if the movements are made simultaneously. An example would be to dispose of a non-delicate part into a large tray with each hand.

A. (3) <u>The Number of Different Operations of Motion Elements</u>.

It is obvious that the more elements there are in a job the longer it takes to learn them. Of course, there is the factor of memory, the operator has to remember the sequence of the elements and the location of the parts. This factor, however, will be overcome after the first few cycles of any normal operation. Once again the factor of co-ordination shows up. As an example, imagine two assembly jobs both consisting of ten motion elements, but Job No. 1 is composed of ten different elements while Job No. 2 is composed of two different elements repeated five times each. After performing one cycle of each job, the operator will have practiced the first element of Job No. 1 only once as opposed to five times in Job No. 2. This is of special importance in wiring operations where the connecting and soldering elements vary in occurrence.

A. (4) The Cycle Time.

Cycles composed of the same number of different motion elements might require different normal times to perform. If, for example, two jobs both consist of the same two-motion elements, but in one job element, Elements 1 and 2 are each performed once, while in the other job, Element 1 is performed four times and Element 2 once. As in the example of building tables, Job 1 consists of building single-leg tables, while Job 2 is building four-leg tables. Element 2 is a difficult motion requiring a high degree of skill such as making the top while Element 1 consists of the simple leg making operations.

First Job: Leg Top

Second Job: Leg Leg Leg Leg Top

Since the difficult element in the second job is performed relatively less often than in the first, it will take more cycles to acquire co-ordination for it in the latter job than in the former. This will change the nature of the learning curve, but not necessarily increase the total per cent of the start-up or small lot effect.

A. (5) Similarity of Elements Within the Same Cycle.

Different motion elements might produce very similar tactile and visual stimuli. Two such different elements, but yet very similar in the stimuli they produce, are to grasp two wires of different colors in the same breakout. A grasp and position of a comparable difficulty, however, produce totally different stimuli. Although there is no evidence at present of the ability to transfer sensory experiences, and that similar sensory experiences have a reducing effect on Start-Up-Loss, it is probable that they do. This factor, therefore, should be kept in mind when developing an allowance.

A. (6) Uniformity of the Product.

The repetitive experience of the same sensory stimuli and the repetitive reaction to them is the basis of learning industrial operations. Non-uniform parts cause different stimuli; it follows, that in such case, the correct reaction to more than one set of stimuli has to be practiced more often, and as a consequence, the time to acquire co-ordination should increase.

A. (7) The Amount of Machine Time.

Machine time is that portion of the cycle not in direct control of the operator, and as such should have no effect on learning other than increasing the cycle time.

A. (8) The Intelligence Required.

This factor has its influence in learning what to do and is of great importance where print references is necessary to learn the job (as is the case in the wiring operations discussed in this report). However, intelligence required to perform an operation should be of little significance for assembly operations.

B. (1) Similarity Between Jobs.

In wired equipment operations, one series of units or frames might be composed of 75 per cent of motion elements which have been learned and for which co-ordination has been acquired in previous jobs. Theoretically, these elements do not require an allowance, and the small lot or start-up effect should be compensated on only 25 per cent of the job. However, recent studies indicate that similarity between tasks was rather a hindrance than an aid to the operator. The process seemed to be one of unlearning the old task before learning the new job. Consequently, the nature of the job must be considered carefully in order that similarity be weighed correctly.

B. (2) <u>Number of Cycles Run at a Time</u>.

The longer each individual operator stays on the same assignment the more co-ordination he will acquire.

B. (3) <u>Lapse Time Between Assignments</u>.

Common sense would dictate that the time interval between assignments would tend to effect the acquired knowledge and co-ordination of an operator. The amount of this effect is a real point of contention and the results of studies on lapse indicate that this factor may have much less effect than was initially anticipated. For example, studies on surface wiring and cable forming show that operators brought back after as much as a year away from a specific job reach efficiency shortly after returning (second unit) to the same job. This was found to be true only in cases where the operator reached efficiency the first time. Therefore, it is very important that work be channeled to operators until efficiency can be attained. It is realized that in a small lot shop this will impair flexibility, but before an allowance can be established, flexibility and lapse time will have to be reconciled.

B. (4) How Well the Job was Engineered.

Manufacturing layouts usually specify what has to be done but they rarely go into detail as to how the operation has to be performed. It remains for the Industrial Engineer to determine the "how" in detail. The better this job is done, the more uniform the cycle will be and the easier it will be for the operators to acquire co-ordination.

B. (5) Supervision.

There is no use to engineer the job well if the operators do not follow the prescribed method. Operators have a tendency to set up the job differently every time they are assigned to it. They may even change their motion pattern in midstream. These practices will increase the start-up or small-lot effect. It is up to supervision to make the operators aware of the necessity to follow the prescribed motion pattern. The better supervision performs this function, the less allowance will be required for the start-up or small-lot effect.

CHAPTER V

PROPOSED PLAN

As previously indicated, the objective of this study is the development of a workable plan for the compensation of production workers for the effect of small-lot or start-up-loss in a wage incentive system. This effect can be shown pictorially for a hypothetical job that has a standard time of 10 minutes and requires eight units to reach this standard time when assigned an operator with experience in the general class of work, but having never seen this particular job.

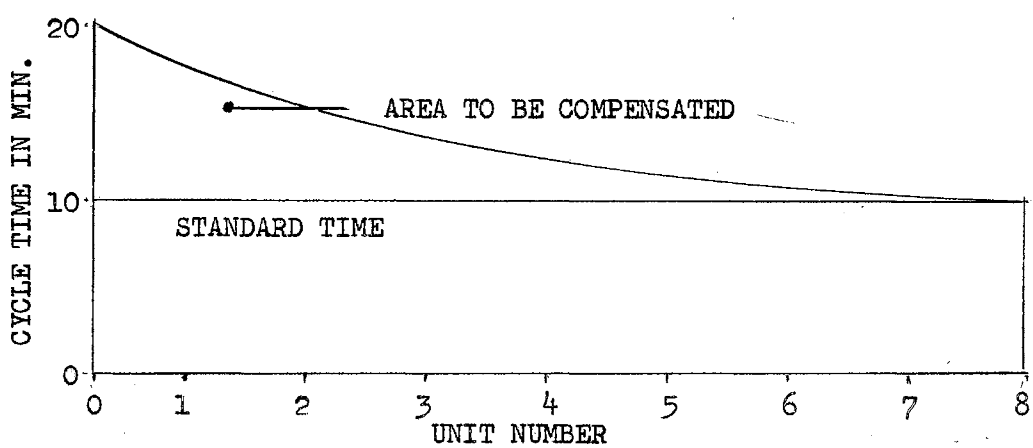

Figure 2. Pictorial Presentation of Learning Process

The first unit might require 20 minutes to complete, the second unit 18 minutes, etc., until the standard time of 10 minutes is finally attained on the eighth unit. The area above the standard time level of 10 minutes, in the example, is the area in which an allowance is required. The objective of this study is to determine a method of assessing this quantity for scheduling and compensation purposes.

The study will be confined to the manufacture of wired equipment and will encompass both large and small wiring jobs; however, small wiring (short cycle) operations will be used to demonstrate the proposed plan due to the relative ease of obtaining data.

In order that a complete understanding be obtained of equipment to be discussed, a brief explanation will be made of the two terms most commonly used:

Wired Equipment Frame -

A large metal framework. Usually 11 feet 6 inches long and 2 to 4 feet wide equipped with a variety of apparatus and units for the purpose of regulating circuits in a telephone central office.

Wired Equipment Unit -

A component designed to be mounted in a wired equipment frame, composed of apparatus (relays, resistors, etc.) fixed on metal plates. A unit is wired and tested prior to being integrated into a frame.

As indicated in the example, if the cycle time may be assumed to approach the standard time or rate along a curve, this curve must be established in advance of production in order to evaluate operator progress. Data collected in the course of this study indicate that operator learning and re-learning cycles follow the same type of exponential reduction curves used by the aircraft industry. After experimenting with several types of curves, including straight lines, an exponential curve of the type $Y = ax^{-b}$ where Y represents the cycle time for the N^{th} unit, a is the first unit time, x is the N^{th} unit, and b is the slope of the curve, was chosen (see Appendix A). This choice was based on empirical data obtained in the study of wired equipment units (see Appendix D). The slope b of the curve can be expressed as a percentage reduction. For each doubled quantity of production (x), the time (Y) for that unit will be a fixed percentage of the previous undoubled quantity. This percentage or slope will play an important role in the operation of the proposed plan.

The proposed plan is based on the premise that the per cent slope (b) is a function of the complexity of the operation being learned. To determine if this relationship does exist, a method of establishing the difficulty of the work must be developed. This is accomplished by the use of an index made up of items present in the job standards (see Appendix C) and arranged in such a manner that the resultant factor is an indicator of job complexity. In the proposed plan, the index, which will subsequently be discussed in detail, will be used to determine the exact curve (value of b) to be applied to the job.

Assuming a relationship between the complexity index and per cent curve exists, it remains necessary to translate the curve, thus obtained into a program for payment. Such a program can be accomplished by using a theoretical standard time of 10 minutes, which, when placed in the general curve $Y = ax^{-b}$ enables actual payment percentages to be derived (Appendix B gives complete calculations for the example of a 90% curve in which percentages are derived for application to lot size).[1] Allowances for curves with any per cent improvement may be determined in this manner and applied directly from the complexity index.

The other function of the complexity index is to determine the number of units required to reach the standard time. In order to generate the tables explained in Appendix B, it is imperative that a specific number of units be established for each job in order that the correct allowance be applied.

The remaining problem is to tie the payment percentages into the complexity index factors. This will be accomplished by the use of studies conducted using modern

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[1]The percentages referred to are to be applied as a percentage of the work standard.

work measurement techniques on sufficient jobs to establish a relationship between the index factors and curve slope values.

To view the entire plan, it is seen that (1) a complexity index must be developed, which, by use of (2) empirical data, establishes (3) a definite slope of the general curve ($Y = ax^{-b}$) and a (4) set number of units to reach the standard time for each job. The slope and number of units to reach standard time designate the (5) per cent allowance to be paid. This relationship may be illustrated in the flow chart (Figure 3) on the following page.

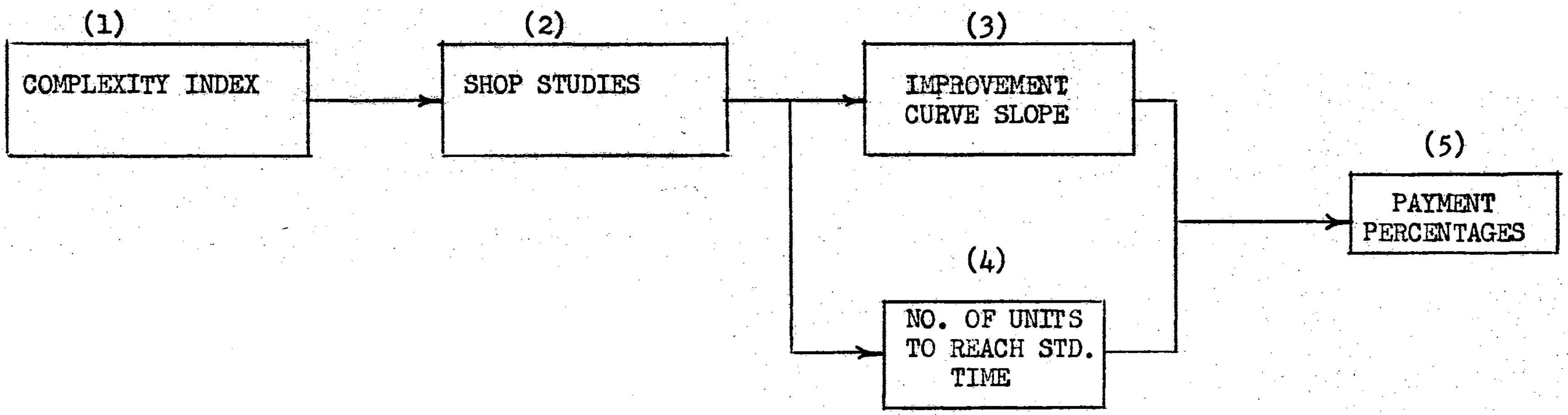
The plan is applicable to all wired equipment operations, but each operation covered will require two phases of the plan be developed for that particular operation.

1. Complexity index calculation.
2. Gathering of empirical data to relate complexity index with the curve slope and number of units to reach standard.

These two phases will be explored at length using both wired equipment frames and units.

1. Complexity index factors were developed both for the frame wiring phase and the surface (unit) wiring phase of wired equipment operations to demonstrate the different operations. The long cycle operation is represented by (A) frame wiring while the short cycle operations

PROPOSED PLAN



Determined from values present on standard time analysis sheets. (See Appendix C)

Work measurement studies of job on which allowance is being established

Developed from study data (See Appendix D for example).

(Appendix B) Table V

After the plan is established, a new job will automatically receive an allowance once the complexity index is established.

Figure 3. Proposed Plan

are represented by (B) unit or surface wiring.

A. Complexity Index - Frame Wiring

In the development of the complexity index, it was realized that while the factor must be readily obtainable from the analysis sheets and other information, it must also place the particular job in the correct category with maximum accuracy. The categories were chosen by the following method, (a) the frames were categorized by job labor grade as set by the wage practices organization (33 grade, 34 grade, etc., see Figure 4), and (b) a list of frames was given to the layout operators in each department and they were told to rate the frames in their department according to difficulty (1. hardest, 2 ... etc.). This information was then correlated with the labor grade information and it was found that the labor grade information was a good indication of complexity. As this information has the frames classed in three categories, it was decided that initial effort would be directed toward determining and index range for these three categories (see Figure 4).

In order that an index be established for each frame, the factors felt to be indicative of complexity, were reviewed, (see

I. Basic Wiring Operations
(33 Grade)

(1) Little difficulty is encountered in identifying apparatus and connection points.
(2) Little difficulty is encountered in associating independent manufacturing information sources and variables with equipment.
(3) Repetitive and limited random wiring patterns.
(4) Ease of accessibility to connection points with some congestion due to heavy distribution in limited areas.
(5) A variety of wire types and colors.
(6) A variety of terminal forms and connections.
(7) Limited wire breakout variations.
(8) Little analysis is required as optional conditions are easily managed and complete wiring information and instructions are furnished.

III. Normal Wiring Operations
(34 Grade)

(1) Some difficulty is encountered in identifying apparatus and connecting points.
(2) Some difficulty is encountered in associating independent manufacturing information sources and variables with equipment.
(3) Random wiring patterns.
(4) Congested wiring due to limited spacing of terminals, number of leads connected to terminals and/or previous wiring.
(5) All wire types gages and colors.
(6) All terminal forms and connections.
(7) Break out variation.
(8) Breakdown of simple facts and conditions from drawings and related independent sources of information to determine connections to be made, wires to use and similar wiring requirements.

III. Complex Wiring Operations
(35 Grade)

(1) Considerable difficulty is encountered in identifying apparatus and connecting points.
(2) Considerable difficulty is encountered in associating multiple interdependent manufacturing information sources and variables with equipment.
(3) Random wiring patterns.
(4) Congested wiring due to limited spacing of terminals, number of leads connected to terminals and/or previous wiring.
(5) All wire types, gages and colors.
(6) All terminal forms and connections.
(7) Break out variation.
(8) Requires breakdown of complex data from multiple interdependent information sources and variables to determine wiring requirements and to re-arrange, simplify and condense wiring information.
(9) This category also includes the wiring of difficult selectors, wafer switches with four and more segments, and the wiring of difficult key, lamp and jack panels (including left handed operations). These items should be wired by wiremen with nine months or more experience.

Figure 4. Identification of Labor Grades

Appendix C) these included:

Typical Hours Frame for Wiring

Number of Wire Ends on Frame

Number of Wiring Notes

Number of Sequence Notes

Number of Lists (Options)

All attempts to put these factors into a form that would give a value of relative complexity ended in failure. In searching for other criteria of complexity, it was found that typical time for testing of frames was also an indicator, but by itself not significant. However, when combined with the factors mentioned above, the typical test time appeared to be the key (see Appendix C for explanation of Source Values). The Index for wired equipment frames is determined from the following relationship:

$$I - \frac{T_x \times L \times N_r \times T_t}{N_c}$$

<u>OR</u>

$$I - K \times 1 \times N_r \times T_t$$

<u>WHERE</u>

$$K = T_w/N_c$$

WHEN

T_t = Typical Hours (test)

T_w = Typical Hours Wiring

N_c = Number of Wire Ends

K = Hours/Wire End or T_w/N_c

N_r = Number of (Wiring Notes + Sequence Notes)

L = Number of Lists

I = Complexity Index

B. Complexity Index - Surface Wiring

In developing an index for surface wiring, it was decided that a value would be more easily handled if put on a per-wire-end basis, but several problems must be overcome. Unit wiring differs from frame wiring in that several units are wired in one fixture or rack at one time. The standards on units are developed on this basis and for a measure of complexity to be correct, this must be resolved to a per-unit value. This was accomplished by taking the operations which were pro-rated to the fixture and dividing by the number of units per fixture. The value thus obtained is then divided by the total number of wire ends. The formula takes the following form:

$$\frac{A + \left(\frac{W}{L}\right) B + C}{\frac{D}{L}} = I$$

<u>THEN</u>

$$\frac{\frac{AL + WB}{LD} + C}{L} = I$$

<u>AND</u>

$$\frac{AL + WB + LCD}{DL^2} = I$$

<u>WHERE</u>

A = Preparation and Handling (per fixture)

B = Reading Time (per fixture)

C = Run Dress and Connect Time (per unit)

D = Units (per fixture)

L = Total Number of Wires

W = Number of wire descriptions (wires on which reading is required)

I = Complexity Index.

See Appendix C for source of values.

2. As mentioned earlier, the use of empirical data is the basis of any workable solution to this problem and must be gathered under shop conditions. The method of gathering this data could entail virtually all types of work measurement from work sampling for extremely long cycle operations to motion picture analysis of extremely

short cycle operations. In any case, a variety of factors must be considered. These include:

Operator efficiency on present assignment.

Instruction should be available.

Schedule.

Work Layout.

To expand on these factors: The operator MUST possess basic skills but should either not have done the job before or have done it a considerable time period ago. This particular factor is complicated even within a work category such as unit wiring on which studies were run on units made up of two separate types of apparatus with different terminal types. Operators experienced on one terminal type tend to improve at a somewhat faster rate given units of that type than when given units of the other type. In order that studies be as free of foreign elements as possible, all type of instruction (if needed) should be available. Also important is the schedule in that enough cycles must be obtained to determine slope and characteristic of the resultant curves. The final factor is that of work layout which has been discussed earlier and means simply that the work location and job should be reasonably engineered.

A. Frame Wiring Studies

In frames, due to the length of cycle, most pertinent data can be accumulated by the use of a properly conducted work sampling study. The required information is basically contained in the two parameters cycle number and cycle time. The gathering of this information can be facilitated by obtaining as few items as possible in the study proper and using the ordering information where possible to give specific frame requirements. This can be accomplished by the following items:

1. <u>Tag Number</u>

   Reference to the ordering information will give "J" number, options (lists), number run per month, and standard time for this specific frame.

2. <u>Employee Number</u>

   Reference to file information will give operator's name and experience on this job as well as history of other experience.

3. <u>Time Elapsed</u>

   This will provide time for the cycle.

4. <u>Frame Studied</u>

   This will provide the cycle number.

5. <u>Effort</u>

This will be a percentage rating by the observer to determine the operator efficiency.

The observation sheet may be constructed similar to the following example and the results evaluated by standard work sampling techniques.

Frame Studied ________

SMALL-LOT OBSERVATION FORM

TAG NUMBER	"E" NUMBER	WORKING OBSERVATIONS EFFICIENCY								OTHER OBSER.	START TIME	FINISH TIME	ELAPSED TIME
		70	80	85	90	95	100	105	110				

Figure 5. Small Lot Observation Form

B. Surface Wiring Studies

Empirical data on the surface wiring of units can best be obtained by the use of time study. Due to the relatively short cycle time of unit operations, this old tried and true work measurement technique gives several advantages on this type of study, these include accuracy, the ability to break out desired elements, and the advantage of having a complete record of each cycle completed. The primary disadvantage is the effect of the stopwatch on the operator being studied. The effect of operator rating tends to lose its importance due to effect of picking operators who have attained 100 per cent efficiency on other work; and therefore, as a rule, exert consistent effort. The elements shown by experience to exert the maximum influence should be broken out as separate elements. The studies in surface wiring showed these elements to be:

Read Time - Time spent reading prints or receiving instruction.

Re-Work Time - Time spent correcting, incorrectly performed work.

These elements are in addition to foreign elements, etc., that are normally deducted from time studies, but enable these variables to be plotted separately. (See illustration for format of study sheet - Figure 6.)

TIME STUDY DATA

UNIT NUMBER ____________________

LISTS ____________________

OBSERVER ____________________

CATEGORY OF WORK ____________________

UNIT CYCLE NUMBER ____________________

TOTAL ELAPSED TIME . . . . ______

TOTAL BASE TIME . . . . ______

RATING . . . . ______

RATED TIME . . . . ______

READ TIME . . . . ______

BASE TIME LESS READ TIME . . . . ______

REWORK TIME . . . . ______

FOREIGN ELEMENT TIME . . . . ______

NUMBER UNITS PER FIXTURE . . . . ______

DATE . . . . ______

- - - - - - - - - - - - - -

Figure 6. Time Study Data Sheet

CHAPTER VI

APPLICATION

As this plan was primarily developed for the purpose of insuring correct compensation in the framework of a wage incentive system, some mention will be made of incentive plans. There are two classes of wage incentive plans; one of which is the Individual Plan where each employee's work is measured separately and his earnings are entirely dependent upon his own contribution. The Individual Plan lends itself quite well to small lot compensation due to the fact that individual operator records are maintained. The other class is known as the Group Plan. Under this plan, the wage incentive rates are issued to work performed by a group of employees, all of whom share in the group's earnings. The size of these groups may vary from two to over one hundred members and may cause serious problems in the application of small lot compensation. As Western Electric is set up on the Group incentive system, these problems are very relevant to the application of our proposed plan.

The question which also must be asked is, if the operator is compensated prior to attaining the standard time, should time also be deducted after he makes standard time and continues to improve? The answer to this is tempered by the method of work measurement. It is realized that time study standards already include a certain amount of time of this nature. But what happens where elemental time standards are the basis of measurement? Motion Time Measurement, in most cases of application, contains some allowances for delay, fatigue, etc. (The "Maytag" application used 18 per cent addition to the basic TMU value.[1]) The standard used by Western Electric Company (Elemental Time Standard for Basic Manual Work[2]) contains 28 per cent allowance broken down in the following manner:

Co-ordination	10.8%
Fumbling	9.6%
Personal and Fatigue	7.6%
	28.0% .

The writer feels these allowances are the answer to the question of reduction after the standard rate is attained. It is reasonable to assume that co-ordination will increase and fumbling will be reduced as more and more cycles are completed. For this reason, a decrease would be justified along the comparable progress function. If this method of application is to be followed, it should be remembered

[1] M.T.M. Application Manual, The Maytag Company, January 10, 1957.

[2] Elemental Time Standard for Basic Manual Work Standard 400, Issue No. 2R, Western Electric Company, Inc., 105 Broadway, New York 7, N. Y.

that the function should asymptote out at some point not too far below a correctly established standard. (See Figure 7.)

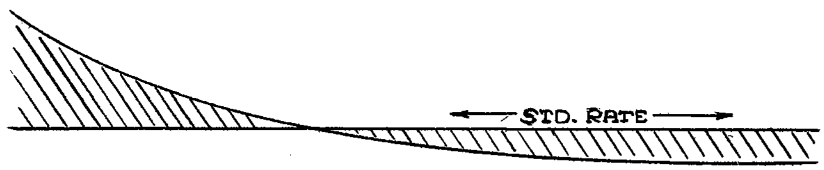


Figure 7. Time Reduction After Standard Rate is Attained

Supervisors aware of this type of application will undoubtedly attempt to see that operators are scheduled so that the deduction will be at a minimum. This is faulty reasoning from the standpoint of experience encountered with operators left on similar work. The increase in performance is usually far in excess of the effect of any deduction.

The actual method of application is a problem that is even more complicated by economic consideration. This consideration centers around the accuracy desired. To some extent, this will depend on the significance of the allowance or deduction (if used) in the rate structure. But even more important is the procedure required to apply the allowances at all. A rapid, yet accurate, manual procedure would be ideal, but impossible. If a practical manual method is to be used, much accuracy will be sacrificed. It would, however, be better than nothing and could be handled with the following assumptions: (1) That all work is channeled to the same operator, (2) a definite lapse period is defined, and (3) that the allowance could be paid on an "End of Period" basis.

One procedure for the manual application of allowances is to group the frames in the category of complexity in which they fall, and use the allowances determined by the correct curve for that index (see Appendix B, Table V). These allowances would be paid until the number of units required to reach standard is attained, then no allowance would be paid, unless manufacture was discontinued on the units and renewed at some later date (dependent upon lapse period) at which time the allowance would be reinstated starting with the first unit. Obviously, this procedure would be based on production records developed for some specific period.

Figure 8 shows a form that could be used for this type of application. The Lot Size would be computed by month until the cumulative number of units exceeded the "No. to Reach Standard" as indicated by the Complexity Index. The allowance would be multiplied by the rate time for the unit and the resulting figure would be totaled for all units and added to the wage incentive compensation for the period.

						Month
UNIT NUMBER	COMP. INDEX	SLOPE OF CURVE	NO. OF UNITS TO REACH STANDARD	LOT SIZE	ALLOWANCE	LOT SIZE $L_1 + L_2$

Figure 8. Form for Manual Application of Allowances

If economic conditions allow, a much more accurate and less cumbersome method of application could be developed by use of computer techniques. The information used in a computerized plan could also be used to give the operating organization and upper management a variety of desired information to aid in decision making. This would be particularly applicable to this Company due to the fact that much of the information needed is already on the tab cards because of a computerized costing and rate application system. This system functions through a process of totaling the rates set on individual options into a complete "Rate" for a "frame" or "unit". This rate is identified by a tag number which corresponds to a particular combination of lists or options for a particular unit or frame. This tag number follows the equipment through the manufacturing process and gives it individual identity.

A "rate" is generated for each tag number and the assignment of a complexity index factor to each frame or unit would allow it to be generated in addition to the "rate". The additional procedure required is shown in detail on the diagram. This procedure would allow automatic computation and application of the allowance regardless of the number of people required on the job. (See Figure 9.)

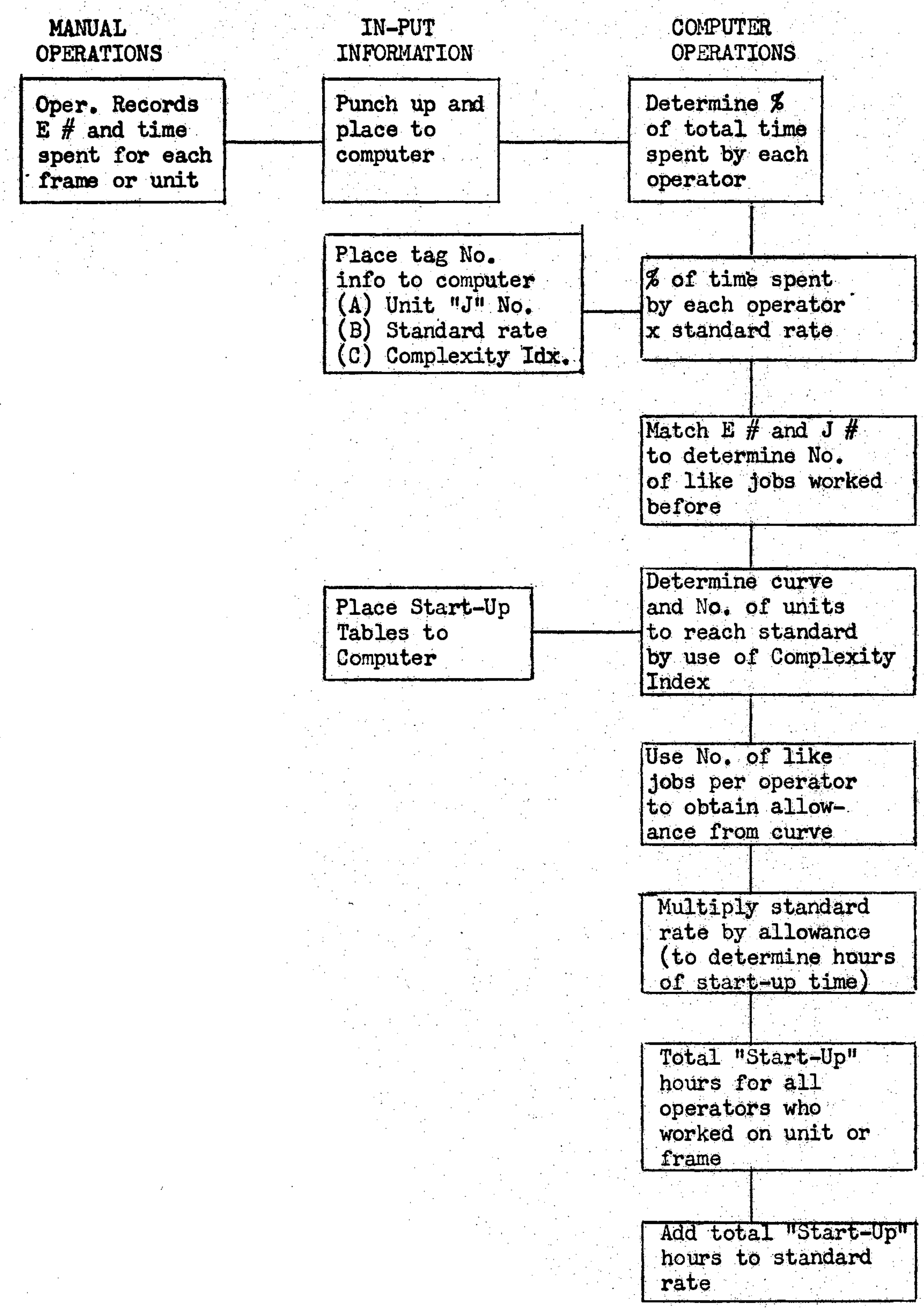


Figure 9. Procedure for Computer Application of Allowances

CHAPTER VII

A SAMPLE PLAN

The plan, as presented, is totally theoretical and to be evaluated must be supported by studies conducted in an actual industrial environment. This has been accomplished by using the "Wired Equipment Unit" phase of the jobs previously outlined. This pilot study along the proposed procedure will give some idea of the magnitude of the errors and the effect of the variables that can be expected from the data. The total time needed to place the plan on all operations of a complete factory might run to years, and such an undertaking should be started only after a preliminary study of the problem. For the purposes of this paper, a portion of the unit phase will be sufficient to demonstrate the practicality of the plan. As the unit phase encompasses relatively short cycle work, stop watch studies were used to record the cycle times. A limited number of units were studied due to the difficulty of setting up the desired conditions. The units studied were:

1. J 27252 D-1
2. J 27551 W-1
3. J 27962 AA-50

4. J 27963 AB-50

5. J 27963 BE-50

6. J 27964 BA-50

7. J 27963 AA-50

8. J 27962 AE-50

These units were broken into two categories: (1) Units wired by operators experienced on the same type of unit, and (2) Units wired by operators experienced on a different type of unit. The difference in types of unit lies in the kind of relays used, the two general types in use require different wiring methods. Studies indicate that operators wiring new units of the same type fall into one category while operators wiring units of a type different than what they are experienced on tend to fall into a completely different category.

A. Units studied in category one are:

1. J 27962 AA-50
2. J 27963 AB-50
3. J 27963 BE-50
4. J 27964 BA-50
5. J 27973 AA-50

B. Units studied in category two are:

1. J 27252 D-1
2. J 27551 W-1
3. J 27962 AE-50

A brief synopsis of the studies in each category will indicate the variables encountered.

A. The operators employed on these units were efficient on unit wiring of the same type and had never wired these units before. However, they put forth conscientious effort to make the studies a success. Outside influences on the operators were at a minimum with very little disturbance from other operators. Physical conditions were satisfactory as the operators had all necessary tools and adequate space in which to work. The layout of materials was well engineered, and the operators had nothing hampering rhythm.

B. The operators used in these studies were experienced on one type of unit and were switched to a type of unit on which they had no experience. This was not only a different unit, but a different type of wiring. While the results are limited, due to the small number of units studied, the studies were satisfactory from the standpoint of operator effort and layout of work with one exception. Two studies were conducted on the J 27551 W-1 on two different operators. One of these studies was disregarded due to operator attitude, the operator in this case was determined to wreck the study.

See Appendix D for plotted results of studies in addition to rate and calculated Complexity Index for each unit studied. The read values will be discussed in a later section. Realizing that no accurate relationship can be established from this limited amount of data, estimated curves will be fit to the Complexity Index - Per Cent Improvement Points. (See Figure 10.) An exponential curve of the type $Y = 10^{M(\log x) + b}$ will be used. Each category of work discussed previously will approximate a different form of this curve. (See Figure 11.)

The wiring of unlike units can be approximated by the curve $Y = 10^{.0755 \log x - .6372}$ while the wiring of like units can be approximated by the curve $Y = 10^{1.588 \log x + 1.901}$. The exponent values for like wiring jobs when converted to per cent slope and compared with the Complexity Index give the following information:

Complexity Index	% Slope
.010 To .020	99
.020 To .070	98
.070 To .100	97
.100 To .150	96
.150 To .250	95
.250 To .300	94
.300 To .400	93
.400 To .500	92
.500 To .600	91
.600 To .900	90

The exponent values for the wiring of unlike jobs

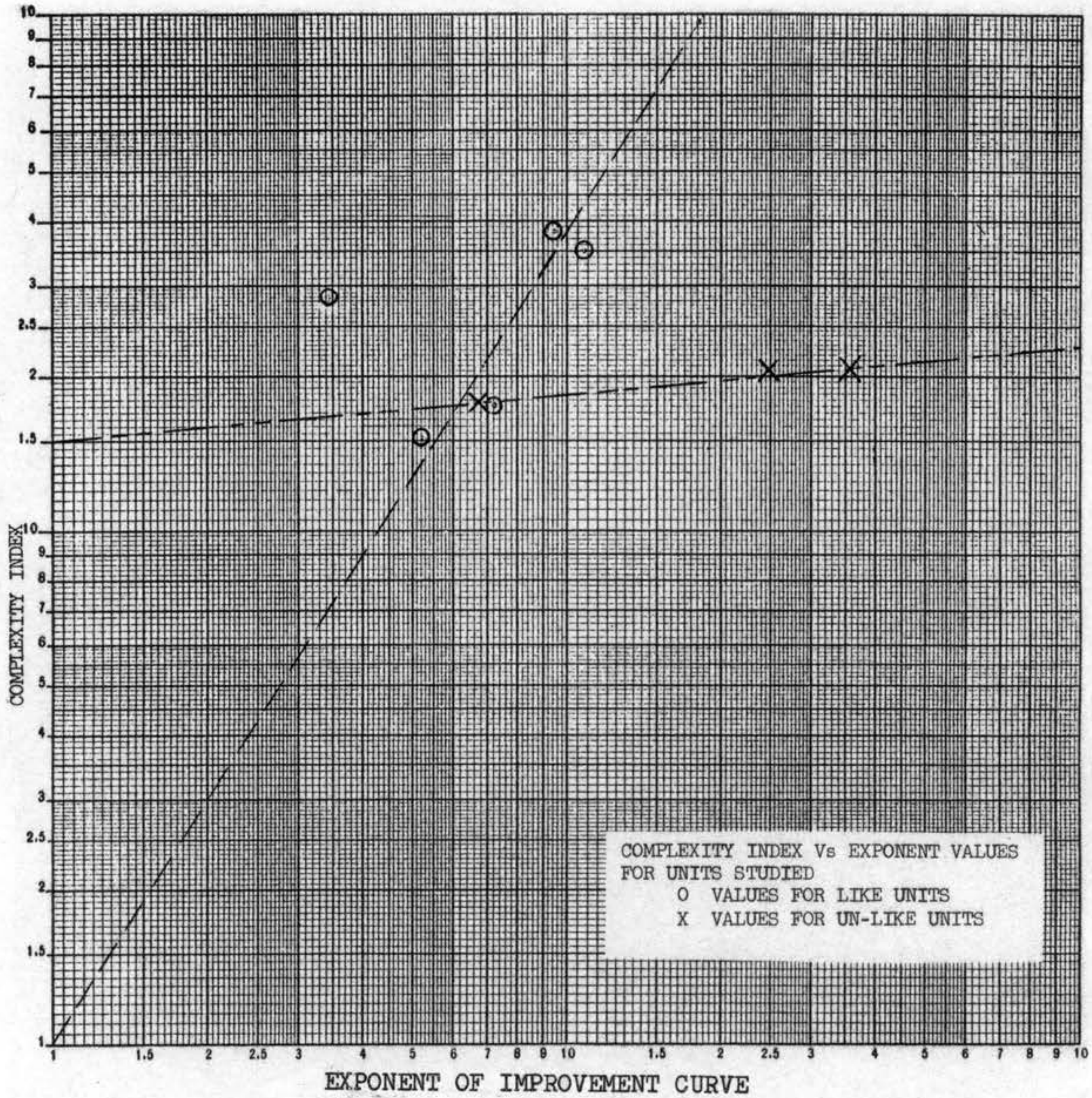


Figure 10. Complexity Index Versus Exponent Values for Units Studied

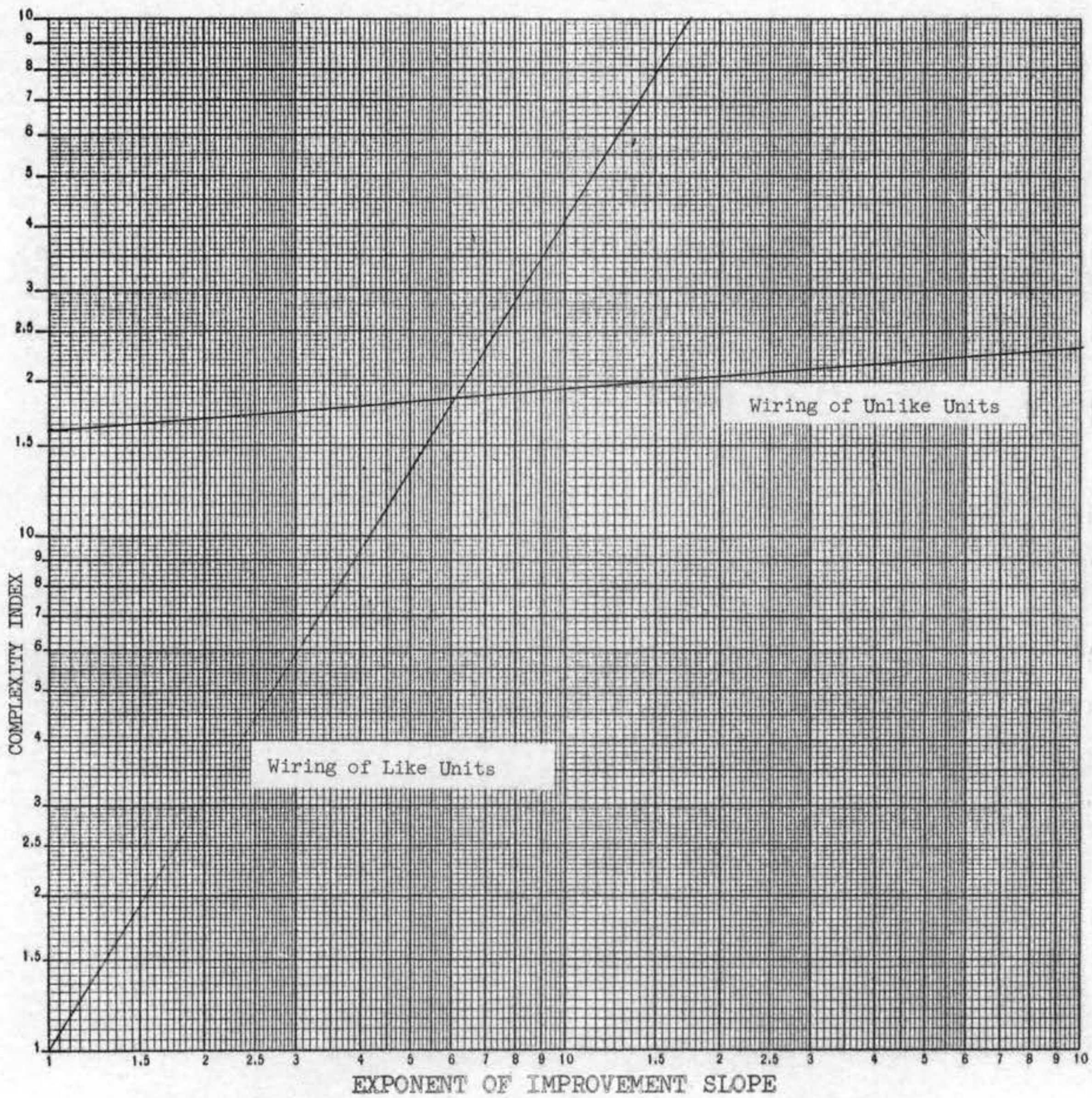


Figure 11. Exponent Versus Complexity Index

gave quite different results:

Complexity Index	% Slope
.1590 To .1595	96
.1595 To .200	90
.200 To .205	87
.205 To .210	81
.210 To .215	76
.215 To .220	70

The "Complexity Index - Improvement Slope" relationship came out quite well for both categories of work; however, the number of units to reach standard rate was not as consistent as anticipated. For the first category of work or the wiring of like jobs, a constant number to reach standard was indicated by the empirical data. Five units to reach standard would give adequate compensation for any index range studied.

The second category, or the wiring of unlike jobs, showed a great deal of variation in the number of units to reach standard. This was due to several reasons: the small number of units studied, the fact the rate was not attained on two of the studies, and limited time which enabled studies of only one operator per unit. Calculation of the cycle number where the standard time would be obtained showed a variation between 3 and 200. This indicates that extensive investigation would be necessary to determine the exact number of units required to attain the standard time for each Complexity Index range. To stay within the limitations of this paper, a constant number of 20 will be used. This number, while determined by judgment, is based on experience in this area of work and in the writer's mind would allow adequate compensation.

The illustration used contains only a portion of the Complexity Index range for both categories. However, it should be sufficient to show the workings of the proposed plan. To consolidate the data in final form, the per cent improvement for each Complexity Index range is used to determine the actual percentage allowance by the method outlined in Appendix B. See Table I for allowance factors for category one and Table II for those in the second category.

The allowance values shown can be utilized by any of the methods discussed in Chapter VI. The computer application requires the exact additional allowance for each consecutive unit, while the manual application uses a cumulative average for each unit lot size ordered.

TABLE I

WIRING OF LIKE UNITS

		% ALLOWANCE (MANUAL)					% ALLOWANCE (COMPUTER)				
		Unit Number					Unit Number				
Complexity Index	Slope	1	2	3	4	5	1	2	3	4	5
.600 To .900	90	27.72	21.33	16.91	13.55	10.84	27.7	14.9	8.1	3.4	0
.500 To .600	91	24.47	18.87	14.98	12.00	9.60	24.5	13.3	7.2	3.1	0
.400 To .500	92	21.30	16.46	13.08	10.49	8.39	21.3	11.6	6.3	2.7	0
.300 To .400	93	18.41	14.26	11.34	9.10	7.28	18.4	10.1	5.5	2.4	0
.250 To .300	94	15.40	11.95	9.52	7.64	6.11	15.4	8.5	4.7	2.0	0
.150 To .250	95	12.65	9.83	7.84	6.30	5.04	12.6	7.0	3.9	1.7	0
.100 To .150	96	9.96	7.76	6.19	4.98	3.98	10.0	5.6	3.1	1.3	0

TABLE II

WIRING OF UNLIKE UNITS

COMPLEXITY INDEX	% SLOPE	% ALLOWANCE (MANUAL)																			
		UNIT NUMBER																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
.215 to .220	70	366.4	296.5	252.7	221.7	198.15	179.4	163.9	151.01	139.9	130.16	121.6	114	107.1	100.9	95.2	90.0	85.3	80.8	76.7	72.9
.210 to .215	76	227.5	188.2	162.8	144.4	130.1	118.6	109	100.9	93.8	87.6	82	77	72.6	68.5	64.72	61.25	58	55	52.3	49.6
.205 to .210	81	148.6	125	109.3	97.8	88.7	81.3	75	69.7	65	60.8	57.1	53.8	50.7	47.9	45.3	42.9	40.7	38.6	36.7	34.8
.200 to .205	87	82.6	70.7	62.6	56.5	51.6	47.6	44.2	41.2	38.5	36.2	34	32.1	30.3	28.7	27.2	25.8	24.5	23.2	22	20.9
.1595 to .200	90	57.7	49.8	44.3	40.2	36.8	34	31.7	29.6	27.7	26.1	24.6	23.2	21.9	20.8	19.7	18.7	17.7	16.8	16	15.2
.1590 to .1595	96	19.3	16.9	15.2	13.9	12.8	11.9	11.1	10.4	9.8	9.3	8.7	8.3	7.8	7.4	7.0	6.7	6.4	6.0	5.7	5.4
		% ALLOWANCE (COMPUTER)																			
		UNIT NUMBER																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
.215 to .220	70	366.4	226.6	165.1	128.7	103.9	85.7	71.5	60.2	50.7	42.8	36	30	24.8	20.1	15.9	12.2	8.7	5.6	2.7	0
.210 to .215	76	227.5	148.9	112	89.1	73.1	61.1	51.5	43.7	37.2	31.6	26.7	22.4	18.6	15.2	12.1	9.2	6.6	4.3	2.1	0
.205 to .210	81	148.6	101.4	78	63.1	52.4	44.2	37.6	32.1	27.5	23.5	19.9	16.8	14	11.5	9.1	7.0	5.1	3.3	1.6	0
.200 to .205	87	82.6	58.9	46.4	38.2	32.1	27.4	23.5	20.2	17.4	14.9	12.8	10.8	9.0	7.4	6.0	4.6	3.3	2.1	1.0	0
.1595 to .200	90	57.7	41.9	33.4	27.7	23.5	20.1	17.3	14.9	12.9	11.1	9.5	8.1	6.8	5.6	4.5	3.4	2.5	1.6	0.8	0
.1590 to .1595	96	19.3	14.6	11.8	10	8.5	7.4	6.4	5.6	4.8	4.2	3.6	3.1	2.6	2.1	1.7	1.3	1.0	0.6	0.3	0

CHAPTER VIII

OBSERVATIONS AND EVALUATION OF SAMPLE PLAN

In reviewing the results of the sample plan, the following observations were made: (A) A wide difference in learning when operators are switched from one type of wiring to another type, versus unfamiliar jobs in the same type of wiring, (B) The limited effect of lapse periods between jobs, (C) The significance of read time on operator improvement, (D) A large variation in the number of units required to reach the standard time, (E) Some deviation from learning theory as to reasons for improvement.

To elaborate on the observations:

A. A wide difference in learning when operators are switched from one type of wiring to another type versus unfamiliar jobs in the same type of wiring.

This phenomena was observed when reviewing the results of all the studies, and is highlighted by the "complexity index - exponent" curves. The difference in per cent improvement was noted because of the very tight band of exponents the wiring of like units fell into, while the wiring of unlike units indicated a large spread of exponents. This conditions was not anticipated and had to be built into the plan after the series of studies were completed.

B. The limited effect of lapse periods between jobs.

As mentioned previously, it was expected that lapse would have significant effect. The empirical data to the contrary, indicated that lapse periods as long as 12 months had only token effect on experienced operators when assigned new jobs of the same apparatus type they were familiar with. This is evident in the efficiency figures for the first unit (time used/standard time), which averaged 98%. This compares with an average first unit efficiency of 75% on unlike jobs. The conclusion to be drawn from this is that the "dexterity" or motor co-ordination required in one type of unit is consistent. To elaborate, the series of motion elements required for any unit does not vary sufficiently to effect the ability of the operator to perform them. This phenomena will be touched on in the discussion of read time.

C. The significance of read time on operator improvement.

The studies were conducted in such a manner that read time was broken out and could be analyzed separately. This data is graphed in

Appendix D and the reduction slope is indicated. It is interesting to note the reduction of read time is the major factor in cycle improvement and many of the factors mentioned earlier in this paper play relatively minor roles. One of the reasons for the limited effect of lapse is the fact that read time reduction tends to overshadow the improvement in motion elements and the particular series of units studied did not require a great deal of read time. "Intelligence" <u>is</u> an important variable where reading is concerned because as blue-print reading or other instruction becomes more complicated, the more read time would be required by an operator with a low intelligence quotient. It is reasonable to conclude that as the required intelligence increases the required small lot increases, assuming that the operators are correctly selected. This theory can be substantiated by experience with the training periods required for new operators. In all instances, the length of these training periods increases as the type of work becomes increasingly difficult.

D. <u>A large variation in the number of units required to reach standard time</u>.

As mentioned previously, the limited scope of this study yielded a great deal of variation in this phase of the plan. It is this writer's opinion, however, that an increase in empirical data would indicate a more definite relationship between complexity index and the number of units to reach standard time. This would require studies of more than one operator per unit; in all probability three operators would be necessary to determine the average number of units to reach standard for the average operator.

E. Deviation from learning theory as to reasons for improvement.

The first portion of this paper dealt with a theory of learning which implied that the acquiring of nervous - muscular co-ordination by the operator was a major factor in start-up-loss. The empirical data obtained in this study did not conclusively prove this, only four of the eight units studied give an indication of improvement due to something other than read. (See plotted values of base time less read time.) The studies that indicate a definite improvement in co-ordination were conducted on the following units:

J 27973 AA-50

J 27962 AE-50

J 27551 W-1

J 27252 D-1

The remainder of the units showed little or no

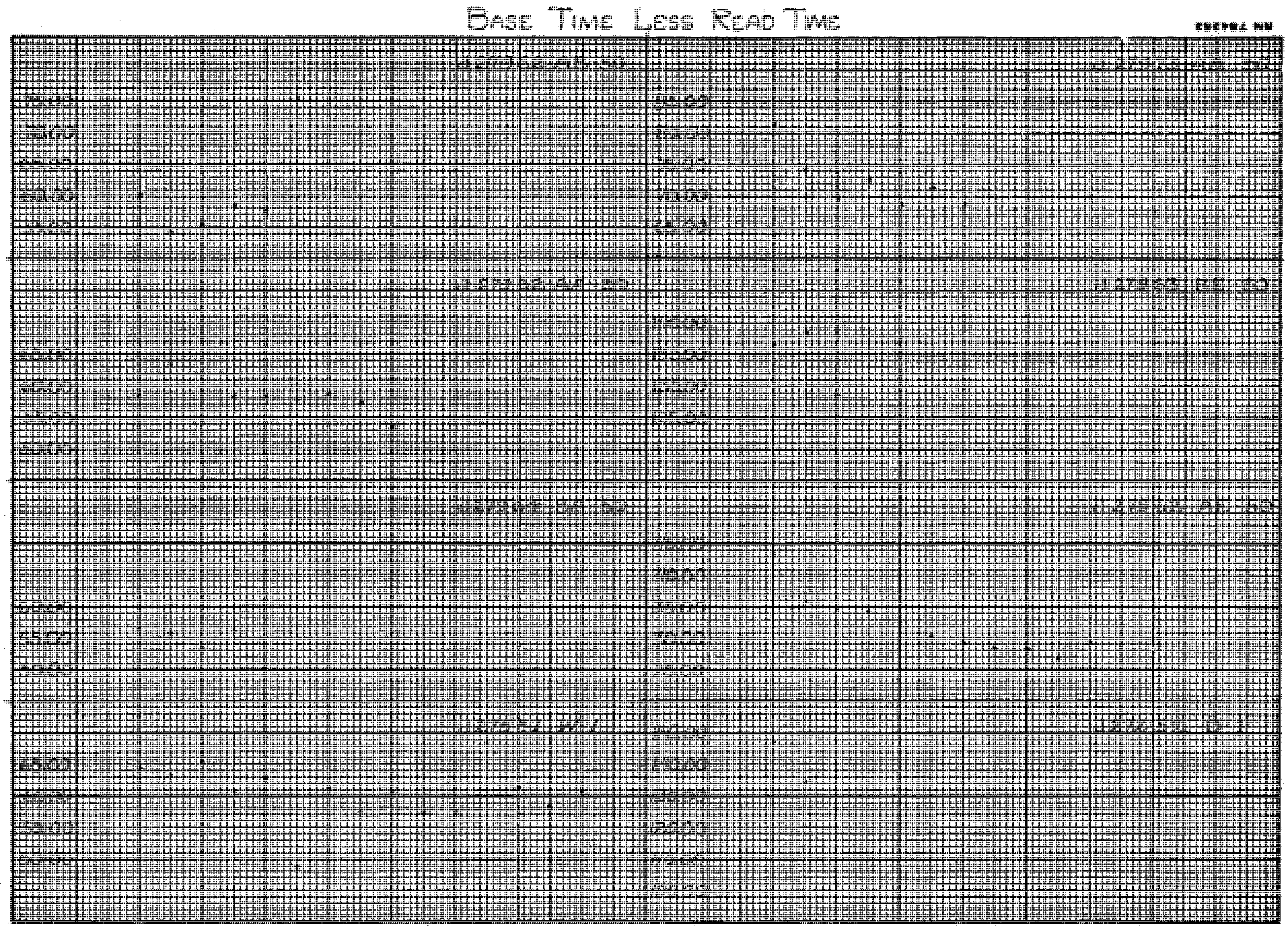


Figure 12. Base Time Less Read Time

improvement when read time reduction was omitted from the results. It is of interest to note that three of the four studies which did indicate co-ordination improvement were conducted on operators wiring jobs of a type on which they were not experienced. This would indicate that the wiring of "unlike" jobs requires a certain amount of co-ordination improvement while in the wiring of "like" units this effect is held to a minimum. This phenomena is somewhat unusual because the motion patterns are very similar on both types and once instructed, an operator should experience similar nervous-muscular reactions in an unlike unit. The instruction time was included with the read in evaluating the results and used in the calculating of read reduction; hence, it is not a factor in the plot of base time less read time.

The sample plan did achieve its purpose as an indicator of what variables to look for as well as the magnitude of the problems to anticipate if a compensation of this nature were integrated into a wage incentive system. The effectiveness of this study is limited by insufficient data which forced the writer to make a number of assumptions. However, the assumptions made should not have an adverse effect in illustrating the practicality of the proposed plan as the only phases effected were in choosing the number of units to reach standard for unlike wiring and in determining the mathematical relationship between complexity index and per cent improvement. Observations indicate these phases could be evaluated accurately with sufficient data.

It was often observed that an operator was transferred from one operation to another within a department, or that a variety of jobs were assigned to him. If this happened too much within a day, it was noticed that the productivity of the individual decreased. A process of re-learning or at least warming up usually occurred.

The factors of cost and accuracy also enter into the results of this study, and generally speaking, the proposed procedure can be followed in this respect. It has to be remembered, however, that it was preferred to apply the mathematical model on primarily data of the progress period as this is what the author was interested in for the purposes of this study.

CHAPTER IX

RECOMMENDATIONS AND SUGGESTIONS

What Could be Done in Future Research

The area of learning and re-learning industrial manual operations offers many challenging possibilities for future research. Some of these possibilities are:

1. The study of models used in describing learning processes. The particular curve used in this study is only one of the many mathematical and statistical models available. How good are these models?
2. The study of lapse time between jobs and the effect this interval has on operator re-learning. What is the optimum length of time between two sessions for specific jobs?
3. A study of application techniques for placing learning and re-learning compensation into different types of wage incentive structures. Will the coverage realized be commensurate with clerical effort required?
4. A study of the factors which determine job complexity. In this study, little consistency was

found between the elements used to indicate job difficulty; however, this phase was not explored at length. Are certain elements present in all jobs which would enable a consistent method of calculating relative complexity?

What is the Future of the Proposed Plan

In connection with the plan outlined in this paper, the writer would suggest the following be done:

1. That laboratory facilities be utilized to set up future studies, if possible. This would allow a tighter control of results and hold outside interference to a minimum. This should include a complete freedom of choice, with regard to operators and units studied, by the engineer conducting the studies. If studies must be obtained only as shop conditions permit, the formulation of a complete plan will require a great deal of time.
2. After sufficient studies are accumulated, establish a mathematical relationship between the three variables: per cent slope, complexity index and number of units to reach the standard, preliminary work in this area indicate that the relationship will be multi-dimensional and might be approximated by the general plane equation. This type of solution would make the application

more finite and should eliminate the need for a great many studies.

3. That computer facilities be utilized where possible, in development as well as in application of the plan. For example, a program could be developed for the evaluation of empirical data. The data, when run in this program, would allow the computer to generate the present slope, number of units to reach standard and correlation of the data to the mathematical model. The computer could also be used to generate the tables developed in Appendix B. Computer handling of the initial data will enable consistent and complete coverage by the plan.
4. That a systematic method of reviewing the start-up or small lot hours paid to a department be established. This could be accomplished by setting up a control chart on which total start-up hours for the month are plotted. This chart would be an indicator of work flow and out of control points should highlight changes in schedule or other conditions to be investigated.

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APPENDIXES

APPENDIX A

A DETAILED DISCUSSION OF THE MATHEMATICAL MODEL

The Model $Y = AX^b$

This model was first developed by T. P. Wright when he found that the relationship between average direct man-hour cost and the cumulative number of air frames produced could be expressed by this function.[1] His contention was that (Y) was the average direct man-hours, (x) the cumulative output with (A) the direct man-hours for the first unit and the value of (b) defining the slope. The cumulative total curve would be expressed by

$$Y_t = Yx = Ax^{1+b}. \qquad (1)$$

And the unit curve will be derived from the derivative of Equation (1)

$$\frac{dY_t}{dx} = Y_i = A\,(1+b)\;x^{\,b}. \qquad (2)$$

This work has been widely acclaimed and used by the aircraft industry, however, other authors have interpreted

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[1]T. P. Wright, "Factors Affecting the Cost of Airplanes," Journal of the Aeronautical Sciences, Vol. 3, February, 1936, pp. 122-128.

the model in a somewhat different manner and the empirical data gathered in this study tends to coincide with the interpretation of J. R. Crawford, a frequent contributor to the literature of progress curve theory.[2] His description of the model is the same as Wright's except that (Y) is defined as the direct man-hours per unit,

or $$Y_i = Ax_i^b \quad (3)$$

Thus, Crawford defines the progress curve in terms of the unit curve being linear on logarithmic grids, whereas Wright defines the progress curve in terms of the cumulative average curve being linear on logarithmic grids. As mentioned earlier, data gathered to date confirms Crawford's contention that the equation Ax_i^b yields the actual unit time and further discussion will be on this basis. For a cumulative output of N units, Equation (3) gives:

$$Y_n = A\sum_{i=1}^{n} x_i^b \quad (4)$$

and the cumulative average formula (for N units)

$$\bar{Y}_n = \frac{A\sum_{i=1}^{n} x_i^b}{N} \quad (5)$$

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[2]J. R. Crawford, Learning Curve, Ship Curve, Ratios, Related Data, Lockheed Aircraft Corporation, Burbank, California, no date.

Equation (4) becomes asymptotic to:

$$Y = A \int_0^n x^b \, dx = \frac{A}{1 + b} n^{1 + b}. \qquad (6)$$

Equation (5) becomes asymptotic to:

$$\bar{Y} = \frac{A}{1 + b} n^b \qquad (7)$$

which is Equation (6) divided by n.

If it is assumed that the learning curve can be approximated by the curve with a mathematical expression $Y = Ax^b$, then the following can be derived further. If A is first unit of time, then for a 90% curve $Y = .9A$, for the second unit substituting into the model:

$$.9A = A2^{-b} \quad \text{or} \quad .9 = 2^{-b}.$$

Thus,

$$b = \frac{-\log 0.9}{\log 2} = -0.152.$$

By this method, b values are determined for the following curves:

% - Curve	b	(1 + b)*
70	-0.514	0.486
71	-0.494	0.506
72	-0.474	0.526
73	-0.454	0.546
74	-0.434	0.566
75	-0.415	0.585
76	-0.396	0.604
77	-0.377	0.623
78	-0.358	0.642
79	-0.340	0.660
80	-0.322	0.678
81	-0.304	0.696
82	-0.286	0.714
83	-0.269	0.731
84	-0.252	0.748
85	-0.234	0.766
86	-0.218	0.782
87	-0.201	0.799
88	-0.184	0.816
89	-0.168	0.832
90	-0.152	0.848
91	-0.136	0.864
92	-0.120	0.880
93	-0.105	0.895
94	-0.089	0.911
95	-0.074	0.926
96	-0.059	0.941

Calculated exponent values for curves of different slopes.

*Value used when determining asymptote curves Equation (6) and Equation (7).

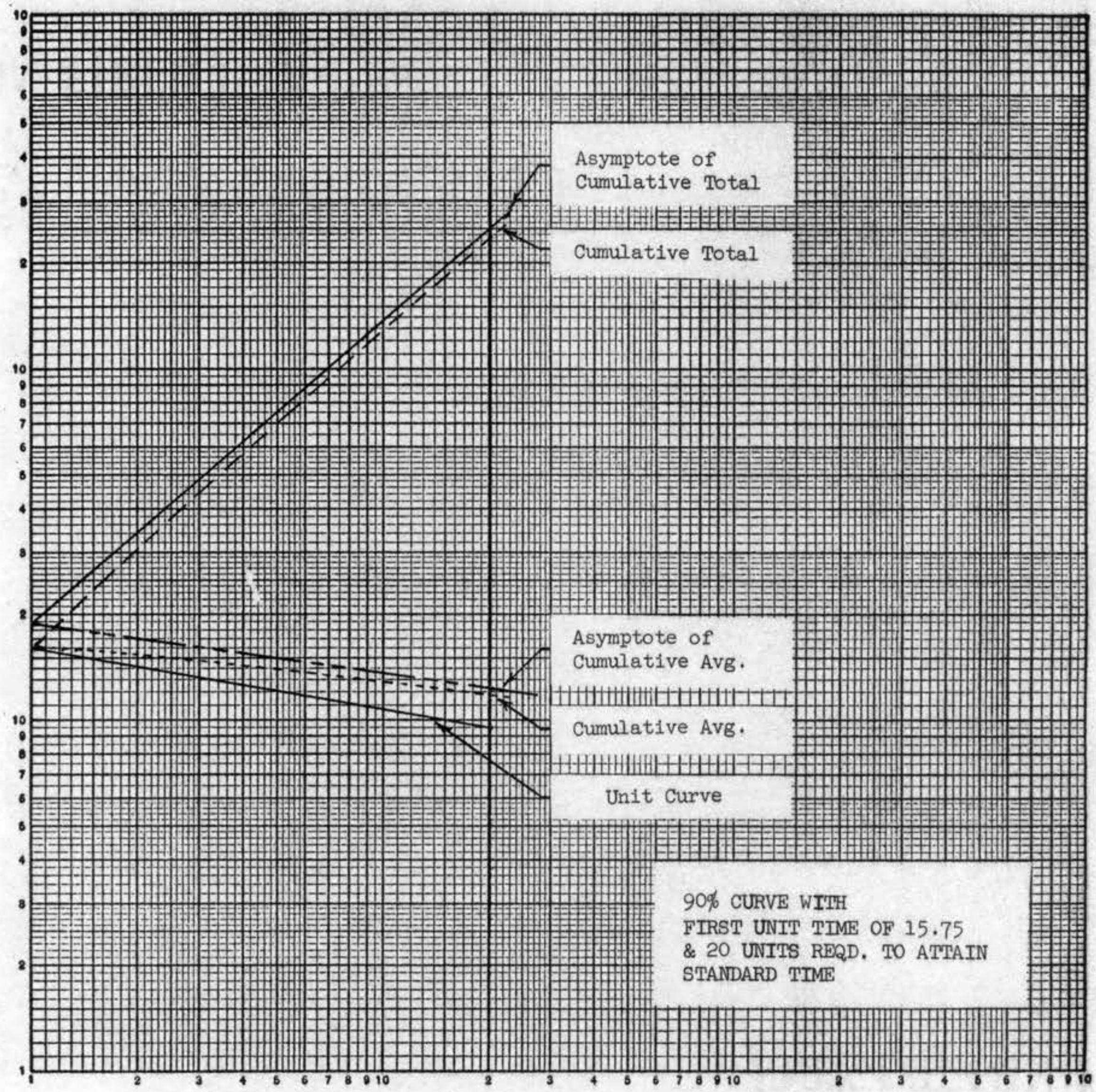

Figure 13. Properties of the Mathematical Model

APPENDIX B

PROCEDURE USED IN DERIVING PAYMENT PERCENTAGES

A. Assume a cycle time of ten minutes. (This figure is used for ease of computation.)

B. Using the formula described in Appendix A, compute the first unit value for each of the quantities (5, 10, 15, etc.) which must be run before the operator should make the base rate (assumed to be ten minutes). See Table B-I for these calculations.

C. Multiply each first unit time by the x^{-b} value for x = 1, 2, 3, etc. For a 90% time reduction curve, -b equals -.152. These calculations are tabulated in Table B-II.

D. Accumulate the time values for each category of quantities used in attaining the rate. The results of these operations are tabulated in Table B-III.

E. Divide each of these cumulative values by the lot size to determine the average time for each lot. The results of these operations are tabulated in Table B-IV.

F. Subtract the base time from each of these average times and divide this result by the base time (assumed to be ten minutes). The results of these calculations are tabulated in Table B-V as a percentage for calculating small lot allowances.

TABLE B-I

FIRST UNIT TIMES

No. of Units Required to Reach Average Efficiency	First Unit Time
3	$a = yx^b = 10\ (3)^{.152} = 11.82$
5	$= 10\ (5)^{.152} = 12.77$
10	$= 10(10)^{.152} = 14.20$
15	$= 10(15)^{.152} = 15.10$
20	$= 10(20)^{.152} = 15.75$
25	$= 10(25)^{.152} = 16.30$
30	$= 10(30)^{.152} = 16.76$
40	$= 10(40)^{.152} = 17.52$
50	$= 10(50)^{.152} = 18.10$
60	$= 10(60)^{.152} = 18.62$
70	$= 10(70)^{.152} = 19.08$
80	$= 10(80)^{.152} = 19.47$

$y = ax^{-b},\ a = y/x^{-b} = yx^b$

TABLE B-II

TIME FOR EACH UNIT

No. of units required for operator to gain or regain average efficiency

		*	3	5	10	15	20	25	30	40	50	60	70	80
1	x	1.000	11.82	12.77	14.20	15.10	15.75	16.30	16.76	17.52	18.10	18.62	19.08	19.47
2	x	.900	10.64	11.49	12.78	13.59	14.18	14.67	15.08	15.77	16.29	16.76	17.17	17.52
3	x	.846	10.00	10.80	12.01	12.78	13.33	13.79	14.18	14.82	15.31	15.75	16.14	16.47
4	x	.810		10.34	11.50	12.23	12.76	13.20	13.58	14.19	14.66	15.08	15.46	15.77
5	x	.783		10.00	11.12	11.82	12.33	12.76	13.12	13.72	14.17	14.58	14.94	15.25
6	x	.762			10.82	11.51	12.00	12.42	12.77	13.35	13.79	14.19	14.55	14.84
7	x	.744			10.57	11.24	11.72	12.13	12.47	13.04	13.47	13.85	14.20	14.49
8	x	.729			10.35	11.01	11.48	11.88	12.22	12.77	13.20	13.57	13.91	14.19
9	x	.716			10.17	10.81	11.28	11.67	12.00	12.54	12.96	13.33	13.66	13.94
10	x	.705			10.00	10.65	11.11	11.49	11.82	12.35	12.76	13.13	13.45	13.73
11	x	.695				10.50	10.95	11.33	11.65	12.18	12.58	12.94	13.26	13.53
12	x	.685				10.34	10.79	11.17	11.48	12.00	12.40	12.76	13.07	13.34
13	x	.677				10.22	10.66	11.04	11.35	11.86	12.25	12.61	12.92	13.18
14	x	.670				10.12	10.55	10.92	11.23	11.74	12.13	12.48	12.78	13.05
15	x	.663				10.00	10.44	10.81	11.11	11.62	12.00	12.35	12.65	12.91
16	x	.656					10.33	10.69	11.00	11.49	11.87	12.22	12.52	12.77
17	x	.650					10.24	10.60	10.89	11.39	11.77	12.10	12.40	12.66
18	x	.644					10.14	10.50	10.79	11.28	11.66	11.99	12.29	12.54
19	x	.639					10.06	10.42	10.71	11.20	11.57	11.90	12.19	12.44
20	x	.634					10.00	10.33	10.63	11.11	11.48	11.81	12.10	12.34
21	x	.630						10.27	10.56	11.04	11.40	11.73	12.02	12.27
22	x	.625						10.19	10.48	10.95	11.31	11.64	11.93	12.17
23	x	.621						10.12	10.41	10.88	11.24	11.56	11.85	12.09
24	x	.617						10.06	10.34	10.81	11.17	11.49	11.77	12.01
25	x	.613						10.00	10.27	10.74	11.10	11.41	11.70	11.94
26	x	.609							10.21	10.67	11.02	11.34	11.62	11.86
27	x	.606							10.17	10.62	10.97	11.28	11.56	11.80
28	x	.603							10.11	10.56	10.91	11.23	11.51	11.74
29	x	.599							10.04	10.50	10.84	11.15	11.43	11.66
30	x	.596							10.00	10.44	10.79	11.10	11.37	11.60
31	x	.593								10.39	10.73	11.04	11.31	11.55
32	x	.591								10.35	10.70	11.00	11.28	11.51
33	x	.588								10.30	10.64	10.95	11.22	11.45
34	x	.585								10.25	10.59	10.89	11.16	11.39
35	x	.5825								10.21	10.54	10.85	11.11	11.34
36	x	.580								10.16	10.50	10.80	11.07	11.29
37	x	.578								10.13	10.46	10.76	11.03	11.25
38	x	.575								10.07	10.41	10.71	10.97	11.20
39	x	.573								10.04	10.37	10.67	10.93	11.16
40	x	.571								10.00	10.34	10.63	10.90	11.12
41	x	.569									10.30	10.60	10.86	11.08
42	x	.567									10.26	10.56	10.82	11.04
43	x	.565									10.23	10.52	10.78	11.00

TABLE B-II (Continued)

			3	5	10	15	20	25	30	40	50	60	70	80
	x	.563									10.19	10.48	10.74	10.96
45	x	.561									10.15	10.45	10.70	10.92
46	x	.559									10.12	10.41	10.67	10.88
47	x	.557									10.08	10.37	10.63	10.85
48	x	.555									10.05	10.33	10.59	10.81
49	x	.553									10.02	10.30	10.55	10.77
50	x	.552									10.00	10.28	10.53	10.75
51	x	.550										10.24	10.49	10.71
52	x	.549										10.22	10.48	10.69
53	x	.547										10.19	10.44	10.65
54	x	.545										10.15	10.40	10.61
55	x	.544										10.13	10.38	10.59
56	x	.542										10.09	10.34	10.55
57	x	.541										10.07	10.32	10.53
58	x	.540										10.05	10.30	10.51
59	x	.538										10.02	10.27	10.48
60	x	.537										10.00	10.25	10.46
61	x	.535											10.21	10.42
62	x	.534											10.19	10.40
63	x	.533											10.17	10.38
64	x	.531											10.13	10.34
65	x	.530											10.11	10.32
66	x	.529											10.09	10.30
67	x	.528											10.07	10.28
68	x	.527											10.06	10.26
69	x	.525											10.02	10.22
70	x	.524											10.00	10.20
71	x	.523												10.18
72	x	.522												10.16
73	x	.521												10.14
74	x	.520												10.12
75	x	.519												10.11
76	x	.518												10.09
77	x	.517												10.07
78	x	.516												10.05
79	x	.515												10.03
80	x	.514												10.01

* **Values in this column are computed as explained in Section c.**

$$\text{for } x = 1 \quad x^{-b} = 1^{(-.152)} = 1.000$$
$$x = 2 \quad x^{-b} = 2^{(-.152)} = .900$$
$$x = 3 \quad x^{-b} = 3^{(-.152)} = .846$$
$$x = 4 \quad x^{-b} = 4^{(-.152)} = .810$$

TABLE B-III

CUMULATIVE UNIT TIMES

		3	5	10	15	20	25	30	40	50	60	70	80
1	**Cum Total**	11.82	12.77	14.20	15.10	15.75	16.30	16.76	17.52	18.10	18.62	19.08	19.47
2		22.46	24.26	26.98	28.69	29.93	30.97	31.84	33.29	34.39	35.38	36.25	36.99
3		32.46	35.06	38.99	41.47	43.26	44.76	46.02	48.11	49.70	51.13	52.39	53.46
4			45.40	50.49	53.70	56.02	57.96	59.60	62.30	64.36	66.21	67.85	69.23
5			55.40	61.61	65.52	68.35	70.72	72.72	76.02	78.53	80.79	82.79	84.48
6				72.43	77.03	80.35	83.14	85.49	89.37	92.32	94.98	97.34	99.32
7				83.00	88.27	92.07	95.27	97.96	102.41	105.79	108.83	111.54	113.81
8				93.35	99.28	103.55	107.15	110.18	115.18	118.99	122.40	125.45	128.00
9				103.52	110.09	114.83	118.82	122.18	127.72	131.95	135.73	139.11	141.94
10				113.52	120.74	125.94	130.31	134.00	140.07	144.71	148.86	152.56	155.67
11					131.24	136.89	141.64	145.65	152.25	157.29	161.80	165.82	169.20
12					141.58	147.68	152.81	157.13	164.25	169.69	174.56	178.89	182.54
13					151.80	158.34	163.85	168.48	176.11	181.94	187.17	191.81	195.72
14					161.92	168.89	174.77	179.71	187.85	194.07	199.65	204.59	208.77
15					171.92	179.33	185.58	190.82	199.47	206.07	212.00	217.24	221.68
16						189.66	196.27	201.82	210.96	217.94	224.22	229.76	234.45
17						199.90	206.87	212.71	222.35	229.71	236.32	242.16	247.11
18						210.04	217.37	223.50	233.63	241.37	248.31	254.45	259.65
19						220.10	227.79	234.21	244.83	252.94	260.21	266.64	272.09
20						230.10	238.12	244.84	255.94	264.42	272.02	278.74	284.43
21							248.39	255.40	266.98	275.82	283.75	290.76	296.70
22							258.58	265.88	277.93	287.13	295.39	302.69	308.87
23							268.70	276.29	288.81	298.37	306.95	314.54	320.96
24							278.76	286.63	299.62	309.54	318.44	326.31	332.97
25							288.76	296.90	310.36	320.64	329.85	338.01	344.91
26								307.11	321.03	331.66	341.19	349.63	356.77
27								317.28	331.65	342.63	352.47	361.19	368.57
28								327.39	342.21	353.54	363.70	372.70	380.31
29								337.43	352.71	364.38	374.85	384.13	391.97
30								347.43	363.15	375.17	385.95	395.50	403.57
31									373.54	385.90	396.99	406.81	415.12
32									383.89	396.60	407.99	418.09	426.63
33									394.19	407.24	418.94	429.31	438.08
34									404.44	417.83	429.83	440.47	449.47
35									414.65	428.37	440.68	451.58	460.81
36									424.81	438.87	451.48	462.65	472.10
37									434.94	449.33	462.24	473.68	483.35
38									445.01	459.74	472.95	484.65	494.55
39									455.05	470.11	483.62	495.58	505.71
40									465.05	480.45	494.25	506.48	516.83
41										490.75	504.85	517.34	527.91
42										501.01	515.41	528.16	538.95
43										511.24	525.93	538.94	549.95
44										521.43	536.41	549.68	560.91
45										531.58	546.86	560.38	571.83

TABLE B-III (Continued)

	3	5	10	15	20	25	30	40	50	60	70	80
Cum Total									541.70	557.27	571.05	582.71
47									551.78	567.64	581.68	593.56
48									561.83	577.97	592.27	604.37
49									571.85	588.27	602.82	615.14
50									581.85	598.55	613.35	625.89
51										608.79	623.84	636.60
52										619.01	634.32	647.29
53										629.20	644.76	657.94
54										639.35	655.16	668.55
55										649.48	665.54	679.14
56										659.57	675.88	689.69
57										669.64	686.20	700.22
58										679.69	696.50	710.73
59										689.71	706.77	721.21
60										699.71	717.02	731.67
61											727.23	742.09
62											737.42	752.49
63											747.59	762.87
64											757.72	773.21
65											767.83	783.53
66											777.92	793.83
67											787.99	804.11
68											798.05	814.37
69											808.07	824.59
70											818.07	834.79
71												844.97
72												855.13
73												865.27
74												875.39
75												885.50
76												895.59
77												905.66
78												915.71
79												925.74
												935.75

TABLE B-IV

AVERAGE TIME FOR EACH SIZE LOT

	3	5	10	15	20	25	30	40	50	60	70	80
Cum Tot + 1	11.82	12.77	14.20	15.10	15.75	16.30	16.76	17.52	18.10	18.62	19.08	19.47
2	11.23	12.13	13.49	14.35	14.97	15.49	15.92	16.65	17.20	17.69	18.13	18.50
3	10.82	11.69	13.00	13.82	14.42	14.92	15.34	16.04	16.57	17.04	17.46	17.82
4		11.35	12.62	13.43	14.01	14.49	14.90	15.58	16.09	16.55	16.96	17.31
5		11.08	12.32	13.10	13.67	14.14	14.54	15.20	15.71	16.16	16.56	16.90
6			12.07	12.84	13.39	13.86	14.25	14.90	15.39	15.83	16.22	16.55
7			11.86	12.61	13.15	13.61	13.99	14.63	15.11	15.55	15.93	16.28
8			11.67	12.41	12.94	13.39	13.77	14.40	14.87	15.30	15.68	16.00
9			11.50	12.23	12.76	13.20	13.58	14.19	14.66	15.08	15.46	15.77
10			11.35	12.07	12.59	13.03	13.40	14.01	14.47	14.89	15.26	15.57
11				11.93	12.44	12.88	13.24	13.84	14.30	14.71	15.07	15.38
12				11.80	12.31	12.73	13.09	13.69	14.14	14.55	14.91	15.21
13				11.68	12.18	12.60	12.96	13.55	14.00	14.40	14.75	15.06
14				11.57	12.06	12.48	12.84	13.42	13.86	14.26	14.61	14.91
15				11.46	11.95	12.37	12.72	13.30	13.74	14.13	14.48	14.78
16					11.85	12.27	12.61	13.19	13.62	14.01	14.36	14.65
17					11.76	12.17	12.51	13.08	13.51	13.90	14.24	14.54
18					11.67	12.08	12.42	12.98	13.41	13.80	14.14	14.43
19					11.58	11.99	12.33	12.89	13.31	13.70	14.03	14.32
20					11.51	11.91	12.24	12.80	13.22	13.60	13.94	14.22
21						11.83	12.16	12.71	13.13	13.51	13.85	14.13
22						11.75	12.09	12.63	13.05	13.42	13.76	14.04
23						11.68	12.01	12.56	12.97	13.35	13.67	13.95
24						11.62	11.94	12.48	12.90	13.27	13.60	13.87
25						11.55	11.88	12.41	12.83	13.19	13.52	13.80
26							11.81	12.35	12.76	13.12	13.45	13.72
27							11.75	12.28	12.69	13.05	13.38	13.65
28							11.69	12.22	12.63	12.99	13.31	13.58
29							11.64	12.16	12.56	12.93	13.24	13.51
30							11.58	12.10	12.50	12.87	13.18	13.45
31								12.05	12.45	12.81	13.12	13.39
32								12.00	12.39	12.75	13.07	13.33
33								11.95	12.34	12.70	13.01	13.28
34								11.90	12.29	12.64	12.96	13.22
35								11.83	12.24	12.59	12.90	13.17
36								11.80	12.19	12.54	12.85	13.11
37								11.76	12.14	12.49	12.80	13.06
38								11.71	12.10	12.45	12.75	13.01
39								11.67	12.05	12.40	12.71	12.97
40								11.63	12.01	12.36	12.66	12.92
41									11.97	12.31	12.62	12.88
42									11.93	12.27	12.58	12.83
43									11.89	12.23	12.53	12.79
44									11.85	12.19	12.49	12.75
45									11.81	12.15	12.45	12.71

TABLE B-IV (Continued)

	3	5	10	15	20	25	30	40	50	60	70	80
Ct ot + 46									11.78	12.11	12.41	12.67
47									11.74	12.08	12.38	12.63
48									11.71	12.04	12.34	12.59
49									11.67	12.01	12.30	12.55
50									11.64	11.97	12.27	12.52
51										11.94	12.23	12.48
52										11.90	12.19	12.44
53										11.87	12.17	12.41
54										11.84	12.13	12.38
55										11.81	12.10	12.35
56										11.78	12.07	12.32
57										11.75	12.04	12.28
58										11.72	12.01	12.25
59										11.69	11.98	12.22
60										11.66	11.95	12.19
61											11.92	12.17
62											11.89	12.14
63											11.87	12.11
64											11.84	12.08
65											11.81	12.05
66											11.79	12.03
67											11.76	12.00
68											11.74	11.98
69											11.71	11.95
70											11.69	11.93
71												11.90
72												11.88
73												11.85
74												11.83
75												11.81
76												11.78
77												11.76
78												11.74
79												11.72
80												11.70

TABLE B-V

PERCENTAGE TO BE ADDED FOR EACH LOT SIZE CURVE - 90%

Lot Size	Number of cycles operator is allowed to reach average efficiency											
	3	5	10	15	20	25	30	40	50	60	70	80
1	18%	28%	42%	51%	57.5%	63%	67.5%	75%	81%	86%	91%	95%
2	12	21	35	43.5	50	55	59	66.5	72	77	81	85
3	8	17	30	38	44	49	53.5	60.5	66	70.5	74.5	78
4		13.5	26	34	40	45	49	56	61	65.5	69.5	73
5		11	23	31	37	41.5	45.5	52	57	61.5	65.5	69
6			21	28.5	34	38.5	42.5	49	54	58	62	65.5
7			18.5	26	31.5	36	40	46	51	55.5	59	63
8			16.7	24	29.5	34	38	44	49	53	57	60
9			15	22	27.5	32	36	42	46.5	51	54.5	58
10			13.5	21	26	30	34	40	45	49	52.5	56
11				19	24.5	29	32.5	38.5	43	47	51	54
12				18	23	27	31	37	41.5	45.5	49	52
13				17	22	26	29.5	35.5	40	44	47.5	50.5
14				16	20.5	25	28.5	34	38.5	42.5	46	49
15				14.5	19.5	24	27	33	37.5	41	45	48
16					18.5	23	26	32	36	40	43.5	46.5
17					17.5	22	25	31	35	39	42.5	45.5
18					17	21	24	30	34	38	41.5	44
19					16	20	23	29	33	37	40	43
20					15	19	22.5	28	32	36	39.5	42
21						18	21.5	27	31	35	38.5	41
22						17.5	21	26	30.5	34	37.5	40.5
23						17	20	25.5	30	33.5	36.5	39.5
24						16	19.5	25	29	33	36	39
25						15.5	19	24	28	32	35	38
26							18	23.5	27.5	31	34.5	37
27							17.5	23	27	30.5	34	36.5
28							17	22	26	30	33	36
29							16.5	21.5	25.5	29	32.5	35
30							16	21	25	28.5	32	34.5
31								20.5	24.5	28	31	34
32								20	24	27.5	30.5	33.5
33								19.5	23.5	27	30	33
34								19	23	26.5	29.5	32
35								18.5	22.5	26	29	31.5
36								18	22	25.5	28.5	31
37								17.5	21.5	25	28	30.5
38								17	21	24.5	27.5	30
39								16.5	20.5	24	27	29.5
40								16	20	23.5	26.5	29
41									19.5	23	26	29
42									19.5	22.5	26	28.5
43									19	22	25.5	28
44									18.5	22	25	27.5
45									18	21.5	24.5	27

TABLE B-V (Continued)

Lot Size	3	5	10	15	20	25	30	40	50	60	70	80
46									18	21	24	26.5
47									17.5	21	24	26
48									17	20.5	23.5	26
49									16.5	20	23	25.5
50									16.5	20	22.5	25
51										19.5	22	25
52										19	22	24.5
53										19	21.5	24
54										18.5	21	24
55										18	21	23.5
56										18	20.5	23
57										17.5	20.5	23
58										17	20	22.5
59										17	20	22
60										16.5	19.5	22
61											19	21.5
62											19	21.5
63											18.5	21
64											18.5	21
65											18	20.5
66											18	20.5
67											17.5	20
68											17.5	20
69											17	19.5
70											17	19.5
71												19
72												19
73												18.5
74												18.5
75												18
76												18
77												17.5
78												17.5
79												17
80												17

APPENDIX C

SOURCE OF FACTORS FOR COMPLEXITY INDEX

Complexity Index - Frame Wiring

In order to establish a wiring rate on a frame, all pertinent drawings must be obtained. The SRJ (Soldering Record Drawing) is the key and all apparatus and wire ends are indicated on this drawing. The analyst counts the different types of connections, notes, etc., and records the totals in colored pencil directly on the print. The counts are then transcribed to the "Frame Wiring Worksheet". This worksheet is constructed to convert the totals into minutes on a list or option basis (one sheet per list). The "Frame Wiring Worksheets" for a frame are then summarized on the "Frame Wiring Summary" sheet. Frame test uses a similar procedure.

The Complexity Index components are found on the following sheets (see examples):

TW	Typical Base Rate (Wiring)	Frame Wiring Summary
L	Number of Lists (Options)	Frame Wiring Summary
NR	Number of Notes	Frame Wiring Worksheet
NE	Number of Wire Ends on Frame	Frame Wiring Summary
TT	Typical Test Rate	Frame Test Summary

FRAME WIRING SUMMARY

List	822 Count	A Typical Quantity	B Solder Conn/List	A x B Typ.Sold. Count	C Eqp'd Min/List	A x C Typical Min. Eqp'd	D Conn. Per List	A x D Typical Conn.	E Rate BH/C Lists	A x E/100 Typical Base Hours	Read Min.	Remarks
				Less Preparation (31.64)								

TOTAL (AB) ________ (AC) ________ (AD) ________ (AE) ________ = Typical BH/Frame

AC + AD = ________ Min/Conn. AE + AD = ________ BH/Conn.

ENGINEER __________ DATE __________ DRWG. ______________

CALC. OPER. ________ APPROVAL ________ SRJ ISS. _____ ISS. ______

W. S. 555, Issue 2(4-62), OKLA. CITY WORKS

Tab 6, S. S. ___

Tab. 6, Sht. ____

FRAME WIRING WORKSHEET

Preparation — Minutes

Constant Time/Frame. . . . . ____ x 31.64 =
Add'l for Dbl Bay Frame...For Each Succ L.C. ____ x 1.622 + ____ x 3.889 =
Obtain 1st Suppl Cable...Each Add'l Cable. . ____ x 1.080 + ____ x .4300 =
Tie L.C. to: "L" or "U"..P40B702 Type Brkt . ____ x .8500 + ____ x 1.560 =
Bar, Cable Arm or Framework. . . . . ____ x .9820 =
Select "PT" Apparatus from File. . . . . ____ x .9421 =
Select Each Different Code of "PT" . . . . ____ x .2568 =
Select Each Add'l "PT" of Same Code. . . . . ____ x .0122 =
Handle & Straighten Cable Arms: (0+" – 12") . . . . ____ x .0696 =
(12+" – 24"). . . . . ____ x .0960 =
(24+" – 36"). . . . . ____ x .1213 =
Prepare to Wire: (1) Jack Panel (Print & Tool). . . . . . . ____ x 2.347 =
(2) Jack Panels (Handling Incl). . . . . . ____ x 3.632 =
Shift to Wire Vertical Arms/Frame Class # (____) . . . . . . ____ x ____ =
Blow Out & Vacuum Frame/Sq Ft. . . . . ____ x .1984 =
Handle Prints/Sht.../Sk with "PT", Nets, Strap . ____ x 1.024 + ____ x .1420 =
____ ____ ____ x ____ + ____ x ____ =
____ ____ ____ x ____ + ____ x ____ =
____ ____ ____ x ____ + ____ x ____ =
____ ____ ____ x ____ + ____ x ____ =

(A) ____

ADD FOR	UNEQ'D									
		From List--								
		Minutes								
		Times								

(B) ____

Cont'd

ADD FOR	UNEQ'D									
		From List--								
		Minutes								
		Times								

(C) ____

UNEQ'D	INEQ'D																	
		Code																
		Sleeve															____ x ____	=
		Sleeve															____ x ____	=
		Stitch															____ x .1123	=
		Tube															____ x ____	=
		Tube															____ x ____	=

(D) ____

CONNECT																		
		Code																
	"PT"	To W.S. – 0 Sl.															____ x .5028	=
	"PT"	To W.S. – 1 Sl.															____ x .5319	=
	"PT"	To W.S. – 2 Sl.															____ x .5610	=
	"PT"	To Flat – 0 Sl.															____ x .4267	=
	"PT"	To Flat – 1 Sl.															____ x .4558	=
	"PT"	To Flat – 2 Sl.															____ x .4849	=
	NETS	To W.S. – 1 Sl.															____ x .2745	=
	NETS	To W.S. – 2 Sl.															____ x .3024	=
	NETS	To Flat – 1 Sl.															____ x .3066	=
	NETS	To Flat – 2 Sl.															____ x .3357	=

(E) ____

Connections ____ Solder Count ____ "PT" & Nets ____

TOTAL MINUTES. . . . .(A + B + C + D + E + H + J + L) – (X) = (T) ____

TOTAL INCIDENTAL ALLOWANCE . . . .(T) x 1.017 = (M) ____

BASE HOURS PER 100 LISTS . . . . (M) x 1.819 = (BH/C) ____

ENGINEER ____ DATE ____ SRJ ____ DRWG. ____

CALC. OPER. ____ APPROVAL ____ ISS. ____ ISS. ____ LIST ____

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Tab 6, Sht. _____

FRAME WIRING WORKSHEET

			Total	Minutes
		SRI Sheet		
	L	Sketch		
	O	Func. Desig.		
	C	Apparatus		
C		Code No.		
O	P	Desc. No.		
N	A	Minutes		*(F) _____
N	R	Count Conn	_____	
E	T	Out. W/O		
C	I	Add Wires		
T	P	Desc. No.		
	A	Minutes		*(G) _____
	R	Count Conn	_____	
	T	Out. W/O		
	II	Add Wires		(F) + (G) = (H) _____
S		W.S. T.S Bare	_____	x .0966 =
T		Other W.S.	_____	x .1092 =
R		Flat	_____	x .1024 =
S		Wire Spring	_____	x .0321 =
O		Flat	_____	x .0278 =
L		Plier W.S.	_____	x .0323 =
		Spread Term.	_____	x .0088 =
M		Clinch Term.	_____	x .0175 =
I		"F" Stitch	_____	x .0100 =
S		Loop 24GA	_____	x .0815 =
C		286 M.C. Dress	_____	x .0306 =
		287 M.C. Dress	_____	x .0612 =
O		Flat Dress	_____	x .0125 =
P	Tool Handle	Gun	_____	x .0288 =
E		Iron	_____	x .0742 =
R		Other	_____	x .0292 =
A		Nets (No S1) W.S.	_____	x .2477 =
T		Nets (No S1) Flat	_____	x .2775 =
I			_____	x _____ =
O			_____	x _____ =
N			_____	x _____ =
S			_____	x _____ =
			_____	x _____ =
			_____	x _____ =
				(J) _____

		Total	Minutes
R	Mfr. Notes	_____	x .0065 =
E	Wiring Notes	_____	x .0401 =
A	Seq. Notes	_____	x .0131 =
D	Wires	_____	x .0265 =
I	Strap Ends	_____	x .0147 =
N	"PT" App.	_____	x .0702 =
G	Networks	_____	x .0215 =
			(K) _____

(Add _____ Times to List _____)

(K) _____ x % _____ = (L) _____

		Total	Minutes
U	Sleeve	_____	x _____ =
N	Sleeve	_____	x _____ =
E	Stitch	_____	x .1123 =
Q	Tube	_____	x _____ =
'		_____	x _____ =
D		_____	x _____ =
			(X) _____

DRWG ________________ LIST ________

* = Total of each Minutes x Count Conn.

(Back) WS 429

OPERATION TEST SUMMARY

Wire End Count For Defect Allowance			List	Base Hours/C	Typical		List	Base Hours/C	Typical	
Description	List	Wire Ends			Occ.	BH			Occ.	BH

APL ____ QTR = $\frac{Fr}{Wk}$ = ______ /Wk (A) ________ (B) ________

Typical Base Hour Value = (A + B) = ________

ENGINEER ________ DATE ____________ IMI ______ DRWG. ________________

CALC, OPER. _____ APPROVAL _______ ISS. _____ ISS. ________

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Complexity Index - Unit Wiring

In order to establish a wiring rate on a unit, the surface wiring drawing (SWJ) and the circuit drawing (T) must be obtained. The analyst using these drawings counts the number of connections, reads tool handlings, etc., and records these counts directly on the "Surface Wiring Worksheet." This worksheet converts the counts into minute values on a per option basis.

The Complexity Index components are found on the following sheets:

Wire Spring Apparatus	Surface Wire - Unit With Wire Spring Relays Worksheet
Flat Type (U and Y) Apparatus	Surface Wire - Unit With U and Y Type Relays Worksheet

The component letters correspond to the worksheet letters (see examples):

A = Preparation and Handling (per fixture)

B = Reading Time

C = Run, Dress and Connect Time

D = Units Per Fixture

L = Total Number of Wires

W = Number of Wire Descriptions.

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SURFACE WIRE
UNIT WITH U & Y TYPE RELAYS
(Oklahoma City Folder D-107.1)

CONNECT PT APPARATUS & SOLDER

Preparation & Handling Per Fixture (Requiring PT App. & Soldering)	____	x 1.6368	=
(Requiring Soldering Only)	____	x 1.3702	=
Turn Fixture to Solder on Apparatus Side	____	x .2799	=
Read List From Sketch Tag	____	x .0252	=
Turn to New Column of Connecting Information	____	x .0460	=
Handle Tools	____	x .0211	=
Select PT Apparatus (Per Type of PT Connected)	____	x .1211	=
Networks (Per Type of Network Connected)	____	x .0456	=
	____	x ____	=
SUB-TOTAL Preparation & Select (Per Fixture)		(A') ____	

Read SWJ Headings (Per Line)	____	x .0128	=
Notes (Per Word or Symbol)	____	x .0065	=
(Per Column Note)	____	x .0050	=
PT Descriptions (Per Line)	____	x .0186	=
Connecting Instructions for Networks (Per Instruction)	____	x .0622	=
Connecting Instructions for Other PT (Per Instruction)	____	x .0862	=
	____	x ____	=
SUB-TOTAL Read		(B') ____	

Connect Networks to Wire Type Terminal-Gun (Per Lead)	____	x .0480	=
" " Flat Type Terminal-Pliers (Per Lead)	____	x .0895	=
Other PT to Wire Type Terminal-Gun (Per Lead)	____	x .0783	=
" " " Flat Type Terminal-Pliers (Per Lead)	____	x .1198	=
" " " Wire Type Terminal-Pliers (Per Lead)	____	x .1713	=
Sleeve Networks & Other PT (1) Lead (Per PT)	____	x .0559	=
" " " " (2) Leads (Per PT)	____	x .0898	=
Solder Connection Without PT (Per Connection)	____	x .0366	=
Connection With PT (Per Connection)	____	x .0552	=
Stamp Operator Identification On Unit (Per Unit)	____	x .0211	=
	____	x ____	=
SUB-TOTAL Connect & Solder		(C') ____	

Units Per Wk		Leads (All Lists)		Base Hrs. Per Lead		Hours Per Week	
____	x	____	x	____	=	____	(Use Table ____)

Fixtures Per Week ____ Units Per Fixture (D) ____
Wire Descriptions ____ Read Factor (F) ____

	WIRING TOTALS		SOLDERING TOTALS	
MODIFIED READ PER FIXTURE	(B x F) = (G)	____	(B' x F) = (G')	____
PREP., SEL. & READ PER FIXT.	(A + G) = (H)	____	(A' + G') = (H')	____
PREP., SEL. & READ PER UNIT	(H ÷ D) = (J)	____	(H' ÷ D) = (J')	____
TOTAL MINUTES PER LIST	(J + C) = (T)	____	(J' + C') = (T')	____
TOTAL INCL. ALLOW.	(T x 1.02) = (M)	____	(T' x 1.02) = (M')	____
BH/C LIST	(M x 1.819) = (BH)	____	(M' x 1.819) = (BH')	____

TOTAL BH/C LIST (WIRING & SOLDERING) (BH + BH') = ____

Lead Count (L) ____	T.C. ____ Engr. ____		
Solder Count ____	Date ____	Drwg. Issues	Drwg. ____
Min./Lead	Comp. Oper. ____	J- ____	
(M) ÷ (L) = ____	Approved ____	SWJ- ____	List ____

UNIT WITH WIRE SPRING RELAYS

WIRING OPERATIONS

Operation		Factor
PREPARATION & HANDLING (Per Fixture)	x	1.2173 =
Turn fixture to wire on apparatus side	x	.2799 =
Flag fixture requiring no soldering	x	.0538 =
Read list from sketch tag	x	.0252 =
Turn to new column of SWJ	x	.1429 =
SELECT Tray ( )	x	=
( )	x	=
Return	x	=
Disp. ( )	x	.0052 =
( )	x	=
Return	x	=
Handle Tool	x	.0202 =
	x	.0211 =
(A)		
READ A	x	=
B	x	=
C	x	=
D	x	=
SWJ Heading	x	.0128 =
Note Ref.	x	.1116 =
Word & Sym.	x	.0065 =
Col. Note	x	.0050 =
OC Conn.	x	.0175 =
OC Not Conn	x	.0314 =
SWJ COL. (B)		
RUN DRESS & CONNECT A2	x	.1092 =
A	x	.1092 =
A3	x	.1228 =
B2	x	.1098 =
B	x	.1098 =
B3	x	.1228 =
B5	x	.1416 =
B9	x	.1544 =
B14	x	.1755 =
C2	x	.1242 =
C	x	.1242 =
C3	x	.1484 =
C5	x	.1594 =
C9	x	.1749 =
C14	x	.1812 =
D3	x	.1582 =
D5	x	.1694 =
D9	x	.1824 =
D14	x	.1919 =
TOTAL		
Plier Conn.	x	.0702 =
Dry Reed	x	(.0012)=
Connect relay rack ground	x	.3940 =
Spread Terminals	x	.0145 =
Tie Group of Wires	x	.2850 =
Mass Dress (Per Unit)	x	.2532 =
(Per Plate)	x	.5175 =
Stamp Operators Identification on Unit (Per Unit)	x	.0211 =
(C)		

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SURFACE WIRE
UNIT WITH WIRE SPRING RELAYS
(OKLAHOMA CITY FOLDER D-107.2)

CONNECT PT APPARATUS & SOLDER

Preparation & Handling Per Fixt. (Requiring PT App. & Soldering)	______	x 1.6368	=
(Requiring Soldering Only)	______	x 1.3702	=
Turn Fixture to Solder on Apparatus Side	______	x .2799	=
Read List From Sketch Tag	______	x .0252	=
Turn to New Column of Connecting Info.	______	x .0460	=
Handle Tools	______	x .0211	=
Select PT Apparatus (Per Type of PT Connected)	______	x .1211	=
Networks (Per Type of Network Connected)	______	x .0456	=
______	______	x ______	=
SUB-TOTAL Preparation & Select (Per Fixture)	(A') ______		
Read SWJ Headings (Per Line)	______	x .0128	=
Notes (Per Work or Symbol)	______	x .0065	=
(Per Column Note)	______	x .0050	=
PT Descriptions (Per Line)	______	x .0186	=
Connecting Instructions for Networks (Per Instruction)	______	x .0622	=
Connecting Instructions for Other PT (Per Instruction)	______	x .0862	=
______	______	x ______	=
SUB-TOTAL Read	(B') ______		
Connect Networks to Wire Type Terminal-Gun (Per Lead)	______	x .0480	=
Flat Type Terminal-Pliers (Per Lead)	______	x .0895	=
Other PT to Wire Type Terminal-Gun (Per Lead)	______	x .0783	=
Flat Type Terminal-Pliers (Per Lead)	______	x .1198	=
Wire Type Terminal-Pliers (Per Lead)	______	x .1713	=
Sleeve Networks & Other PT (1) Lead (Per PT)	______	x .0559	=
(2) Leads (Per PT)	______	x .0898	=
Solder Connection Without PT (Per Connection)	______	x .0366	=
Connection With PT (Per Connection)	______	x .0552	=
Stamp Operator Identification On Unit (Per Unit)	______	x .0211	=
______	______	x ______	=
SUB-TOTAL Connect & Solder	(C') ______		

Units Per Wk		Leads (All Lists)		Base Hrs ~~Per~~ Lead		Hours Per Week	
______	x	______	x	______	=	______	(Use Table ____)

Fixtures Per Week ______ Units Per Fixture (D) ______
Wire Descriptions ______ Read Factor (F) ______

	Wiring Totals		Soldering Totals	
MODIFIED READ PER FIXTURE	(B x F) = (G)	______	(B' x F) = (G')	______
PREP., SEL. & READ PER FIXT.	(A + G) = (H)	______	(A' + G') = (H')	______
PREP., SEL. & READ PER UNIT	(H + D) = (J)	______	(H' + D) = (J')	______
TOTAL MINUTES PER LIST	(J + C) = (T)	______	(J' + C') = (T')	______
TOTAL INCL. ALLOW.	(T x 1.02) = (M)	______	(T' x 1.02) = (M')	______
BH/C LIST	(M x 1.819) = (BH)	______	(M' x 1.819) = (BH')	______

TOTAL BH/C LIST (WIRING & SOLDERING) (BH + BH') = ______

Lead Count(L) ______	T.C. ______ Engr. ______	Drwg. Issues	Drwg. ______
Solder Count ______	Date ______		
Min./Lead	Comp. Oper. ______	J ______	
(M) + (L) ______	Approved ______	SWJ ______	List ______

LIST ____________

UNIT WITH U & Y TYPE RELAYS

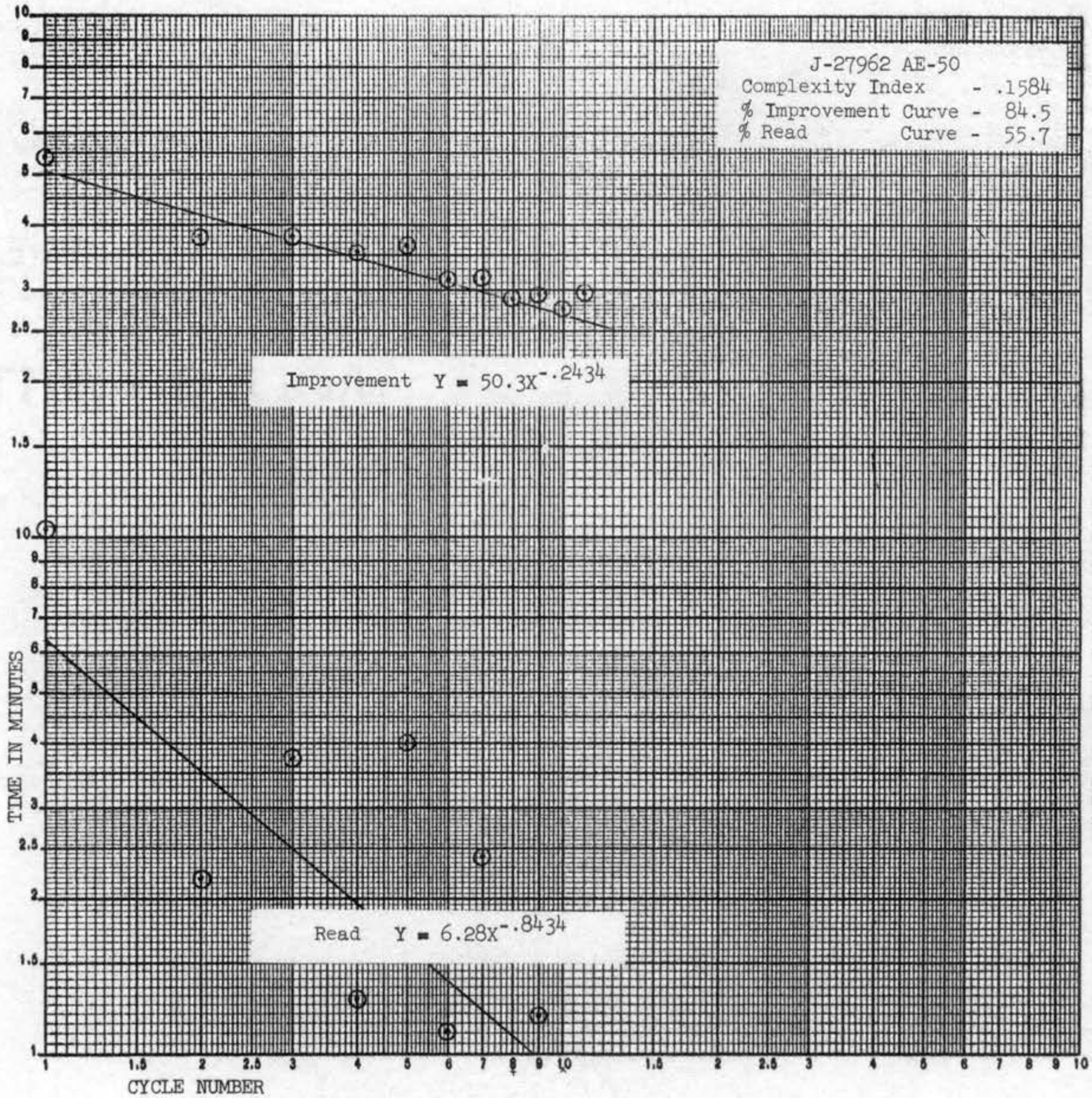
WIRING OPERATIONS

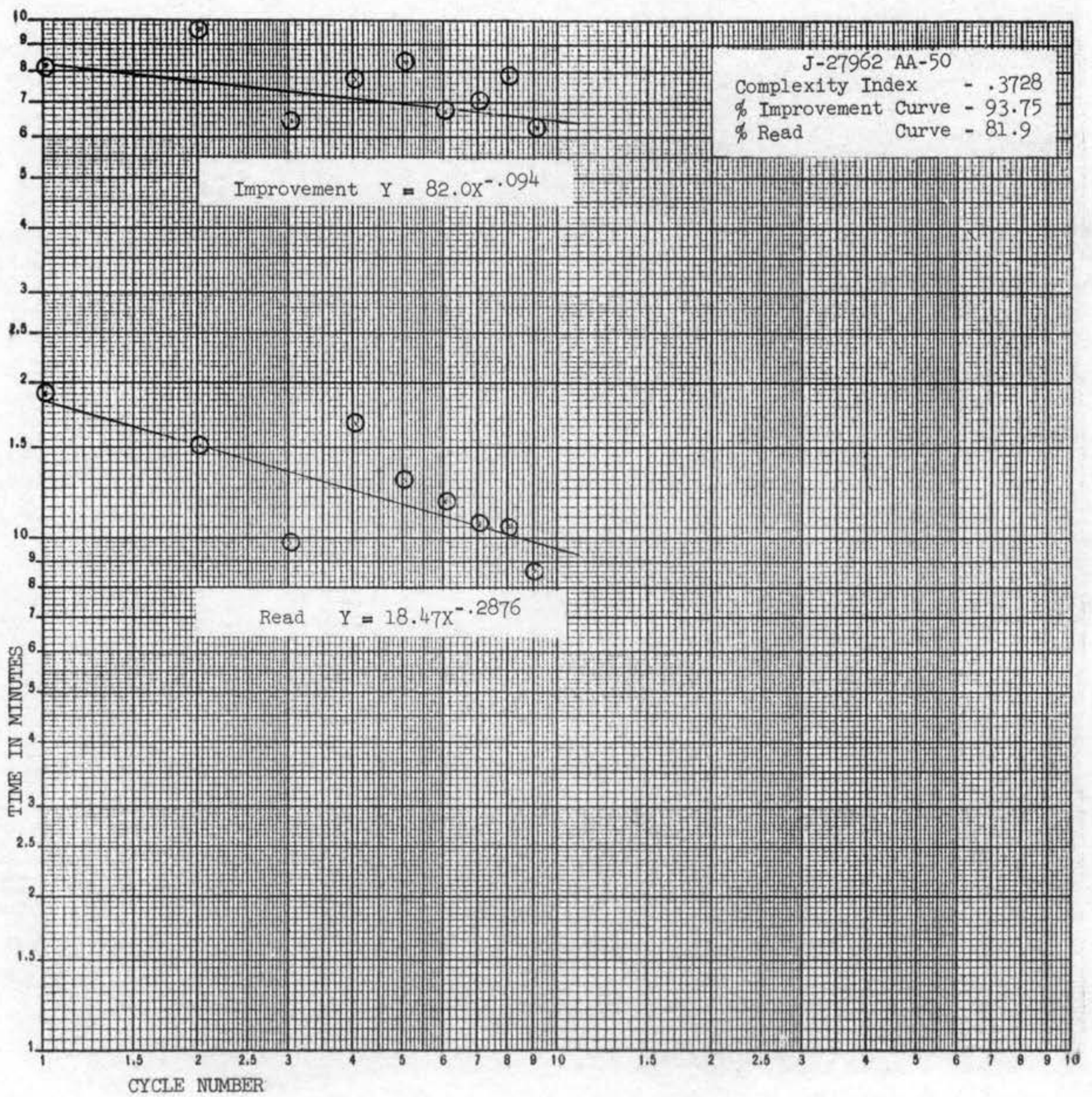
Operation	Quantity	Factor
PREPARATION & HANDLING (Per Fixture)		x 1.2173 =
Turn fixture to wire on apparatus side		x .2799 =
Flag fixture requiring no soldering		x .0538 =
Read list from sketch tag		x .0252 =
Turn to new column of SWJ		x .1429 =
		x ______ =
SELECT Tray ( )		x ______ =
SELECT Tray ( )		x ______ =
SELECT Tray Return		x .0052 =
SELECT Disp. ( )		x ______ =
SELECT Disp. ( )		x ______ =
SELECT Disp. Return		x .0202 =
Handle Tool		x .0211 =
(A)		
READ A		x ______ =
READ B		x ______ =
READ C		x ______ =
READ D		x ______ =
Strap/Line		x .0362 =
SWJ Heading		x .0128 =
Note Ref.		x .1116 =
Word & Sym.		x .0065 =
Col. Notes		x .0050 =
OC Conn.		x .0175 =
OC Not Conn		x .0314 =
SWJ COL. (B)		
RUN DRESS & CONNECT A2		x .1118 =
A		x .1118 =
A3		x .1248 =
B2		x .1118 =
B		x .1118 =
B3		x .1248 =
B5		x .1400 =
B9		x .1659 =
B14		x .1755 =
C2		x .1190 =
C		x .1190 =
C3		x .1329 =
C5		x .1449 =
C9		x .1677 =
C14		x .1760 =
D3		x .1523 =
D5		x .1735 =
D9		x .2166 =
D14		x .2278 =
TOTAL		
Plier Conn		x .0713 =
227 T.S.		x .0735 =
Bare strap two flat type terminals (per strap)		x .1367 =
Series of flat terminals (1st Loop) ______ x .1524 + (Ea. Add'l)		x .0395 =
Wrap two network terminals together		x .1097 =
Connect relay rack ground		x .3940 =
Spread Terminals		x .0145 =
Tie Group Of Wires		x .2850 =
Mass Dress (Per Unit)		x .2532 =
Mass Dress (Per Plate)		x .5175 =
Stamp Operators Identification on Unit (Per Unit)		x .0211 =
		______ =
		______ =
(C)		

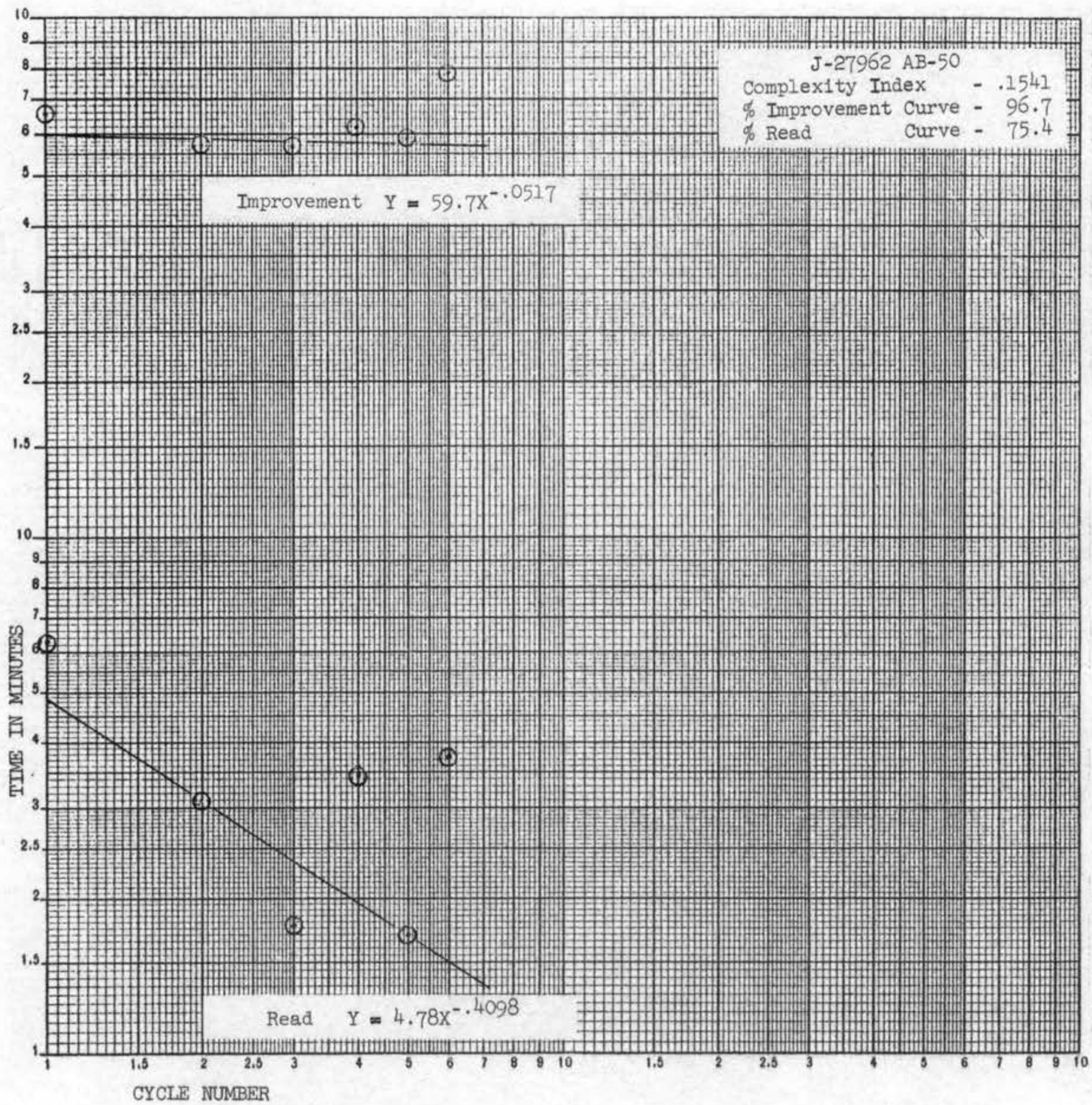
WS-78 (Back)

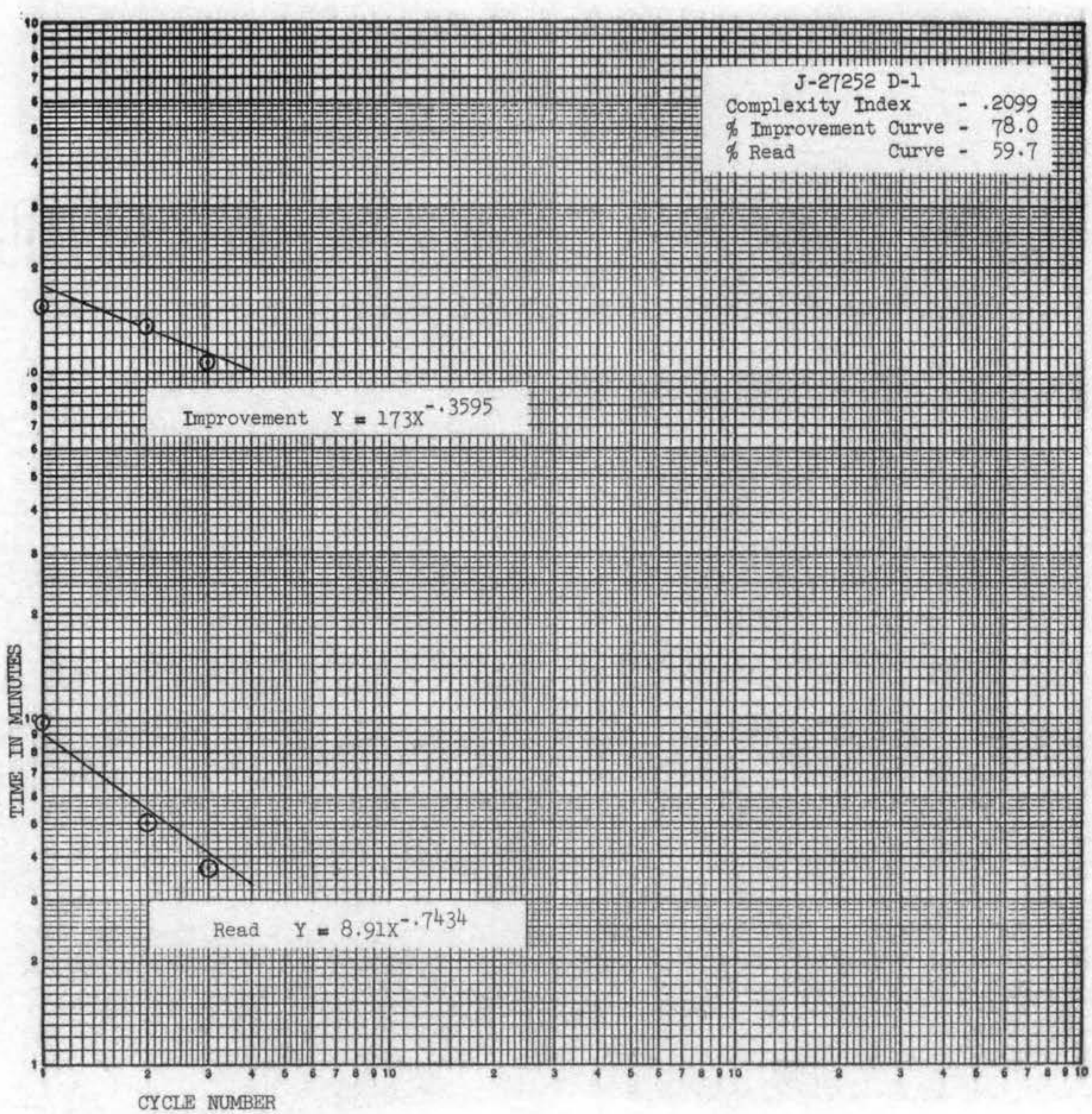
APPENDIX D

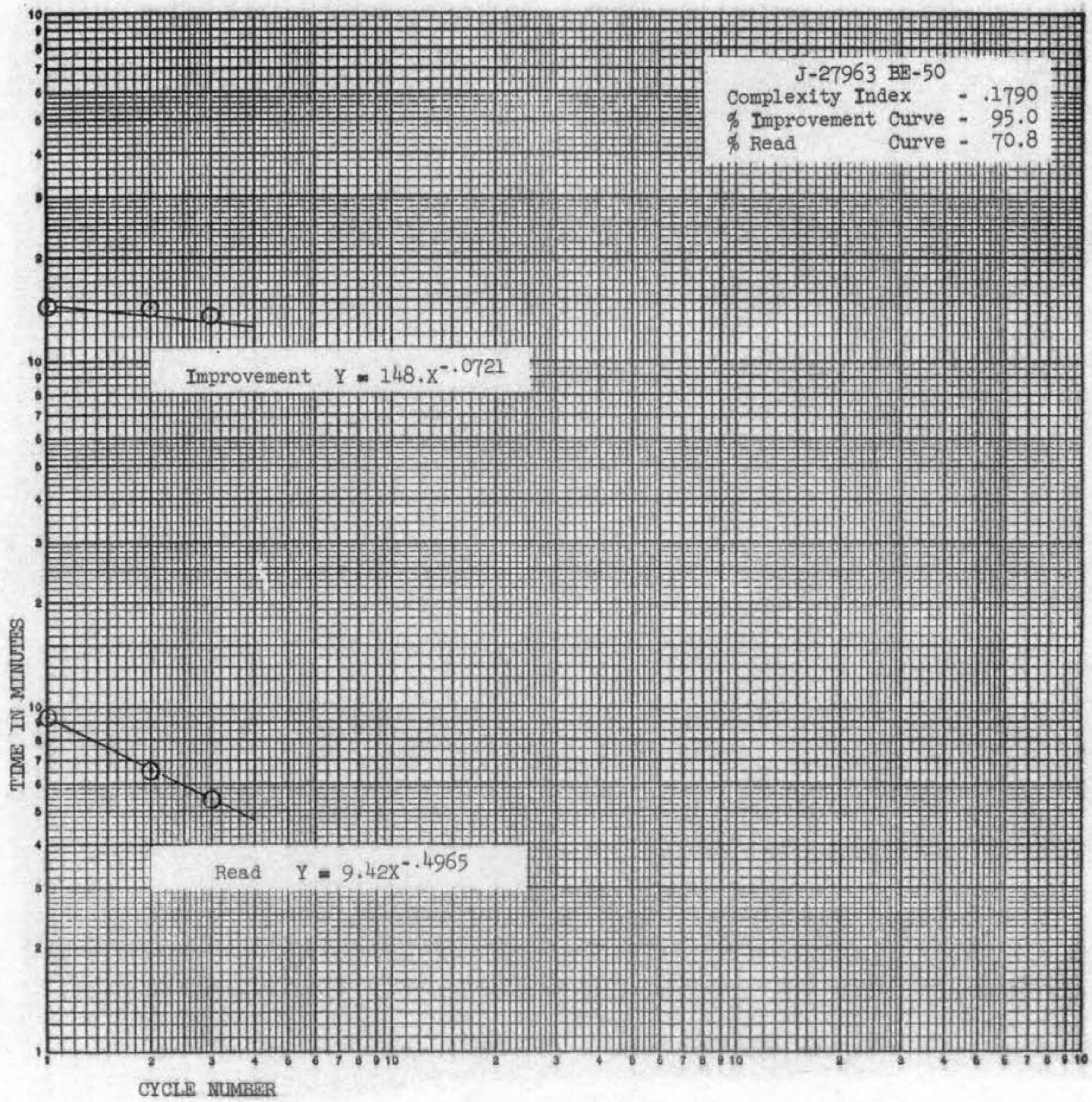
RESULTS OF WIRED EQUIPMENT UNIT STUDIES

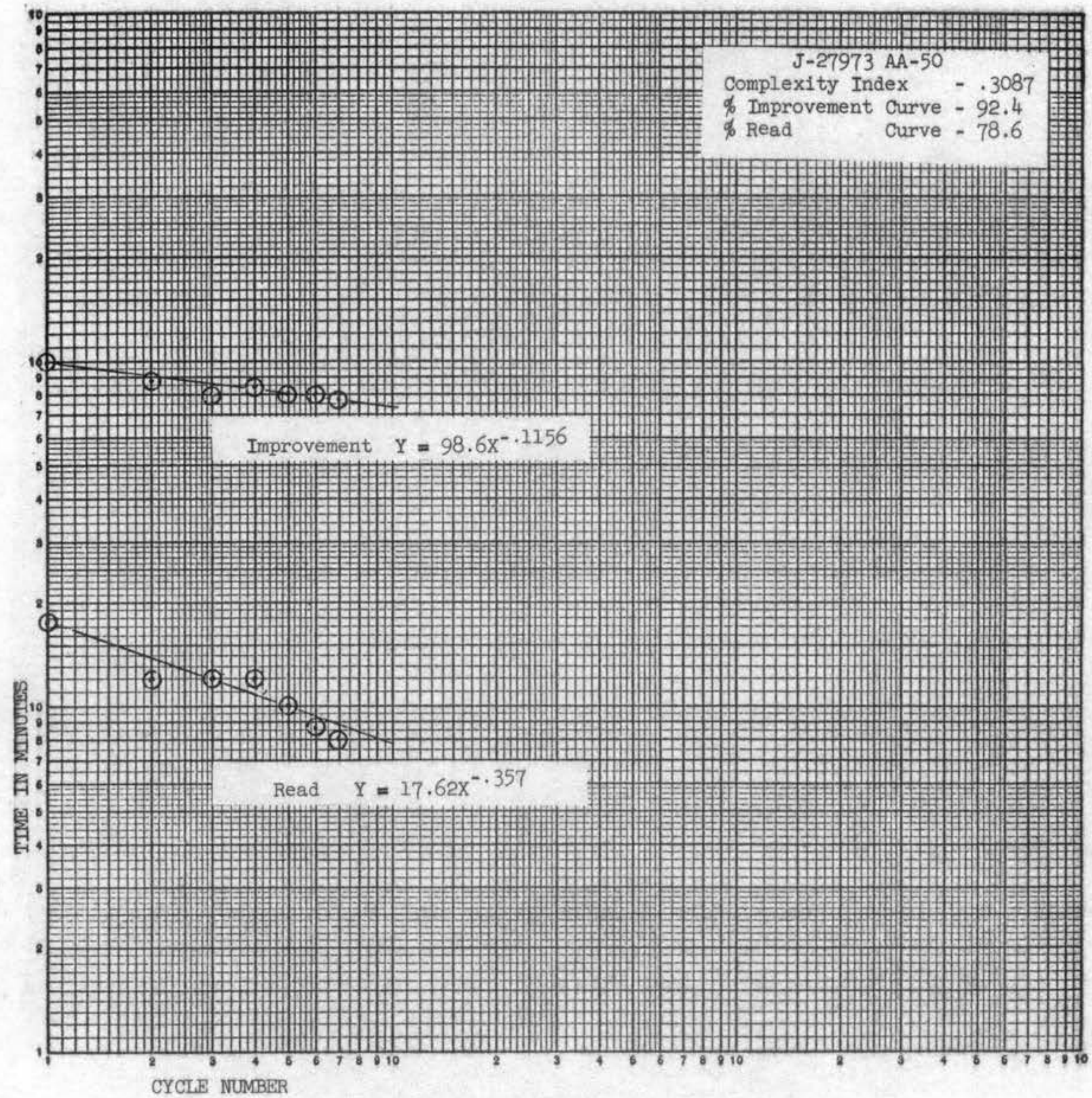

J-27962 AE-50
Complexity Index - .1584
% Improvement Curve - 84.5
% Read Curve - 55.7
Improvement Y = 50.3X^-.2434
Read Y = 6.28X^-.8434
TIME IN MINUTES
CYCLE NUMBER

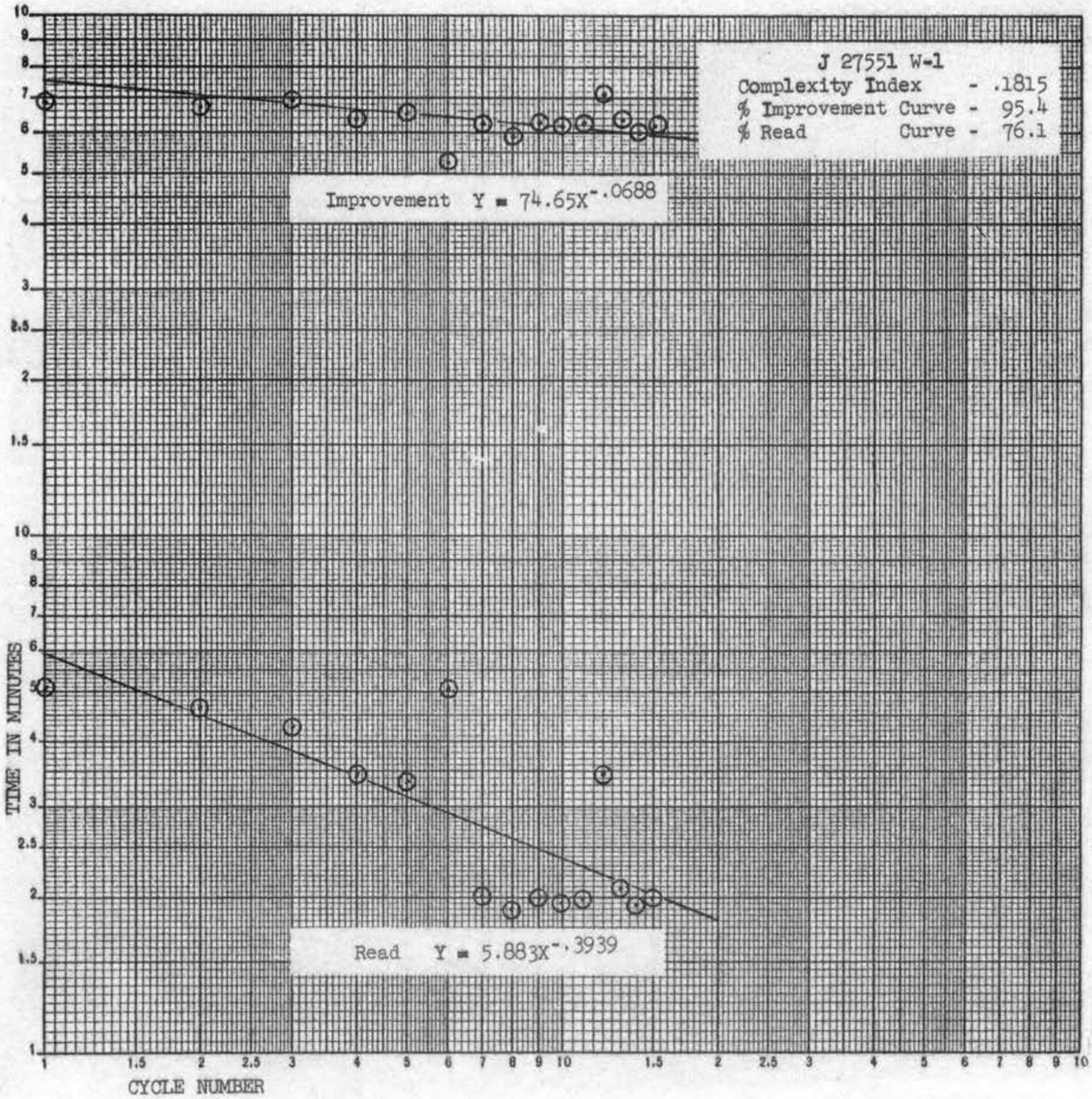

J-27962 AA-50
Complexity Index - .3728
% Improvement Curve - 93.75
% Read Curve - 81.9
Improvement Y = 82.0X^-.094
Read Y = 18.47X^-.2876
TIME IN MINUTES
CYCLE NUMBER

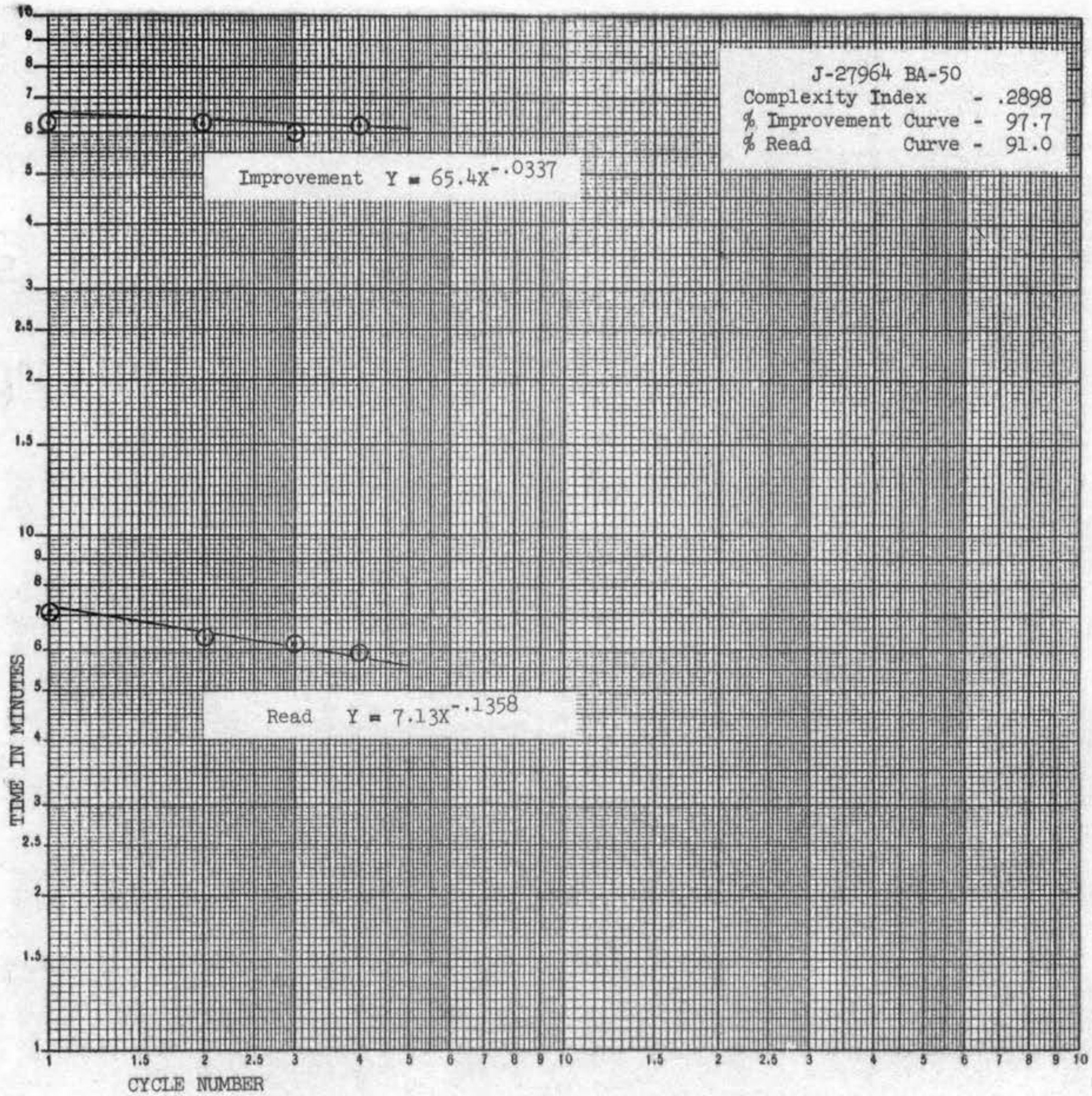

J-27962 AB-50
Complexity Index - .1541
% Improvement Curve - 96.7
% Read Curve - 75.4
Improvement Y = 59.7X^-.0517
Read Y = 4.78X^-.4098
TIME IN MINUTES
CYCLE NUMBER


J-27252 D-1
Complexity Index - .2099
% Improvement Curve - 78.0
% Read Curve - 59.7
Improvement Y = 173X^-.3595
Read Y = 8.91X^-.7434
TIME IN MINUTES
CYCLE NUMBER


J-27963 BE-50
Complexity Index - .1790
% Improvement Curve - 95.0
% Read Curve - 70.8
Improvement Y = 148.X^-.0721
Read Y = 9.42X^-.4965
TIME IN MINUTES
CYCLE NUMBER


J-27973 AA-50
Complexity Index - .3087
% Improvement Curve - 92.4
% Read Curve - 78.6
Improvement Y = 98.6X-.1156
Read Y = 17.62X-.357
TIME IN MINUTES
CYCLE NUMBER


J 27551 W-1
Complexity Index - .1815
% Improvement Curve - 95.4
% Read Curve - 76.1
Improvement Y = 74.65X^-.0688
Read Y = 5.883X^-.3939
TIME IN MINUTES
CYCLE NUMBER


J-27964 BA-50
Complexity Index - .2898
% Improvement Curve - 97.7
% Read Curve - 91.0
Improvement Y = 65.4X^-.0337
Read Y = 7.13X^-.1358
TIME IN MINUTES
CYCLE NUMBER

VITA

Jerry L. Janzen

Candidate for the Degree of

Master of Science

Thesis: A PROCEDURE FOR THE EVALUATION OF START-UP EFFECT IN MANUAL INDUSTRIAL OPERATIONS

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