1965

The reliability of simple progressive dies

David F. Weigel
Lehigh University

THE RELIABILITY OF SIMPLE PROGRESSIVE DIES

by

David Forrest Weigel

A THESIS
Presented to the Graduate Faculty
of Lehigh University
in Candidacy for the Degree of
Master of Science

Lehigh University

1964

Certificate of Approval

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

Sept. 22, 1964
Date

Wallace J. Richardson
Wallace J. Richardson
Professor in Charge

Sept 22, 1964
Date

Arthur F. Gould
Arthur F. Gould
Head of the Department

ACKNOWLEDGEMENTS

The writer wishes to thank Professor Wallace J. Richardson of the Department of Industrial Engineering, Lehigh University, for his guidance, criticism, and enthusiasm during the preparation of this thesis; and to thank Professors George Kane and Arthur F. Gould, also of the Department of Industrial Engineering, Lehigh University, for their helpful suggestions.

A special debt is owed to the many people in the Tool Maintenance, Tool Inspection, and Engineer of Manufacture Organizations at Western Electric Company's Kearny, New Jersey and Baltimore, Maryland Works for their interest and time spent in collecting the data used herein and in answering the writer's questions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The stamping process, of which the punching process is a major division, is one of the most important metal parts production methods in industry. Punching dies are the heart of the punching process.

Die performance, as measured by the number of strokes (or hits) between sharpenings and/or repairs, determines the important per part costs of die depletion and maintenance; yet few quantitative studies of die performance have been published. Existing quantitative studies are principally on tool wear and punchability. Maintenance, which has both a cause and effect relationship with performance, has received little attention. Even though die performance is influenced by many factors, some advance idea of performance is necessary for the cost control which is essential to realizing process economy.

The problem of forecasting die performance has been approached through punchability studies, and both performance and maintenance forecasting have been approached via performance index studies. This paper covers the opening phase of a reliability approach to performance prediction; i.e., the investigation of the applicability to die performance of a particular statistical model which is used in the field of reliability. The more extensive reliability approach would include relating tool and piece part application factors to model parameters, thereby affording a basis for prediction.

Performance and maintenance data on a number of Class A progressive perforate and blank dies were extracted from inspection records

in six shops at Western Electric Company's Kearny and Baltimore Works. A representative sample of twenty five dies which included a range of shops, toolrooms, tool materials, and piece part materials was drawn from the collected data.

A mixed Weibull model, originally proposed by Professor J. H. K. Kao for application to electron tube failures, was assumed for die performance since a mixed distribution of "early failure" and "normal wear" failures was indicated by preliminary analysis of the data. Also, the "weakest link" concept used in development of the Weibull distribution itself is appealing in application to dies.

The data were, after processing, analyzed using modifications of procedures outlined by Kao. The mixed model was found to be consistently applicable to certain classes of die and piece part material combinations and applicable only partially to other combinations of tool and piece part materials. Parameters for separate "early failure" and "normal wear" distributions are tabulated for consistent applications.

The time dependence of the separate "early failure" and "normal wear" distributions for dies for which complete life histories were available was also investigated. The central tendency of the "normal wear" distributions was studied with an approach akin to control chart techniques. No consistent patterns or trends in central tendency were found in plots of means and medians of successive samples from truncated "normal wear" distributions. "Early failures" were found to follow a hypothesized Poisson distribution of occurrences per unit time, and can thus be said to occur randomly over the life of the die.

Recommendations for further study include a more thorough investigation of the mixed Weibull model, a study of the relationship of design and application factors to model parameters, and a more extensive consideration of time dependence.

INTRODUCTION

> "Production of metal parts in presses is one of the major manufacturing processes in America." [1, p. 180]

This sweeping statement encompasses a wide range of part configurations, metalworking processes, and equipment. Press operations range from production of jewelry on small foot operated presses to stamping of automobile body sections on one thousand ton hydraulic presses. Table 19.1 of [5, p. 772] lists twenty-five groups of stamping and drawing applications with a specialized press for each. The principal presswork processes are cutting, forming, and drawing in various combinations and with subdivisions of each. According to Keinzle [12, p. 1]

> "There is probably no working of sheet metal in which punching does not have a part. It is, therefore, one of the most important processes in stamping technology."

The heart of the stamping process, to focus further, is the die itself. The piece part, which is the output of the whole system of man and machines, is processed in the die. Thus, this study of one aspect of punching dies centers on an important area of a widely used process.

The cost of producing functionally acceptable parts is the main consideration in any manufacturing process. The selection of the stamping process as opposed to alternate means of production is in itself a very involved subject [6, Sec. 3]. The stamping process is assumed, however, to have been justified for piece parts which are studied in this thesis. It remains now to identify the major costs associated with the process and to get an idea of their relative importance.

Costs of stamping can be viewed in several different contexts depending on the interest of the observer. The usual cost accounting classifications of direct labor, direct materials and overhead fail to be particularly descriptive since the many important indirect costs which make or break the operation get "lost in the shuffle." Operating labor and material costs (assuming a reasonable scrap rate) are pretty well frozen once the tool design and press applications are set. Punching dies, like other cutting tools, get dull with use, and thus go through a cycle of setup, operation, inspection and maintenance. Setup and inspection are the same each cycle no matter how many parts are produced, and maintenance (assuming a constant grinding time) is semi-fixed depending on the extent to which the tool is damaged. The tool[1] also represents a short-lived asset which is depleted in use. A more complete cost picture would thus take into account the costs of setup, maintenance, inspection and tool depletion.[2] Devlin [10] and Schmidt [15] offer illustrations of cost comparisons which take cognizance of maintenance, setup (Schmidt only),

1. The terms "tool" and "die" are used interchangeably throughout this paper.

2. "Tool depletion" cost measures the asset value which is lost in each die use cycle, and is calculated by multiplying the thickness of die ground off in sharpening by the asset value per unit of available die thickness (usually thousandths of an inch). Capital investment, in the usual concept of depreciation, is recovered over fixed lengths of time which may well exceed the actual life of the die.

and depletion. Inspection is included in the writer's list since it takes place, whether formally (as at Western Electric) or informally, each time the tool is used. A simple example will serve to illustrate the relative magnitudes of these costs.

Costs are taken from [10] Example V, p. 10, and are rearranged into a context of fixed costs per cycle. Setup and inspection costs are not detailed in Example V, but a reasonable estimate of 1.5 hours per cycle (run) will be used. Thus, the costs of setup and inspection, maintenance, and die depletion are:

Setup and inspection: (1.5 hrs. @ $12.00)	$ 18.00
Maintenance (6 hrs. @ $8.00)	$ 48.00
Die Depletion (9,000/20)	$450.00

(NOTE: The figure of 20 grinds over the entire die life seems low.)

The importance of maintenance and die depletion costs may be further illustrated by the following tabulation of experience with five of the tools in this study for which complete life records were available.

Table 1: Die Depletion and Maintenance Costs for Five Dies

Tool Number	Total Runs	Avg. Die Depletion Cost/Run*	Total Maint. Hours	Avg. Maint. Hrs./Run	Avg. Maint. Cost/Run**
1501	67	$45	869	13	$78
1403	77	39	835	11	66
1504	100	30	1197	12	72
1508	52	58	406	8	48
1109	56	54	862	15	90

* Based on an estimated tool cost of $3,000 which is typical for these tools, and assuming linear depletion.

**Based on maintenance labor charges of $6.00 per hour.

The subject of die performance takes into account both maintenance and depletion. Dies which perform well obviously effectively utilize die life, require less maintenance in total, and allow the costs per cycle of setup, maintenance, and inspection to be spread over more piece parts. There are, however, few quantitative studies on die performance in the die literature. Griffiths states [12, p.1]:

> "Metal Stamping was found to be a very complex subject. It was found that many engineers had serious misconceptions on the accuracy and amount of data available."

The quantitative studies relating to die performance are generally concerned with tool wear and "punchability." Keinzle and Keinzle [13] published on tool wear in cutting carbon, silicon, and stainless sheet steels, and proposed punchability ratings. Punchability is defined by Wucusick and Zeno [19, p. 64] in their study on punchability of electrical steels as:

> "Punchability = characteristic of the material that allows a reproducible number of stampings under standard conditions."

The American Society of Tool and Manufacturing Engineers sponsored punchability research at Syracuse University under the direction of Professor J. E. Biegel. This work is described in [8, 9].

Fewer articles yet are available in the area of tool maintenance. Griffiths [11] wrote an excellent paper on maintenance expense control, and McRae and Castracane [14] followed up with a paper on tabulation and analysis of the records described by Griffiths. All three authors were then with Westinghouse Electric Corporation. This is not to imply that there is a lack of general interest in die performance and maintenance. The lack of published information is probably due more to the reticence of companies to part with information from which costs might be derived than to a lack of work in the field. This writer hopes, however, to add via this study to the fund of quantitative information available, and to offer a new perspective on some old ideas.

The total cost effects of die performance extend much further than the major categories discussed thus far. Direct labor and material costs, although generally proportional to production, will be increased by poor die performance due to operator idle time while damaged dies are being pulled out of presses and to material wasted in setting up for more frequent runs. Poor performance also usually requires more maintenance than that required merely to sharpen the die. Additional paperwork and expediting are also necessary if schedules are missed. Engineers and supervisors must devote more time to correcting poor performance and less time to more productive duties. Defective parts produced by poorly performing dies require unnecessary detailed inspection and repair operations. Additional capital may also be tied up in spare tools needed to meet production schedules.

What, then, are the factors which affect die performance? Measurement, in an operating environment, of die performance is actually the measurement of the combined effects of a large number of factors. Strasser [16] lists eight of these factors as:

1. Kind, hardness, and thickness of stock
2. Size and shape of blank
3. Tool design
4. Steel quality of cutting members

5. Heat treatment of cutting members

6. Tool setting

7. Press selection

8. Stock and tool lubrication

To this list can be added the factors of:

9. Proper maintenance

10. Attentiveness of operators.

Tilsley and Howard [18, Fig. 16.1, p.2] present a comprehensive picture of factors affecting the perforating and blanking operation. Their diagram is included here as Figure 1.

Cost control is essential in realizing the economies of any production process. The term "control" also connotes an advance idea of some reference level of performance. Since stamping process performance is measured in terms of die performance, and since costs of stamping are heavily influenced by die depletion and maintenance costs, a knowledge of die performance is an important prerequisite to control. Maintenance, as well as being a major cost element in the process, is both a cause and effect of die performance. That is, poor maintenance can cause poor performance, and poor performance leads to increased maintenance. An advance idea of maintenance requirements would also be prerequisite to control. The cost control aspect of the stamping process leads to a statement of the problem.

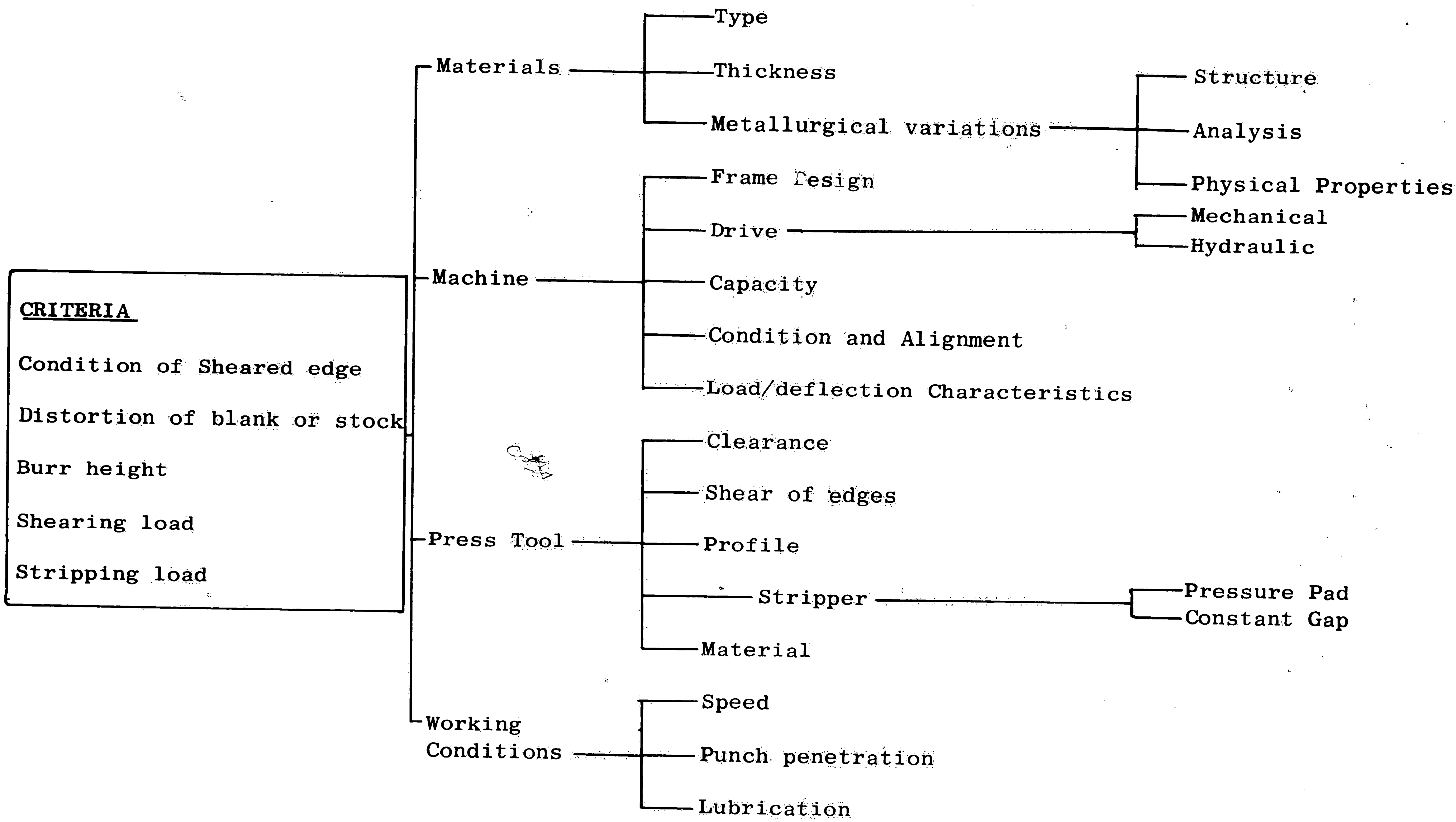


FIGURE 1 . Factors Affecting the Blanking and Piercing Operation. (Taken from Tilsley and Howard [18, Fig. 16.1, p. 2])

THE PROBLEM

The larger problem of which this study is only a preliminary consideration is:

Given a specific die application, can we predict or forecast die performance and maintenance requirements?

There are several ways in which this problem can be approached. The punchability studies cited earlier represent one approach. The rationale of this approach is material centered, and runs somewhat as follows: The end product of punching is a metal part. A specified increase in height of burr on the part is the usual reason for stopping a run as well as being a good indicator of die wear. Tests are run on various materials under standard conditions, and burr heights are recorded at various numbers of punchings. Die users can then get an idea of how well their dies will stamp specific materials by consulting the tables resulting from punchability tests. There are, however, several questions which this approach raises. One of these is how can actual application and working environments be related to the carefully controlled conditions under which punchability tests would be conducted? The carefully controlled conditions are, of course, necessary to give a constant reference for all users, but the questions of practical application still remain. Wukusick and Zeno [15] consider performance in punchability tests to be an upper bound on production performance. Another question arises from the implied but not stated assumption that the only mode of tool failure to be expected is edge wear. Strasser [16] states:

"The most frequent casualties in metal stamping shops are, without doubt, the small, round punches used in progressive-type and compound dies. Causes of breakage are many and varied."

The writer observed the same thing when coding the data used in this study.

A second approach is the Westinghouse concept of "economical die run" as described by Griffiths in [11]. An "economical" die run is one in which the combined cost of maintenance and die depletion are minimal. The idea here is that very long die runs may result in higher maintenance cost and abnormal die wear. Griffiths classified materials into two groups, three thickness ranges, and three material grades. Thus, there are nine combinations of thickness and grade for each material group. Economical die run ranges are shown in Figure 9 of [11, p. 16] for several types of presswork and combinations of material classifications. Economic die runs for individual dies are apparently determined by matching the individual applications as closely as possible with the established classifications. Not apparent, however, is whether the published figures represent ranges of lower bounds, lower and upper bounds on runs, or ranges of expected values. Westinghouse, for control purposes, initially established standards for pieces per hour of repair, pieces produced per .001" of die life, and pieces produced per .001" of punch life. A cumulative index of performance of [(repair hours)^3/number of pieces] was subsequently developed [14]. The Westinghouse approach offers both a means of control where none existed previously and an organized means of recording information for further studies. The concept of the economic die run may be more deterministic and arbitrary than is warranted by the situation. The performance index technique, being cumulative, is also somewhat akin to cumulative sum control chart techniques.

The varying performance of dies is to be expected; especially under operating conditions. The same die is maintained by different toolmakers, set in a variety of presses by different diesetters, cuts different batches of material, and may change characteristics as it wears. A statistical description of this performance would enable anyone concerned with die cost control, capacity planning, production scheduling, design, or any other phase of die economics to do a more knowledgeable job.

The concept of reliability is almost made to order for statistical descriptions of performance. A quantitative definition of reliability is given by Budne [20, p. 22] as:

> "It (reliability) is also used as a quantitative measure and in this sense can be defined as the probability that the equipment will perform a specified function under given conditions for a specified period of time without failure."

This definition ties in well with the idea of a statistical measure of die performance. The field of reliability has thus far centered mainly on military electronic equipment. Consequently, most of the literature on reliability concerns reliability of electronic devices and their component parts. The underlying concepts are, however, applicable to any kind of equipment.

The overall approach to the die reliability problem resolves itself into two main divisions. The first is a statistical description of die performance under operating conditions, and the second is the relationship of tool design and application[1] factors to the distributions which describe performance. This study concerns itself with the statistical description of die performance. Ideally, die performance could be forecast if definite relationships between application, design, and reliability could be established. This is the ultimate aim both of the laboratory type punchability studies and of this study based on performance under operating conditions.

1. The term "application" includes the piece part material, punch press and auxiliaries, and other elements in the tool's operating environment.

AREA OF INVESTIGATION

This study is concerned with the problem of finding a statistical model for the performance of simple progressive dies. Performance is measured herein by the number of strokes between failures[1] of the tool. The specific questions considered are:

1. Is there a statistical model which will consistently describe die performance?

2. Is the statistical model, if one exists, time dependent? That is, does tool performance change as the available die life[2] is expended?

1. The term "failure" is defined here to mean the failure of the die to produce acceptable piece parts. The formation of excessive burr (due to tool edge wear) on piece parts would thus be termed a die failure.

2. Available die life refers to the amount of the die which can be ground away without exceeding dimensional tolerances on the part.

METHOD OF STUDY

The plan of attack consisted of choosing a representative type of die, collecting data on the performance of several these dies, assuming a statistical model as the model underlying die performance, and investigating the appropriateness of the model.

The Type of Die

Simple progressive dies which perform the important cutting operations of perforating and blanking (several include forming) were chosen. Cutting operations were established in the Introduction as being the most important operations in the stamping field. Progressive dies are also of growing importance in the area of high production tooling since they eliminate costly handling operations. Dies are also sometimes classified into Classes A, B, C, and Temporary depending on the volume of parts they are intended to produce. The Tool Engineers Handbook [7, p. 57-2&3] has this to say about Class A dies:

> "Class A Dies - These dies represent the best tools it is possible to build. They are used for high production only. The best types and grades of material are used, and all wear points and intricate or delicate sections are carefully designed for ready replacement. A combination of long die life, constant required accuracy throughout this life, and ease in maintenance are prime considerations, regardless of tool cost."

All tools in this study are Class A dies. This class was chosen due to its general use in high production industries where maintenance and performance are of more importance in the die economic picture than is the case with lower die classifications where initial investment is of greater importance.

The Data

The data sources were tool inspection records at Western Electric's Kearny and Baltimore Works. It was initially hoped that data could be secured from other sources, but this hope never materialized due in part to the press of business at one source and to the reluctance of another source to part with cost related operating information. Even so, the data from within Western Electric represent a fairly diverse cross section of shops, toolrooms, inspection stations, and policies. A table of these relationships is shown below:

Table 2: Relationships of Shops, Inspection Stations and Toolrooms

Shop	Inspection Station	Toolroom
1	A	I
2	B	I
3	B	I
4	C	II
5	C	II
6	D	III

Shop Numbers 1, 2, 3, 4, and 5 are at Kearny and Shop Number 6 is at Baltimore. Kearny builds its own dies for all shops except Shop Number 5, which utilizes carbide dies purchased from an outside source. Shop Number 6 at Baltimore purchases most of its dies. All other carbide dies are purchased (as in the case of the carbide die from Shop Number 3). Specific dies and piece parts will be described later in a discussion of choosing the sample.

Die inspection records at Western Electric are the best source of performance data within the Company. The die operating cycle consists of the steps of operation, inspection, and maintenance (if required). The system operates as follows:

1. Dies are stored in die storage areas. Machine setters remove the tools from storage when they are needed, and set them in the presses. The first parts are checked carefully by the machine setter; and, if acceptable, an operator monitors the operation, keeps the tool supplied with stock, handles part pans, and periodically inspects parts. If the first parts are unacceptable, the tool is removed from the press, and returned to the tool inspector; or in some cases, the tool inspector is summoned to the press to ascertain whether conditions can be corrected without removing the die.

2. The run is stopped when the scheduled run is completed, if the tool starts producing unacceptable parts for any reason, of if the press or auxiliary equipment fails. The operator, die setter, or tool inspector may make the decision to stop the run.

3. The die setter fills out a Tool Performance Record which details the following information:

   A. Tool number

   B. Part number

   C. Amount of parts this run

   D. Set-up man

   E. Difficulty - here the die setter lists his ideas of what is wrong with the tool

The tool and the performance record are then returned to the tool storage area.

4. The tool inspector usually opens the die and assesses the amount of damage to the tool. (Ordinary edge wear is "damage" in this sense). The tool is sent to Maintenance for sharpening and other repairs deemed necessary, or may be returned to the shelf if no maintenance appears necessary. A tag on which, among other things, the inspector's observations of defects are recorded accompanies the tool to Maintenance. At the same time, the inspector records the length of run (in parts), date delivered to Maintenance, and reason for maintenance on a tool record which is kept in the tool inspection cage. These records were the data source for this study.

5. Maintenance inspects the tool to verify the inspector's account of the damage, performs the necessary maintenance, and returns the tool to the tool inspector. Maintenance may in some cases find more extensive damage than that reported by the inspector since at times the inspector does not open the tool (as in the case, for example, of excessive burr). The Maintenance Department at Kearny also kept informal records of run length, reasons for repair, and repair hours. These records are considered by the writer to be more detailed than those kept by Inspection, but unfortunately were not complete. It might

be noted that the toolmaker, prior to returning the tool to Inspection, records repair hours on the repair tag which accompanies the die.

6. The tool inspector completes the record for a particular run by entering the date of return and repair hours. The heights of punch and die are entered at intervals on the tool record. These measurement intervals are at the discretion of the tool inspector, and are not systematic.

The questions now are whether the die performance records as maintained by Tool Inspection actually measure die performance, and whether run lengths are accurately recorded?

The first noticeable thing about the data was the reporting of run lengths, in many cases, to the nearest thousand parts. This round off was variously attributed to the vagaries of shop arithmetic and to the method of counting parts by weight. There is, however, no reason seriously to question part count data since nothing is to be gained by overstating part counts to Tool Inspection. The entire inspection operation is also periodically audited by procedural auditing groups within the Company. The round off also does not affect the accuracy of the study.

Another area of possible contention is how the point is determined at which a run is stopped for reason of excessive burr. Shop Number 5 at Kearny, which produces electrical laminations, has a definite standard, and stops a run if the burr height exceeds .004".

The other shops stop a run generally at the discretion of the die setter depending on experience with the particular tool and piece part. That is, the die setter would be more likely to allow a larger burr on parts which can be easily deburred in subsequent tumbling operations. The tool would also probably be allowed to complete a schedule if excessive burr appears late in the scheduled run. Defects such as broken perforators will, of course, be picked up as soon as the operator notices the lack of a hole in the piece part. Even with the somewhat arbitrary and flexible criteria for stopping a run, the data are considered an accurate portrayal of the operational environment performance of the dies. A strong support of this contention stems from the fact that wage incentives are paid only for good production. Operating people would thus have strong incentive for stopping the run as soon as the tool starts producing defective parts; especially since detailing of defective lots is at the expense of incentive payments. The die performance thus measured is strictly the practical performance rather than a performance based on laboratory conditions.

The case in which a scheduled run falls short of the die capability is another point open to argument. Shop Number 2 at Kearny stated that their policy was to sharpen the die if the next anticipated run plus the current run would exceed the cutting edge endurance (as estimated by the inspector) of the tool. The other shops follow essentially a policy of run to failure. A special code was accordingly assigned to those runs in Shop Number 2 for which the only notation on the tool inspection record is "G" (for grind).

Theoretical Considerations

Since this study places die performance in a reliability context, a discussion of some of the theoretical considerations of reliability is appropriate at this point.

Statistical distributions in the field of reliability are distributions of times or discrete events between failures. The binomial, geometric, Pascal (negative binomial), and Poisson discrete distributions and the exponential, gamma, Weibull, log normal, normal, and extreme value continuous distributions have been applied in reliability as failure distributions. Although the number of hits[1] between failures of a die is a discrete variable, nothing is lost in using a continuous variable approximation of the discrete case since the magnitude of the discrete variable is large; thus, unit differences are insignificant.

Some of the terms used in reliability are defined and explained below:

Fatigue Life is the operating time between failures of a piece of equipment, and is denoted as the random variable T with probability distribution function F(t).

Reliability Function (or Survival Function) R(t) is the probability that the random variable T will exceed t. It follows that:

$$R(t) = 1-F(t)$$

1. The terms "hit" and "stroke" are interchangeable; i.e., the piece part stock is "hit" each time the punch press ram descends (or is "hit" once each "stroke").

The Conditional Failure Rate h(t) - sometimes called hazard rate - is the conditional probability that the equipment will fail in the time interval from t to t+ dt given that the equipment has survived to time t. Mathematically:

$$h(t)dt = \frac{f(t)\ dt}{1-F(t)} = \frac{f(t)\ dt}{R(t)}$$

The conditional failure rate and distribution function are related by:

$$F(t) = 1 - e^{-\int_0^t h(\tau)\, d\tau}$$

The reasons for choosing one distribution over another for describing failure times have at best weak theoretical justification. Robins [30] and Nylander [28] offer good discussions of the present state of theory.

Choice of a Statistical Model for Die Failure

Preliminary histograms of the data suggested the existence of two distributions rather than of a single distribution underlying the overall distributions of die failures. A typical histogram is shown in Figure 2 below:

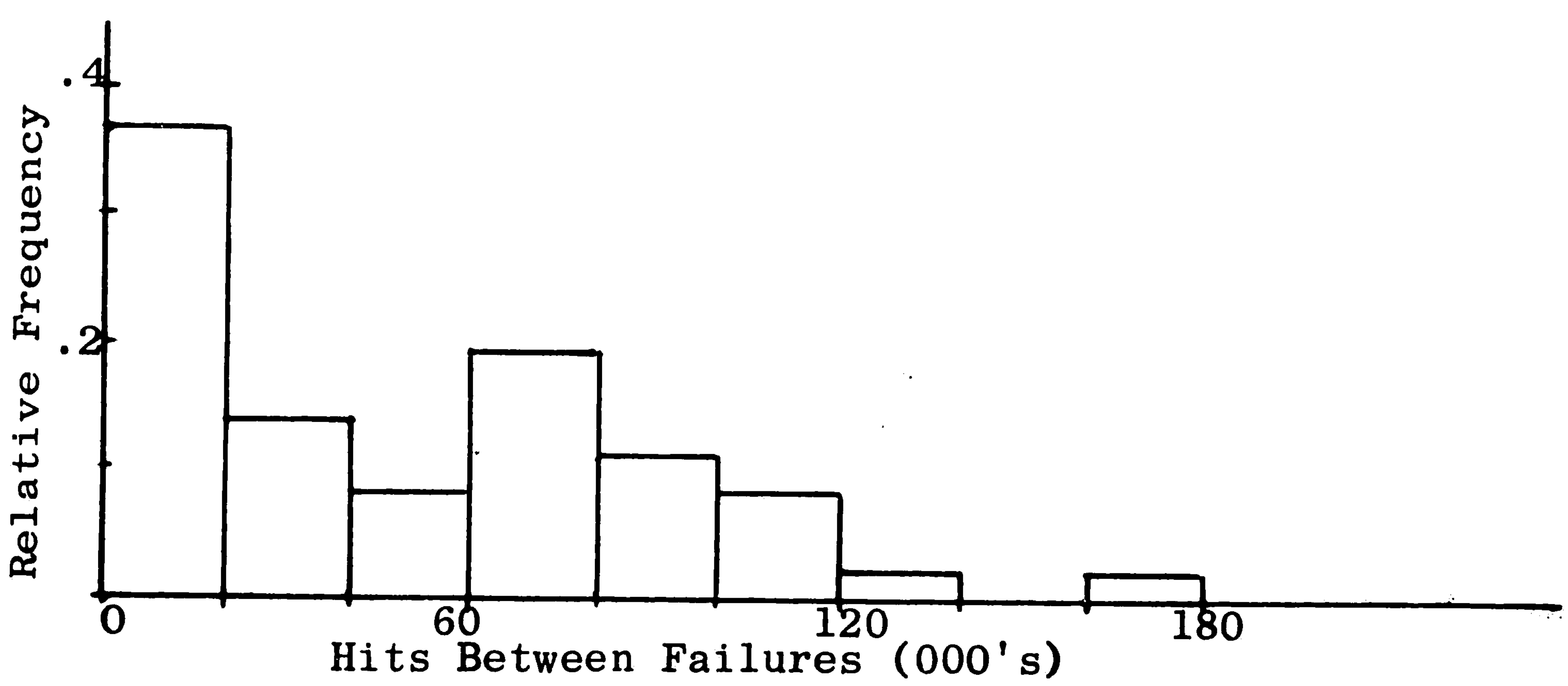


Figure 2 - Histogram for Tool Number 1505

The two distributions appear to consist of one exponential type and one positively skewed type. The exponential type distribution could logically represent "early failures" in which the die fails at setup or shortly thereafter due to careless diesetting, to poor maintenance, or to other conditions which would cause rapid failure. The positively skewed unimodal distribution could represent a "normal wear" failure[1] distribution of operation under more usual circumstances. The "early failure" phenomenon is recognized in the field of electronic component reliability [24,26]. Weibull also notes the possibility of several underlying distributions in his original paper [31] when he discusses complex distributions describing physical phenomena other than electronic equipment failure.

The experimental work in this study is based on a mixed Weibull model proposed by Kao [24] which takes cognizance of "early" and "normal wear" failures in electron tubes.

The simple Weibull distribution is a very flexible three parameter distribution whose probability distribution function is given by:

$$F(t) = 1 - \exp\{-(t-\gamma)^{\beta}/\alpha\} \quad \text{for } t \geq \gamma$$

$$= 0 \text{ elsewhere}$$

and whose probability density function is:

$$f(t) = \frac{\beta(t-\gamma)^{\beta-1}}{\alpha} \exp\{-(t-\gamma)^{\beta}/\alpha\} \quad \text{for } t \geq \gamma$$

$$= 0 \text{ elsewhere}$$

1. The terms "early failure" and "normal wear" will be used throughout this paper to describe the respective distributions of "early" and "normal wear" failures.

The distribution parameters are:

α = a scaling parameter

β = a shaping parameter

γ = a location parameter

The shaping parameter β is the most important of the three since it gives the distribution flexibility. If β is set equal to 1, the distribution reduces to the Exponential Distribution; and for β of 3.25 the distribution closely approximates a Normal Distribution. Values of β less than 1 give exponential type distributions, while values between 1 and 3.25 result in positively skewed curves. Figure 3 shows the shape of the probability density function for several values of β.

Characteristic life, denoted by η, is an important property of the Weibull Distribution when applied in Reliability. Probability of failure prior to η is a constant equal to (e-1)/e or 0.632, and is independent of β. η is given by:

$$\eta = \alpha^{\frac{1}{\beta}}$$

The instantaneous failure rate, or hazard rate previously defined as

$$h(t)dt = \frac{f(t)\ dt}{R(t)}$$

is expressed as an instantaneous rate as $dt \to 0$. For the Weibull Distribution:

$$h(t) = \beta(t-\gamma)^{\beta-1}/\alpha$$

Hazard rate for selected values of β is shown in Figure 4.

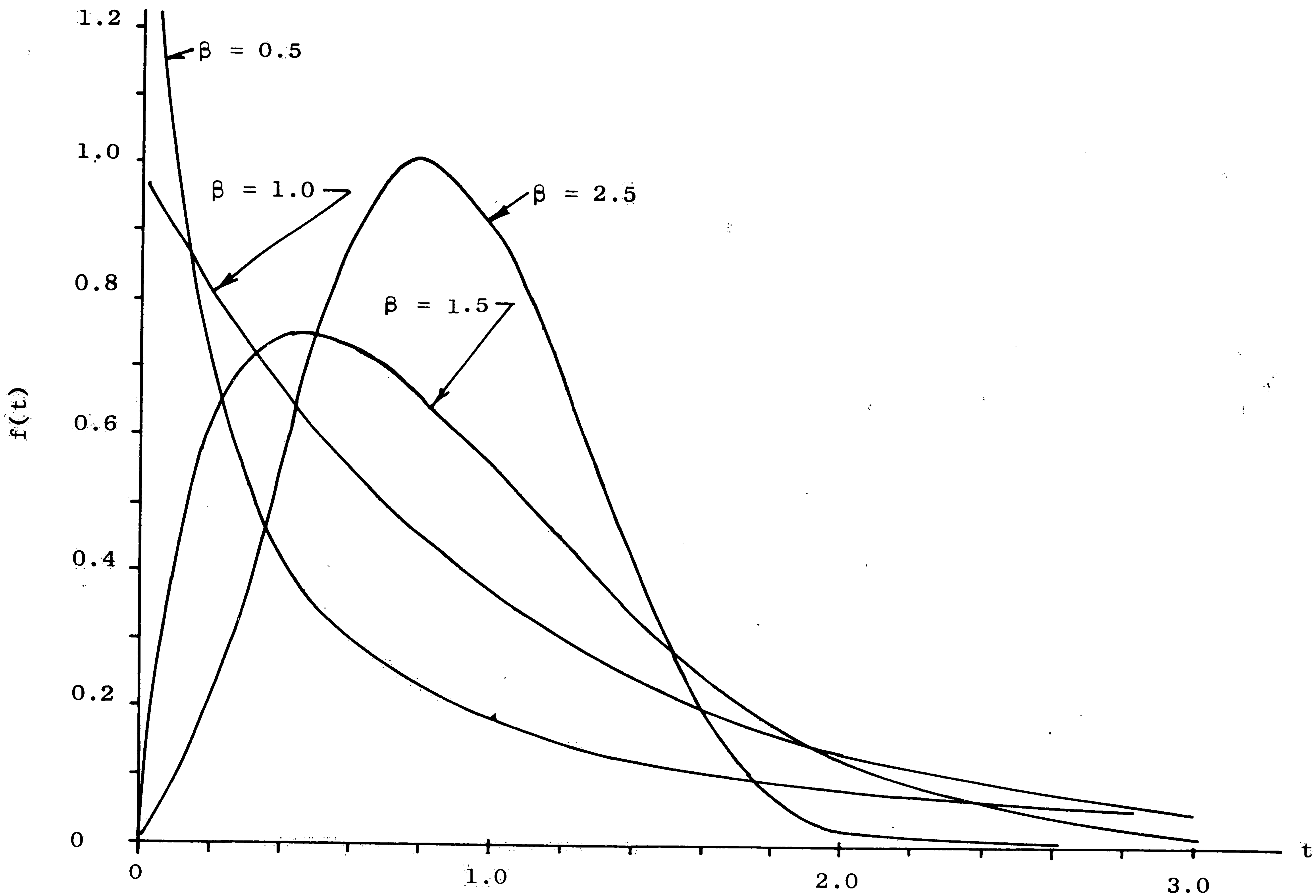


Figure 3: The Weibull Probability Density Function for Selected Values of β and α = 1.0, γ = 0.

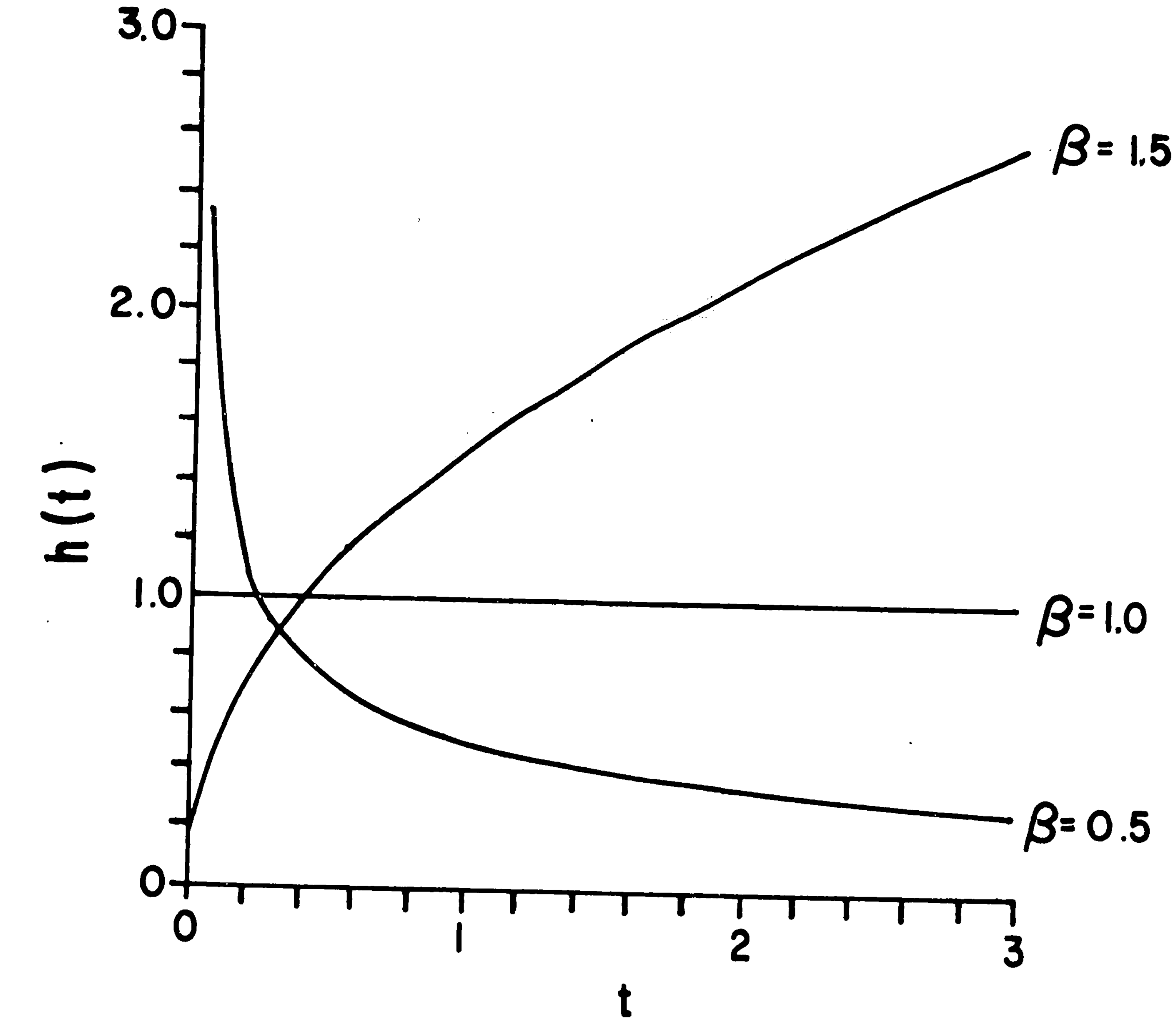


FIGURE 4 WEIBULL HAZARD RATE FOR SELECTED VALUES OF β AND $\alpha = 1.0, \gamma = 0$

The intuitive reasoning which leads to the Weibull Distribution [31] is appealing in possible application to die failure. Weibull's original development was based on a "weakest link" concept. That is, the object of study was deemed to have failed if any of its parts failed. Weibull states: [31, p. 293]

> "the same method of reasoning may be applied to the large group of problems, where the occurrence of an event in any part of an object may be said to have occurred in the object as a whole."

This line of reasoning seems to describe the case of die failure. The die will no longer produce satisfactory parts if any cutting or forming member fails. In a smaller sense, if the cutting edge of any punch or die section is considered as an entity, the failure of any part of this edge will result in a burr which is reason enough for stopping the run. In a larger sense, if any element of the man-machine system which produces the piece part fails, then the system could be said to have failed.

The behavior of hazard rate for different values of β (as shown in Figure 4) also appeals intuitively in the die failure application. The hazard rate decreases with increasing t for β less than 1, and increases with increasing t for β greater than 1. The analogy to the situation indicated by the preliminary histogram and to the actual operating situation is a high initial hazard rate as the die is set in the press followed by a decreasing hazard rate as the die survives setup and the first few strokes. This description would apply until the die runs long enough to be in the "normal wear" distribution whose β is greater than 1. The hazard rate then increases as the cutting edge wears.

The mixed model proposed by Kao [24] for electron tube failures, and which is applicable to die failures, consists of two sub-populations; one for "early failures" given by:

$$F_1(t) = 1 - \exp\{-t^{\beta_1}/\alpha_1\} \text{ for } t > 0,\ \alpha_1 > 0$$
$$\text{and } 0 < \beta < 1$$

and one for "normal wear" given by:

$$F_2(t) = 1 - \exp\{-(t-\gamma_2)^{\beta_2}/\alpha_2\} \text{ for } t > \gamma_2,$$
$$\alpha_2 > 0, \text{ and } \beta_2 > 1$$

The mixed model is given by:

$$F(t) = p\, F_1(t) + q\, F_2(t)$$

$$= 1 - p \exp\{-t^{\beta_1}/\alpha_1\} - q \exp\{-(t-\gamma_2)^{\beta_2}/\alpha_2\}$$

where $p + q = 1$

The expression for $F(t)$ states that the number of hits between failures of a die is a mixed random variable which depends both upon the normal wear characteristics of the die in a given application and upon how well the die was set in the press or maintained. The parameters p and q delineate the proportions of die runs which fall respectively into "early failure" and "normal wear" populations.

Kao also proposed a composite model for small p and large γ_2. This model is:

$$F(t) = F_3(t) = 1-\exp\{-t^{\beta_3}/\alpha_3\}$$
$$\text{for } 0 \leq t \leq \delta,\ \alpha_3 > 0,\ 0 < \beta_3 < 1$$
$$F(t) = F_4(t) = 1-\exp\{-t^{\beta_4}/\alpha_4\}$$
$$\text{for } \delta \leq t \leq \infty,\ \alpha_4 > 0,\ \beta_4 > 1$$

$F(t)$ in this case states that the distribution of die failures follows an "early failure" distribution up to some intersection parameter δ, and thereafter follows a "normal wear" distribution.

Practical considerations in using the mixed and/or composite Weibull models described above are centered on the versatility of the Weibull distribution and on the availability of special probability paper which allows rapid graphical analysis of data based on cumulative distributions. Parameters of the simple distribution can also be estimated graphically as is discussed in Appendix A. These parameters can be estimated by more sophisticated methods [23,29], but graphical methods are considered adequate for this preliminary study.

Selection of the Sample

Selection of a sample was based on guiding criteria of drawing a sample which covered a range of shops, toolrooms, tool materials, and piece part materials; yet, at the same time, which covered a limited range of applications. These two objectives appear contradictory; but each has a specific purpose. The coverage represented by the first aim was required to see whether there is a generally applicable statistical model of failure for one type of punch press die. The narrowing effect of the second aim was intended to limit the number of variables whose effects on reliability would have to be considered.

A sample of twenty five representative tools was selected from the fifty six for which data were collected. The sample size is arbitrary, and represents a compromise between time requirements for experimentation and data handling and the size of a sample required to relate tool design and application factors to reliability via multiple regression techniques. The sample size limits the number of independent variables which can be studied since the degrees of freedom in testing the significance of regression equals the number of observations (sample size) minus the number of variables.

Data were collected on simple two and three station progressive perforate and blank dies. Tools which were strip fed by hand were eliminated since hand feeding operation was considered to introduce an extra variable. Dies in which two kinds of material or two thicknesses of the same material were cut were also eliminated.

The presses in which the tools were operated could also affect die performance. Fortunately, the different types of presses were restricted to two or three; partly by Western Electric preference and partly by the nature of the operation. The majority of the tools are run in Bliss High Production Presses of varied capacities, and several are run alternately in Minster or Bliss Presses. Both types of press have short (1 to 2 inch) strokes, and are designed for high speed production. All presses are equipped with roll feed.

The tools all have the common characteristics of performing perforating and blanking operations and of running in similar presses equipped with roll feed. The following information on tool and piece part characteristics and operating conditions is summarized in Table 3:

Tool Number

Tool Material

Piece part material

- Type
- Thickness
- Hardness

Operating Data

Press

Speed

Material feed rate (where tool drawings were available)

The table is arranged into the four principal applications of:

1. Steel tools cutting plain carbon steel (and magnetic iron)
2. Carbide tools cutting electrical steel (silicon alloy)
3. Steel tools cutting brass.
4. Steel tools cutting nickel silver.

Note that tool materials are classified simply as steel or carbide. While considerable variation exists among different types of tool steels and among tungsten carbides, this study will assume that tool steels and carbide are properly applied; thus the simple two-way classification.

The sample covers a good range of shops and applications for purposes of studying statistical models of die performance under operating conditions. The sample was also chosen, though, with an eye toward possible future studies relating tool design and application factors to the performance models.

Steel tools producing steel parts offer the best opportunity for multiple regression study since a fairly wide range of thicknesses and hardnesses of the same material is represented within this classification. The parts themselves, being principally spacers and brackets, offer a variety of perforated hole sizes and tool cutting edge lengths if tool geometry is of interest.

Table 3: Tool and Piece Part Materials and Tool Operating Conditions

Tool No.	Tool Matl.	Piece Part Material: Type	Hardness Rockwell B Scale	Thickness (In.)	Operating Conditions: Punch Press	SPM	Feed Rate (IPM)
1501	Steel	Steel CR #3T[1]	60-75	.125	Bliss 650	90	138
1502	"	Steel CR $1T	90 Min.	.032	Bliss 650	180	60
1403	"	Magnetic Iron	70-85	.093	Bliss 650	80	NA[6]
1504	"	Steel CR #3T	84 Min.	.071	Bliss 650	100	35
1505	"	Steel CR #5T	55 Min.	.063	Bliss 660	120	142
1508	"	Steel CR #5T	55 Max.	.063	Bliss 6045	250	NA
2507	"	Steel HRPOCQ	50-75	.063	Bliss 625	350	195
4508	"	Steel CR #3T	60-75	.071	Bliss 620	140	88
4509	"	Steel CR #3T	60-75	.056	Bliss 620	140	139
6501	"	Steel CR #2T	70-85	.025	Minster #5	125	234
6507	"	Steel HRPOCQ	50-75	.028	Bliss 6045	300	155
5602	Carbide	H.R.Silicon[2]	Hardness	.014	Waterbury	200	656
5603	"	Steel	Not	.014	Farrel	200	612
5604	"	AlSl	Spec.	.014	#2	200	256
5605	"	M-10		.014	DC	200	712
1109	Steel	Brass Alloy A[3]	68-78	.020	Bliss 630	200	NA
6105	"	Brass Alloy C	71-78	.025	Bliss 6045	200	91
6106	"	Brass Alloy A Tin Coated	70-81	.040	Bliss 6045	200	150
3102	Carbide	Brass Alloy A	55-72	.032	Bliss 6045	250	NA
2202	Steel	Nickel Silver	X-Hard[5]	.013	Bliss 625	300	NA
2204	"	Alloy D[4]	78-91	.036	Bliss 625	350	520
4201	"	" "	94-98	.032	Bliss 20C	250	133
4202	"	" "	94-98	.028	Bliss 20C	250	150
4203	"	" "	94-98	.020	Bliss 20C	250	156
4207	"	" "	94-98	.025	Bliss 20C	250	150

1. Grade designations are from [34]. CR #3T is the abbreviation, for example, for Cold Rolled - No. 3 Temper.

2. See [37] for detailed specifications.

3. Grade (alloy) designations are from [35]. Alloy A is 65% Copper and 35% Zinc while Alloy C is 85% Copper and 15% Zinc.

4. Grade (alloy) designations are from [36]. Alloy D is 59% Copper, 12% Nickel, and 29% Zinc.

5. Designated "Extra Hard". Hardness is not specified for material less than .020"thick.

6. NA - Not Available.

All carbide tools producing electrical laminations are cutting the same material, while five of the six tools producing nickel silver parts are cutting various thicknesses of the same material.

These relationships are, however, pointed out principally to show how the sample was chosen since mathematical analysis does not extend to multiple regression. The choice was, of course, limited by the availability of tools which met the requirements previously discussed and upon which records were available.

Processing and Analyzing the Data

The first step in processing the data was to design a data card which would retain in numeric form as much as possible of the information in the die inspection records. Additional principles in designing the card were to:

1. Allow easy identification of tool, shop, and piece part material.
2. Provide a format which could be read both visually and by machine.
3. Establish a die failure and maintenance code which would discriminate among possible causes of failure and which would lend itself to sorting operations.

Card format and tool identification and failure/maintenance codes are shown in Appendix B, Figures B1, B2, and B3.

The tool identification code is straightforward, and needs no further explanation. The failure and maintenance coding system is, however, somewhat more involved. The more common reasons for tool failure are coded into a sixteen item alphabetic code for the inspection records at Kearny. Failures and maintenance not covered in the code are spelled out. All reasons for failure are spelled out in the Baltimore inspection records. The failure and maintenance code used here was devised to convert the alphabetic coded and written reasons for failure into numeric codes suitable for electronic data processing. The code was patterned after that used by Westinghouse and described by Griffiths [11]. The code is, however, all integer, and is simpler than the Westinghouse code. The ascending order of the code was generally designed to assign higher numbers to more serious categories of failure. That is, perforator failures are grouped from 040 through 049; and, assuming that blanking punch failures require more maintenance, blanking punch failures are grouped from 050 through 059. Likewise, a three in the units position generally corresponds to a shear failure. The ascending severity of damage is, however, not too consistent, and may be open to question. The essential point is that like failures are grouped in the same decile. The code is also generally designed for ease of sorting.

Failure codes run from 000 through 100. Higher codes run from 300 through 910, and cover maintenance which is recorded on the inspection record but which was not occasioned by the failure for which the maintenance is recorded. An example of this type of maintenance is the manufacture of spare punches.

An individual card was punched with the following information for each run of each tool:

1. Tool number

2. Run sequence number

3. Length of run (in parts)

4. Repair hours

5. Up to six failure and maintenance codes depending on the extent of tool damage and maintenance performed.

The first failure code is, as a general rule, the most likely reason for stopping the run, although some of the precedences are debatable. That is, a sheared tool will, for example, produce a large burr which would be the indication for the operator to stop the run; but it is open to debate whether the reason for stopping the run is the sheared tool or the burred part. In either event, both occurrences are recorded on the data card along with codes forother tool damage and maintenance.

The initial data analysis job was to edit the data and to rank order the edited data. Editing was necessary because of the occurrence of runs on which no maintenance occurred, the differing policies under which the different shops sent tools in for sharpening, and the difference between the tools in parts produced per stroke. An Edit and Rank order computer program was written in FORTRAN (FORMAT) for and IBM 1620 computer. The program flow diagram and coding are shown in Appendix B, Figures B4 and B5 respectively. The following program options are available:

1. Neglect runs which have code 010 only in the reason for failure coding. This option was used to see whether the stated policy of Shop Number 2 (i.e., that of grinding

in anticipation of a long run) made a difference in tool reliability.

2. Neglect runs in which code 011 was the only entry in reason for failure coding. This option could be used if the inspector's judgement might be considered questionable in sending in a tool for grinding without noting an excessive burr on the part.

3. Punch an edited card deck in which runs of the tool on which no maintenance occurred had been successively added to the next run until a run on which maintenance had occurred was reached.

   The run lengths were also put on a hit or stroke basis instead of a parts basis. The edit out options in 1 and 2 above are also reflected in the edited deck. All other data are transferred intact from original data cards to edited cards.

The runs on which no maintenance occurred (hereafter called "no maintenance runs") were saved along with the run which followed the no maintenance run. The idea here was to be able to investigate the probability of a very short run following a no maintenance run. This information could be used in appraising a blanket policy of sharpening after every run, but is not utilized in this study.

The rank order section of the program places the edited runs in ascending order, calculates a mean rank plotting position, and cumulative distribution function. The mean rank plotting position of an order statistic is an estimator of the cumulative distribution function, and is discussed by Kao [24]. The median rank of an order statistic is preferred by some investigators [21,27], but for the sample sizes in this study, the mean rank, median rank, and cumulative distribution function are almost identical.

A typical output of the edit and rank order program is shown in Appendix B, Figure B6.

Selected points from the ordered samples were then plotted on Weibull probability paper, and curves were fitted by eye to the plotted points. The procedure outlined in Appendix A for separating the mixture of "early failure" and "normal wear" populations was followed with several exceptions. Kao [24] simplifies the separation considerably by identifying early failures via autopsy. Identification of die failures by autopsy may be possible if done at the time of occurrence. This is, however, not possible with records which date back as much as ten years. The following modification in procedure was therefore made. The number of sample points in each population was calculated as $n\hat{p}$ and $n\hat{q}$ for "early failure" and "normal wear" populations respectively. The straight line representing (on Weibull probability paper) the "early failure" distribution was estimated from the first fifty percent or so of the $n\hat{p}$ sample points on the assumption that these points had a much higher probability of being in the "early failure" population than would sample points near the intersection of the two populations. In like manner, the line representing the "normal wear" distribution was estimated from the last fifty percent or so of the $n\hat{q}$ sample points in the normal failure population on a complementary assumption. This modification was necessary since spurious indications of a high value of γ_2 would appear in the "normal wear" plot if the $n\hat{q}$ sample points in the "normal wear" population were taken sequentially from the upper ranks of the sample. In like manner the straight line representing the "early failure" distribution in a separate distribution Weibull plot bends sharply upwards at its right hand end if the $n\hat{p}$ sample points in the "early failure" population are taken sequentially from the lower ranks of the combined sample.

The method used herein for estimating "normal wear" distribution shaping parameter γ_2 for three of the five carbide tools (Tools No. 3102, 5604, and 5605) also represents a departure from the method prescribed by Kao for the mixed model [24], but is consistent with methods used in estimating γ for a single population [25,27]. This modification was necessitated by the difficulty in estimating the line tangent to the upper end of the mixed model c.d.f. plot. The intersection of this tangent with the lower scale (failure age) of Weibull probability paper estimates $\hat{\gamma}_2$ in the mixed model plot. The locational difficulty arose from a combination of the wide range of hits over which the carbide tools operate and the relatively few sample points for the carbide tools. The curvilinearity which indicates a greater than zero value of γ in single distribution Weibull plots occurred near the upper end of the separate "normal wear" plots rather than at the lower end (which happens if all the $n\hat{q}$ sample points are taken sequentially in the more usual case). The values of $\hat{\gamma}_2$ were thus estimated from the separate "normal wear" distribution plots rather than from the mixed model plots.

Results for the mixed Weibull model[1] applicability are summarized in Table 5, and Weibull plots are shown in Appendix C, Figures C1.0 through C27.0.

Ninety percent confidence limits were placed on the estimates of the separate distributions of "early failure" and "normal wear" for the eleven tool steel dies which produce steel piece parts, for the four carbide dies which produce electrical steel parts, and for the carbide die which produces brass parts. (The most consistent results were obtained for these sixteen dies)[2]. These confidence limits are based on the distributions of individual order statistics. The derivation and application of these limits are given by Kao [24]. Approximate ninety percent confidence levels were also placed on estimates of the Weibull slope $\hat{\beta}$ for the separate "early failure" and "normal wear" distributions. These limits were estimated graphically from Figure 7 of [27, p. 410] on the assumption that all sample points in the respective subpopulations were used to estimate $\hat{\beta}$. Actual estimation was done from fewer points, but the mean rank positions of the points used for estimation are based on the total number of points in the subpopulation; thus the assumption.

The policy of Shop Number 2 of sharpening in anticipation of a run which would exceed the inspector's estimate of edge endurance was investigated by editing out all runs on their tools for which the code 010 was the sole maintenance entry. Cumulative distributions were

1. The composite Weibull model was not considered since the criterion of a low proportion p of "early failures" was not satisfied.

2. Confidence limits were also placed on separate distributions for Tool Number 1109 since it was used in the time dependence studies.

plotted for tools in which the number of runs differed substantially from the number of runs with code 010 included.

The Time Dependence of the Distributions

"Normal wear" and "early failure" distributions have thus far been hypothesized. The next aspect to be considered is the time dependence of these distributions. The two distributions were, however, considered from two different viewpoints. The "normal wear" distribution was studied from the aspect of central tendency over time, while the "early failure" distribution was considered on the basis of random occurrence in time. Time dependence studies are limited to the eight dies for which complete life histories were available.

The choice of whether to classify an individual run as "early failure" or "normal wear" is complicated by the mixture of the distributions; especially since some of the "normal wear" distributions start at or near zero. In the practical sense, though, die runs which actually represent low values in the "normal wear" distribution, although statistically possible, do not represent good performance. The first ten percent point of the estimated "normal wear" subpopulation was accordingly established as an arbitrary lower bound for "normal wear" runs. This point is high enough to exclude well defined "early failure" runs, yet ninety percent of the "normal wear" population is included above the lower bound. Any "early failure" run of length greater than the lower bound, although statistically possible, is scarcely distinguishable from acceptable performance. Lower bounds are tabulated in Table 4.

Table 4: Lower Bounds of "Normal Wear" Distributions

Tool No.	Lower Bound (Hits)
1109	42,000
1501	26,000
1403	26,000
1504	53,600
1508	16,500
4508	20,000
4509	1,000[1]
6501	50,000

Time Dependence of the "Normal Wear" Distribution

An approach akin to $\overline{X}$ Control Chart techniques was employed to get a rough idea of the time dependence of the "normal wear" distribution. The intent here was to see whether there was a persistent pattern of performance over the life of the tool. Means and medians for successive samples of three runs of length equal to or greater than the lower bound were used. These values were calculated with the aid of a computer program written in FORTRAN (FORMAT) for an IBM 1620 computer. The program flow diagram, coding, and typical output are shown in Appendix B, Figures B7, B8, and B9 respectively. The successive sample medians and medians give a picture of the central tendency of die performance, and are plotted in Appendix D, Figures D1 through D8.

Grand means and medians of the truncated samples (sample here means all runs equal to or greater than the lower bound) are shown as reference levels for the plots of means and medians of successive

1. This lower bound is much lower than the first decile of the "normal wear" distribution. It was set arbitrarily low to exclude (for data processing purposes) the one "early failure" run in a otherwise single distribution of "normal wear" runs only.

subsamples of three runs. These reference levels estimate the means and medians of the truncated population; but, in the absence of theoretical development of their statistical properties as estimators, no limits are included. The sample median and mean approach is thus used as a device to spot obvious patterns rather than as a process capability study technique.

Time Dependence of "Early Failure" Distributions

The time dependence of the "early failure" runs was investigated from a different viewpoint than that of "normal wear" runs. The viewpoint in the case of "normal wear" runs is essentially a control chart approach; i.e., the idea that sample means or medians should vary randomly around some central value. In the case of "early failures" though, the occurrence of the event is more important than the length of the run. The "early failure" runs might be expected to occur when the die is first put into use, near the end of useful die life, or perhaps to occur in groups when a particular trouble such as a slightly misaligned press is encountered. That is, the combination of dieset and press alignment might be just bad enough so that a particular die is sheared regularly on a certain press, but other tools are not sheared with enough regularity to suspect the press.

The total number of runs for seven of the eight dies in this area of study were accordingly divided into blocks of ten runs each. (The eighth die had only one "early failure" run.) The upper bound for "early failures" is the same as the lower bound for "normal wear" (as previously discussed); i.e., except that runs "less than" rather than "less than or equal to" the bound are classified as "early failure" runs. Runs classified as "early failure" runs were distributed by sequence number among the blocks of ten runs for each die.

The random variable in this experiment is the number of "early failure" runs per unit (which in this case is the block of ten runs)[1]. The random variable should, under the hypothesis that "early failure" runs occur randomly in time, follow a Poisson distribution. (See Kramér [2, pp.104,105] for a derivation of this approach.) Due to the small number of observations on the random variable, a Kolmogorov-Smirnov Goodness of Fit Test [3, p. 47-52] was used rather than the customarily applied Chi-Square Goodness of Fit Test to test the hypothesis of a Poisson distribution. Results are summarized in Table 6. The test is described in Appendix E, and detailed tests for "early failure" occurrences for individual tools are shown in Appendix E, Figures E1 through E7.

1. Fractional blocks resulting from total numbers of runs not being even multiples of ten were dropped if there were less than five runs in the block, or were considered to be a full block if there were five or more runs in the block. An occurrence rate could have been established to convert fractional blocks, but this procedure would violate the random occurrence assumptions of the Poisson distribution. The overall validity of the approach is not seriously affected by losing fractional blocks.

DISCUSSION OF RESULTS

The evaluation of the applicability of the mixed Weibull model in statistically describing die performance in an operating environment was the primary objective of this investigation. The study of time dependence of "early failure" and "normal wear" distributions was a first step in analyzing the constituent distributions of the mixed model. Mixed model applicability was thus a prerequisite for the time dependence investigation. The possible effect of time dependence on applicability will, however, also be discussed.

Weibull plots of the mixed model cumulative distribution function for all twenty-five tools in the sample are shown in Appendix C, Figures C1.0 through C27.0[1]. Separate "early failure" and "normal wear" c.d.f.'s (cumulative distribution functions) for seventeen of the twenty-five tools[2] are shown in Appendix C, Figures C1.1 and C1.2 through C18.1 and C18.2[3]. These separate plots are shown only for tools for which, as a class, consistent results were obtained[4]. The

1. Twenty-seven cumulative distributions are shown since curves are shown for Tools Nos. 2204 and 2507 both including and excluding runs for which code 010 was the only failure or maintenance code. Reasons for this distinction were previously explained.

2. Tools Nos. 4509 and 5603 had "normal wear" distributions only since Tool Number 4509 had only one "early failure" and Tool Number 5603 had none.

3. See Appendix C for an explanation of the systematic numbering of Weibull plots.

4. Separate plots are also shown for Tool Number 1109 which is not in a class of applications for which consistent results were obtained, but which included in the time dependence study.

criterion for a class of applications to be considered to have consistent results is that the underlying "early failure" and "normal wear" distributions meet the requirements of the mixed model; viz, "early failure" distribution shaping parameter $\beta_1 \leq 1$, "normal wear" distribution shaping parameter $\beta_2 > 1$, and "normal wear" location parameter $\gamma_2 > 0$. Results for tools which had only "normal wear" failures were also considered to be consistent. Tool and piece part material types define a class of applications. Tool steel tools which produce steel piece parts are thus a class of applications. Classes will, for convenience, be described hereafter by specifying (in a broad sense) tool material and piece part material. Tool steel tools which produce carbon steel piece parts will, for example, be referred to as the steel tools-steel parts class.

Consistent results were obtained for the following classes:

1. Steel tools - steel parts[1]
2. Carbide tools - steel parts
3. Carbide tool - brass part

while inconsistent results were obtained for:

1. Steel tools - brass parts
2. Steel tools - nickel silver parts

Table 5 lists sample sizes and estimates of mixed Weibull model parameters[2] for all tools for which (as a class) consistent results in applying the model to tool failures were obtained. Ninety percent

1. Steel Tool Number 1403 which produces magnetic iron piece parts is listed, for convenience, with the steel tools-steel parts class.

2. A $\wedge$ on α, β, γ, p, or q denotes value estimation from the data

Table 5: Estimated Parameters of The Mixed Weibull Model

Tool No.	n	$\hat{p}$	$\hat{\beta}_1$	90% Conf. Int.(β_1)	$\hat{q}$	$\hat{\beta}_2$	90% Conf. Int.(β_2)	$\hat{\alpha}_1$	$\hat{\alpha}_2$	$\hat{\gamma}_2$
Steel/Steel										
1501	67	0.75	0.70	0.60-0.80	0.25	1.61	1.16-2.03	1.26×10^3	1.01×10^8	450
1502	87	0.30	0.30	0.23-0.37	0.70	2.35	2.00-2.70	16.8	1.59×10^{12}	900
1403(mag. iron)	77	0.26	0.33	0.24-0.42	0.74	2.47	2.07-2.86	19.7	7.55×10^{11}	1.1×10^3
1504	100	0.32	0.36	0.28-0.43	0.68	2.05	1.76-2.34	29.6	2.24×10^{10}	600
1505	52	0.38	0.33	0.24-0.42	0.62	2.15	1.70-2.60	8.50	5.91×10^{10}	1.5×10^3
1508	52	0.33	0.37	0.27-0.47	0.67	1.65	1.32-1.98	40.7	8.84×10^7	200
2507	34	0.23	0.50	0.29-0.71	0.77	1.65	1.28-2.02	78.5	7.23×10^7	430
2507(010 out)	26	0.31	0.37	0.21-0.53	0.69	1.92	1.21-2.44	25.1	1.59×10^9	300
4508	47	0.48	0.25	0.19-0.31	0.52	1.24	0.94-1.54	9.55	2.35×10^6	300
4509	64	0			1.00	2.75	2.34-3.16	None	9.92×10^{13}	0
6501	50	0.18	0.28	0.17-0.39	0.48	3.20	2.62-3.78	19.7	5.13×10^{15}	1.5×10^4
6507	31	0.22	0.65	0.36-0.94	0.40	2.00	1.52-2.48	595	1.81×10^{10}	2×10^3
Carbide/Steel										
5602	21	0.34	0.20	0.11-0.29	0.66	1.40	0.96-1.83	11.4	3.58×10^7	700
5603	22	0			1.00	2.05	1.54-2.56	None	5.22×10^{11}	1.8×10^5
5604	34	0.52	0.95	0.67-1.23	0.48	2.55	1.83-3.26	1.80×10^5	2.39×10^{14}	4.0×10^5
5605	24	0.60	0.75	0.41-0.99	0.40	3.65	2.26-5.00	6.17×10^3	2.38×10^{20}	2.0×10^5
Carbide/Brass										
3102	68	0.30	1.0	.74-1.26	0.70	1.30	1.08-1.52	6.17×10^4	2.12×10^7	2.0×10^5
Steel/Brass										
1109	56	0.33	0.25	0.18-0.32	0.67	1.20	0.97-1.43	20.1	3.44×10^6	800

confidence intervals for shaping parameters $\hat{\beta}_1$ and $\hat{\beta}_2$ are also included.

Estimated parameters for "early failure" and "normal wear" distributions for all tools meet the criteria for applicability of the mixed Weibull model. The mixed model could also be said to be applicable to tools for which there is no "early failure" distribution (previously noted as an exception) if proportion p of "early failures" is assumed to equal zero. This assumption is reflected in tabulations of results for Tools Nos. 4509 and 5603.

The ninety percent confidence bands shown on Weibull plots of separate "early failure" and "normal wear" distributions(Appendix C, Figures C1.1 and 1.2 through C18.1 and 18.2) contain the majority of plotted points. Several end points (the highest ranked point in the sample) fall outside of the bands, but these points could well be regarded as freak occurrences or as outliers. Occasional single mid-distribution points fall on or slightly outside of the confidence bands. Only in the case of Tool Number 4509, which had no "early failure" distribution, did several successive mid-distribution points in succession fall outside of the lower confidence band. The confidence band itself, however, is not to be regarded as exact since it is constructed by drawing a smooth curve through the end points of confidence intervals about individual order statistics, and is thus an approximation of the statistical limits within which ninety percent of order statistics of samples from the estimated distributions would be expected to fall. In this context, some of the data points could be expected to fall outside of the confidence bands. The point here is that the confidence bands are not used as a goodness of fit test of the hypothesis that the estimated Weibull distributions are the actual distributions of "early failure" and "normal wear" runs. The fact that most of the sample points fall within the confidence bands does, however, strongly support the assumption of the underlying Weibull distributions.

Values of $\hat{\beta}_1$ (estimated shaping parameter for the "early failure" distribution) in Table 5 range from 0.18 to 1.0 and are distributed as shown in Table 6 below:

Table 6: Distribution of Estimated Values of "Early Failure" Shaping Parameter $\hat{\beta}_1$

Range	Number of Values	Percent of Values
.01 - .20	1	7
.21 - .40	8	53
.41 - .60	1	7
.61 -1.00	5	33
	15	100

1. Tool Number 2507 was counted only once (with code 010 included), and Tools Nos. 4509 and 5603 had no "early failure" distributions.

The bulk of the "early failure" distributions have shaping parameters of .21 - .40. Weibull distributions which have shaping parameters in this range have probability density functions similar to that shown in Figure 3 for $\beta = 0.5$. Thos functions which have values of β lower than 0.5, however, exhibit an even more rapid initial decay and a slower decay at higher values of t than the function which has β=0.5. These low values of $\hat{\beta}$ also indicate a high initial hazard rate (ref. Figure 4) as the die is set in the press, and thus reinforce the idea that the probability of a short run is very high if the conditions which could cause "early failure" are operative when the die is set in the press. The decreasing hazard rate with time supports the idea that the die is less exposed to "early failure" hazards as the number of successful hits increases. Three of the five values of $\hat{\beta}_1$ greater than .61 were associated with carbide tools. The initial hazard rate for higher values of β_1 is less than for lower values, and the probability density function decays initially less rapidly. The typical rugged construction of carbide dies might well be an underlying factor in the association of higher values of $\hat{\beta}_1$ with these dies. Carbide dies are usually more heavily constructed than their tool steel counterparts; primarily to prevent the shear failures which are the principal type of "early failure" for the steel tools and which are particularly damaging to carbide tools. The "early failures" for carbide tools may thus be due to causes such as poor grinding which would show up soon enough for the run to be classified as an "early failure" but not so soon after setup as would a shear failure at setup.

Tabulated values (Table 5) of proportion $\hat{p}$ of "early failure" runs ranged from 0 to 0.75, and were distributed as shown in Table 7 below:

Table 7: The Distribution of Estimated Values of Proportion $\hat{p}$ of "Early Failure" Runs

Range	Number of Values[1]	Percent of Values
0 - .20	3	18
.21 - .40	10	58
.41 - .60	3	18
.61 and over	1	6
	17	100

1. Tool Number 2507 is counted only once (Code 010 included).

The majority of values fall within the .21 - .40 range. The reasons for differing proportions of "early failure" runs are not readily apparent, although several observations can be made. The highest proportion of "early failure" runs is for Tool Number 1501 which punches .125 inch thick carbon steel. Tool Number 4509, on the other hand, which had only one "early failure" run (which was disregarded) punches .056 inch thick steel of the same temper in a much easier application. This observation is, though, made only in passing and cannot be generalized. The causes of "early failure" runs will be considered further in a discussion of "Recommendations for Further Study". The proportion of "early failure" runs, as mentioned previously, refers to the proportion of runs in the statistical population which is called the "early failure" population. The decreasing decay rate of the "early failure" density function guarantees that some runs which are statistically in the "early failure" population will be long enough to be considered "normal wear" runs. For practical purposes, a lower bound based on the "normal wear" distribution (such as was used in the time dependence study) should be used to differentiate between "early failure" and "normal wear" runs.

Conversely, to reiterate another previously discussed point, runs which are statistically in the "normal wear" population can be, for practical purposes, short enough to be considered "early failure" runs. The point here is that proportion p does not mean that np[1] "early failure" (for practical purposes) runs will occur.

The ninety percent confidence intervals on the estimates of $\hat{\beta}_1$ and $\hat{\beta}_2$ serve principally to illustrate the range of values which could contain the true value of the shaping parameters when samples of the size encountered in this investigation are used to estimate the parameters. The upper limit of the confidence interval for true value of β_1 , even with the relatively wide confidence intervals associated with the die life limited sample sizes, exceeds 1.0 for only two $\hat{\beta}_1$ estimates. Likewise, the lower limit of the confidence interval for the true value of β_2 is less than 1.0 in only three instances. The true values of the Weibull slope parameters β_1 and β_2 can thus, in the majority of cases, be anywhere in the confidence interval without affecting applicability of the mixed Weibull model.

Estimated values of $\hat{\beta}_2$ (Table 5), ranging from 1.20 to 3.65, are distributed as shown in Table 8 below:

1. Where n is the total number of runs over the life of the die.

Table 8: The Distribution of Estimated Values of "Normal Wear" Shaping Parameter $\hat{\beta}_2$

Range	Number of Values[1]	Percent of Values
1.20 - 1.80	6	35
1.81 - 2.40	7	41
2.41 - 3.20	2	12
3.21 and over	2	12
	17	100

1. Tool Number 2507 is again counted only once (with Code 010 included).

The typical "normal wear" distribution has a shaping parameter of about 1.80, and is thus positively skewed (ref. Figure 3). All estimated values of $\hat{\beta}_2$ meet the criterion of the mixed Weibull model. Implications of the ninety percent confidence intervals for β_2 were discussed earlier along with the discussion of the corresponding confidence intervals for β_1.

Estimated values of scaling parameters $\hat{\alpha}_1$ and $\hat{\alpha}_2$ are included in Table 5 for completeness of results rather than for their own importance. The wide variation which exists among values of $\hat{\alpha}_1$ and $\hat{\alpha}_2$ within their own groups is due to the nature of the scaling parameter itself and to the use of scaling factors in plotting c.d.f.'s. The natural logarithm of α rather than α itself is estimated from Weibull probability paper. A linear increase in the value of $\ln \alpha$ would thus result in an exponential increase in the value of α. The use of scaling factors also requires that the estimated value of α be multiplied by 10^{jb} where j is the exponent of 10 which is required to properly scale Weibull probability paper for failure age and β is the shaping parameter. Typical values of j were 3 for "early failure" distributions and 4 (sometimes 5) for "normal wear" distributions. The exponential effects of these multipliers can thus easily cause large variations in the values of α_1 and α_2.

The values (Table 5) of "normal wear" distribution location parameter $\hat{\gamma}_2$ show that the $\gamma_2 > 0$ criterion of the mixed model is satisfied.[1] The values of $\hat{\gamma}_2$ estimated for the majority of steel tools are not high enough to be reflected in the "normal wear" plot. The "normal wear" distribution of Tool No. 1501 has, for example, an estimated $\hat{\gamma}_2$ of 450 hits and a 10% lower bound (ref. Table 5) of 26,000 hits, and 26,000 (t) is virtually indistinguishable from 25,550 ($t-\gamma_2$).

Values of $\hat{\gamma}_2$ for carbide tools range from 700 to 400,000. The value for Tool Number 5603's "normal wear" distribution offers some indication that the higher values are reasonable. This tool had only a "normal wear" distribution. The estimate of 180,000 hits for $\hat{\gamma}_2$ was obtained via the method prescribed by Kao [25] for single Weibull plots instead of by the method prescribed by Kao [24] for the mixed model c.d.f. plot. The high estimates of $\hat{\gamma}_2$ for carbide tools were thus estimated, as discussed in "Method of Study," from "normal wear" distribution plots rather than from mixed model c.d.f. plots. Estimation of $\hat{\gamma}_2$ from small sample mixed model c.d.f. plots is difficult. This difficulty could be alleviated in the separate "early failure" and "normal wear" plots if individual sample points in the mixed sample could be identified as "early failure" or "normal wear" runs.

1. Except in the case of Tool Number 4509, which had only a "normal wear" distribution.

The typical mixed Weibull model for the preponderant steel tool-steel part application is constituted approximately as follows:

1. 30% "early failure" component distribution with shaping parameter $\beta_1 = .30$.
2. 70% "normal wear" component distribution with shaping parameter $\beta_2 = 1.80$ and location parameter $\gamma_2 = 400$ hits.

The typical constituent distributions are thus (1) an exponential type "early failure" component which has a high initial decay rate followed by a decreasing rate and (2) a positively skewed "normal wear" component.

Mixed model c.d.f. plots for tools for which class results were considered inconsistent are included in Appendix C as Figures C19.0 through C27.0. The mixed model c.d.f. plot for Tool Number 6106 (Appendix C, Figure C20.0) is an example of an application for which results are inconsistent. A single straight line represents the mixed model c.d.f. This linearity indicates that the underlying distribution is Weibull; however, the estimated value of shaping parameter $\hat{\beta}$ is less than 1.0. Shaping parameters of 1.0 and under give rise to exponential type distributions (ref. Figure 3). The exponential type distribution is widely used in Reliability [28], and may well describe the performance of this particular die; but the criteria for the mixed Weibull model are not met unless the entire distribution is considered as an "early failure" distribution. The mixed model c.d.f. plot for Tool Number 2202 (Appendix C, Figure C22.0) is another example of inconsistency; this time in the steel tool-nickel silver part class. Two linear segments joined by a curved segment are fitted to the sample points, thus suggesting the mixed Weibull model. The estimated shaping parameters for the two underlying distributions are, however, both less than 1.0; thus indicating exponential type distributions for both "early failure" and "normal wear" populations. This mixture of two exponential distributions is also encountered in Reliability [26], but again the criteria for the mixed Weibull model are not met. The mixed Weibull model appears, however, to be applicable in the cases of Tools Nos. 4201 (Appendix C, Figure C25.0) and 4202 (Appendix C, Figure 26.0). Performance of Tool Number 4207 (Appendix C, Figure C27.0), another in the steel tools-nickel silver parts class, defies analysis by the methods used herein. The mixed model c.d.f. plot appears to consist of two parallel linear segments, each of slope greater than 1.0.[1] Further investigation may reveal the reasons for consistence and inconsistence within the classes of steel tools-brass parts and steel tools-nickel silver parts; but results as classes will be considered inconsistent for purposes of this study.

Shop Number 2's stated policy of sharpening tools if the combined current run and anticipated next run exceeds the inspector's estimate of cutting edge wear endurance is not generally reflected in the inspection records and in the performance of their tools which were included in the sample. The edited rank order computer outputs showed differences of more than two runs only for Tools Nos. 2507 and 2202 when runs which were maintenance coded 010 (grind) only were removed. The respective mixed model c.d.f. plots including and excluding code 010 runs are virtually identical (Appendix C, Figures C7.0 with 010 and

1. The slope of the straight line in a Weibull plot is, as explained in Appendix A, an estimate of shaping parameter $\hat{\beta}_1$.

C8.0 without 010 for Tool Number 2507 and Figures C22.0 with 010 and C23.0 without 010 for Tool Number 2202). Parameter estimates in Table 4 for Tool Number 2507 with and without code 010 differ in individual values primarily due to changes in the makeup and size of the sample. The code 010 runs which were omitted were principally "normal wear" runs. As a result, $\hat{p}$ was greater in the smaller sample, and the effect was to decrease $\hat{\beta}_1$ and increase $\hat{\beta}_2$ (probably since many of the code 010 runs were toward the low side of the "normal wear" population. The 90% confidence intervals for the true values of β_1 and β_2 are, however, comparable in the two cases.

Medians and means for successive samples of three runs from the truncated "normal wear" distributions for the eight tools in the time dependence study are plotted in Appendix D, Figures D1 through D8. No trend or pattern applicable to all tools appears in the plots, although plots for Tools Numbers 1508, 4508 and 4509 (Figures D5, D6 and D7 respectively) show upward trends with increasing sample number. A possible explanation for this trend is that tool performance improves as punch and die clearances become greater as the result of grinding. This upward trend is, however, not universal since plots for Tools Numbers 1501, 1403, 1504 and 6501 (Appendix D, Figures D2, D3, D4 and D8 respectively) vary with differing degrees of randomness around estimated grand medians and grand means of the truncated "normal wear" distributions. The plot for Tool Number 1109 (Appendix D, Figure D1) is unique in that the central tendency of die performance appears to change abruptly from a low level to a higher level after the seventh sample of three. This change is particularly evident on the plot of sample means. Of the eight tools, then; three show apparent performance improvement with time, four tools indicate fluctuation in varying degree around the same central tendency, and one tool's performance appears to fluctuate first around a low level and then around a higher level of performance. The terms "indicate" and "appears" are used in describing results since, in the absence of a knowledge of the distributions of the sample medians and means, definite statistical statements cannot be made.

Results of the statistical tests for the random occurrence of "early failure" runs are summarized in Table 9, and individual tests for the seven tools which had "early failure" runs are shown in Appendix E, Tables E1 through E7. The hypothesis that the random variable X = number of "early failure" runs per block of ten runs follows a Poisson distribution cannot be rejected at a .20 level of significance; except in the case of Tool Number 1403 for which the hypothesis cannot be rejected at a .01 level of significance. The level of significance refers to the probability of making a Type I error rather to the degree of acceptance of the hypothesis. The level of significance is thus of greater importance in rejecting the hypothesis. The fact, however, that the test statistic D is, in the majority of cases, less than the least tabulated value of D, is a good indication that the hypothesized Poisson distribution underlies the occurrence of "early failure" runs.

The time dependence studies of "early failure" and "normal wear" distributions have indicated that the "early failure" runs occur randomly in time and that "central tendency" of die performance may

Table 9 Summary of Kolmogorov-Smirnov Goodness of Fit Tests

Ho: The distribution of the random variable X = number of "early failure" runs per block of ten runs is Poisson with parameter $\hat{m}$.

Tool No.	N	m	D	$\alpha_{.20}$	Reject Ho?
1109	10	1.4	.104	.322	no
1403	21	2.6	.301	.231	yes[1]
1501	26	3.7	.171	.210	no
1504	40	4.0	.166	.169	no
1508	11	1.7	.150	.216	no
4508	17	3.4	.147	.250	no
6501	13	2.2	.210	.284	no

1. The hypothesis can be rejected at a .20 significance level but cannot be rejected at a .01 significance level.

in some instances change over time. The applicability of the Weibull distribution in the "normal wear" case might be challenged due to the change of the distribution with time (as indicated by the trends of sample means). Several observations can be made on this point. The first is that the mixed Weibull model appears applicable for dies which are in varied stages of life ranging from the relatively "young" carbide dies from Shop Number 5 to the eight dies for which complete life histories are available. The second observation is that, in the practical sense, the mixed model would most likely be used to identify extremes; that is, to differentiate "early failure" and "normal wear" runs. Some shifting of the level of die performance could thus be tolerated.

CONCLUSIONS

The summary conclusions to be drawn from this investigation are as follows:

1. The mixed Weibull model is, to the extent indicated by the analysis herein, a consistent statistical model for the performance (or reliability) under actual operating conditions of certain classes of simple progressive dies. The model could thus be said to be applicable to the reliability of simple progressive dies.
2. Die performance, as indicated by the "normal wear" component distribution, fluctuates in some cases around a constant central level and in other cases around a rising trend. Further investigation is required before definite statistical statements can be made concerning the time dependence of the "normal wear" distribution.
3. The "early failure" runs which comprise the "early failure" component distributions occur randomly in time. The distributions of "early failure" runs are thus not time dependent.

RECOMMENDATIONS FOR FURTHER STUDY

This investigation was centered on the initial sub-problem of the larger problem of forecasting the reliability and maintenance requirements of punch press dies; i.e., the sub-problems of finding a statistical model of die performance (or reliability). Recommendations for further study are along two principal paths; the first concerns questions inherent in this investigation, and the second concerns the larger problem of reliability and maintenance forecasting.

The application of the mixed Weibull model should be investigated more thoroughly. Kao [24] simplifies the application considerably when he is able to identify specific failures as being "early failures" or "normal wear". In the general case, though, specific failures are difficult to classify even though the existence of several underlying distributions is clearly indicated by the mixed model c.d.f. plot. Separation of the underlying distributions is also very difficult when proportions and shaping parameters of the respective distributions are almost equal. It is thus recommended that the mixed Weibull model be studied via simulation by sampling from known "early failure" and "normal wear" distributions for various combinations of parameters.

The time dependence of the "normal wear" distribution should be further investigated. A control chart approach (with theoretical justification of the control limits) is recommended. Time dependence of the "early failure" distribution could also be further studied by using different upper bounds. A relatively low upper bound would, for example, show whether the more flagrant "early failures" also occurred randomly in time.

Another pertinent question is whether dies of allegedly identical design and construction have the same reliability, or whether each tool has individual reliability characteristics?

The immediate next step in investigating the larger problem of reliability forecasting is to try to relate tool design and application factors to the tool reliability (or performance) which is indicated by the statistical model. The initial problem here is to try to discover principal factors affecting die performance and to measure their relative effects. Again, the investigation could proceed along two paths; one directed toward "early failures" and the other toward "normal wear" performance. Early failures could, for example, be tool related, shop related, or could be related to a combination of these factors. The proportion p of "early failures" rather than the distribution parameters would be the logical variable to study. The "normal wear" distributions would also most likely be studied from the aspect of relating tool geometry to performance. The starting point, at least for simple progressive dies, would be perforator size and arrangement. The relative proportions of individual component failures should also be included in the geometry-performance study.

Maintenance hours were also punched into the data cards. Different tools would be expected to require different amounts of maintenance. Possible areas of interest here are the relationship of maintenance hours to tool geometry or tool application and the correlation of maintenance hours with length of run; i.e., do long runs require increased maintenance?

The policy of maintaining tools after every run could also be investigated via the detail of "no maintenance" runs which is part of the "Edit and Rank Order" computer program output. An approach would be to determine the probability and economic effects of an "early failure" run following a "no maintenance" run.

The writer hopes that the preceding recommendations for further study will provide ideas for future investigations.

APPENDIX A - ANALYSIS OF SINGLE AND MIXED WEIBULL DISTRIBUTIONS

Weibull probability paper is based on the following logarithmic transformations for linearity of the cumulative distribution function:

$$F(t) = 1 - e^{-[t-\gamma]^{\beta}/\alpha}$$

$$1 - F(t) = e^{-[t-\gamma]^{\beta}/\alpha}$$

$$\frac{1}{1 - F(t)} = e^{[t-\gamma]^{\beta}/\alpha}$$

$$\ln \frac{1}{1 - F(t)} = (t-\gamma)^{\beta}/\alpha$$

$$\ln \ln \frac{1}{1 - F(t)} = \beta \ln (t-\gamma) - \ln \alpha$$

This transformation is of the linear form

$$y = mx + b$$

thus the linear scales on Weibull probability paper are:

$$\text{abscissa} = \ln (t-\gamma)$$

and

$$\text{ordinate} = \ln \ln \frac{1}{1 - F(t)}$$

Auxiliary scales of failure age and cumulative percent failure are provided for direct plotting of data.

Estimation of parameters α, β, and γ is fairly straightforward in application to simple Weibull distributions. The cumulative distribution function, or its mean or median rank estimate, is plotted on the probability paper. Note, though, that the abscissa is $(t-\gamma)$. The line will curve downward and to the right if γ is not zero. The location parameter is estimated by trying various values of γ until a straight line is obtained. The slope of the resulting straight line (in terms of transformed axes) estimates shaping parameter $\hat{\beta}$, and the principal ordinate intercept estimates $- \ln \alpha$. Additional scales are provided on the special paper (available from Professor Kao) for estimating mean μ and standard deviation σ.

Graphical treatment of the mixed Weibull model is similar to that of the simple Weibull distribution, but is somewhat more involved. The procedure is to plot the combined "early failure" and "normal wear" distributions, to estimate proportions $\hat{p}$ and $\hat{q}$ and location parameter $\hat{\gamma}_2$ from the combined plot, and then to estimate separate distribution parameters on separate single distribution plots. The procedure will be explained briefly and with the aid of Figure A1 below:

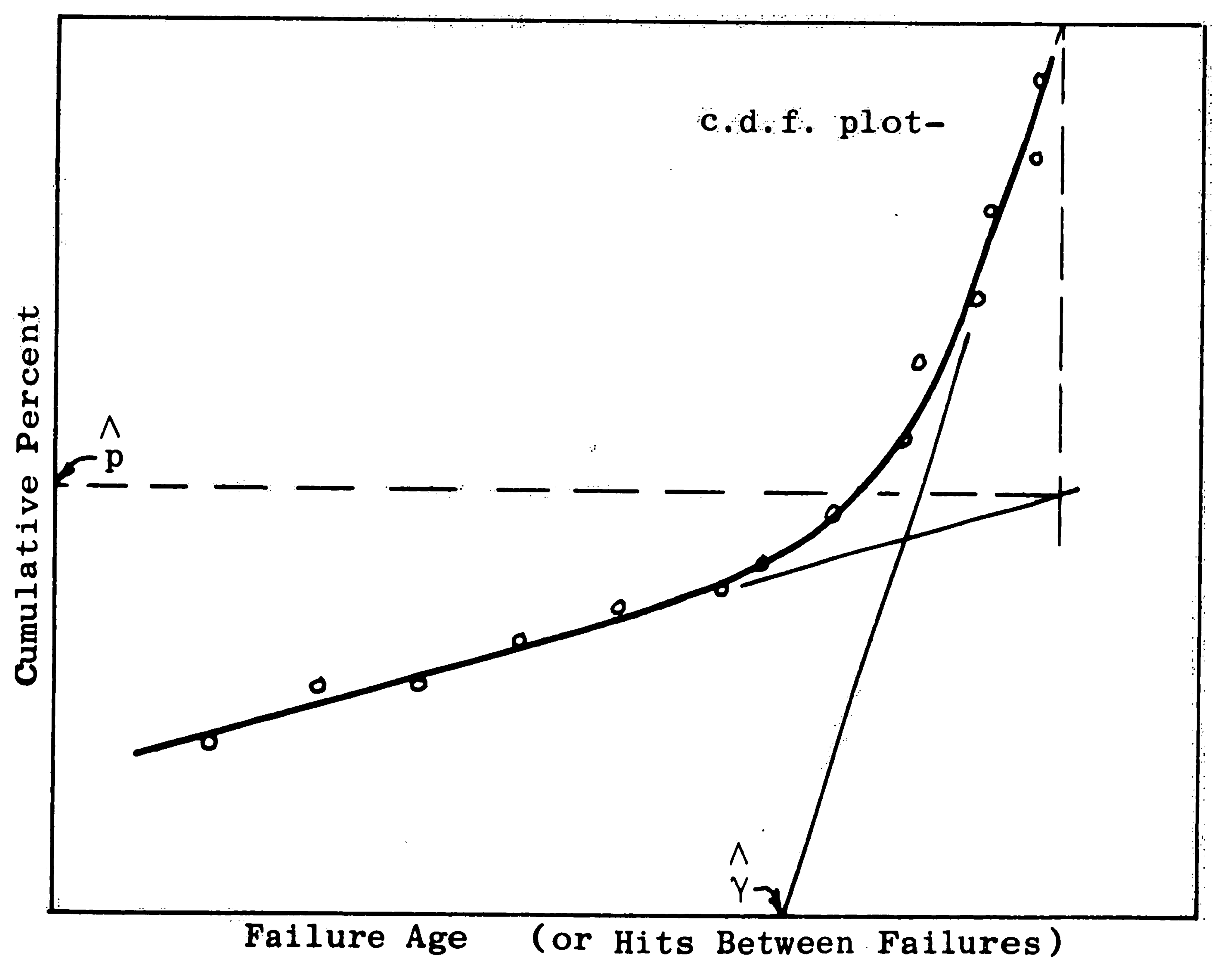


Figure A1 - Analysis of the Mixed Weibull Model

The mixed model c.d.f. is plotted as shown above, and a smooth curve is fitted to the points. Tangents, as shown by the thin solid lines, are then drawn to the extremities of the curve. The proportion $\hat{p}$ of "early failures" is estimated by the ordinate of the intersection of the tangent to the lower end of the curve and a perpendicular dropped from the intersection of the other tangent and the uppermost abscissa. This construction is shown by dashed lines in Figure A1. "Normal wear" distribution location parameter $\hat{\gamma}_2$ is estimated by the intersection of the tangent to the upper end of the curve and the failure age scale and is so denoted in the illustration. Proportion $\hat{q}$ of "normal wear" failures is given by $\hat{q} = 1 - \hat{p}$. The n points of the sample are then separated into $n\hat{p}$ and $n\hat{q}$ "early failure" and "normal wear" points respectively, and separate distribution plots are made accordingly.

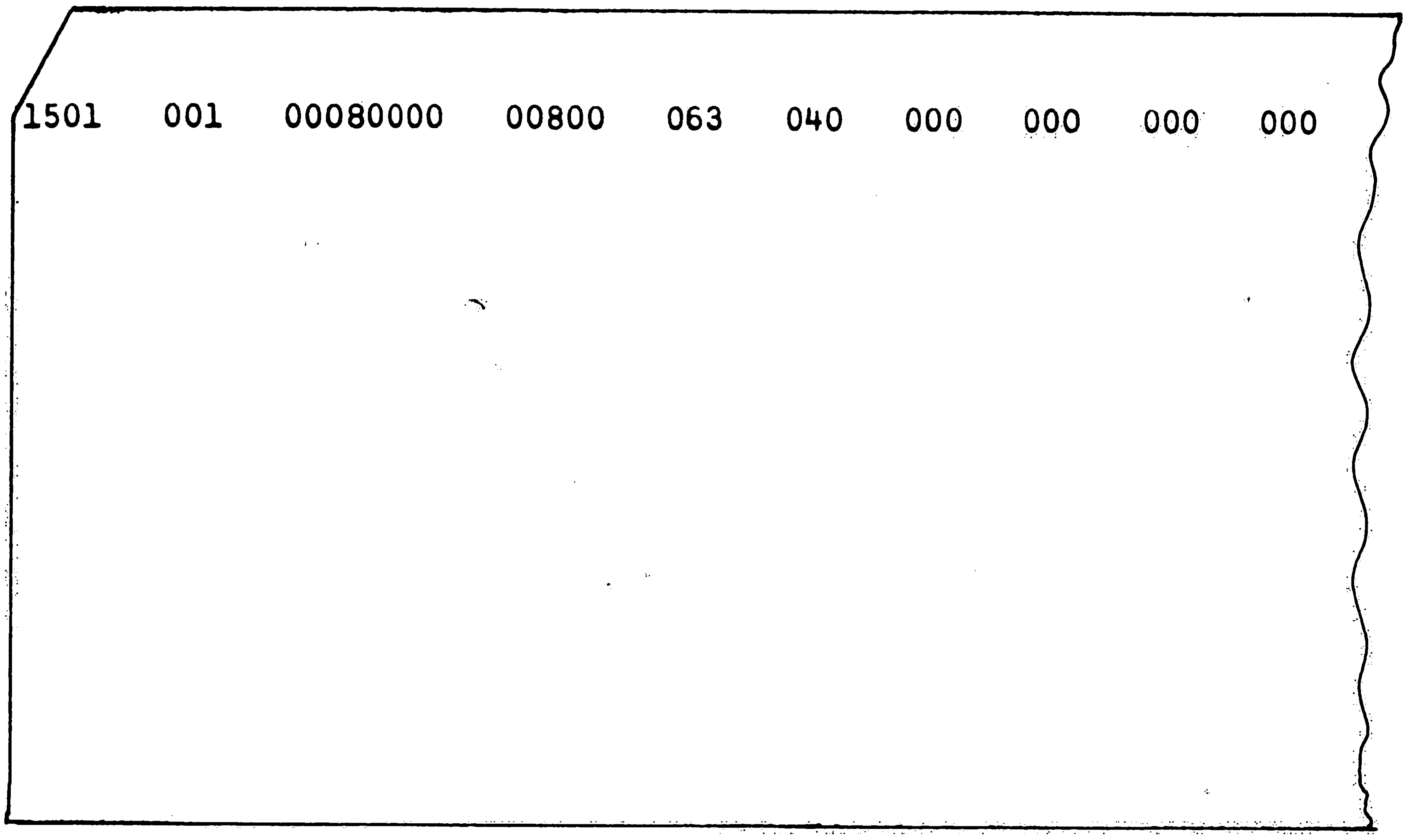
More detailed discriptions and illustrations of the preceding procedures are given in [23] and [24].

APPENDIX B - DATA PROCESSING

List of Figures

FIGURE B1 Data Card Format

The data card format is as shown below for a typical card:



Columns	Data
1-4	Tool identification number.
7-9	Run sequence number.
12-19	Run length in parts. The number in the example is read as 80000.
22-26	Repair hours. The number in the example is read as 8.00. If information is not available, 00001 is entered.
29-31	Principal failure code.
33-35	Additional failure or maintenance code.
38-40	Additional failure or maintenance code.
43-45	Additional failure or maintenance code.

Columns	Data
48-50	Additional failure or maintenance code.
53-55	Additional failure or maintenance code.

FIGURE B2 Tool Identification Number

Tools are identified by a four-digit number which identifies the using shop and the piece part material. The format is as follows:

1 4 0 6

- 0 6 — Control number assigned for within shop identification.
- 4 — Material identification digit.
- 1 — Shop identification digit.

1. Six digits are used for shop identification. Shop Numbers 1 through 5 are at Western Electric's Kearny Works, and Shop Number 6 is at Western Electric's Baltimore Works.
2. Materials are:

   (1) Brass

   (2) Nickel silver

   (3) Phosphor bronze

   (4) Magnetic iron

   (5) Carbon steel

   (6) Silicon alloyed steel

Tool Number 1406, used as an example, would thus be used by Shop Number 1 for cutting magnetic iron and would be the sixth tool in the sample from Shop Number 1.

FIGURE B3 Die Failure and Maintenance Codes

000 - No Maintenance

000-019 - Cutting edge

010 - Die ground - No record of excessive burr. Shop policy is grind after long run.

011 - Die ground - No record of excessive burr. Shop policy is to run until cutting edge fails.

012 - Die ground - Excessive burr noted.

020-029 - Pulling slugs or parts

020 - Perforator pulling slugs

022 - Punch pulling parts

030-039 - Defective pilots

030 - Broken

031 - Bent

032 - Too long

040-049 - Defective perforators

040 - Broken

041 - Bent

042 - Chipped

043 - Sheared

044 - Fired up[1]

---

[1] The term "fired up" is used at Kearny to describe the buildup of a softer metal on a cutting member or on a guide or liner pin.

045 - Undersize

046 - Oversize

050-059 - Defective punches

050 - Broken

051 - Bent

052 - Chipped

053 - Sheared

054 - Fired up

055 - Undersize

060-069 - Defective die sections, inserts, and bushings

060 - Cracked

061 - Chipped

062 - Fired up

063 - Sheared

064 - Sunken

065 - Oversize

066 - Slugged

067 - Too tight

070-072 - Defective forming details

070 - Broken

071 - Chipped

072 - Not forming correctly

073 - Tool sheared; component not specified

080-089 - Defective stripper components

080 - Stripper plate broken

081 - Stripper plate bent

082 - Stripper springs broken

083 - Stripper springs weak

084 - Subliner pins pushed out

085 - Defective perforator guide bushings

086 - Stripper not set properly

088 - Defective stripper bushings

090-099 - Defective die set and auxiliary components

090 - Liner pins "fired up"

091 - Liner pins pushed out

092 - Broken punch holder

093 - Auto or finger stop broken

094 - Broken or bent stock guide

096 - Defective push pin

097 - Broken bumper

098 - Bad alignment

100 - Not detailed and miscellaneous

Auxiliary Maintenance Codes

300 - Make new pilots

310 - Grind back pilots

315 - Set pilots

400 - Make new perforators

410 - Grind back perforators

500 - Make new punches

510 - Grind back punches

515 - Rework punches

600 - Make and install new die section

605 - Stone die

800 - Repair stripper - not detailed

810 - Grind stripper plate

815 - Grind subliner pins

820 - Relieve punches in stripper

900 - Grind liner pins

901 - Install new push pins and springs

910 - Miscellaneous repairs

FIGURE B4 - FLOW CHART FOR "EDIT AND RANK ORDER"

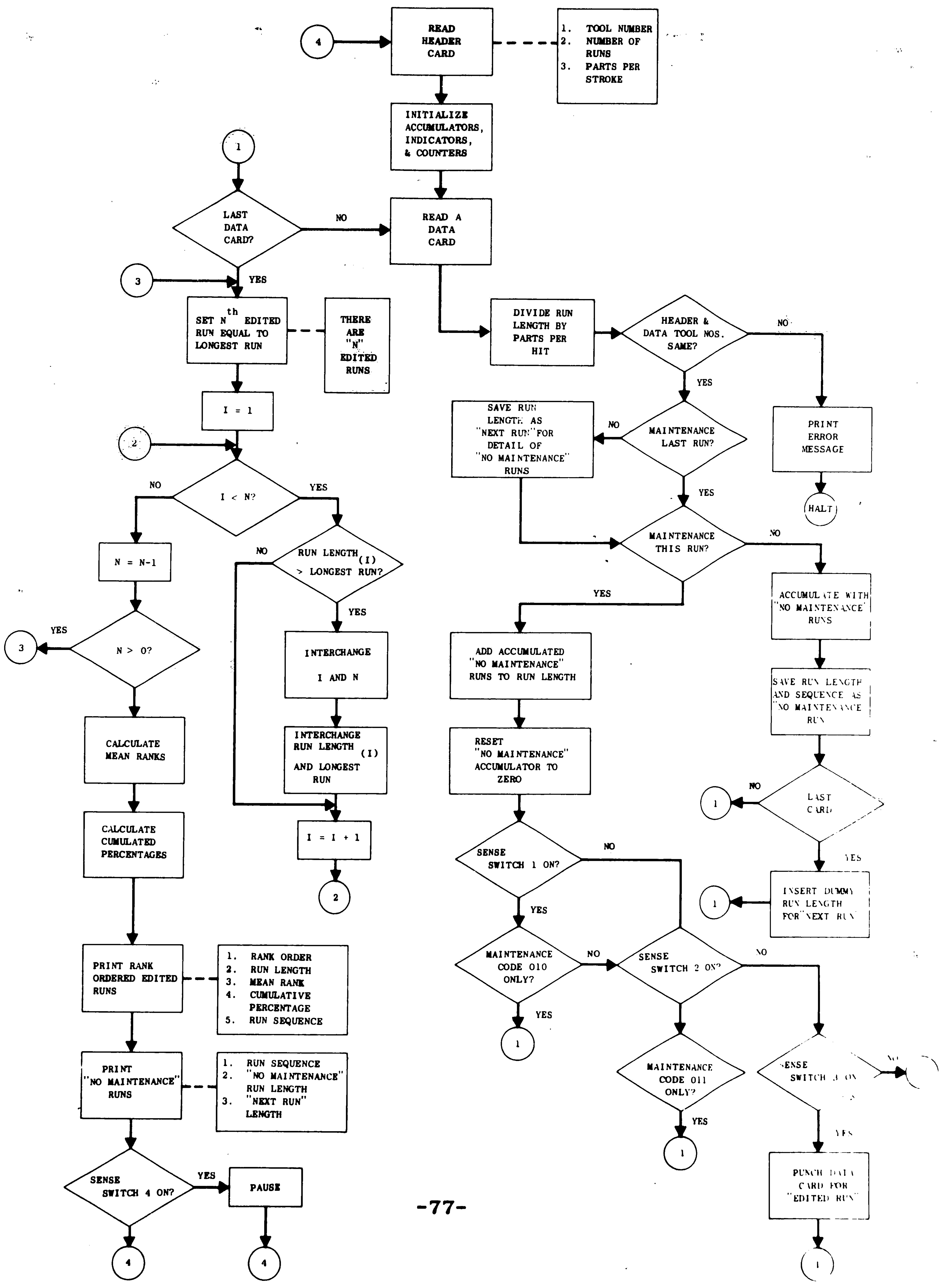


FIGURE B5 FORTRAN (FORMAT) CODING FOR THE "EDIT AND RANK ORDER" PROGRAM

```
C EDIT AND RANK ORDER DFW 5-18-64
C SENSE SWITCH 1 ON IGNORES CODE 010
C SENSE SWITCH 2 ON IGNORES CODE 011
C SENSE SWITCH 3 ON PUNCHES EDITED DECK
C SENSE SWITCH 4 ON PUTS PAUSE AFTER OUTPUT
      DIMENSION RUN(125),RUNM(35),RNXT(35),KSEQ(125),NSEQ(35)
  100 READ 191,ITN,N,PER
  191 FORMAT (I4,2XI3,2XF3.0)
      CRUN=0.
      NM=1
      JC=1
      INM=1
      DO 190 I=1,N
      READ 192,JTN,JSEQ,DRUN,HRS,IFC1,IFC2,IFC3,IFC4,IFC5,IFC6
  192 FORMAT (I4,2XI3,2XF8.0,2XF5.2,2XI3,2XI3,2XI3,2XI3,2XI3,2XI3)
      DRUN=DRUN/PER
      IF(ITN-JTN)105,110,105
  105 PRINT 193
  193 FORMAT (15X17HWRONG TOOL NUMBER)
      PAUSE
      GO TO 100
  110 GO TO (150,145),INM
  145 RNXT(NM)=DRUN
      NM=NM+1
  150 IF(IFC1)155,155,170
  155 CRUN=CRUN+DRUN
      RUNM(NM)=DRUN
      NSEQ(NM)=JSEQ
      INM=2
      IF (N-I)160,160,165
  160 RNXT(NM)=999.
      NM=NM+1
  165 GO TO 190
  170 DRUN=DRUN+CRUN
      CRUN=0.
      INM=1
      IF(SENSE SWITCH 1)115,125
  115 IF(IFC1-10)125,120,125
  120 IF(IFC2)190,190,140
  125 IF(SENSE SWITCH 2)130,140
  130 IF(IFC1-11)140,120,140
  140 RUN(JC)=DRUN
      KSEQ(JC)=JSEQ
      NTR=JC
      JC=JC+1
      IF(SENSE SWITCH 3)175,190
  175 PUNCH 196,JTN,JSEQ,DRUN,HRS,IFC1,IFC2,IFC3,IFC4,IFC5,IFC6
  196 FORMAT (I5,1XI4,F10.0,F7.2,1XI4,1XI4,1XI4,1XI4,1XI4,1XI4)
  190 CONTINUE
```

```
C RANK ASCENDING ORDER EDITED DATA
      NNTR=NTR-1
  205 DO 225 K=1,NNTR
      IF (RUN(K)-RUN(NNTR+1))225,225,210
  210 TSTO=RUN(K)
      RUN(K)=RUN(NNTR+1)
      RUN(NNTR+1)=TSTO
      ITEM=KSEQ(K)
      KSEQ(K)=KSEQ(NNTR+1)
      KSEQ(NNTR+1)=ITEM
  225 CONTINUE
      NNTR=NNTR-1
      IF (NNTR-1)235,205,205
  235 BOTT=RUN(1)
      TOP=RUN(NTR)
C PRINT OUT RESULTS
      PRINT 801,ITN
  801 FORMAT (15X11HTOOL NUMBER,2XI5/)
      PRINT 815
  815 FORMAT (18X25HRANK ORDER OF EDITED RUNS/)
      PRINT 819,BOTT,TOP
  819 FORMAT (20XF10.0,2X2HTO,1XF10.0/)
      PRINT 831
  831 FORMAT (36X3HRUN,6X4HMEAN,7X4HCUM.)
      PRINT 833
  833 FORMAT (20X4HRANK,9X6HLENGTH,6X4HRANK,7X4HPCT.,5X4HSEQ./)
      DO 836 L=1,NTR
      ENTR=NTR
      EL=L
      CPCT=(EL/ENTR)*100.0
      RME=(EL/(ENTR+1.0))*100.0
  836 PRINT 837,L,RUN(L),RME,CPCT,KSEQ(L)
  837 FORMAT (20XI4,5XF10.0,5XF5.1,5XF6.1,5XI4)
      PRINT 809
  809 FORMAT (//18X19HNO MAINTENANCE RUNS/)
      PRINT 839
  839 FORMAT (20X7HRUN NO.,9X6HLENGTH,7X8HNEXT RUN)
      KPAR=NM-1
      IF (NM-1)280,280,810
  810 DO 840 J=1,KPAR
  840 PRINT 841,NSEQ(J),RUNM(J),RNXT(J)
  841 FORMAT (23XI4,5XF10.0,5XF10.0)
  280 IF(SENSE SWITCH 4)285,290
  285 PAUSE
  290 GO TO 100
      END
```

FIGURE B6 - Typical Computer Output From the "Edit and Rank Order" Program

TOOL NUMBER 5602

RANK ORDER OF EDITED RUNS

50. TO 619000.

RANK	RUN LENGTH	MEAN RANK	CUM. PCT.	SEQ.
1	50.	4.5	4.7	15
2	100.	9.0	9.5	3
3	10000.	13.6	14.2	18
4	17000.	18.1	19.0	6
5	23000.	22.7	23.8	4
6	99500.	27.2	28.5	13
7	110000.	31.8	33.3	7
8	115000.	36.3	38.0	22
9	116000.	40.9	42.8	20
10	146000.	45.4	47.6	5
11	153000.	50.0	52.3	21
12	166000.	54.5	57.1	23
13	175000.	59.0	61.9	19
14	215000.	63.6	66.6	2
15	235000.	68.1	71.4	12
16	320000.	72.7	76.1	11
17	400000.	77.2	80.9	10
18	410000.	81.8	85.7	9
19	450000.	86.3	90.4	8
20	548000.	90.9	95.2	17
21	619000.	95.4	100.0	14

NO MAINTENANCE RUNS

RUN NO.	LENGTH	NEXT RUN
1	150000.	65000.
16	100000.	448000.

FIGURE B7 — FLOW CHART FOR "MEDIANS AND MEANS"

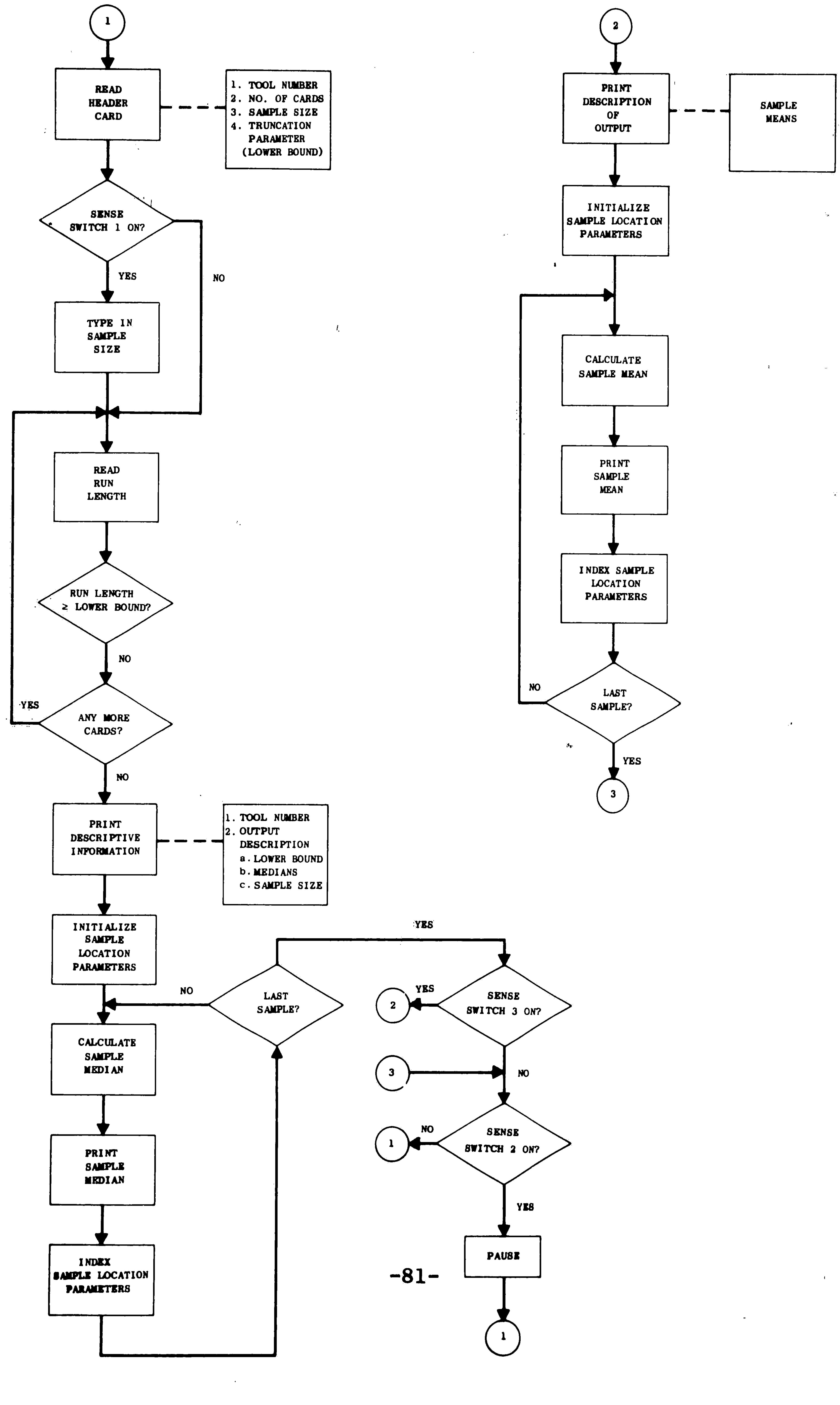


FIGURE B8 FORTRAN (FORMAT) CODING FOR THE "MEDIANS AND MEANS" PROGRAM

```
C SUCCESSIVE MEDIANS AND MEANS ABOVE A LOWER BOUND DFW 6-14-64
C SENSE SWITCH 1 ON PUTS NO. OF PERIODS INPUT ON TYPEWRITER
C SENSE SWITCH 2 ON PUTS PAUSE AFTER OUTPUT
C SENSE SWITCH 3 ON PRINTS SUCCESSIVE MEANS
      DIMENSION RUN(125)
  100 READ 101,ITN,NCRDS,NPER,CUT
  101 FORMAT (I4,2XI3,2XI3,2XF8.0)
      IF (SENSE SWITCH 1)105,110
  105 ACCEPT 106,NPER
  106 FORMAT (I3)
  110 LC=0
      DO 120 I=I,NCRDS
      READ 111,DRUN
  111 FORMAT (10XF10.0)
      IF (DRUN-CUT)120,115,115
  115 LC=LC+1
      RUN(LC)=DRUN
  120 CONTINUE
      PRINT 201,ITN
  201 FORMAT (15X11HTOOL NUMBER,I5)
      PRINT 202
  202 FORMAT (16X22HSUCCESSIVE MEDIANS FOR)
      PRINT 203,CUT
  203 FORMAT (18X29HRUNS EQUAL TO OR GREATER THAN,F9.0)
      PRINT 204,NPER
  204 FORMAT (18X3HAND,I3,1X14HRUNS AT A TIME/)
      LPAR=LC/NPER
      JLOW=1
      NTR=NPER
      DO 240 L=1,LPAR
      NNTR=NTR-1
  205 DO 225 K=JLOW,NNTR
      IF (RUN(K)-RUN(NNTR+1))225,225,210
  210 TSTO=RUN(K)
      RUN(K)=RUN(NNTR+1)
      RUN(NNTR+1)=TSTO
  225 CONTINUE
      NNTR=NNTR-1
      IF (NNTR-1)235,205,205
  235 M=JLOW+(NPER/2)
      RMED=RUN(M)
      PRINT 137,RMED
  137 FORMAT(20XF8.0)
      JLOW=JLOW+NPER
      NTR=NTR+NPER
  240 CONTINUE
      IF (SENSE SWITCH 3)250,260
  250 PRINT 251
  251 FORMAT (/16X16HSUCCESSIVE MEANS)
```

```
      JLOW=1
      JHI=NPER
      DO 140 K=1,LPAR
      CRUN=0.
      DO 135 J=JLOW,JHI
      CRUN=CRUN+RUN(J)
  135 CONTINUE
      APER=NPER
      AVG=CRUN/APER
      PRINT 136,AVG
  136 FORMAT (20XF8.0)
      JLOW=JLOW+NPER
      JHI=JHI+NPER
  140 CONTINUE
  260 IF (SENSE SWITCH 2)145,150
  145 PAUSE
  150 GO TO 100
      END
```

FIGURE B9 - Typical Computer Output from the "Medians and Means" Program

```
TOOL NUMBER 1501
 SUCCESSIVE MEDIANS FOR
   RUNS EQUAL TO OR GREATER THAN    26000.
   AND  3 RUNS AT A TIME

       85000.
       77000.
       56000.
       75000.
      153000.
       66000.
       47500.
       54000.
       36000.
       50000.
       54000.
       44300.
       70500.

 SUCCESSIVE MEANS
       73333.
       81666.
       71666.
       65000.
      128333.
       63100.
       46426.
       48833.
       43333.
       50333.
       46333.
       59100.
       75166.
```

APPENDIX C - WEIBULL CUMULATIVE DISTRIBUTION FUNCTION PLOTS

List of Figures

Note: The figures in this appendix are titled and numbered as follows:

1. The mixed model plot for a given tool is titled:

   TOOL NUMBER XXXX
   WEIBULL C.D.F. PLOT
   FOR THE
   MIXED MODEL

   and is numbered CN.0

2. The associated "early failure" distribution plot is titled:

   TOOL NUMBER XXXX
   WEIBULL C.D.F. PLOT
   FOR
   "EARLY FAILURES"

   and is numbered CN.1

3. The associated "normal wear" distribution plot is titled:

   TOOL NUMBER XXXX
   WEIBULL C.D.F. PLOT
   FOR
   "NORMAL WEAR"

   and is numbered CN.2

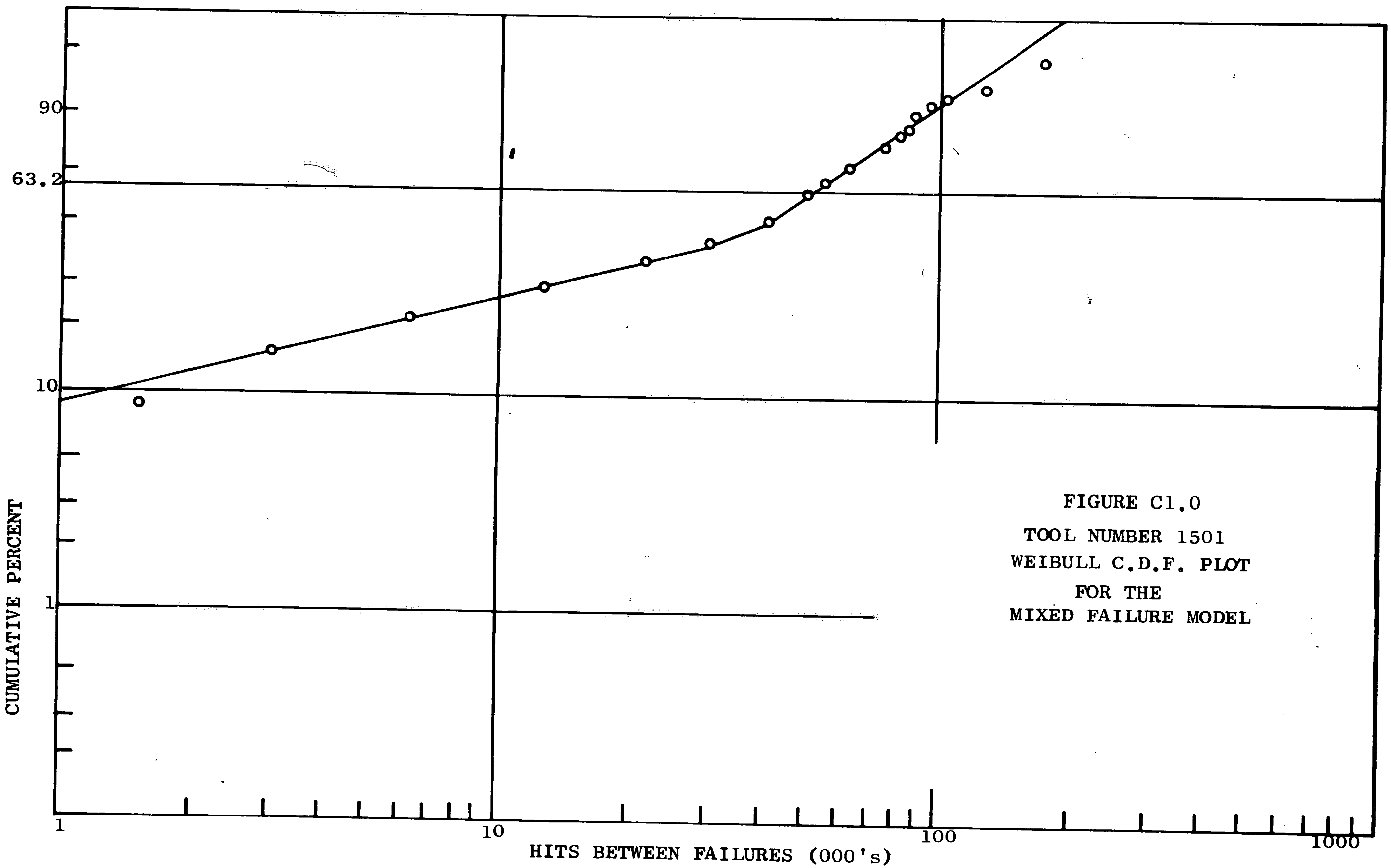


FIGURE C1.0
TOOL NUMBER 1501
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

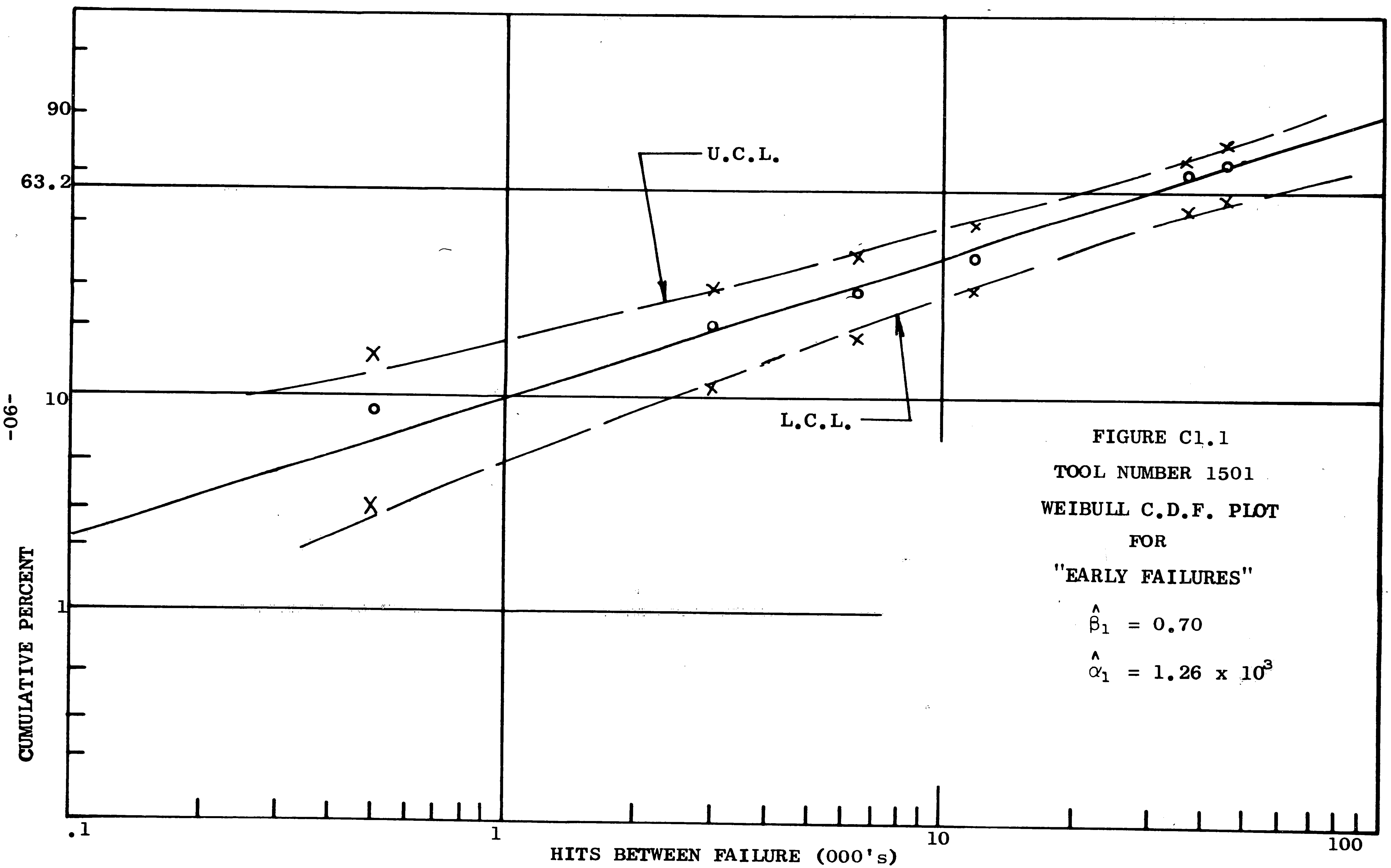


FIGURE C1.1

TOOL NUMBER 1501

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.70$

$\hat{\alpha}_1 = 1.26 \times 10^3$

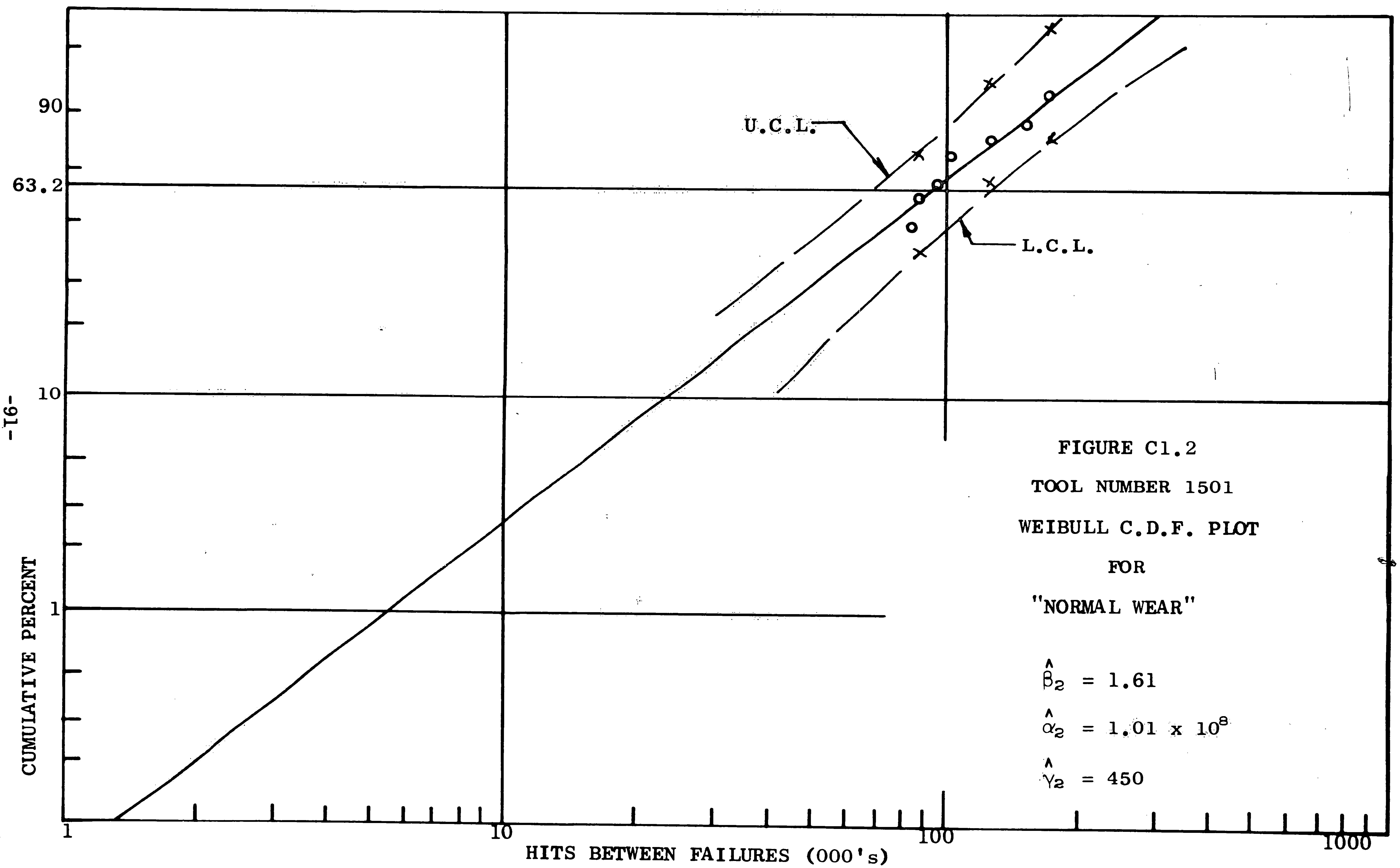


FIGURE C1.2

TOOL NUMBER 1501

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 1.61$

$\hat{\alpha}_2 = 1.01 \times 10^8$

$\hat{\gamma}_2 = 450$

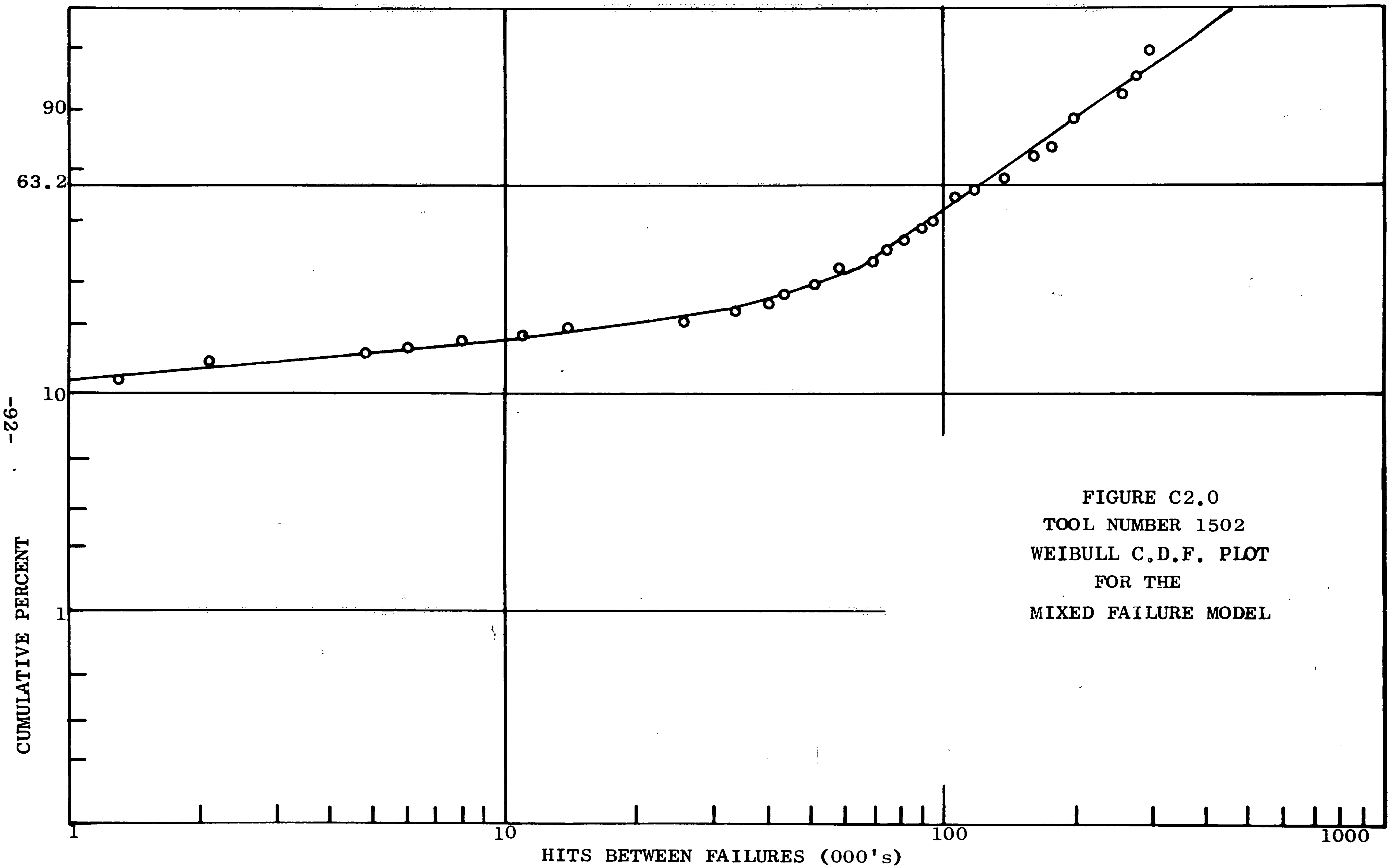


FIGURE C2.0
TOOL NUMBER 1502
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

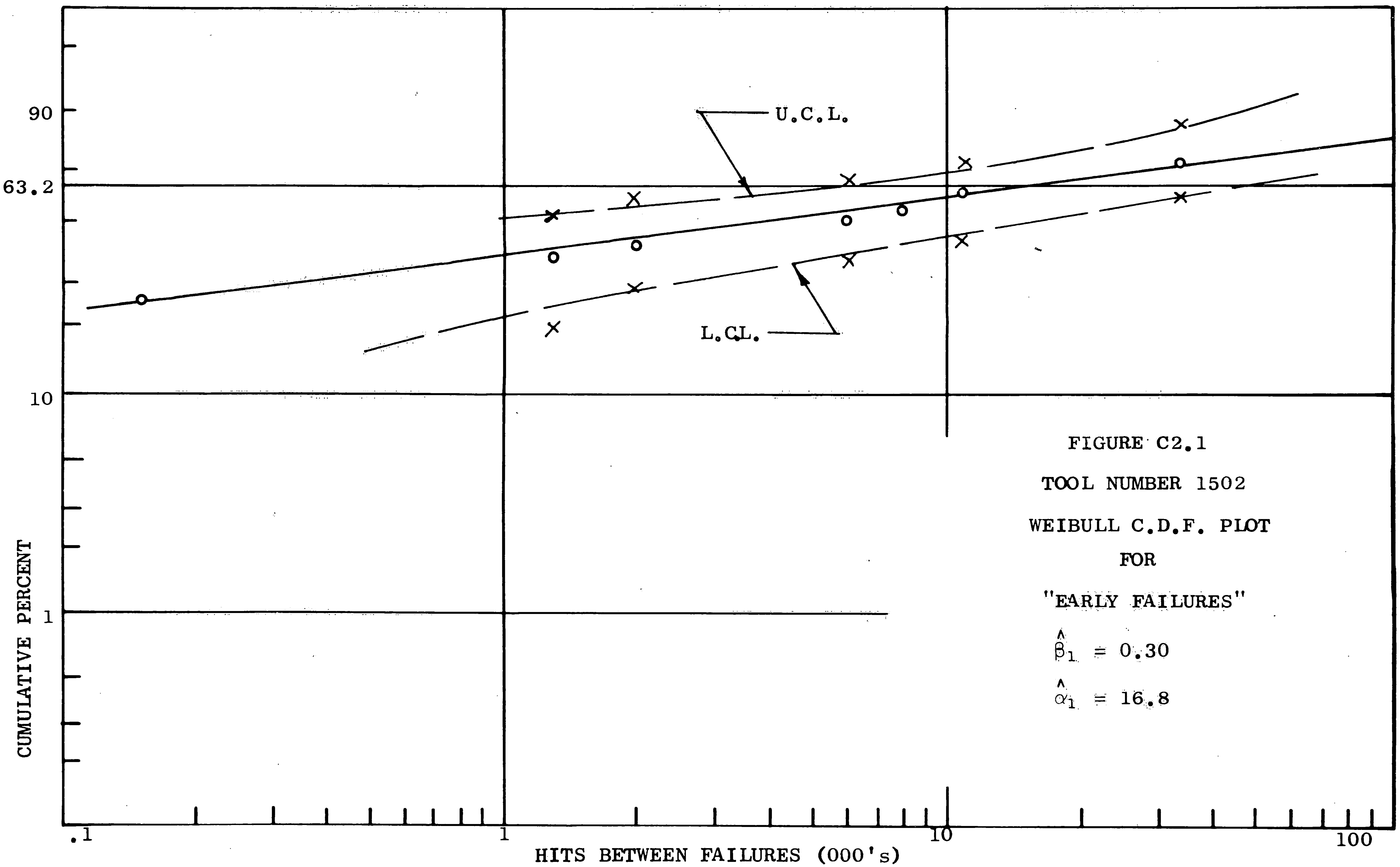


FIGURE C2.1

TOOL NUMBER 1502

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.30$

$\hat{\alpha}_1 = 16.8$

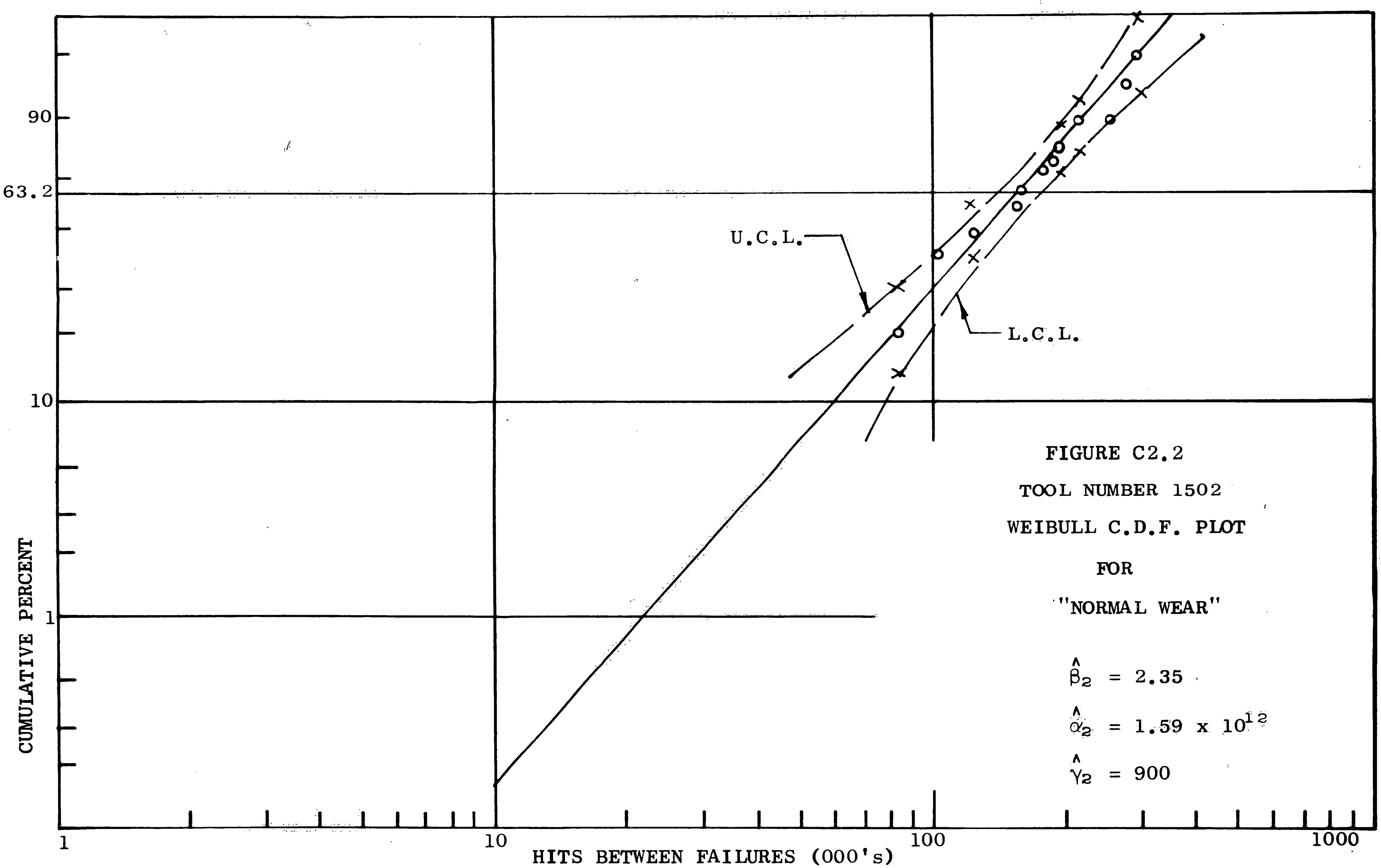


FIGURE C2.2
TOOL NUMBER 1502
WEIBULL C.D.F. PLOT
FOR
"NORMAL WEAR"

$\hat{\beta}_2 = 2.35$

$\hat{\alpha}_2 = 1.59 \times 10^{12}$

$\hat{\gamma}_2 = 900$

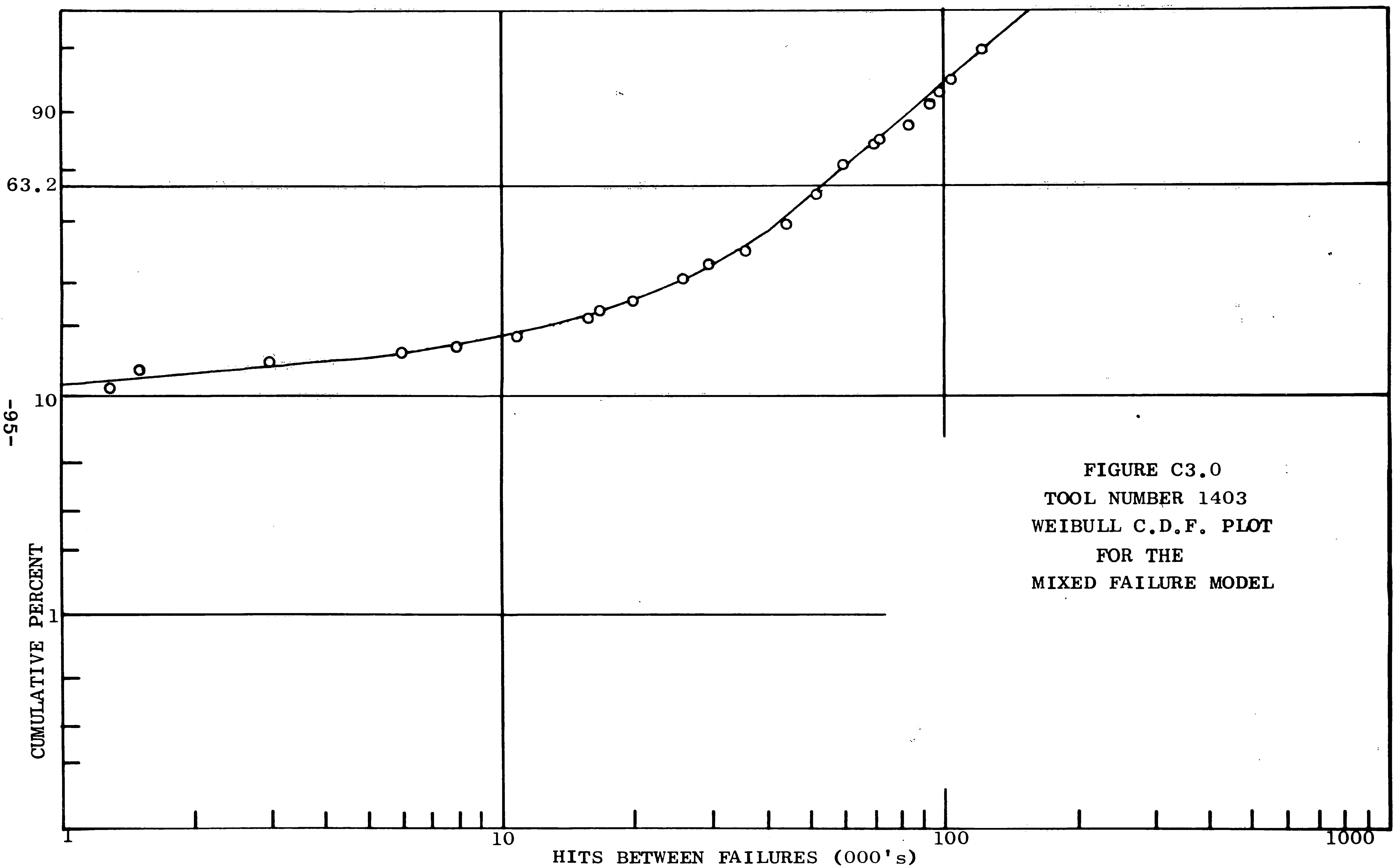


FIGURE C3.0
TOOL NUMBER 1403
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

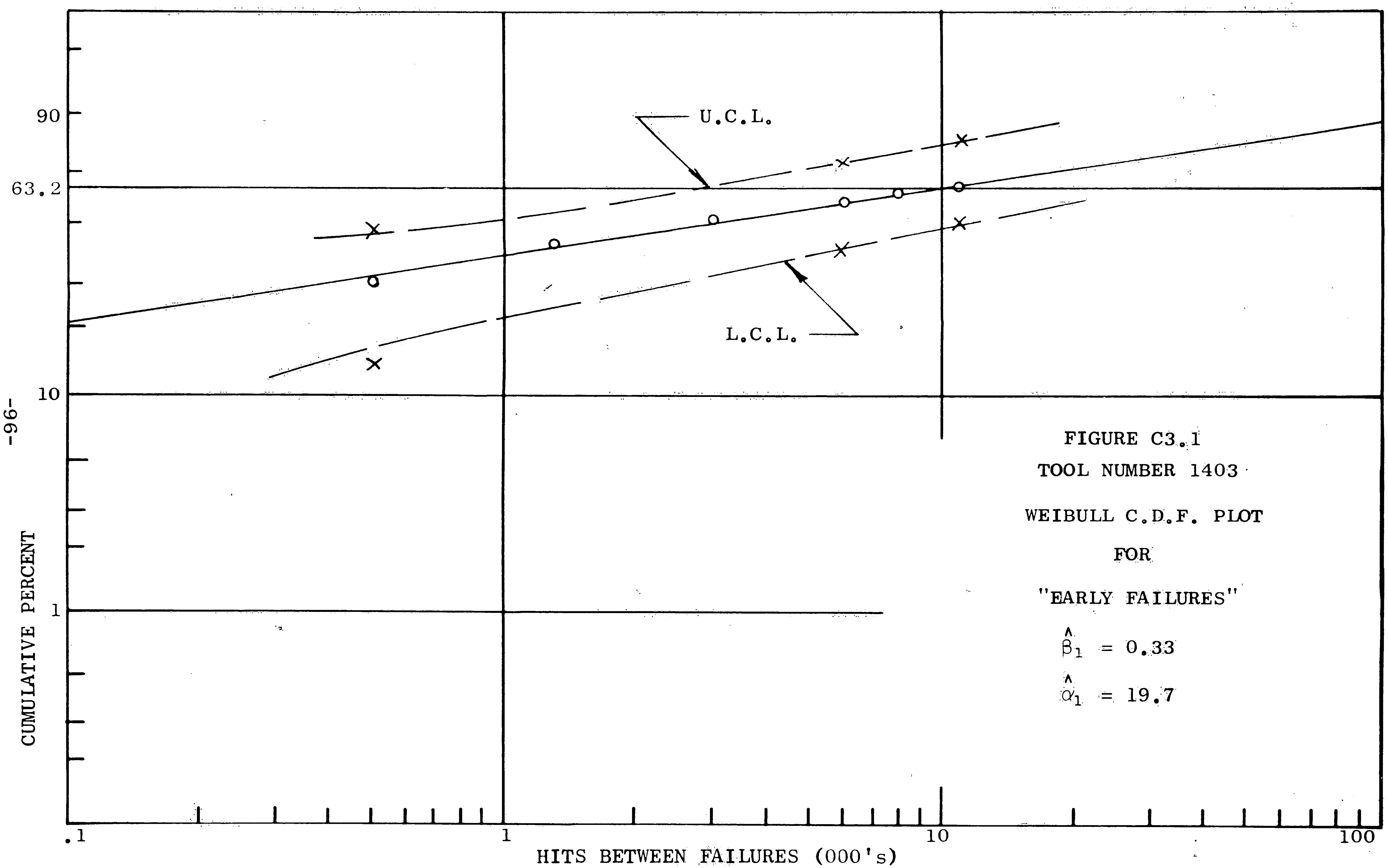


FIGURE C3.1
TOOL NUMBER 1403
WEIBULL C.D.F. PLOT
FOR
"EARLY FAILURES"

$\hat{\beta}_1 = 0.33$

$\hat{\alpha}_1 = 19.7$

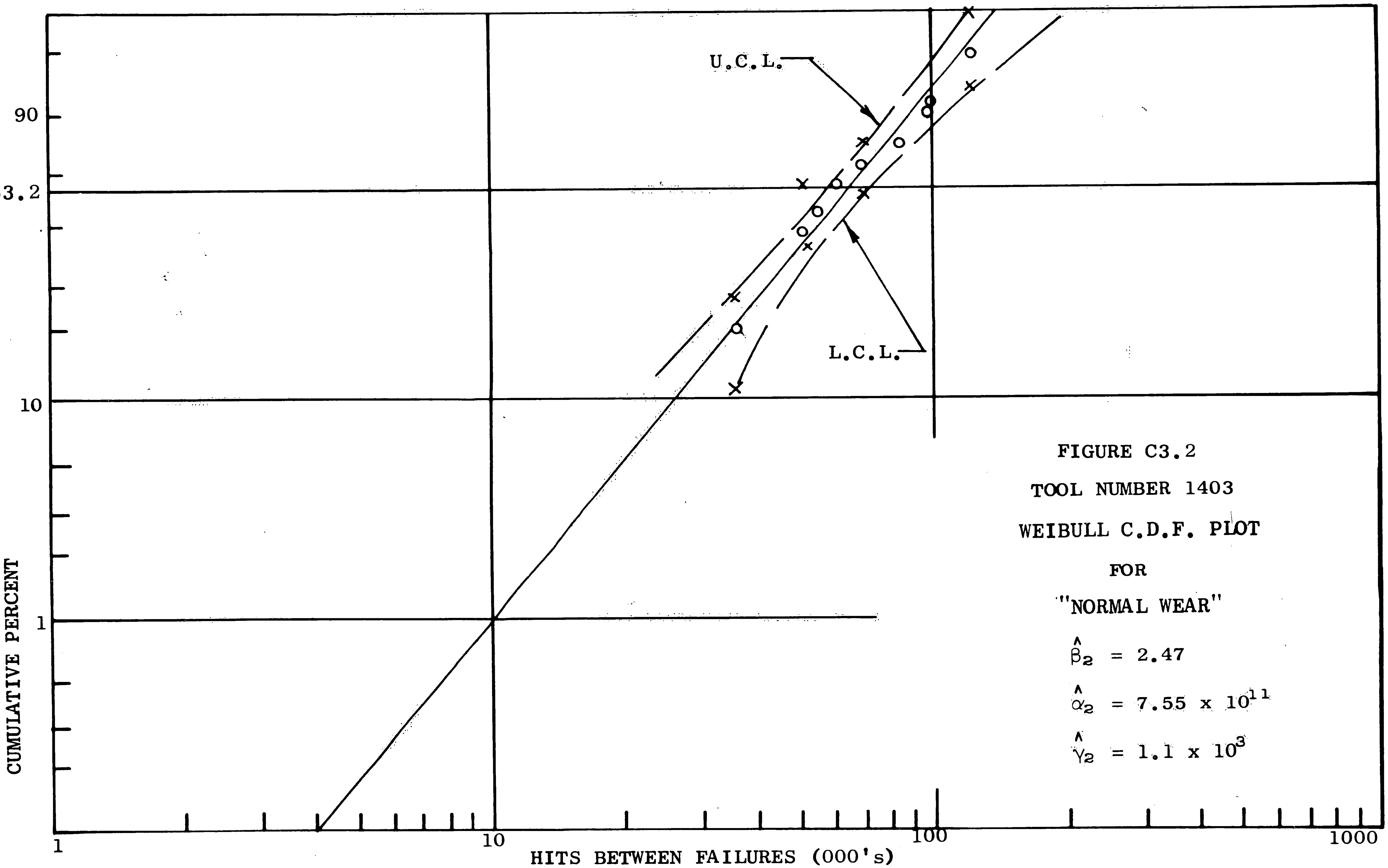


FIGURE C3.2

TOOL NUMBER 1403

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 2.47$

$\hat{\alpha}_2 = 7.55 \times 10^{11}$

$\hat{\gamma}_2 = 1.1 \times 10^{3}$

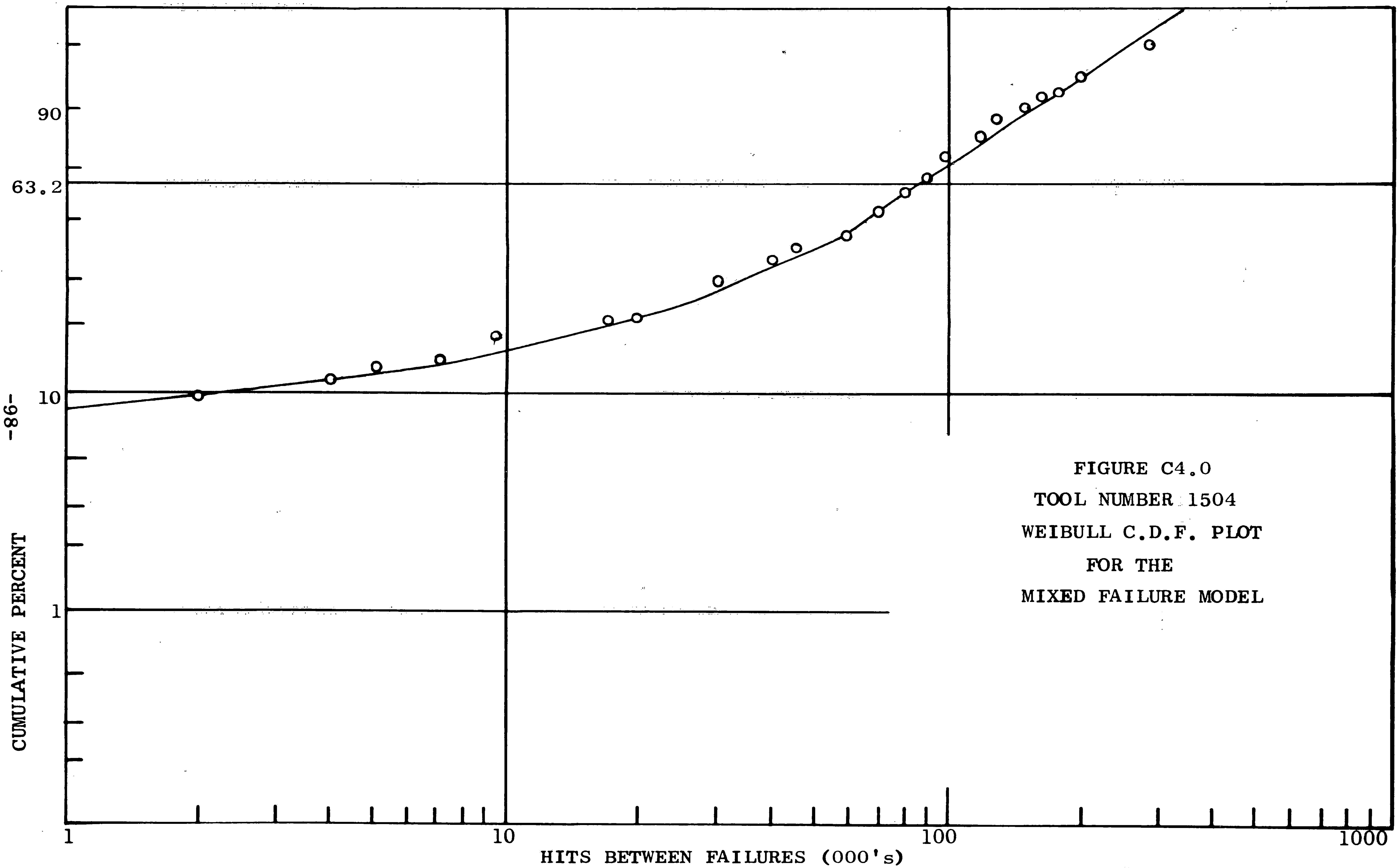


FIGURE C4.0
TOOL NUMBER 1504
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

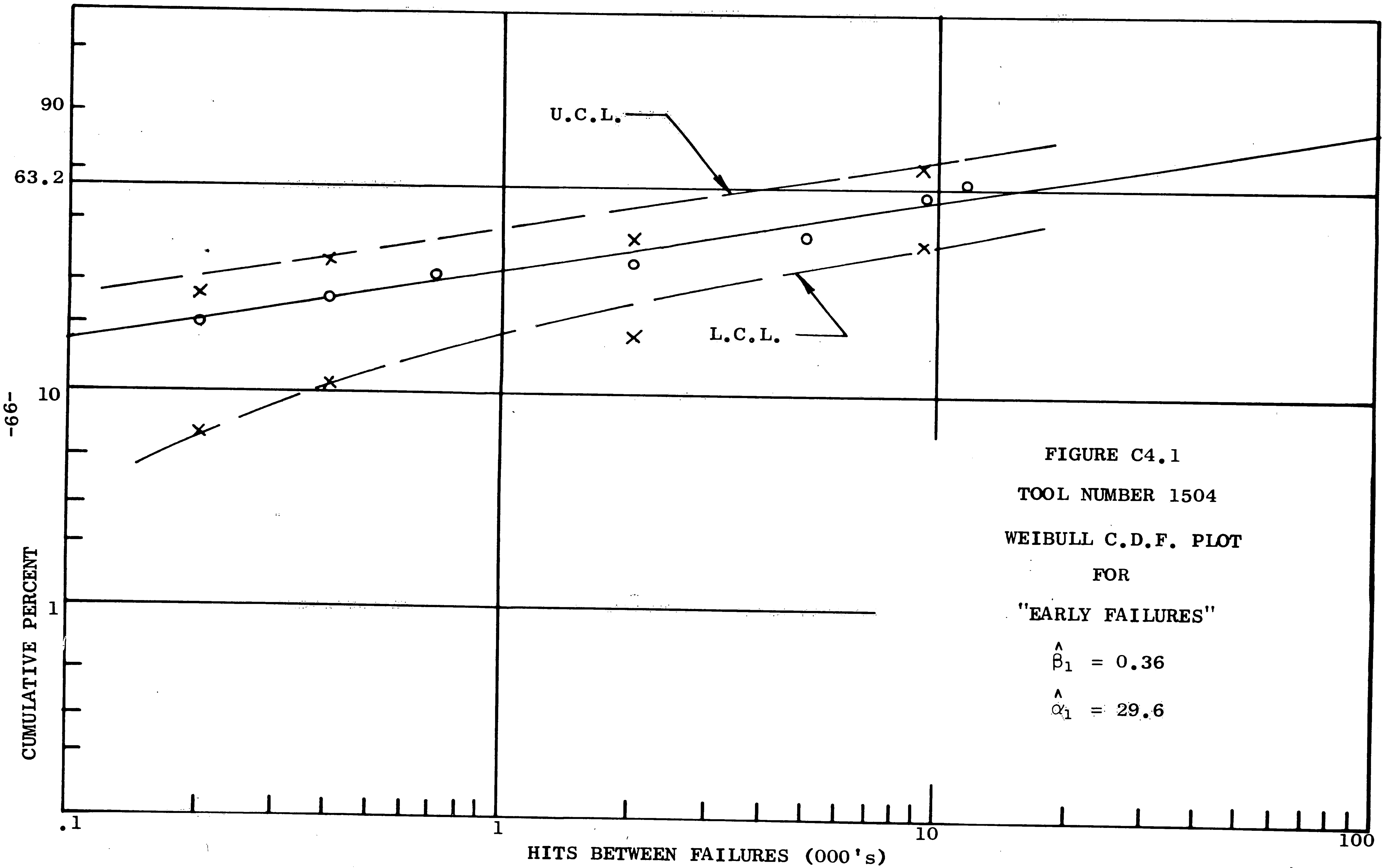


FIGURE C4.1

TOOL NUMBER 1504

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.36$

$\hat{\alpha}_1 = 29.6$

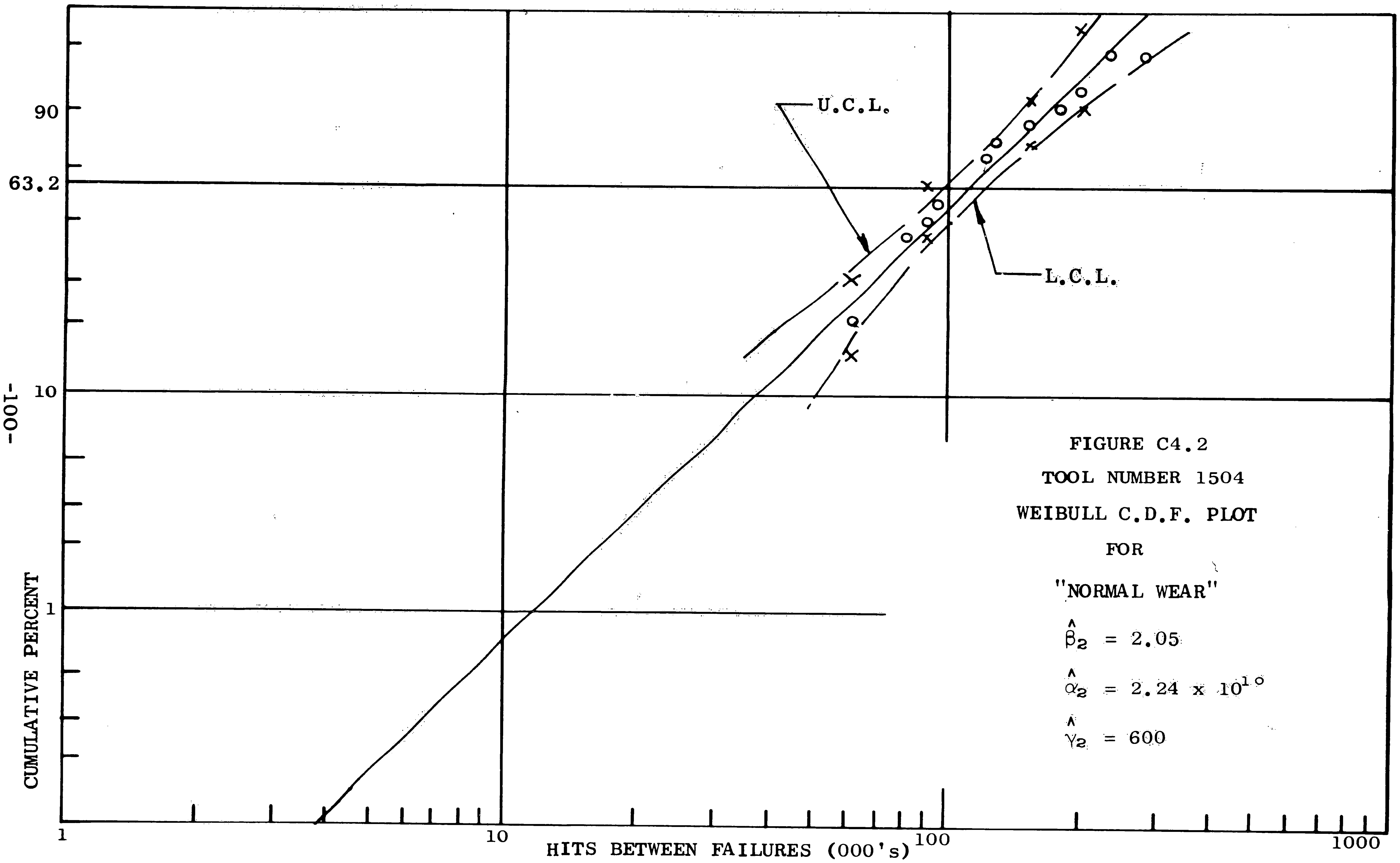


FIGURE C4.2
TOOL NUMBER 1504
WEIBULL C.D.F. PLOT
FOR
"NORMAL WEAR"

$\hat{\beta}_2 = 2.05$

$\hat{\alpha}_2 = 2.24 \times 10^{10}$

$\hat{\gamma}_2 = 600$

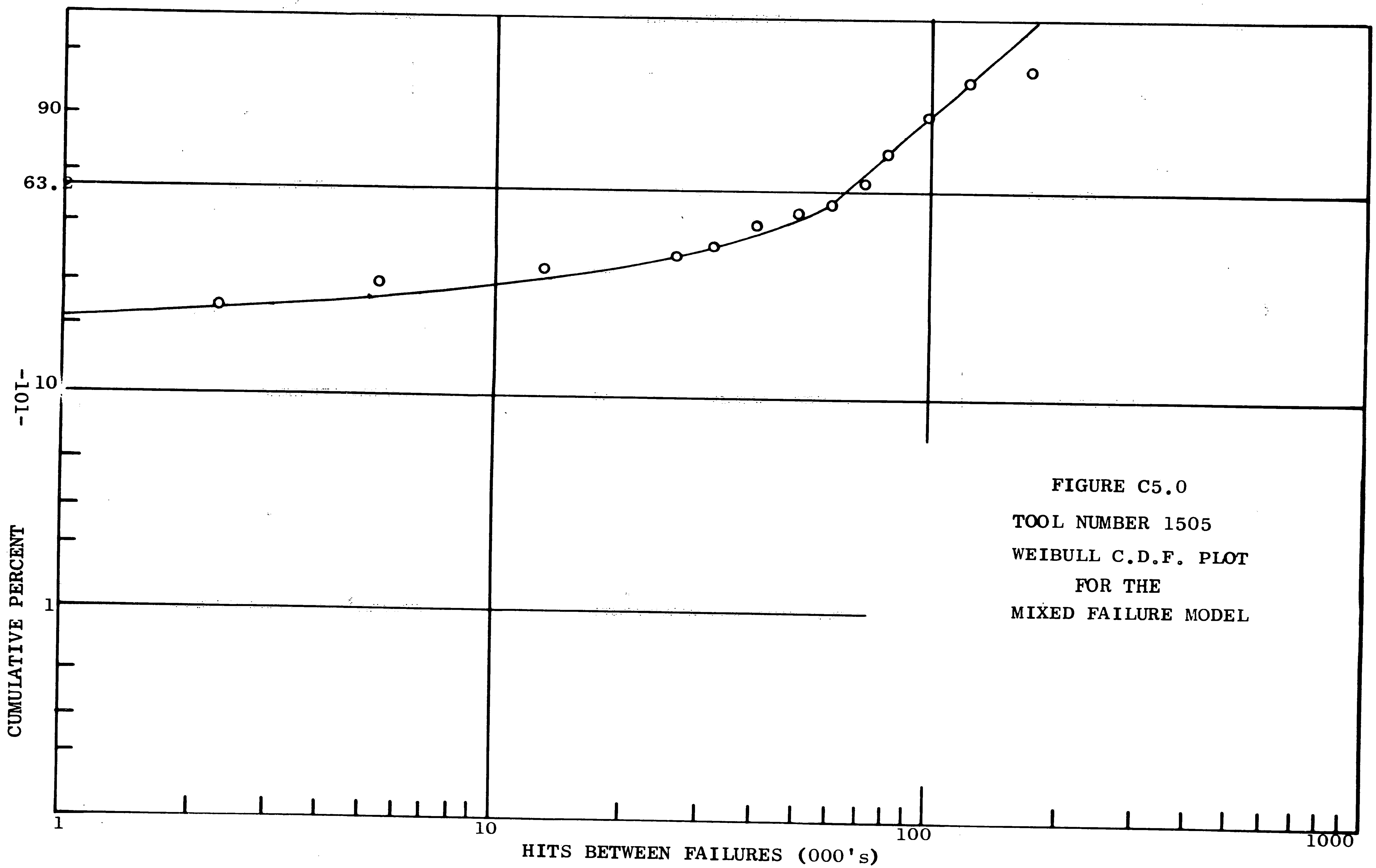


FIGURE C5.0
TOOL NUMBER 1505
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

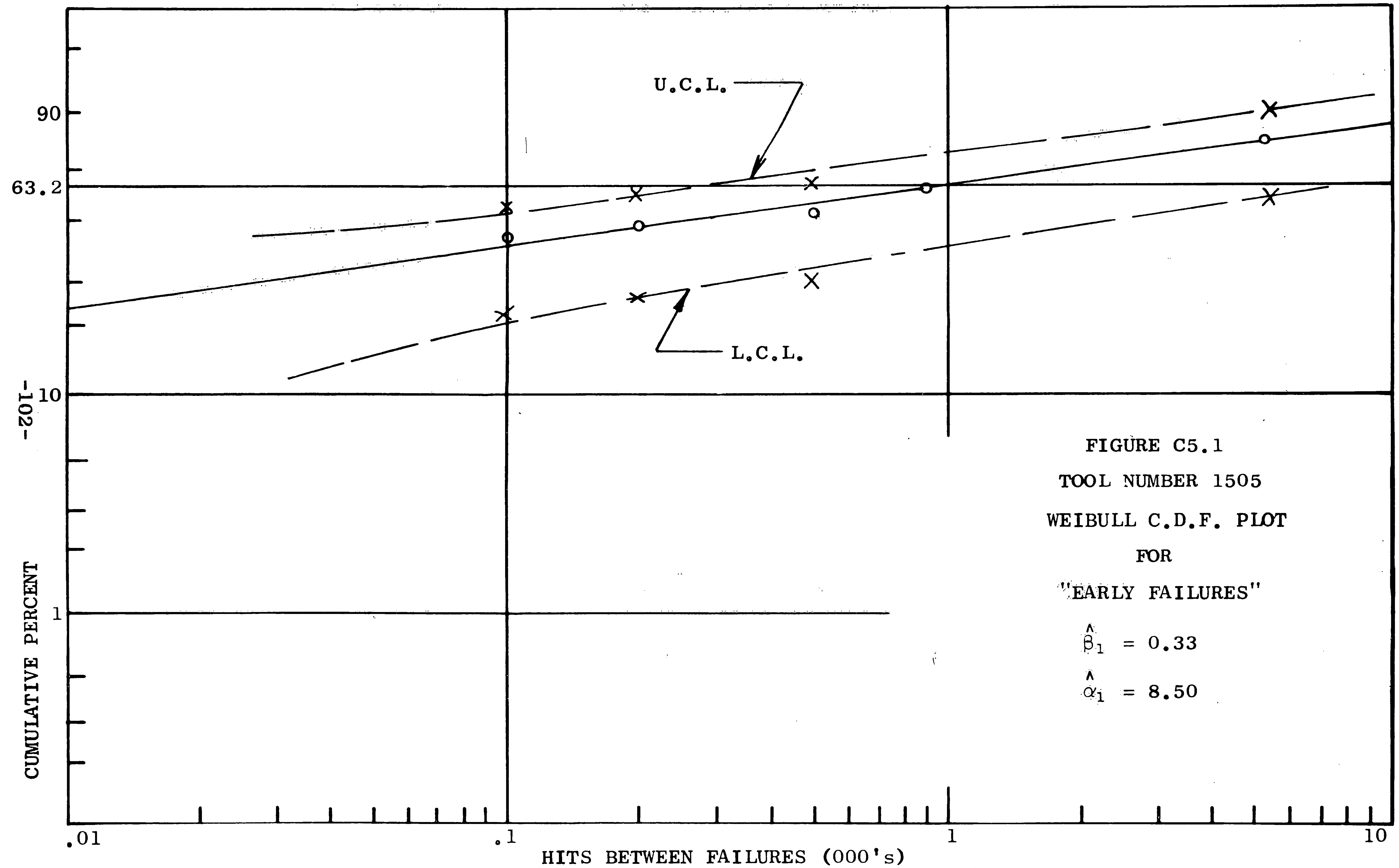


FIGURE C5.1

TOOL NUMBER 1505

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.33$

$\hat{\alpha}_1 = 8.50$

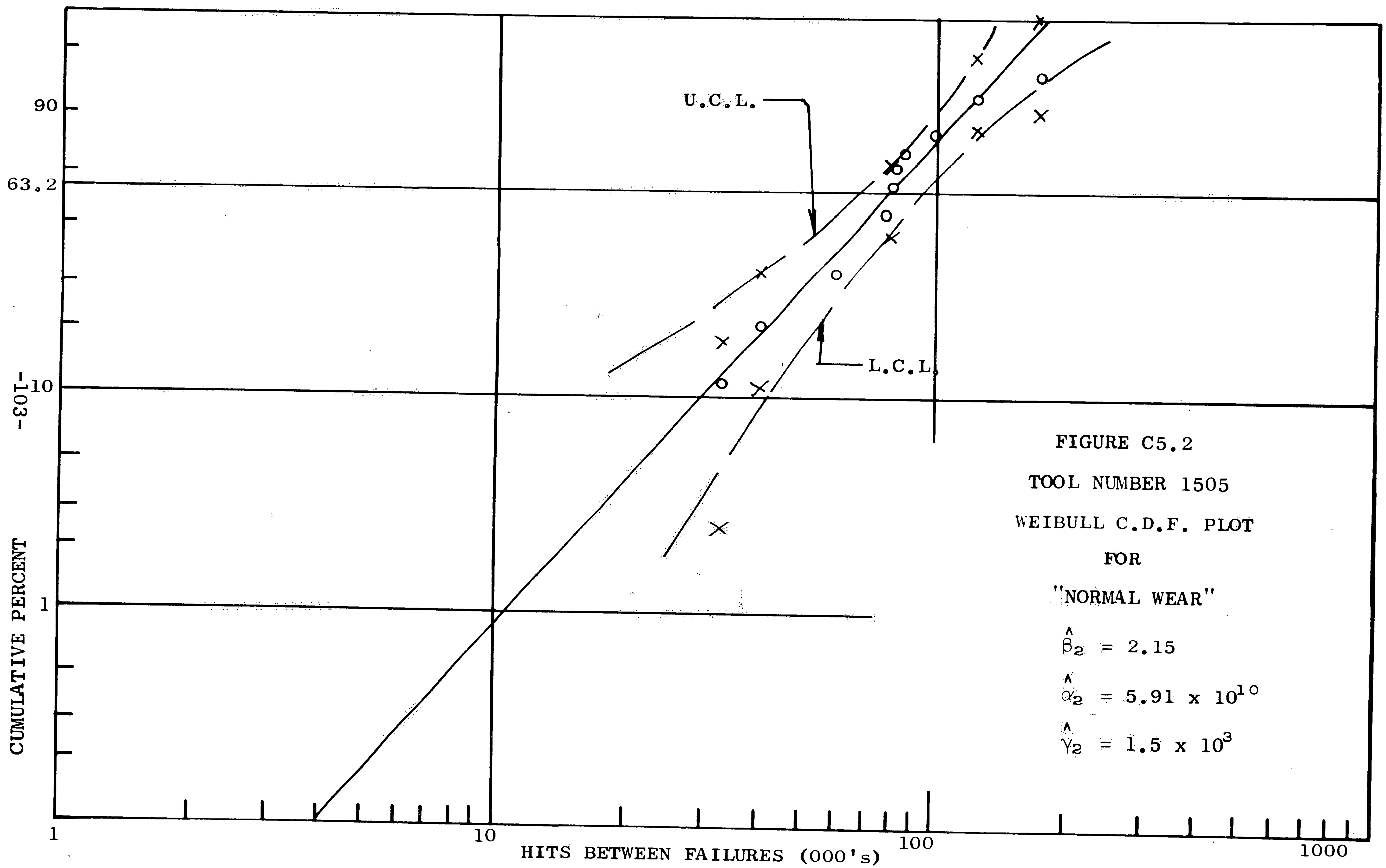


FIGURE C5.2

TOOL NUMBER 1505

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 2.15$

$\hat{\alpha}_2 = 5.91 \times 10^{10}$

$\hat{\gamma}_2 = 1.5 \times 10^{3}$

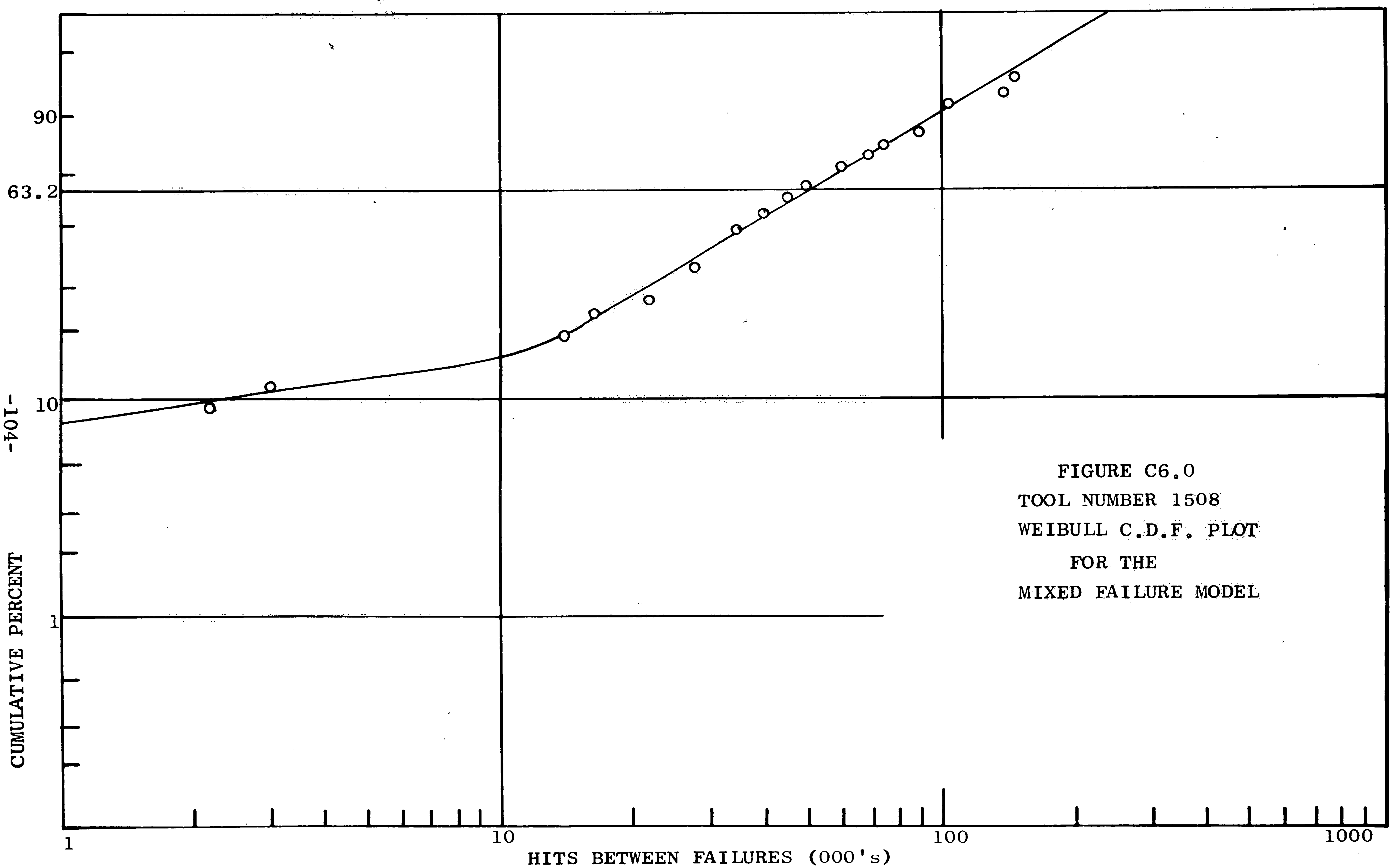
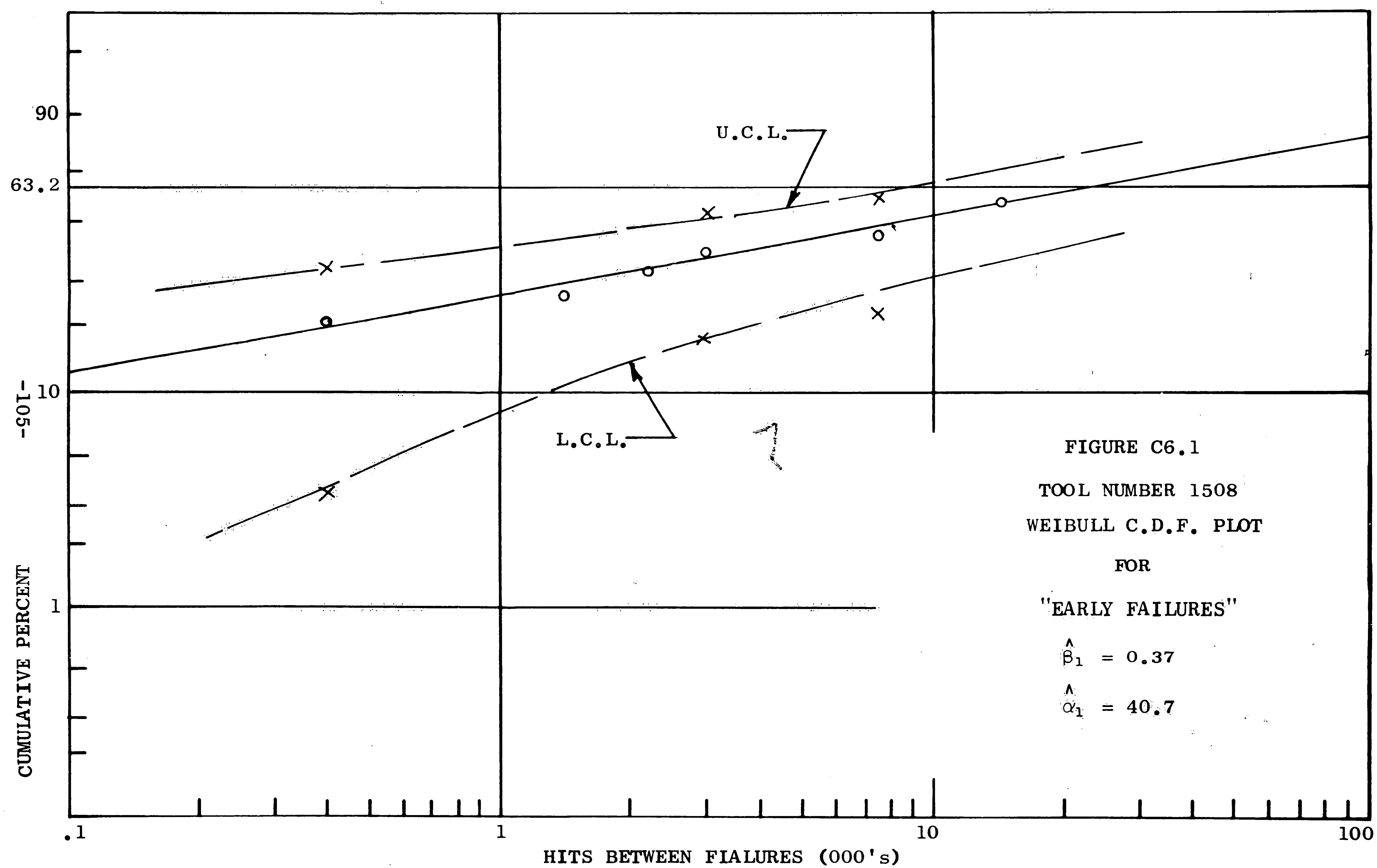


FIGURE C6.0
TOOL NUMBER 1508
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL


90
63.2
10
1
CUMULATIVE PERCENT
U.C.L.
L.C.L.
.1
1
10
100
HITS BETWEEN FIALURES (000's)
FIGURE C6.1
TOOL NUMBER 1508
WEIBULL C.D.F. PLOT
FOR
"EARLY FAILURES"
$\hat{\beta}_1 = 0.37$
$\hat{\alpha}_1 = 40.7$

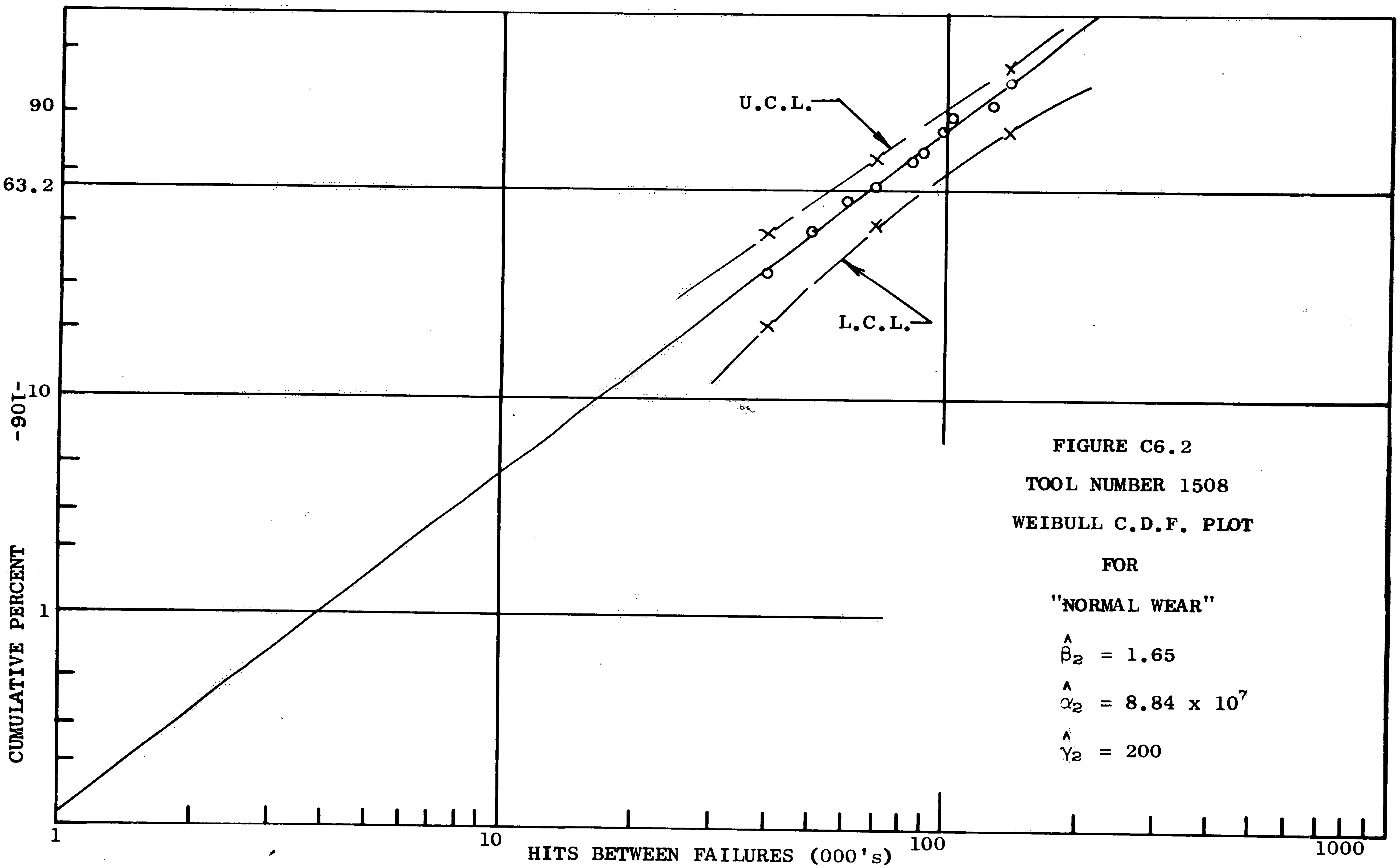


FIGURE C6.2

TOOL NUMBER 1508

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 1.65$

$\hat{\alpha}_2 = 8.84 \times 10^7$

$\hat{\gamma}_2 = 200$

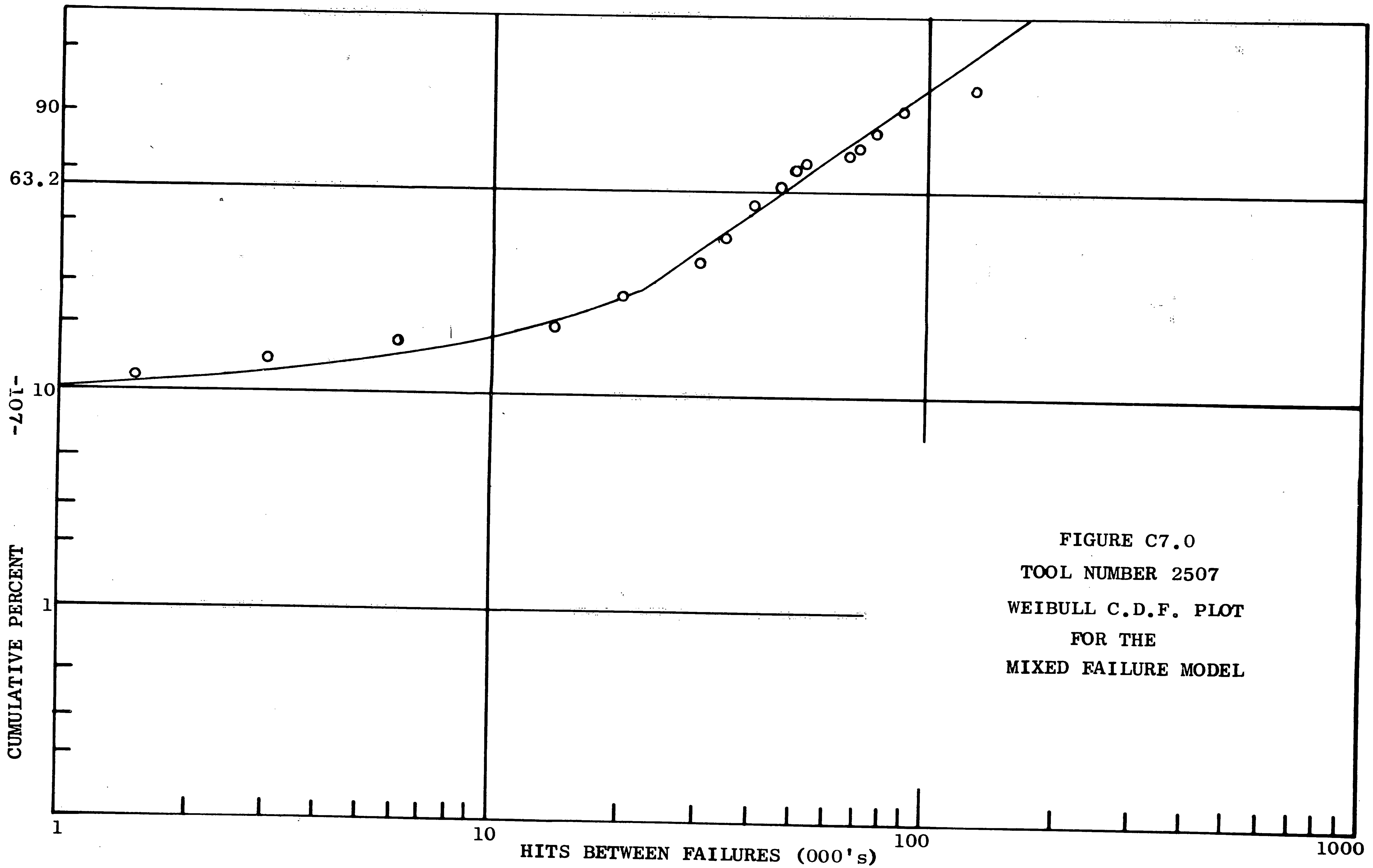


FIGURE C7.0

TOOL NUMBER 2507

WEIBULL C.D.F. PLOT

FOR THE

MIXED FAILURE MODEL

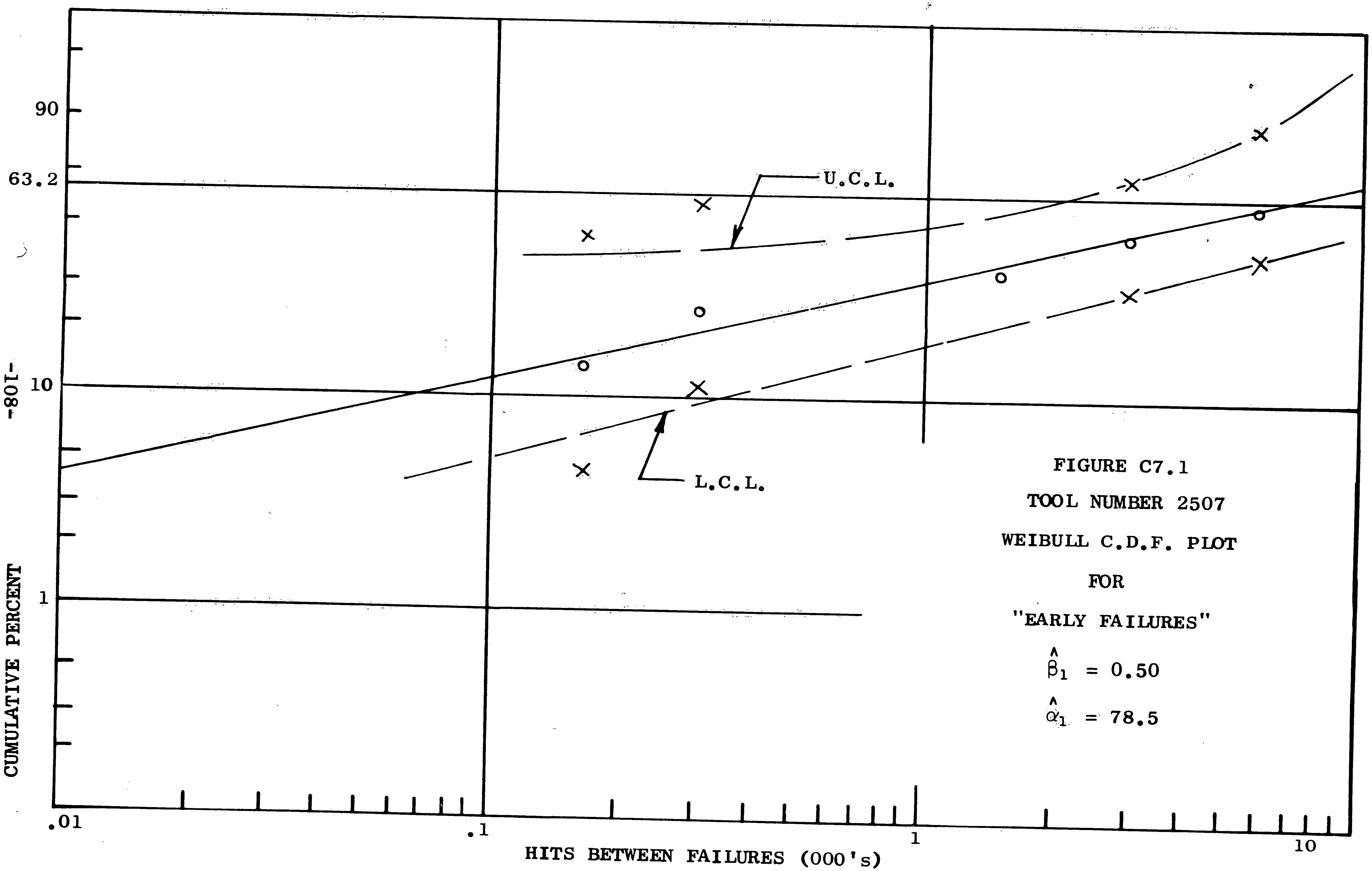


FIGURE C7.1
TOOL NUMBER 2507
WEIBULL C.D.F. PLOT
FOR
"EARLY FAILURES"

$\hat{\beta}_1 = 0.50$

$\hat{\alpha}_1 = 78.5$

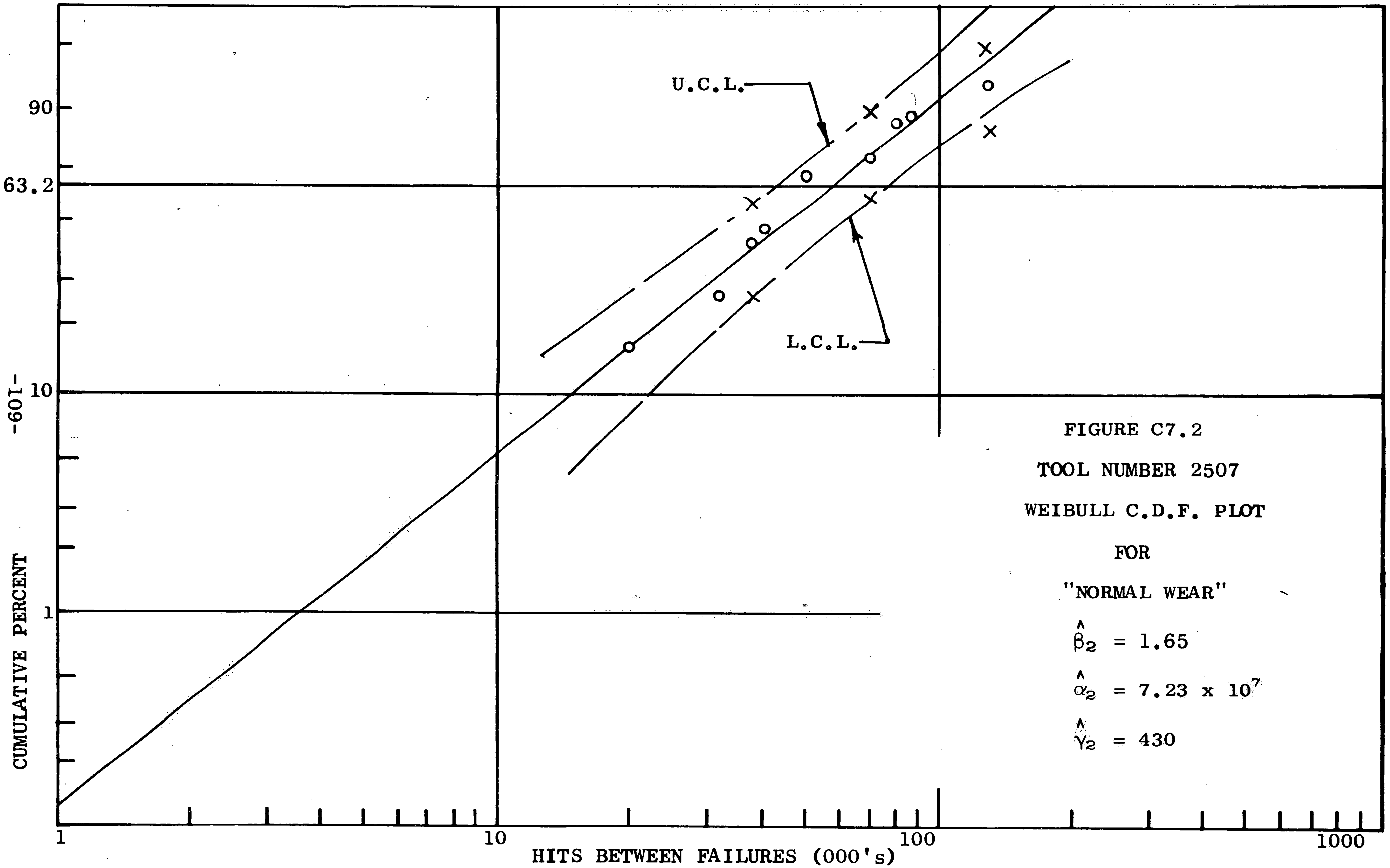


FIGURE C7.2

TOOL NUMBER 2507

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 1.65$

$\hat{\alpha}_2 = 7.23 \times 10^7$

$\hat{\gamma}_2 = 430$

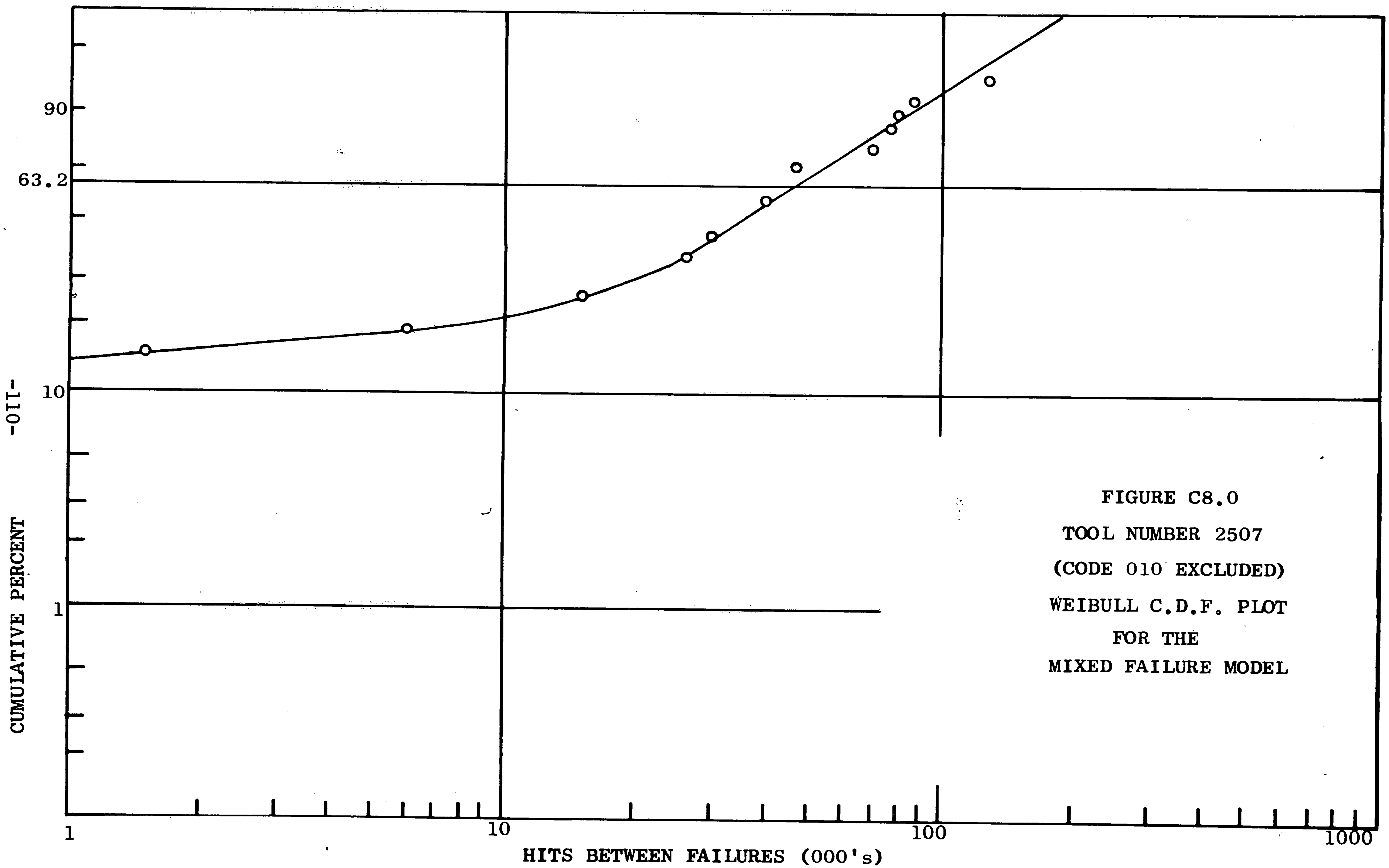


FIGURE C8.0
TOOL NUMBER 2507
(CODE 010 EXCLUDED)
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

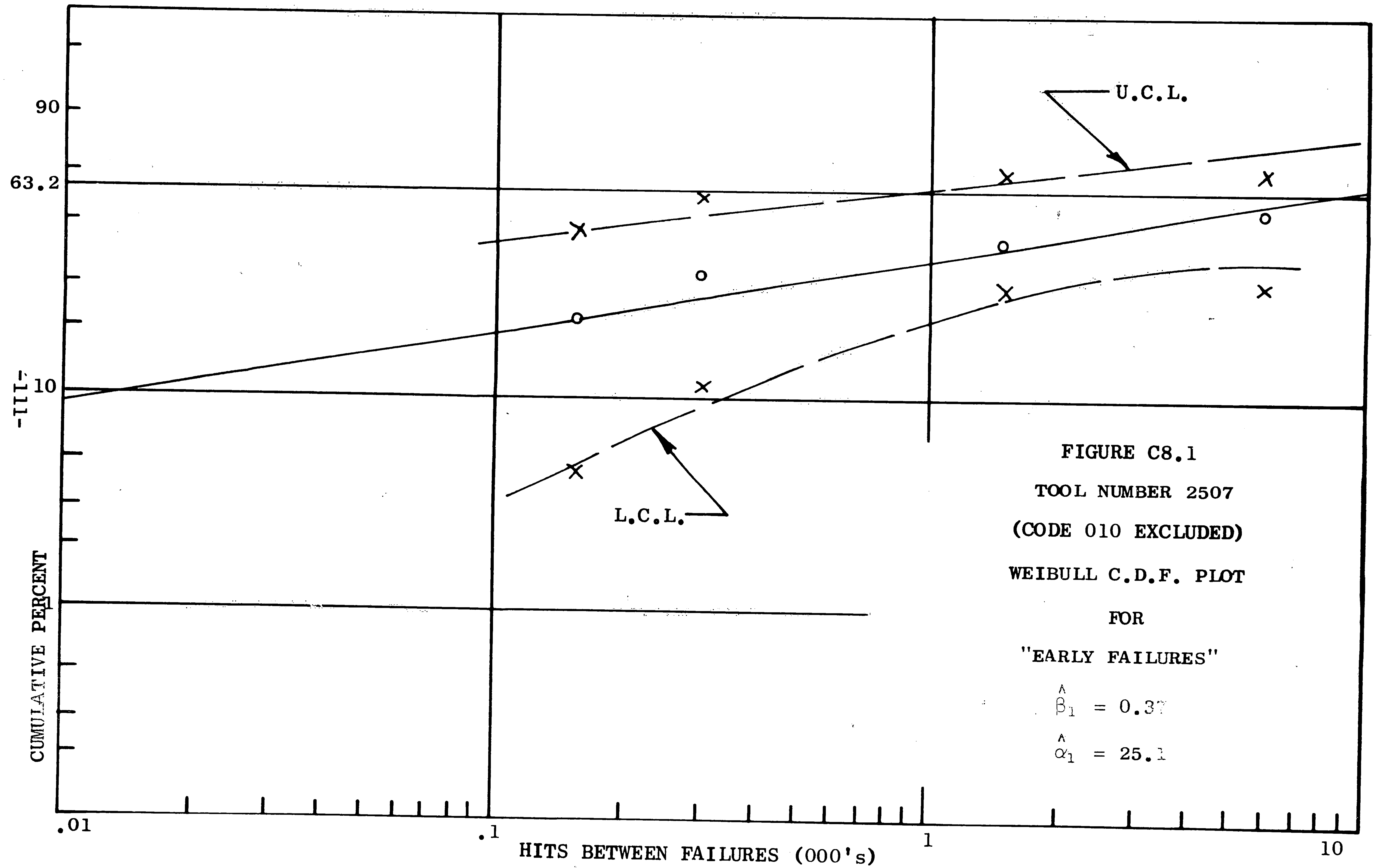


FIGURE C8.1

TOOL NUMBER 2507

(CODE 010 EXCLUDED)

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.37$

$\hat{\alpha}_1 = 25.1$

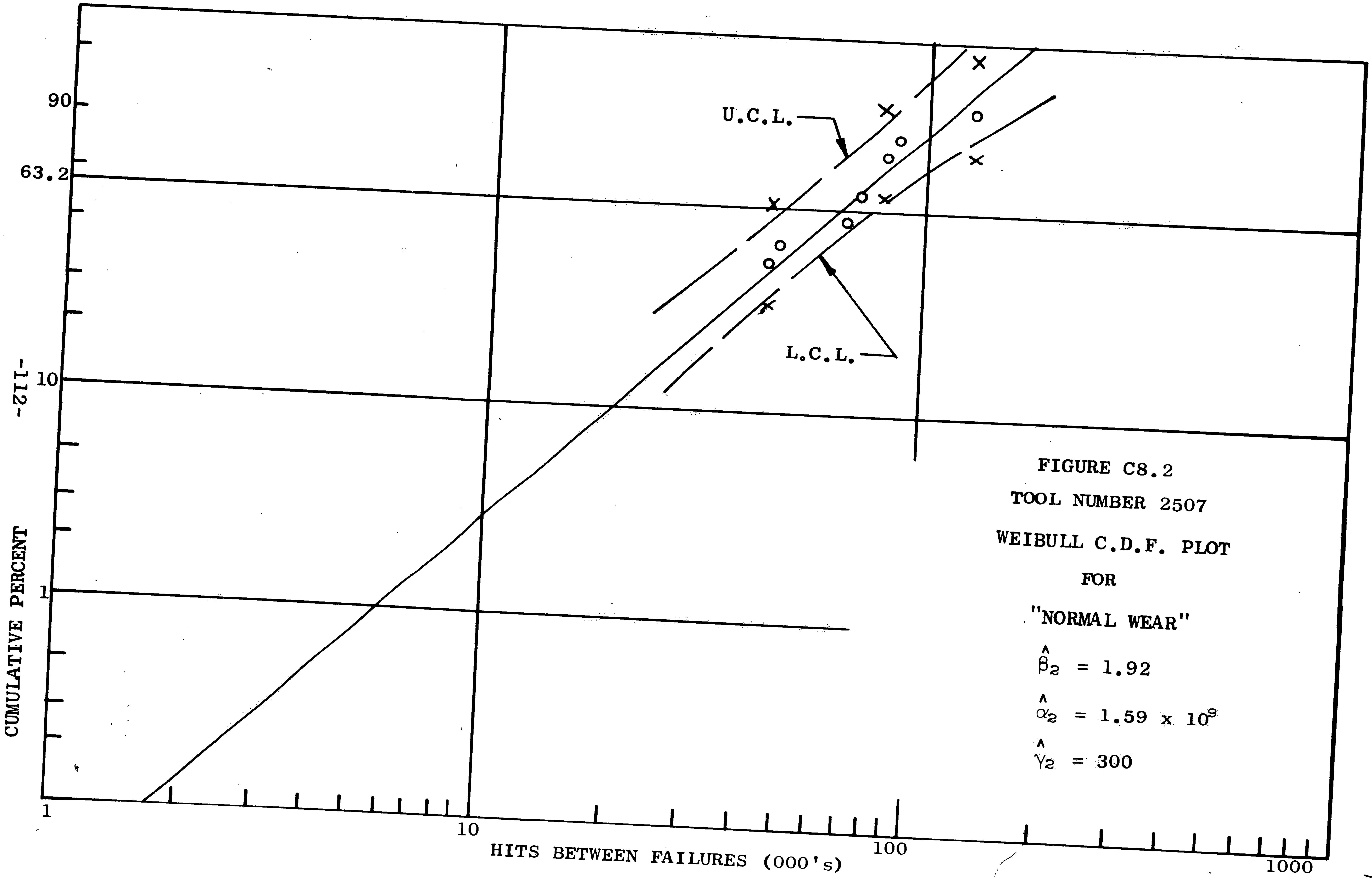


FIGURE C8.2

TOOL NUMBER 2507

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 1.92$

$\hat{\alpha}_2 = 1.59 \times 10^9$

$\hat{\gamma}_2 = 300$

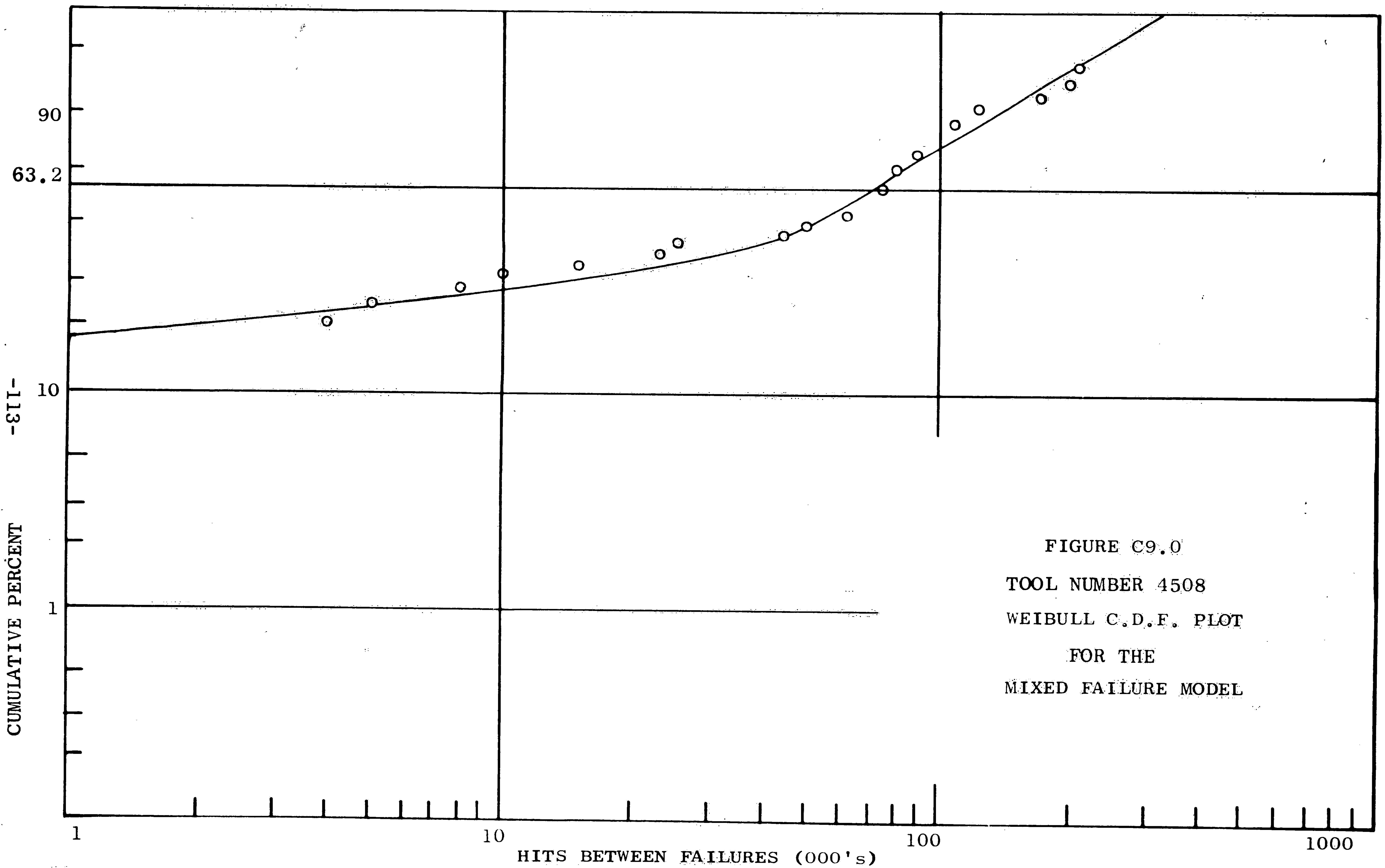


FIGURE C9.0

TOOL NUMBER 4508

WEIBULL C.D.F. PLOT

FOR THE

MIXED FAILURE MODEL

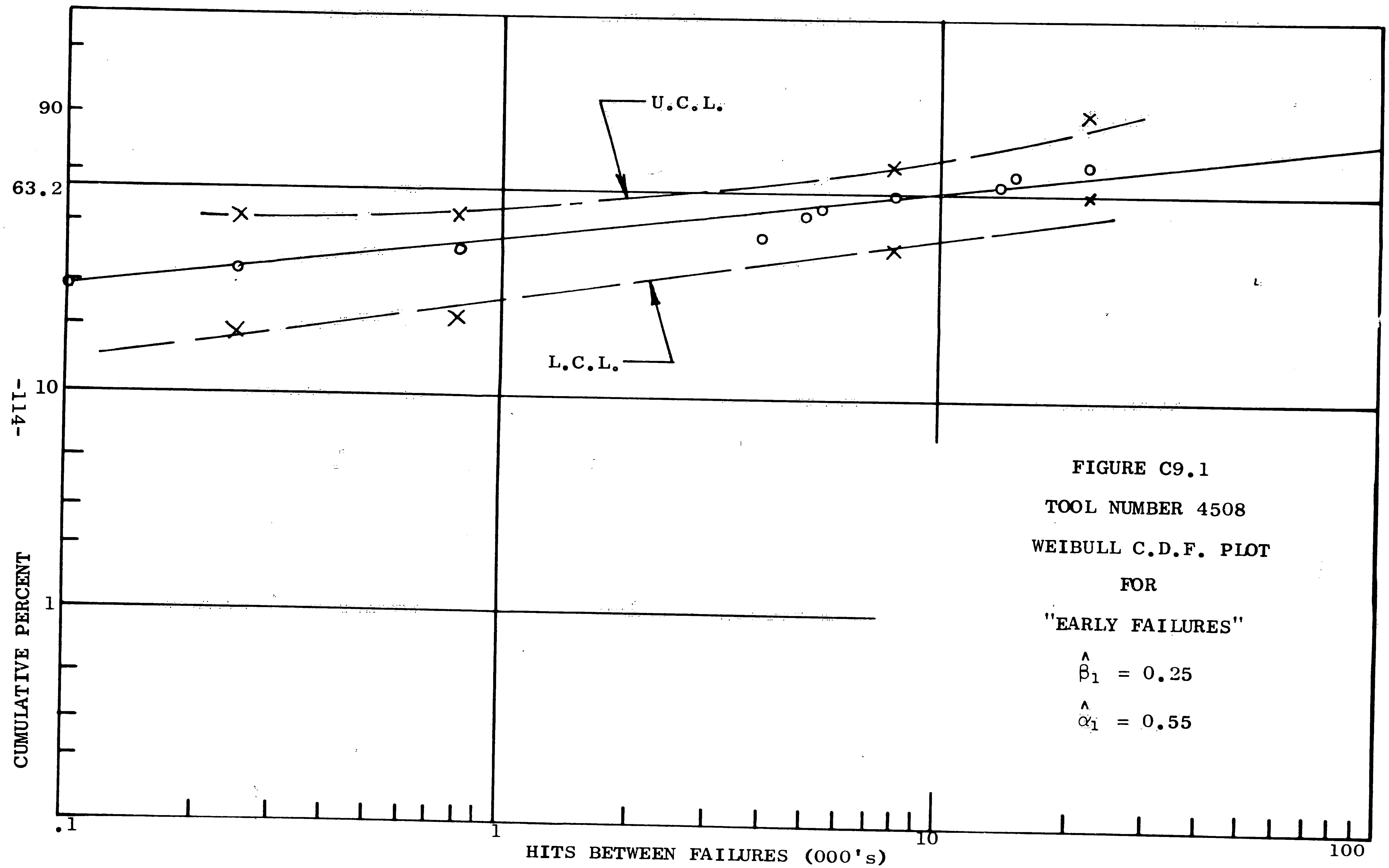


FIGURE C9.1

TOOL NUMBER 4508

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.25$

$\hat{\alpha}_1 = 0.55$

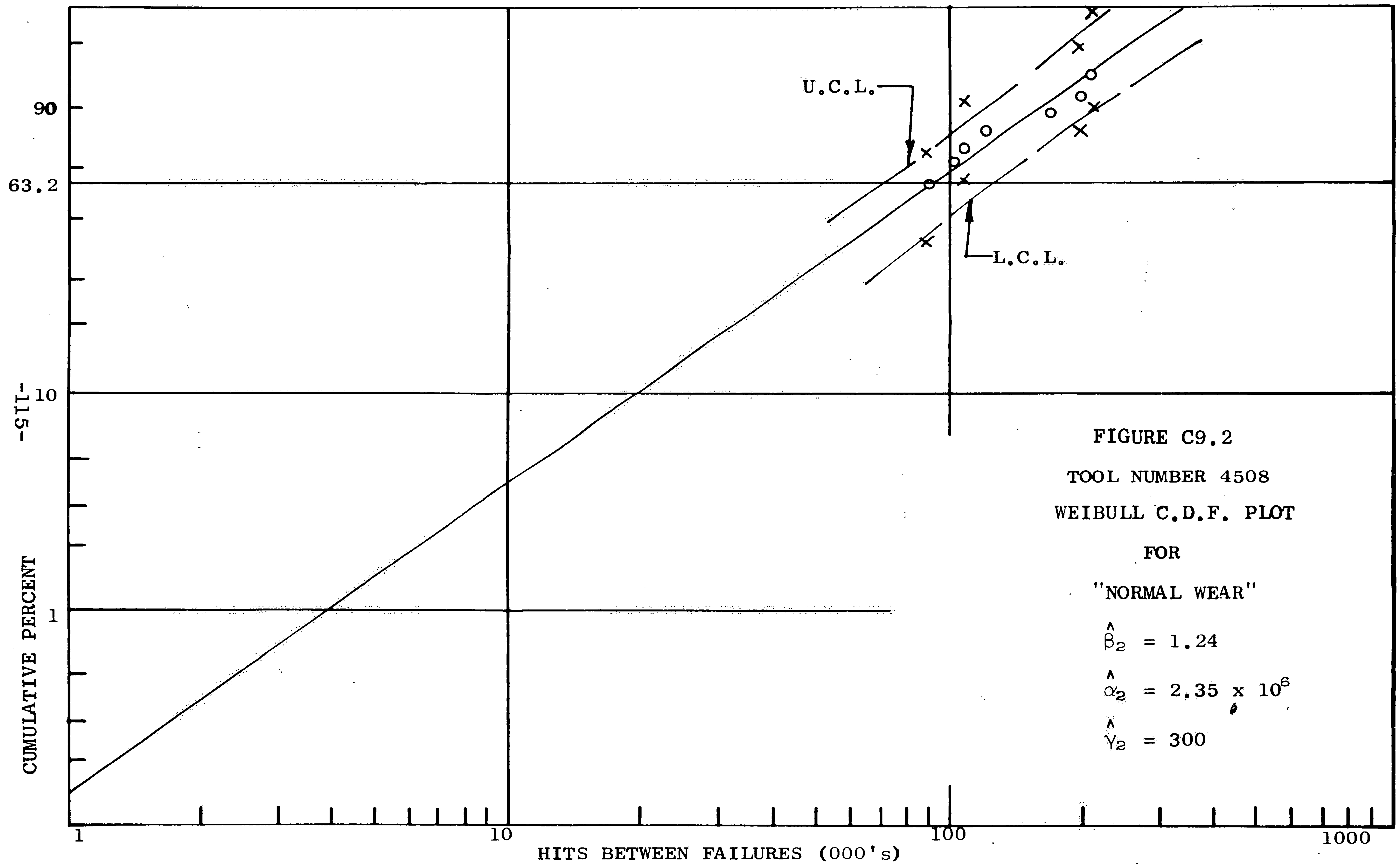


FIGURE C9.2

TOOL NUMBER 4508

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 1.24$

$\hat{\alpha}_2 = 2.35 \times 10^6$

$\hat{\gamma}_2 = 300$

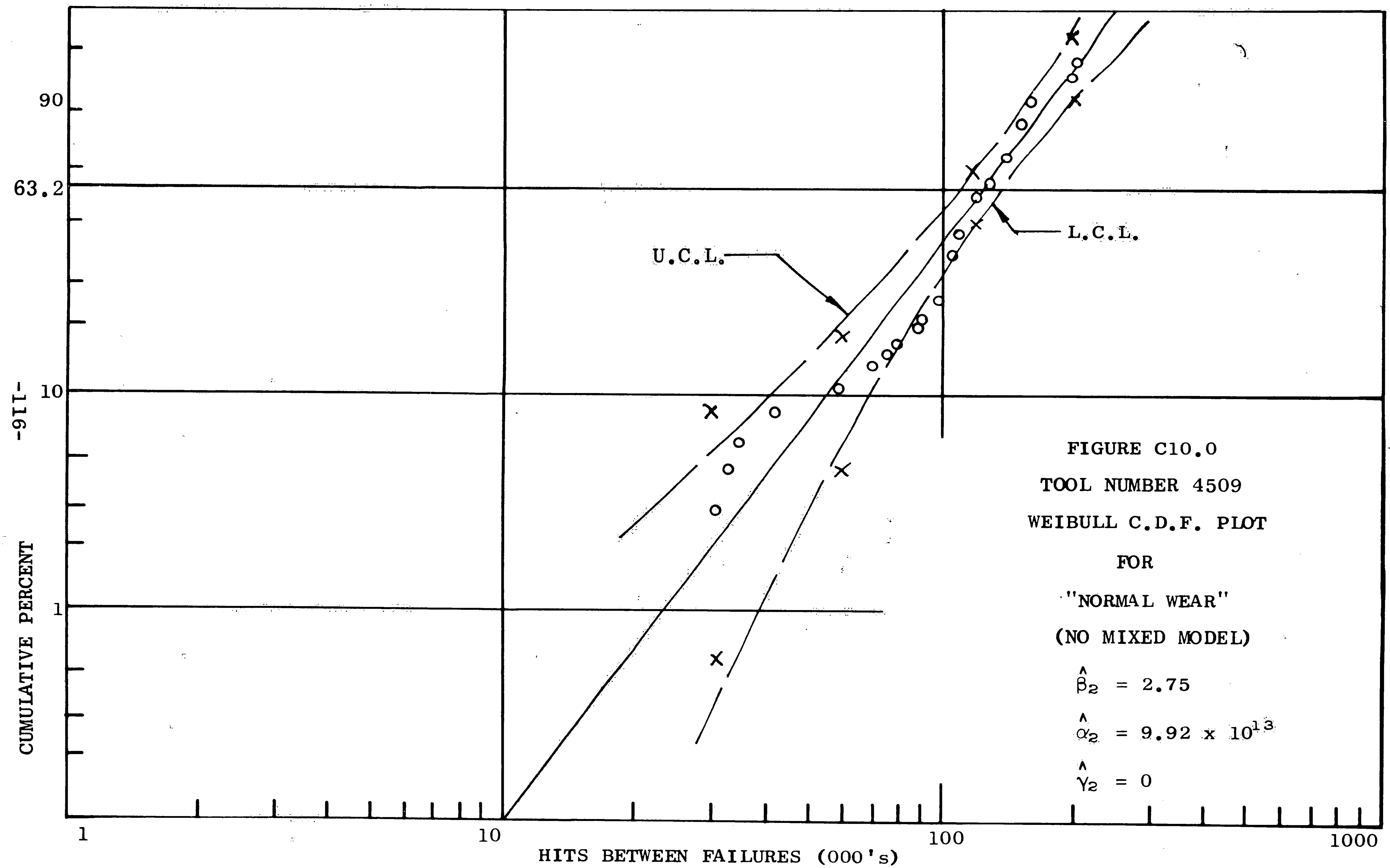


FIGURE C10.0

TOOL NUMBER 4509

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

(NO MIXED MODEL)

$\hat{\beta}_2 = 2.75$

$\hat{\alpha}_2 = 9.92 \times 10^{13}$

$\hat{\gamma}_2 = 0$

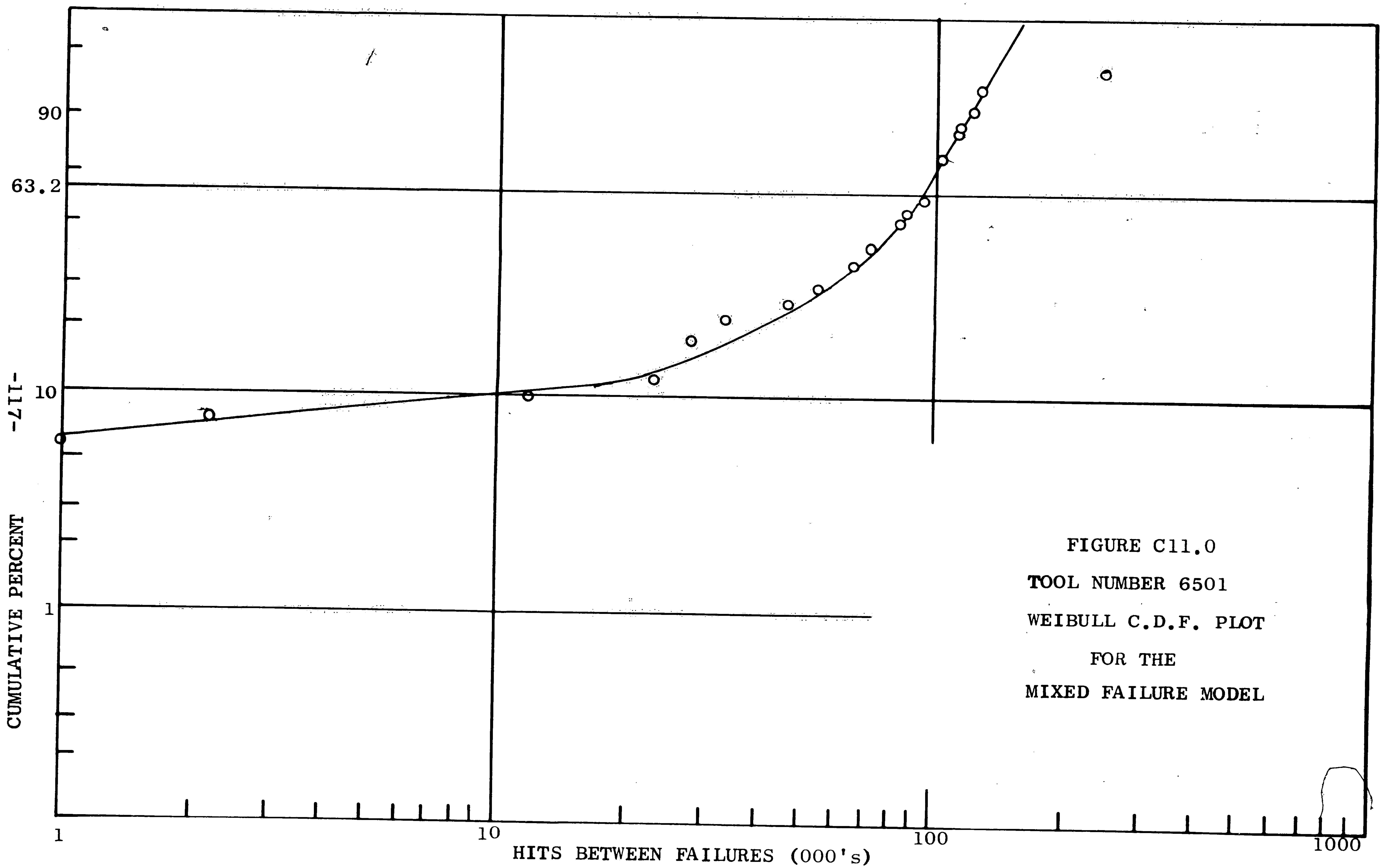


FIGURE C11.0
TOOL NUMBER 6501
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

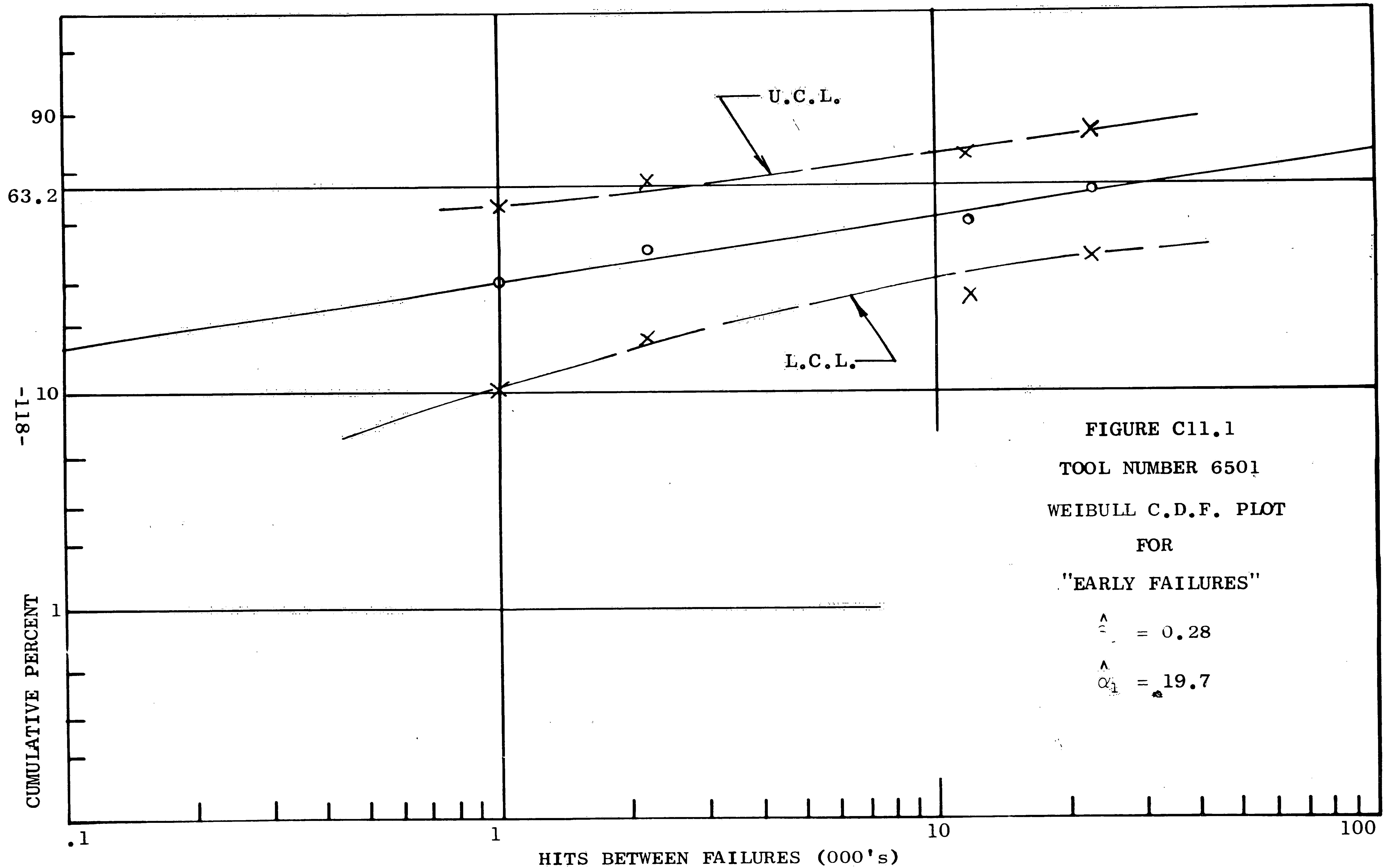


FIGURE C11.1

TOOL NUMBER 6501

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta} = 0.28$

$\hat{\alpha}_1 = 19.7$

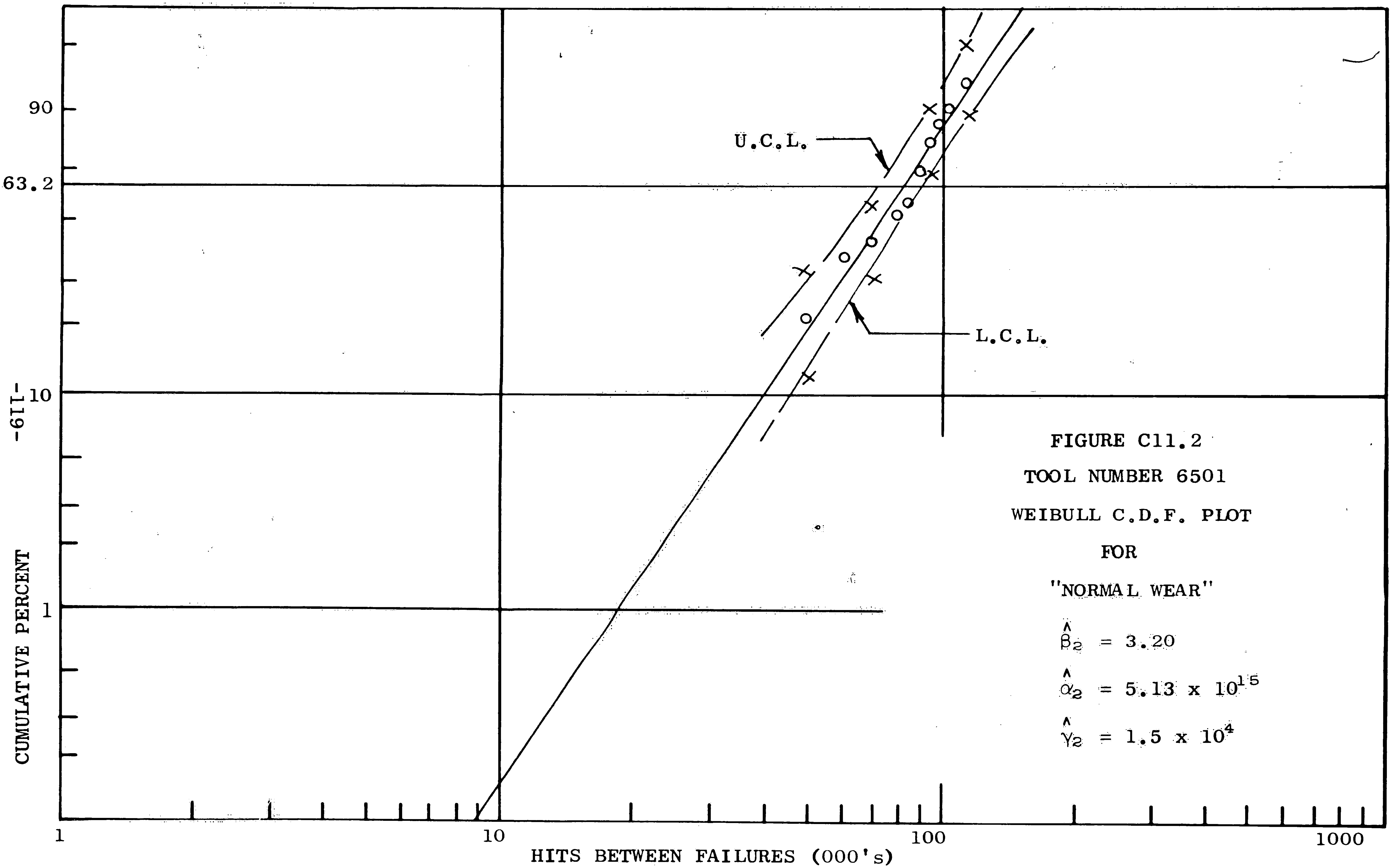


FIGURE C11.2

TOOL NUMBER 6501

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 3.20$

$\hat{\alpha}_2 = 5.13 \times 10^{15}$

$\hat{\gamma}_2 = 1.5 \times 10^4$

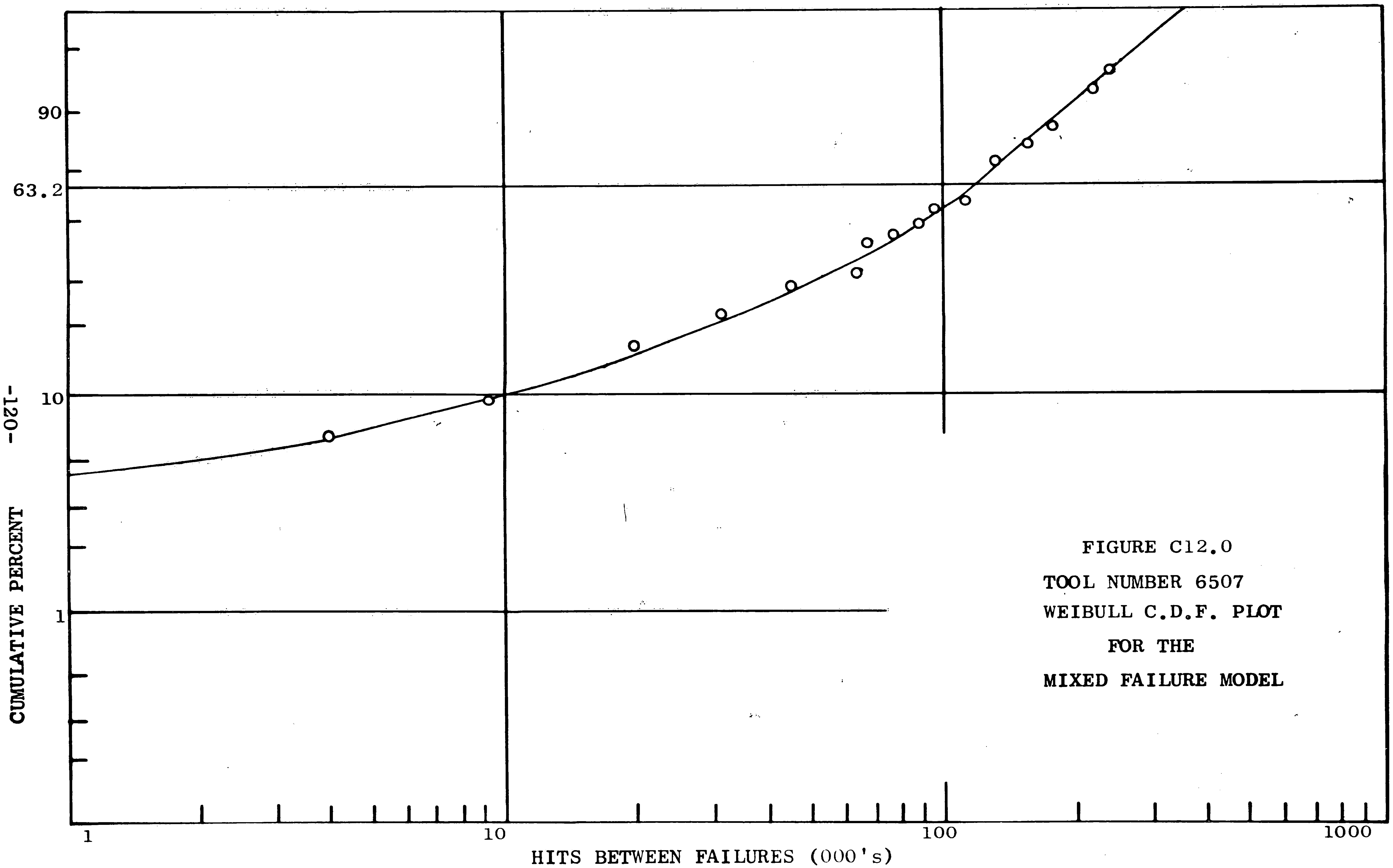


FIGURE C12.0
TOOL NUMBER 6507
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

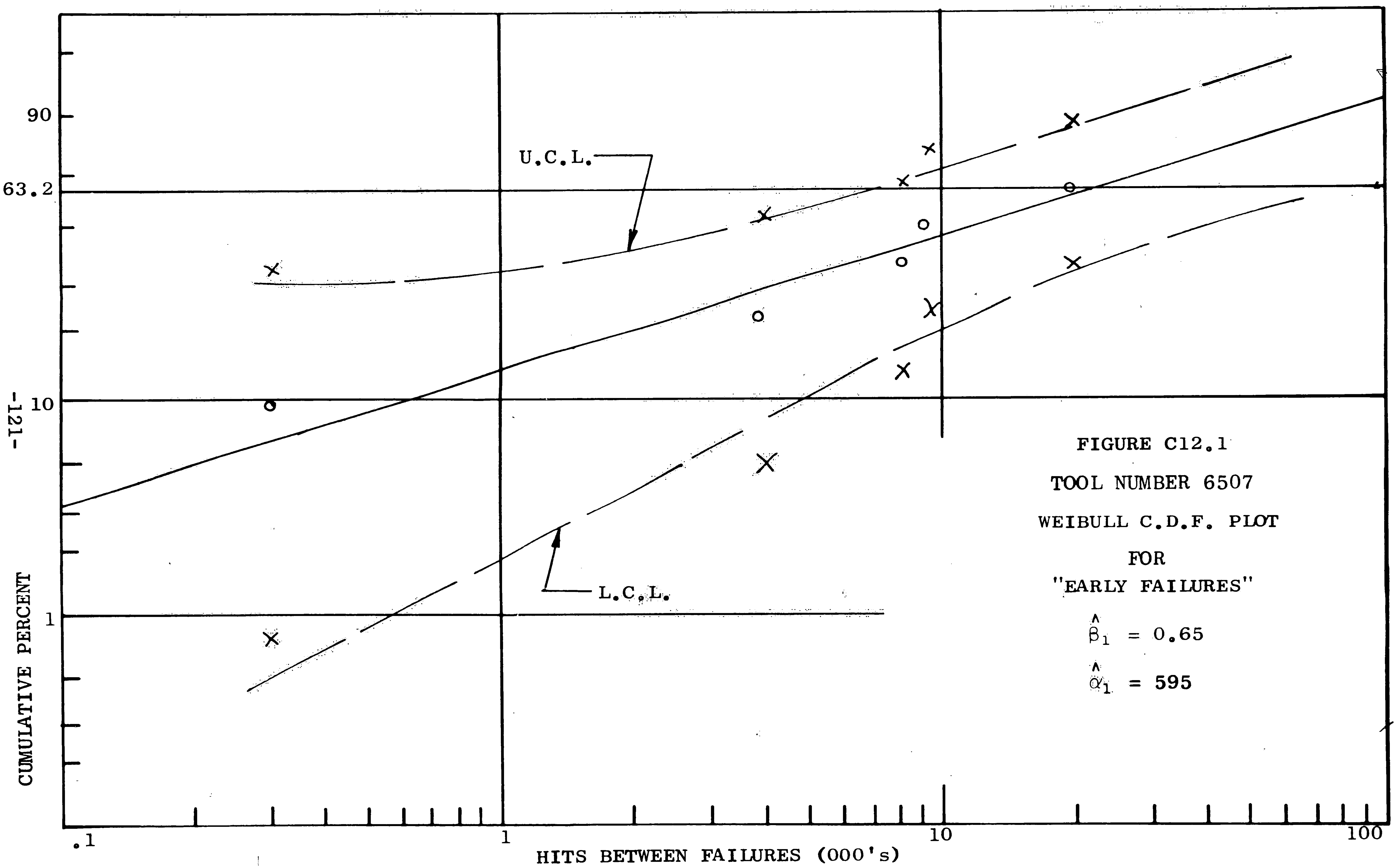


FIGURE C12.1

TOOL NUMBER 6507

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.65$

$\hat{\alpha}_1 = 595$

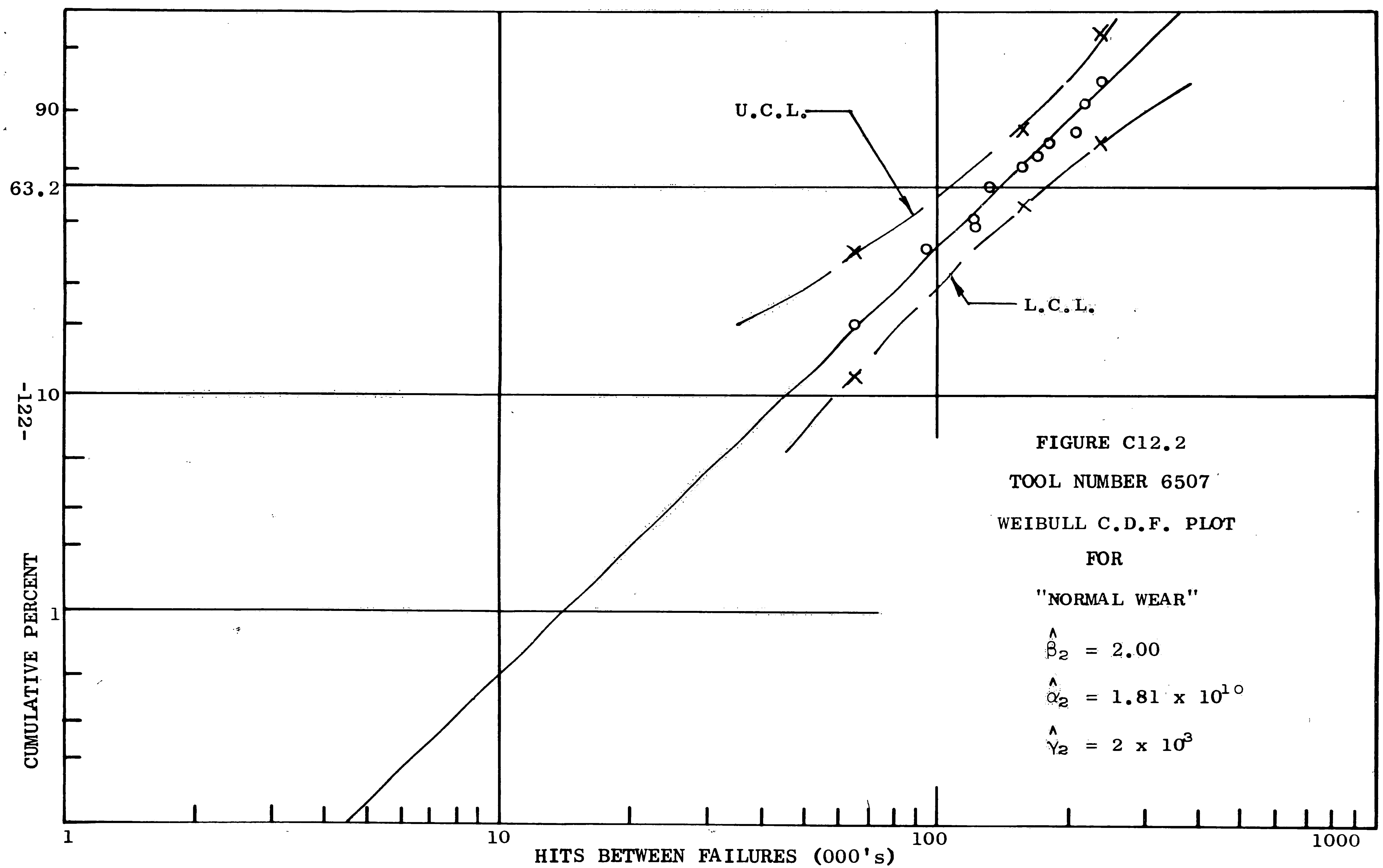


FIGURE C12.2

TOOL NUMBER 6507

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 2.00$

$\hat{\alpha}_2 = 1.81 \times 10^{10}$

$\hat{\gamma}_2 = 2 \times 10^{3}$

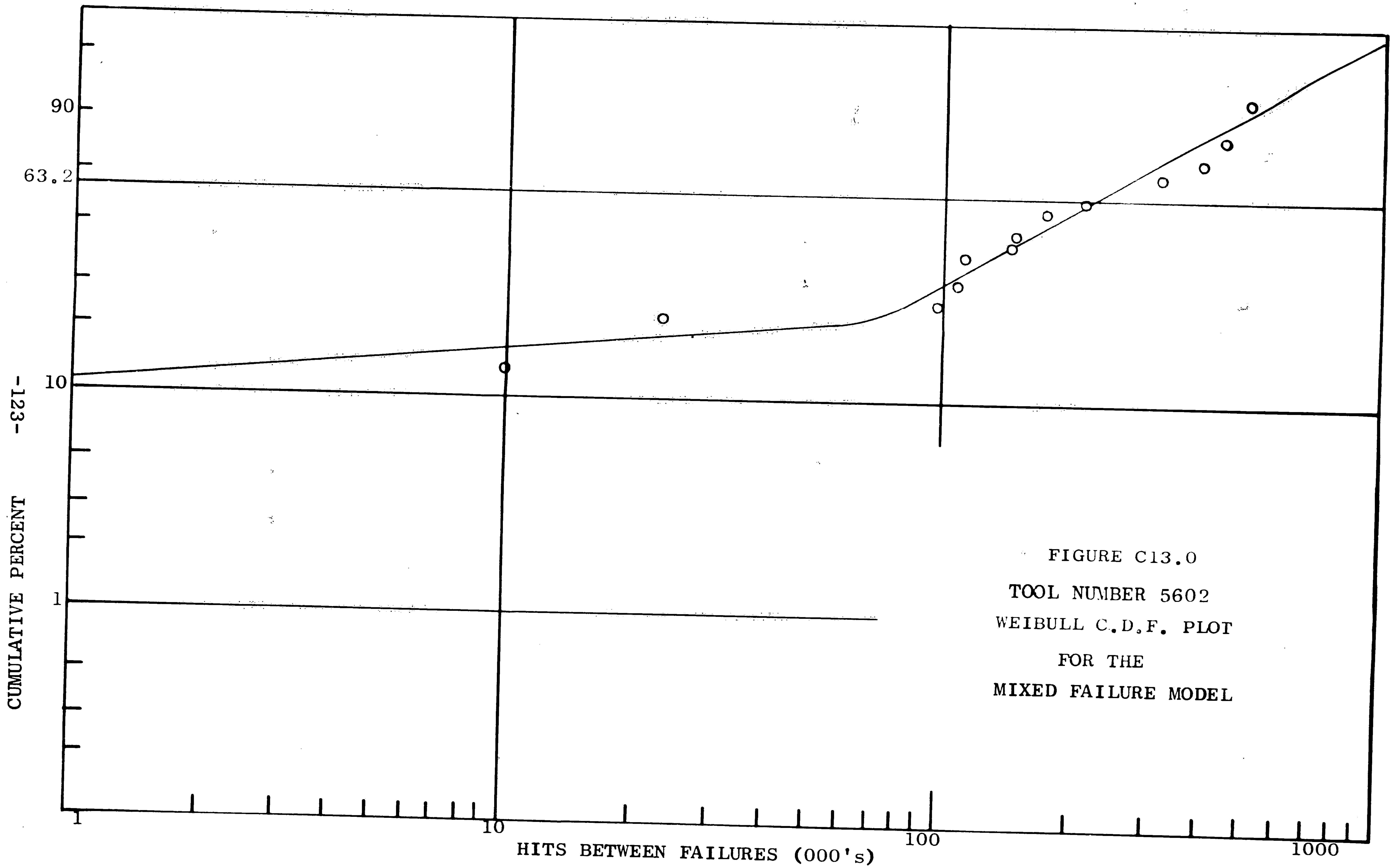


FIGURE C13.0

TOOL NUMBER 5602

WEIBULL C.D.F. PLOT

FOR THE

MIXED FAILURE MODEL

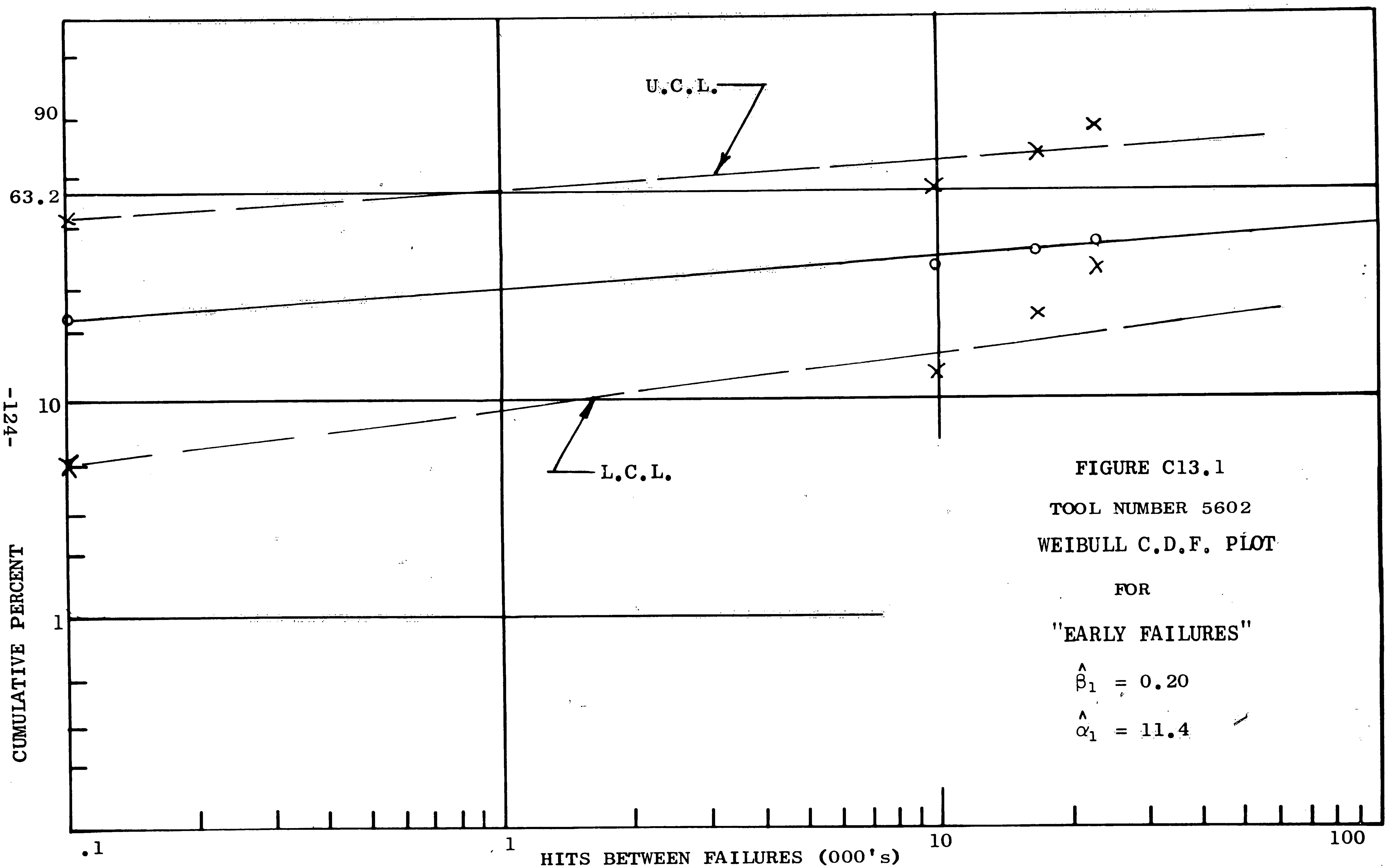


FIGURE C13.1

TOOL NUMBER 5602

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.20$

$\hat{\alpha}_1 = 11.4$

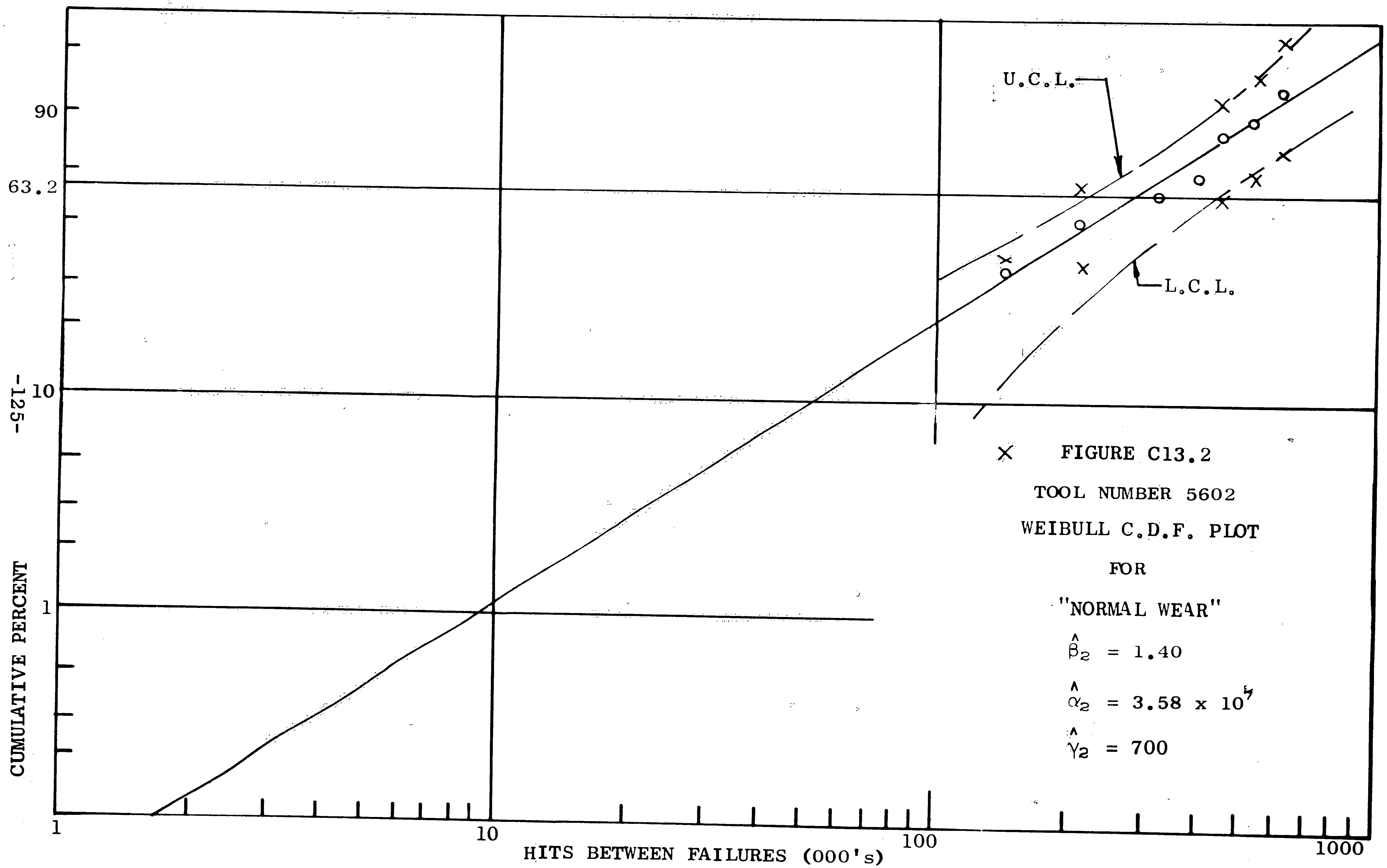


FIGURE C13.2

TOOL NUMBER 5602

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 1.40$

$\hat{\alpha}_2 = 3.58 \times 10^5$

$\hat{\gamma}_2 = 700$

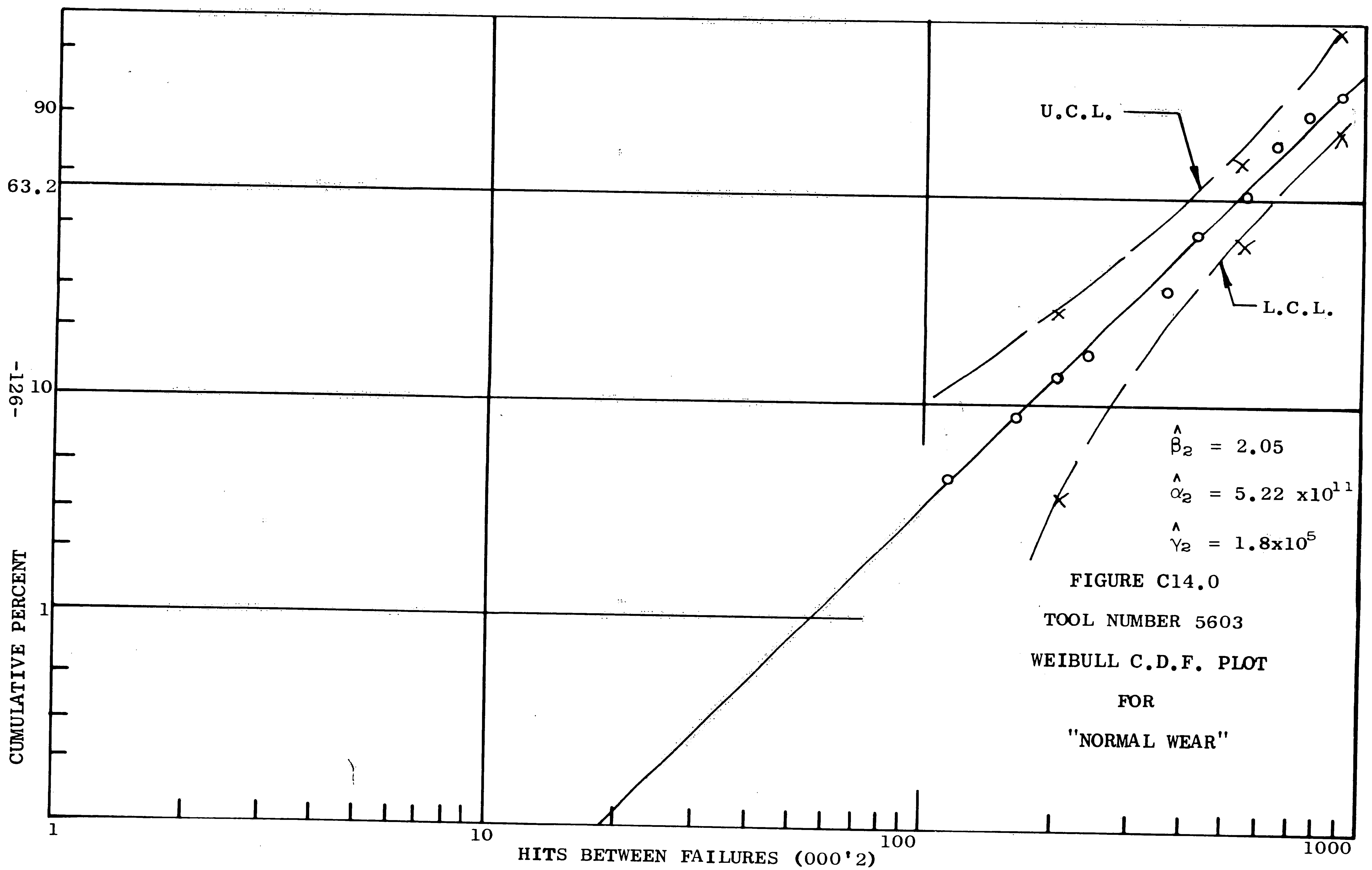


FIGURE C14.0
TOOL NUMBER 5603
WEIBULL C.D.F. PLOT
FOR
"NORMAL WEAR"

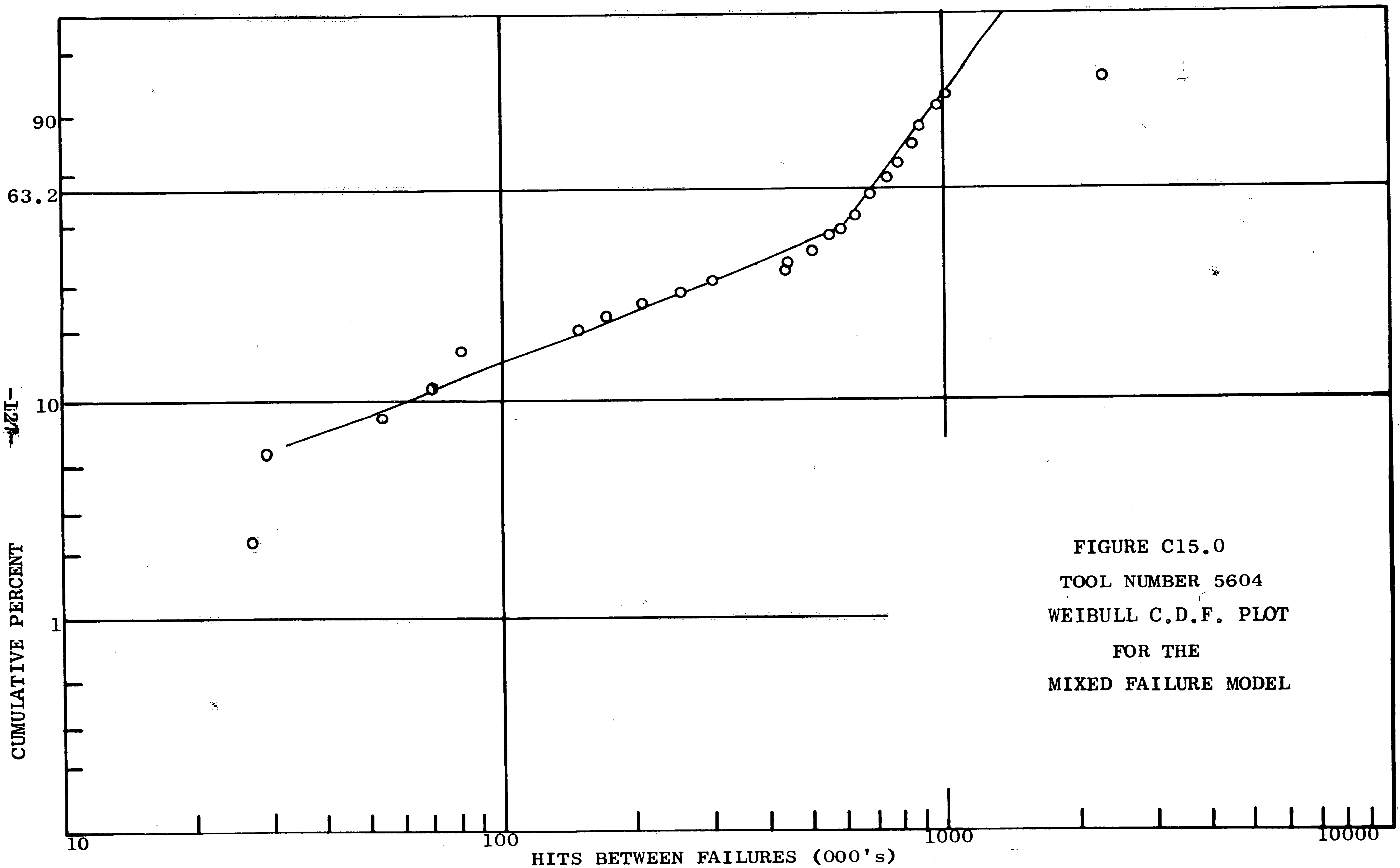


FIGURE C15.0
TOOL NUMBER 5604
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

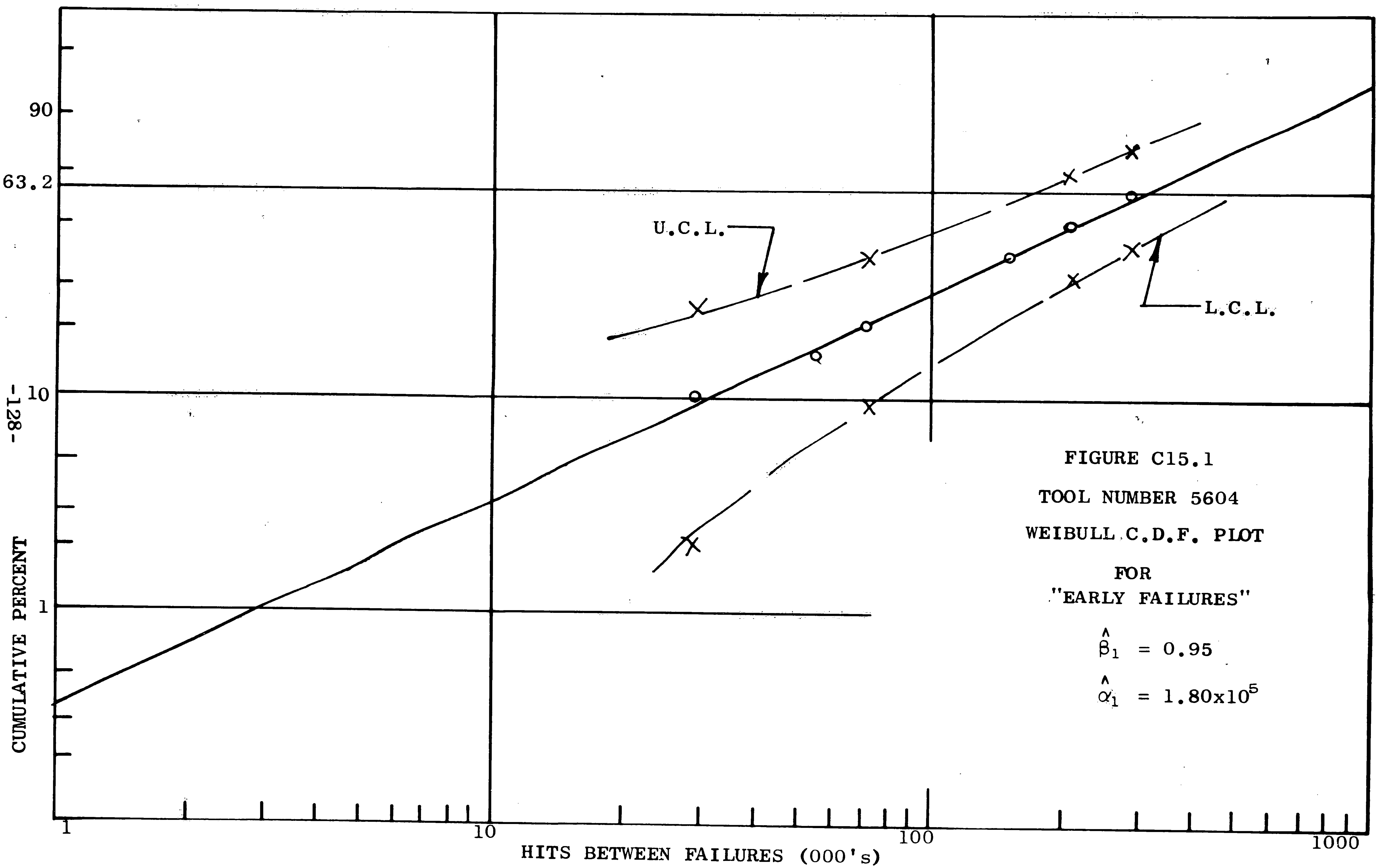


FIGURE C15.1

TOOL NUMBER 5604

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.95$

$\hat{\alpha}_1 = 1.80\text{x}10^5$

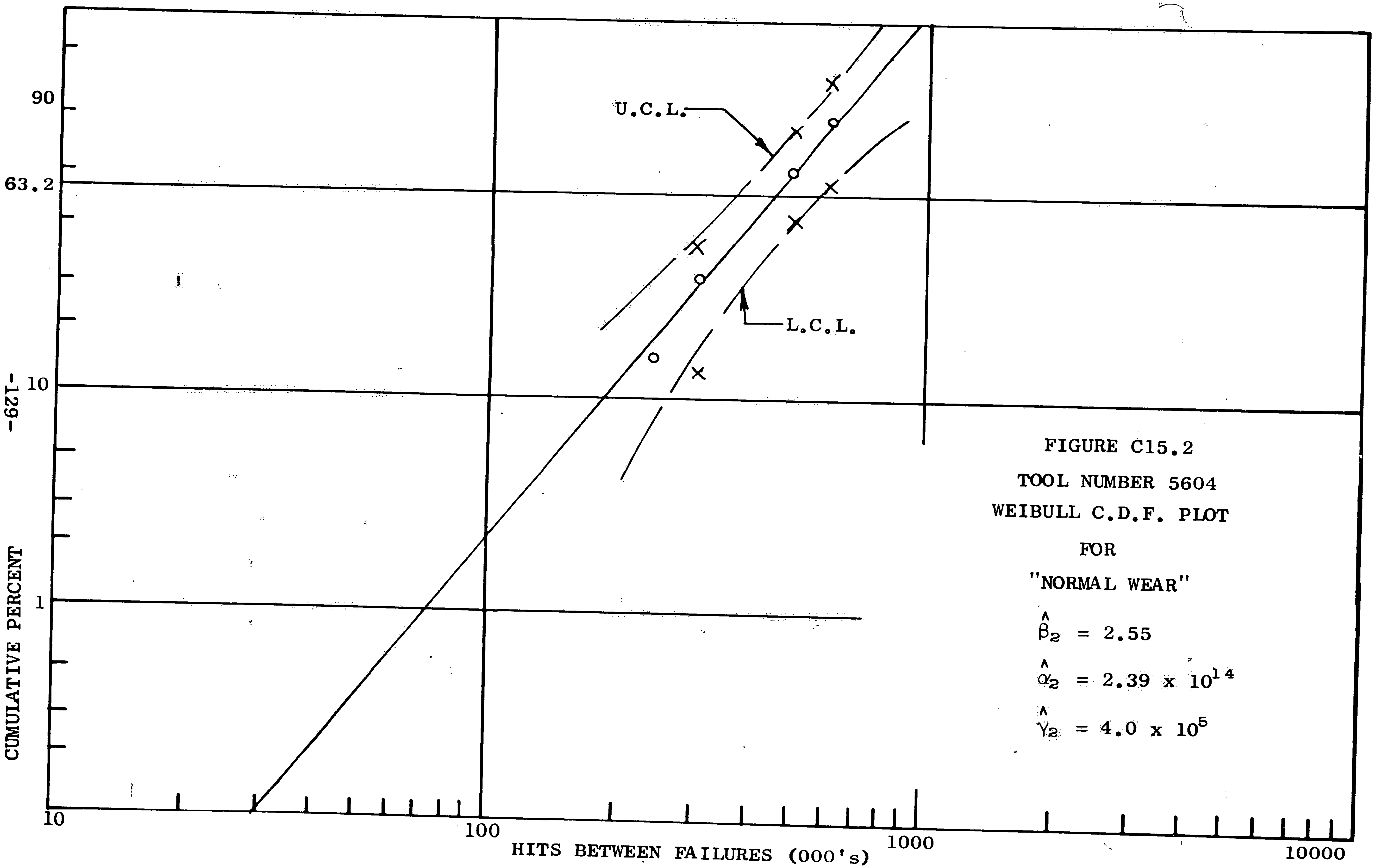


FIGURE C15.2
TOOL NUMBER 5604
WEIBULL C.D.F. PLOT
FOR
"NORMAL WEAR"

$\hat{\beta}_2 = 2.55$

$\hat{\alpha}_2 = 2.39 \times 10^{14}$

$\hat{\gamma}_2 = 4.0 \times 10^5$

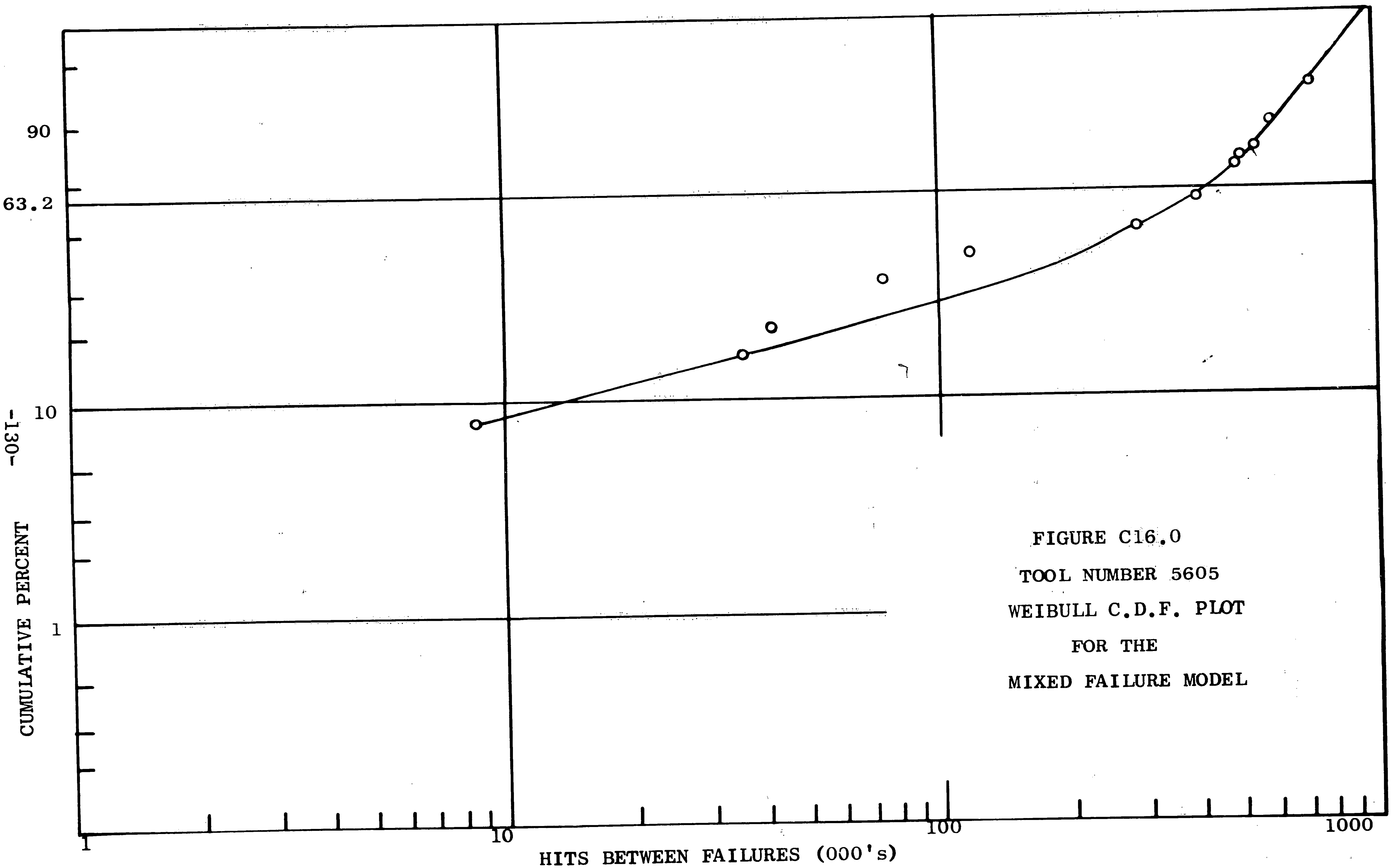


FIGURE C16.0
TOOL NUMBER 5605
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

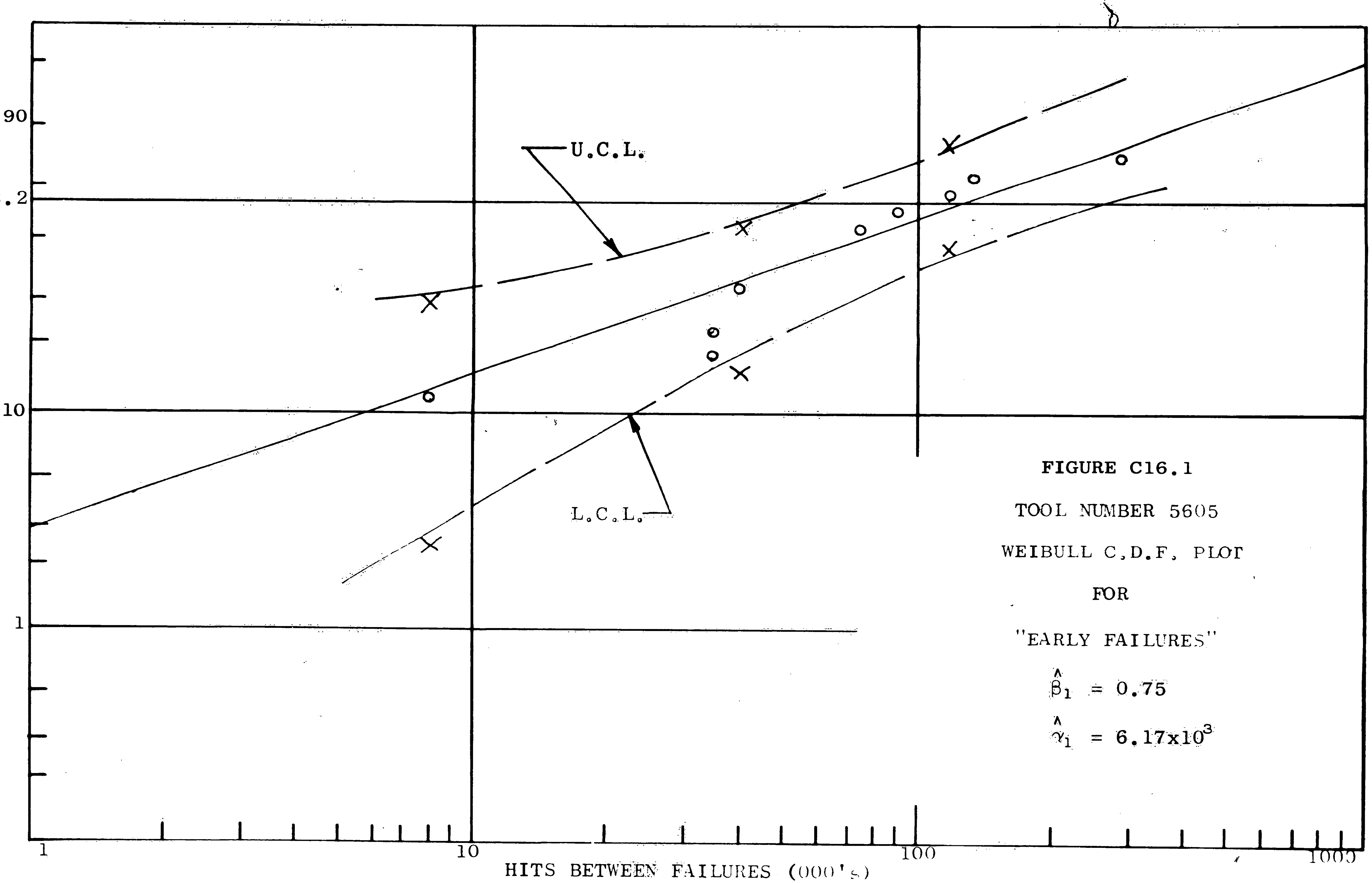


FIGURE C16.1

TOOL NUMBER 5605

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.75$

$\hat{\gamma}_1 = 6.17 \times 10^3$

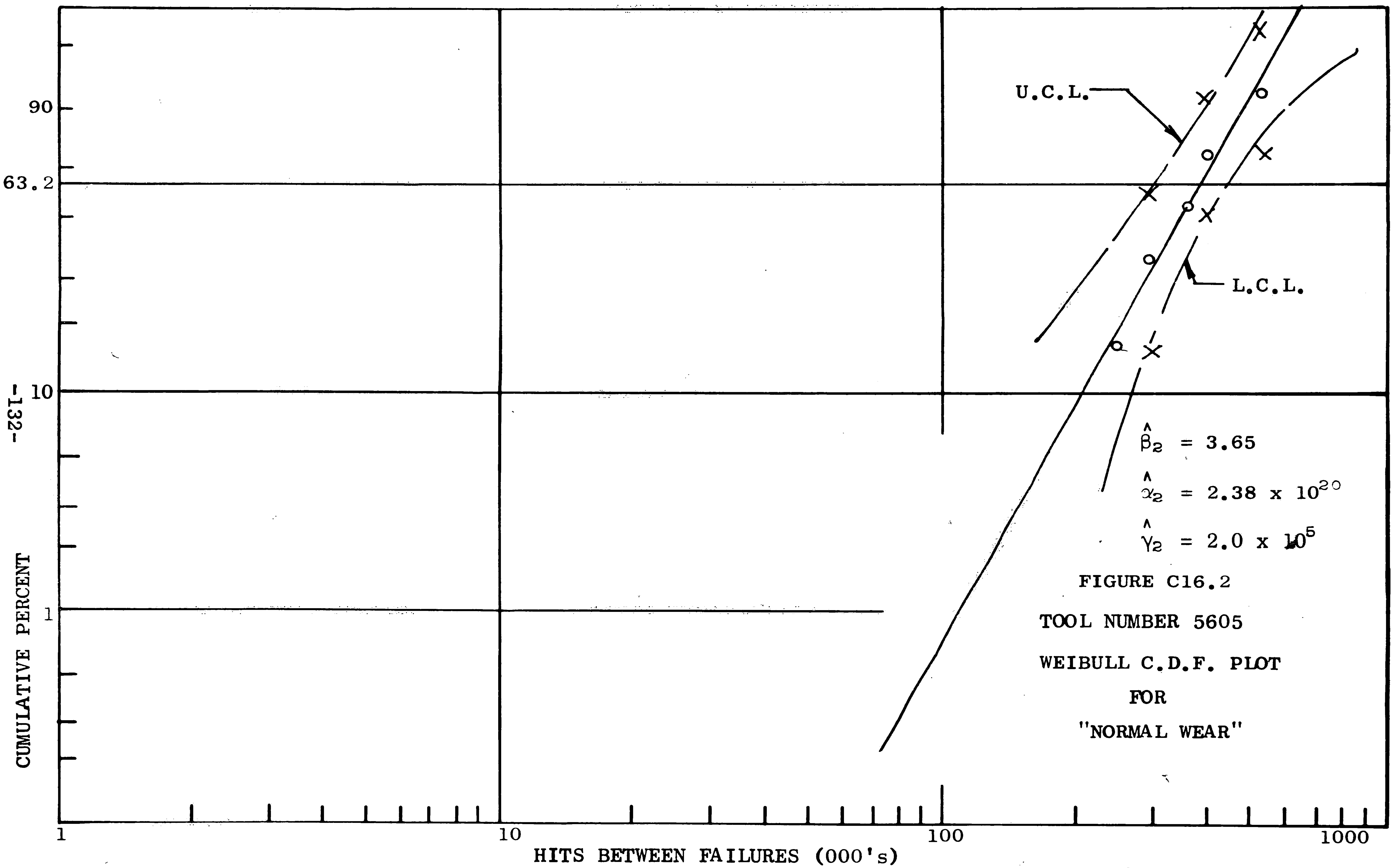


FIGURE C16.2

TOOL NUMBER 5605

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

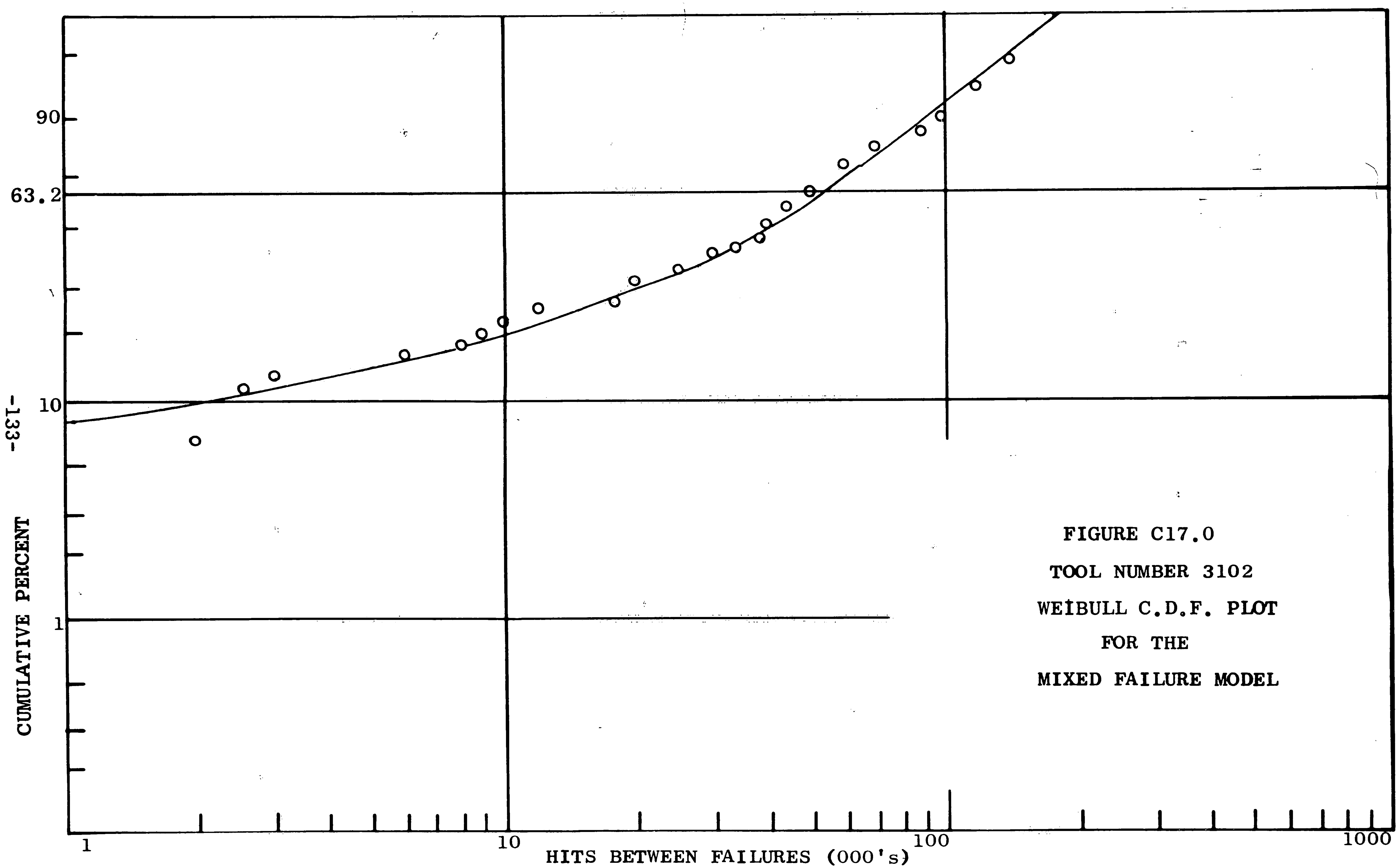


FIGURE C17.0
TOOL NUMBER 3102
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

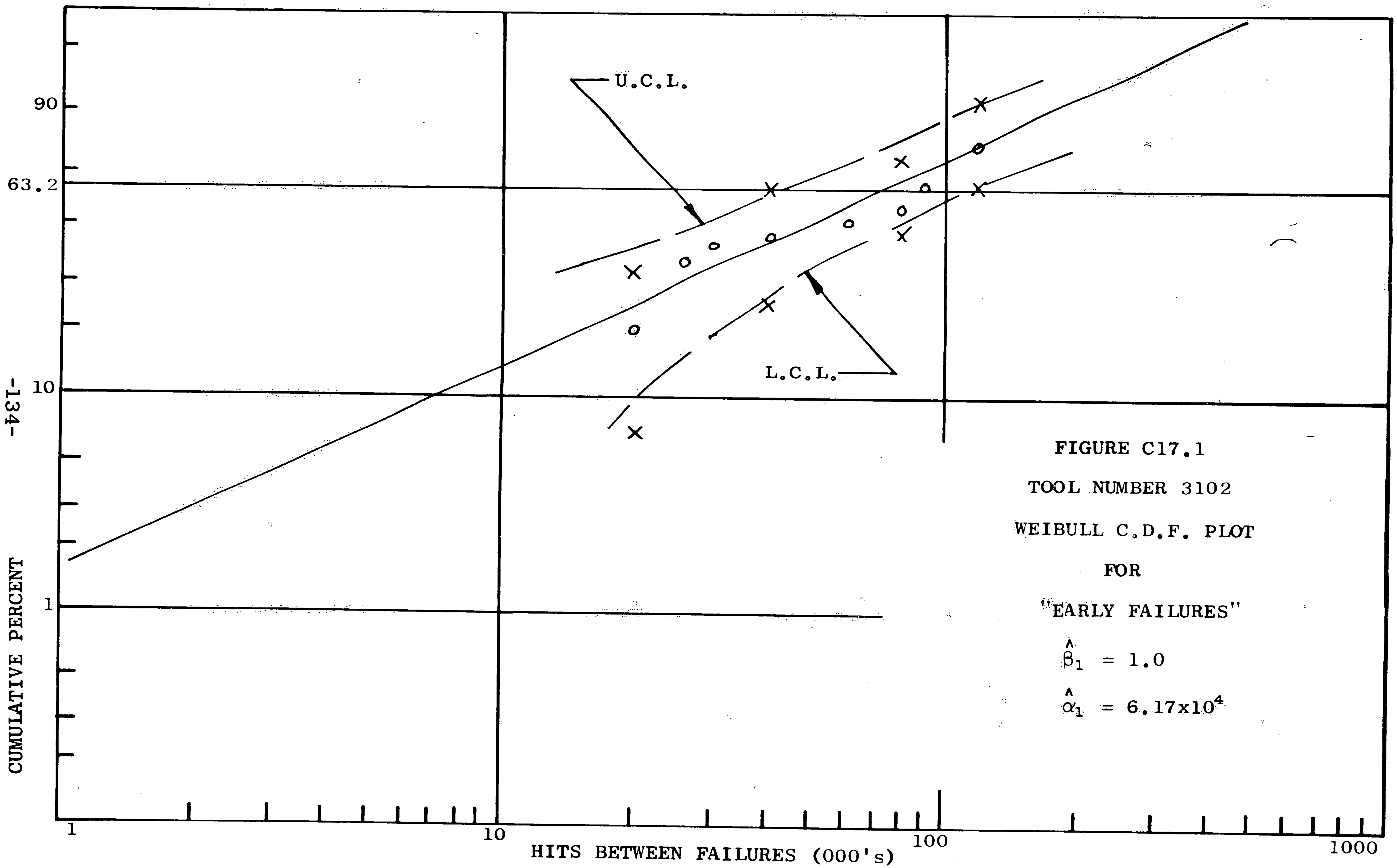


FIGURE C17.1

TOOL NUMBER 3102

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 1.0$

$\hat{\alpha}_1 = 6.17 \times 10^4$

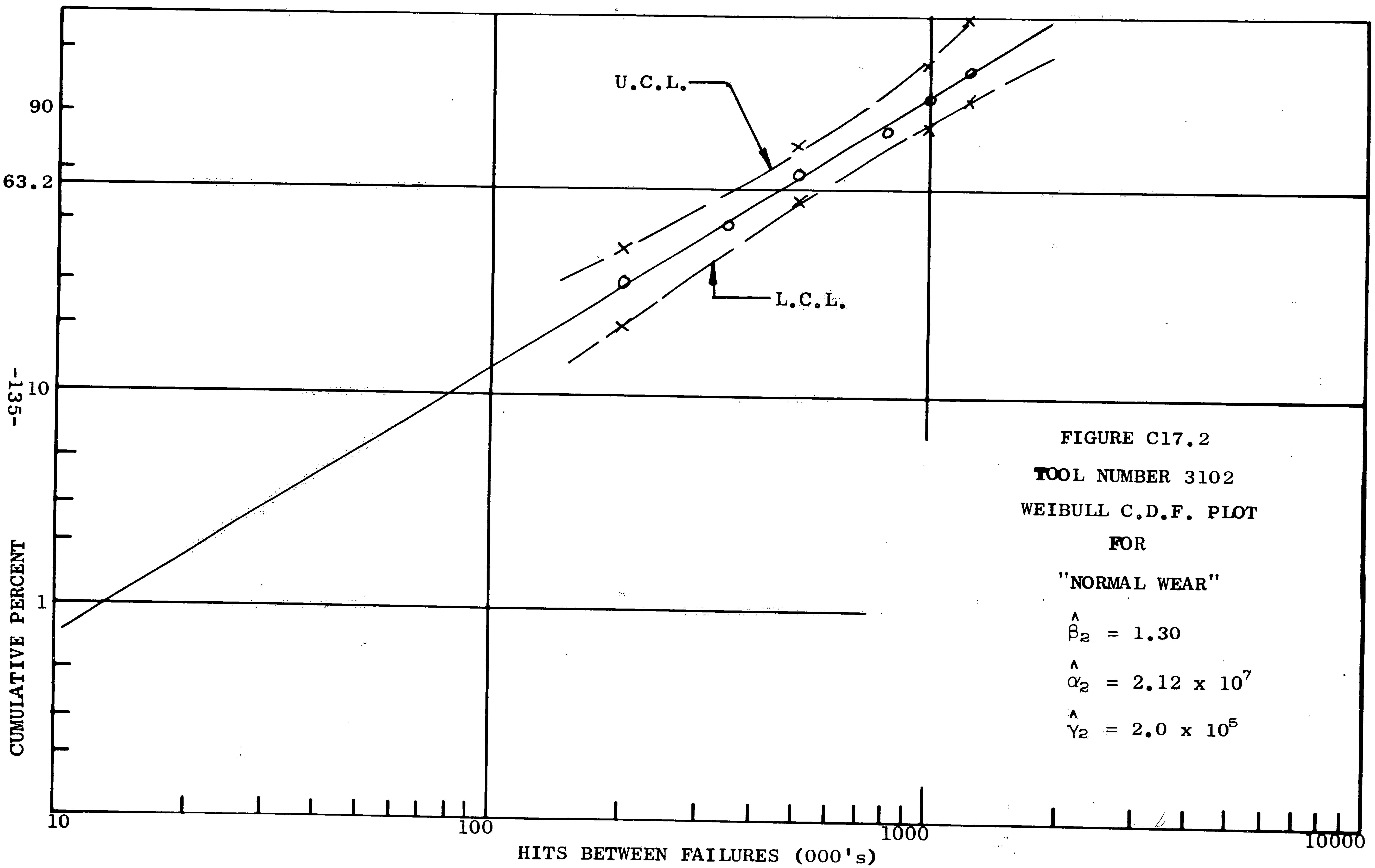


FIGURE C17.2

TOOL NUMBER 3102

WEIBULL C.D.F. PLOT

FOR

"NORMAL WEAR"

$\hat{\beta}_2 = 1.30$

$\hat{\alpha}_2 = 2.12 \times 10^7$

$\hat{\gamma}_2 = 2.0 \times 10^5$

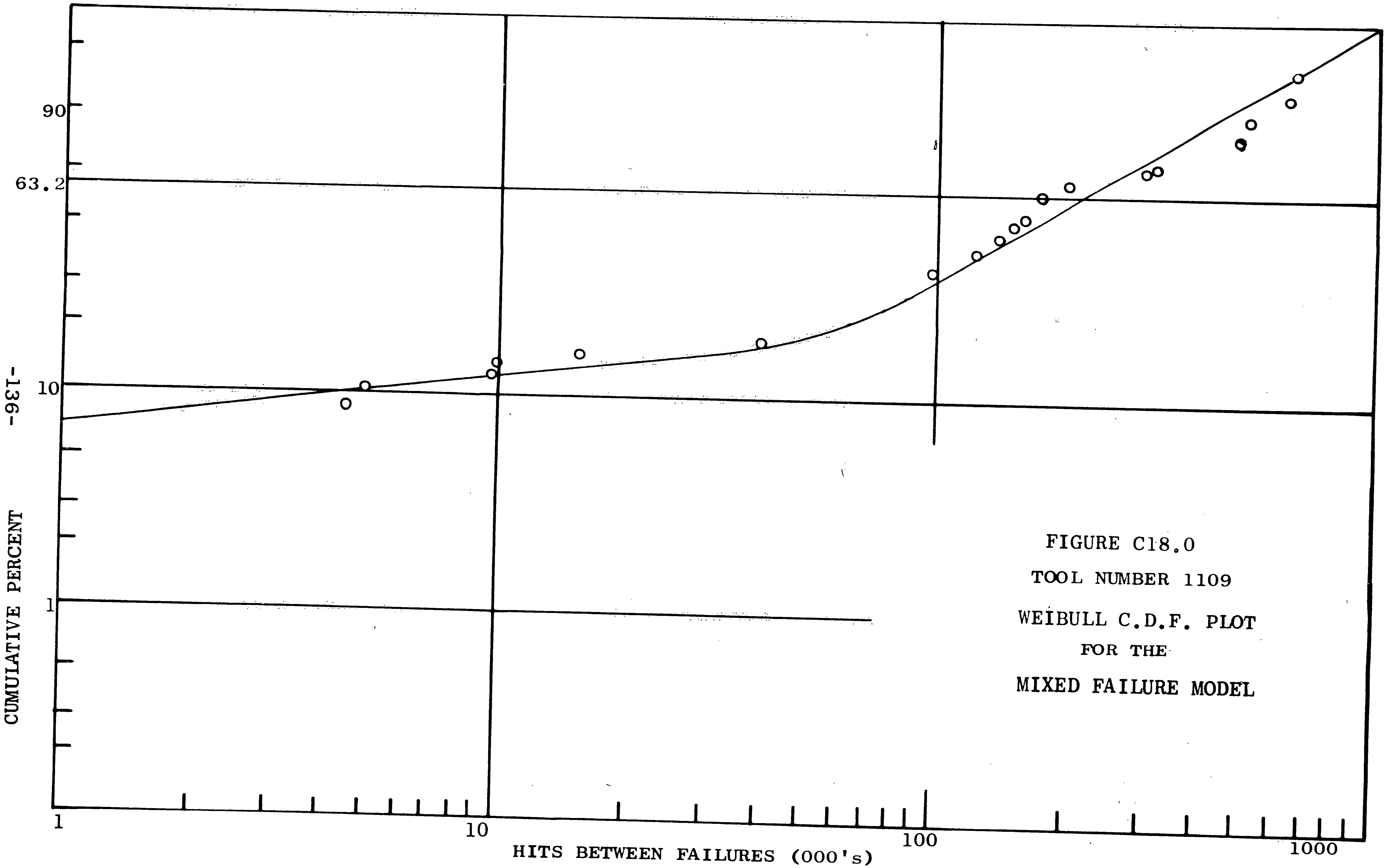


FIGURE C18.0
TOOL NUMBER 1109
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

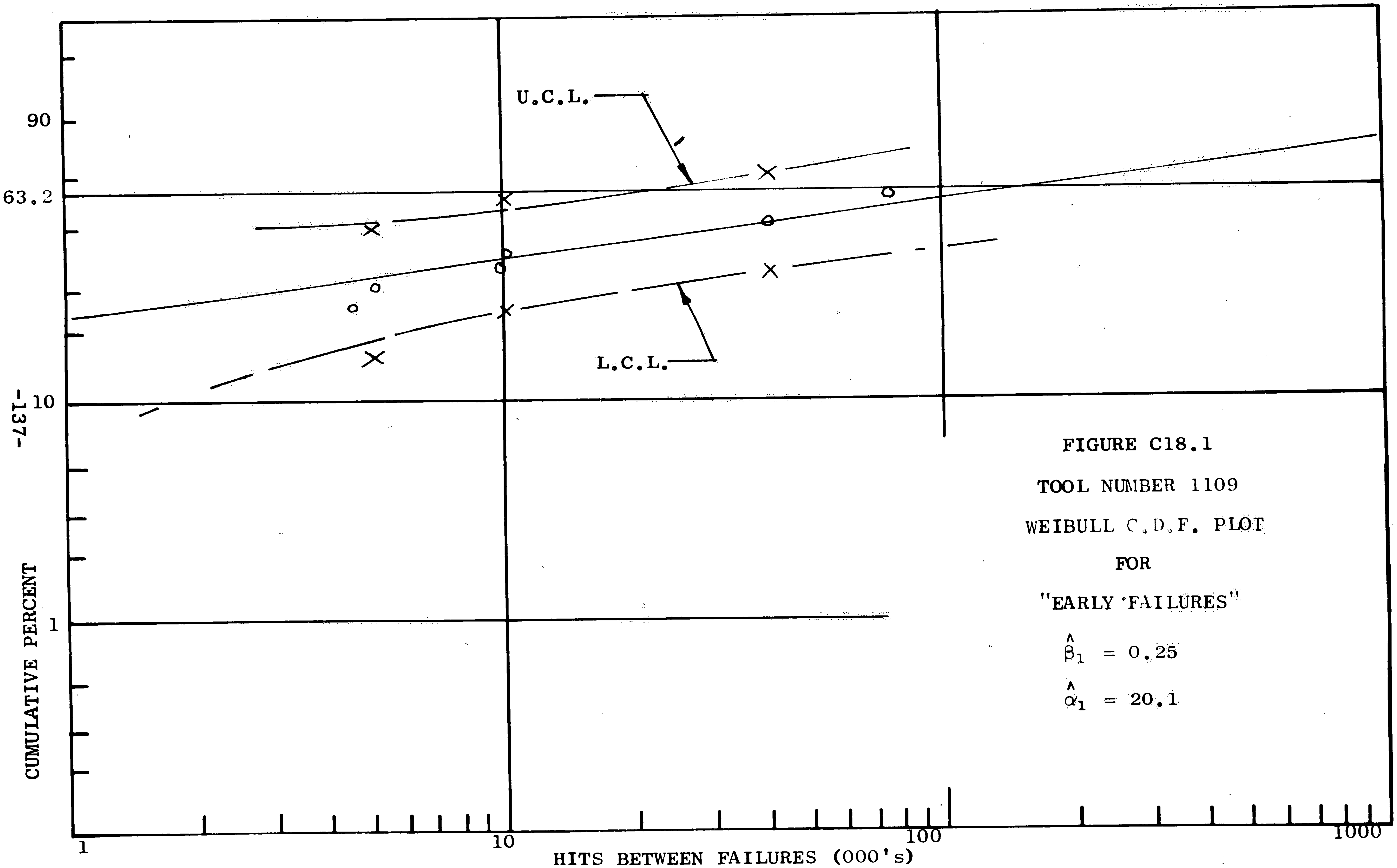


FIGURE C18.1

TOOL NUMBER 1109

WEIBULL C.D.F. PLOT

FOR

"EARLY FAILURES"

$\hat{\beta}_1 = 0.25$

$\hat{\alpha}_1 = 20.1$

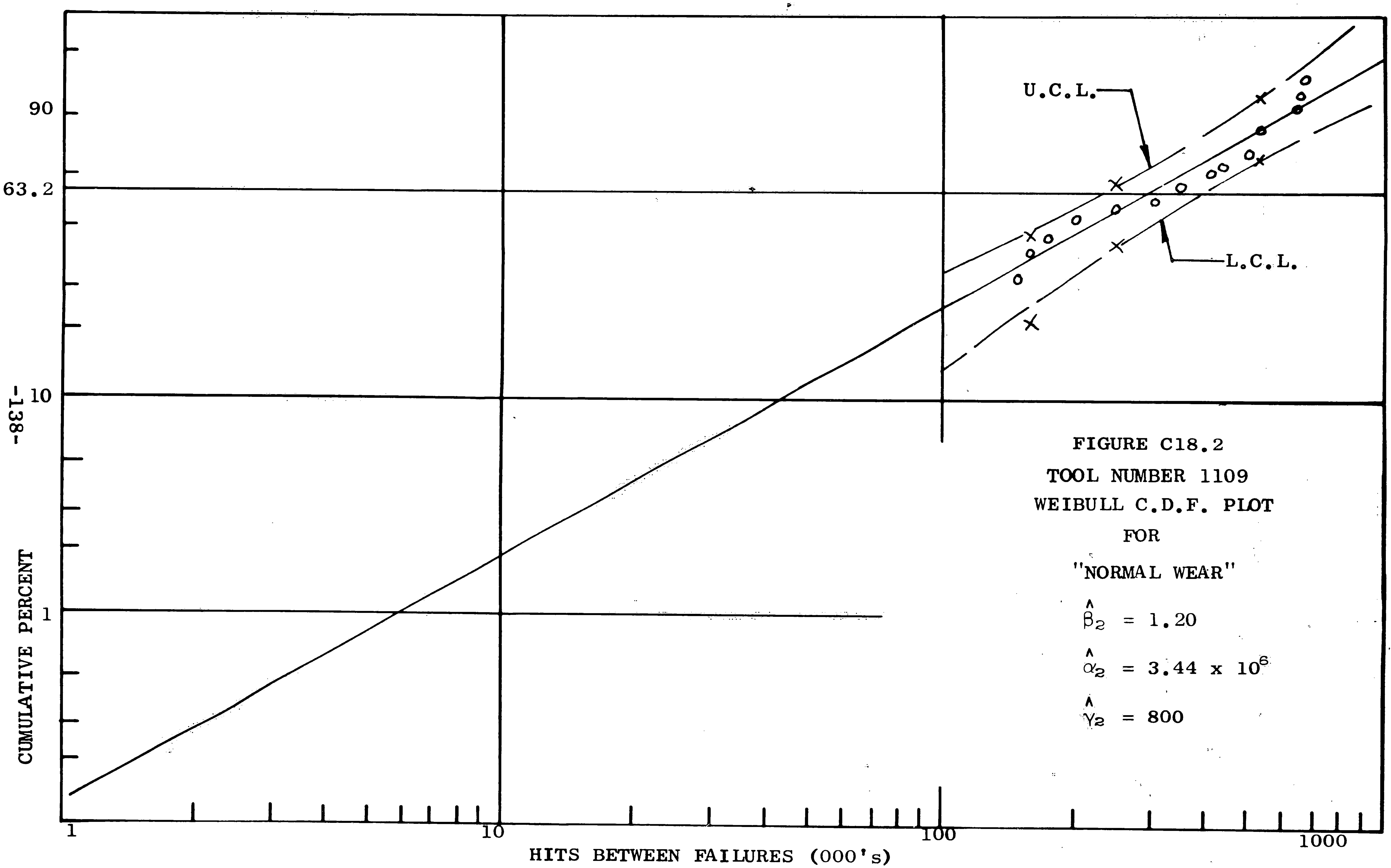


FIGURE C18.2
TOOL NUMBER 1109
WEIBULL C.D.F. PLOT
FOR
"NORMAL WEAR"

$\hat{\beta}_2 = 1.20$

$\hat{\alpha}_2 = 3.44 \times 10^6$

$\hat{\gamma}_2 = 800$

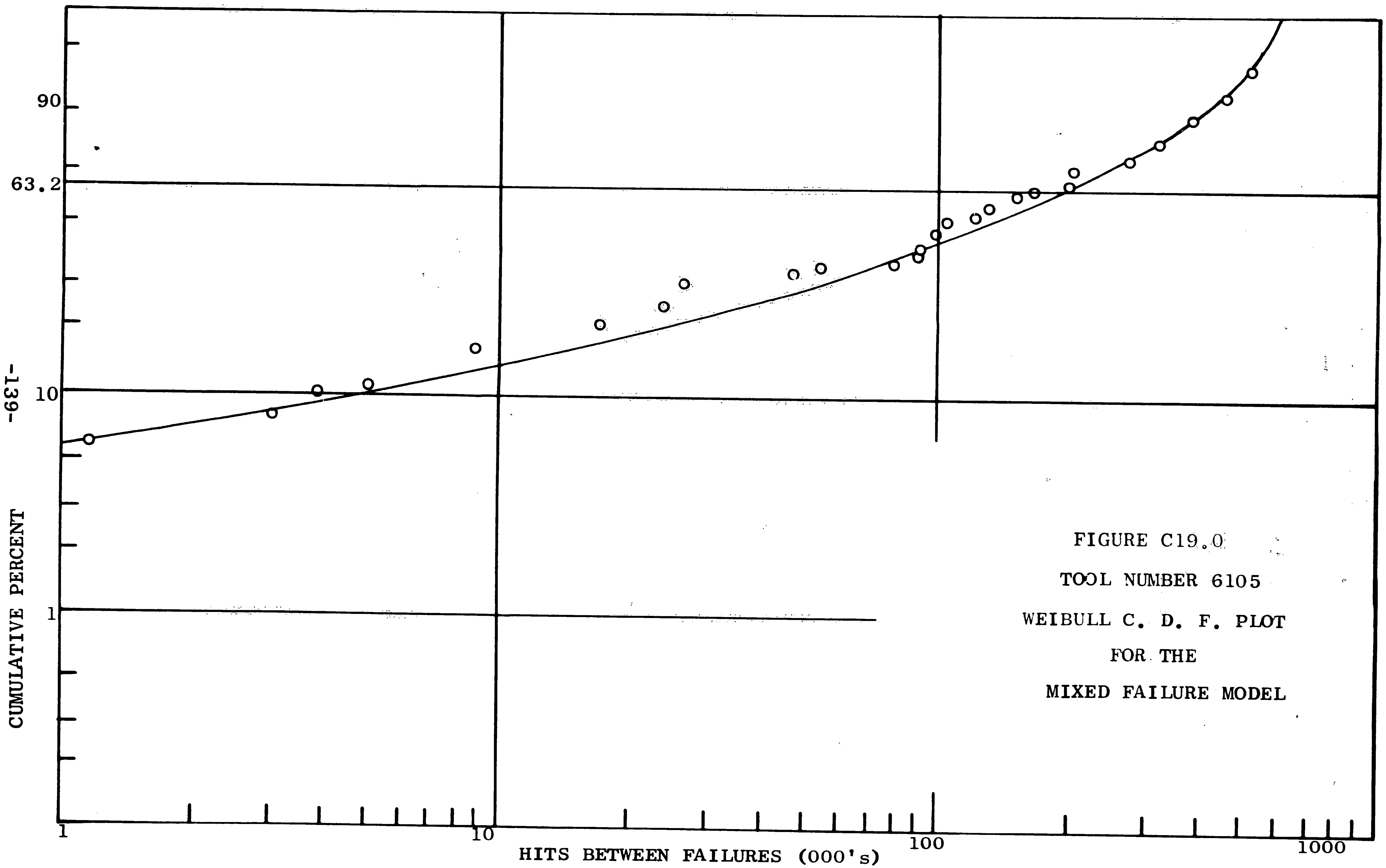


FIGURE C19.0
TOOL NUMBER 6105
WEIBULL C. D. F. PLOT
FOR THE
MIXED FAILURE MODEL

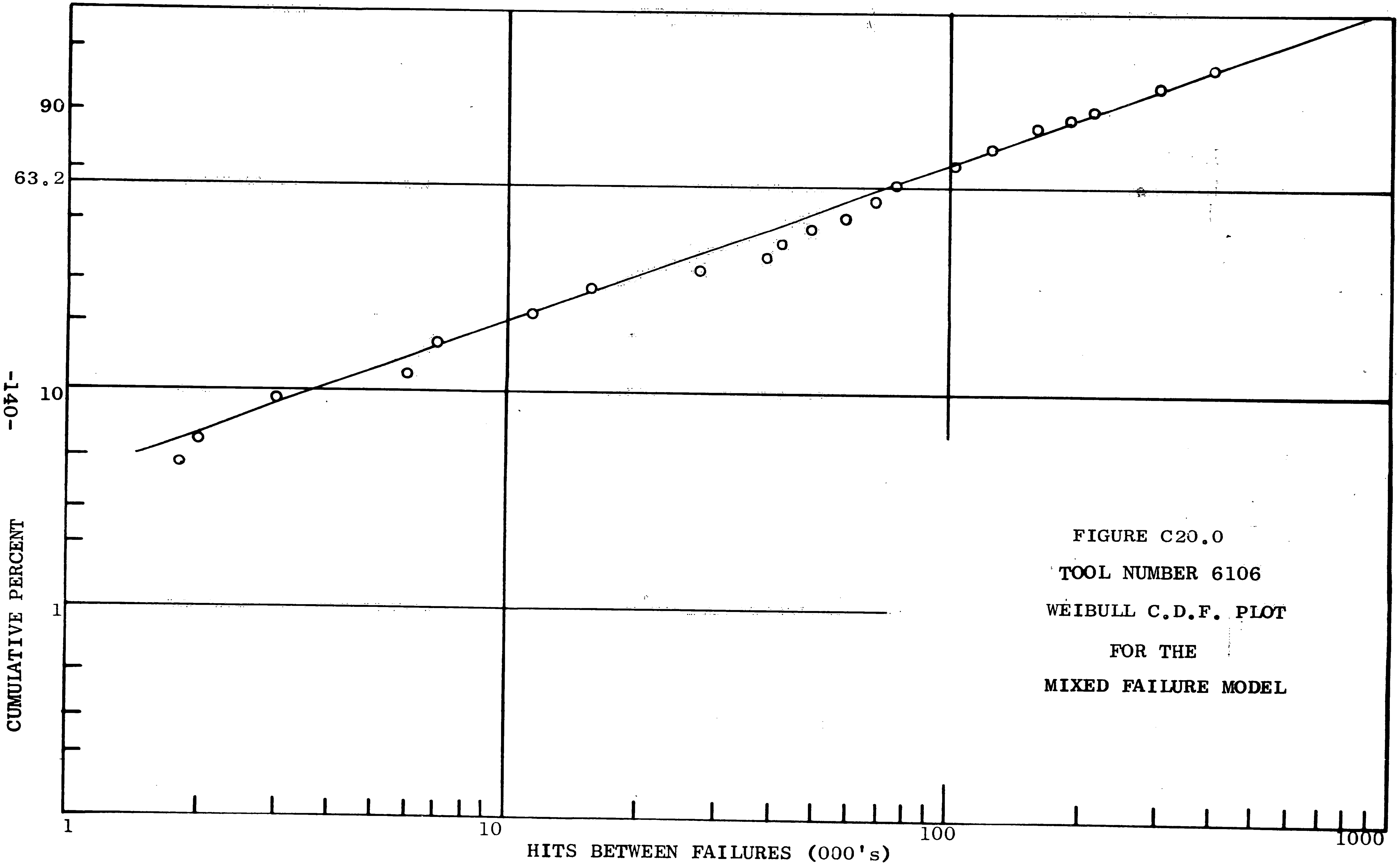


FIGURE C20.0
TOOL NUMBER 6106
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

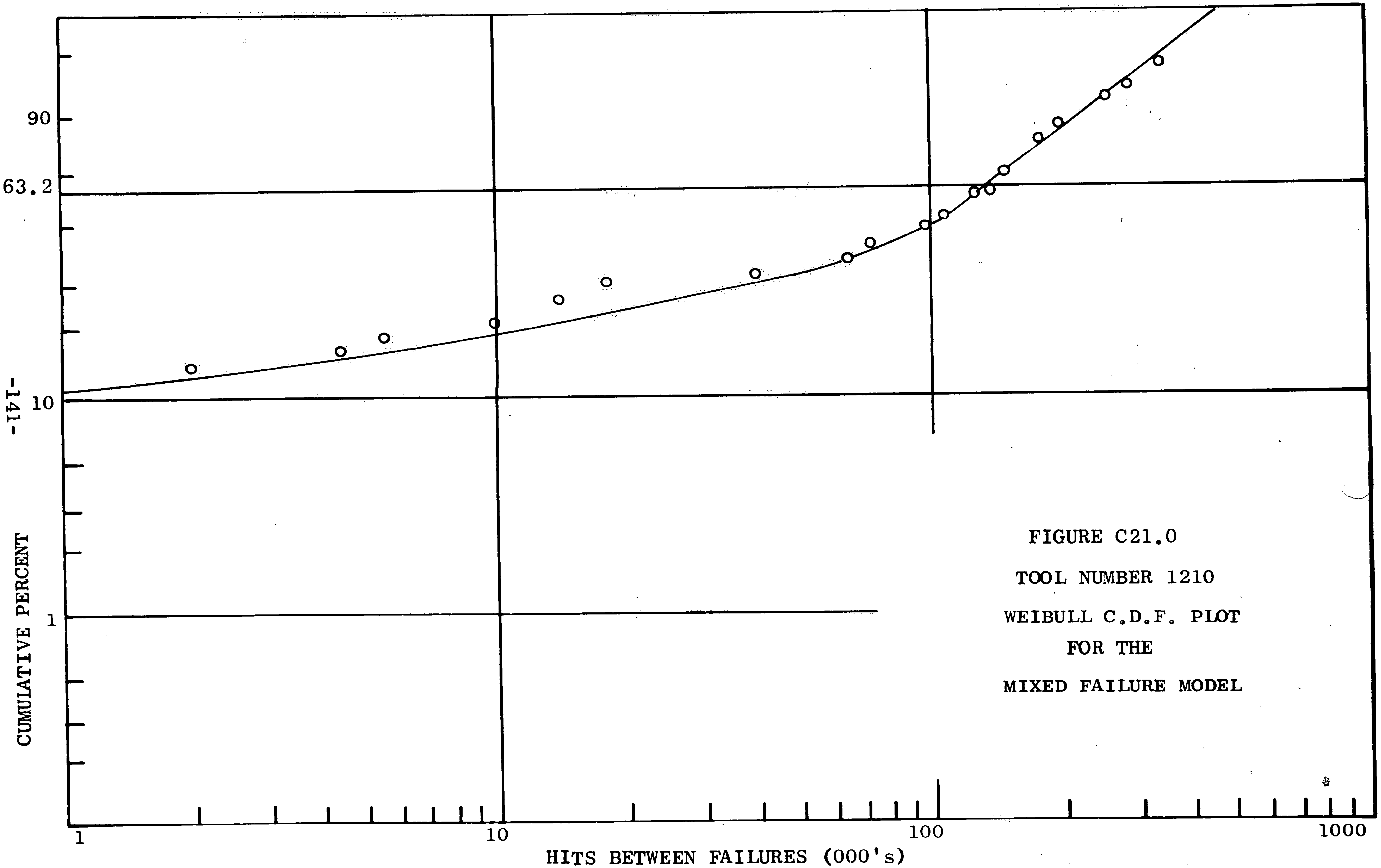


FIGURE C21.0

TOOL NUMBER 1210

WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

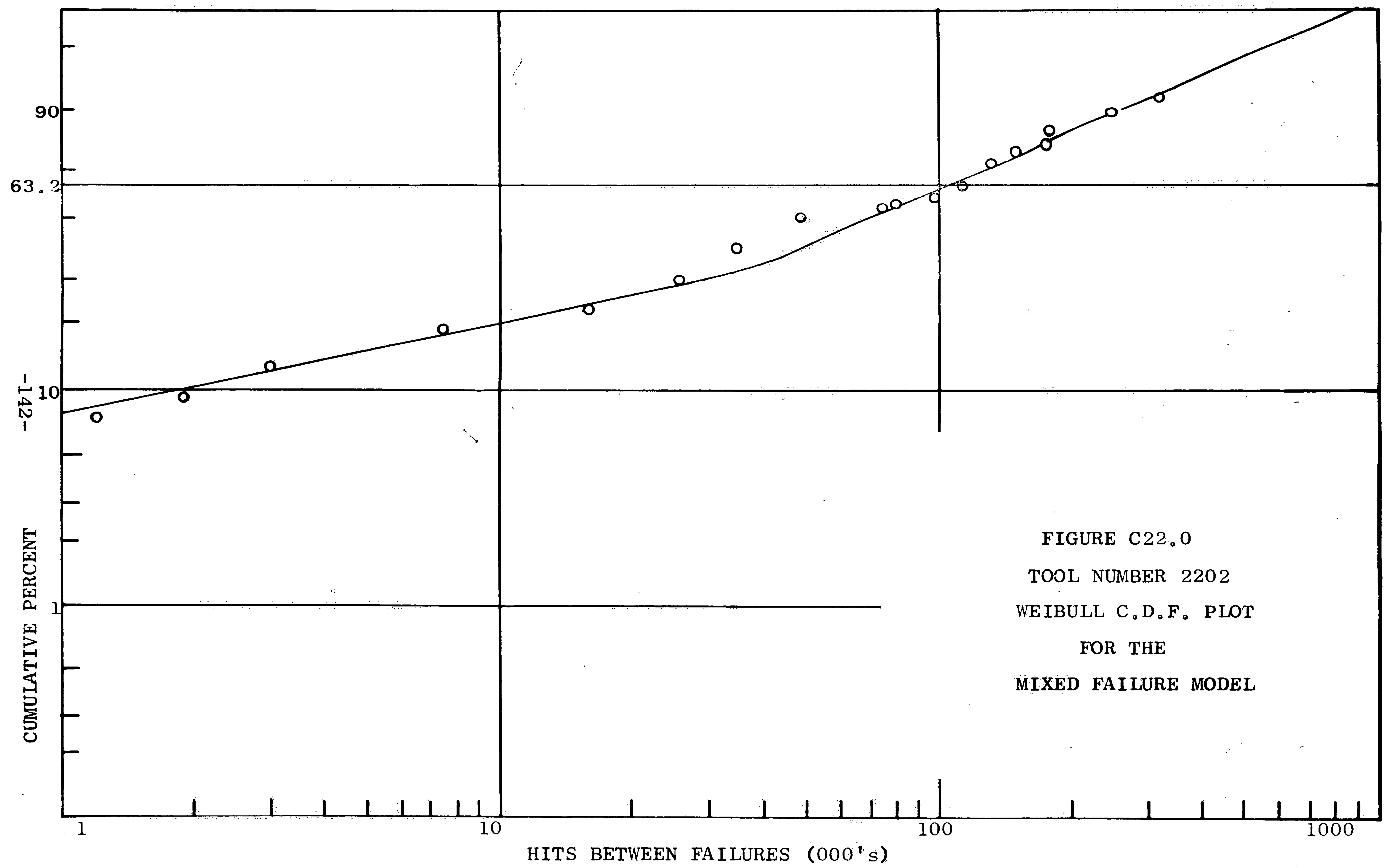


FIGURE C22.0

TOOL NUMBER 2202

WEIBULL C.D.F. PLOT

FOR THE

MIXED FAILURE MODEL

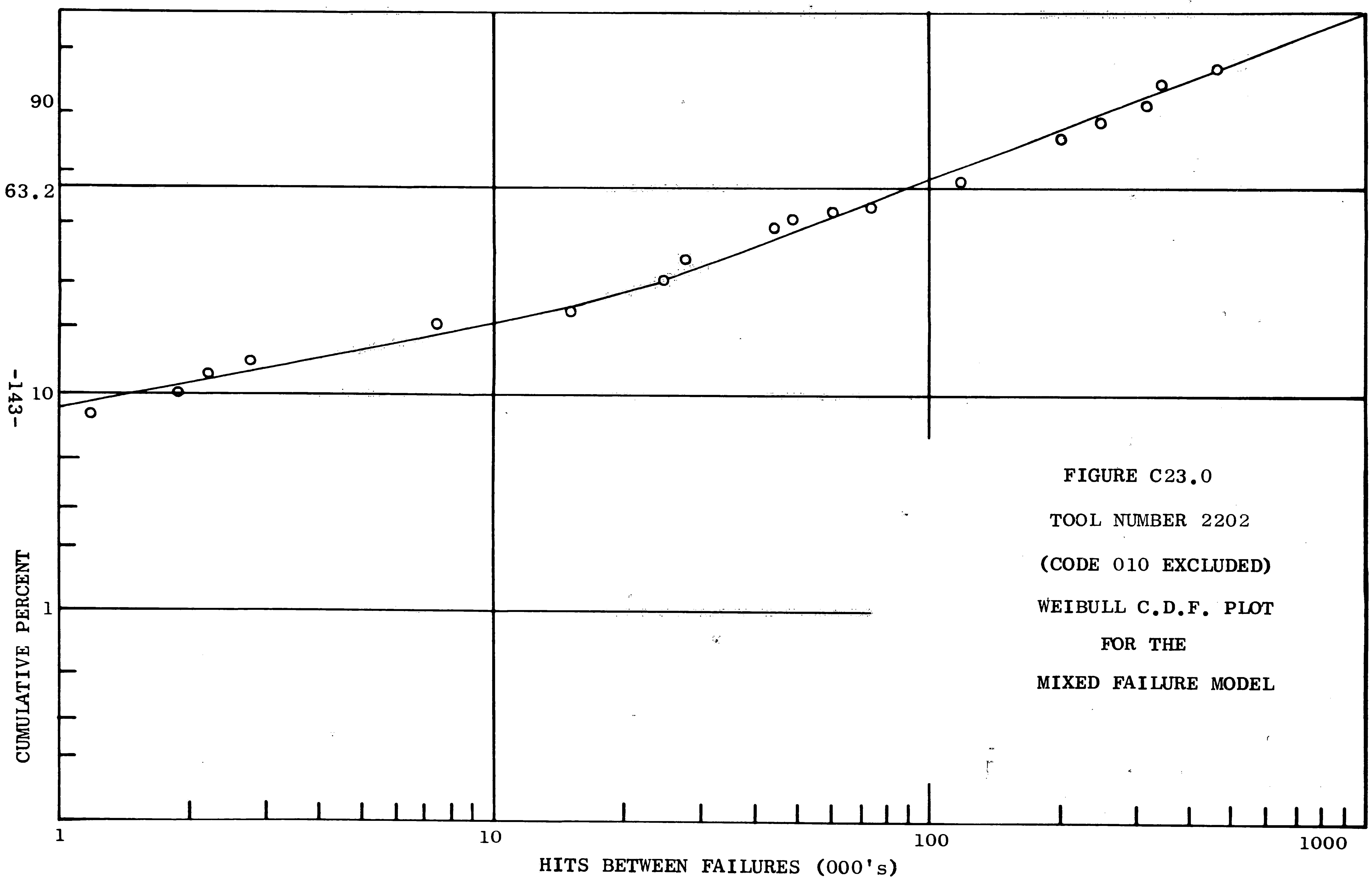


FIGURE C23.0
TOOL NUMBER 2202
(CODE 010 EXCLUDED)
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

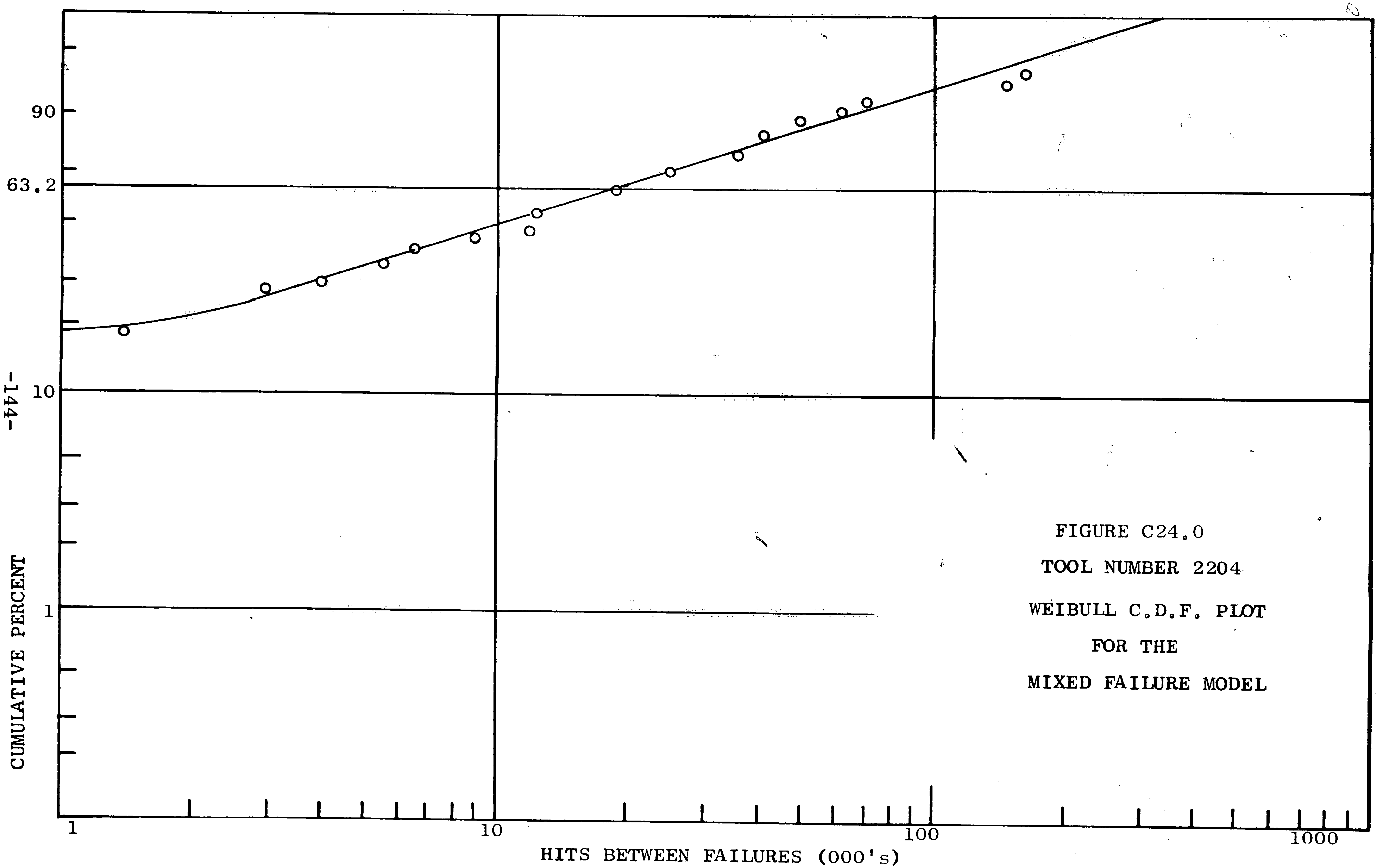


FIGURE C24.0
TOOL NUMBER 2204
WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

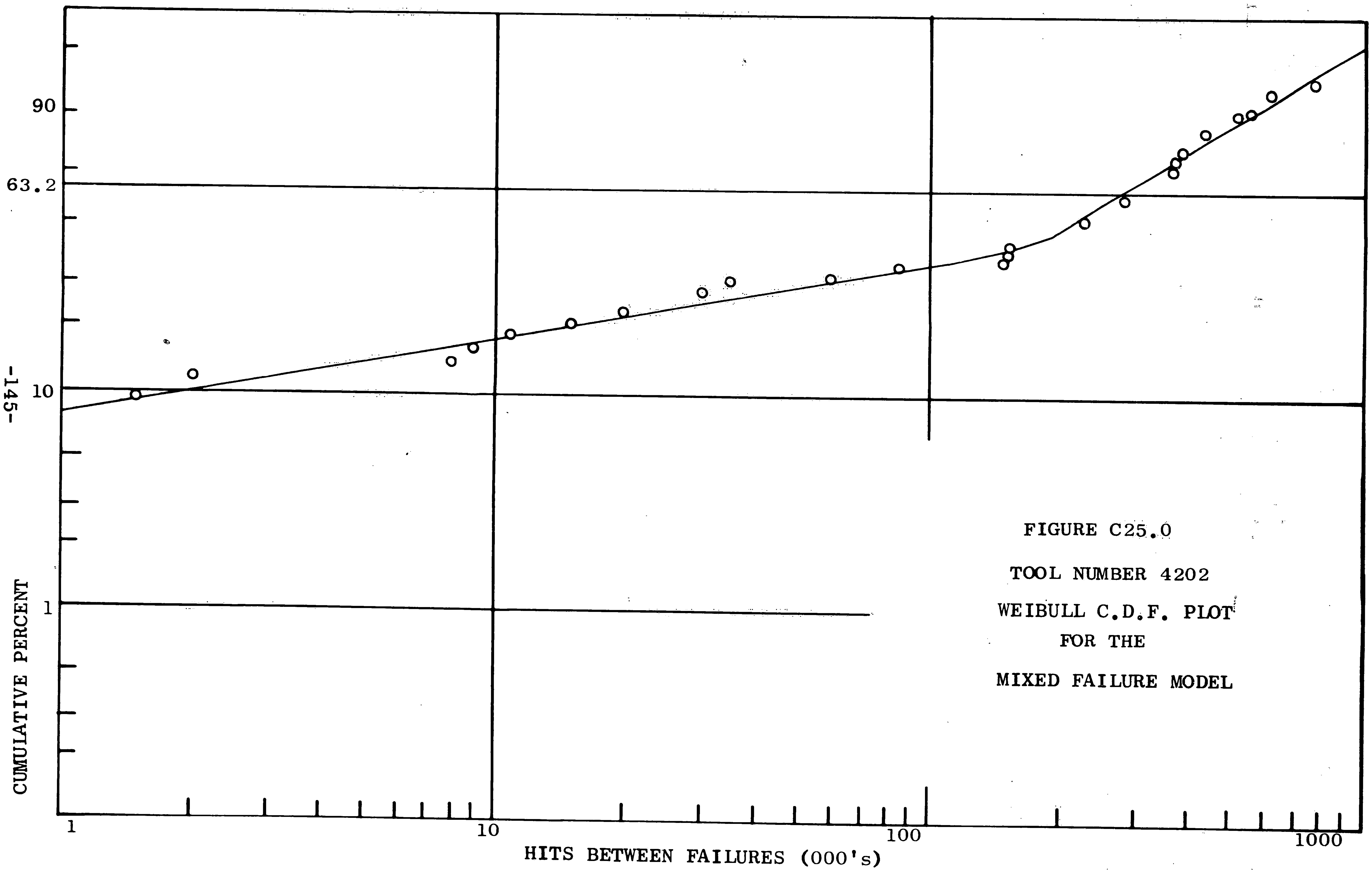


FIGURE C25.0

TOOL NUMBER 4202

WEIBULL C.D.F. PLOT
FOR THE
MIXED FAILURE MODEL

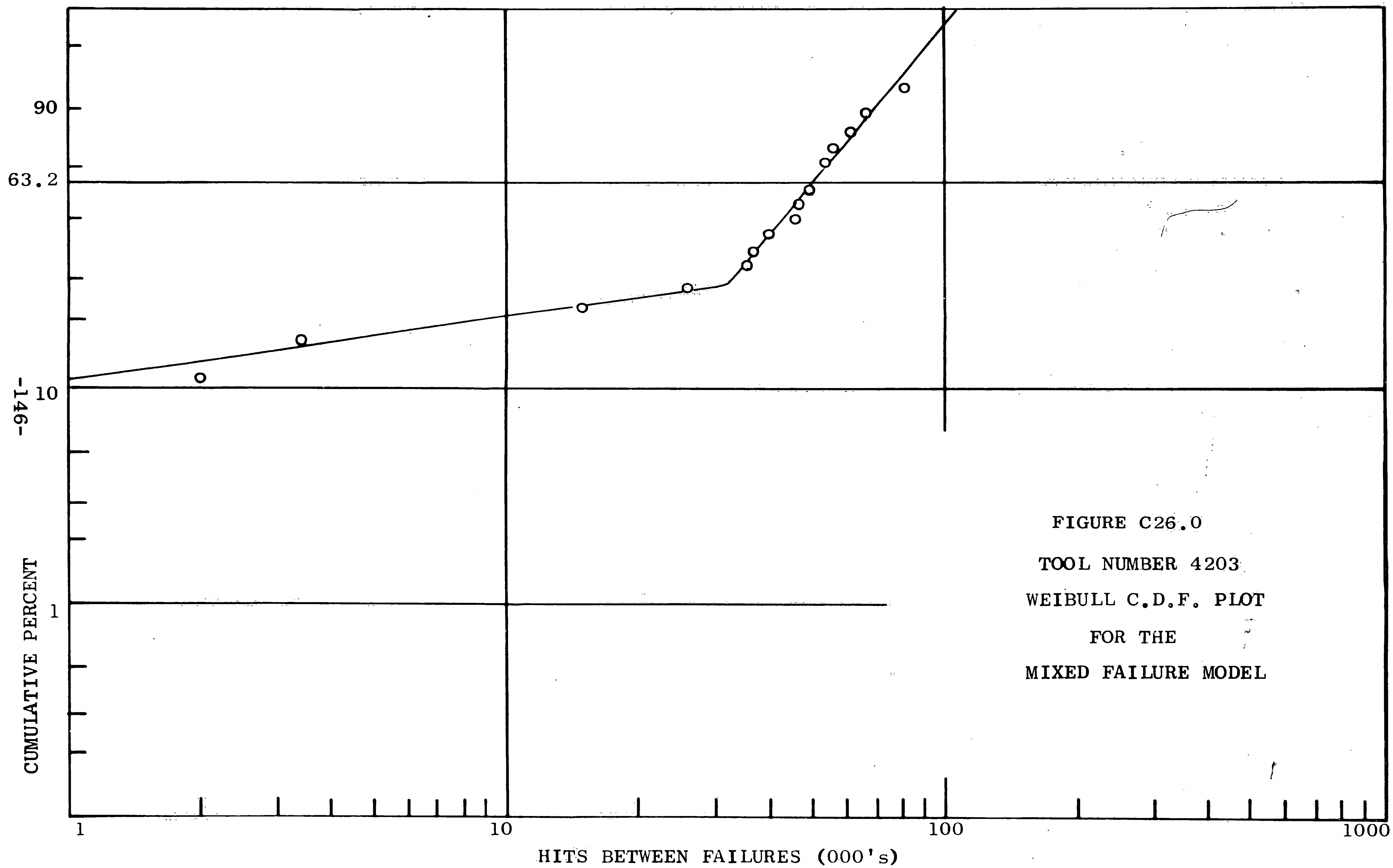


FIGURE C26.0

TOOL NUMBER 4203

WEIBULL C.D.F. PLOT

FOR THE

MIXED FAILURE MODEL

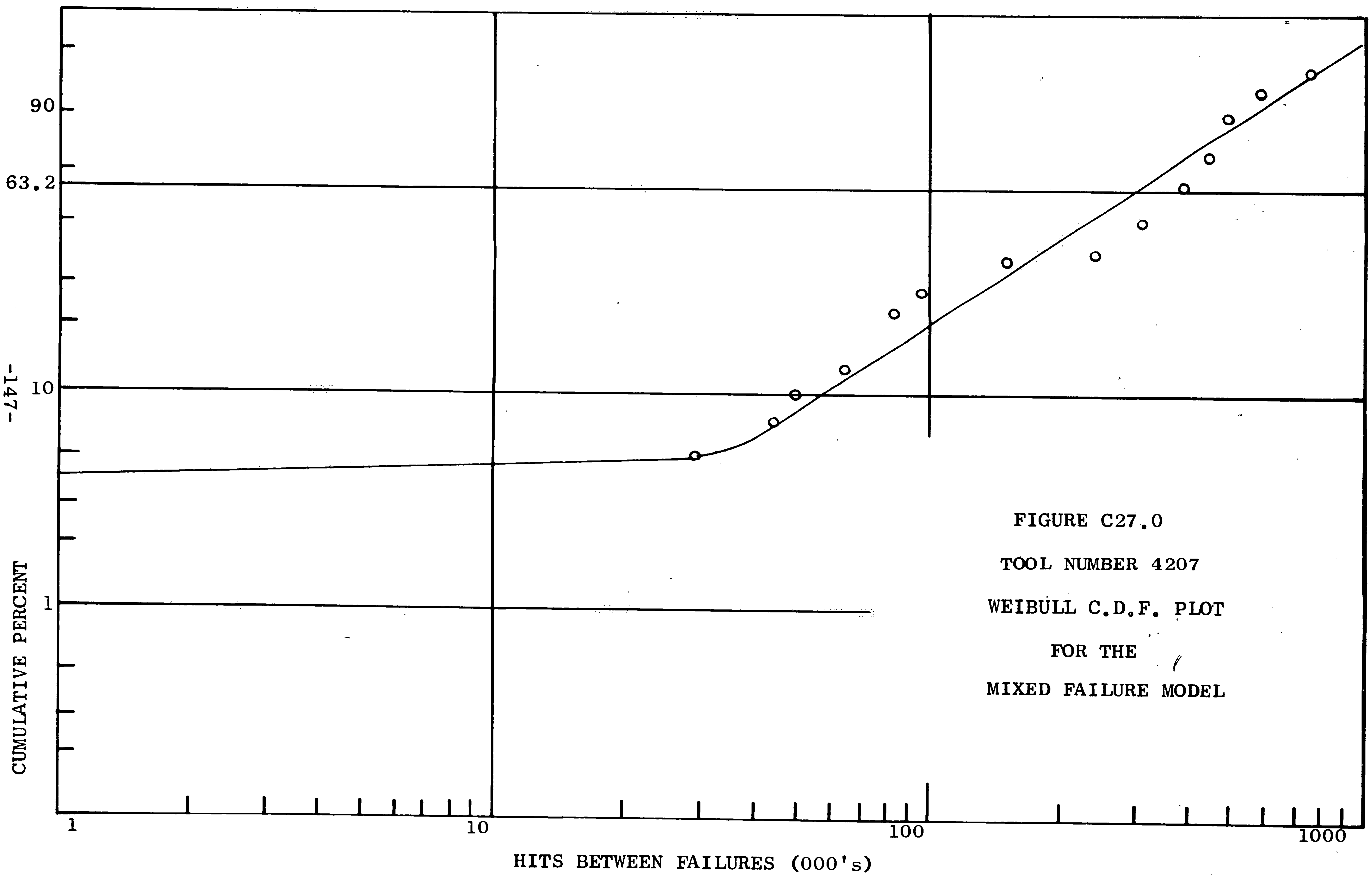


FIGURE C27.0

TOOL NUMBER 4207

WEIBULL C.D.F. PLOT

FOR THE

MIXED FAILURE MODEL

APPENDIX D - PLOTS OF MEDIANS AND MEANS FROM TRUNCATED "NORMAL WEAR" DISTRIBUTIONS

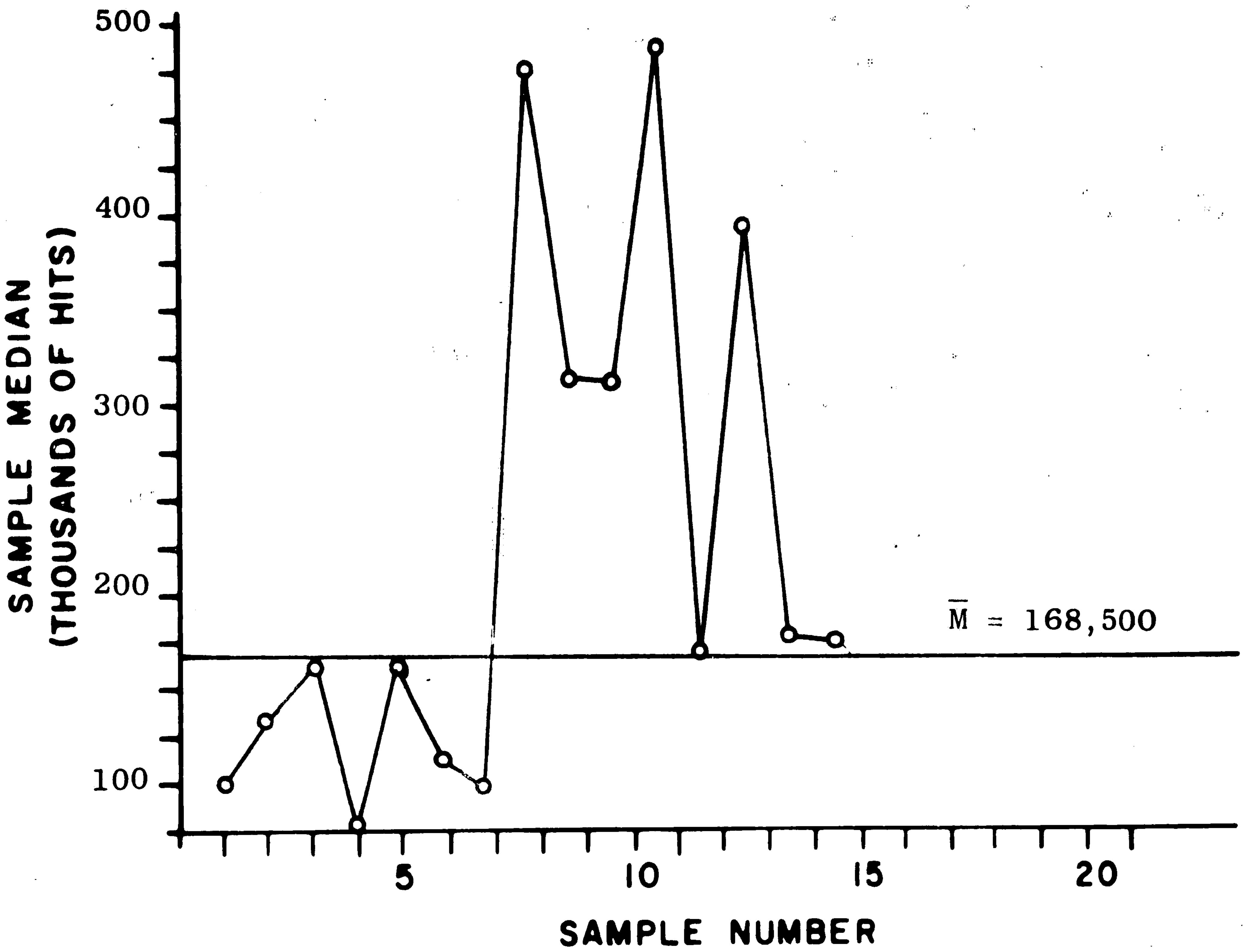
Notes:

1. All figures in this Appendix are plots of medians and means of successive samples of three runs each from "normal wear" distributions which were truncated at a lower bound (as explained in METHOD OF STUDY).

2. The symbol $\overline{M}$ denotes grand median (of sample values from the truncated distribution).

3. The symbol $\bar{\bar{X}}$ denotes grand mean (of sample values from the truncated distributions)

<u>List of Figures</u> (tabulated)



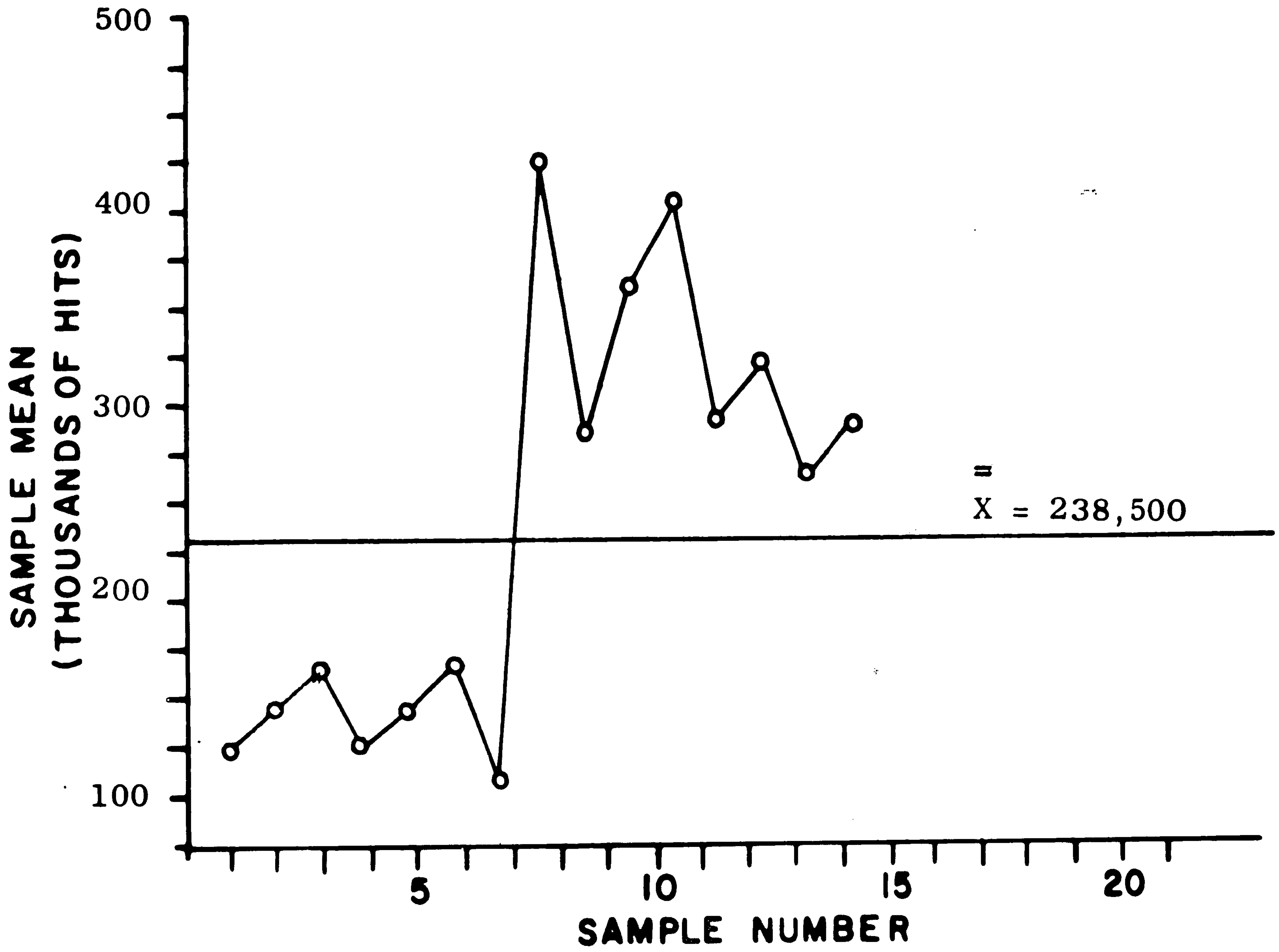
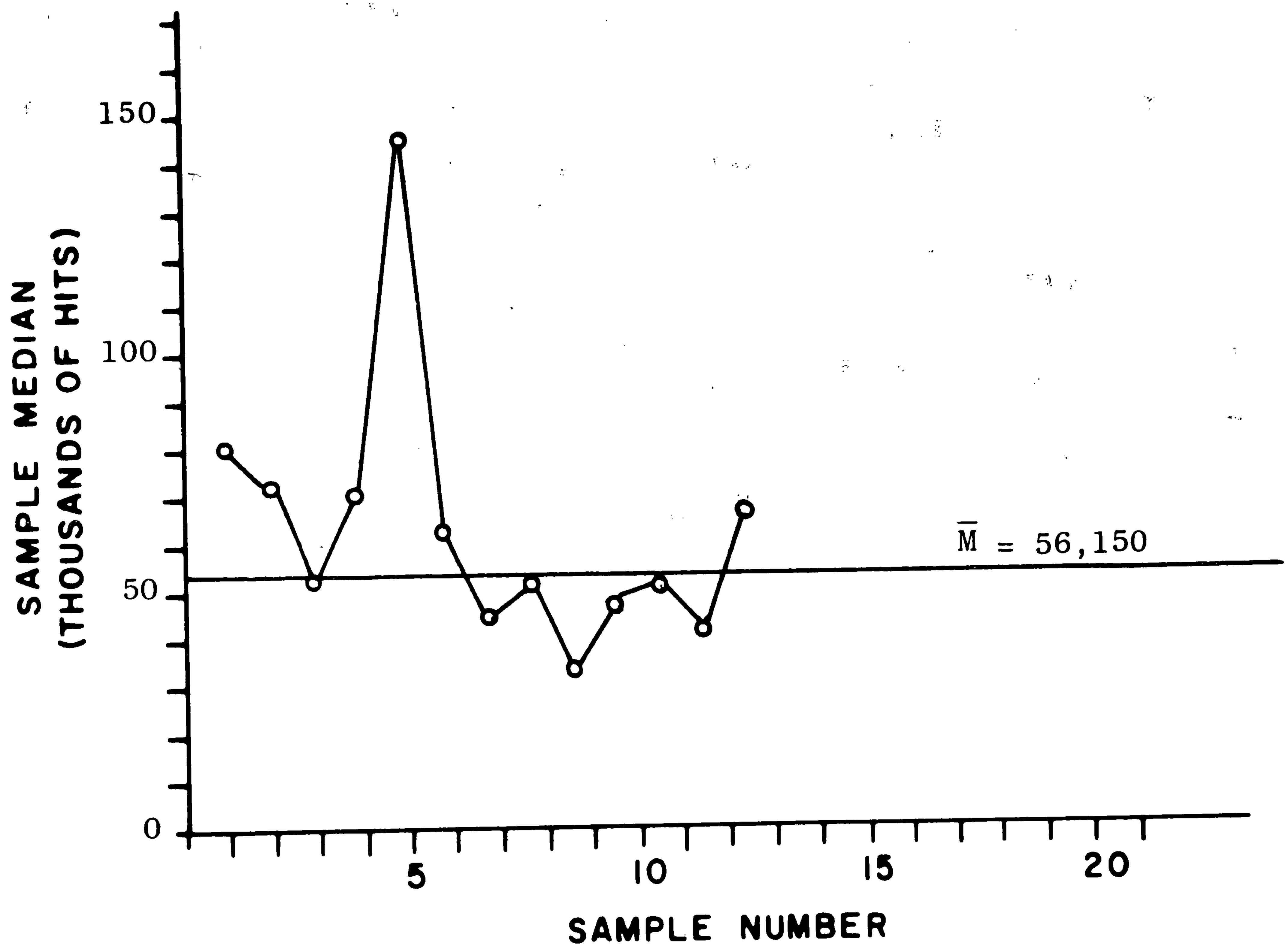


FIGURE: D1 **TOOL NUMBER:** 1109

LOWER BOUND: 42,000



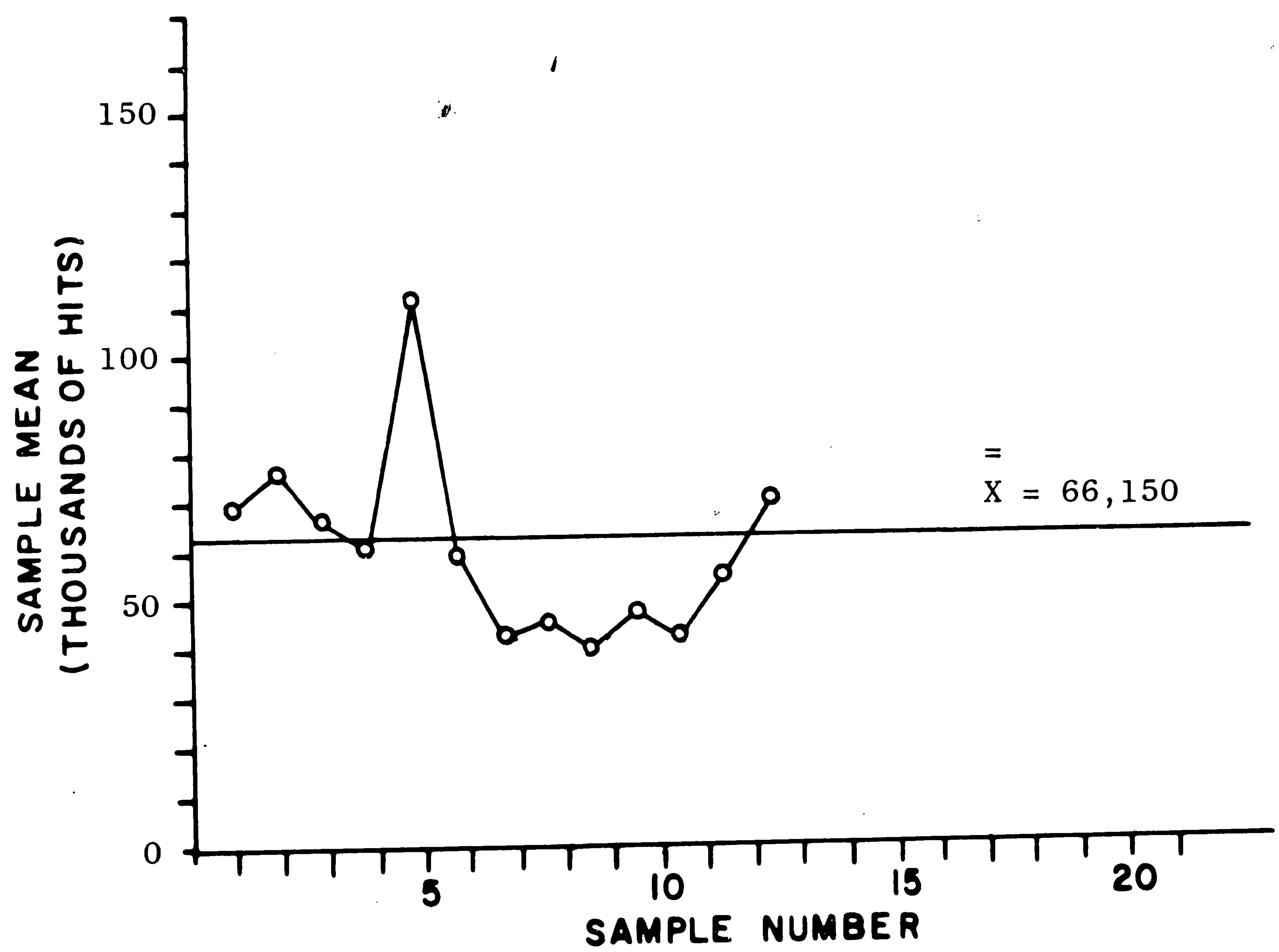
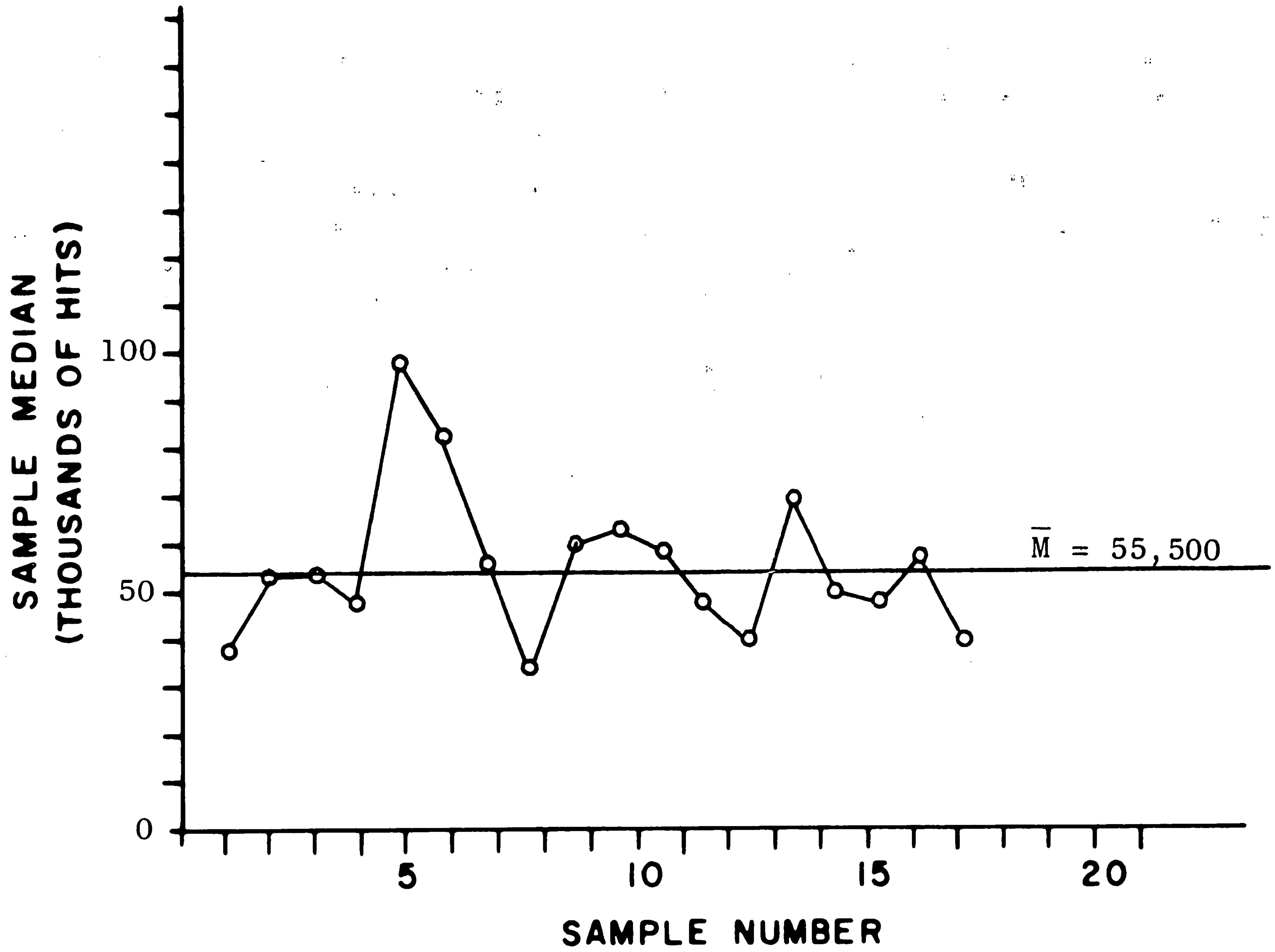


FIGURE: D2 **TOOL NUMBER** : 1501

LOWER BOUND : 26,000



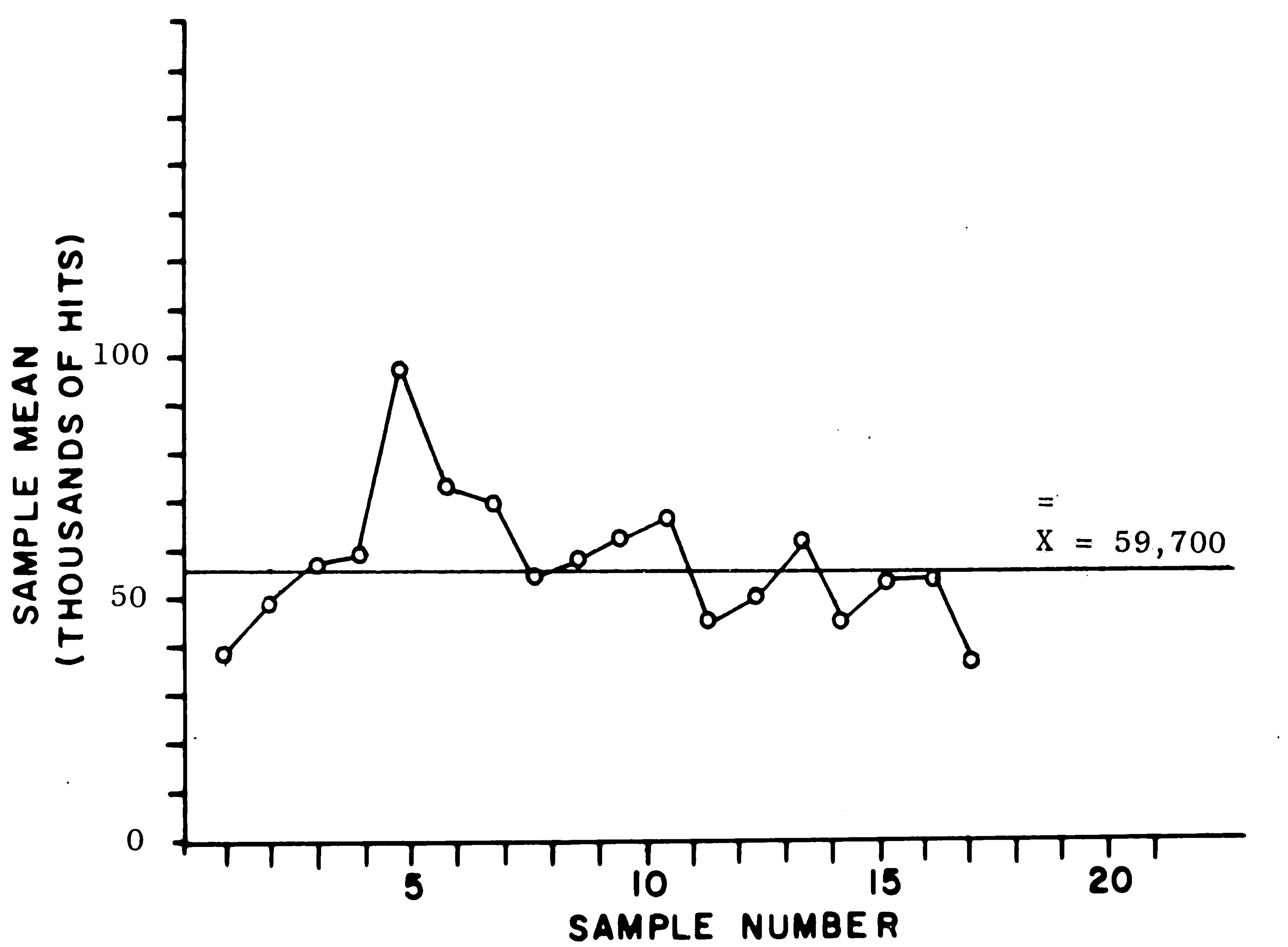


FIGURE: D3 **TOOL NUMBER**: 1403

LOWER BOUND: 26,000

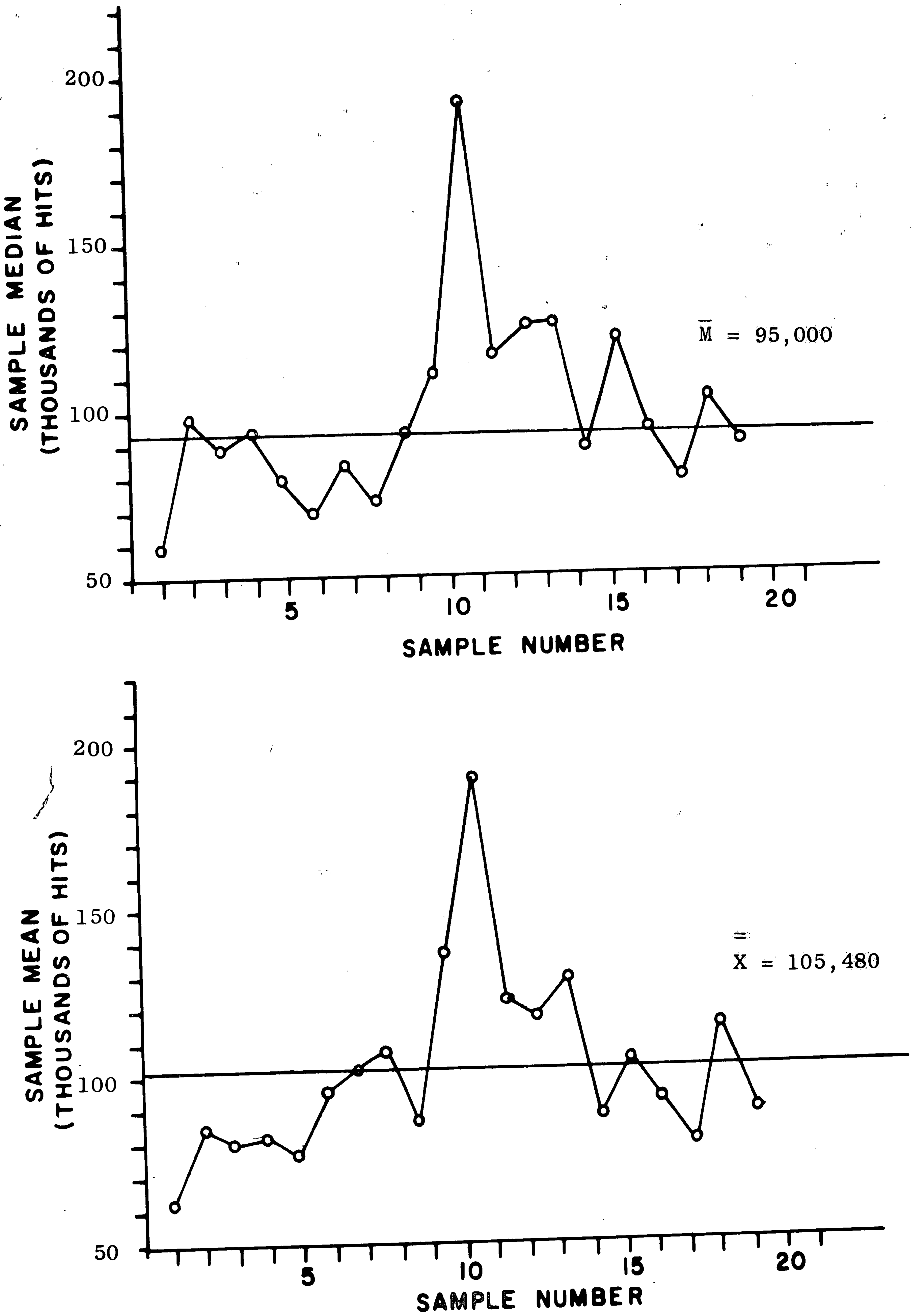
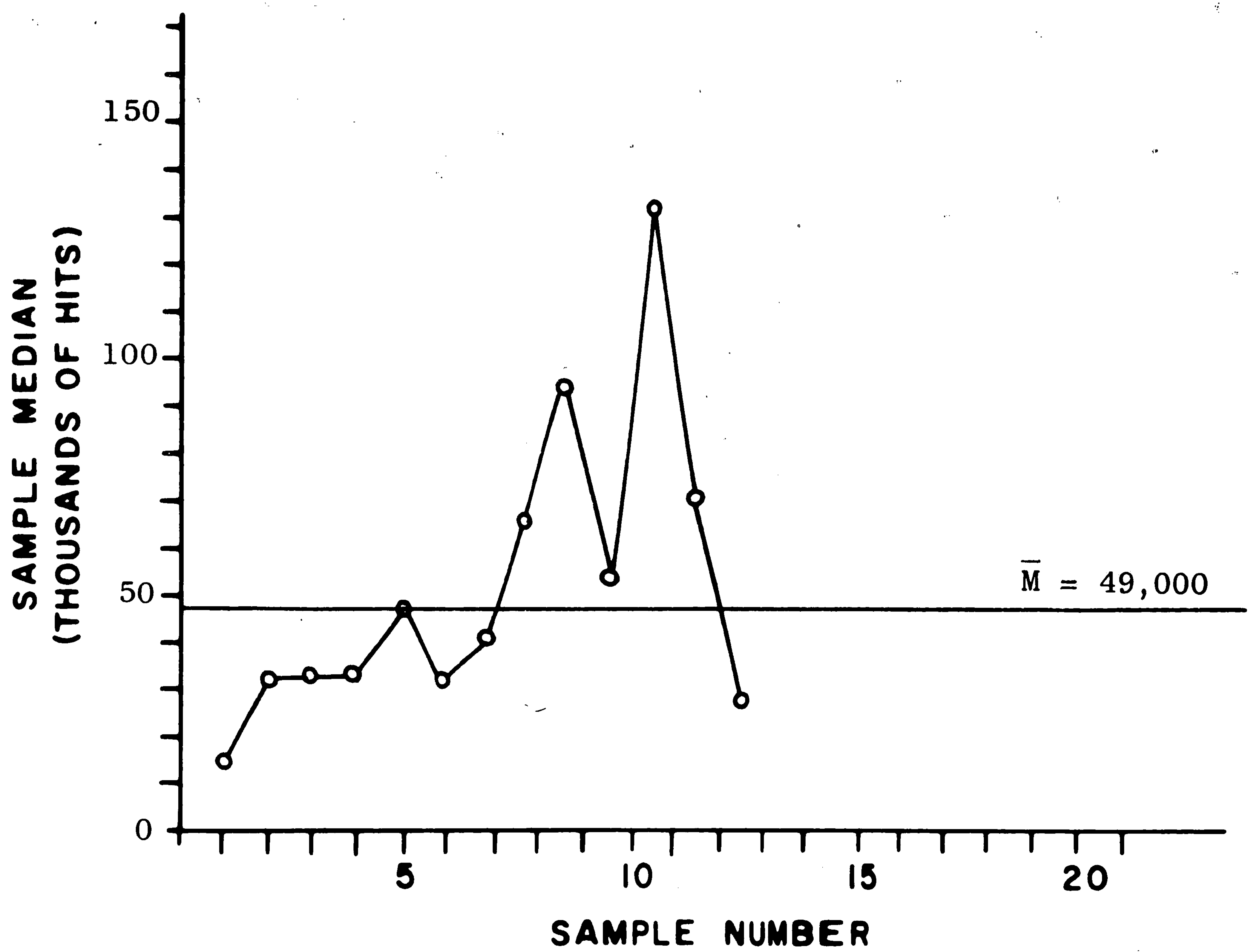


FIGURE: D4 TOOL NUMBER : 1504

LOWER BOUND : 53,600



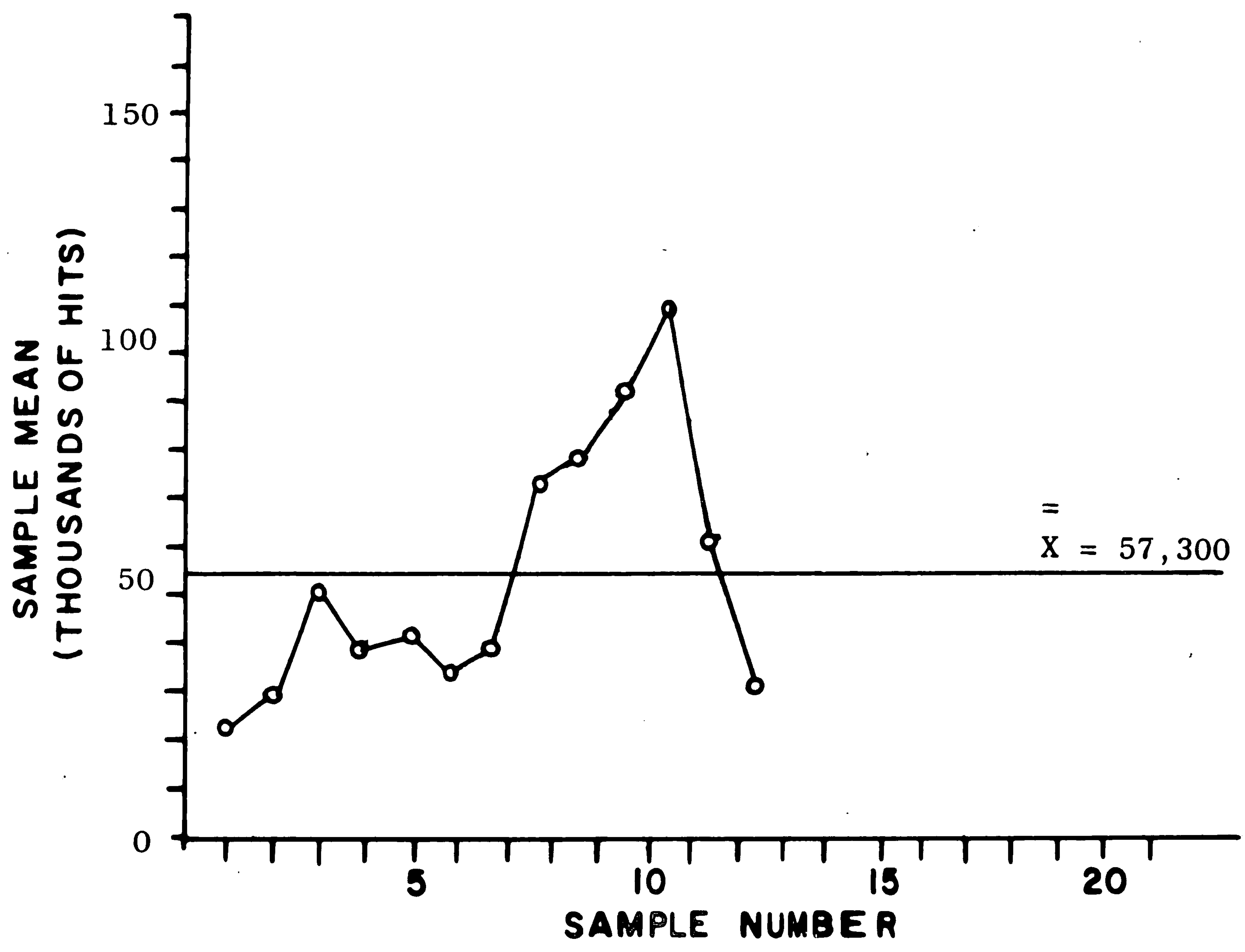
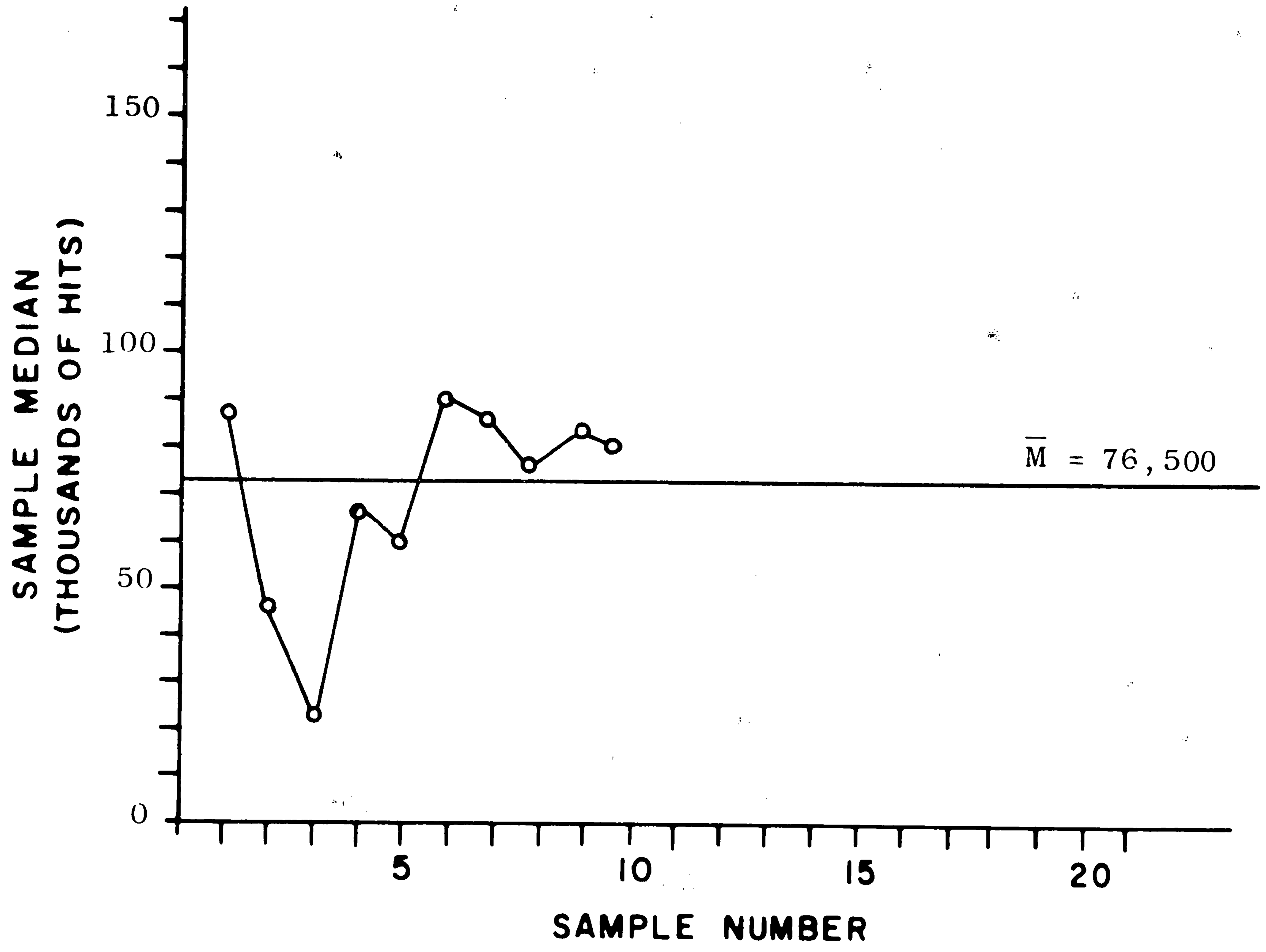


FIGURE: D5 **TOOL NUMBER**: 1508

LOWER BOUND: 16,500



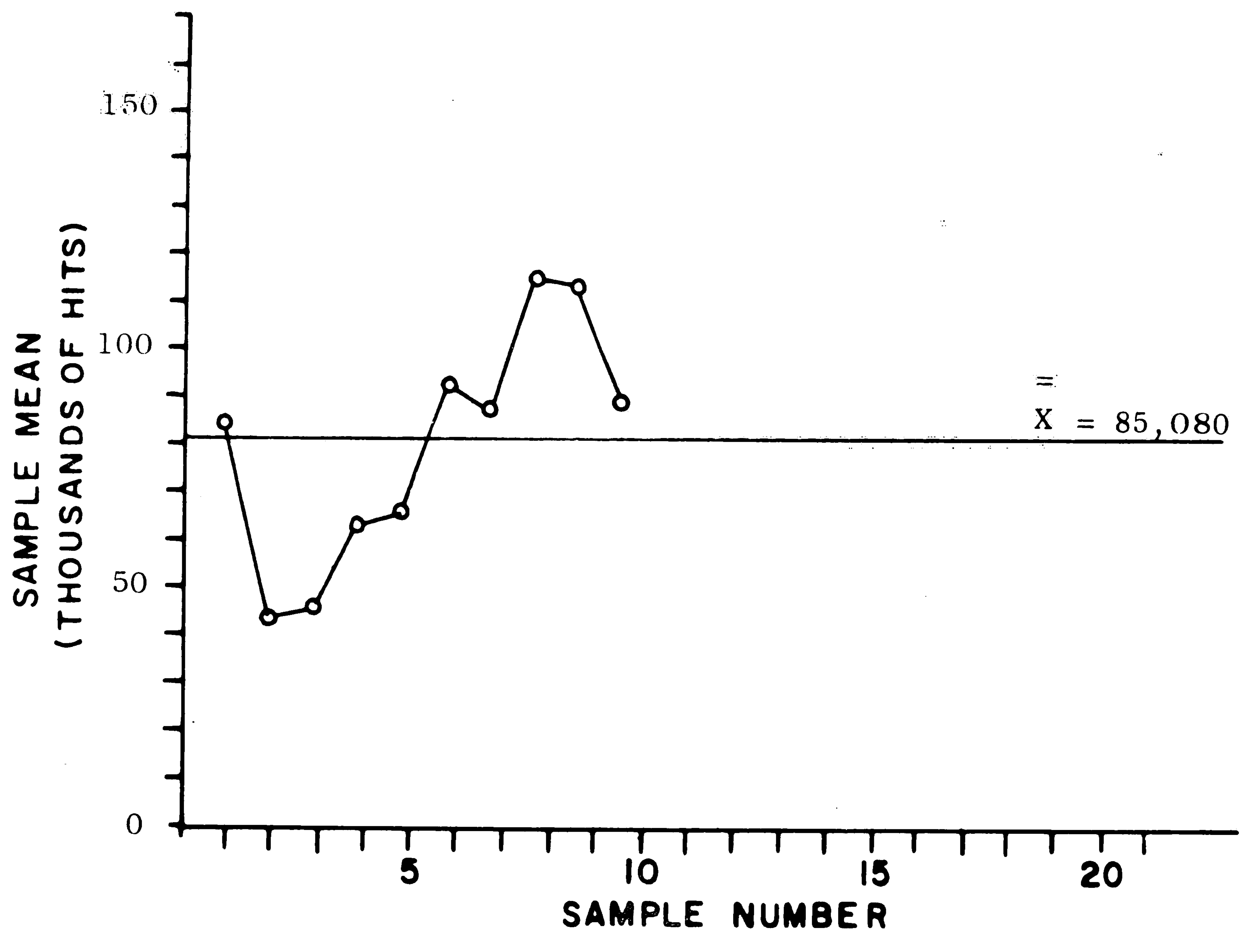
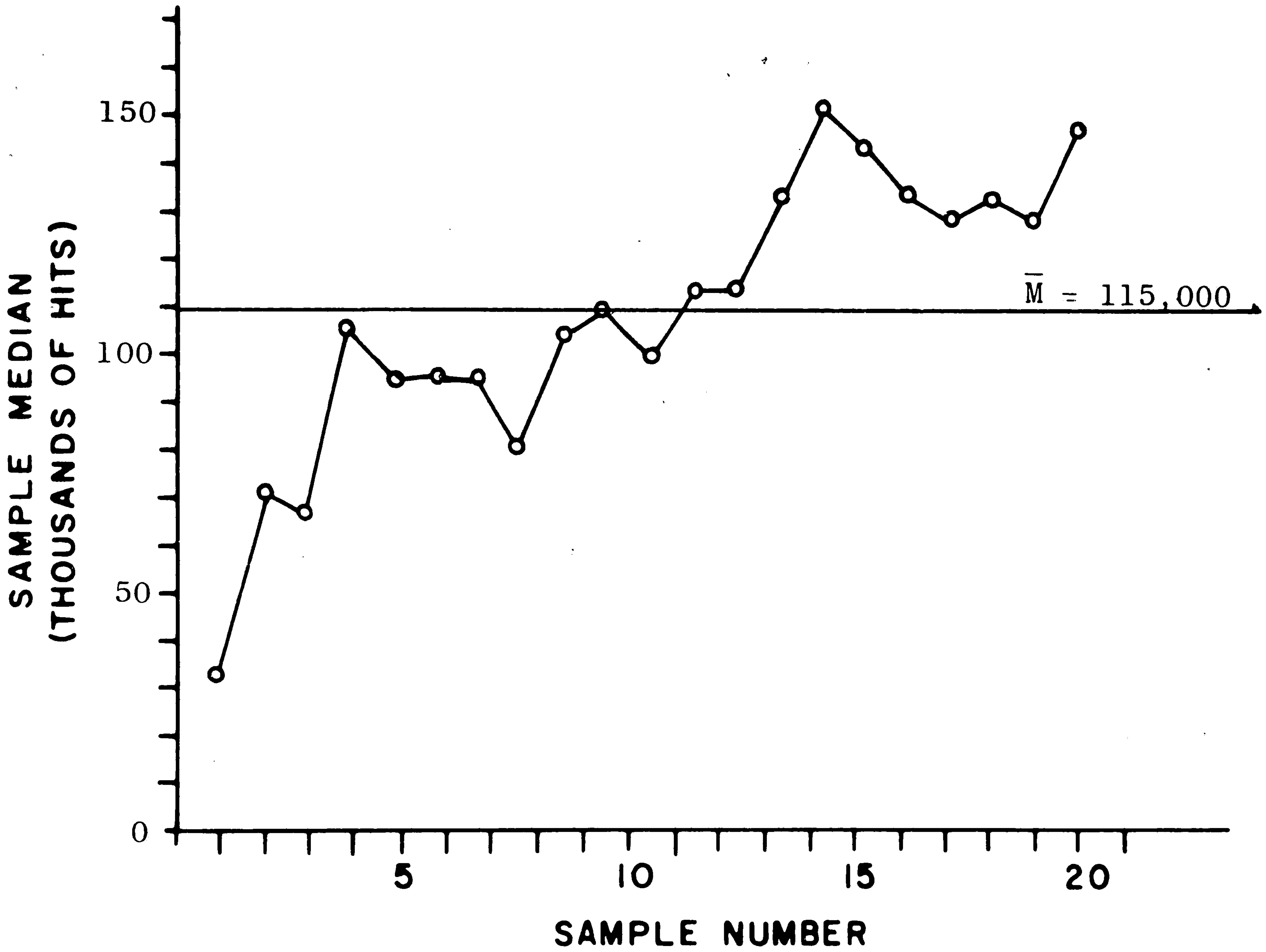


FIGURE: D6 **TOOL NUMBER:** 4508

LOWER BOUND: 20,000



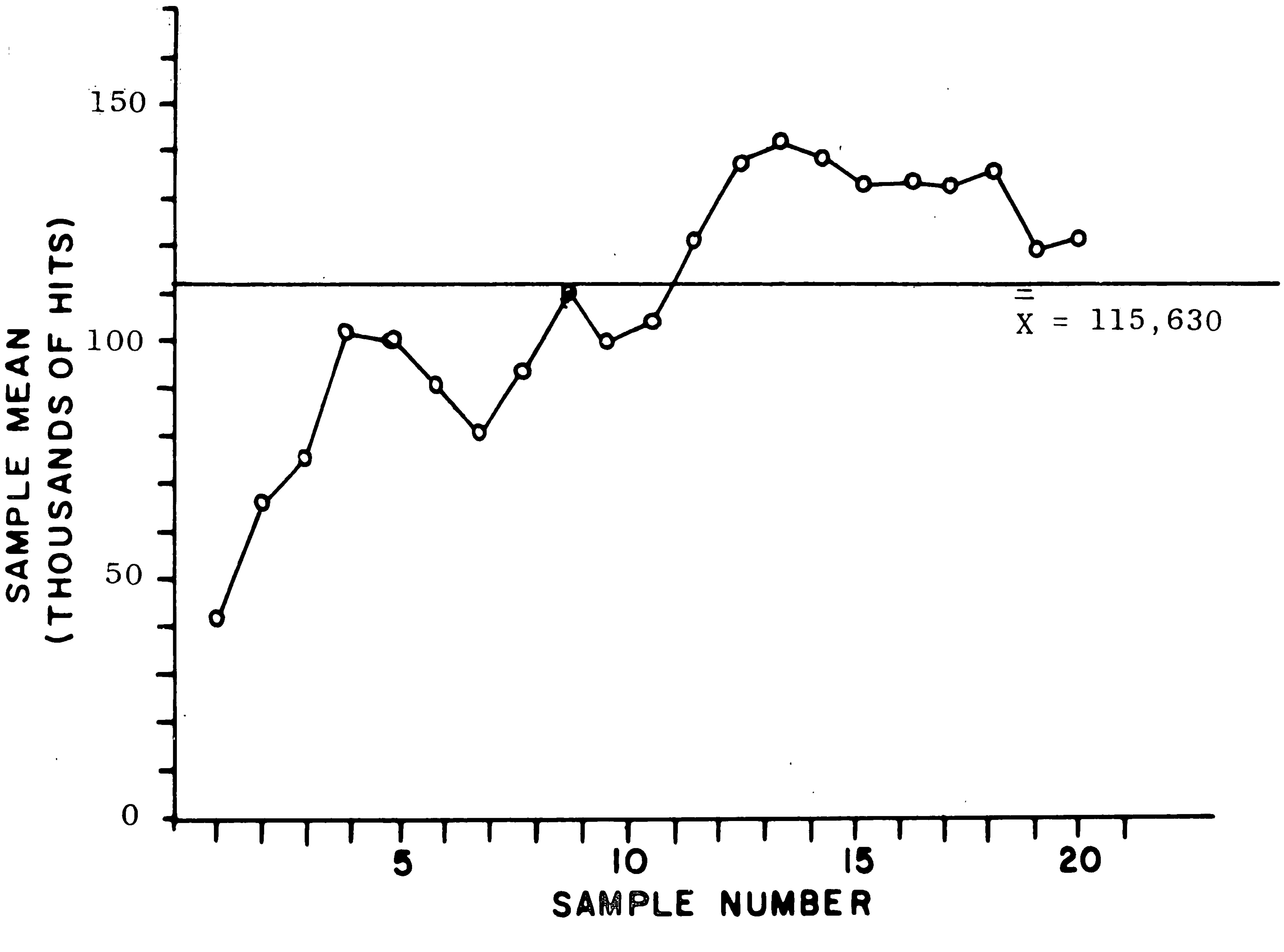
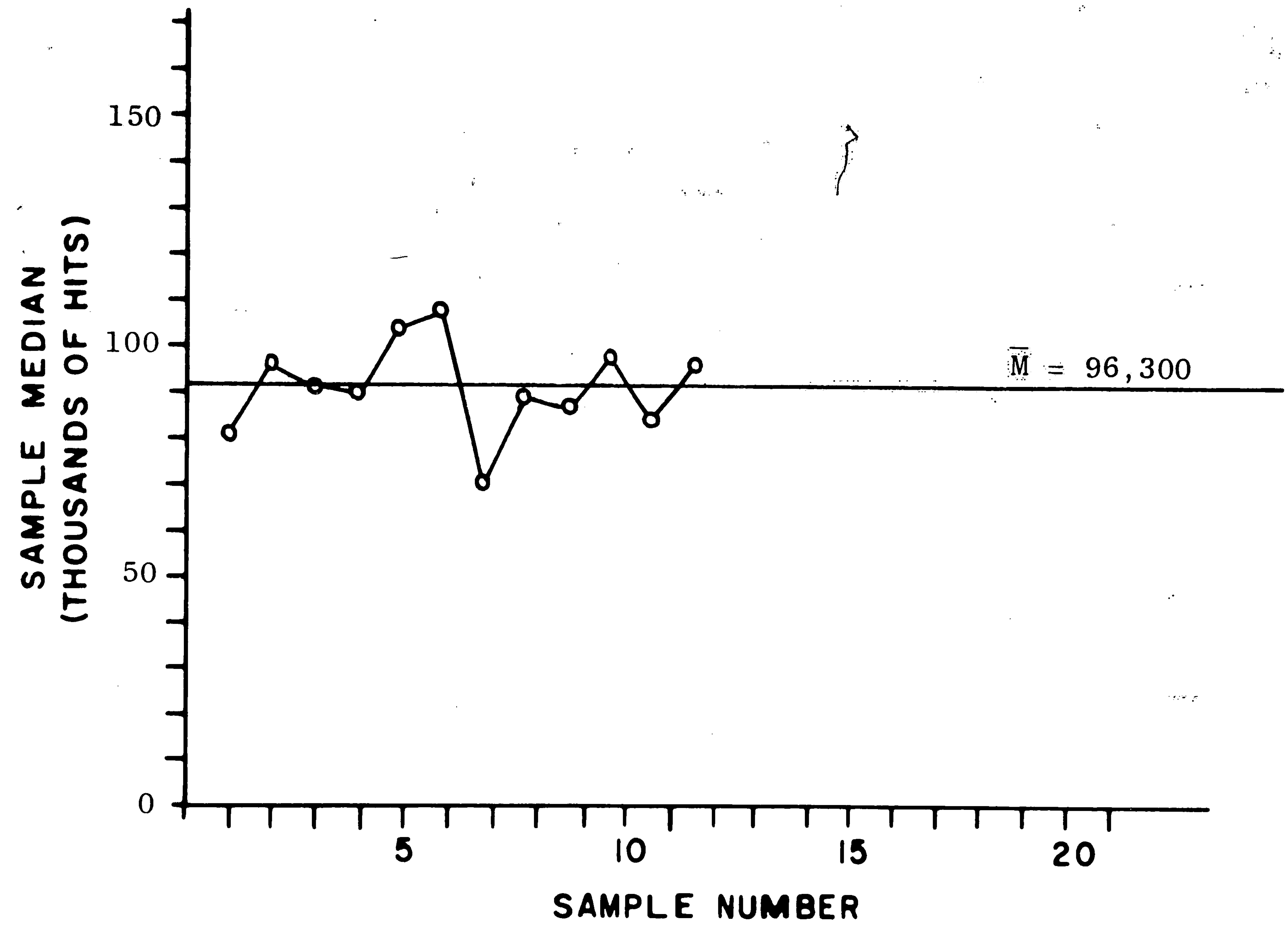


FIGURE: D7 **TOOL NUMBER:** 4509

LOWER BOUND: 1,000



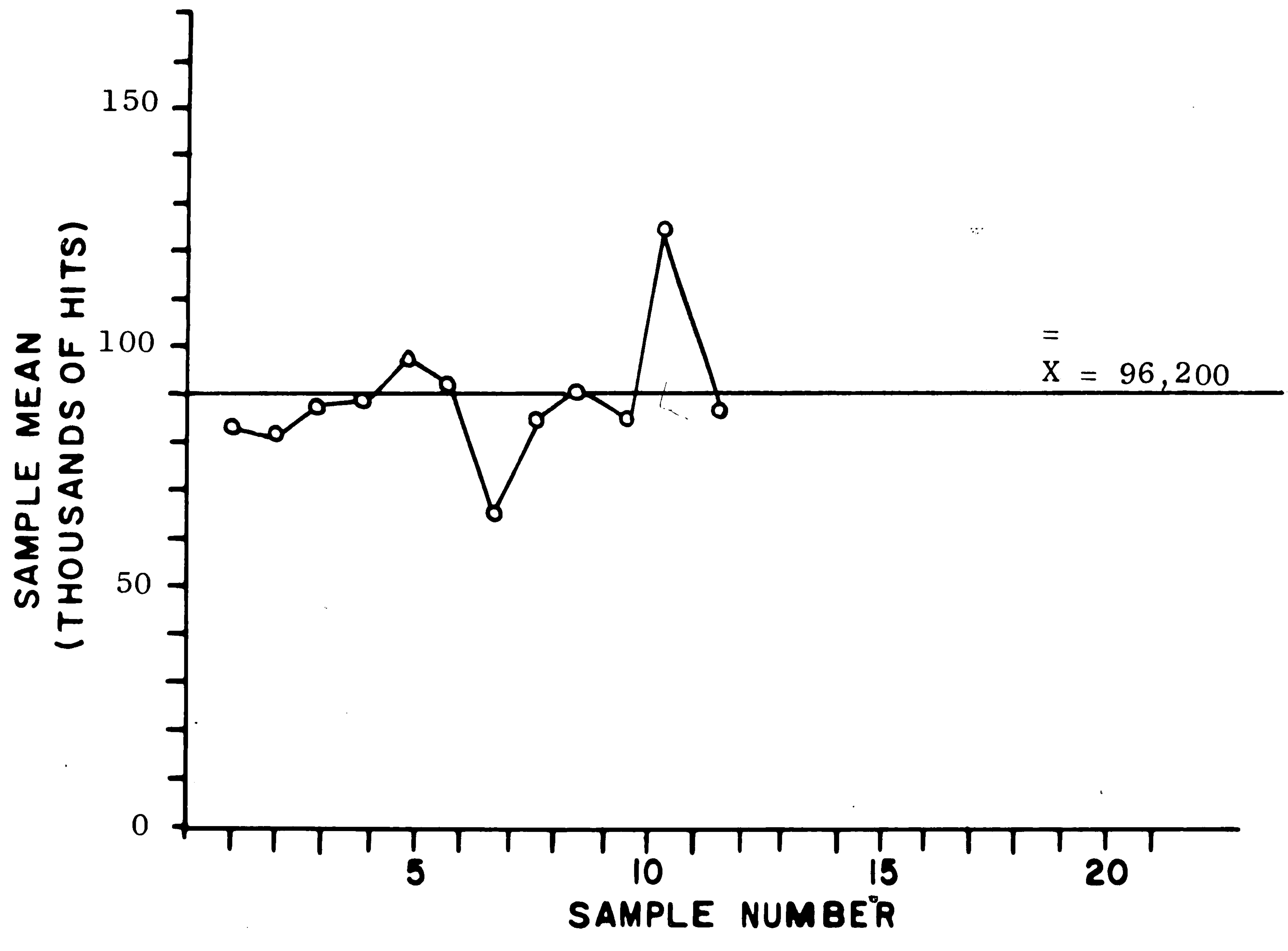


FIGURE: D8 **TOOL NUMBER:** 6501

LOWER BOUND: 50,000

APPENDIX E - KOLMOGOROV - SMIRNOV TESTS

Note: All tables in this Appendix are titled:

Kolmogorov-Smirnov Goodness of Fit Test for Poisson Distribution of the Occurrence of "Early Failure" Runs.

List of Figures (tabulated)

Kolmogorov-Smirnov Tests

The Kolmogorov - Smirnov one sample goodness of fit test [3, pp. 47-52] is based on the maximum absolute deviation of a sample cumulative frequency distribution from an hypothesized theoretical cumulative frequency distribution. The null hypothesis is that the sample was drawn from the theoretical distribution, and the test statistic is the maximum absolute deviation D which is defined as:

$$D = \text{maximum } |F_O(X) - S_N(X)|$$

where $F_O(X)$ = value of theoretical c.d.f.

$S_N(X)$ = corresponding value of the sample c.d.f. of D.

Critical values of D at significance levels of .20, .15, .10, .05, and .01 are tabulated in Table E, p. 251 of [3].

The particular test conducted in this study hypothesized the Poisson frequency distribution which is given by:

$$f(x) = \frac{x^m e^{-m}}{x!}$$

Values of m for the test were estimated from the sample by dividing the number of "early failure" runs by the number of blocks of ten runs. Fractional blocks were handled as described previously in "Method of Study". Only those "early failure" runs which fell within whole blocks were used to estimate m.

The null hypothesis Ho for the test is:

Ho: The distribution of the random variable X = number of "early failure" runs per block of ten runs is Poisson with parameter $\hat{m}$.

The critical region was set at $D \geq \alpha_{.20}$ where $\alpha_{.20}$ is the value of D at a significance level of .20; i.e., there is probability of .20 of getting a value of D equal to or greater than $\alpha_{.20}$. The .20 significance level is the highest tabulated level, and lends most credence toward accepting the null hypothesis. Lower levels such as .01 would be of greater importance in rejecting the null hypothesis, but the intent of this study is to not reject (or accept) the null hypothesis; thus the high significance level.

The following notation is used in the tabulations of results and tests:

N = number of "early failure" runs

X = number of "early" failures per block of 10 runs

c.d.f. = cumulative distribution function

$\alpha_{.20}$ = critical value of D at .20 significance level

$\hat{m}$ = estimated value of Poisson parameter

Theoretical values for the Poisson cumulative distribution function were calculated from Table VIII pp. 263--266 of [33].

Table: E1 Tool Number: 1109

Kolmogorov-Smirnov Goodness of Fit Test For Poisson

Distribution of the Occurrence of "Early Failure" Runs

$\hat{m} = 1.4$

N = 10

	Actual			Theoretical	Deviation
X	Freq.	Cum. Freq.	c.d.f.	c.d.f.	
0	2	2	.143	.247	.104
1	2	4	.572	.592	.020
2	2	6	.857	.834	.023
3	0	6	.857	.946	.089
4	1	7	1.000	.986	.014

D = .104

$\alpha_{.20} = .322$

∴ The hypothesis cannot be rejected.

Table: E2 Tool Number: 1403

Kolmogorov-Smirnov Goodness of Fit Test For Poisson Distribution of the Occurrence of "Early Failure" Runs

$\hat{m} = 2.6$

$N = 21$

	Actual			Theoretical	Deviation
X	Freq.	Cum. Freq.	c.d.f.	c.d.f.	
0	3	3	.375	.074	.301
1	0	3	.375	.267	.108
2	0	3	.375	.518	.143
3	2	5	.625	.736	.111
4	2	7	.875	.877	.002
5	0	7	.875	.951	.076
6	0	7	.875	.983	.108
7	1	8	1.000	.995	.005

$D = .301$

$\alpha_{.20} = .231$

∴ The hypothesis can be rejected at a .20 level of significance.[1]

1. Note, however, that $\alpha_{.01} = .356$. The hypothesis could not be rejected at a .01 level of significance.

Table: E3 Tool Number: 1501

Kolomogorov-Smirnov Goodness of Fit Test For Poisson

Distribution of the Occurrence of "Early Failure" Runs

$\hat{m} = 3.7$

N = 26

Actual				Theoretical	Deviation
X	Freq.	Cum. Freq.	c.d.f.	c.d.f.	
0	0	0	0	.026	.026
1	1	1	.143	.116	.027
2	2	3	.429	.285	.171
3	0	3	.429	.494	.065
4	2	5	.714	.687	.027
5	0	5	.714	.830	.116
6	1	6	.857	.918	.061
7	1	7	1.000	.964	.036

D = .171

$\alpha_{.20} = .210$

∴ The hypothesis cannot be rejected

Table: E4 Tool Number: 1504

Kolmogorov-Smirnov Goodness of Fit Test For Poisson

Distribution of the Occurrence of "Early Failure" Runs

$\hat{m} = 4.0$

N = 40

	Actual			Theoretical	Deviation
X	Freq.	Cum. Freq.	c.d.f.	c.d.f.	
0	0	0	0	.018	.018
1	0	0	0	.092	.092
2	2	2	.200	.238	.038
3	4	6	.600	.434	.166
4	1	7	.700	.629	.071
5	1	8	.800	.785	.015
6	1	9	.900	.889	.011
7	0	9	.900	.949	.049
8	0	9	.900	.979	.079
9	1	10	.900	.992	.008

D = .166

$\alpha_{.20} = .169$

∴ The hypothesis cannot be rejected

Table: E5 Tool Number: 1508

Kolmogorov-Smirnov Goodness of Fit Test For Poisson Distribution of the Occurrence of "Early Failure" Runs

$\hat{m} = 1.7$

N = 11

Actual				Theoretical	Deviation
X	Freq.	Cum. Freq.	c.d.f.	c.d.f.	
0	2	2	.333	.183	.150
1	1	3	.500	.493	.007
2	1	4	.667	.757	.110
3	1	5	.833	.907	.074
4	0	5	.833	.970	.137
5	1	6	1.000	.992	.008

D = .150

$\alpha_{.20} = .216$

∴ The hypothesis cannot be rejected

Table: E6 Tool Number: 4508

Kolmogorov-Smirnov Goodness of Fit Test For Poisson Distribution of the Occurrence of "Early Failure" Runs

$\hat{m} = 3.4$

N = 17

	Actual			Theoretical	Deviation
X	Freq.	Cum. Freq.	c.d.f.	c.d.f.	
0	0	0	0	.033	.033
1	0	0	0	.147	.147
2	2	2	.400	.340	.060
3	1	3	.600	.558	.042
4	1	4	.800	.744	.056
5	0	4	.800	.871	.071
6	1	5	1.000	.942	.058

D = .147

$\alpha_{.20} = .250$

∴ The hypothesis cannot be rejected

Table: E7 Tool Number: 6501

Kolmogorov-Smirnov Goodness of Fit Test For Poisson Distribution of the Occurrence of "Early Failure" Runs

$\hat{m} = 2.2$

$N = 13$

	Actual			Theoretical	Deviation
X	Freq.	Cum. Freq.	c.d.f.	c.d.f.	
0	0	0	0	.111	.111
1	2	2	.333	.355	.022
2	3	5	.833	.623	.210
3	0	5	.833	.819	.014
4	0	5	.833	.928	.072
5	1	6	1.000	.975	.025

$D = .210$

$\alpha_{.20} = .284$

∴ The hypothesis cannot be rejected

BIBLIOGRAPHY

Books

1. DeGroat, George H., Metalworking Automation, McGraw-Hill, New York, 1958.

2. Kramer, H., The Elements of Probability Theory, John Wiley and Sons, New York, 1955.

3. Siegel, S., Non Parametric Statistics, McGraw-Hill, New York, 1956.

4. Snedecor, G. W., Statistical Methods, Iowa State University Press, Ames, Iowa, 1956.

5. Young, James F., Materials and Processes, John Wiley and Sons, New York, Second Edition, 1954.

6. American Society of Tool and Manufacturing Engineers, Die Design Handbook - Frank W. Wilson, Editor, McGraw-Hill, Inc., 1955.

7. American Society of Tool and Manufacturing Engineers, The Tool Engineers Handbook, Frank W. Wilson, Editor, McGraw-Hill, New York, Second Edition, 1959.

Articles and Papers

A. On Stamping Technology

8. Beigel, John E., "Development of Punchability Rating Method For Electrical Steels, American Society of Tool and Manufacturing Engineers Research Report Number 26, November 16, 1959.

9. Biegel, John E., "Investigation of Punchability Tests for Electrical Steels," American Society of Tool and Manufacturing Engineers Research Report Number 30, March 1, 1961.

10. Devlin, John P., "Economics of Die Selection in High and Low Production," A.S.T.M.E. Technical Paper Number SP63-111, 1963.

11. Griffiths, Edward E., "Maintenance Expense Control of Tools, Dies, Fixtures and Equipment," A.S.T.M.E. Paper Number 21T6, March, 1953.

12. Griffiths, E., "Super Finishing of Die Parts - What are the Advantages and Disadvantages," A.S.T.M.E. Research Report Number 23, September 15, 1959.

13. Keinzle, Otto and Keinzle, Werner, "Tool Wear in Cutting Thin Gauge Sheet Steels," A.S.T.M.E. Research Report No. 22, May 1, 1959.

14. McRae, N. G. and Castracane, N. B., "Mechanically Tabulating and Analyzing Die Performance Records, The Tool Engineer, Vol. 39, No. 4, October 1957, Pages 102-106.

15. Schmidt, Joseph P., "How Do Steel Dies Compare with Carbide Dies," Carbide Engineering, Vol. 10, No. 12, December 1958, Pages 9-15.

16. Strasser, Federico, "How to Reduce Breakage of Small Piercing Punches," The Iron Age, Vol. 183, No. 4, January 22, 1959.

17. Strasser, Federico, "How to Increase Life of Cutting Dies, The Iron Age, Vol. 171, No. 20, Pages 144-146.

18. Tilsley, R. and Howard, F., "Recent Investigations into the Blanking and Piercing of Sheet Metals," A.S.T.M.E. Research Report Number 27, May 3, 1960.

19. Wukusick, C. S. and Zeno, R. S., "Improving Punchability of Silicon Steel," The Tool Engineer, Vol. 41, No. 6, December 1958, Pages 63-70.

B. Articles and Papers on Reliability and the Weibull Distribution

20. Budne, Thomas, A., "Basic Philosophies in Reliability," Industrial Quality Control, Vol 18, No. 3, September 1961, Pages 21-27.

21. Johnson, L. M., "The Median Ranks of Sample Values in Their Population With an Application to Certain Fatigue Studies," Industrial Mathematics, Vol. 2, 1951, Pages 1-9.

22. Johnson, N. L., "Cumulative Sum Charts and the Weibull Distribution," University of North Carolina Institute of Statistics Mimeo Series No. 386, April, 1964.

23. Kao, John H. K., "Computer Methods for Estimating Weibull Parameters in Reliability Studies," Institute of Radio Engineering Transactions on Reliability and Quality Control, PGRQC-7, April 1957.

24. Kao, John H. K., "A Graphical Estimation of Mixed Weibull Parameters in Life Testing of Electron Tubes," Technometrics, Vol. 1, No. 4, November 1959, Pages 389-407.

25. Kao, John H. K.,"A Summary of Some New Techniques on Failure Analysis," Proceedings of the Sixth National Symposium on

Reliability and Quality Control in Electronics, Pages 190-201, 1960.

26. Miller, Rupert G., Jr., "Early Failures in Life Testing" Journal of the American Statistical Association, Vol. 55, No. 291, September 1960, Pages 491-502.

27. Moyer, C. A., Bush, J. J. and Ruley, B. T., "The Weibull Distribution Function for Fatigue Life," Material Research and Standards, Vol. 2, No. 5, May 1962, Pages 405-411.

28. Nylander, John E., "Statistical Distributions in Reliability," IRE Transactions on Reliability and Quality Control, RQC-11, No. 2, July 1962, Pages 43-53.

29. Ravenis, Joseph, V. J., "Life Testing: Estimating the Parameters of the Weibull Distribution," 1963 Institute of Electrical and Electronics Engineers International Convention Record, Part 6, March 25-28, 1963, Pages 18-33.

30. Robins, Richard S., "On Models for Reliability Prediction," IRE Transactions on Reliability and Quality Control, Vol. RQC-11, No. 1, May 1962, Pages 33-43.

31. Weibull, W., "A Statistical Distribution Function of Wide Applicability, Journal of Applied Mechanics, Vol. 18, No. 3, September 1951, Pages 293-297.

C. Tables

32. Biometrika Tables for Statisticians, Vol. 1, E. S. Pearson and H. O. Hartley, Editors, Cambridge, 1956.

33. Burington, R. S. and May, D. C., Handbook of Probability and Statistics with Tables, Handbook Publishers, Inc., Sandusky, Ohio, 1958.

D. Specifications

34. Material Specification 57612, Carbon Steel Sheet, Strip, and Flat Wire, Issue 14, January 19, 1962, Western Electric Company, Inc., New York.

35. Material Specification 58206, Brass Plate, Sheet, Strip and Rolled Bar, Issue 12, October 22, 1962, Western Electric Company, Inc., New York.

36. Material Specification 58210, Nickel Silver Plate, Sheet, Strip, and Rolled Bar, Issue 10, March 1, 1961, Western Electric Company, Inc., New York.

37. Steel Products Manual Flat Rolled Electrical Steel, American Iron and Steel Institute, New York, January, 1958.

VITA

Personal History:

Name: David Forrest Weigel

Birth Place: Takoma Park, Maryland

Date of Birth: November 25, 1930

Parents: Charles A. and Mildred M. Weigel

Education:

1948 Diploma, Coolidge High School, Washington, D.C.

1953 Bachelor of Science in Engineering (Industrial), University of Michigan, Ann Arbor, Michigan

1957 Master of Business Administration, University of Michigan, Ann Arbor, Michigan

1964 Candidate for Master of Science in Industrial Engineering, Lehigh University

Honors:

Pi Tau Sigma

Tau Beta Pi

Phi Kappa Phi

Beta Gamma Sigma

Experience:

Administrative Engineer - Nuclear Products Division of A.C.F. Industries.

Planning Engineer, Western Electric Company, Inc., Baltimore, Maryland

Research Engineer, Western Electric Company, Inc., Princeton, New Jersey