A RELIABILITY ANALYSIS OF FELLER-BUNCHERS IN USE IN THE SOUTH

by

Robert Allen Tufts

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APPROVED:

Thomas A. Walbridge, Jr., Chairman

Richard G. Oderwald

Marshall S. White

Robert P. Davis

John V. Perumpral

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Blacksburg, Virginia

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INTRODUCTION

Today's economic conditions force the timber harvester to obtain the maximum return from each tree removed. This dictates that the logger be able to handle multiple products and this requires mechanization. Along with this mechanization come the problems of machine availability and the associated high cost of "downtime."

Harvesting equipment is designed to have a high rate of productivity to offset the rapidly increasing costs of ownership. Unexpected loss of operating time due to mechanical failures can result in lost profits from the decrease in production as well as the direct expenses for repair.

Mechanization creates the need for information on machine reliability and, hence, operating time and causes of downtime. This information provides the basis for planning and organizing harvesting and maintenance operations to minimize downtime due to mechanical problems.

Development of Mechanization

The mechanization of the timber harvesting industry has evolved over the last three decades. It began with the invention and general acceptance of the chain saw by the early 1950's.[1] During the 50's and 60's almost all of the pulpwood was produced by crews of about three men using several chain saws and a straight truck which may or may not have been equipped with a simple cable loader, pallets, or some other loading device. The first skidders came into being in the early 60's, but they were not accepted as standard equipment until 1965. The skidder allowed the truck to remain on the road rather than being a prehaul vehicle as well as the main hauling vehicle. With the possibility of concentrating wood at the roadside more efficient loaders were developed and larger trucks could be used. The first hydraulic knuckleboom loaders appeared in the early 60's and were quickly adopted.

At this point the skidding, loading, and hauling phases of harvesting were mechanized leaving felling and limbing the only partially manual operations. The next step in the mechanization process was the invention of the tree shear in

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[1] dates from Cline (1975)

1966 and the feller-buncher which evolved from the tree shear by the late 60's. The feller-bunchers not only improved the productivity of the felling phase, but also greatly increased the productivity of grapple skidders by creating piles or bunches of trees. Limbing, when it occurs, is still primarily a manual operation although there are some mechanical limbers and non-mechanical devices available.

Mechanical harvesters that perform more than one operation have also been developed. However, most of these were designed to produce shortwood lengths of pulpwood. Because they produce only one product and can handle only one tree at a time their application has been limited. Also, most of these rather sophisticated machines are expensive and exhibit a rather low availability.

The increase in the degree of mechanization in timber harvesting is the result of a number of factors. Harvesting methods of the 50's and 60's were very labor intensive and, therefore, sensitive to increasing labor costs and the decreasing availability of woods workers. Weather and terrain are also severe limitations to the productive capacity of these systems. These constraints are slowly but surely reducing the use of these systems (Sterle and

Walbridge 1973). Rolston (1978) proposed three other reasons why these smaller operators are going out of business: (1) the desire for security, (2) the small employer does not enjoy the economies of scale available to the larger, and (3) laws, such as the Occupational Safety and Health Act and other social legislation, are set up for major corporations making it difficult for the smaller operator to comply.

Pulpwood production in the South reached 47.4 million cords in 1976 (Bertelson 1977). To harvest this amount of wood using the methods of the 50's and 60's would have required over 135,000 men. From the area represented by the Southwest Technical Division of the American Pulpwood Association 16.4 million cords of roundwood were harvested. A survey (Watson et al 1977) conducted by all the paper mills in that area produced a summary of 6662 questionnaires that represented 70 percent of the roundwood delivered. "Blowing up" the results to 100 percent provides an estimate of about 23,000 woods workers. The labor intensive methods would have required approximately 46,000 men, twice the actual number employed.

The importance of mechanization is also evident from this survey. Labor intensive operations typically produce 50 cords of wood or less per week. Eighty-five percent of the producers fell in this category, but accounted for only 48 percent of the roundwood delivered to the paper mills. The remaining 15 percent who were mechanized to some degree were responsible for 52 percent of the wood harvested.

The change in the market for forest products was also a major factor leading toward mechanization. The chipping headrig revolutionized the market because it allowed sawmills to compete with pulp mills for the smaller sized trees. Also, the South's first softwood plywood plant began operation in 1963. By 1975 there were 50 plants in operation and they were competing with the other wood using industries for their raw material needs. According to Cline (1975) these technological developments together with significant changes in social and economic conditions, resulted in important changes in timber harvesting methods. Whereas pulpwood and sawmill logging were formerly identifiable as separate industries, logging came to have but one identity. Most loggers now sell their products either to timber dealers who have multi-product markets or they sell directly to mill complexes where each tree is processed for its greatest value. In the process of this transition, a trend evolved toward tree length or multi-log length harvesting systems. These dictated greater mechanization. And, as Cline (1975) states, "Loggers either mechanized or quit their trade."

Feller-Bunchers

There are two major reasons for the acceptence of the feller-buncher: labor and production.

The size of the work force willing to endure the environmental conditions and physical stress involved in the felling of standing timber is diminishing. The alternative to mechanical felling is the chain saw and time studies have shown that most sawyers are physically able to work only four hours per eight hour shift. One contractor who normally employed four full time sawyers summed up the situation as "...almost impossible to find and keep good piece cutters." His solution to the problem was a small feller-buncher that reduced his needs to one sawyer and increased the productivity of the operation (Bryan 1978).

Tree volume is the major determinant of felling productivity, and since a 5-inch tree has one-half the volume of a 7-inch tree the incremental cost of harvesting the smaller diameter trees is very large. One study (Davidson 1978) reported that the average cost per cunit(100 cu. ft. of solid wood) increased 9.3 percent by harvesting the 6-inch trees and larger as opposed to cutting only trees that were in the 7-inch class or larger. However, the incremental cost of adding the 6-inch trees was 200 percent higher than the average cost of harvesting only the 7-inch and larger trees. Davidson's (1978) conclusion was that single stem harvesting would require dramatic and probably unrealistic increases in productivity in order to combat rapidly rising costs associated with the reduced diameters. He contends that methods of package handling the small stems are essential for achieving reasonable costs.

One wood procurement manager explained that the sawmills take wood that is 8-inches in diameter and up so he is forced to go to smaller and smaller trees for pulpwood[2]. The only way he can economically harvest these trees is with a feller-buncher because of the high productivity of these machines.

Disadvantages of Mechanization and Feller-Bunchers

Although mechanization and feller-bunchers offer

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[2] personal communication with Don Tufts, Wood Procurement and Logging Manager, Pineville Kraft Corporation, Pineville Louisiana

solutions to labor shortages and productivity they also have some other limitations. The capital outlay necessary to equip and operate this type of harvesting system is quite large. Also, even though the requirement for labor has decreased a more specialized worker is required to operate the equipment. In addition to labor and management, another major problem with mechanization comes from the mechanical failures and maintenance associated with the use of harvesting equipment. Meckler (1968) reported that for every dollar spent in acquisition of equipment another $1.25 is spent for maintenance. In a five-year study from 1972 until 1976 maintenance costs increased 64.3 percent (Anon. 1977).

The success of a machine will usually depend not only on its productivity, but also on its availability and the cost of maintenance (Heidersdorf and Folkema 1976). Typical studies of mechanized harvesting operations report availability figures ranging from 50 to 70 percent (Folkema 1979, Folkema 1977, Heidersdorf 1978, and Boyd 1975). However, these studies do not mention the variation in availability. Also, Boyd (1975) in a study of 21 machines of the same type over two years found that the range of times spent actually repairing the machines without any delays was only three percent and accounted for about 21 percent of scheduled machine hours. The remainder of the downtime and also the variability was due to non-mechanical delays and time waiting for repair parts and mechanics.

As the application of feller-bunchers in the South increases it becomes more important to analyze not only the productive capacity of these machines, but also the reliability of these machines. At present, there is a posity of information and procedures needed to make an objective analysis of reliability, repair, or maintanance data. A complete reliability analysis is needed to provide information that can be used to more accurately plan future operations, reduce costs, and improve efficiency. The analysis should include information to determine optimum replacement strategies, estimate the frequency of failures, compare the reliability and maintainability of different machines, identify strategies to improve efficiency, and determine the reasons for failures.

Objectives

Based on the above, the objectives of this research are twofold:

1. Adapt existing analytical techniques from other fields or develop techniques where needed to produce a procedure to evaluate reliability, repair, and maintenance information on forestry equipment, and

2. Use this procedure to make a reliability analysis of three types of feller-bunchers in use in the South.

LITERATURE REVIEW

Before reviewing past studies the basic concepts of availability, reliability, and maintainability will be discussed.

Availability

"Availability is defined as a measure of the impingement of failures on the operation of an item, system, or service, and therefore indicates how often a system is in a condition to deliver satisfactory service to a user" (Heimann 1976). The availability factor represents the probability of uptime of the equipment (Forgit 1976). It depends primarily on reliability, the effect of failures, maintainability, failure management policies, demand patterns, and user requirements. In other words, it is a function of how often failures occur (reliability), how they degrade the system when they do occur (the effect of failures), how long the system takes to recover from them (maintainability and failure management policies), and how the system's loss of capability because of failure affects the user (demand patterns and user requirements) (Heimann 1976).

Availability is a ratio of mean time between failures to mean downtime. However, there are various methods of defining these two quantities. There are three types of availability based on how the mean time between failures and mean downtime are defined, inherent, mechanical or achieved, and operational.

Inherent availability considers only the inherent features of the system and excludes such things as preventive maintenance and supply and administrative time (Forgit 1976). Or, as Axelsson (1972) states, "it is the inherent time for repair of failures provided spare parts, repair facilities, and skilled mechanics without any waiting time." It is the availability from the machine design point of view. It is expressed as:

$$\text{Inherent availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \qquad (1)$$

Where: MTBF - mean time between failures
MTTR - mean time for active repair

Mechanical or achieved availability considers both corrective and preventive maintenance, but excludes supply and administrative time (Forgit 1976). Only two factors are considered: the productive machine hours (PMH) achieved and the amount of active repair and service time necessary in order to achieve this productive time. This provides a measure of the machine's manufacturing characteristics, independent of operational and maintenance support factors (Axelsson 1972). It is expressed as:

$$\text{Mechanical availability} = \frac{MTBM}{MTBM + M} \qquad (2)$$

Where: MTBM - mean time between measures resulting from corrective and preventive actions
M - the mean active downtime resulting from corrective and preventive actions

Mechanical availability is a good measure for comparing similar machines, but it does not indicate what portion of the scheduled machine hours (SMH) the piece of equipment is operationally ready to perform its assigned task. Therefore, it is not indicative of the actual operating time of a machine.

Operational availability considers the time necessary for active corrective and preventive measures as well as supply and administrative time (Forgit 1976). It is expressed as:

$$\text{Operational availability} = \frac{\text{MTBM}}{\text{MTBM} + \text{MDT}} \qquad (3)$$

where: MDT - mean down time, includes both active
repair and service and delays or
waiting time

or

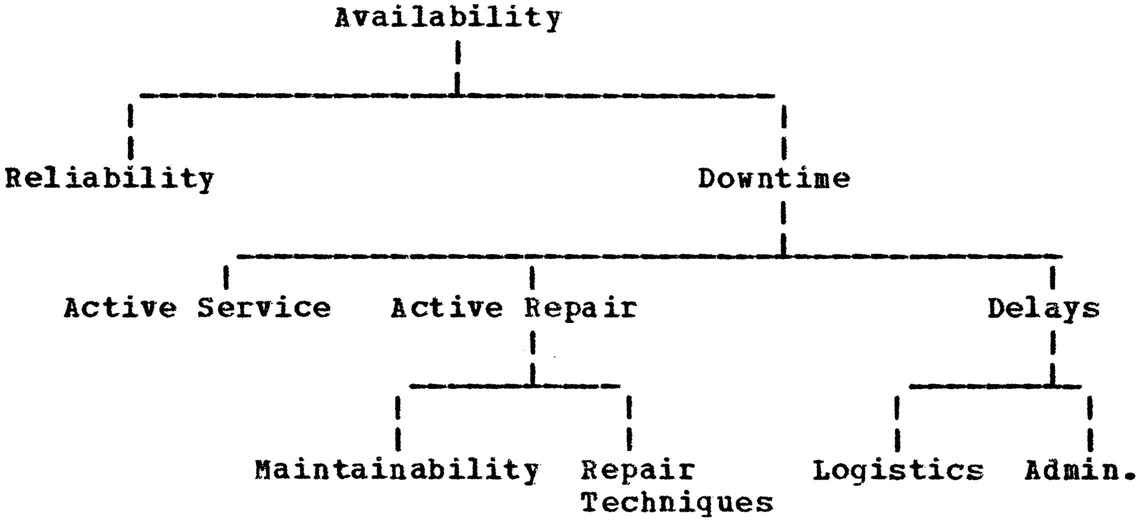
$$\text{Operational availability} = \frac{\text{SMH - Maint. downtime (in-shift)}}{\text{SMH}}$$

where: SMH - scheduled machine hours
Maint. downtime - includes all active
maintenance and waiting maintenance
during SMH

This definition includes only maintenance and repair performed "in-shift", therefore it is possible to increase operational availability by performing as much maintenance and repair as possible out-of-shift. Also, because operational availability includes waiting as well as active maintenance it is a measure of the efficiency of the maintenance support facilities.

Operational availability does not provide information suitable for comparison of machines because of the influence of operational parameters. However, according to Axelsson (1972), "calculations of operational availability, supplemented by a utilization figure, give a good picture of the efficiency achieved on an actual machine operation."

The components of availability and their relationship are shown below (Hetreed and Sweet 1972).



Delays include waiting for labor, parts, facilities, information, authority, or movement
Delays and repair techniques make up failure management policies

The benefit of an availability analysis is that it identifies the stability of the system. It will also point out areas that need attention such as a part that fails frequently, poor repair procedures, or some policy that precludes the rapid procurement of replacement items. Once these problems are identified steps can be taken to remedy them.

Reliability

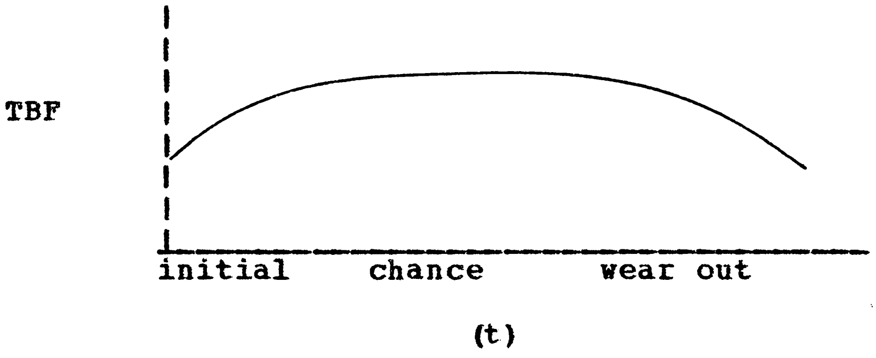
"Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered" (Radio-Electronics-Television Manufacturers Association 1955). The measure of an equipment's reliability is the infrequency with which failures occur through time.

Reliability of equipment involves more than a simple statistical probability in which system reliability would be related to the reliability of the components by the product rule as is the case in the smooth loading situation. To obtain 80 percent reliability in a series system with 400 components would require a mean component reliability of 99.95 percent. As a simple example consider a queue of 20 cars at a traffic light. Each vehicle has at least 100 components in series in its transmission system giving some 2000 components in series at the light. Yet, how often does the queue fail to move because of a mechanical failure (Carter 1972)? Chaddock (1960) carried out a more scientific investigation of the supposed correlation between reliability and number of components, studying a number of weapons for which accurate data existed. He concluded that there was no such correlation. Success is achieved when the weakest or least adequate individual component of a system is capable of coping with the most severe loading or environment to be encountered (Carter 1972).

In order to describe the reliability of a piece of equipment that is subjected to rough (variable) loading, failure distributions are used. A failure distribution represents an attempt to describe mathematically the length of life of a material, a structure, or a device. There are many physical causes that individually or collectively may be responsible for the failure of a device at any particular instant. At present it is not possible to isolate these physical causes and mathematically account for all of them, and therefore, the choice of a failure distribution is still an art (Mann et al 1974).

Failures and Failure Distributions

Three types of failures generally have been recognized as having a time characteristic. The first one, called the "initial failure", begins shortly after a piece of equipment is put in use and gradually decreases during the initial period of operation. These early failures can result from improper design or improper manufacture. The second type, called the "chance failure" occurs during the period in which a device exhibits a constant failure rate, generally lower than that prevailing during the initial period. The cause of this failure is attributed to unusually severe and unpredictable environmental conditions occuring during the operating time of the device or improper use. The last type, called the "wear-out failure", is associated with the gradual depletion of a piece of equipment. The three types of failures have been classically represented by the "bath-tub" curve, wherein each of the three segments of the curve represents one of the three time periods: initial, chance, and wear-out (Mann et al 1974). However, if time between failures rather than failure rates are considered the pattern would be represented by an inverted "bath-tub" shaped curve as shown below.



Several functions are used and are equally suitable for describing the failure distribution. They are the probability density f(t) when it exists, the cumulative probability F(t), and the failure rate r(t) (Barlow and Proschan 1965) or hazard function h(t) (Bain 1978).

These quantities are related by :

$$F(t) = \int f(t)dt \tag{5}$$

$$r(t) = \frac{f(t)}{1 - F(t)} \tag{6}$$

$$h(t) = r(t) \tag{7}$$

A variety of families of distributions have been used for the fatigue failure of materials and the life length of electronic and mechanical components. Some of these include the exponential, the gamma, the Weibull, the modified extreme value, the truncated normal, and the log normal (Barlow and Proschan 1965).

The exponential distribution has a constant time between failures. The modified extreme value and normal distributions have decreasing times between failures while the gamma and Weibull may have either increasing or decreasing times between failures. The log normal has increasing times between failures in the long-life range and is therefore of limited value. The exponential and the

Weibull distributions are two of the most popular parametric distributions used in reliability studies.

Exponential Distribution

In reliability studies, the exponential distribution plays a role of importance analogous to that of the normal distribution in other areas of statistics. Its desirability is due to its simplicity and its inherent association with the well developed theory of Poisson processes. Also, many times certain quantities computed from the exponential distribution serve as bounds for similar quantites that need to be computed from other, less tractable distributions. The applicability of the exponential distribution is limited, however, because of its "lack of memory" property (Mann et al 1974). The faliure rate for the EXP($\underline{O}$) is:

$$r(t) = \frac{f(t)}{1 - F(t)} = \frac{1}{\underline{O}} \qquad (8)$$

This constant time between failures means that the exponential distribution is an appropriate model for the lifetime of an item when there is no wearing out or aging. That is, a used item is equivalent to and no more apt to fail than a new item (Bain 1968). In other words, if a machine has not failed up to a time t, the probability distribution of its future life length T-t is the same as if the machine were quite new and had just been placed in use at time t (Barlow and Proschan 1965). The exponential distribution is the only distribution with this property (Feller 1957).

There is a situation in which the exponential distribution plays a prominent role. Consider a system consisting of many components, each subject to an individual pattern of malfunction and replacement and all parts making up the failure pattern of the equipment as a whole. Barlow and Proschan (1965) proved, under some reasonably general conditions, that the distribution of the time between equipment failures tends to the exponential as the complexity and the time of operation increase. If failure is due principally to external causes rather than internal wear, then the exponential distribution is likely to be realistic (Hoel 1971). The exponential does not represent the distribution of the first time to failure for equipment in which all components are initially new.

Weibull Distribution

Recently the Weibull distribution has emerged as the most popular parametric family of failure distributions (Mann et al 1974). The three parameter Weibull distribution is a natural extension of the exponential distribution. The parameters B, O, and n are referred to as the shape, scale, and location parameters, respectively. In many applications the location parameter is assumed known and thus may be taken to be zero without loss of generality, by simply translating the data (Bain 1978). This model includes the exponential distribution with a constant time between failures for $B=1$ and provides decreasing time between failures for $B>1$ and increasing time between failures for $B<1$. This model is quite popular as a life testing distribution and for many other applications where a skewed distribution is required. It is quite flexible and has the advantage of having a closed form cumulative distribution function. A disadvantage is that the principle of sufficient statistics is not helpful in reducing the sample data, and the model has been relatively difficult to analyze statistically. Probably the main justification for consideration of the Weibull distribution is that it has been shown experimentally to provide a good fit for many different types of characteristics (Bain 1978).

Nonparametric Distributions

Another useful approach in reliability studies, developed during the last ten years is to classify the life distributions for components or systems according to the qualitative behavior of their failure modes. This approach leads, in many cases, to a more practical, easier to assume and justify reliability model. These are what have been called the nonparametric models in reliability studies. The most rewarding feature of these models is that not much is lost, in terms of answering the typical questions of concern in reliability studies, as compared to the more restrictive parametric models. Other advantages of nonparametric methods include insensitivity to outliers in the data, superior power properties for a wide class of alternative distributions, and estimators and distribution free confidence intervals for the population parameters from the test statistics (Shimi and Tsokas 1977). The empirical distribution function is known to be an excellent nonparametric estimator of the cumulative distribution function (Hollander and Korwar 1977).

Maintainability

Maintainability is defined as "the inherent characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time when maintenance action is performed with the prescribed procedures" (Forgit 1976). In other words, it is the ability to maintain in a rapid manner with optimum support costs and other resources.

This definition refers to maintenance action and not solely to repair. A device does not always fail to accomplish its assigned task because of a failure requiring a repair. Maintenance action is a general term used to describe any type of maintenance activity whether it be preventive or repair action.

Maintainability, like reliability, is a probability statistic. Maintainability is the probability of restoring a piece of equipment which has failed or is functioning abnormally to its full operating effectiveness within a period of time, whereas reliability is the probability of survival of a machine with respect to time. Because they are similar in that both relate the occurance of a single type of event over time, the same kinds of analytical techniques can be used for assessing them.

As stated in the definition, maintainability is affected by both design and installation factors. Some of the design factors include accessibility, complexity, compatability, interchangeability and replaceability, visibility, and configuration.

Installation parameters involve the person working on the equipment as well as the associated environment. These include experience, training, skill, and supervision of maintenance personnel, and the techniques used for maintenance and logistic support.

The time to repair is usually considered to follow an exponential distribution. This is the simplest and most popular method of analyzing maintainability. There is also a substantial amount of empirical evidence that the time required to perform a variety of tasks of the same type but of different levels of difficulty is lognormally distributed.

Failure Management Policies

One of the major causes of low operational availability is excessive repair time resulting from poor failure management policies. Maintanance studies by the Forest Engineering Research Institute of Canada (Boyd 1976) suggest that there is a potential for as much as a 75 percent reduction in repair downtime on some harvesting operations. Repair downtime in this sense includes both active repair and delays. Policies or procedures that would reduce the time in either category are potential time and thus money savers.

Some of the strategies suggested may be cost prohibitive to smaller operators, but modification could make them applicable to a degree. These maintenance strategies include:

don't repair parts that can be replaced,
make the right tools available,
do the repair at the right place,
set maintenance priorities,
supervise for low downtime,
organize to produce not to maintain,
don't live with problems—modify in the field,
don't just repair--improve,
provide support services, and
use the best available technology.

In another study of 21 machines over two years Boyd (1975) found that differences in availability were due largely to waiting rather than active repair time. He also found that repair downtime increased in the winter and decreased in the summer, but the average downtime had little tendency to either increase or decrease from one year to the next.

Active repair time is largely a characteristic of machine design while delay time is more a function of operational and maintenance support. A company can chose to have as much or as little waiting time as it desires (Boyd 1976).

The objective of an operation should be to determine the optimum balance of reliability and maintainability in the system to insure the best level of availability. The balance between these is usually inverse, or as reliability increases the need for maintainability may decrease.

Reliability Studies

A study of the literature on reliability can produce volumes of material. For any given month for the last several years Engineering Abstracts will contain at least ten articles dealing with reliability. However, most of the work to date deals with electronics, avaiation, and weapons, and more often concerns derivation of techniques for specialized problems rather than case studies. There are several reasons for this. The loads or stress on these types of components are relatively well defined and have little variation (smooth loading) making design easier. Therefore, most failures are due to variation in the manufacturing process. Testing procedures are easier and cheaper, usually involving placing a number of items on test and recording the times to first failure of the components. And, because of this the statistics are simpler. However, as Long (1972) states, "The classical approach to reliability assessment, such as that used in the electronics industry, could not be realistically applied to construction and industrial machinery."

Very few studies have been published on the reliability of mobile industrial equipment. In a review of the literature Renoll (1978) could find "...no studies relating to farm machine reliability under Southeastern farm conditions..." Also, Kumar, Gross, and Studer (1977) report that, "very little literature is available on the use of reliability in design and manufacture of farm machinery." Almost all major manufacturers of equipment maintain a reliability program and one has a post warranty reliability program as well[3] ; however, the information produced is proprietary.

More work has been published in the field of agriculture than forestry and several of these will be used to describe past reliability studies. There have been three types of studies reported in the area of reliability.

One type of study involves nothing more than the subjective opinions of owners of a particular piece of equipment and areas where they experienced problems. The

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[3] personal communication with Tom Dickerson, Product Support, Deere And Company, Moline, Illinois

Professional Farmers of America conducted a qualitative reliability survey of 1776 owners of 100 plus horsepower farm tractors. Of these only one percent experienced major engine failures or overhauls within the first 3100 hours of operation. Hard starting was one of the most frequently reported engine problems. Others included cam shaft, oil pump, water pump, and oil seals. Additional problem areas were injector pumps, poor fuel filters, alternator repairs, transmission failures, clutch problems, hard shifting, rear end failures, and poor brakes. Hydraulic systems received almost as many complaints as all other tractor components combined. However, nine percent reported no serious mechanical problems (Buckingham 1976). The report also rated the nine brands of tractors by name according to the user's perception of reliability.

The second type of study involved collecting reliability information and reporting the results. One rather large study conducted over ten years is the subject of several papers. The University of Illinois Agricultural Engineering Department questioned over 1500 corn and soybean farmers in Indiana and Illinois about the incidence of, and the time lost from, breakdowns during specific field operations (Hunt 1971).

Findings indicated that because of the high failure rates farm managers need to anticipate some costs in time, inconvenience, and crop loss due to breakdowns when planning and scheduling the year's farm program (Hunt 1971a). Also, the relatively simple, lightly loaded implements seemed to have greater reliabilities and the probability of breakdown was directly related to the amount of machine use.

Several conclusions were reached when comparing breakdowns to machine age and use (Hunt 1971b). The reliability of the simple machines--tillage implements, row cultivators and planters--seems to increase with age, possibly because all the weak or poor quality parts fail early in the life of these machines. Tractors and other complex machines showed considerable variation, but at the end of 10 years they showed as good or even better reliability than they had during the first year. One possible explanation for this is that a few machines, even new ones, "die" every year. Those machines that proved to be unreliable were discarded rather early in their life and did not appear as aged machines in the study. The survey showed a considerable drop in the numbers of machines after they reached the age of five. Apparently farmers who could afford to do so traded in their tractors and combines after about four years of use.

When comparing reliability with machine use rather than age the results were somewhat different (Hunt 1971b). The simpler machines exhibited a rather strong tendency toward more breakdowns with accumulated use and the complex machines showed considerable variation but did have a slight trend toward a decrease in relaibility. Individual returns of the survey seemed to substantiate the popular view that there are "lemons" as well as highly reliable machines in the population.

With respect to the amount of downtime the complex machines required considerably more time to repair than the simpler machines. In several instances repair time was disproportionately long because replacement parts were not available at the local dealer. The amount of repair time seemed somewhat insensitive to accumulated use of the machine (Hunt 1971b).

One other finding indicates that there is a differnece in reliability among the various manufacturers. Significant differences in usage costs were reported for all types of machines studied (Hunt 1971c).

A detailed analysis of tractor failures was also made on the data taken in this study (Hunt and Fujii 1976). Of the major components engine failures were responsible for slightly more than half of the occurrences and cost, followed in order by power train, wheels and tires, body, battery, and other. Components causing the greatest expense were not the same as those responsible for most of the occurrences. The category causing the most expense was pistons, rings, sleeves, and crankshaft followed by tires and tubes, fuel system, valves, clutch, and transmission. Frequency of repair was lead by oil filters followed by electrical system, fuel system, tires and tubes, and hydraulics.

The last type of study involves collecting operating and downtime information and then using simulation techniques to predict reliability. Von Bargen (1970) collected field data on the delay intervals and delay times for self-propelled windrowers. He found that times between stops were exponentially distributed and after removing a constant component from delay times they also fit an exponential distribution. He then used these distributions in a simulation model to predict performance of the machine system. Von Bargen (1970) explained that "Simulation studies were made to show the random characteristics of field machine delays and their effect upon the performance of machine systems." By using simulation techniques the effect of changing parameters can also be studied. Von Bargen analyzed the effect of adding machines, changing the average time between failures and changing the renewal rate. Simulation has great potential for analyzing machine systems, but as Von Bargen (1970) explains, "before the full potential of such models can be exploited in design or management, more data needs to be collected on field machine activities." He advocates the use of different probability distributions and time dependent failure rates as operational data become available to justify such models.

Another study was conducted to determine the reliability of a combine harvester (Kumar, et al 1977). Data were collected from the repair records of six farmers, each of whom were using the same make and model of rice combine. The machine ages varied from one to five years. The failure rate for the machine as a whole and the failure rates for the machine as three subsystems were estimated. The Weibull distribution was used to model the times between failures and provided a good fit as indicated by the Kolmogorov-Smirnov test. The confidence interval on the shape parameter ($\underline{B}$) for the whole combine was much higher than one ($1.5619 < \underline{B} < 1.9081$). Thus, "any assumption of negative exponential distribution for finding the time between failures for the machine will not give a good estimate of the true situation." Application of the Weibull distribution for combine subsystems gave values quite near unity. Therefore, the exponential distribution would have given good estimates for the times between failures of the subsystems. Simulation using Monte Carlo techniques was performed to predict the expected times between failures. Also, Bartlett's test for homogenity of variance and analysis of variance was used to test the difference in mean time between failures in the machines and diffenence in mean time between failures at different machine ages. No significant differences were found.

Reliability studies of forestry equipment are almost non-existent. Typical studies of equipment (Axelsson 1972, Boyd 1975, Folkema 1979, and Powell 1978) do little more than report the availability of the machine system and sometimes for subsystems as well. Downtime due to mechanical problems and maintenance in these reports ranged from 13 to 52 percent of scheduled operating time with an approximate average around 30 percent.

A more detailed analysis of downtime for skidders was performed by Vidrine (1979). He collected information on 213 machine-week reports covering 8277 scheduled operating hours, and reported the incidence of and time to repair failures of components of the machines. Downtime due to active repair amounted to 16.5 percent of scheduled hours. The failure classes causing 5 percent or more of the total downtime were engine replacement (10.25 percent) transmission (8.57), rear differential (7.65), and winch drive (7.56 percent). Hydraulic hoses and fittings caused the most frequent failures. Downtime due to repair of forestry equipment is rather high. Conditions under which the repair must be effected are far from ideal. Average repair time for skidders (Vidrine 1979) ranged from 1.99 hours for hydraulic hoses and fittings to 28.71 hours for engine replacement or major overhaul. The average tire repair/replacement required 4.33 hours. The problem is further compounded by what appears to be unusually early wear-out of components. Of the seven engine replacements and/or major overhauls reported by Vidrine (1979) the average hour meter reading at the time of failure was 3225 hours which is far less than the target design of 12,000 hours. Hydraulic pumps experience the same problem. The study reported five pump failures at an average hour meter reading of 2916 hours which, again, is considerably lower than the 8,000 hours suggested for road building and construction machinery (Vidrine 1979).

Any piece of equipment in use will experience failures;

however, the manufacturer does not have sole responsibility for the reliability of a piece of equipment, part of the responsibility rests with the user (Mundell 1970). The manufacturer must provide equipment that is properly designed and properly assembled. The user must maintain the equipment as recommended and at the correct time and must use good judgement in the operation of the equipment.

METHODS AND PROCEDURES

One of the major reasons that few studies of this type have been conducted is the difficulty in obtaining information. Not only must the data be long term, but it must also be continuous. And, the information usually must be recorded by the operator, mechanic, or supervisor none of whom are very favorably motivated toward paperwork, especially at the end of the day.

Larger contractors and paper companies usually have a record keeping system in place and the additional information required for a reliability study does not create a burden for them. Also, their supervisors are in the habit of completing data collection forms. The smaller, independent contractor, however, usually does not keep records other than receipts for tax purposes. Because of this it is a burden for him to keep accurate records, especially if he doesn't see any immediate benefit.

Because of the importance of feller-bunchers in the timber harvesting industry this type of machine was chosen for this analysis. There are many configurations of feller-bunchers, but in general a feller-buncher is made up of a shear head and a carrier. The shear basically consists of two knives that are forced together hydraulically to shear the tree at or near the groundline and a set of holding arms that control the tree so that it can be picked up vertically and moved to another location. So, trees can be felled and put into piles or bunches, hence the name feller-buncher. Some shears also have accumulating devices which allow the shear to sever another tree while holding trees that have been previously cut but not released. Some feller-bunchers use a large chainsaw rather than the knives, but these are not very common in the South. The shear head is attached to the carrier which is a tractor that provides locomotion and power for the shear. These tractors are hydrostatically or gear driven and equipped with tracks, tires, or tracks over tires.

There are two broad categories of feller-bunchers, limited area machines and tree-to-tree machines. The shear of a limited area feller-buncher is mounted on the end of a knuckled boom which is on a turntable. To cut a tree the boom is rotated and extended to move the shear head to the tree. After the tree has been severed from the stump the boom is rotated and extended or retracted to place the tree in the desired location before it is released. The carrier remains stationary during the entire felling and bunching process. All the trees are cut within the limited area which is defined by the boom reach of the machine. The carrier then moves forward and the process is repeated. This type of feller-buncher is usually used for larger timber or in areas with low soil strength. The shear of a tree-to-tree machine is mounted on a short boom which cannot be extended and usually can't be rotated. Therefore, the machine must be driven to each tree to fell it and then moved to the location where the tree will be placed. These feller-bunchers are usually smaller and less expensive than the limited area machines and are used to cut smaller timber.

Since so few of these studies have been conducted there is no standard method for analyzing the data once it has been collected. The objective in developing this procedure is to propose methods that are as simple and easy to perform as possible. The analysis is divided into five areas, the data that must be collected, a means of examining changes through time, a method of comparing machines, a process for examining different strategies, and a listing of reasons for failures.

Data Collection

Eight different cooperators supplied information for this study. Four of them are paper companies that own and supervise the harvesting operations. Two are located in Georgia, one in Florida, and one in Louisiana. All four of the cooperators are located in the physiographic region of the lower coastal plain. Three of them have field mechanics that serve one or more harvesting operations the fourth does not. The company that does not employ mechanics is a "parts exchanger". Rather than repair a part it is replaced by the operator with a new or rebuilt part and the faulty part is sent off to be repaired. Each of these cooperators maintained a parts inventory, and two of them have their own company garages for major repairs. One of these cooperators had a data collection procedure established prior to this study and it was possible to extract the required information from these records. The other four cooperators are independent contractors. It was intended to use the data they provided in a comparison with the data from the paper companies to examine differences due to the size of the harvesting operation. However, the data was either not accurate enough or of sufficient duration to be used.

Therefore, this study includes only the data from the four paper companies.

Data was collected on 32 feller-bunchers in use on pulp and paper company pulpwood harvesting operations. These machines fall into three types. Type 1 is a limited area feller-buncher that is hydrostatically driven and equipped with tracks. It is pictured in Figure 1. There were 14 type 1 machines in the study and data was supplied by three different cooperators. Type 2 is a gear driven tree-to-tree machine that has an articulated frame and rubber tires. It is shown in Figure 2. Twelve of the feller-bunchers were of this type and three cooperators supplied data on them. Type 3 is a tree-to-tree machine that is hydrostatically driven and smaller than the type 2 machine. It is designed so that one set of tires can go forward while the other set is in reverse allowing the machine to turn in a small area. This machine is known as a skid steer machine. It is pictured in Figure 3. Six of this type feller-buncher were included in the study, but the data was provided by only one cooperator.

Cooperators completed weekly reliability reports that provided information about operating time and downtime. And, for each machine failure, a repair form was completed. Copies of these forms are shown in Appendix A.

Figure 1. An example of a Type 1 Feller-Buncher.

Figure 2. An example of a Type 2 Feller-Buncher.

Figure 3. An example of a Type 3 Feller-Buncher.

From this data the following information was extracted:

Time between failures,
Time for active repair,
Delay time due to parts non-availability,
Delay time due to waiting for a mechanic, and
Time for servicing the machine.

Data from the repair forms also supplied information on:

Where the repair was performed,
Where the parts were obtained,
The reason for the failure, and
The specific parts repaired and/or replaced.

For identification throughout this report machines are given a three digit number code. The first digit defines the machine type as listed previously and is, therefore, either a 1, 2, or 3. The second number identifies the cooperator and the third denotes the number of like machines reported by a cooperator. As an example, machine 114 is a type 1 machine, the data was supplied by cooperator number one, and it is the fourth type one machine for which cooperator number one supplied data.

Data Analysis

Four different analytical techniques were used to examine the data. The first was an analysis of trends in the time between failures as a function of time. This information is important because it denotes the time between failures pattern for the life of a machine and the changes with respect to time are necessary to determine optiumum replacement strategies. The second procedure is a means of comparing two or more time-between-failure or time-to-repair distributions to identify significant differences. The reason for the differences would depend on the design of the study. In this analysis it was used to detect differences due to the type of feller-buncher. The third area of analysis considered the effect of changes in reliability, maintainability, or maintenance strategies on availability. Since operational availability is affected by a number of variables that interact, a simulation program was written to determine the effect of changing these variables. The effect of changes in time between failures, time to repair, and delay time was examined. The last method of analysis was a listing of reasons for machine failures. This information can be used to determine the frequency of failure for various parts and the amount and type of parts that should be stocked to minimize downtime. It can also be used to identify skills a mechanic should have.

Analyzing trends in time between failures

Analyzing changes in time between failures with time is a good management tool. Not only can it be used to determine optimum replacement strategies, but it can also be used as an indicator of the short term performance of a machine. If an operation is performing at its "steady state" the attention of a manager is not required, but a trend toward a decreasing time between failures for a machine would be an indicator that production is about to suffer unless the problem can be solved.

Graphical methods

The simplest types of analyses are graphical methods. Graphical methods are important both in quickly finding the grosser features of the data and also help in choosing more formal methods of data manipulation. Another advantage is that they are easily constructed and understood and can be brought up to date as new information is acquired.

There are two graphical methods that are very effective in demonstrating changes in the rate of occurence of failures or trends in the data. They are both cumulative plots. The first is simply a plot of the total number of failures that have occurred at or before time, t, against t. Plots of this type are shown in Figures 4 and 5. Since these graphs were constructed after all the data was collected the y-axis is a percent rather than the total number.

Examination of these cumulative plots can provide an indication of the presence of trends. If the slope of the curve is constant, as in Figure 4, no trend with time is present. If the slope does change then the time between failures is changing. A curve that is convex with respect to the x-axis as in Figure 5 indicates decreasing times between failures. Conversely, a concave curve represents an increase in the times between failures. The slope of a line joining any two points on the plot is the average number of failures per unit time for that period. While long term trends are readily evident in this type of plot, it is difficult to detect short term trends.

The second type of plot is also a cumulative plot, but the data are adjusted by a factor roughly equal to the average time between failures. The points plotted are:

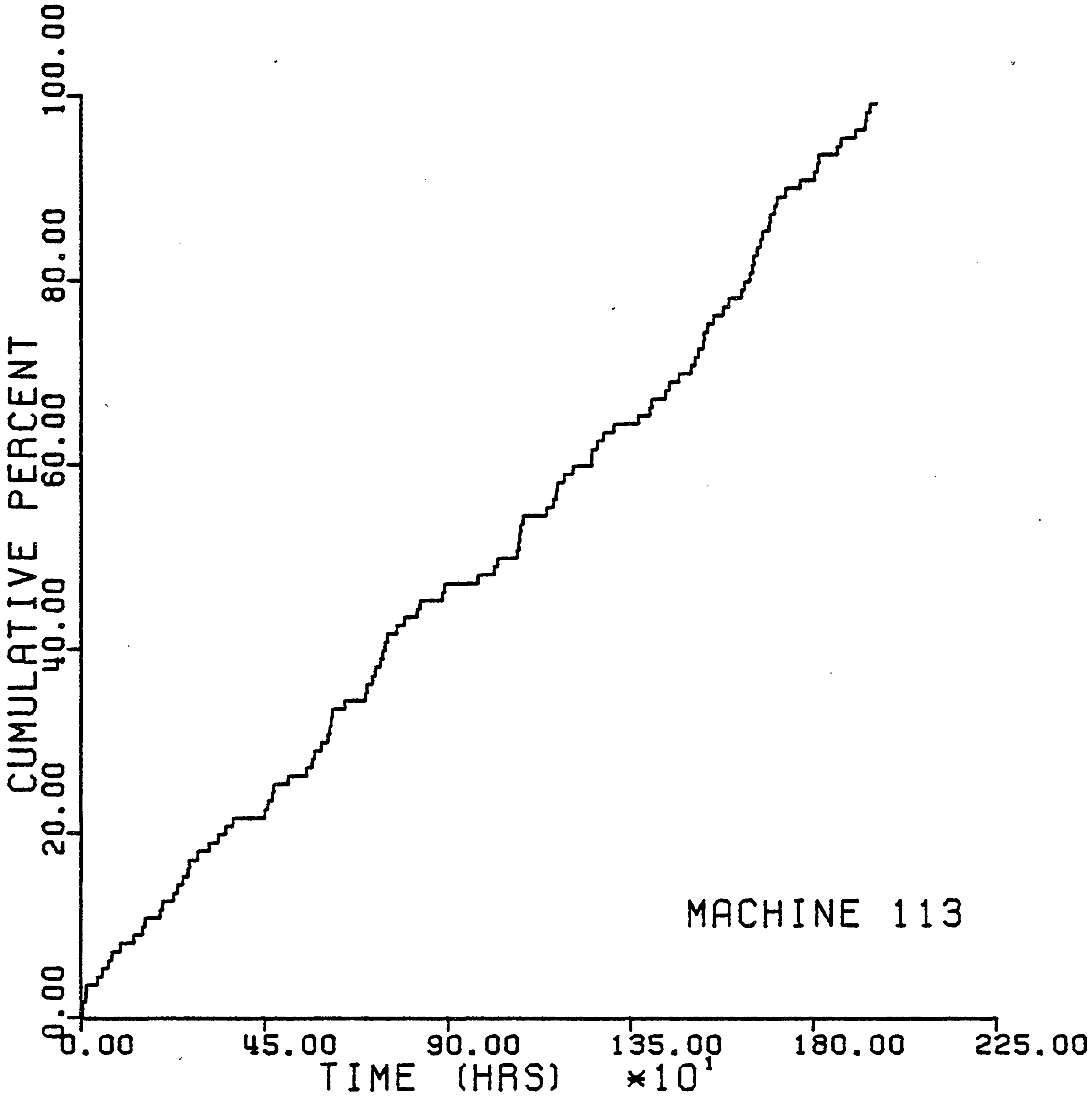

Figure 4. Cumulative percent of failures by the time of failure in operating hours for machine 113.

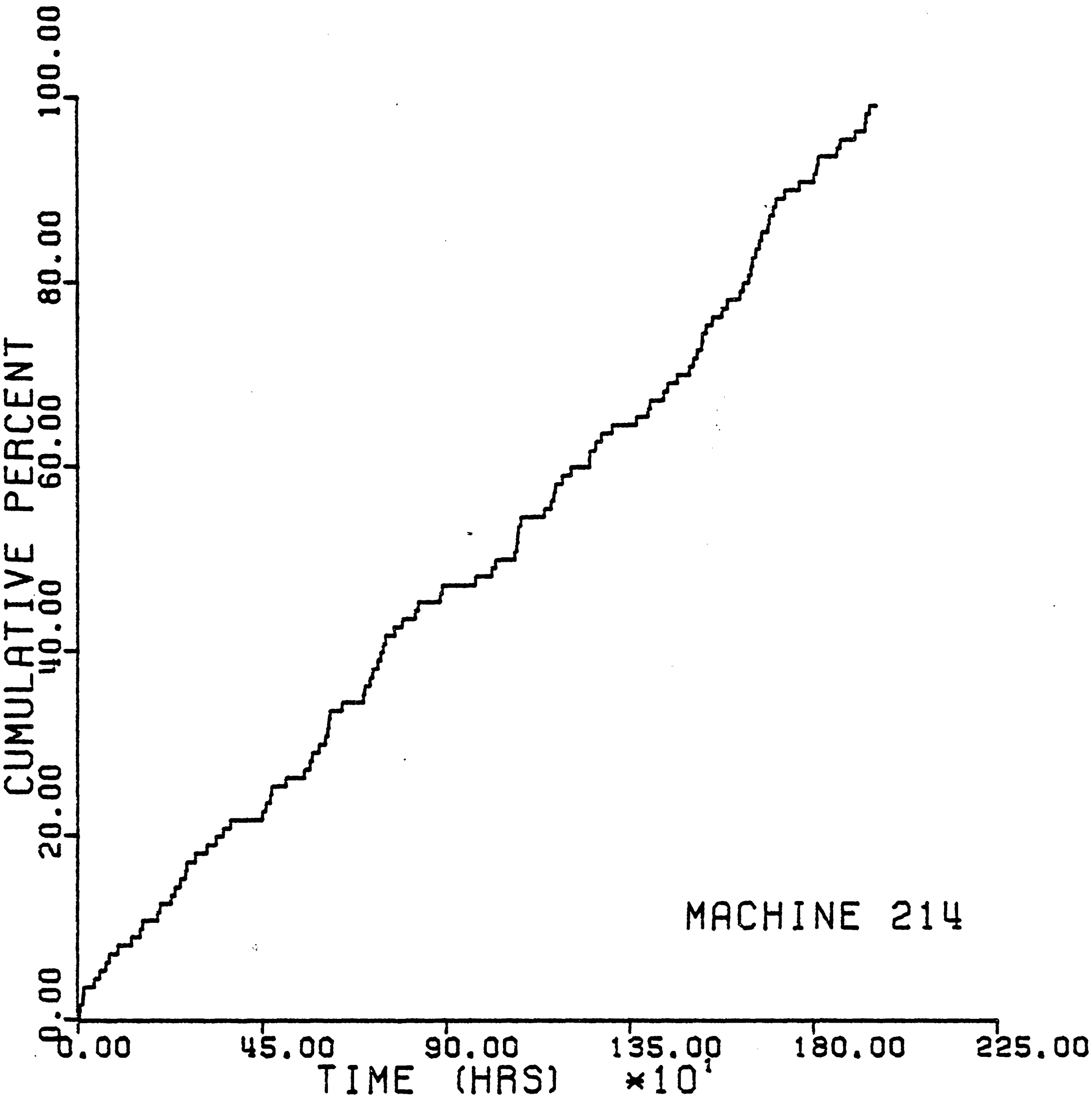

Figure 5. Cumulative percent of failures by the time of failure in operating hours for machine 214.

no. of events - a*t

where; a = the average number of failures per unit time and
t = time at which the failure under consideration occurred.

This method produces a plot that is approximately horizontal if there is no trend with time. Figures 6 and 7 are examples of this type of plot. The horizontal line represents the average number of failures.

Figure 6 is a plot of the data collected on machine 113. The average time between failures for this machine was 17.8 hours, so the average number of failures per hour (unit time) is 1/17.8 = .0562. To calculate the plotting point for the sixth failure we need to know when it occurred. Since the sixth failure occurred 53 hours into the study, the plotting point is:

$$6. - 0.0562 * 53. = 6 - 2.98 = 3.02$$

or (53., 3.02).

The plot in Figure 6 is for the same machine as Figure 4. Although there is no significant long term trend in the data there is a short term trend. Any time the slope between two points is positive the machine is failing at a rate faster

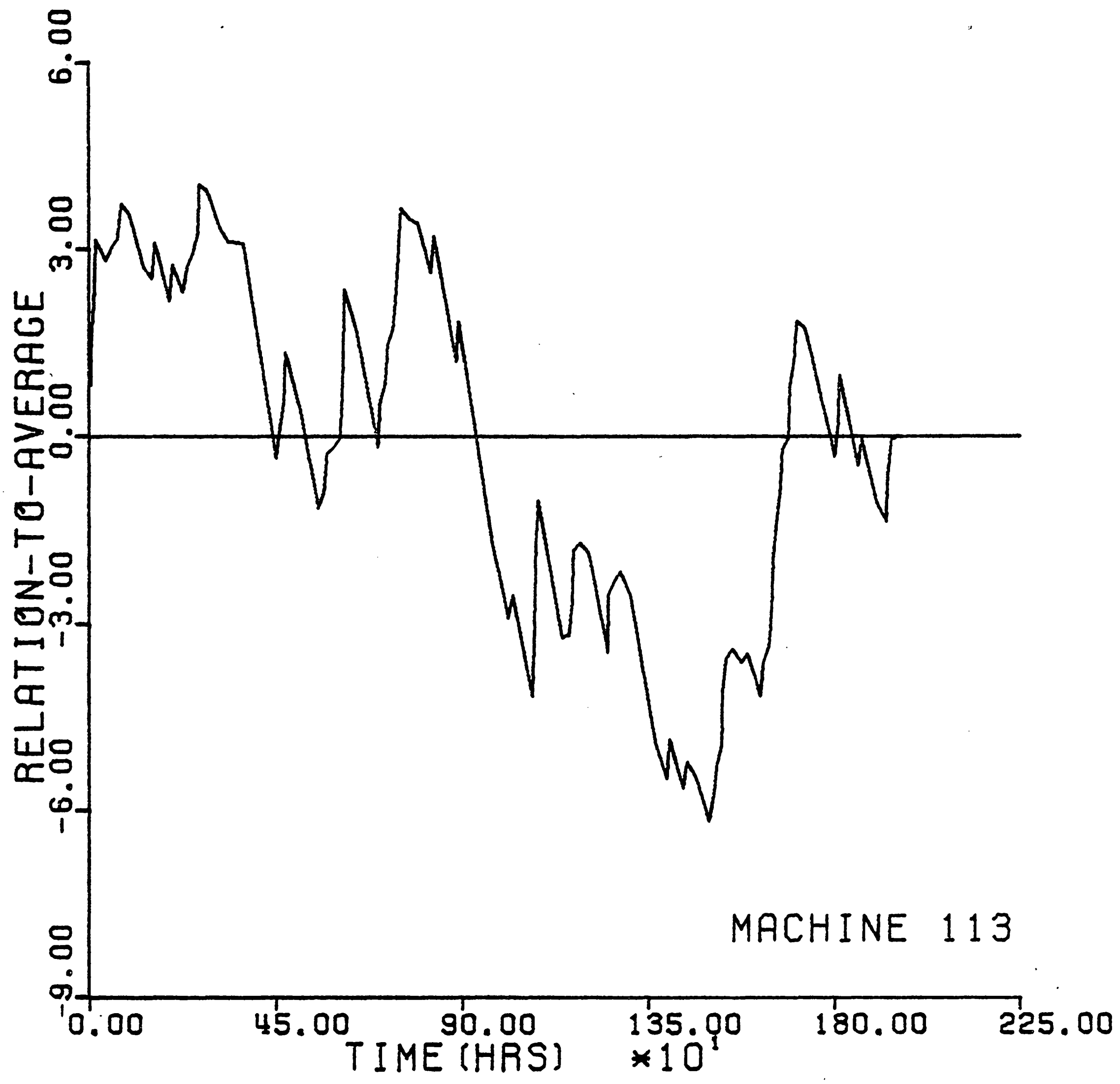

Figure 6. Cumulative number of failures above or below the average time between failures against the time of failure in operating hours for machine 113.

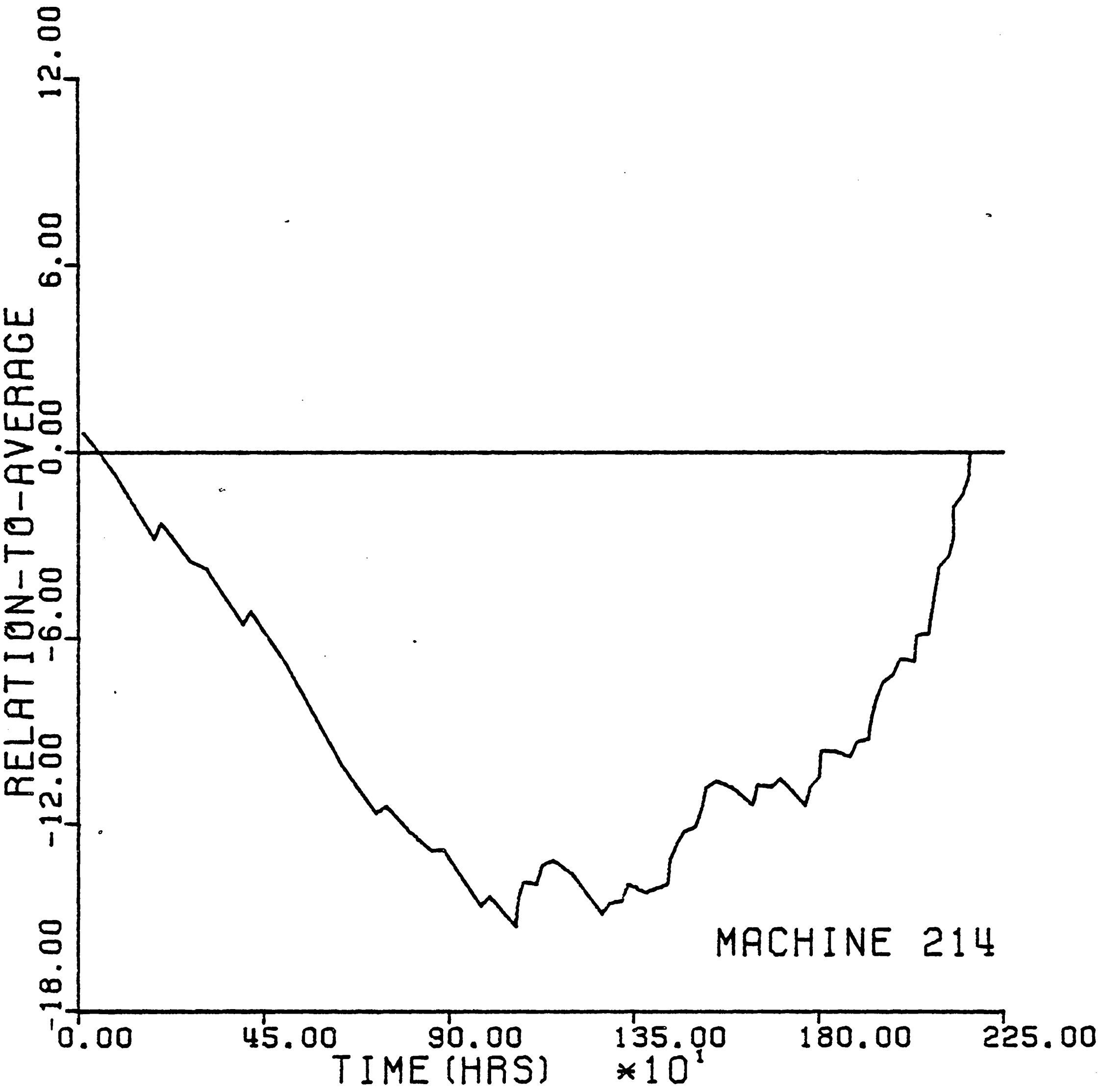

Figure 7. Cumulative number of failures above or below the average time between failures against the time of failure in operating hours for machine 214.

than the average. Conversely, if the slope is negative the failure rate is below average.

Figure 7 is a graph of the same machine as in Figure 5. The "U" shaped curve is an indication of a trend toward an increasing failure rate. Since the plotted points are adjusted for the average failure rate over the study period the curve ends at zero. The graph shows that the machine was failing less frequently than the average rate during the first half of the period and faster than average during the second half. An inverted "U" would suggest a decreasing failure rate. There is also very little fluctuation, unlike the curve in Figure 6.

Graphs of this type could be used by a manager to examine the performance of a machine. A "target" and acceptable range of time between failures could be established. Then any time a point falls outside this range the manager could determine the cause and make any changes necessary.

Numerical methods

Testing for trend is important for two reasons. First, the existance of any trend is important information in itself. Also, a trend indicates that the data does not represent a stationary point process, i.e. it is not all identically distributed and, hence, should not be modeled with a single distribution.

The times between failures are in the form of point events occurring in a continuum of time. Data of this type are considered a time series. The analysis techniques to perform this test are described in Cox and Lewis (1966). The objective is to obtain a dependent variable, successive values of which are independently distributed with constant variance, and for which the probability distribution is moderately non-normal.

To accomplish this the observations are first grouped to remove short-term variability. The dependent variable is, then, the natural logarithm of the total of the observations in the group and the independent variable is time. The test is a regression analysis that tests the significance of the slope parameter. The validity of the model can be checked by comparing the residual mean square about the regression line with the theoretical variance.

The Statictical Analysis System (Barr et al 1976) was used to conduct the regression analysis once the dependent and independent variables were calculated. A 95 percent confidence level was used for all the tests.

Comparing failure and repair distributions

When comparing different machines, reliability is almost as important as the production rate. A slower machine that is more reliable may be more cost effective than a faster machine. Currently, the common method of assessing the reliability of a machine is to obtain a user's subjective opinion. Also, there are variables that affect the reliability just as there are variables that affect the production rate. The major determinants of skidder productivity are skid distance and load size. This has been confirmed by many production studies. However, the major factors affecting skidder reliability have not been identified. The methods proposed in this section can be used to detect differences and, thereby, determine these variables.

In an effort to make the analysis techniques as simple, practical, and applicable as possible a technique using logarithmic transformations, linear regression analysis and an F test were used. The procedure described in this section is taken from Carter (1972) and Cunia (1973).

The first step in comparing the times between failures or repair times is to arrange the data into some form that is amenable to statistical analysis. The Weibull distribution was chosen to model the time-between-failure and time-to-repair data because of its adaptability and use in other reliability studies. Although the exponential distribution is somewhat easier to use, it was not sufficiently flexible to accurately represent much of the data.

The Weibull distribution has a probability density function and cumulative distribution function (CDF), but only the cumulative distribution function was used in the analysis. The equation for the CDF is:

$$F(t) = 1 - \exp(-(t - \underline{n}/\underline{O})**\underline{B}) . \qquad (9)$$

Where the constants appearing in the expression are as follows.

$\underline{n}$ - is the locating constant defining the starting point or origin of the distribution.

$\underline{O}$ - is a scaling constant that stretches the distribution along the time axis. It is also the time at which 63.2 percent of the events have occured regardless of the value assigned to $\underline{B}$. For this reason it is often referred to as the characteristic life.

$\underline{B}$ - is the shaping constant which primarily controls the shape of the curve. The Weibull distribution is very adaptable. For $\underline{B} = 1$ it reduces exactly to the exponential distribution and for $\underline{B} = 3.44$ it is an approximately normal distribution.

Since the Weibull distribution was used to model the time-between-failure and time-to-repair distributions the parameters for the distributions were predicted. Maximum likelihood procedures have been developed for determining these parameters, but the procedure requires a strong statistics and mathematical background as well as a computer. And, tests for differences between or among parameters requires tables that are not commonly available.

A simpler method to predict the parameters is to use Weibull probability plotting paper. Plotting the data on this paper will produce a linear graph as explained in Carter (1972). The slope of the line is the shape parameter and the intercept on the y-axis is the shape parameter times the natural log of the scale parameter. If Weibull probability plotting paper is not available Carter (1972) explains how to transform the data so it will plot as a straight line. The data transformation method was used in this analysis.

Once the data has been plotted some scatter will exist and the best fitting line can be determined using the method of least squares or regression techniques. The regression analysis calculates values for the slope of the line and the y-axis intercept from which the shape and scale parameters can be determined. This method is explained in almost any basic statistics book, such as, Dixon and Massey (1969) or in greater detail in books specifically on this technique such as Draper and Smith (1964). This analysis can be done using many hand held calculators, however for speed and convenience it was performed on the computer using the Statistical Analysis System (SAS) (Barr et al 1976).

After the parameters were estimated, tests for goodness of fit were conducted to determine how well the distributions represented the actual data. Two tests were used, the Kolmogorov-Smirnov test (Hollander and Wolfe 1973) and the Chi-squared goodness of fit test (Dixon and Massey 1969). Tests were conducted at a 95 percent confidence level.

The method used to compare the distributions is a combination of the data transformation described by Carter (1972) and a method of comparing parameters from regression analyses using dummy variables explained by Cunia (1973).

For two Weibull distributions to be the same they must have the same shape and scale parameters. So, a method of testing both parameters is needed. The technique of using dummy variables in regression analysis allows simultaneous comparisons of any number of lines and can be used to test for parallel slopes or equal y-axis intercepts individually or test for both parallel slopes and equal intercepts at the same time. A test for parallel slopes is a test for equal shape parameters. The test for equal intercepts, however, has no meaning unless the shape parameters are equal since the intercept is $\underline{B}*\ln(\underline{O})$. It is possible for the intercepts to be the same when the shape parameters are not because the differences in one can offset the differences in the other. When the shape parameters are determined to be the same, then a test for different intercepts is a test for different scale parameters.

Since the tests were conducted at the 95 percent confidence level there is some error present when accepting the shape parameters as being the same. When the shape parameters are accepted as being the same and the intercepts are tested, this error is introduced into the test for equal scale parameters because the intercept is a combination of the shape and scale parameters.

This method has not been used to compare Weibull distributions so the effect of introducing the error involved in accepting the shape parameters into the test for similar scale parameters could not be assessed. However, the objective in developing this methodology was to suggest methods that were simple and practical. This method has advantages over other comparison techniques because of its simplicity and selectivity and it allows multiple comparisons. Since no other studies have used this method for comparing distributions the Kolmogorov-Smirnov test was used as a check on the results. Also, since this technique includes the regression analysis mentioned above, the parameters for the distributions can be predicted at the same time the comparisons are made.

This analysis can also be performed without a computer because of the additive property of the sum of squares as explained by Cunia (1973). Since a computer was available, once the models were properly formulated SAS was used to complete the tests. Tests were conducted first to determine which distributions had similar shape parameters. Then these distributions were tested for similar scale parameters.

Once the regression analysis calculated which distributions were identical it was necessary to determine how the remaining distributions were different. If $G(x)<F(x)$ then obviously the machine represented by the function $G(x)$ has longer times between failures than the machine represented by $F(x)$. This is the case when two machines have the same or similar shape parameters but different scale parameters. However, if the shape parameters are not the same the comparison is more complicated. If the shape parameter for $F(x)$ is less than that for $G(x)$, then $G(x)<F(x)$ for some interval $(0,y)$; for $x>y$, $F(x)<G(x)$.

When the second case exists the user must exercise his own judgement to determine which is more desirable. To aid in determining which distributions were more desirable the means of the distributions were calculated. The mean for a Weibull distribution is given by:

$$(\underline{Q} * \Gamma(\underline{B})) + \underline{n} \qquad (10)$$

where $\Gamma(\underline{B})$ is the gamma function of $\underline{B}$.

Comparisons of these mean values aided in determining which machines had more favorable distributions.

This test is very sensitive to differences between distributions and could not be used to test for differences among the machine types because of the amount of variability within each machine type. To test for differences among the three types of feller-bunchers a Kruskal-Wallis test (Conover 1971) was used to test for differences among the distribution means for the three machine types.

After the analysis was performed on the machine as a unit, the times between failures were separated into two categories, failures of the carrier and failures of the shear head. The procedure described above was then used to calculate distributions and means to represent this data. These numbers were used in comparisons to identify differences among machine types and machine ages for the carriers only, excluding the failures of the shear head.

Analyzing Availability for Different Strategies

Calculation of Inherent Availability

Before considering different maintenance and repair strategies the inherent availability was calculated for each machine. These availabilities exclude some effects due to cooperators, such as, repair parts inventory, mechanic availability, service time, and maintenance strategies. They do, however, include the effect of operators, harvesting conditions, and the mechanic's ability since these affect the time between failures and the time to repair those failures.

The inherent availability (IA) was determined using the distribution mean time-between-failures (MTBF) and the distribution mean time-to-repair (MTTR) for each machine. The formula used was:

$$IA = \frac{MTBF}{MTBF + MTTR}. \qquad (11)$$

A Kruskal-Wallis test (Conover 1971) was conducted at the 95 percent confidence level to identify any significant differences among the inherent availabilities of the three types of machines.

These availabilities represent the maximum that could be attained on a sustained basis. To achieve these availabilities it would be necessary to have a mechanic available to work on the machine the moment it failed and he would have to have all the tools and parts necessary to effect the repair. Also, the machine would have to be serviced during other than scheduled machine operating time.

This situation is not practical and, in fact does not exist. A mechanic is necessary and any time there is more than one piece of equipment on a harvesting operation there is a possibility that both will be down at the same time. Since it would be difficult to economically justify a mechanic for only two machines, the probability is relatively high. It is also impractical to have on hand all the parts necessary to effect any repair. There is some optimum level, but it is important to know the effect of deviating from this level.

The machine also must be serviced every day, fluid levels checked, fueled, greased, and minor repairs performed. Since some of the service is necessary just prior to operation, the equipment operator is the most logical person to perform this service. Therefore, it is usually accomplished during scheduled operating time. This will decrease availability.

Two other factors that affect availability are the reliability and maintainability of the machine. These are expressed by the time between failures and the time to repair, respectively. It would be desirable to have the longest possible time between failures and the shortest possible time to repair, but this would greatly increase the price of the machine. There is a point of diminishing returns where the increased expense would outweigh the benefit gained.

Simulation of operational availability

To determine the effect of each of these variables operational availabilities must be determined over the probable range each of these variables would assume. Also, since some of these variables are interrelated the calculations are not straightforward. For example, as the time between failures increases the proportion of the time spent servicing the machine also increases. Because of this a simulation program was written to calculate these operational availabilities. A benefit of using a simulation program is that it not only calculates an average, but it can provide information on just how bad or good things can be.

The program is based on three distributions, time-between-failures, times-to-repair, and delay time. It also includes daily service on the machine. Other variables are the service rate, scheduled hours per day, days per week, and seed values for the random number generators for each of the distributions.

The simulation program is a relatively simple next event type of simulator. The machine is scheduled to be serviced at the beginning of each day unless the machine is down. The occurrence of a failure generates the time of the next failure. Failures are always followed by a delay time and a repair time.

The time between failures and times to repair were modeled with Weibull distributions, but the delay time was modeled with a simple straight line relationship with a positive y-axis intercept. This is because most equipment owners have parts on hand to repair recurring failures so there is usually no delay waiting for parts and the operator can effect the repair without the help of a mechanic. So, for a certain percentage of the repairs the delay time will be zero.

Events are stored in a file and removed chronologically. After the event is removed from the file it is checked to determine if it is the next logical step. For example, if a beginning of service event occurs, but the machine is being repaired, the service is rescheduled to occur at the proper time.

There are four different states that the machine can be in, operating, service, down due to a delay, and down due to active repair time. The program records the amount of time in each state. It also calculates a mean and a standard deviation for the time between failures, time to repair, and delay time.

The program was validated by comparing the sequence of operations in the program with the normal sequence of operations for a harvesting operation and by comparing results with actual field data. Five sets of random numbers were used and the averages were compared to the actual field data.

Once the program was validated it was used to evaluate the effect of changes in some of the parameters on machine operational availability. Those examined were reliability, time to repair, and delay time. Each in turn was varied as all the others were held constant. Each time a variable was changed the program was run five times using each of the five sets of random numbers used to validate the program and the averages for these five runs were calculated. The simulated time approximated one year of actual machine operation.

The effect of changes in reliability on machine availability was observed by predicting the availability while varying the reliability. The mean time between failures was used as a measure of reliability. To determine the availability different machine time-between-failure distributions were used in the simulation program. Since the time to repair would have some effect, two different time-to-repair distributions were used.

Changes in availability due to different times to repair were evaluated in the same manner. Different time-to-repair distributions were used as input to the simulation program while the other parameters were held constant. Two analyses were conducted, one for a machine with a relatively high reliability, the other for one with a relatively low reliability.

To determine the effect of changes in the delay time the same procedure was used; different delay distributions were substituted into the simulation program. However, actual data was not used to derive these distributions, only provide guidance. It was assumed that no delay would take more than two days and there would be some percent of the repairs for which there would be no delay time. The three percentages used were 40, 60, and 85. The other variable would be the slope of the line which would reach its maximum at two days or in this case 16 hours. For example, in the case of the 60 percent, 60 percent of the time the delay will be zero. The other 40 percent of the time the delay will be between zero and 16 hours. Again, the same two machines with different reliabilities were used.

Listing the Reasons for Failures

A timber harvesting operation must maintain a parts inventory to reduce the amount of downtime caused by equipment failures. Since most harvesting operations are not located near parts suppliers, it is impractical to drive to town every time a repair is necessary. However, the amount of parts on hand should be balanced against the availability of the part, the frequency of use, and the cost of carrying the part in inventory. Generally, too many slow-moving parts are kept in inventory. A Forest Engineering Research Institute of Canada study (Garner and Novak 1980) reported that on some operations in eastern Canada a 50 percent reduction in present stocking levels would not increase downtime. A knowledge of the type of repairs necessary would also provide an indication of the training a field mechanic should have.

A listing of repairs performed by major categories was produced to provide information about the cause of failures, parts used, and skills a mechanic should have.

RESULTS AND DISCUSSION

Data Collected

Table 1 lists each of the 32 machines used in the analysis along with the number of operating hours during which the machine was observed and the number of failures that occurred during the study period. The total number of machine operating hours covered by the study was 41,300 with 16,801, 14,267, and 10,232 hours for machine types 1, 2, and 3, respectively. The total number of failures observed was 1814 and the breakdown was 826, 553, and 435 failures for machine types 1, 2, and 3, respectively.

The study period time frame extended from a low of ten weeks to two years. Table 2 shows the length of time data was collected on each machine. It also includes the model year of each machine and the average number of operating hours per week by machine. Analysis of the data revealed that there was no significant difference in the number of operating hours per week at the 95 percent confidence level among the type 1 machines for which three different

Table 1. Operating hours and the number of failures by machine for the 32 machines included in the study.

Machine	Operating hours	Number of failures
111	2246	126
112	694	43
113	1965	111
114	1359	71
115	248	15
116	1756	72
117	2196	156
118	2391	111
119	2518	90
Total	15,373	795
121	400	7
122	334	5
131	158	20
132	336	14
133	200	5
Total	694	19
211	1857	80
212	1516	76
213	2150	85
214	2180	68
215	1303	47
216	1187	22
217	625	30
Total	10,818	408
221	356	9
222	180	7
241	1106	54
242	1163	46
243	644	129
Total	2913	129
311	2405	74
312	1833	115
313	2151	66
314	967	58
315	1498	65
316	1378	57
Total	10,232	435

Table 2. The model year, study period in weeks, and the average number of operating hours per week by machine for each of the 32 machines included in the study.

Machine	Model year	Study period (weeks)	Average operating hours per week
111	72	104	21.6
112	73	29	23.9
113	73	104	18.9
114	74	60	22.6
115	72	16	15.5
116	72	72	24.4
117	72	104	21.1
118	77	104	23.0
119	73	104	24.2
Average			22.1
121	77	11	36.4
122	77	11	30.4
Average			33.4
131	73	10	15.8
132	75	10	33.6
133	78	10	20.0
Average			23.1
211	77	81	22.9
212	78	79	19.2
213	78	79	27.2
214	78	75	29.1
215	78	60	21.7
216	79	37	32.1
217	78	33	18.9
Average			24.4
221	78	12	29.7
222	78	6	30.0
Average			29.8
241	78	33	33.5
242	78	33	35.2
243	79	22	29.3
Average			33.1
311	76	104	23.1
312	76	104	17.6
313	77	104	20.7
314	77	104	9.3
315	77	104	14.4
316	77	104	13.2
Average			16.4

cooperators supplied data. However, the average number of operating hours for machine type 1 for cooperator two was significantly higher than that of cooperator one at the 94.2 percent confidence level. Cooperator one's type 2 machines were used significantly less than cooperator two's and cooperator four's type 2 machines.

When comparing the three types of machines from cooperator one's operation the type 3 machines were used significantly less than the type 1 or 2 machines, but there was no difference in the usage of type 1 and 2 machines. This is probably due to the method of harvesting in which the type 3 machines were used, their full capacity was not required.

From these results it seems logical to assume that the number of operating hours per week a machine is scheduled for use is a function of company policy as it affects operator performance and repair time as well as the machine capacity.

Analysis of Trends in Time Between Failures

Of the 32 machines for which data was supplied only 24 were tested for trends in time between failures with time.

Those not tested were 115, 121, 122, 131, 132, 133, 221, and 222. Data on these eight machines was not of sufficient duration.

Results from the test for trend with time using the simple linear model are given in Table 3. Nine of the machines did exhibit significant decreases in their times between failures. Two were type 1 machines, 111 and 118; four were type 2 machines, 211, 212, 214, and 241; and three were type 3 machines, 311, 312, and 314. Adding the squared term to the model increased the number of machines with significant changes to 12. These machines were 216, 315, and 316.

Although only 12 of the machines had significant changes in their times between failures, twenty of the machines did exhibit a trend toward decreasing times between failures as indicated by the negative coefficient for the z(i) term in the model as listed in Table 3. Their significance levels are also given.

The data was arranged into groups of five to eleven based on the amount of data. Mulitples greater than four were used for reasons explained by Cox and Lewis (1970) and the group size that minimized the amount of unused data was

Table 3. Regression analyses data for the simple linear model by machine for the 24 machines on which tests for trend were conducted.

Machine	Significance level (%)	R-square	Coefficient of z(i) (E-03)
111	99.96	.492	-.6376
112	11.20	.004	.0716
113	0.66	.000	-.0014
114	85.43	.245	-.4234
116	57.63	.082	.2222
117	88.04	.154	-.2159
118	98.36	.490	-.5184
119	94.28	.345	-.4198
211	97.37	.306	-.5726
212	97.45	.329	-.5627
213	92.37	.239	-.2656
214	99.99	.863	-.8486
215	59.46	.101	-.4280
216	60.07	.361	-.9121
217	7.54	.002	.1641
241	96.08	.478	-.9235
242	73.59	.174	.3932
243	60.83	.124	-1.1348
311	99.79	.630	-.9111
312	99.56	.388	-.5071
313	61.84	.070	-.1755
314	99.79	.669	-1.5981
315	77.71	.204	-.4060
316	89.74	.246	-.8742

chosen. Because of the nature of the data there was still a considerable amount of variability. This is indicated by the range of R-square terms from the analysis as listed in Table 3. In a few cases the linear model could not account for any of the variability in the data. Since the coefficient for the z(i) terms for these machines are close to zero, then a more or less constant time between failures with some sort of fluctuation, possibly seasonal, is suggested and further analysis was necessary. For those machines with significant results, R-square values were somewhat higher, ranging from 0.306 to 0.863, indicating there is still some deviation from a linear model. It is possible that larger group sizes would reduce the variability and provide a better test for trend. This would require data for a longer period than available for this study.

Adding the squared term to the model did significantly increase the R-square for seven of the machines and helped slightly for three others. In all these cases the plot of the data resembled an inverted "u" with a long right-hand tail. This was probably due to the fact that the study was started in January. As will be mentioned later, there was a tendency toward shorter times between failures during the winter with an increase during the summer. This causes the initial group values to be slightly below those immediately subsequent producing a deviation from linearity. This is assumed to be due to the data collection procedures and not a departure from the simple exponential model.

Four of the machines, numbers 112, 116, 217, and 242, tended to have a increase in their times between failures as indicated by the regression analysis. However, none of them were significant. An examination of the data shows a very large amount of variability as is indicated by R-square values of 0.002 to 0.174.

Machine 112 was an older type 1 machine that was dropped from the study after 694 operating hours due to a catastrophic failure. The reason for the appearance of an increasing time between failures was due to the study period. The initial shorter times between failures during the winter were followed by a time of increasing times between failures during the summer just before the machine was removed from the study.

Machine 116 was also retired during the study. For the 1756 operating hours for which the machine was observed the times between failures first decreased, then remained relatively constant for approximately 750 hours followed by a period of increasing, then decreasing times between failures. The regression analysis, which was not significant, indicated an increasing time between failures; however, it appears that the times between failures were more or less constant with periods of fluctuation.

Machines 217 and 242 were new machines. Regression analyses, again, were not significant, but indicated an increasing time between failures. This could be characterized by the inverted "bath tub" shaped distribution of times between failures, a low initial time between failures followed by a period of increasing time between failures as the "bugs" are worked out of the machine. The change, however, was not enough to be significant.

The purpose of grouping the data in the numerical analysis was to reduce the variability among the data points. This tended to mask any type of fluctuation. Because of this, cumulative plots of the second type mentioned in the methods and procedures section were prepared for each machine to examine the variation in times between failures. They are included in Appendix B.

An examination of these plots for the type 1 machines indicated that the time between failures for all machines tended to fluctuate. For machines 111 and 118 the trend toward a decrease in the time between failures was stronger than any seasonal fluctuation. There was no pattern to the variation for machines 112 and 116. However, machines 113, 114, 117, and 119 exhibited fluctuations that appeared to be seasonal. The average time between failures increased from May through July with a slight decrease in August followed by a shorter times between failures through late winter and early spring.

Results of the graphical analysis for type 2 feller-bunchers was the same as type 1. For machines 212, 214, 241, and 243 the trend toward a decreasing time between failures was more obvious than any fluctuation. There was no pattern to the fluctuation for machine 242. And, machines 211, 213, 215, 216, and 217 exhibited lower times between failures during the winter than in the summer.

Only one type 3 machine, 312, demonstrated the typical seasonal fluctuation in time between failures. The variation for machine 313 did not follow any seasonal pattern. The trend toward a decrease in the time between failures was most evident for machines 311 and 314. The same is true for machines 315 and 316 except that there was an early period of low times between failures during the summer.

These results seem to indicate that machines with a strong tendency toward a decrease in their times between failures do not exhibit significant seasonal fluctuations. For those machines not having significant trends, the time between failures does seem to vary with the time of year, increasing in the summer and decreasing in the winter. Because of the area of the country in which this study was conducted it is expected that the seasonal fluctuation is not due to temperature extremes, but rainfall.

This information substantiates the hypothesis that times between failures are time dependent, and do decrease with time. Although the general tendency is for the times between failures to decrease with time, there are periods when the times between failures increase. There could be several causes for these increases, such as, seasonal fluctuations or the time after a major overhaul.

Comparison of Time-Between-Failure Distributions

Time-between-failure (TBF) distributions were generated for all 32 machines in the study. Those machines that had significant changes in their times between failures could not be represented by a single distribution. To determine which part of the data was identically distributed plots of the data from the tests for trends in the time between failures section were examined and divided into periods during which there was little change in the times between failures. The test for trends with time was then conducted for each period. This produced a total of 41 time-between-failure distributions.

There are two types of failures, instantaneous and gradual or depletion. To some extent, the time of failure was determined by the operator or mechanic since they chose the exact time to repair a gradual failure, such as a leaking hydraulic hose. This would have some effect on the distribution of time between failures, but it was not possible to control this time. The sample should be of sufficient size to produce a realistic average.

The first step was to determine parameters for each of the distributions. These are listed in Table 4.

Results of the Kolmogorov-Smirnov goodness of fit test indicate that all of the calculated distributions are no different than the empirical distribution functions at the 95 percent confidence limit. The Chi-squared goodness of

Table 4. Shape, scale, and location parameters for the Weibull distributions that represent the time-between-failure distributions for the 32 machines included in the study.

Machine number	Parameters		
	Shape	Scale	Location
111-1	1.135	22.32	0.
-2	1.254	11.05	0.08
112	0.681	13.16	1.99
113	0.816	15.59	0.99
114	0.748	16.32	1.99
115	0.963	15.54	0.
116	1.121	25.14	1.40
117	0.743	10.83	0.99
118-1	1.303	31.98	0.04
-2	0.986	13.17	1.42
119	0.744	25.75	0.99
121	0.946	38.33	0.
122	1.250	31.39	0.
131	1.692	8.46	0.
132	0.959	19.24	1.49
133	0.681	16.06	0.
211-1	0.927	22.42	2.74
-2	0.947	10.96	1.68
212-1	0.989	20.27	1.80
-2	1.196	14.10	0.
213	1.070	24.54	0.28
214-1	1.313	61.63	0.
-2	1.352	21.54	0.
215	0.912	23.53	0.50
216	0.941	45.66	0.
217	0.875	14.97	0.38
221	0.801	28.01	0.
222	0.747	22.31	0.
241-1	0.717	19.81	1.87
-2	0.766	11.05	1.43
242	0.655	20.08	1.49
243	0.745	14.01	0.88
311-1	0.963	42.04	0.
-2	0.789	6.91	1.83
312-1	1.037	16.98	0.
-2	0.734	7.83	1.94
313	0.966	25.35	2.65
314	1.391	16.33	0.
315	1.117	22.49	0.61
316-1	0.659	28.83	0.99
-2	1.280	7.18	0.

fit test, however, rejected two of the calculated distributions.

The reason that these two distributions were rejected was because of "flat spots" in the data. For example, when ranking the times between failures for machine 241-1, there were none between 8 and 20 hours. This causes a long horizontal line in the empirical distribution function. Because of this a smooth curve cannot fit the data, but probably does represent the "real world" situation. For this reason all of the calculated distributions were considered acceptable representatives of the empirical data.

The 41 time-between-failure distributions are shown in Appendix C. For 35 of the machines 50 percent of the time the machine will fail within 18 hours or less of the last failure. This means that most of the machines required some type of repair activity approximately every two days. And, the chances of operating an entire week without a failure were less than one out of five.

Shape parameters ranged from 0.656 to 1.692 and scale parameters from 6.91 to 61.63. This wide variability in shape indicates that a simple model, like the negative exponential distribution, could not accurately represent all of the data. It also shows that there is no characteristic shape for the TBF distribution for feller-bunchers as a whole.

Results of the tests to determine which failure distributions were identical resulted in reducing the number of shape parameters necessary from 41 to seven while tests for similar shape and scale parameters resulted in the need for 26 different distributions to represent the original 41.

Table 5 is a listing of the machines by shape parameter group and in order of scale parameters. Single spacing in the table indicates those machines for which there were no significant differences among the parameters at the 95 percent confidence level, double spacing represents significant differences. The -1 and -2 are used to indicate those machines which had significant trends in their times between failures and, therefore, required two distributions to represent the data. The -1 is the distribution for the early and, hence, longer times between failures.

Table 5 shows that no one machine type dominates any of the seven groups based on shape parameters, nor does one type tend to have higher or lower than average scale parameters. In fact, there are cases where machines of each

Table 5. Results of tests for similar time-between-failure distributions.

	Machine number	Parameters	
		Scale	Shape
Group I			0.728
	311-2	6.91	0.789
	312-2	7.83	0.734
	117	10.83	0.743
	241	11.05	0.766
	112	13.16	0.681
	243	14.01	0.745
	113	15.59	0.816
	133	16.06	0.681
	114	16.32	0.748
	241-1	19.81	0.717
	242	20.08	0.655
	222	22.31	0.747
	119	25.75	0.744
	221	28.01	0.801
	316-1	28.83	0.659
Group II			0.938
	211-2	10.96	0.947
	118-2	13.17	0.986
	217	14.97	0.875
	115	15.54	0.963
	132	19.24	0.959
	212-1	20.27	0.898
	211-1	22.42	0.927
	215	23.53	0.912
	313	25.35	0.966

Table 5. Continued

	Machine number	Parameters	
		Scale	Shape
Group II (cont)	121	38.33	0.946
	311-1	42.04	0.963
	216	45.66	0.941
Group III			1.057
	312-1	16.98	1.037
	213	24.54	1.070
Group IV			1.124
	111-1	22.32	1.135
	315	22.49	1.117
	116	25.14	1.121
Group V			
	212-2	14.10	1.196
Group VI			1.314
	316-2	7.18	1.280
	111-2	11.05	1.254
	314	16.33	1.391
	214-2	21.54	1.352
	122	31.39	1.250
	118-1	31.98	1.303
	214-1	61.63	1.313
Group VII			
	131	8.46	1.692

different type have indentical TBF distributions as is the case for machines 119, 221, and 316-1.

A comparison of these results with the results of the Kolmogorov-Smirnov (K-S) test indicated that the K-S test is much more conservative than this test. The K-S test accepted as being the same all distributions that the proposed method accepted and some that the proposed method had rejected as being the same.

The maximum and minimum TBF distributions for each of the three machine types are shown in Figure 8. The remaining distributions lie between these extremes. As can be seen there are no differences between the type 1 and type 3 machines. However, the type 2 machines have more favorable extremes. Most of this difference is probably due to machine age rather than type. All of the type 2 machines were new when they were studied whereas the types 1 and 3 machines ranged from 1972 to 1977 models.

Also, there are other reasons for the unusually short average time between failures for the lower extremes for type 1 and type 3 machines. Machine 316 which is the lower extreme for the type 3 machines had been put into storage during the study. Before being put into storage it was

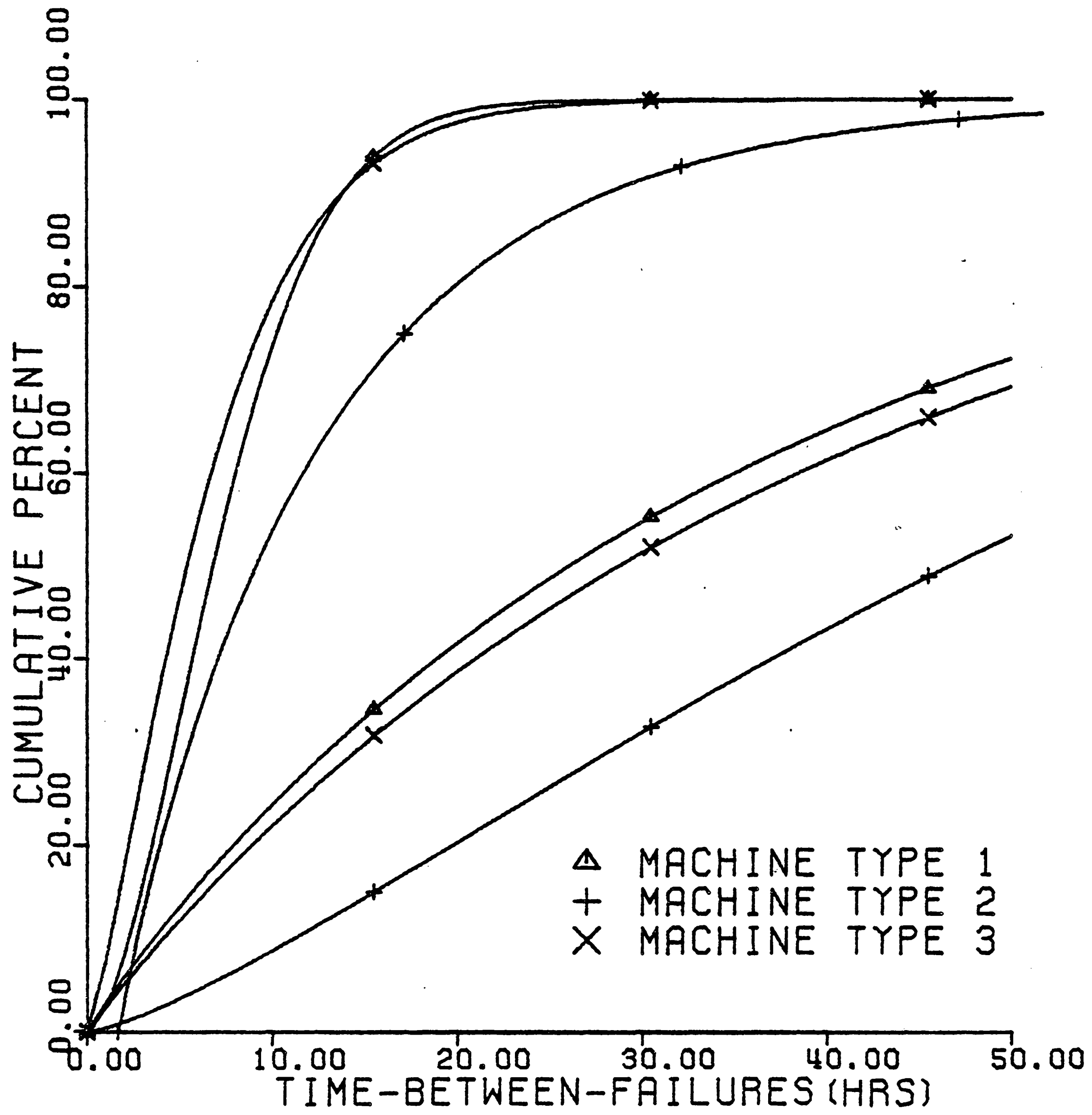

Figure 8. Weibull distributions that represent the longest and shortest time-between-failure distributions for each of the three types of feller-bunchers.

experiencing normal times between failures, but its repair time was rather high. After being put back into service without being rebuilt it experienced an unusually high number of failures. Machine 131 which represents the lower extreme for the type 1 machines has an auger cutting head rather than a shear. All of the other type 1 machines have shears. This auger head had a higher frequency of failure than the others and the carrier was rather old. This is the reason for its shorter than usual times between failures.

To help understand the differences in time between failures among the machines Table 6 is included. It is a listing by machine type of the distribution means for the times between failures.

Although the extremes for machine type 2 look more favorable, if you consider the middle half there are no real differences. From the numbers in Table 6 and considering the middle half rather than the extremes, the upper and lower values would be:

	Machine Type		
	1	2	3
lower mean	15.8	17.7	11.4
upper mean	25.5	26.6	28.4

Table 6. Distribution means for the Weibull distributions that represent the times between failures for each machine by machine type.

Type 1		Type 2		Type 3	
Machine number	Mean (hours)	Machine number	Mean (hours)	Machine number	Mean (hours)
131	7.551	211-2	13.281	316-2	6.652
111-2	10.634	212-2	13.274	311-2	9.738
117	13.986	241-2	14.366	312-2	11.430
118-2	14.676	217	16.383	314	14.899
115	15.805	243	17.654	312-1	16.731
113	18.412	214-2	19.748	315	22.202
112	19.104	212-1	23.150	313	28.353
133	20.886	213	24.184	316-1	39.790
132	21.090	215	25.087	311-1	42.758
111-1	21.325	211-1	25.996		
114	21.464	241-1	26.392		
116	25.507	222	26.650		
122	29.236	242	28.696		
118-1	29.555	221	31.710		
119	31.855	216	46.939		
121	39.309	214-1	56.814		

So, even though the extremes look more favorable the averages are about the same. A Kruskal-Wallis test for differences in the means also indicates no differences among the machine types.

These results indicate that there were no differences in time between failures due to machine type for these machines. However, the type 2 machines were newer than the type 3 machines which were newer than the type 1 machines. So, since the data included such a wide range of machine ages another test was performed on only the 1977 and 78 model machines. Again, there were no differences in time between failures due to machine type.

If in fact there are no differences in times between failures due to machine type, then differences in times to repair, production rates, or other special considerations must be used to justify the more expensive machines.

There were some differences due to cooperators in this study, but they were not very pronounced. Three different cooperators provided data on type 1 and type 2 machines. There did not appear to be any differences between Cooperators One, Three, and Four. However, all four of Cooperator Two's machines had high average times between failures. The other Cooperators had machines that performed as well, but when considering their entire equipment fleets they were not as good.

From the data collected it was not possible to determine the reason that Cooperator Two's machines had better TBF distributions. It is possible that they have more effective maintenance strategies or it could be an interaction of other factors such as operator, logging conditions, or tree size.

There was a considerable amount of variability in the TBF distributions for machines of the same age belonging to the same cooperator. In an effort to reduce some of this variability failures were separated into failures of the carrier and failures of the shear.

Most failures of the shear were minor failures involving only replacing hydraulic fittings and hoses, shimming the cutting blades, or packing a cylinder. Because these are common malfunctions, parts were available and repairs did not require extended periods of time and in many cases could be performed by the operator. Failures of the carrier, on the other hand, covered a wider range. There were no recurring problems except as will be mentioned for machine type 1. Because of this there were times when the part was not available and the repair usually required the attention of a mechanic. Therefore, failures of the carrier are more critical than failures of the shear.

The study periods for some machines were not long enough to obtain a sample of sufficient size after separating the failures into the two categories. Therefore, only 25 machines were considered in this analysis. Table 7 lists the machines and the distribution mean time between failures for the carrier and the shear in order of the time between failures for the carrier.

Failures of the shear have a relatively minor effect when compared to failures of the carrier. They are usually dependent on harvesting conditions and the operator. Because of this there is a great deal of variability in TBF distributions. Also the initial cost of the shear is minimal when compared to the cost of the carrier. A Kruskal-Wallis test indicated that there were no significant differences at the 95 percent confidence level among the shears of the three types of feller-bunchers. However, the shears on the type 2 machines had significantly shorter times between failures at the 78 percent confidence level. For these reasons they will not be considered further,

Table 7. Distribution means for the Weibull distributions that represent the times between failures for the shear head and the carrier.

Machine number	Mean (hours)	
	Carrier	Shear head
117	15.69	106.10
112	17.16	52.32
111	22.64	51.29
113	23.26	62.74
114	24.18	41.30
116	26.87	93.67
118	32.66	42.49
132	37.40	30.44
119	51.36	62.21
217	28.27	31.63
212	30.16	45.33
243	32.48	24.65
211	33.83	61.34
241	36.64	37.29
215	41.01	51.82
214	45.73	60.84
242	45.76	39.51
213	50.09	40.50
312	15.46	89.32
314	20.87	31.18
315	38.22	48.31
313	40.19	58.14
311	41.68	83.61
316	41.96	41.66

except to point out that the auger head had much shorter times between failures than the conventional shear head.

The amount of variability in the distribution mean time between failures for the carriers was less than for the entire machine. The type 1 and 2 machines exhibited an even spread, but the type 3 machines seemed to fall into two distinct groups. It was not possible to determine the reason for the two groups.

There are no significant differences among the three types of carriers according to the results of a Kruskal-Wallis test for differences conducted at the 95 percent confidence level. The results were significant at the 91 percent level however. For this case the type 2 carriers had significantly longer times between failures than the type 1 carriers. Again, if only the 1977 and 78 model machines are considered there are no significant differences.

There is another consideration for the type 1 carriers. The brand of type 1 carriers in this study had a problem with final drives on earlier model machines. The manufacturer has since corrected the situation and made conversion kits available for the older models. Cooperator

One chose not to purchase the "kits" and is continuing to experience excessive recurring final drive and track pin failures. The result of the new final drives is readily apparent. Machines 111 through 117 have the older final drives. Machines 118, 119, and 132 have the new final drives, and as shown in Table 7 have the longest times between failures of the type 1 machines. In fact, machine 119 is a 1973 model equipped with the "wide gauge logger" option which includes the new final drives and its mean time between failures is twice as long as the other 1973 model machines. Although the new final drives significantly improved the distribution mean time between failures, the change does not appear to be enough to cause the type 1 carriers to be different from the type 2 or 3 carriers regardless of age.

Although there were no significant differences in times between failures among the three types of feller-bunchers, the harvesting conditions should be considered. Data was collected from typical harvesting operations. This means that the type 1 feller-bunchers were cutting larger trees and probably operating over softer soil than the other types. This progression continues with the machine type; the type 2 machines being intermediate. The type 3 feller-bunchers would be cutting the smallest trees, operating over favorable soil conditions, and working on minimum slopes. If all three machine types were operating under the same conditions, the results may have been different. Also, all of the machines in this study were operating on relatively flat terrain and results may be different for the same machines operating on steeper terrain.

Times between failures decrease with machine age. This fact has long been accepted. It has been hypothesized that a new machine when placed in service will demonstrate times between failures that conform to the inverted "bath-tub" shaped curve, low initial times between failures that increase to some higher level where they remain constant followed by a period of decreasing times between failures. Data from this study suggests a modified inverted "bath-tub" shape.

Of the 12 type 2 machines in the study ten were new or less than 200 operating hours old when they entered the study. Distribution means for the initial operating hours ranged from 16.4 to 56.8 hours indicating a very wide range in times between failures. Since seven of the machines belonged to Cooperator one, the differences must be due to inherent machine differences, operators, or operating conditions. Two of the 12 machines had slightly increasing times between failures, but the others had decreasing times between failures and; in fact, four had significant decreases in their times between failures.

An examination of type 1 machines also supports the hypothesis that times between failures are time dependent. Cooperator One had one 1977 model machine and the others were 1974 or older models. The times between failures of the initial distribution were much higher than the older machines. However, during the second year of the study the TBF distribution was no different than the other machines. Cooperator Two's two type 1 machines were 1977 models and they had significantly more favorable TBF distributions than the older machines.

Tests for trends on Cooperator One's type 1 machines covering 60 to 104 weeks indicated that only two of the nine had times between failures that decreased significantly and one of these was their newer machine. The others had decreases in their times between failures that were not significant.

The combined information from the test for trends section and the comparison of times between failures for different aged machines suggests a time between failure history that would start out at some high point which could vary widely. The time between failures would then drop rather steeply for possibly a year or more at which time it would tend to level off slightly but still decrease. As the machine begins to age there appear to be two reasons for the machines economical life to end. The machine will experience some catastrophic failure, the repair cost of which would be prohibitive and the machine will be retired. Or, as the machine begins to wear out the times between failures will decrease steeply until it becomes less expensive to own and operate a newer machine at which time the older machine will be retired.

The proposed time between failure pattern would follow a curve similar to that shown in Figure 9. The cross-hatched area would represent the variability in the initial times between failures. The initial change could range from slightly increasing to strictly decreasing.

Comparison of Time-To-Repair Distributions

Time-to-repair (TTR) distributions were generated for all 32 machines in the study. These distributions are included in Appendix C. Parameters for each of these distributions are listed in Table 8. Results of the Kolmogorov-Smirnov

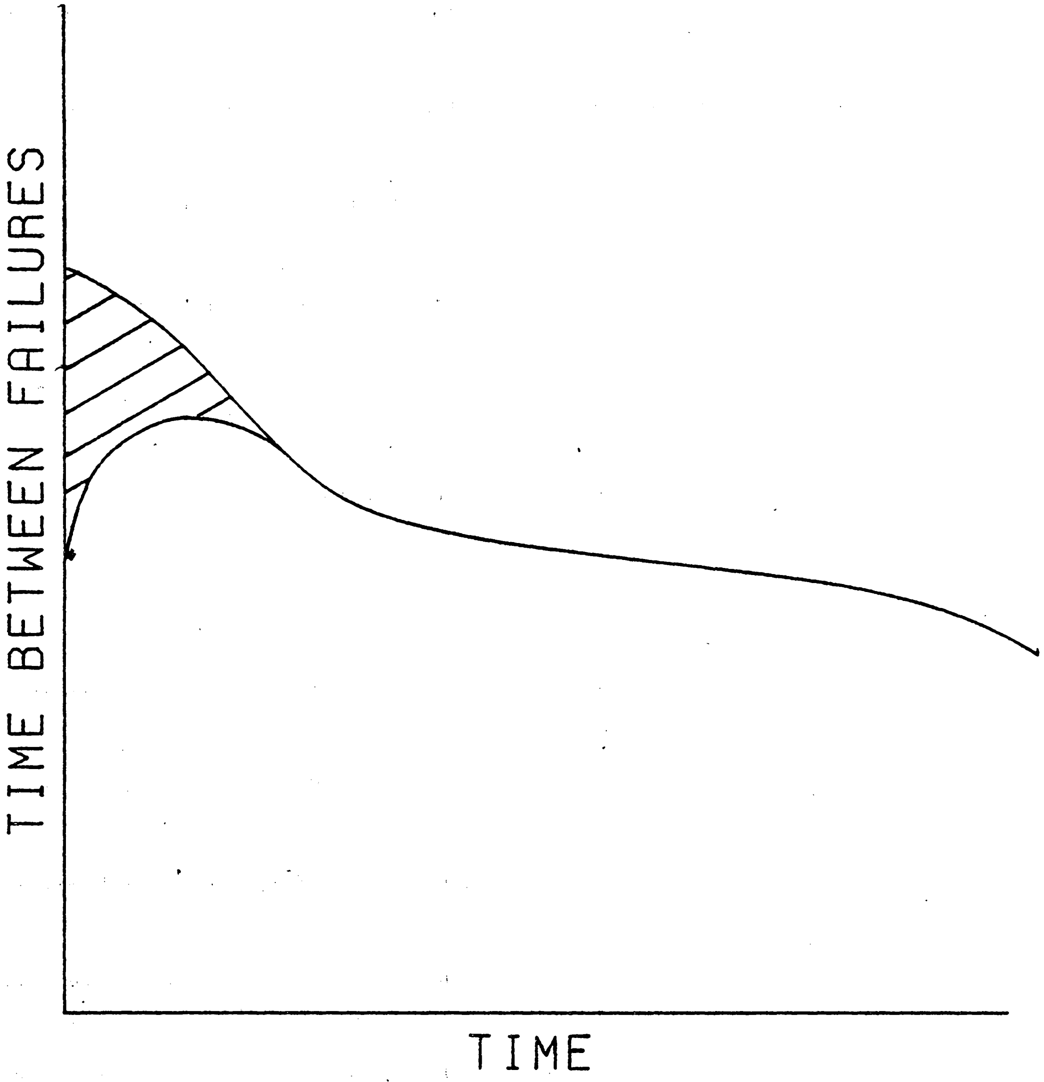

Figure 9. A proposed curve to represent the change in time between failures with time suggested by the machines in this study.

Table 8. Shape, scale, and location parameters for the Weibull distributions that represent the time-to-repair distributions for the 32 machines included in the study.

Machine number	Parameters		
	Shape	Scale	Location
111	0.542	2.56	0.64
112	0.631	1.49	0.99
113	0.643	3.17	0.87
114	1.259	4.99	0.
115	0.372	1.70	0.99
116	0.801	1.87	0.83
117	0.736	3.38	0.89
118	0.651	2.10	0.71
119	0.575	3.14	0.76
121	0.708	0.71	0.25
122	0.470	3.43	3.30
131	1.232	2.40	0.44
132	0.854	2.19	0.50
133	1.241	3.23	0.
211	0.399	0.85	0.90
212	0.562	1.06	0.81
213	0.466	1.07	0.90
214	0.520	2.06	0.55
215	1.034	1.18	0.47
216	1.415	1.40	0.
217	0.953	1.34	0.53
221	0.491	1.48	0.90
222	1.008	1.20	1.80
241	0.581	1.30	0.40
242	0.875	1.13	0.40
243	0.782	1.57	0.40
311	0.491	1.45	0.90
312	0.626	3.09	0.84
313	0.637	0.94	0.90
314	0.696	3.64	0.70
315	0.440	2.27	0.98
316	0.574	4.05	0.93

and Chi-squared goodness of fit tests indicated no significant differences between the calculated distributions and the empirical distributions at the 95 percent confidence level.

These TTR distributions represent the actual active repair time, they do not include time waiting for parts or a mechanic. A few of the repairs do include travel time for the mechanic to pick up a part because the repair times were short and the amount of delay time was not reported. In most cases this travel time was minimal. The distributions do include the total time spent in a shop. This shop time includes transportation and waiting time as well as the actual repair time. This is the reason for the extremely long times to effect some of the repairs.

Shape parameters ranged from 0.372 to 1.415 and scale parameters from 0.71 to 4.99. Again, this wide variability in shape indicated that a simple model like the negative exponential distribution could not represent all of the data. Also, there is no characteristic shape for the TTR distribution for these feller-bunchers.

Tests to determine which repair distributions were identical reduced the number of shape parameters from 32 to five, and the total number of different distributions from 32 to 19. Table 9 like Table 5 is a listing of the machines by shape parameter group in order according to scale parameters. Single spacing represents those machines for which there were no significant differences among the parameters at the 95 percent confidence level, double spacing represents significant differences.

No one machine type dominates any of the five groups based on shape parameters, although there are no type 3 machines in the last two groups. Again, there are cases where machines of all three types have identical distributions as is the case for machines 111, 214, and 315.

The maximum and minimum TTR distributions are shown in Figure 10. The remaining distributions for each machine type lie between these extremes. The differences between machine types 1 and 3 are minor, but machine type 2 seems to have shorter times to repair.

Table 10 is a listing of the distribution means for each of the machines by machine type ranked according to the mean. A Kruskal-Wallis test indicated significant differences among the machine types at the 98.6 percent confidence level. The type 2 machines required

Table 9. Results of tests for similar time-to-repair distributions.

	Machine number	Parameters	
		Scale	Shape
Group I			
	211	0.85	0.399
	115	1.70	0.372
Group II			
	212	1.06	0.562
	213	1.07	0.466
	311	1.45	0.491
	221	1.48	0.491
	214	2.06	0.520
	315	2.27	0.440
	111	2.56	0.542
	122	3.43	0.470
Group III			
	121	0.71	0.708
	313	0.94	0.637
	241	1.30	0.581
	112	1.49	0.631
	118	2.10	0.651
	312	3.09	0.626
	119	3.14	0.575
	113	3.17	0.643
	117	3.38	0.736
	314	3.64	0.696
	316	4.05	0.574

Table 9. Continued

	Machine number	Parameters	
		Scale	Shape
Group IV			
	242	1.13	0.875
	222	1.20	1.008
	217	1.34	0.953
	243	1.57	0.782
	116	1.87	0.801
	132	2.19	0.854
Group V			
	216	1.40	1.415
	131	2.40	1.232
	133	3.23	1.241
	114	4.99	1.259

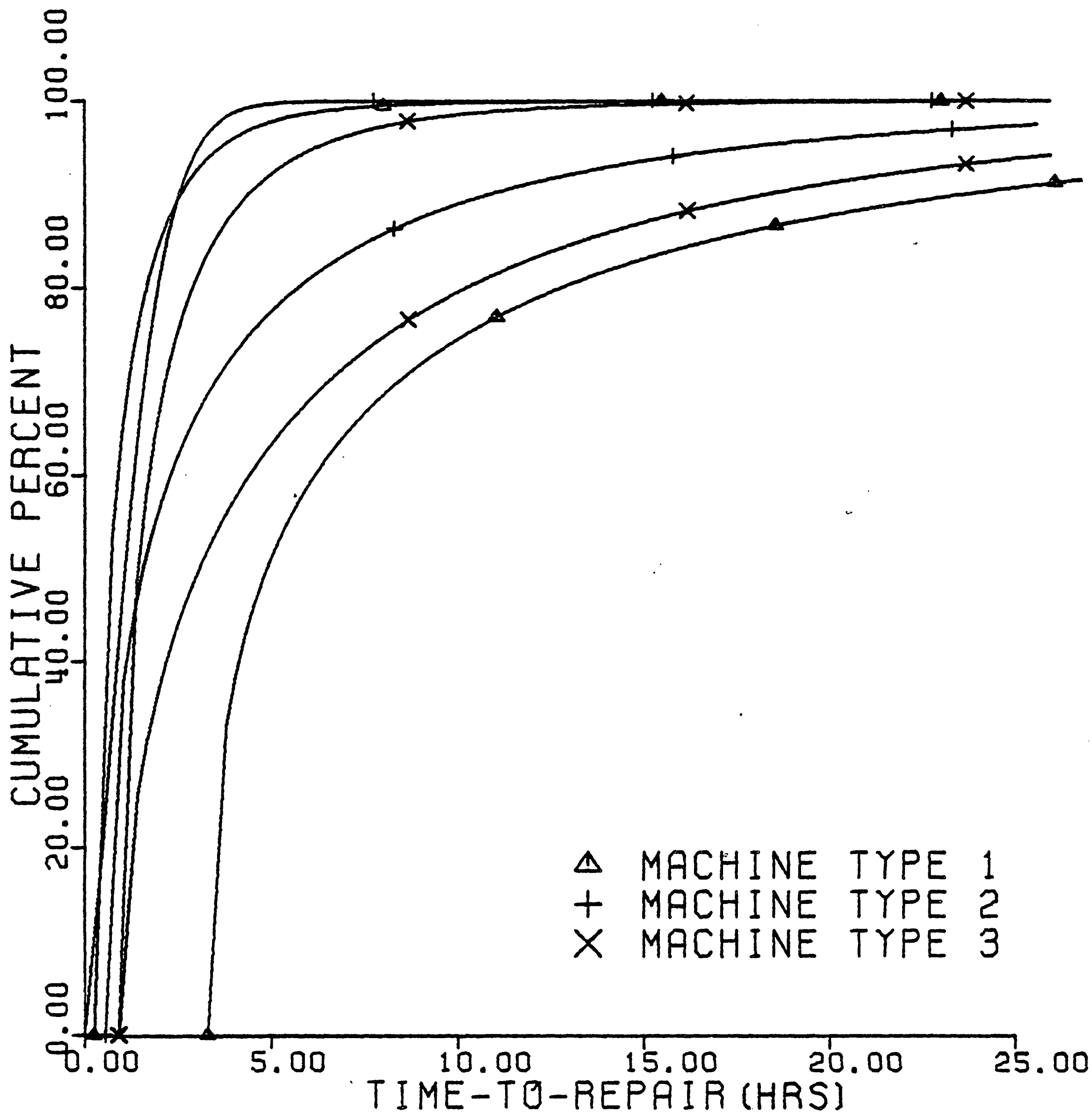

Figure 10. Weibull distributions that represent the longest and shortest time-to-repair distributions for each of the three types of feller-bunchers.

Table 10. Distribution means for the Weibull distributions that represent the times to repair for each machine by machine type.

Type 1		Type 2		Type 3	
Machine number	Mean (hours)	Machine number	Mean (hours)	Machine number	Mean (hours)
121	1.139	216	1.272	313	2.214
131	2.682	242	1.608	311	3.900
132	2.871	215	1.627	312	5.249
116	2.950	217	1.899	314	5.355
133	3.017	243	2.210	315	6.902
112	3.096	241	2.442	316	7.404
118	3.574	212	2.555		
114	4.643	222	2.999		
111	5.098	213	3.355		
117	5.188	211	3.747		
113	5.254	221	3.962		
119	5.767	214	4.288		
115	7.983				
122	11.041				

significantly shorter times to repair than types 1 and 3. There were no differences between types 1 and 3.

A comparison of the 1977 and 78 model machines indicated no significant differences among the three types of machines at the 95 percent confidence level. However, the type 3 machines had longer times to repair than the type 1 and type 2 machines at the 76 percent confidence level. There were no differences between the newer type 1 and type 2 machines.

Machines 121 and 122 are not good representatives of type 1 machines. Each was observed for 11 weeks during which only seven and five failures, respectively, were reported. Machine 121 experienced only minor hydraulic problems so its repair time was shorter than would be expected. Machine 122, on the other hand, experienced two major failures, one of which was beyond the repair capabilities of the cooperator. Thus, its mean time to repair is much longer than would be expected.

For machine type 1, Cooperator Three had shorter average times to repair than Cooperator One. Cooperator Three employs no field mechanics. When a failure occurs the operator replaces the bad part with a good one, and the bad one is sent to a shop for the needed repairs. Cooperator

One on the other hand employs field mechanics. When a failure occurs the mechanic removes the part, repairs it, and then replaces it. In one case the mechanic removed and repaired a part three times before deciding to get a new part to replace the bad one. This substantiates two of Boyd's (1976) conclusions for reducing downtime: do not repair parts that can be replaced, and do not use the machine for a test bench.

The policy of exchanging parts and having the operator perform field repairs seems to reduce downtime. The actual repair work is more efficient and it eliminates waiting for a mechanic. It was not possible to determine the cost effectiveness of the system. However, a parts inventory must be maintained no matter which method is used. And, repairing parts in a shop should be more efficient than repairing them in the field.

There were no significant differences among the three cooperators supplying data for the type 2 machines according to a Kruskal Wallis test conducted at the 95 percent confidence level.

Analysis of Availability for Different Strategies

Calculation of Inherent Availability

Machine 119 had the longest times between failures for type 1 machines, but it also had one on the longest times to repair. Machine 131 which has the auger head had the shortest times between failures, but it also had one of the shortest times to repair. To have a complete picture of machine availability the frequency of failure and service and the duration of the downtime must be examined together.

The inherent availability is a measure of availability from the machine design point of view. It represents the maximum availability the owner can achieve. The machine will not be available any more than the inherent availability, but the amount less will be determined by administrative policies and maintenance and repair strategies. It considers only the time between failures and the active time to repair those failures. It excludes all waiting time and preventive maintenance. Table 11 is a listing of the inherent availabilities for each of the machines in the study.

Table 11. Inherent availabilities for each machine in the study by machine type in order of their inherent availability.

Type 1		Type 2		Type 3	
Machine number	IA (%)	Machine number	IA (%)	Machine number	IA (%)
121	97.18	216	97.36	313	92.76
116	89.63	242	94.69	311-1	91.64
118-1	89.21	215	93.91	316-1	84.31
132	88.02	214-1	92.98	315	76.29
133	87.38	241-1	91.53	312-1	76.10
112	86.05	212-1	90.06	314	73.56
119	84.67	222	89.88	311-2	71.40
114	82.22	217	89.61	312-2	68.51
111-1	80.71	221	88.89	316-2	47.32
118-2	80.42	243	88.87		
113	77.80	213	87.82		
131	73.79	211-1	87.40		
117	72.94	241-2	85.47		
122	72.59	212-2	83.86		
111-2	67.59	214-2	82.16		
115	66.44	211-2	78.00		

There was a significant difference in inherent availabilities among the three machine types at the 99.5 percent confidence level as indicated by the results of the Kruskal-Wallis test. The type 2 machines had significantly higher availabilities than the types 1 and 3. There was no difference between the type 1 and type 3 machines.

When comparing the 1977 and 78 model feller-bunchers there were no differences among the three types at the 95 percent confidence level. However, the type 2 machines did have availabilities that were significantly higher than the types 1 and 3 machines at the 85 percent confidence level. There were no differences among the cooperators.

The inherent availabilities for Machines 121 and 316-2 are not good representatives for their respective machine types. As mentioned earlier the mean time to repair for Machine 121 was lower than would be expected because only seven failures were obsrved and almost all were minor repairs. Therefore, the inherent availability is higher than would be expected. Machine 316 was placed in storage during the study and put back into service without any repairs. This time period is represented by the distribution 316-2 during which an unusually high number of failures occurred. So, the availability is lower than would be expected.

Simulation of Operational Availability

Operational availability is a measure of the amount of time the machine is actually mechanically ready to perform the job for which it was designed. It takes into account not only actual mechanical problems, but also service and delay time. Because of the number of variables considered and their interrelationships a simulation program was used to calculate operational availability.

The first step in using the simulation program was to validate it. The sequence of operations for this program is relatively simple since only operating time and downtime were modeled. Once a failure occurs there will be some delay time waiting for a mechanic or part, but for some of the repairs this time will be zero. Then the machine is repaired. This is the sequence the simulator uses. The only other downtime is preventive maintenance. This includes preoperation checks, greasing, fueling, and possibly minor adjustments or repairs. This may occur prior to operation for the day or it may be spread throughout the day with only a portion occurring in the morning. The simulator takes out the time in the morning before operation. Since the program does not calculate production it doesn't matter whether the time is all taken out at the beginning of the day or spread throughout the day.

The program was run using the distributions for one of the machines for which field data was available. The results from the five simulations each using a different set of random number seeds and the numbers calculated from the field data are shown in Table 12. The averages of the simulations and the actual results agree reasonably well.

The actual data included an extra 3.9 hours of service time because the operation was "rained out" one day and rather than send the men home, the monthly service which is normally performed "out-of-shift" was done during scheduled working time. If this time is removed from the field data it produces the adjusted averages, and the service time only differs by 0.08 percent rather than 0.39 percent and the availability only differs by 0.69 percent.

The amount of time spent actively repairing the machine differed by 0.55 percent, but this could have been caused by the choice of random number seeds and the number of repairs since for the five simulation runs the amount of time spent repairing the machine for two of the runs was above the

Table 12. Results of the five runs to validate the simulator and the actual field data.

	Percentage of Time in Each Category			
	Availability	Service	Repair	Delay
	79.60	12.27	7.57	0.56
	79.64	12.23	6.44	1.69
	81.32	12.33	5.47	0.89
	79.89	12.32	7.44	1.29
	78.92	12.32	7.44	1.32
Average	79.87	12.30	6.68	1.15
Field data	78.87	12.69	7.23	1.21
Adj. field	79.18	12.38		

	Average Time Between Occurrence (hrs)		
	TBF	TTR	Delay
	23.27	2.046	0.159
	23.68	1.891	0.572
	28.95	1.940	0.309
	28.20	2.241	0.441
	23.44	2.190	0.477
Average	25.51	2.062	0.392
Field data	27.8	2.05	0.34

actual time and three were below. The average time between failures, time to repair and delay time from the simulation runs and the field data are also very close.

An added benefit of the simulation program is that it is capable of providing an indication of the amount of variability that can be expected. For the validation process 60 four week periods were simulated. The averages are shown in Table 12, but the ranges for each of the categories for four week periods are given below:

Low		High
66.86	Availability (%)	87.50
11.31	Service (%)	12.50
0.0	Active repair (%)	20.64
0.0	Delay time (%)	5.32
1.49	Time between failures (hrs)	310.21
0.41	Time to repair (hrs)	16.72
0.0	Delay (hrs)	6.02

For the 60 four week periods there were only two in which a failure did not occur. Since the machine is serviced for one hour during each eight hour shift the maximum availability is 87.5 percent with a corresponding service time of 12.5 percent as expected. The service time, however, does not have a very wide range.

The range of time between failures may be too large. The actual data ranged from 1.5 to 98.5 hours and apparently the distribution used to model the time between failures flattens out too much on the high end; although, time between failures longer than 98.5 hours would be expected. The range in times to repair does represent the actual data which ranged from 0.5 to 14.5 hours. The range for delay times also seems appropriate since the actual data had a high of five hours.

Since the simluator does seem to provide an accurate representation of the true situation it was used to examine the effect of changing some of the operational parameters and observing the resulting effect. The reliability, maintainability, and delay time were examined to evaluate the effect of deviating from their optimums.

The optimum in reliability would be a machine that never failed. Even if one of these could be produced it would still need servicing. And if the machine was serviced a total of one hour per eight hour shift its maximum availability would only be 87.5 percent. Figures 11, 12, and 13 show the effect of reliability or time between

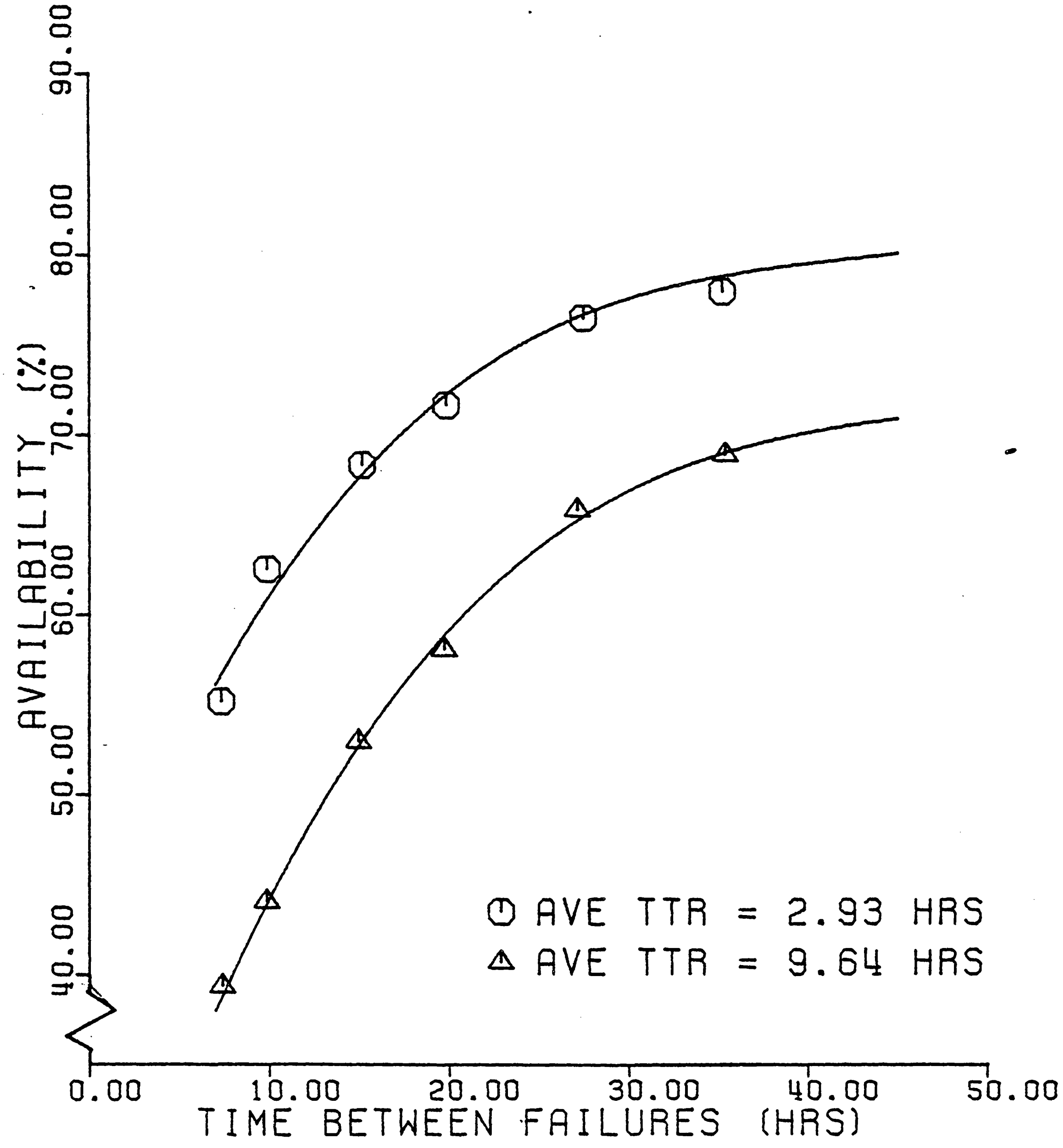

Figure 11. Operational availability for different times between failures for two repair rates and an average delay time of 1.31 hours for type 1 Feller-Bunchers.

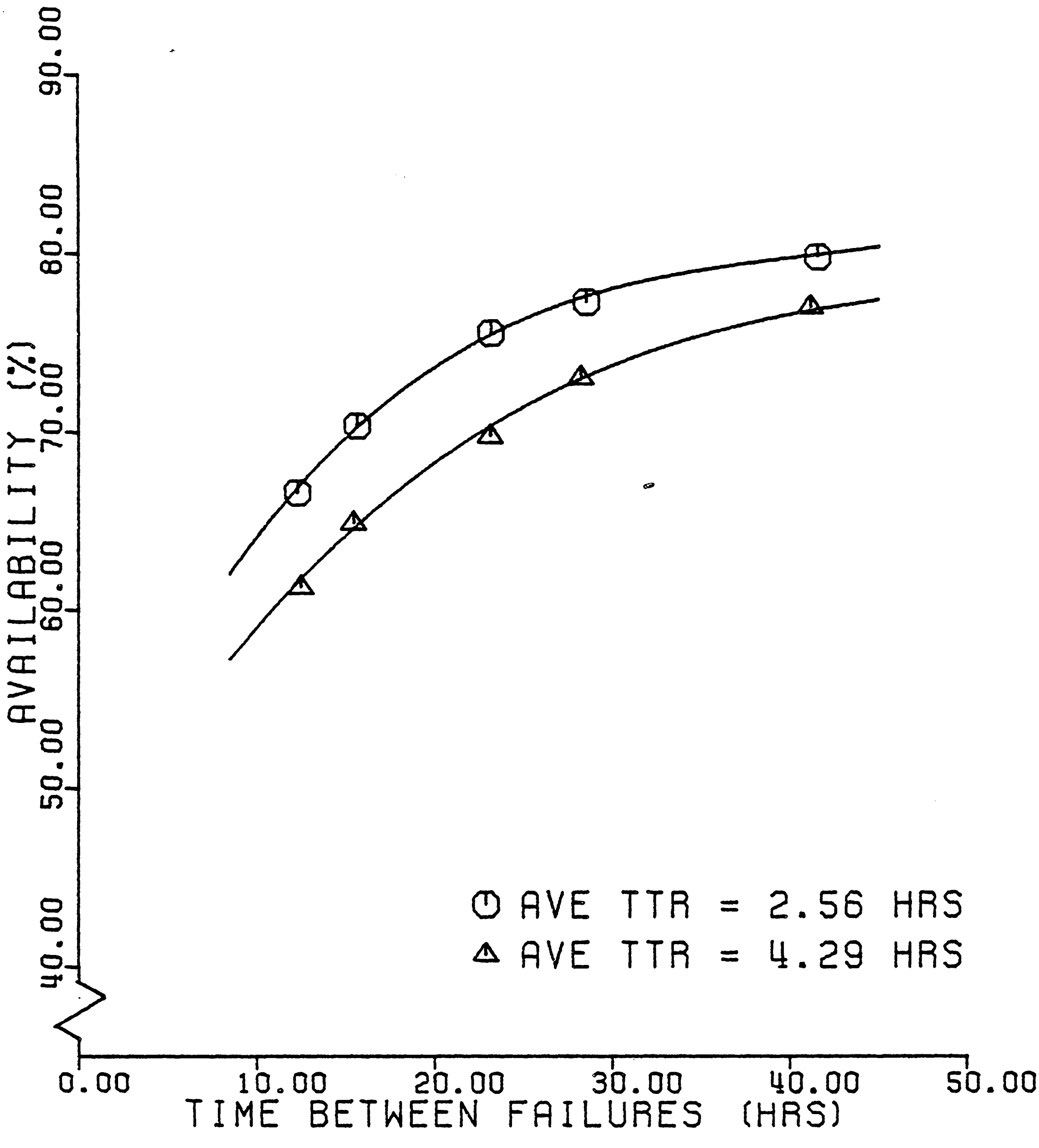

Figure 12. Operational availability for different times between failures for two repair rates and an average delay time of 1.16 hours for type 2 Feller-Bunchers.

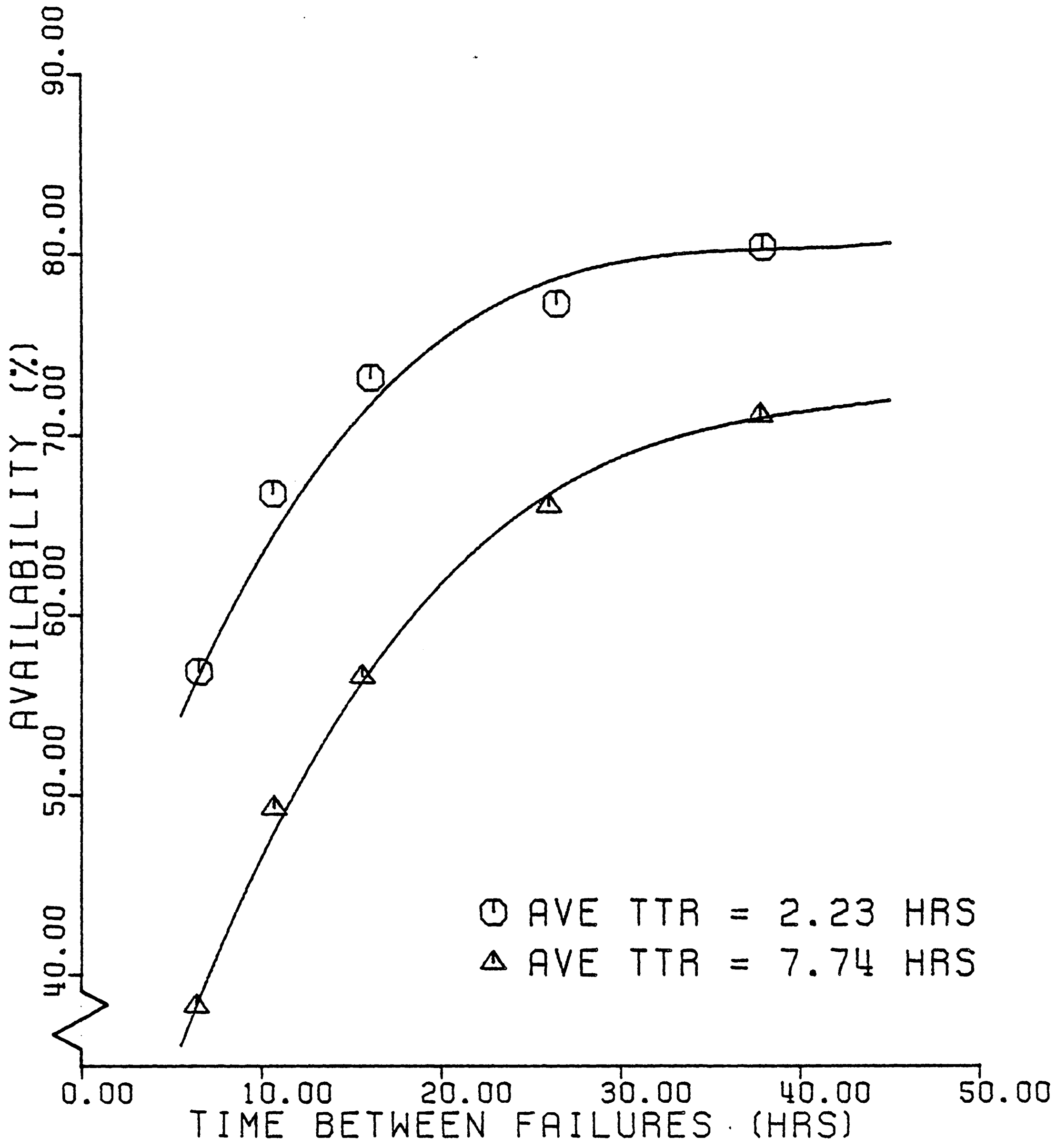

Figure 13. Operational availability for different times between failures for two repair rates and an average delay time of 1.14 hours for type 3 Feller-Bunchers.

failures on availablility. Figure 11 represents the type 1 machines. Different time-between-failure distributions and two time-to-repair distributions for type 1 machines were used in the simulation program to produce the average availabilities represented by the points on the graph. A best fitting curve was then estimated using regression techniques. The same procedure was used to produce Figures 12 and 13 which represent the type 2 and type 3 feller-bunchers, respectively. The general shapes of the curves are the same regardless of machine type; the slight variability is caused by the differences in the distributions. Two distributions could produce the same average time between failures, but have different shape and scale parameters. The major difference among the three machine types is the height of the curve which is a function of the repair and delay times. Since the delay time distribution was the same for all simulations, the differences in the heights of the curves in this case are due to the time-to-repair distributions.

These curves represent the range for which actual data was available. Since this study covered over 41,000 hours and 32 machines, it is not likely that another feller-buncher of the types studied would fall outside this range. Although the range seems rather narrow, an average time between failures of about 40 hours represents times between failures from less than one hour to over 150 hours depending on the machine considered.

Although the curves are not exact they should be a good representation of the true situation within the range of data available. The curves were fitted with third power functions and the formulas given below could be used to calculate the slope of the line at any point to determine the marginal benefit of increasing the reliability above a given point. The equation is of the general form:

$$\text{Availability} = b(1) + b(2)*TBF + b(3)*TBF^2 + b(4)*TBF^3$$

and the coefficients are:

Type 1 Feller-Bunchers

	b(1)	b(2)	b(3)	b(4)
TTR = 2.93	0.4099	0.02537	-0.000577	0.00000415
TTR = 9.64	0.1948	0.03057	-0.000626	0.00000446

Type 2 Feller-Bunchers

	b(1)	b(2)	b(3)	b(4)
TTR = 2.56	0.4689	0.02185	-0.000507	0.00000415
TTR = 4.29	0.4487	0.01705	-0.000305	0.00000193

Type 3 Feller-Bunchers

	b(1)	b(2)	b(3)	b(4)
TTR = 2.23	0.3914	0.03178	-0.000818	0.0000070
TTR = 7.74	0.1955	0.03410	-0.000769	0.0000060

There is definitely a point of diminishing returns as far as reliability is concerned. An increase from an average of

20 hours between failures to 40 hours between failures increases availability by 18 percent or less for all of the repair times considered. However, the shorter the average repair time the less the difference.

Figures 11, 12, and 13 represent availability as a function of time between failures over the range of data available. The theoretical curve, however, would start at (0,0) with a slope that would continually decrease until it reached zero at 87.5 percent availability and an infinitely long time between failures. Figure 14 is a hypothesized availability as a function of time between failures curve. The points were calculated from the simulation program by using a characteristic shape parameter and varying the scale parameter. The curve was drawn by hand because regression techniques would not produce a curve that had the correct shape. Three points were not shown because their inclusion would have required a much smaller scale on the x-axis.

These points were:

Time between failures (hrs)	Availability (%)
146.97	83.64
193.29	84.75
439.04	85.61

So, the curve had not reached its maximum height of 87.5 percent availability even at an average time between failures of 440 hours. The critical region, as shown in the

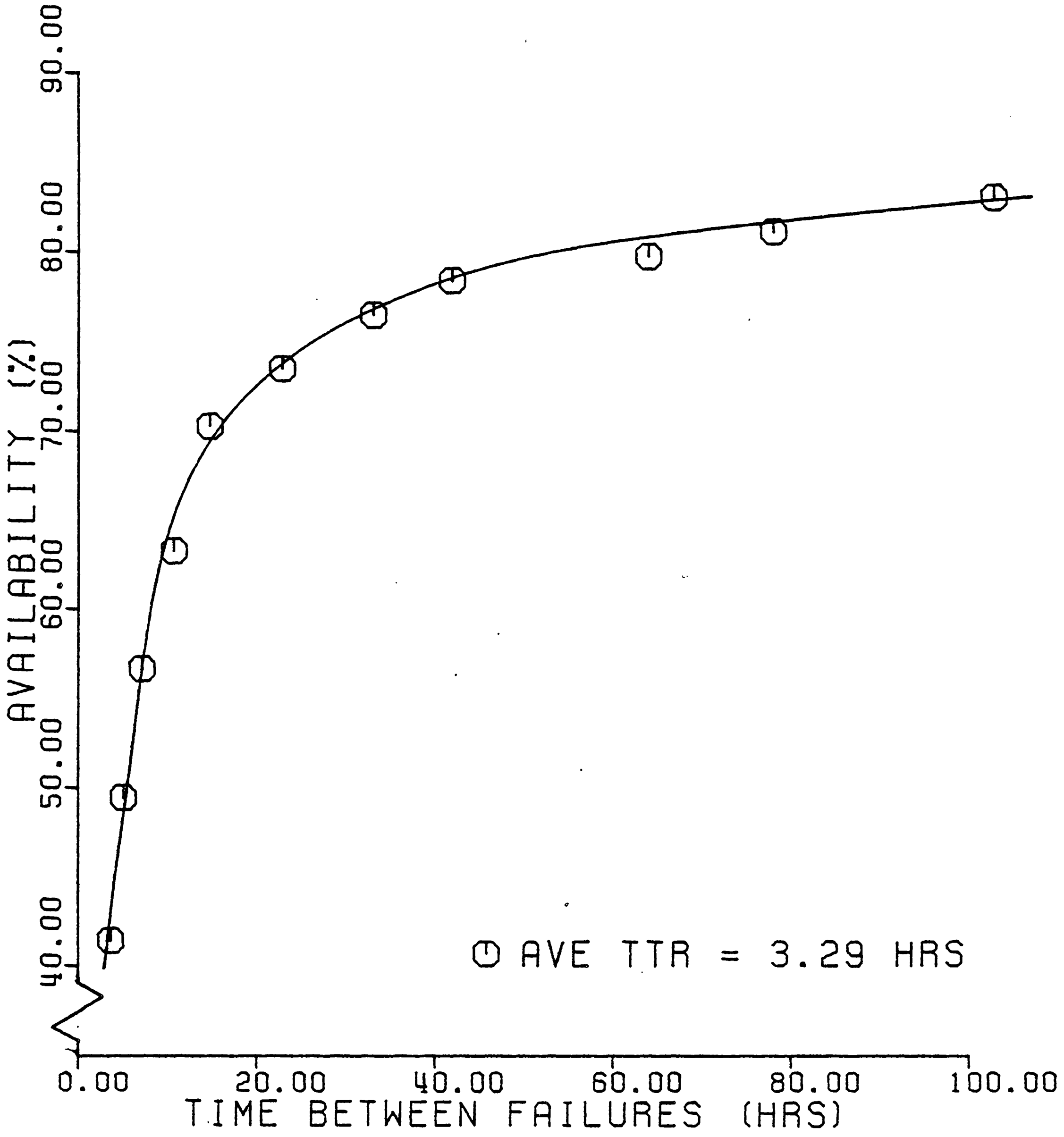

Figure 14. Hypothesized availability as a function of time between failures for average repair and delay times of 3.29 and 1.56 hours, respectively. hours.

other graphs also, is from zero to 40 hours between failures. The point of diminishing returns is probably between 30 and 60 hours between failures.

Equipment owners would also like to minimize delay and repair times. Unlike reliability, however, these are linear relationships as shown in Figures 15 and 16 and there is no point of diminishing returns. The marginal benefit of reducing the average repair time from five hours to four hours is the same as reducing the average repair time from two hours to one hour. However, the marginal cost of decreasing the repair time does increase greatly as the amount of repair or delay time decreases.

For the analysis, if the downtime was reduced by one hour the effect would be the same on the availability whether the hour was saved repairing the machine or the delay time was decreased. The two curves, however, are not identical. These two figures show the interrelationship among all four categories of time. Since the curves are straight lines the form of their equations are:

$$\text{Availability} = b(1) + b(2)\,(\text{TTR/delay}),$$

and their coefficients are:

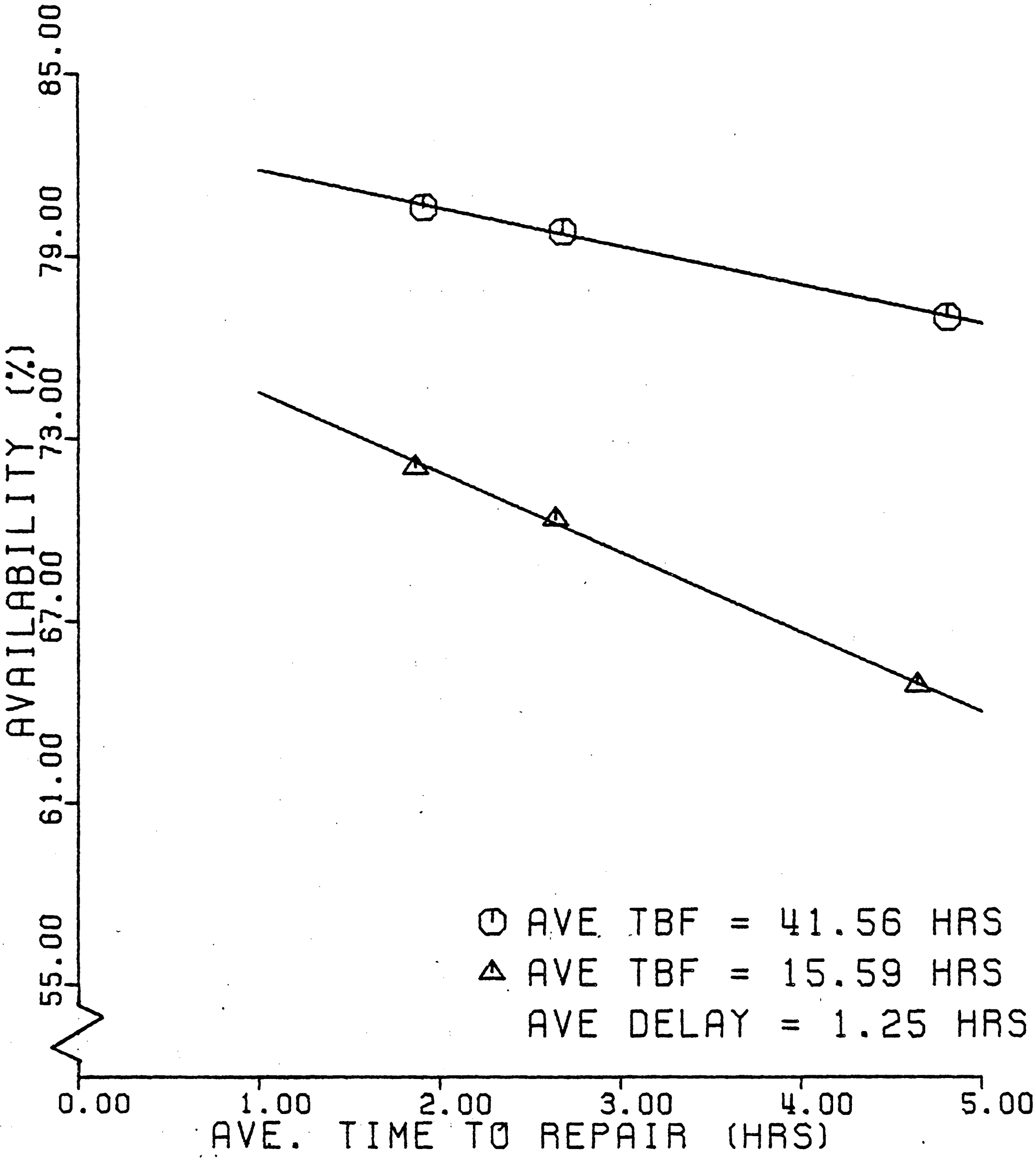

Figure 15. Operational availability for different times to repair for two TBF distributions and an average delay time of 1.25 hours.

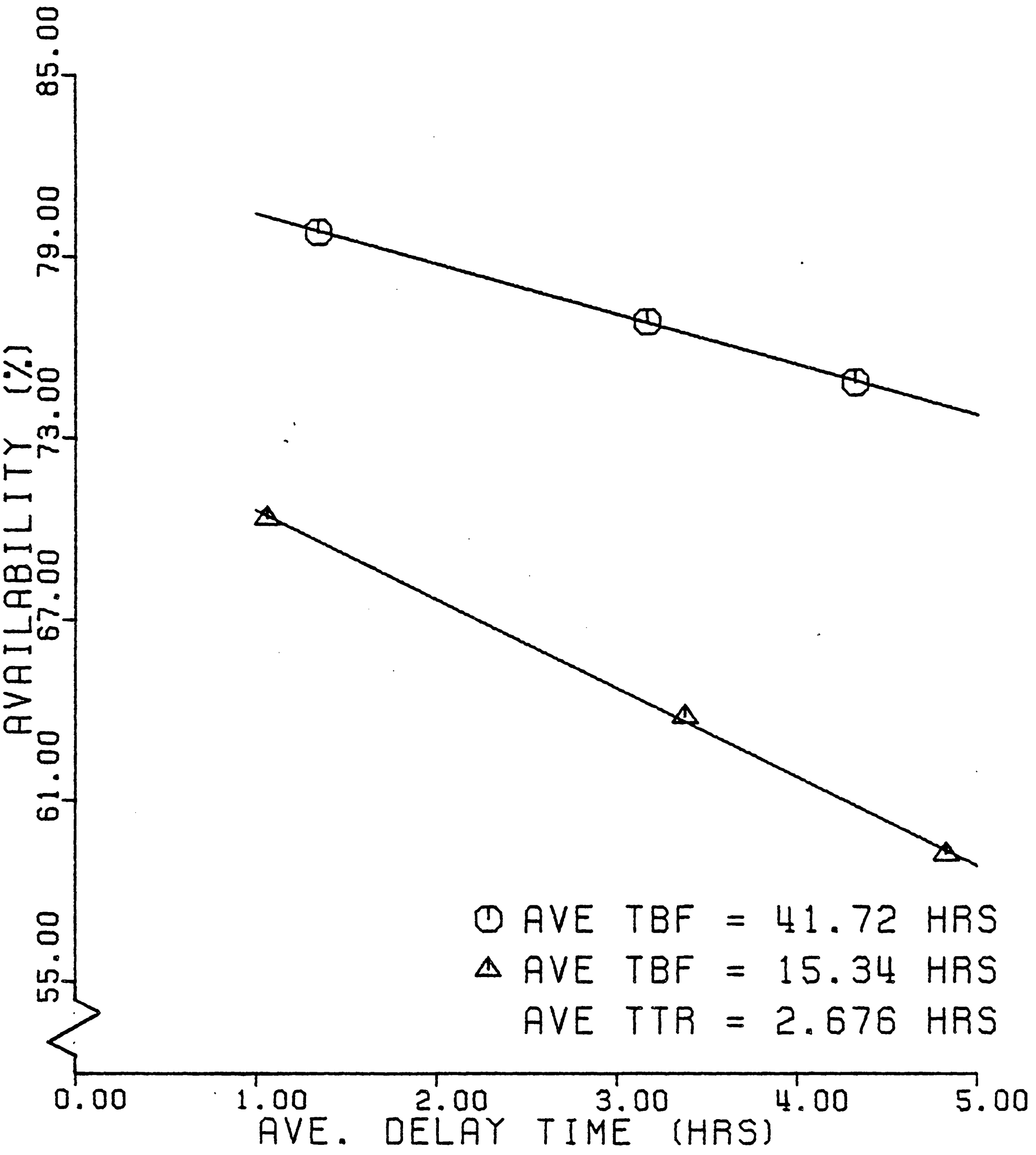

Figure 16. Operational availability for different delay times for two TBF distributions and an average time to repair of 2.68 hours.

Time-to-repair

	b(1)	b(2)
Ave TBF = 41.56	0.8313	-0.0127
Ave TBF = 15.59	0.7714	-0.0262

Delay time

	b(1)	b(2)
Ave TBF = 41.72	0.8209	-0.0167
Ave TBF = 15.34	0.7357	-0.0294

So, for a machine with an average time between failures of 15.5 hours and an average delay time of 1.25 hours for each hour the average time to repair is reduced the availability will be increased 2.62 percent. And for a machine with an average time between failures of 41.5 hours and an average delay time of 1.25 hours for each hour the average time to repair is reduced the availability will be increased 1.27 percent. The effect of reducing the delay time by one hour for an average repair time of 2.68 hours and the two time between failures above would be increases in availability of 2.94 and 1.67 percent, respectively.

Decreasing the average time between failures from 15.5 hours to 41.5 hours decreased the slope coeffeicent of the lines by only 0.013, although this is approximately a 50 percent reduction. A change in the third component, ie. delay for the time to repair graph, from 1.25 hours to 2.68 hours increased the slope coefficient by 0.03.

In general, then, there is a linear relationship between availability and downtime due to active repair and delay time. And the shorter the time between failures the greater the effect. Also, a decrease in one can offset an increase in the other.

The effect of service time is to decrease the effect of the other variables. As the number of failures increase the amount of service time decreases because there will be fewer services and some of the service time can be performed during downtime. Conversely, as the number of failures decreases the amount of time the machine is down for service increases.

Parts Repaired

Tables 13, 14, and 15 are lists of the parts repaired by major categories for machine types 1, 2, and 3, respectively. Some of the categories, such as, cooling system cover a wide variety of repairs because of the diversity, but if a part had a high frequency of failure, such as, cables and linkages for type 2 machines or the repair was major, such as, a transmission failure they were listed separately.

Table 13. List of parts repaired and frequency of failure by major categories for type 1 Feller-Bunchers.

Part Repaired	Number		Percent
Hydraulic system		481	40.8
Hoses, fittings, and leaks	124		
Hydraulic pipes	90		
Cylinders	97		
Final drive	84		
Set or check pressure	38		
Valve bank	25		
Pump	23		
Tracks		163	13.8
Pins	134		
Other	29		
Welding		150	12.7
Shear (other than hydraulic)		134	11.4
Electrical system		72	6.1
Cooling system		40	3.4
Cables and linkage		23	2.0
Exhaust system		22	1.9
Swing gear reducer		20	1.7
Miscellaneous		73	6.2

Table 14. List of parts repaired and frequency of failure by major categories for type 2 Feller-Bunchers.

Part Repaired	Number		Percent
Hydraulic system		240	37.5
Hoses, fittings, and leaks	184		
Hydraulic pipes	6		
Cylinders	29		
Valve bank	18		
Pump	3		
Shear (other than hydraulic)		80	12.5
Welding		78	12.2
Drive train		44	6.9
Leaks and lines	19		
Transmission	10		
Planetary	9		
Power transfer dump valve	6		
Brakes		35	5.5
Wheels and tires		26	4.1
Cables and linkage		24	3.8
Center section		14	2.2
Exhaust system		13	2.0
Electrical system		4	0.6
Miscellaneous		82	12.8

Table 15. List of parts repaired and frequency of failure by major categories for type 3 Feller-Bunchers.

Part Repaired	Number		Percent
Hydraulic system		212	48.4
Hoses, fittings, and leaks	102		
Hydraulic pipes	25		
Cylinders	49		
Hydrostatic drive problems	15		
Pump	14		
Valve bank	7		
Drive train		65	14.8
Drive chain and linkage	20		
Idler gear and sprocket	19		
Clutch	10		
Axle	6		
Hub	5		
Transfer case	3		
Gear reducer	2		
Shear (other than hydraulic)		35	8.0
Welding		33	7.5
Electrical system		32	7.3
Wheels and tires		20	4.6
Cooling system		11	2.5
Fuel lines and leaks		10	2.3
Exhaust system		7	1.6
Fuel pump		5	1.1
Miscellaneous		8	1.8

The most common cause of failure was the hydraulic system, accounting for 41.4 percent of the repairs. Hydraulic hoses, pipes, fittings, and leaks were responsible for 23.5 percent of the total number of repairs. Also of significance were the number of hydraulic pumps replaced, an average of two pumps per machine for the type 1 feller-bunchers and 2.5 pumps per machine for the type 3 feller-bunchers. The type 1 machines also experienced a high number of final drive problems, but the reason for this was discussed earlier. Repacking cylinders also occurred frequently for all three machine types. These results indicate that a mechanic should have an adequate knowledge of hydraulics. And, hoses, fittings, and materials to repack cylinders as a minimum should be maintained in inventory.

There are two major reasons that the hydraulic system is a problem. One, it is very difficult to adequately protect the hoses and fittings on the shear and the shear head must frequently be forced through underbrush and other obstacles that snag the lines. And, two, it is almost impossible to keep foreign matter out of the hydraulic system when performing repairs in the woods.

The list of repairs performed also indicated that a welder would be a necessary piece of equipment for a mechanic to have since approximately 12 percent of all the repairs required the use of a welder. This also indicates an additional skill a mechanic should have.

Shear failures which included reshimming the head, sharpening the blades, changing pins and bushings, and other miscellaneous repairs accounted for 11.0 percent of all the repairs.

Drive train repairs are listed separately because they are usually major failures. Any time a transmission repair is necessary the machine must be sent to a shop. The type 2 feller-bunchers are the only gear driven machines so they should have more drive train failures than the other two types. This is true in relation to the type 1 machines; although, they did have a high number of final drive problems which were listed under the hydraulics category. However, the type 3 machines had a higher percentage, 14.3 percent, of drive train failures than the type 2 machines, 6.9 percent. And, this percentage for type 1 machines does not include hydraulic drive problems. The manufacturer has also recognized the problem and the machine has been redesigned to reduce the number of failures of the drive train.

Other areas of importance for the type 1 feller-bunchers include track pins, the electrical system, and possibly the swing gear reducer. Additional areas frequently requiring attention on the type 2 machines include wheels and tires, cables and linkage, and brakes. Type 3 feller-bunchers experienced some problems with the electrical system, tires, and the cooling system.

SUMMARY AND CONCLUSIONS

The first objective of this research was to adapt analytical techniques used in other fields to develop procedures to analyze reliability, repair, and maintenance information on forestry equipment. The four analytical procedures used are set out below:

1. Analyzing trends in the time between failures as a function of time. The technique used to perform this was time series analysis.

2. Modeling and comparing two or more time-between-failure or time-to-repair distributions to identify significant differences. Weibull distributions were used to model the data and comparisons were conducted by transforming the data and then comparing parameters using dummy variable techniques in regression analysis.

3. Determining the effect of changes in reliability, maintainability, and maintenance strategies on availability. Since operational availability is affected by a number of variables that interact, a simulation program was written to determine the effect of changing these variables.

4. Estimating the frequency distribution of failures to provide a list of the reasons for machine failures. If a sufficient amount of data had been available the expected life of various parts could have also been calculated.

The second objective was to use the above procedures to analyze reliability, repair, and maintenance data for feller-bunchers. To accomplish this, data was collected on three different types of feller-bunchers in use on harvesting operations in the South. Type 1 was a hydrostatically driven, limited area machine equipped with tracks. Its shear was mounted on a knuckleboom. Type 2 was a gear driven, articulated-frame, tree-to-tree machine equipped with rubber tires. Type 3 was a hydrostatically driven, skid steered, tree-to-tree machine equipped with tracks over tires. Four different cooperators supplied information over 41,300 operating hours which included 1814 documented failures on 32 machines.

The results and their implications are discussed below in the same order as the analyses were performed.

Analyzing Trends in Time Between Failures

Results indicate that the time between failures is time dependent and does decrease with machine age. A possible exception would be an increase when the machine is first put into service. In most cases, even the new machines exhibited decreases in their times between failures. The times between failures seem to decrease rather rapidly during some initial operating period. After this initial period the times between failures still decrease although at a much lower rate. If a machine were rebuilt its times between failures would be increased, but they would start decreasing shortly after the rebuild. When the times between failures are decreasing at a lower rate some machines appear to exhibit seasonal fluctuations with higher times between failures for May through July and a slight decrease in August followed by shorter times between failures in late winter and early spring. For the South, this response is probably due to changes in soil moisture rather than temperature.

The results of this portion of the research indicates that the equipment owner can expect the reliability of his machine to be at its maximum when purchased or shortly thereafter. And, the reliability will drop rather rapidly for about the first year. So, initial data should not be used to estimate long-term costs.

Modeling and Comparing Times Between Failures

An attempt to model the data indicated that a simple model, such as the negative exponential distribution, was not able to represent the time-between-failure or time-to-repair data for the machines in this study. The Weibull distribution, however, did represent the data very well.

For 85 percent of the machines, 50 percent of the time the machine will fail within 18 hours or less of the last failure. This means that most of the feller-bunchers required some type of repair activity approximately every two days. And, the chance of operating an entire week without a failure was less than one out of five.

When comparing the different types of feller-bunchers, there were no differences in times between failures among the different machine types. However, there was a large amount of variability within each machine type which would tend to mask differences due to the type of feller-buncher. This variability was due to factors which were not analyzed, such as differences due to operators, harvesting conditions, or the quality of assembly. It is possible that differences among the three types of feller-bunchers exist. Removing the shear failures did decrease the variability, but there were still no significant differences among the three types of carriers. This would indicate that effects not considered in this study may have a greater effect on machine availability than differences due to machine types, cooperators, or even machine age. If in fact there are no differences in times between failures due to machine type, then differences in times to repair, production rates, harvesting conditions, or other special considerations must be used to justify the more expensive machines.

Although there were no significant differences in times between failures among the three types of feller-bunchers, the harvesting conditions should be considered. Data was collected from normal harvesting operations. This means that the type 1 feller-bunchers were cutting larger trees and probably operating over softer soil than the other types. This progression continues with machine type; the type 2 machines being intermediate. The type 3 feller-bunchers would be cutting the smallest trees, operating over favorable soil conditions, and working on minimum slopes. If all three machine types were operating under the same conditions, the results may have been different.

When the failures were separated into shear failures and carrier failures it was observed that most failures of the shear were minor involving only replacing hydraulic fittings and hoses, shimming the cutting blades, or packing a cylinder. Because these are common malfunctions, parts were available and repairs did not require extended periods of time and in many cases could be performed by the operator. Failures of the carrier, on the other hand, covered a wider range. Because of this there were times when the part was not available and the repair usually required the attention of a mechanic. Therefore, failures of the carrier are more critical than failures of the shear.

Modeling and Comparing Times to Repair

A comparison of times to repair for all machines indicated that the type 2 feller-bunchers had shorter times to repair than the types 1 and 3 which were the same. However, when only the newer machines were compared there were no significant differences; although, the type 3 machines required somewhat longer times to repair than the other two types.

For machine type 1, Cooperator Number Three had shorter average times to repair than Cooperator Number One. Cooperator Number Three employs no field mechanics. When a failure occurs the operator replaces the bad part with a good one, and the bad one is sent to a shop for the needed repairs. Cooperator Number One on the other hand employs field mechanics. When a failure occurs the mechanic removes the part, repairs it, and then replaces it. In one case the mechanic removed and repaired a part three times before deciding to get a new part to replace the bad one.

This indicates that replacing parts rather than repairing them has the potential to reduce the amont of machine downtime due to repair because it eliminates the repair and testing time. The greater the cost of the machine the more important this becomes.

Simulating Operational Availability

Results indicate that an increase in time between failures does increase availability; however, the magnitude of the effect decreases as the time between failures increases. There is definitely a point of diminishing returns. However, the longer the average repair or delay time the more pronounced the effect of the time between failures. Thus, if the times to repair and delay times are short, frequent failures may still result in a relatively high availability, but if the times to repair or delay times are long, frequent failures will greatly reduce availability. For all three types of feller-bunchers, the point of diminishing returns was less than an averge time between failures of 40 hours. This would suggest that it would not be economical to produce a machine that had an average time between failures of about 40 hours or more. This, in fact, seems to be the current situation. Of the 32 machines studied only one had an average time between failures greater than 40 hours. So, it would be unrealistic to expect that equipment manufacturers will produce machines that are significantly more reliable than those currently on the market unless some of the basic considerations change.

Unlike time between failures, there is a linear relationship between availability and downtime due to active repair or delay time. This means that there is no point of diminishing returns, but the marginal cost of increasing the availability will increase, probably exponentially. And, as mentioned previously, the shorter the time between failures the greater the effect. Also, a decrease in one can offset an increase in the other. When trying to increase availability by decreasing downtime it does not matter whether the downtime is reduced by shortening the repair time or reducing the delay time; the effect is the same.

Service time tends to decrease the effect of the other variables. As the number of failures increase the amount of service time during scheduled operating time decreases because there will be fewer services. Conversely, as the number of failures decreases the amount of time the machine is down for service increases. So, the proper scheduling of service can dampen the effect of short times between failures or long repair or delay times. This is accomplished by performing as much service as posible during downtime.

Determining Frequency of Failure

The most common cause of failure for all three types of feller-bunchers was the hydraulic system, accounting for 41.4 percent of all repairs. Therefore, a mechanic should have an adequate knowledge of hydraulics. And, hoses, fittings, and materials to repack cylinders as a minimum should be maintained in inventory. One reason that the hydraulic system was a major cause of failure is the difficulty of keeping foreign matter out of the system when repairing a component. This contamination causes secondary failures in other components. Other results indicate that another necessary piece of equipment is a welder.

In conclusion, as the cost of doing business increases it becomes more important to reduce costs wherever possible. This dictates careful planning which requires information about the future. In the timber harvesting business accurate predictions of production rates, operating time or downtime, and the reasons for downtime are badly needed. While production rates are relatively easy to calculate and are, therefore, available, information on the other two areas is practically nonexistant. Unfortunately, when it can be found it is rather simplistic. This research sets forth four methods of analyzing reliability, repair, and maintenance data. These methods provide a procedure to estimate the expected operating time at the present and in the future. The amount of downtime due to repair, maintenance, and mechanical delays can also be determined. And, the cause of failure and the life of parts can also be estimated. To make accurate predictions of this kind, more data is needed. Analyses of this type can improve the efficiency of harvesting and maintenance operations and provide data to more accurately predict future costs.

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APPENDIX A

Data Collection Forms

<u>FELLER-BUNCHER</u> - Reliability Report for week of ________

Cooperator ________________ Machine no. __________

Was the machine "down" for any mechanical reason (periodic service, repair, adjustment, etc.)? do not include daily PM

	M	T	W	Th	F	S
	yes	yes	yes	yes	yes	yes
circle one						
	no	no	no	no	no	no

Please fill out a Repair Form to describe each repair.

	M	T	W	Th	F	S
Shift length						
Non-productive operating time *						
Service daily or periodic						
Active repair, in-shift						
Active repair, out-shift						
Waiting for part(s)						
Waiting for mechanic						
Engine hours (end of day)						
Ground conditions (muddy, soft,firm, hardpacked)						
Production						
Lost time due to weather						

Weekly high temp. _______ Weekly low temp. ________

Terrain (flat, hilly, etc.) ______________.

* Time spent working on jobs other than the machines primary mission. For example, travel time.

If any repairs or service were performed while not working due to weather, please fill out a repair form to describe the action and time required.

REPAIR FORM

Date __________

Cooperator ____________________ Machine no. ____________.

Time of day ____________ Hour meter reading __________.

Repair location ___woods ___deck ___your shop ___dealer

Replacement parts were available:
__ a) at the crew site
__ b) on the mechanic's truck
__ c) at the company garage
__ d) dealer for your brand of machine
__ e) other type of dealer
__ f) speciality shop, eg. one that specializes in bearings
__ g) auto parts store
__ h) machine shop
__ i) other

A new replacement part will be reordered and maintained at ____ (a through i above)

Distance involved in delivering the part __________.

Reason code for the downtime (see list to right) _______.

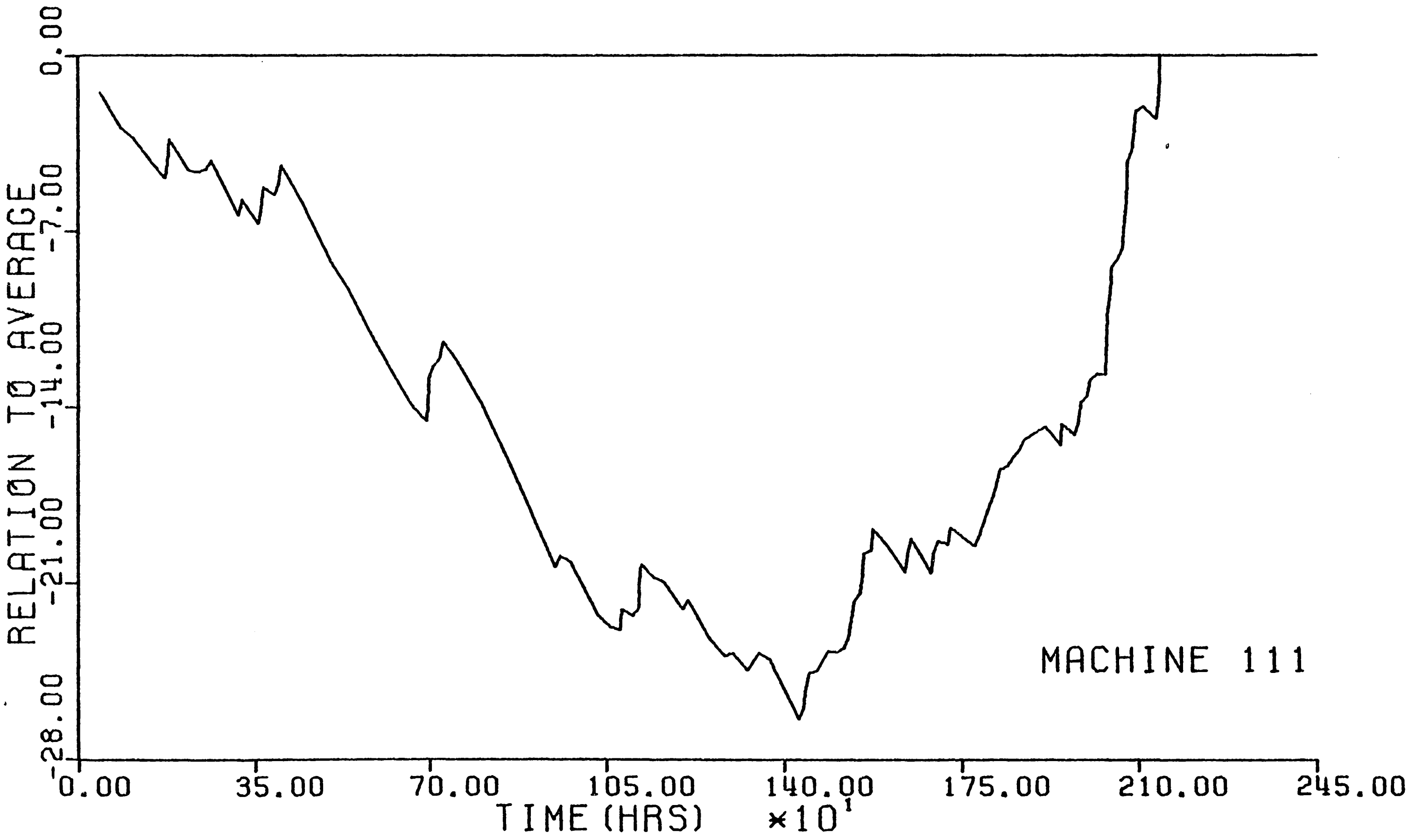
Total active repair time (do not include delays) _______.

01 bent
02 broken
03 clogged
04 cracked
05 cut
06 flat
07 leaking
08 loose
09 part missing
10 overheated
11 seeping
12 sheared
13 short circuit
14 split
15 twisted
16 warped
17 worn

If the repair involved more than one component, then split the time among the components involved.

APPENDIX B

Cumulative number of failures above or below the average time between failures against the time of failure in operating hours for the 24 machines that were tested for trends in their time between failures with time. It is possible to identify trends and/or seasonal fluctuations.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-21.00
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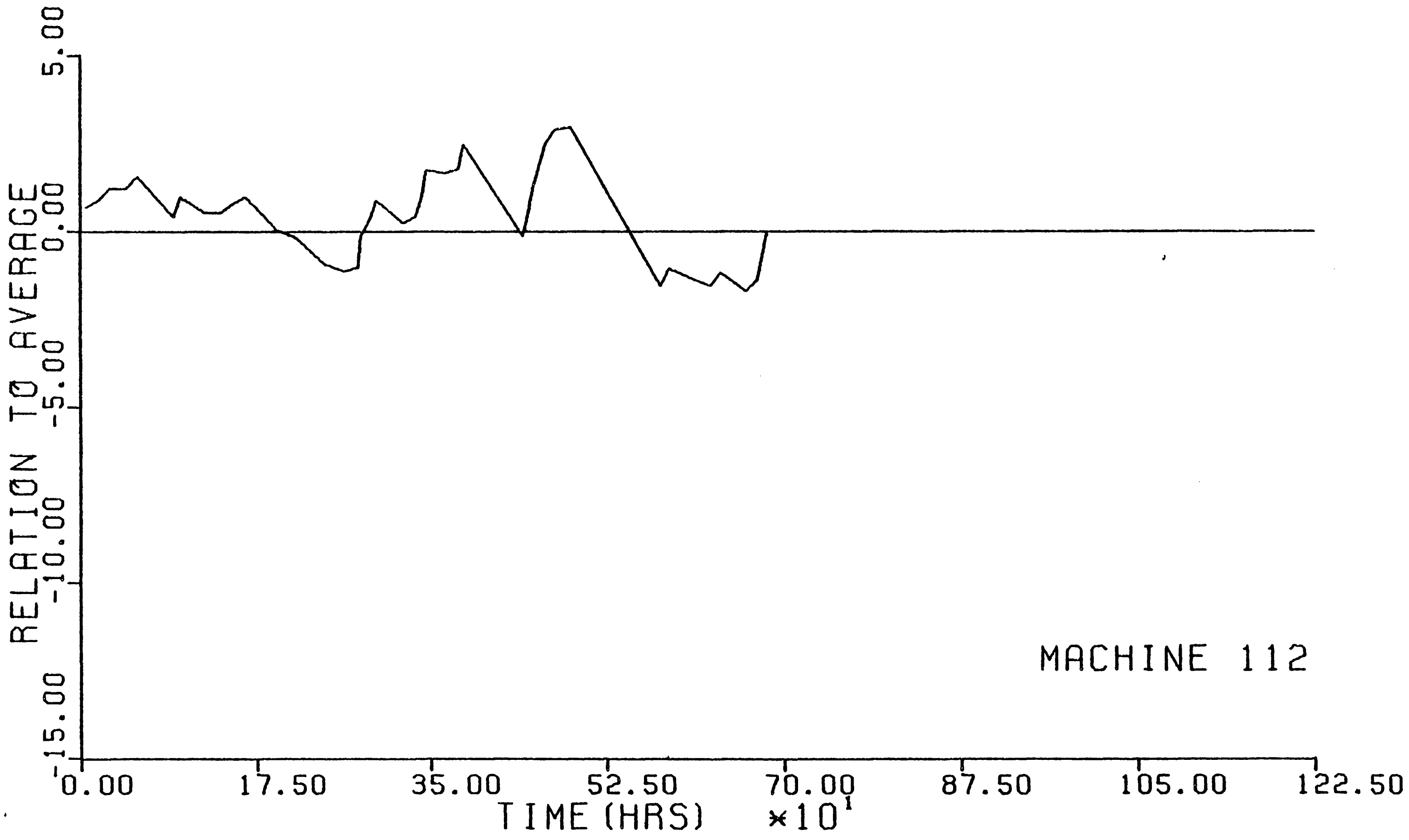
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) ×10¹



5.00
0.00
-5.00
-10.00
-15.00
RELATION TO AVERAGE
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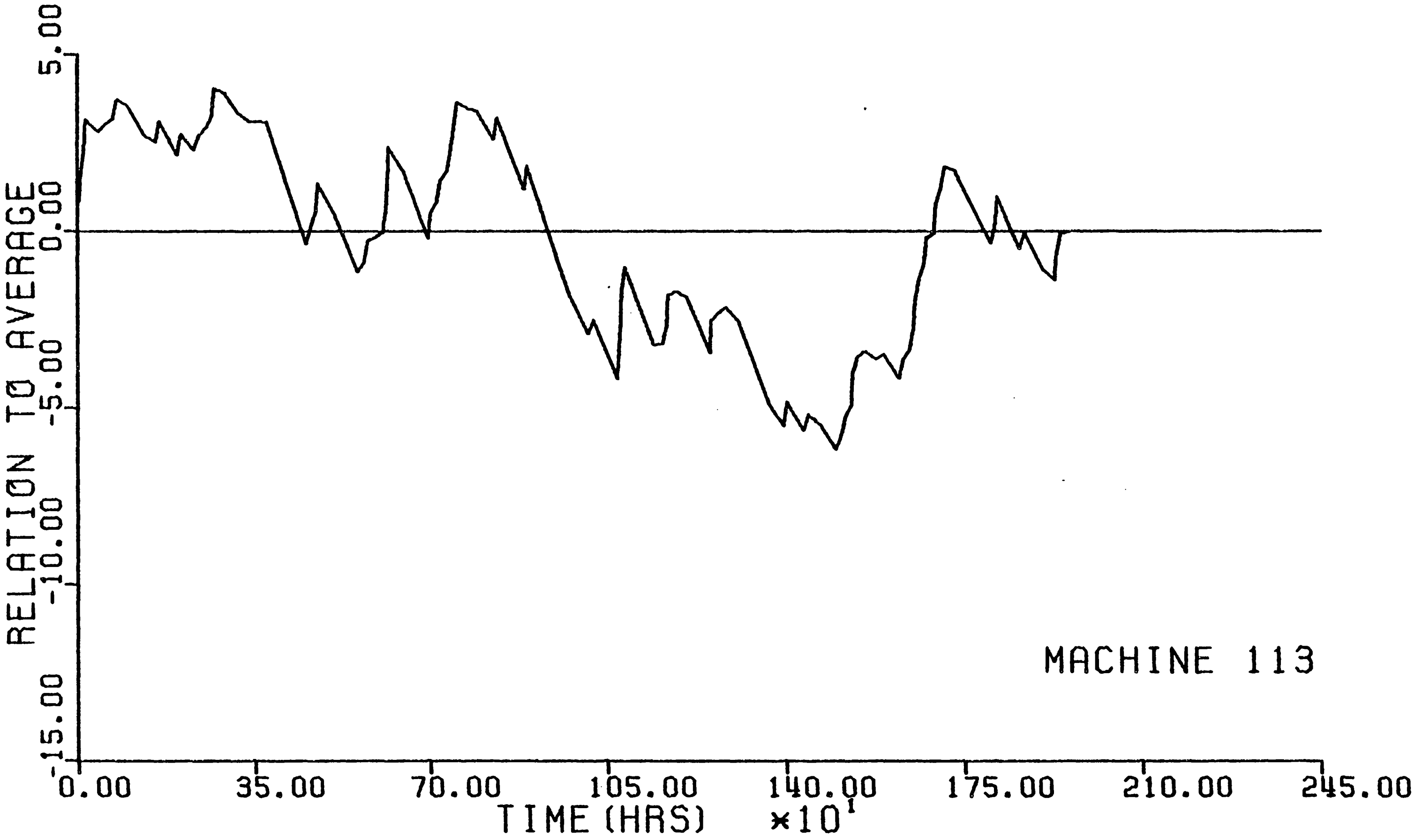
17.50
35.00
52.50
70.00
87.50
105.00
122.50
TIME (HRS) ×10¹
MACHINE 112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0.00
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-10.00
-15.00
0.00
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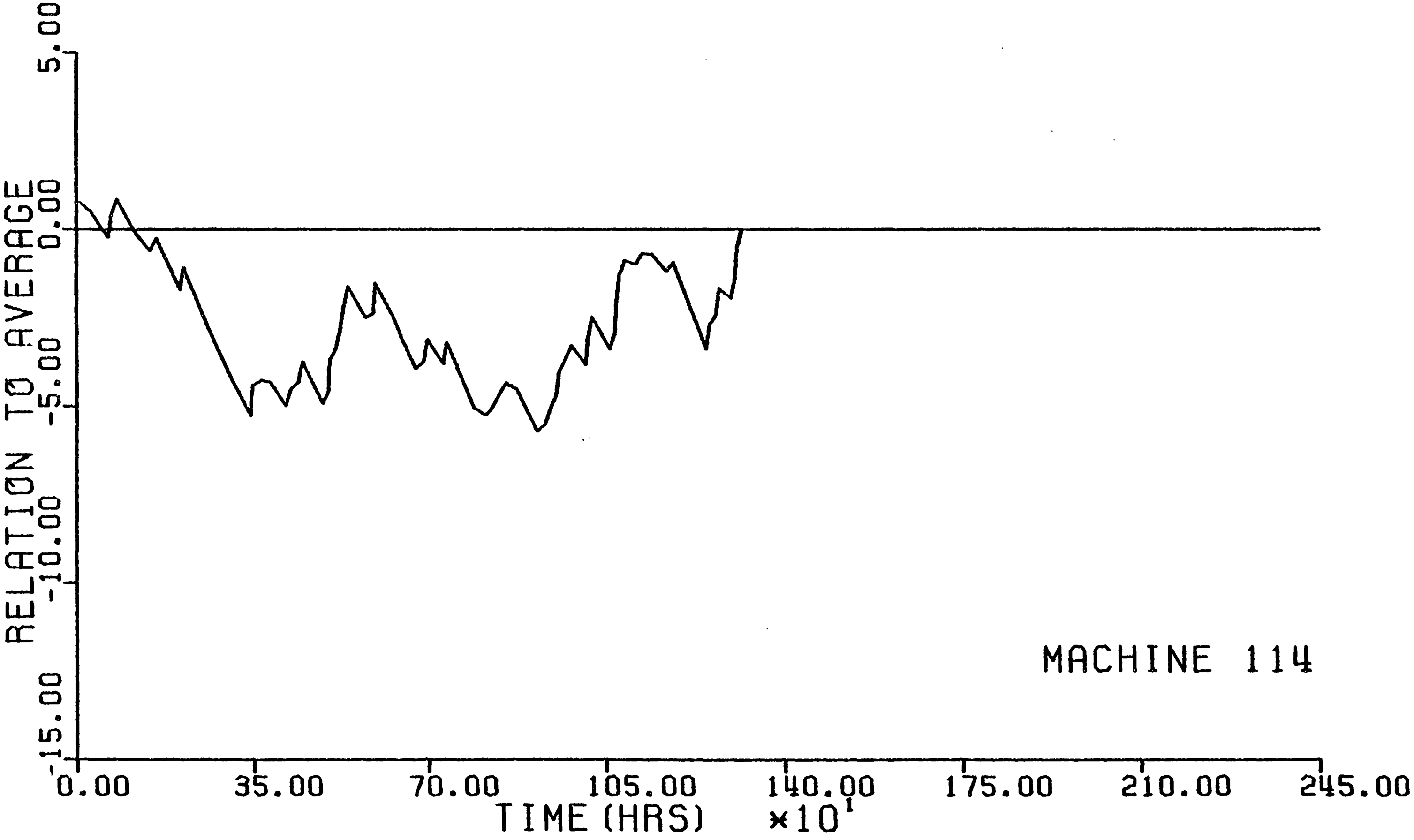
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) ×10^1
MACHINE 113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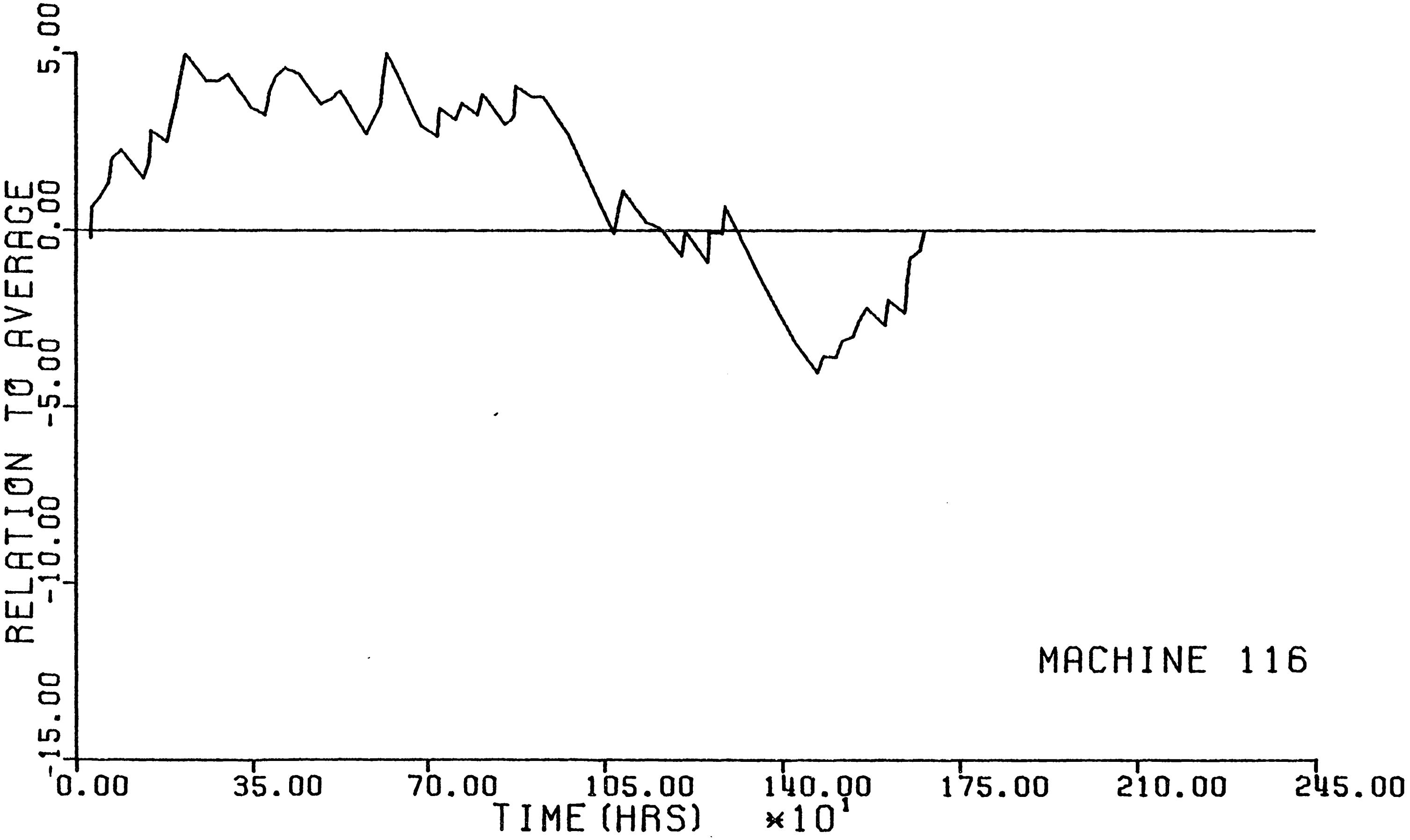
175.00
210.00
245.00
TIME (HRS) $\times 10^1$
MACHINE 114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-15.00
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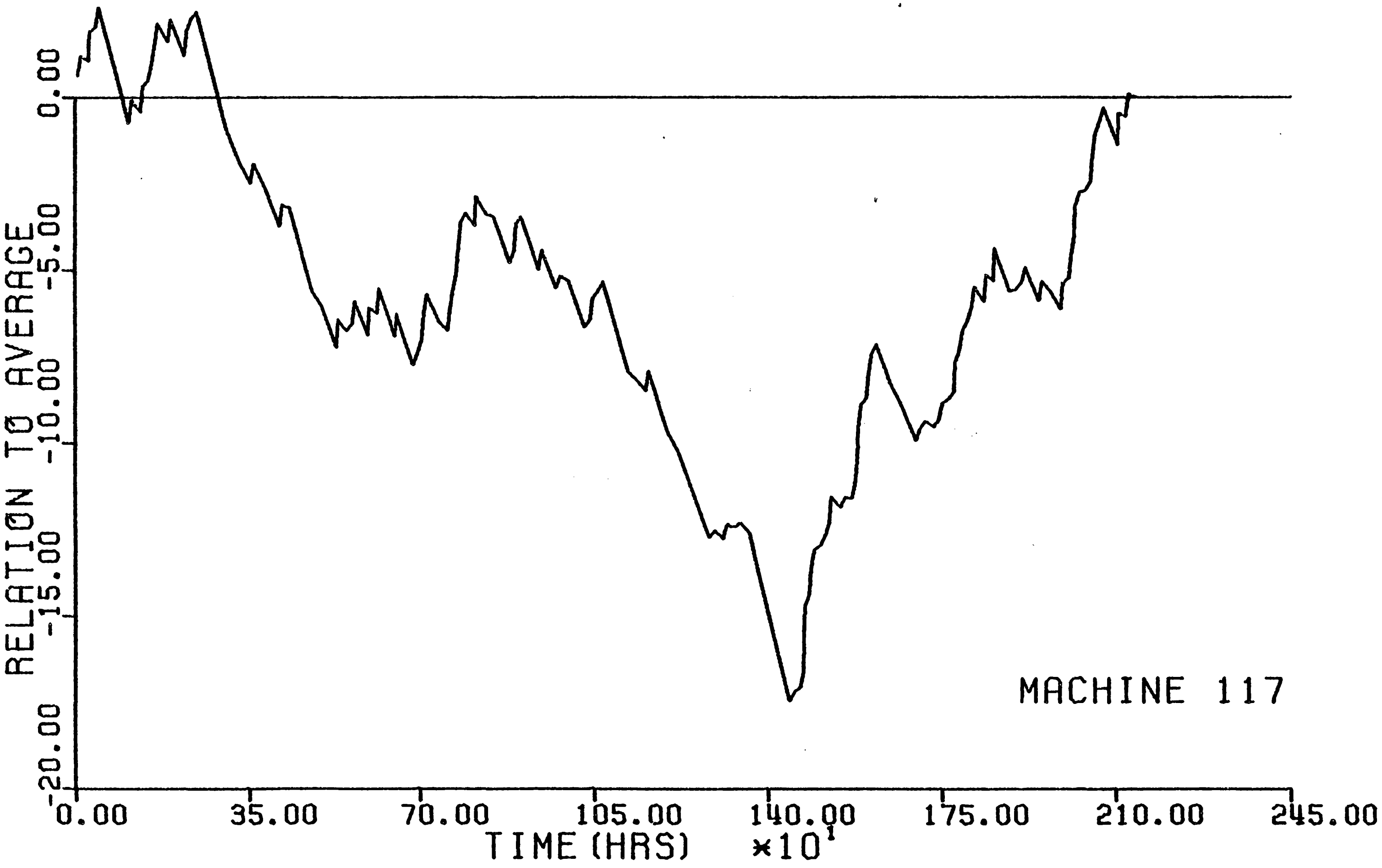
140.00
175.00
210.00
245.00
TIME (HRS) ×10¹
MACHINE 116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0.00
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70.00
105.00
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175.00
210.00
245.00
TIME (HRS) $\times 10^1$
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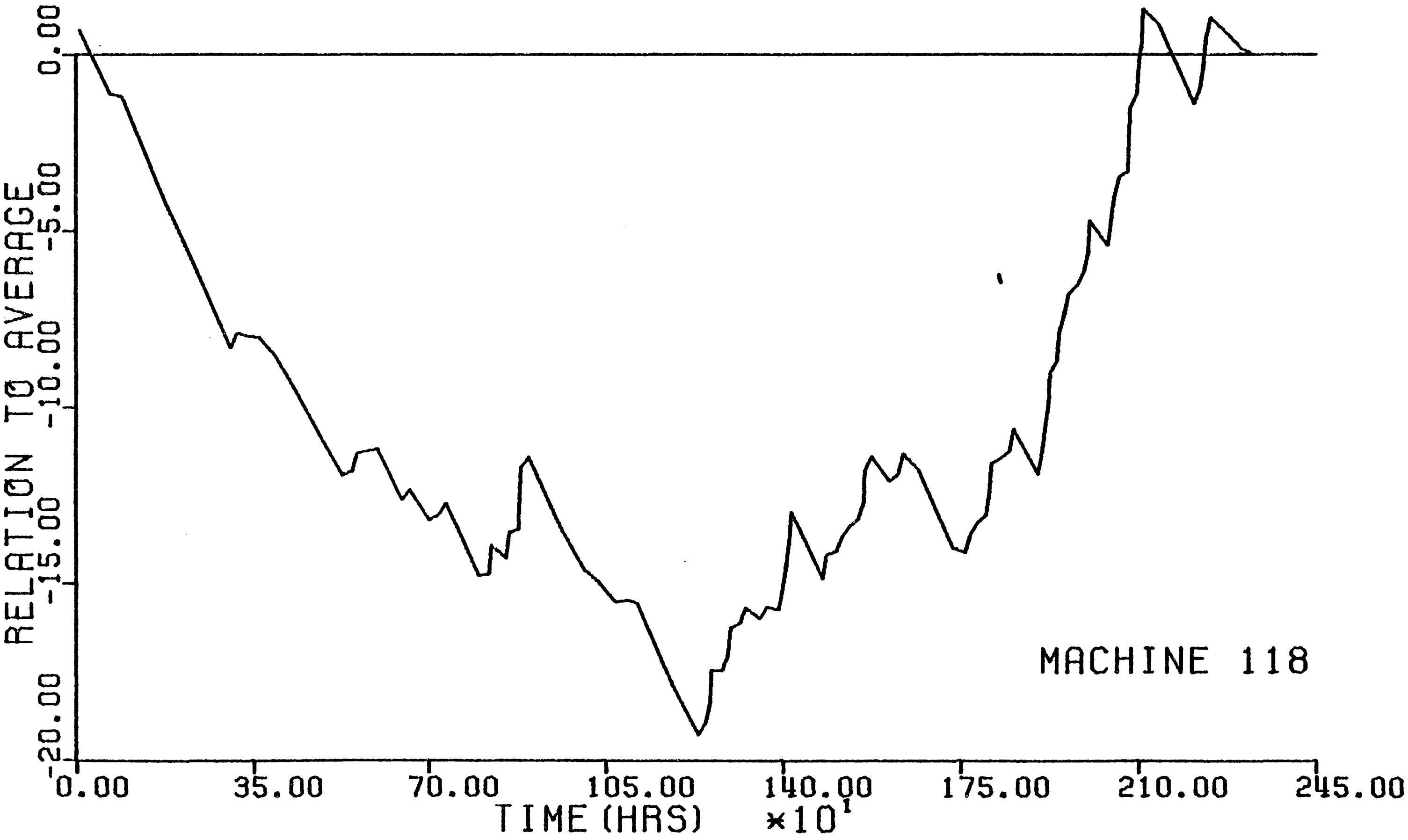
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210.00
245.00
TIME (HRS) $\times 10^1$
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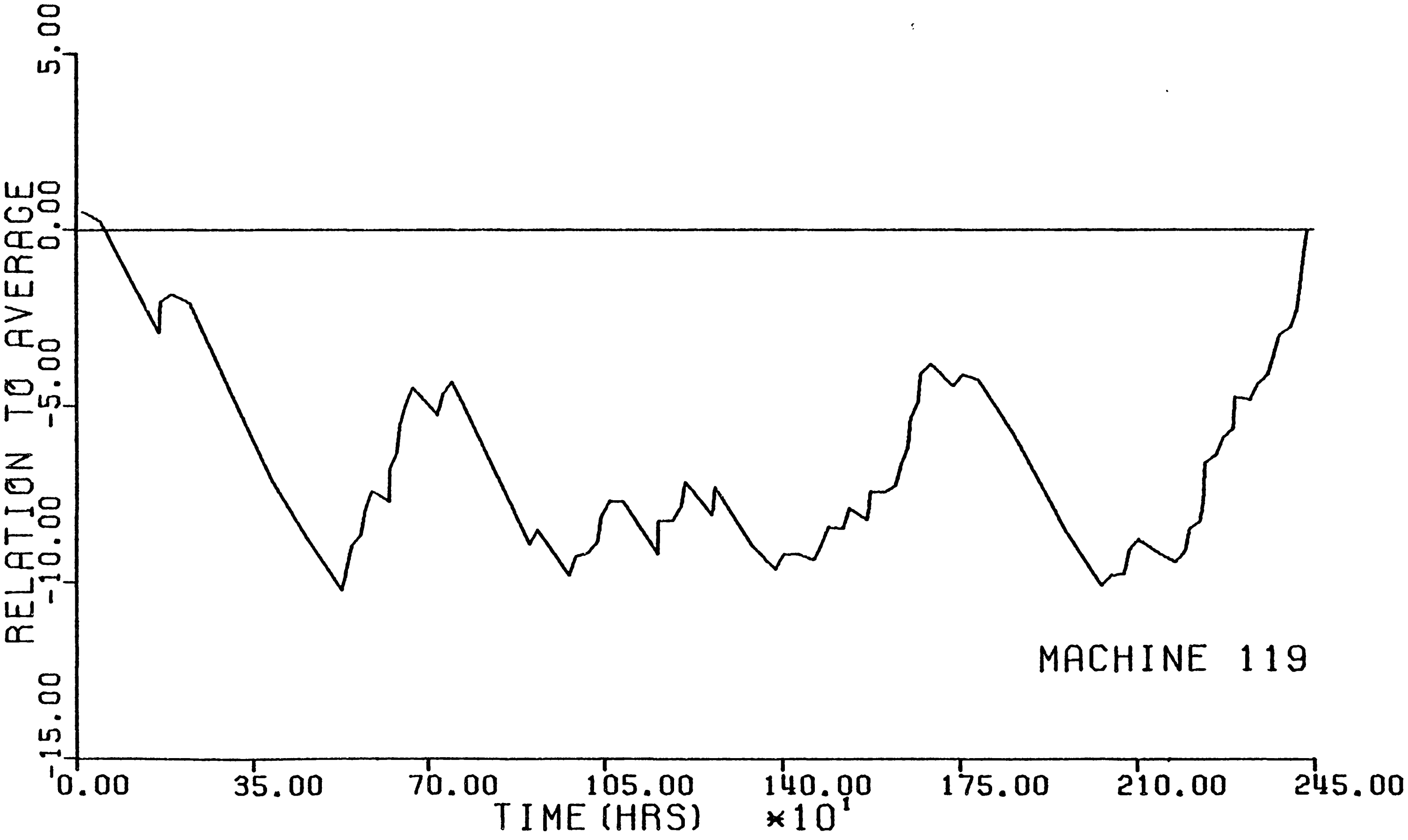
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175.00
210.00
245.00
TIME (HRS) *10¹
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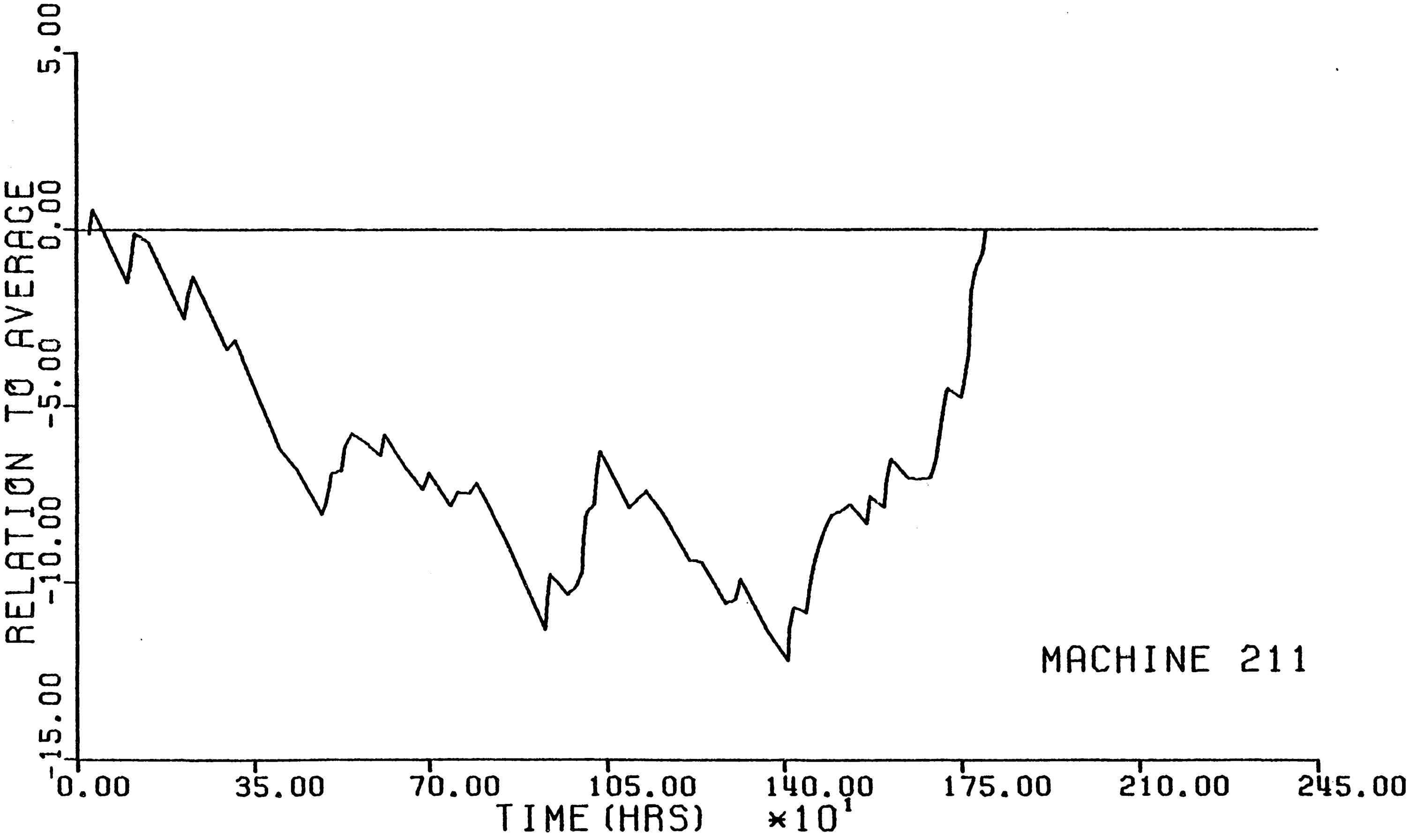
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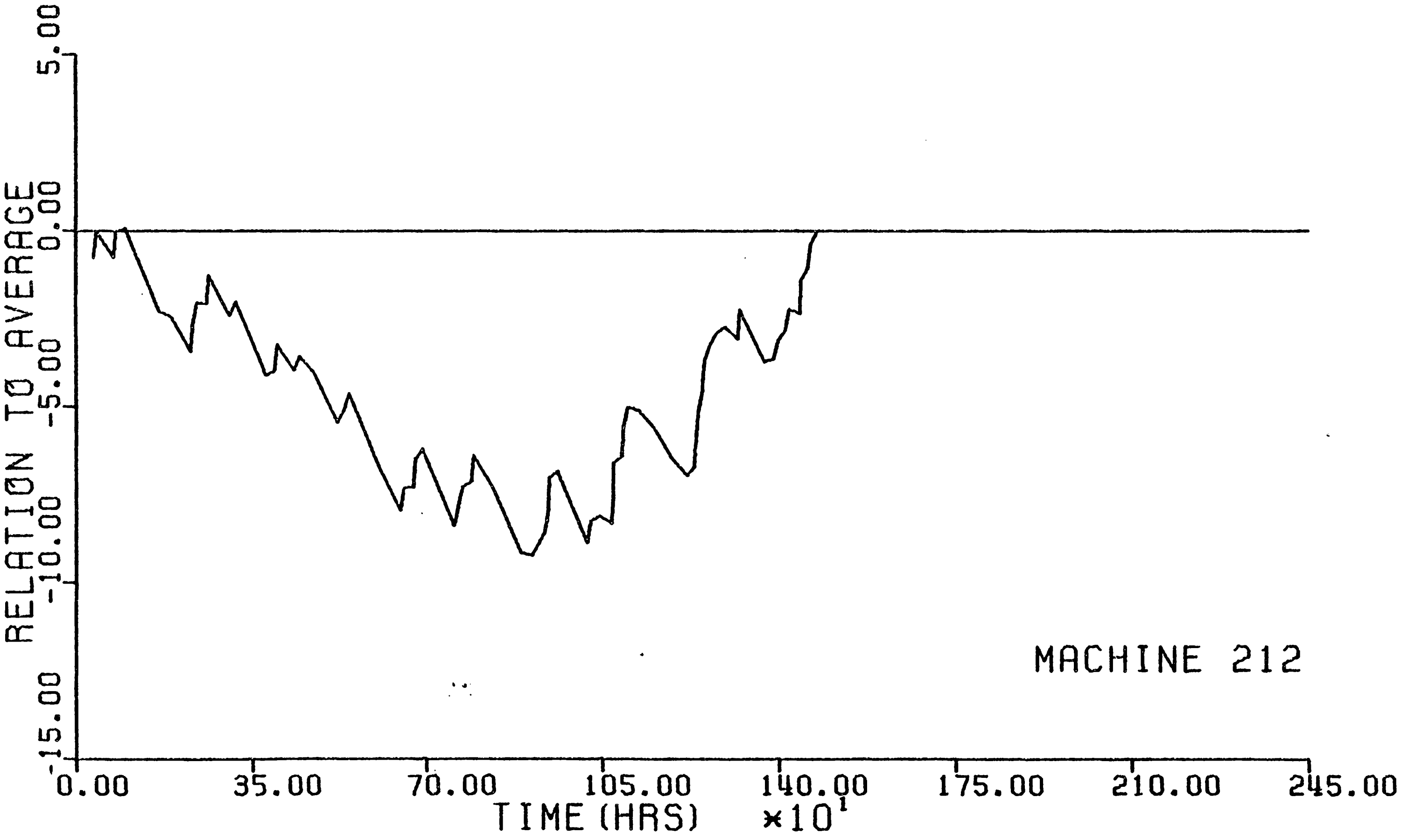
105.00
140.00
175.00
210.00
245.00
TIME (HRS) ×10¹
MACHINE 211



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70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) ×10¹
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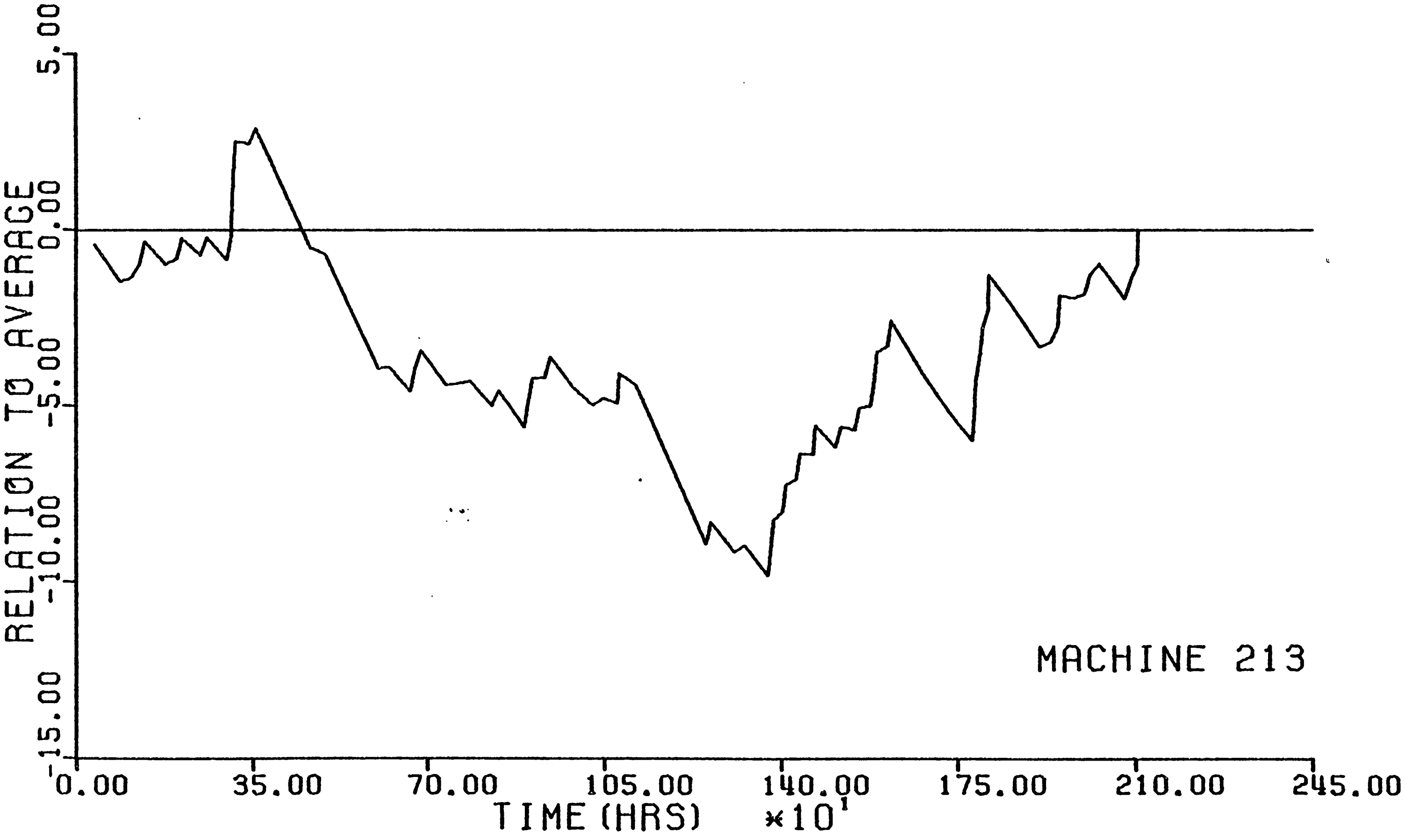
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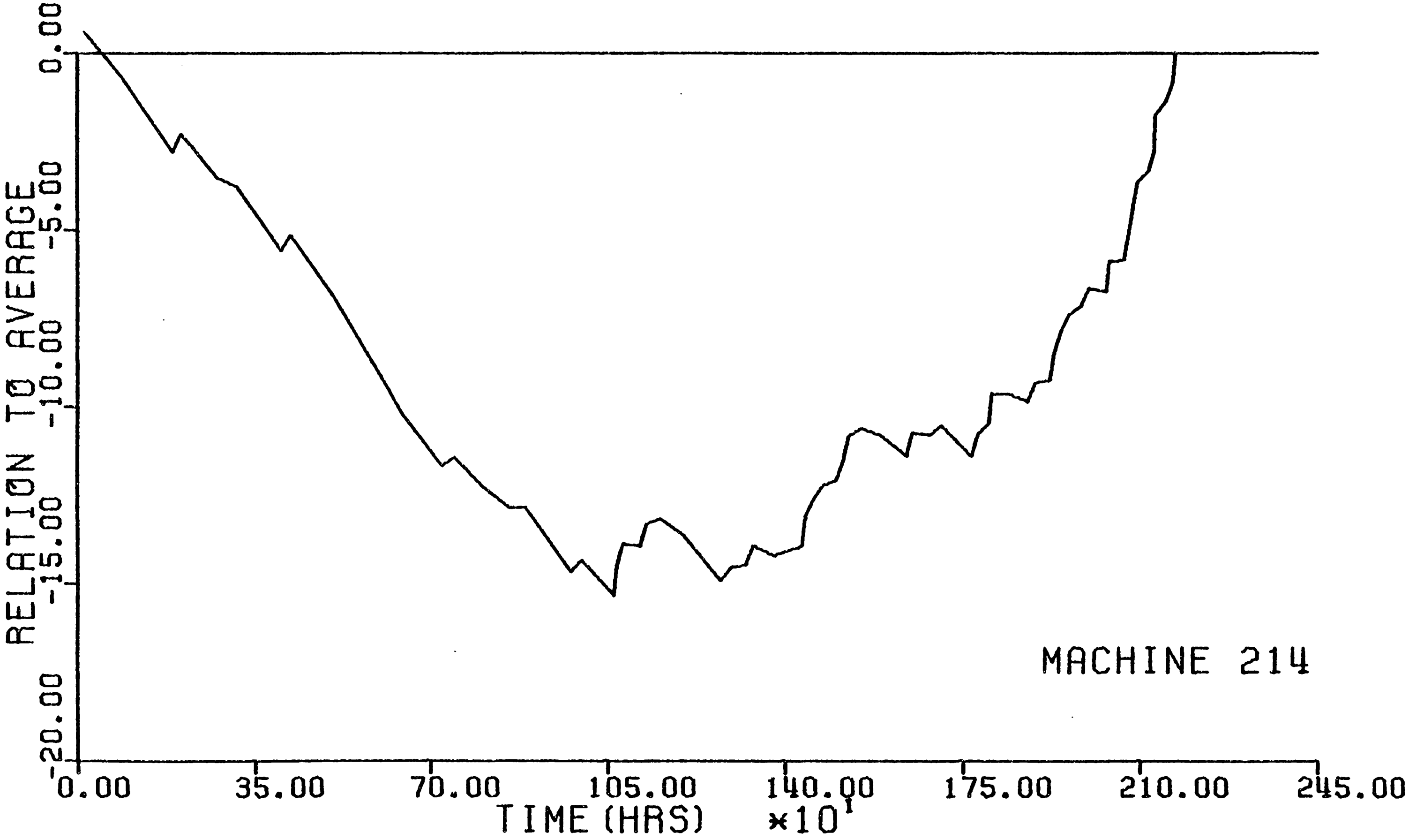
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) $\times 10^1$
MACHINE 213

RELATION TO AVERAGE
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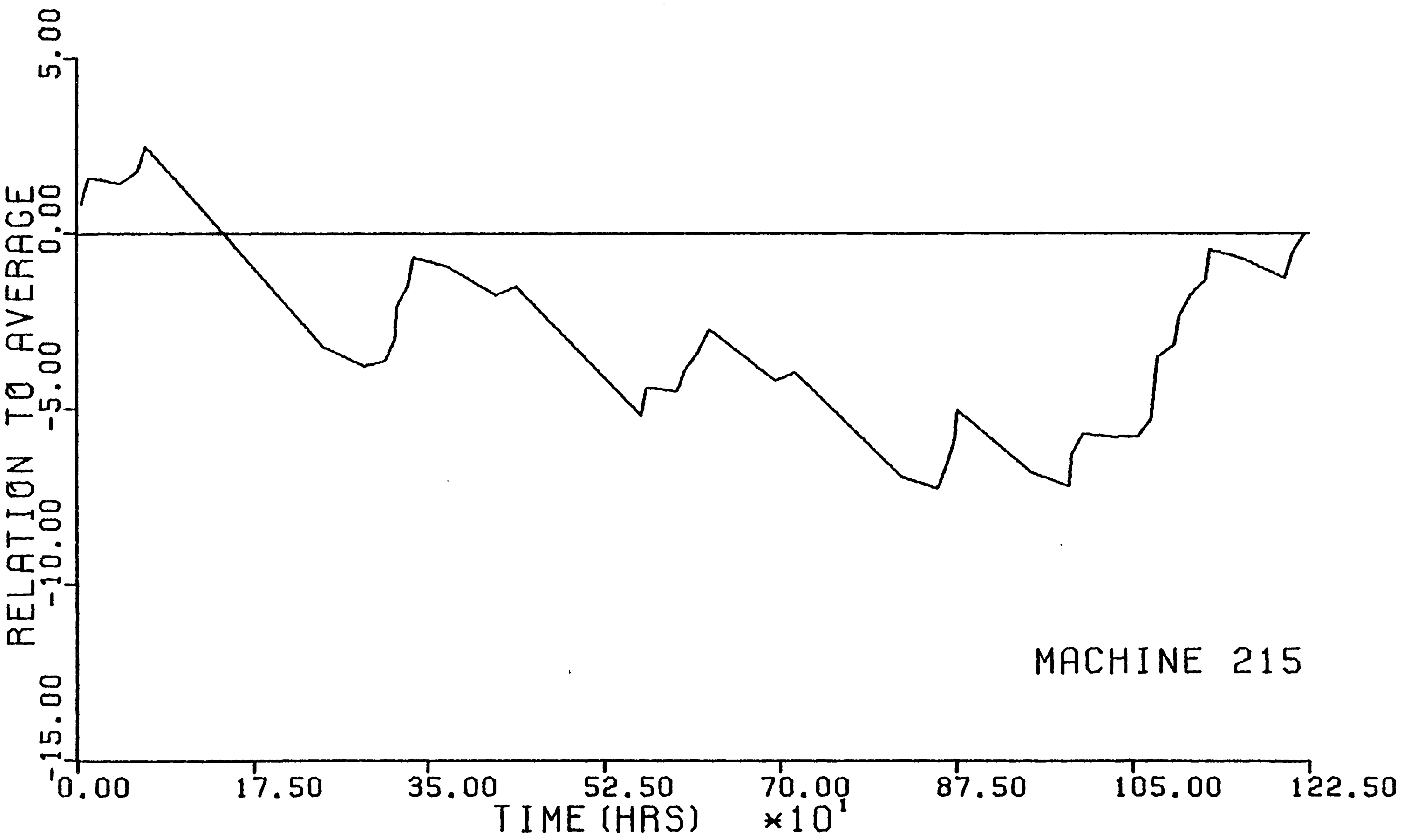
0.00
35.00
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) $\times 10^1$
MACHINE 214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0.00
-5.00
-10.00
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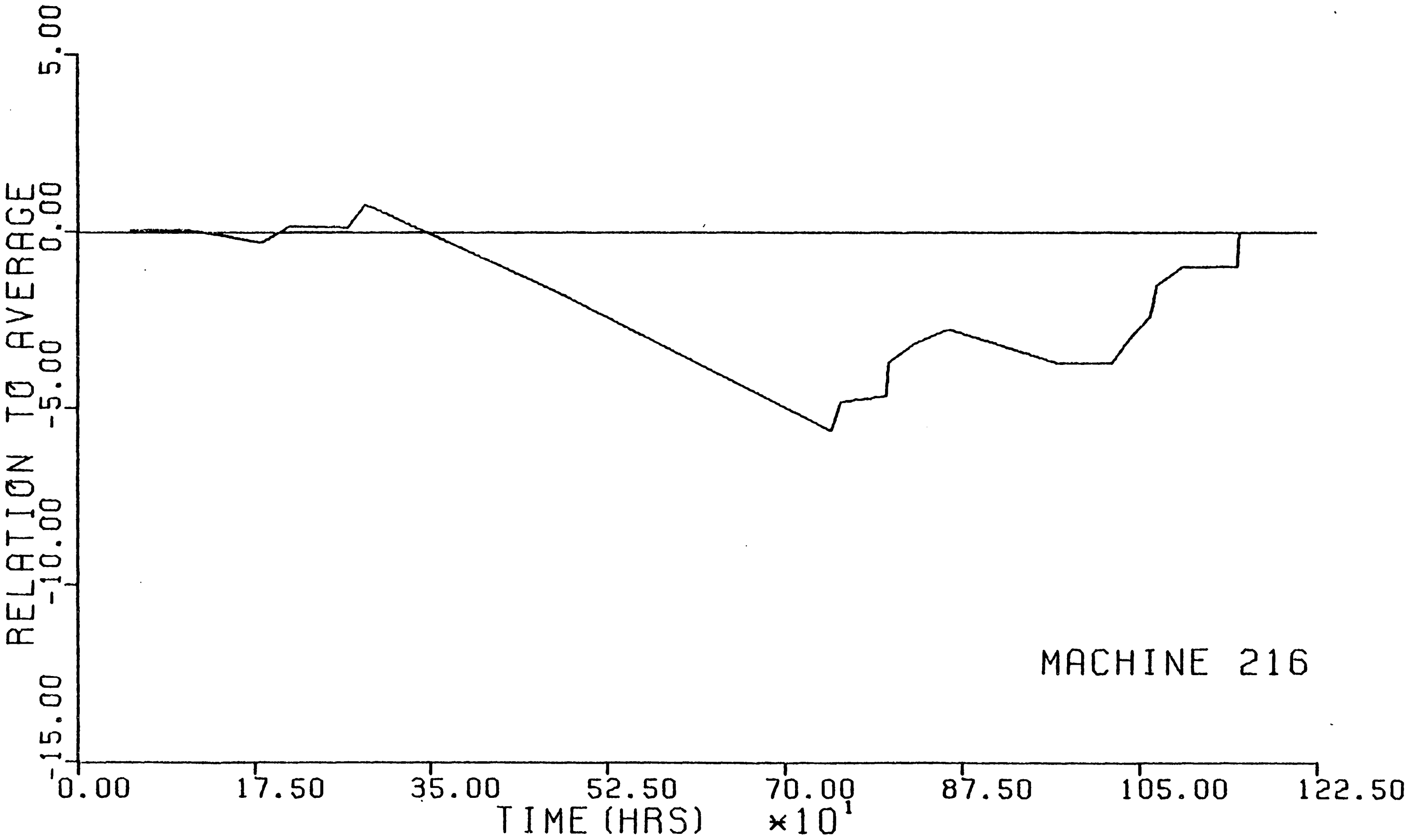
17.50
35.00
52.50
70.00
87.50
105.00
122.50
TIME (HRS) ×10¹
MACHINE 215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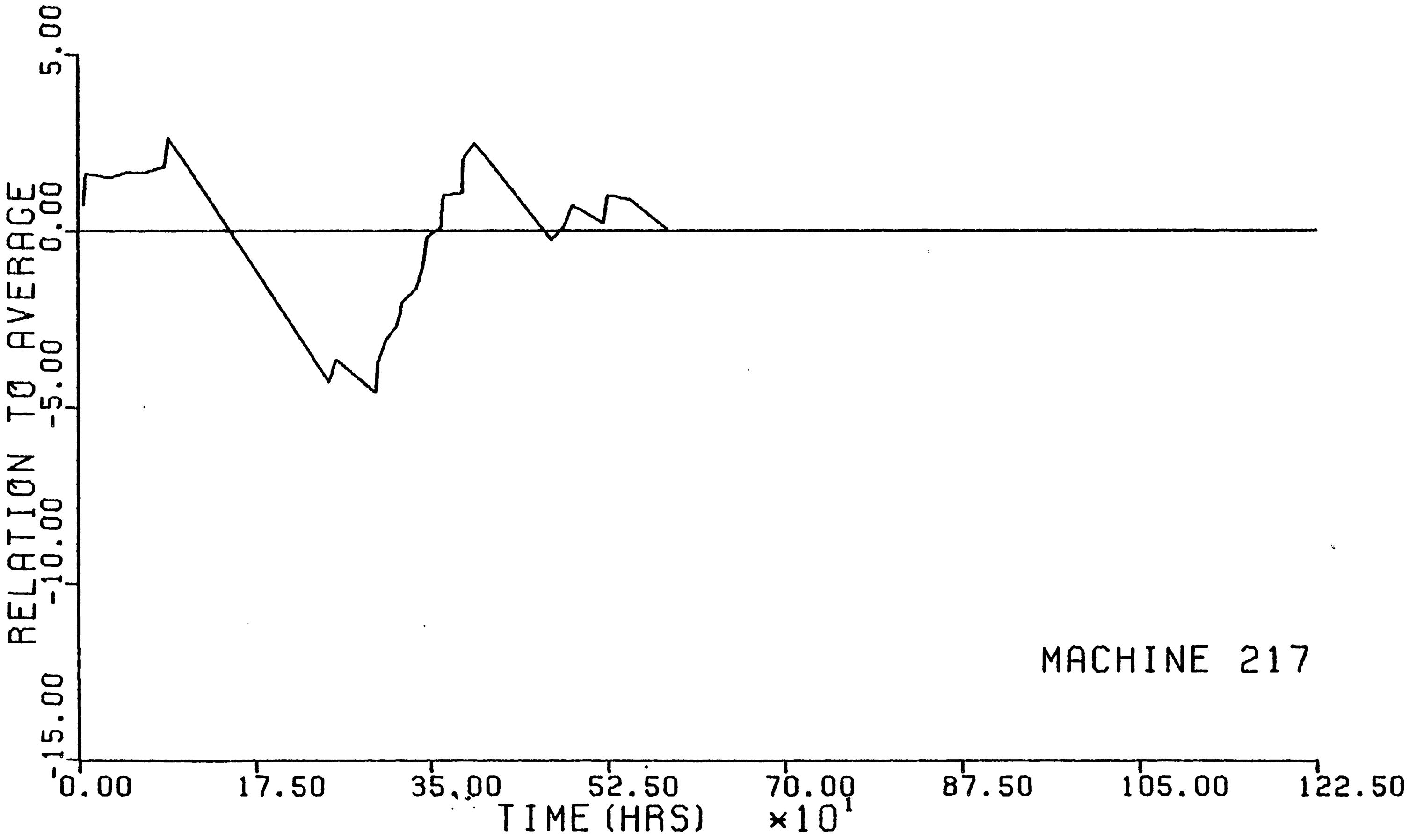
70.00
87.50
105.00
122.50
TIME (HRS) ×10¹
MACHINE 216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-15.00
RELATION TO AVERAGE
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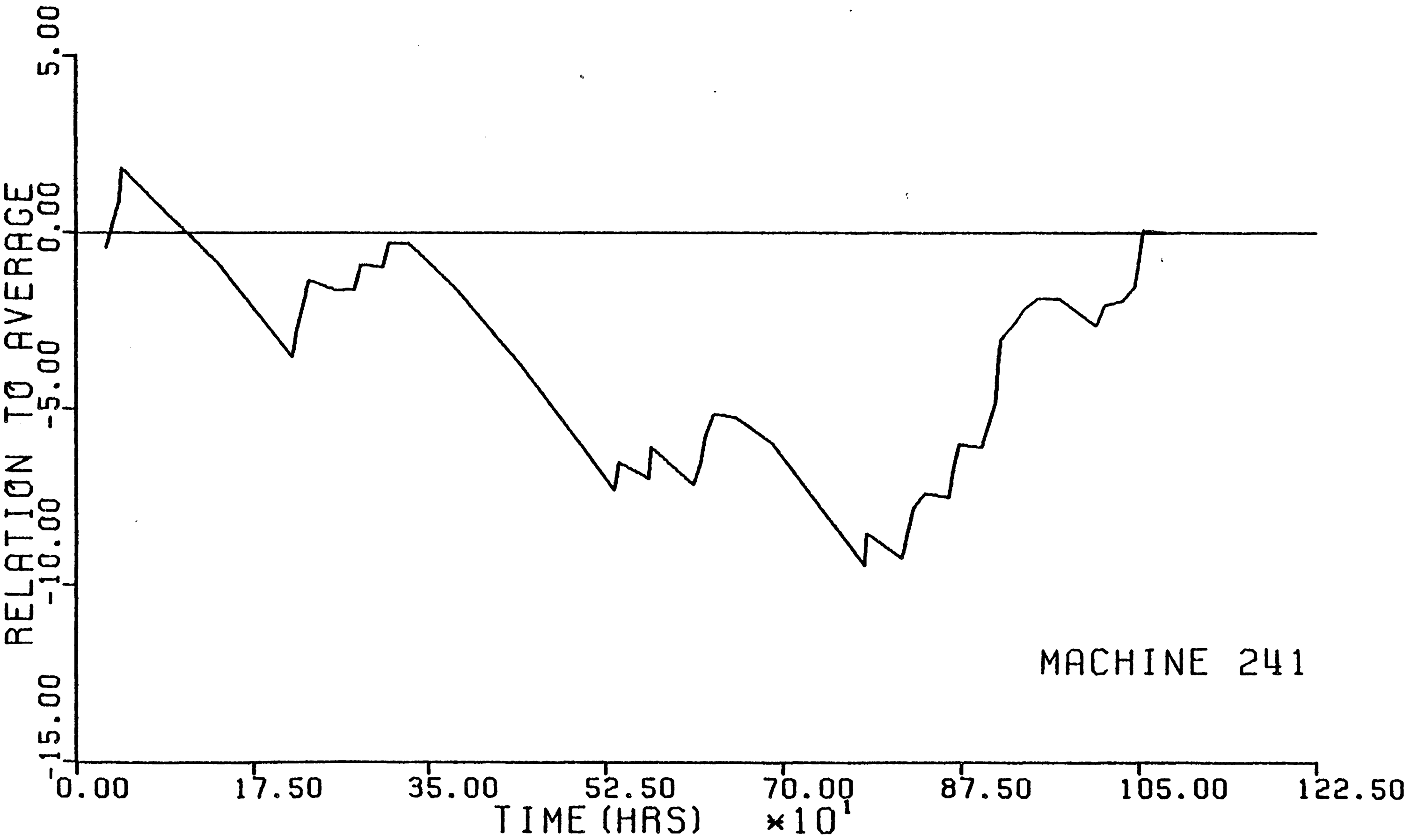
70.00
87.50
105.00
122.50
TIME (HRS) ×10^1
MACHINE 217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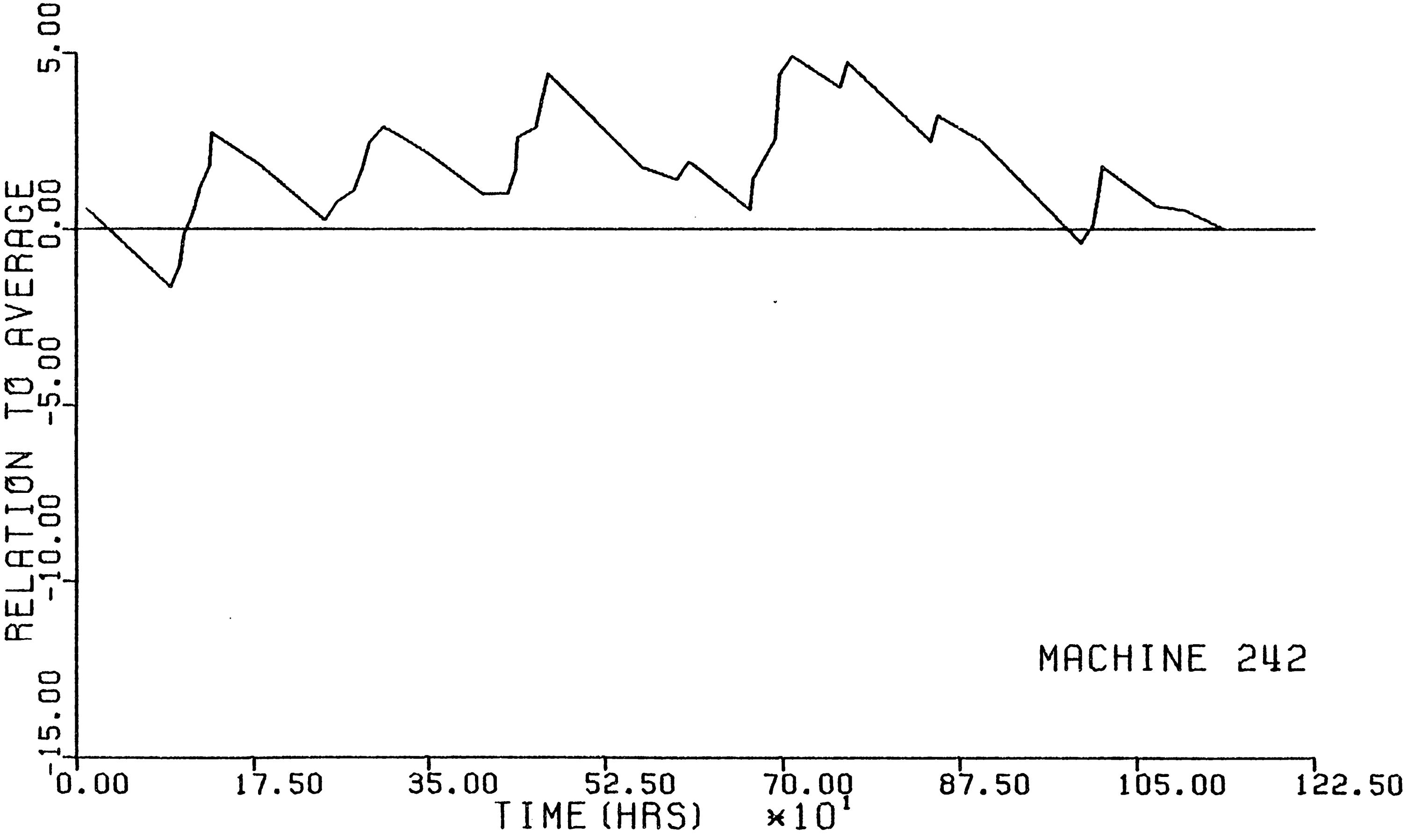
17.50
35.00
52.50
70.00
87.50
105.00
122.50
TIME (HRS) ×10^1
MACHINE 241


RELATION TO AVERAGE
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0.00
-5.00
-10.00
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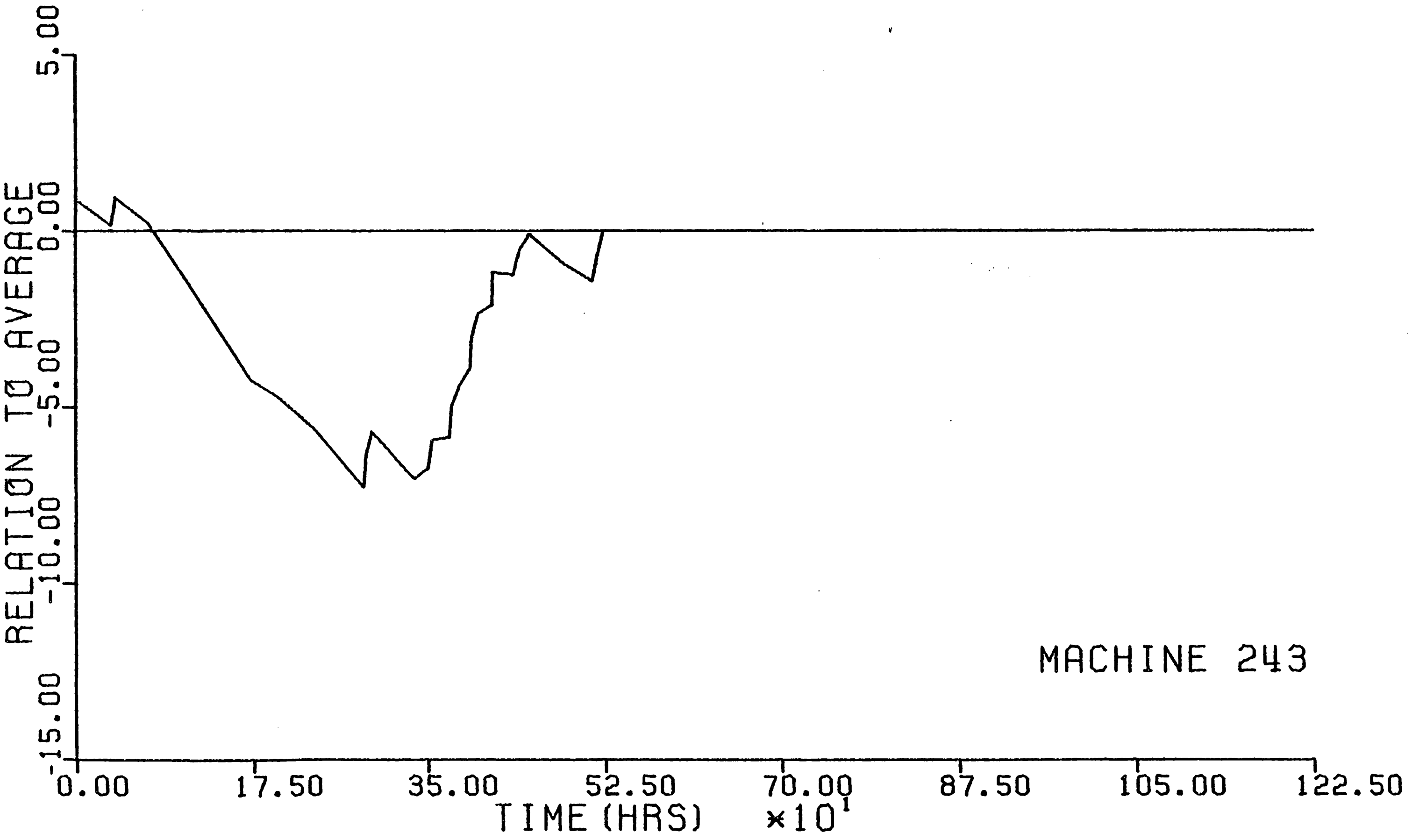
0.00
17.50
35.00
52.50
70.00
87.50
105.00
122.50
TIME (HRS) ×10^1
MACHINE 242


RELATION TO AVERAGE
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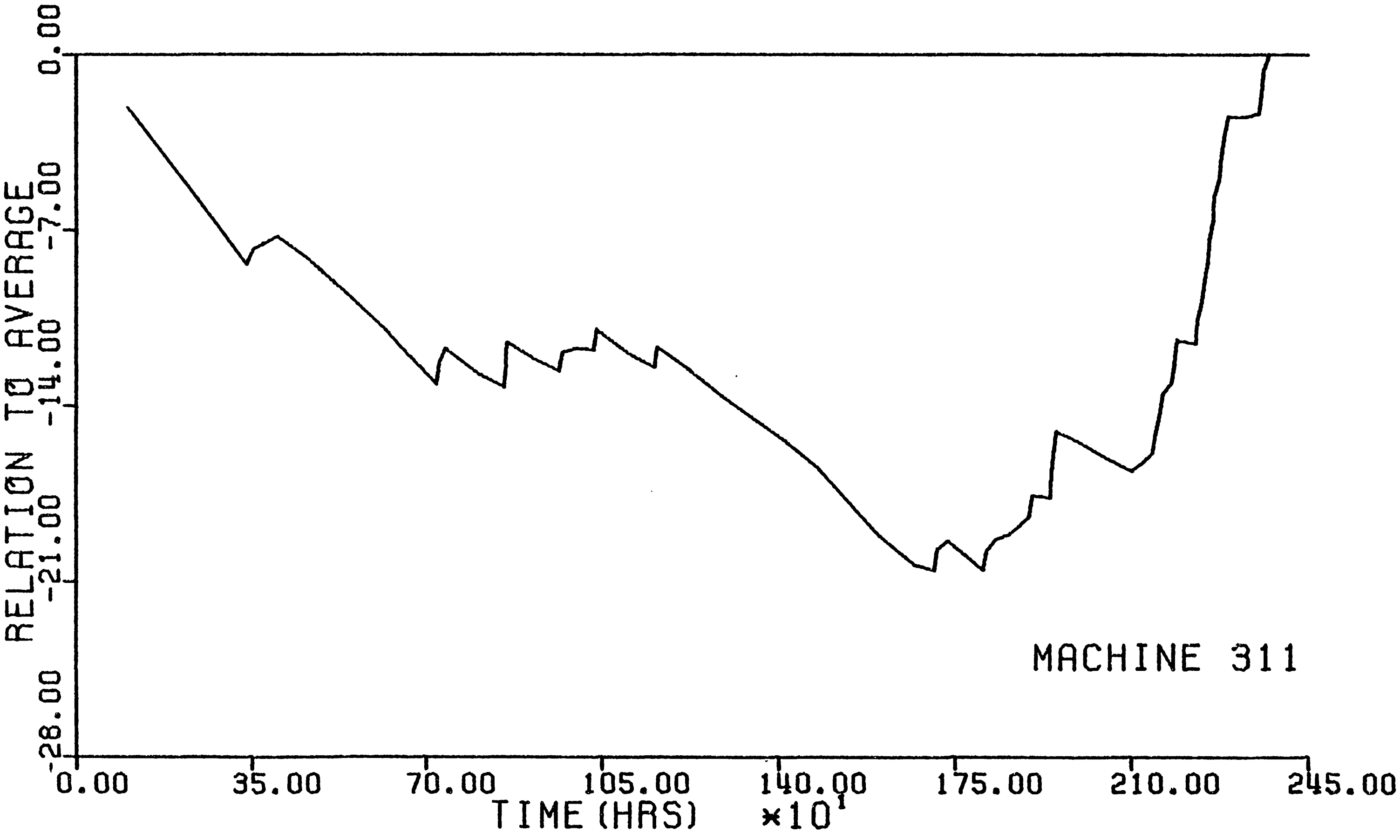
0.00
-5.00
-10.00
-15.00
0.00
17.50
35.00
52.50
70.00
87.50
105.00
122.50
TIME (HRS) ×10¹
MACHINE 243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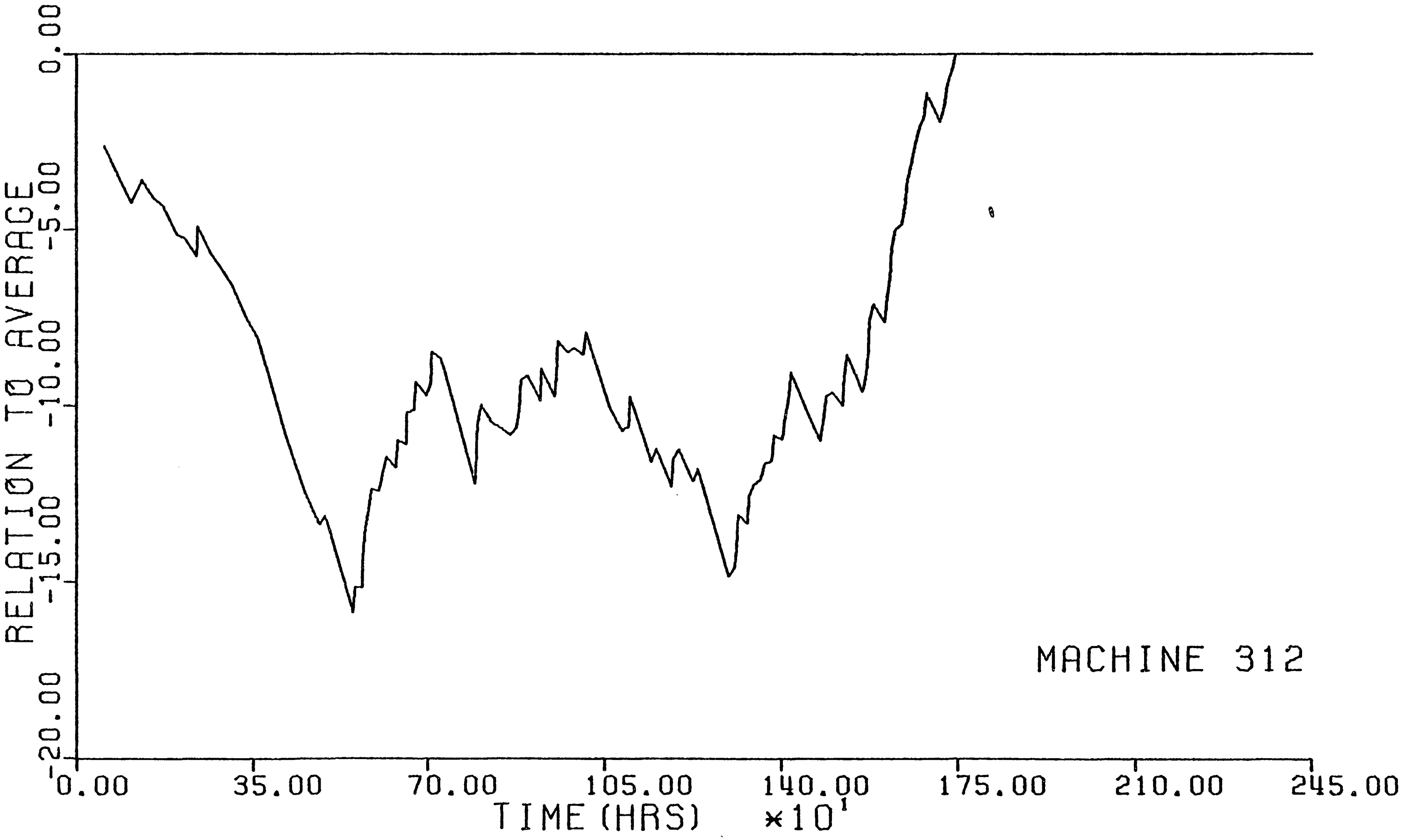
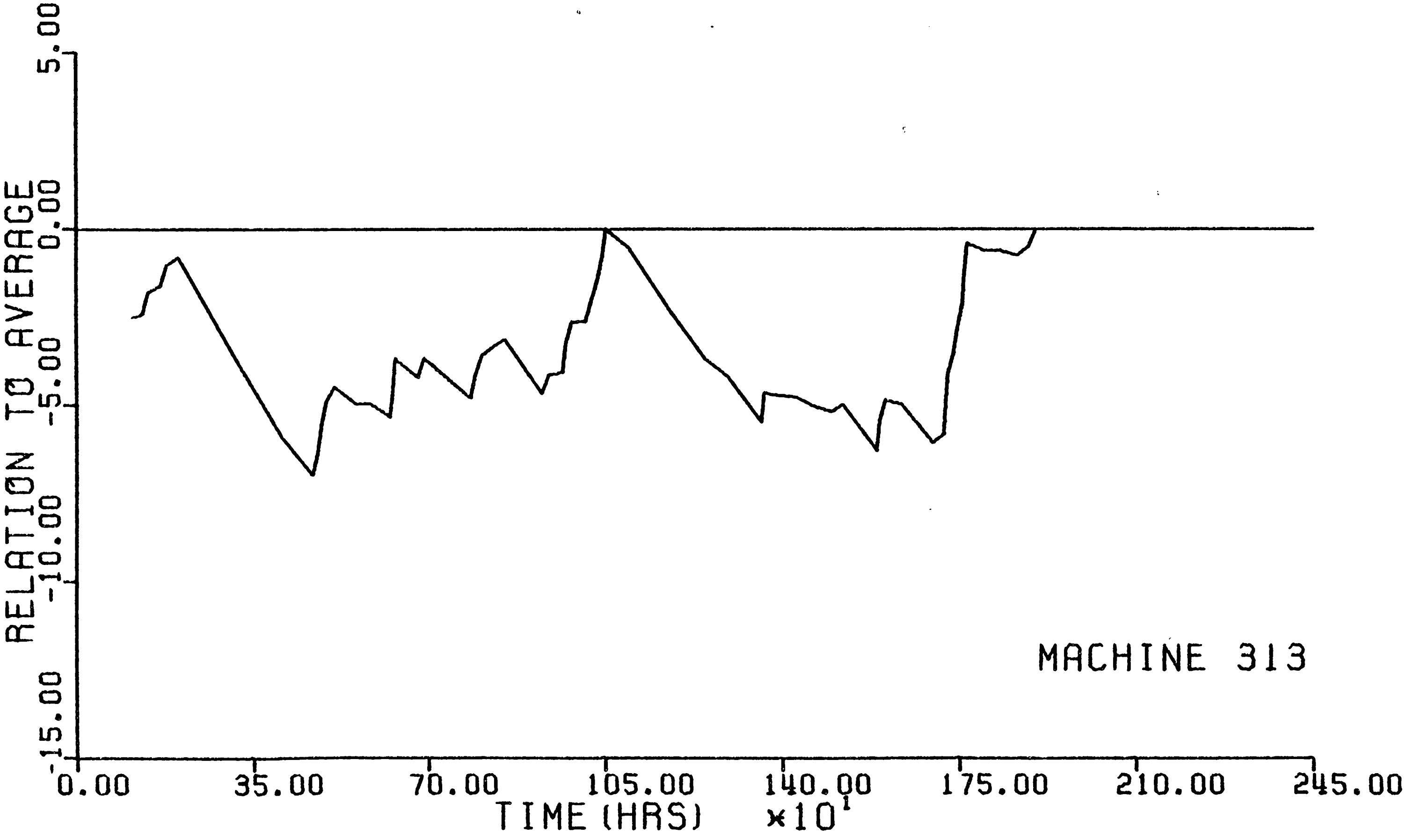
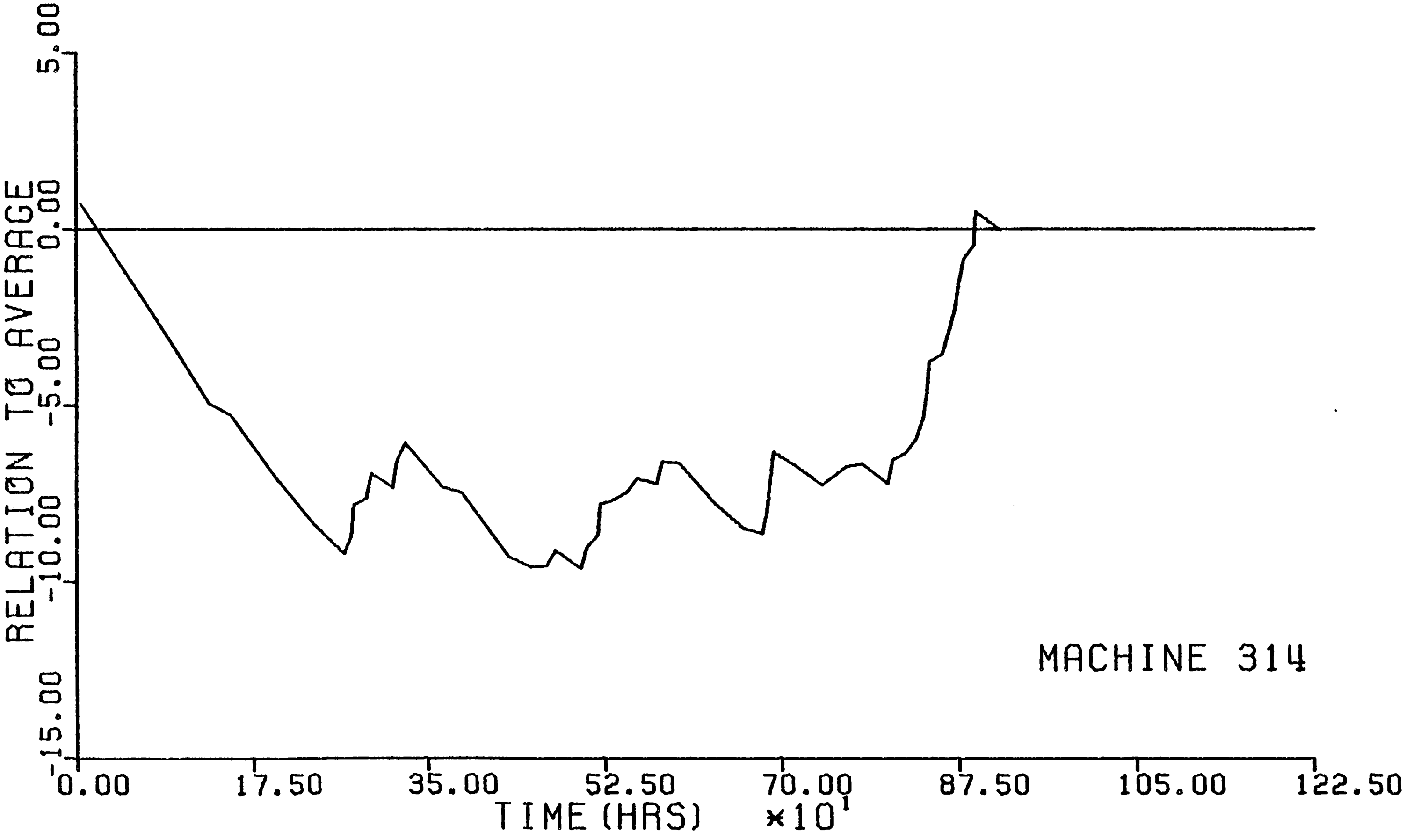
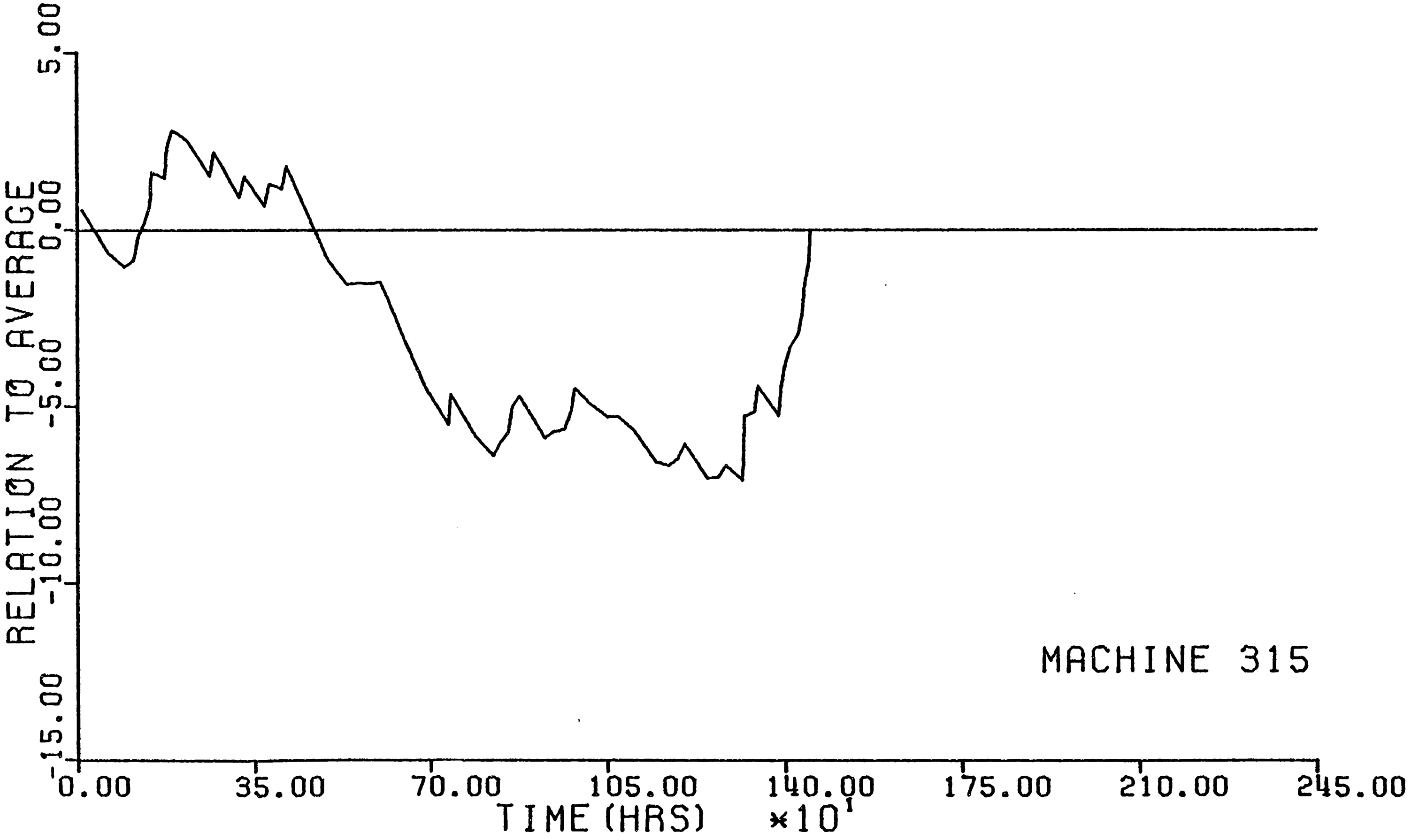
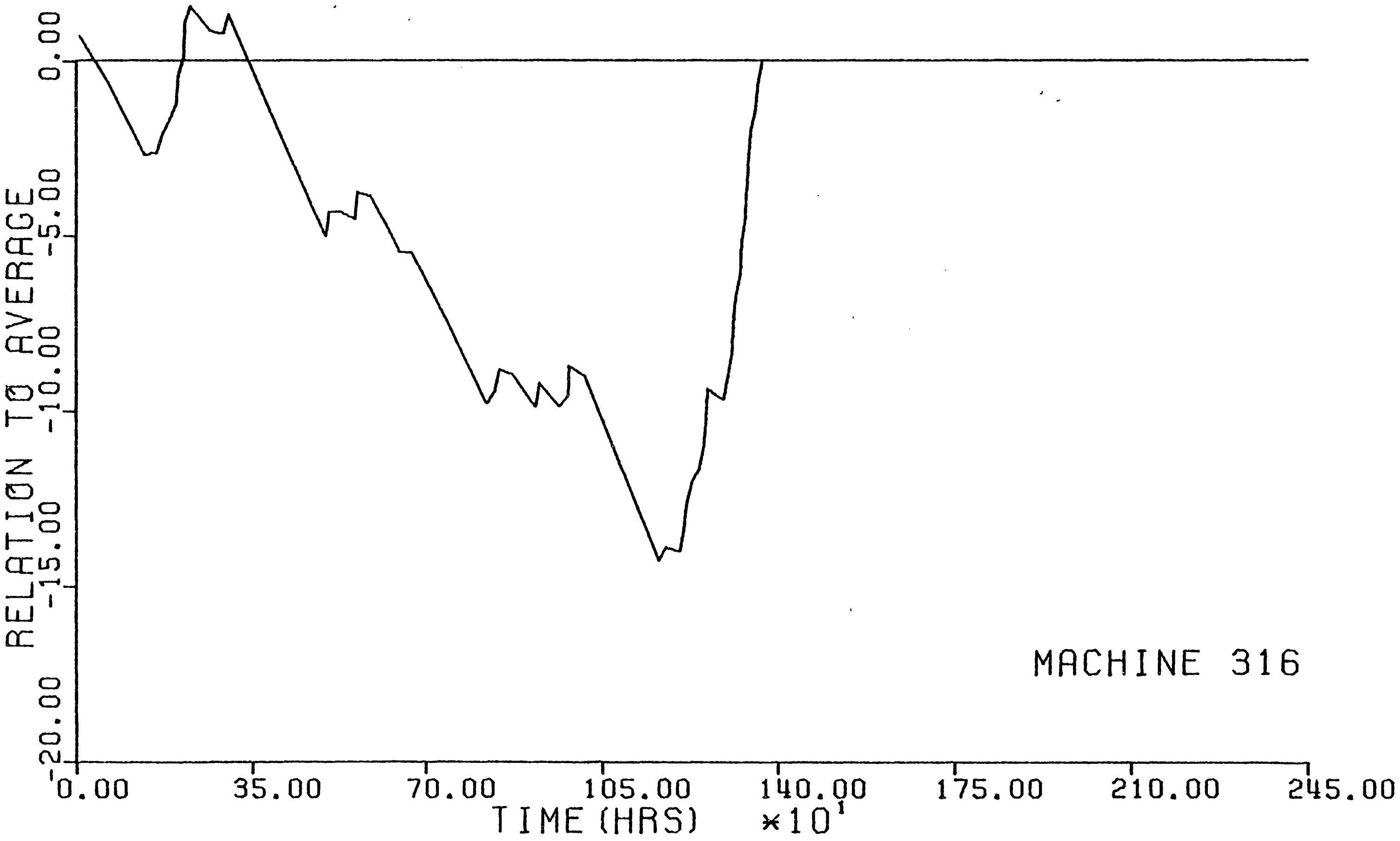
-7.00
-14.00
-21.00
-28.00
0.00
35.00
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) *10¹
MACHINE 311


RELATION TO AVERAGE
0.00
-5.00
-10.00
-15.00
-20.00
0.00
35.00
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) ×10¹
MACHINE 312


RELATION TO AVERAGE
5.00
0.00
-5.00
-10.00
-15.00
0.00
35.00
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) ×10¹
MACHINE 313


5.00
0.00
-5.00
-10.00
-15.00
RELATIØN TØ AVERAGE
0.00
17.50
35.00
52.50
70.00
87.50
105.00
122.50
TIME (HRS) ×10¹
MACHINE 314


5.00
0.00
-5.00
-10.00
-15.00
RELATION TO AVERAGE
0.00
35.00
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) ×10¹
MACHINE 315


RELATION TO AVERAGE
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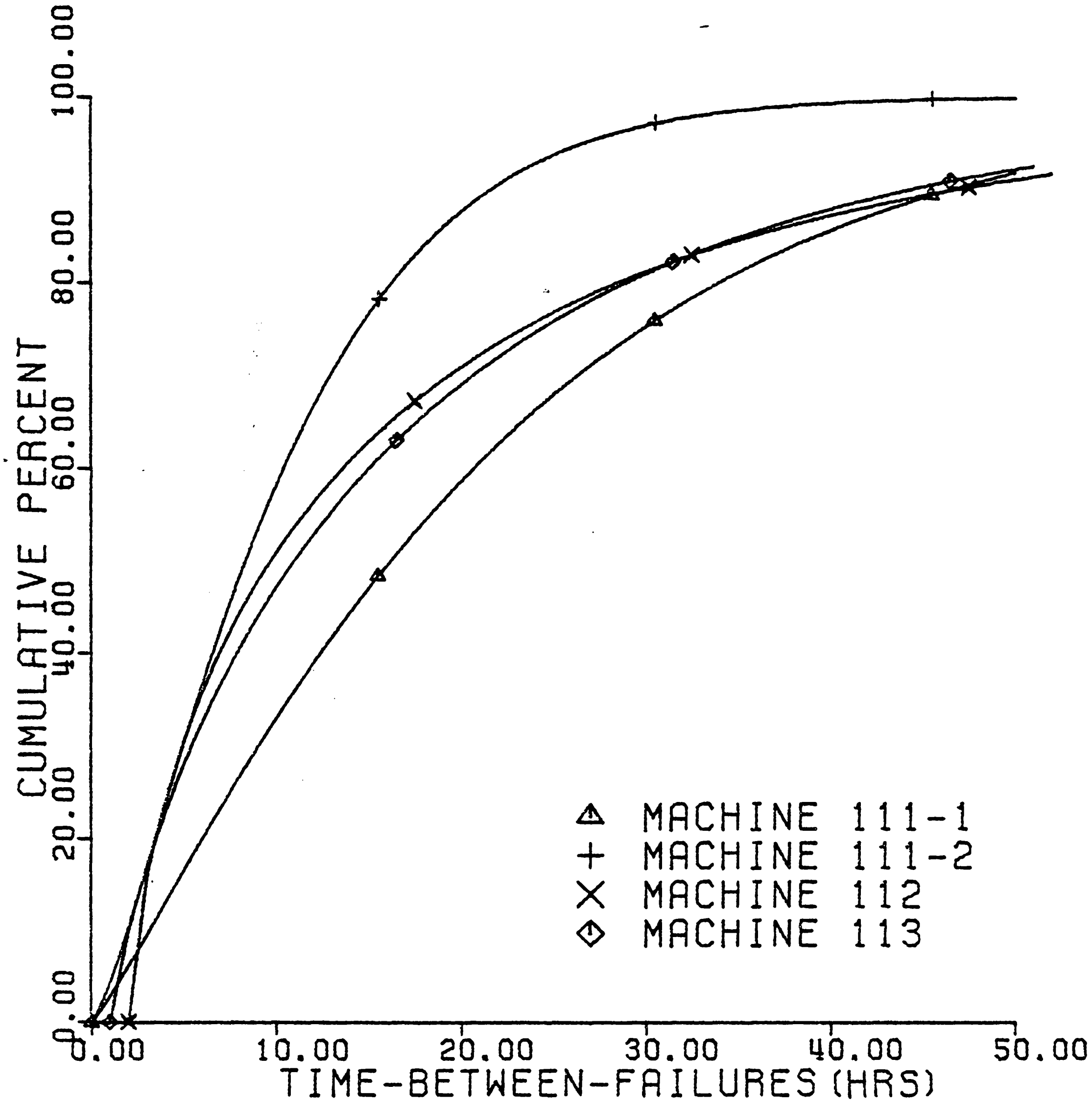
-5.00
-10.00
-15.00
-20.00
0.00
35.00
70.00
105.00
140.00
175.00
210.00
245.00
TIME (HRS) $\times 10^1$
MACHINE 316

APPENDIX C

Weibull distributions that represent the time between failures and times to repair for the 32 machines included in the study.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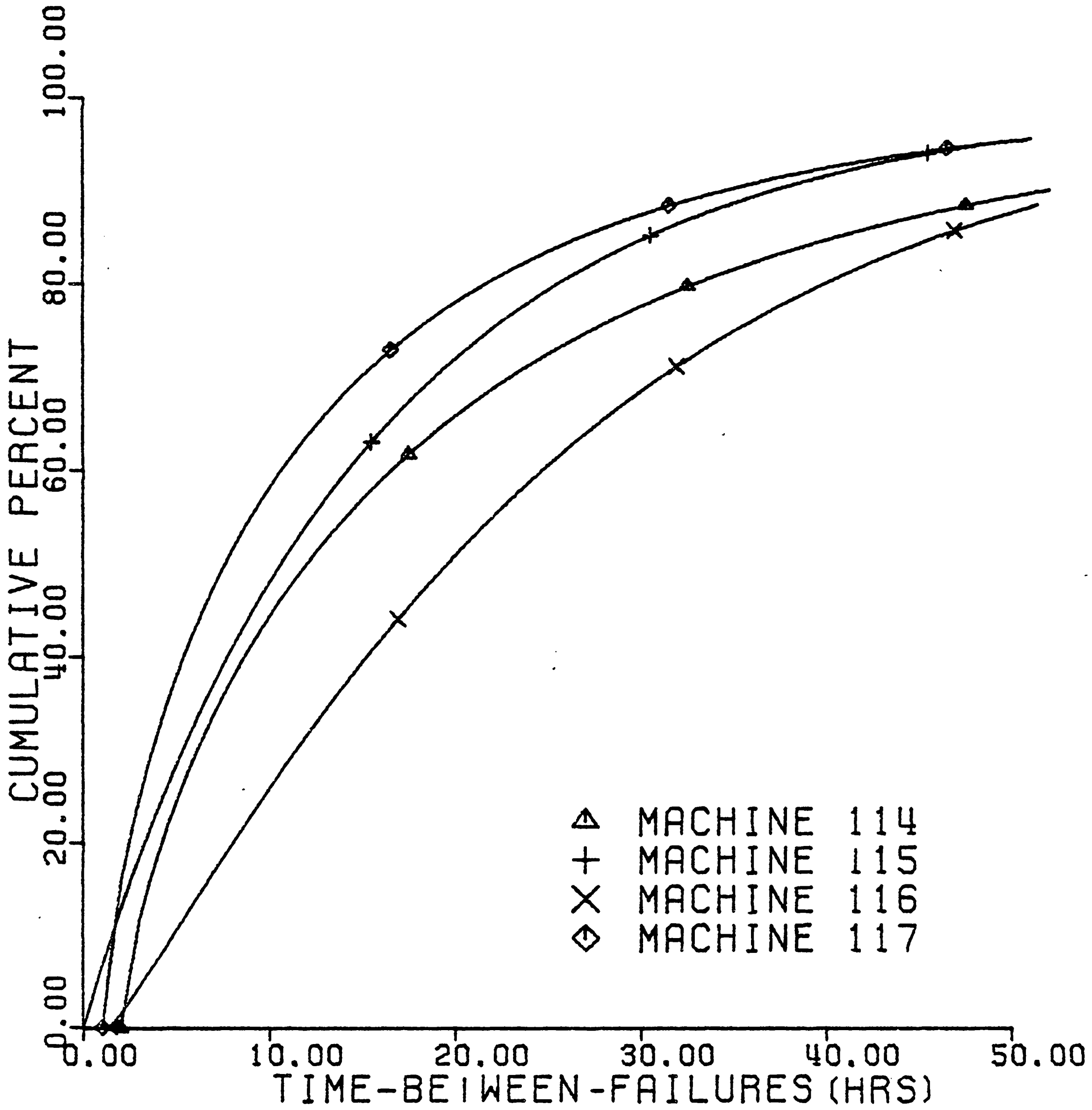
20.00
40.00
60.00
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 111-1
+ MACHINE 111-2
× MACHINE 112
◇ MACHINE 113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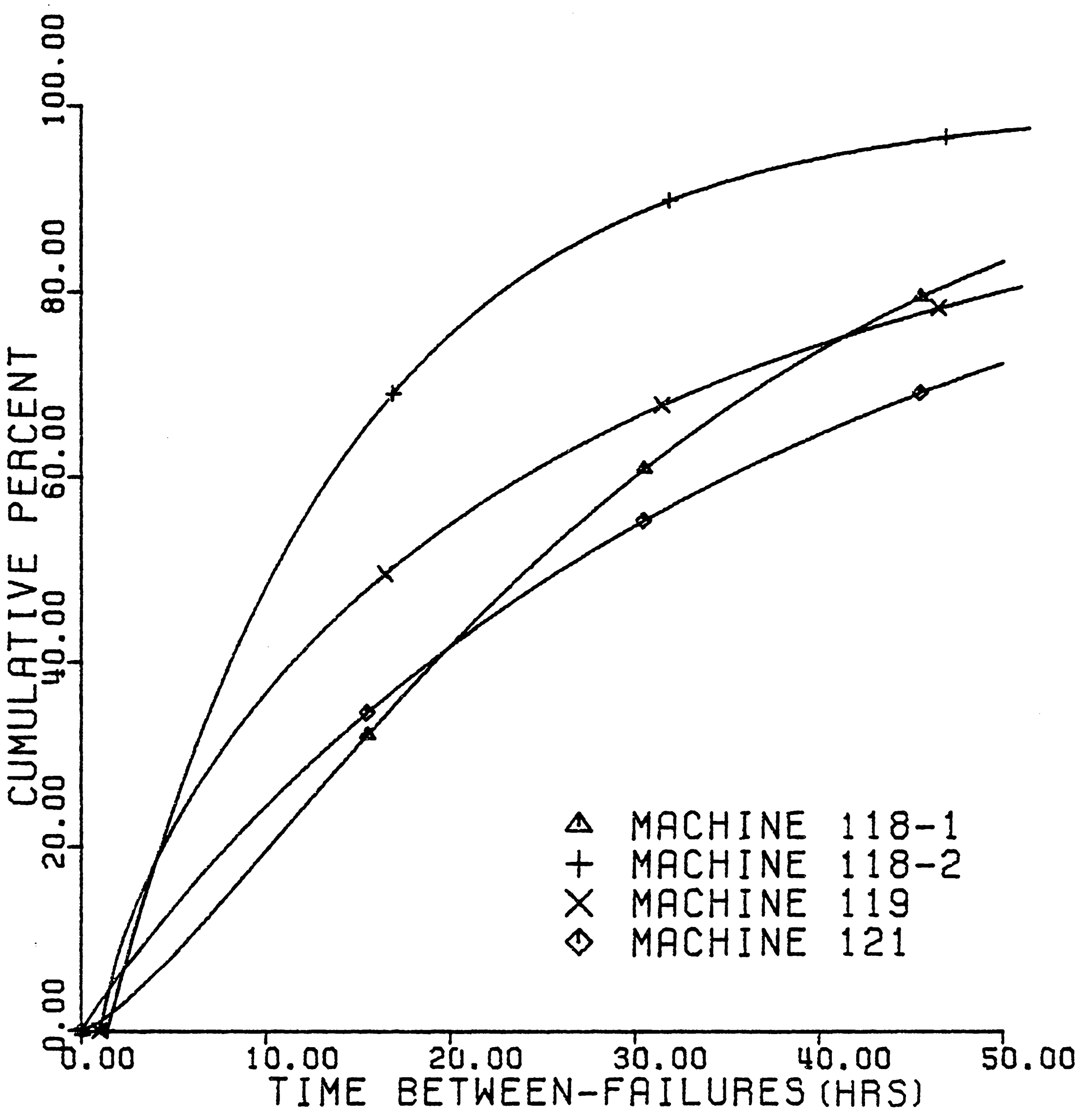
60.00
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 114
+ MACHINE 115
X MACHINE 116
◇ MACHINE 117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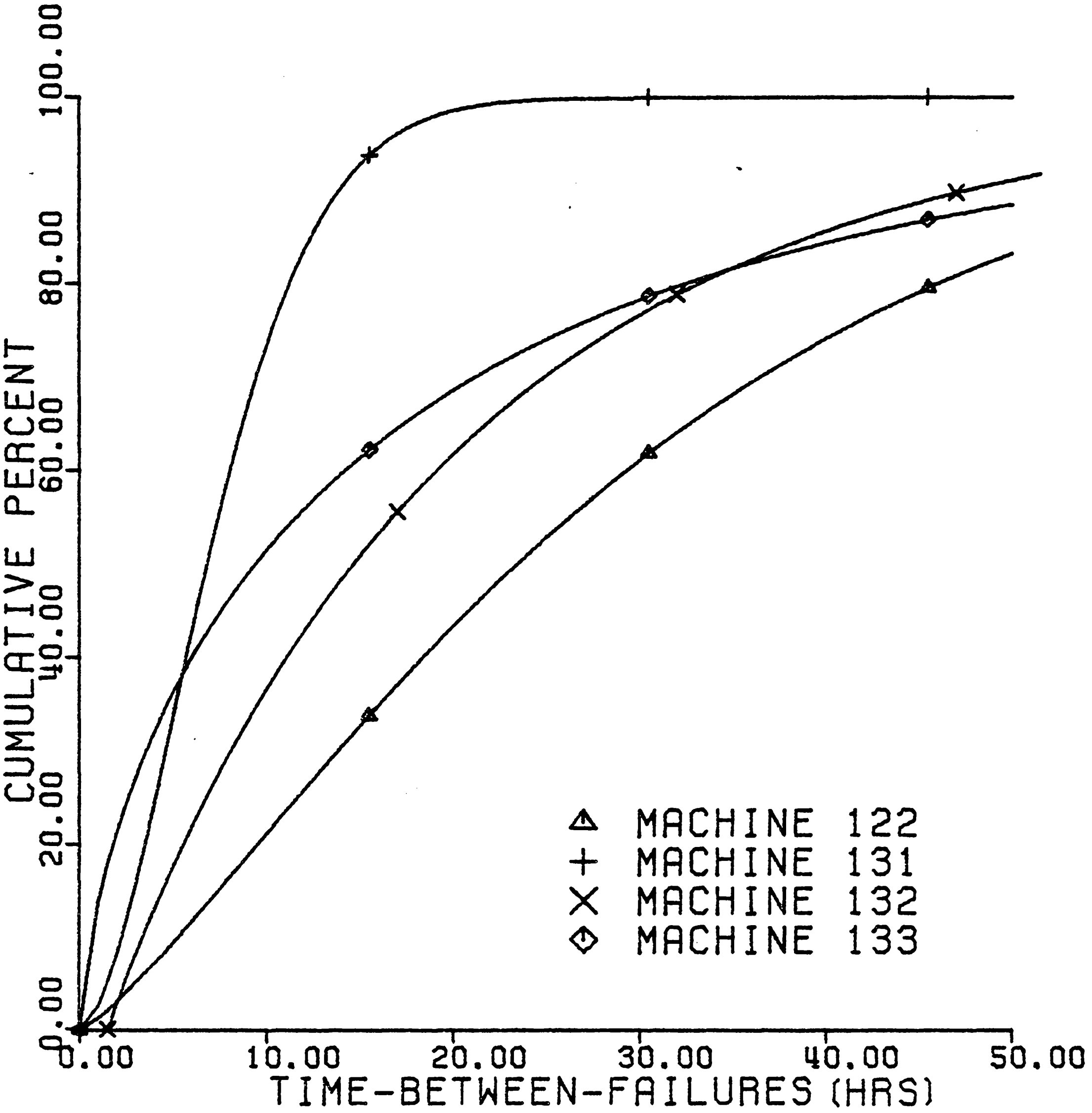
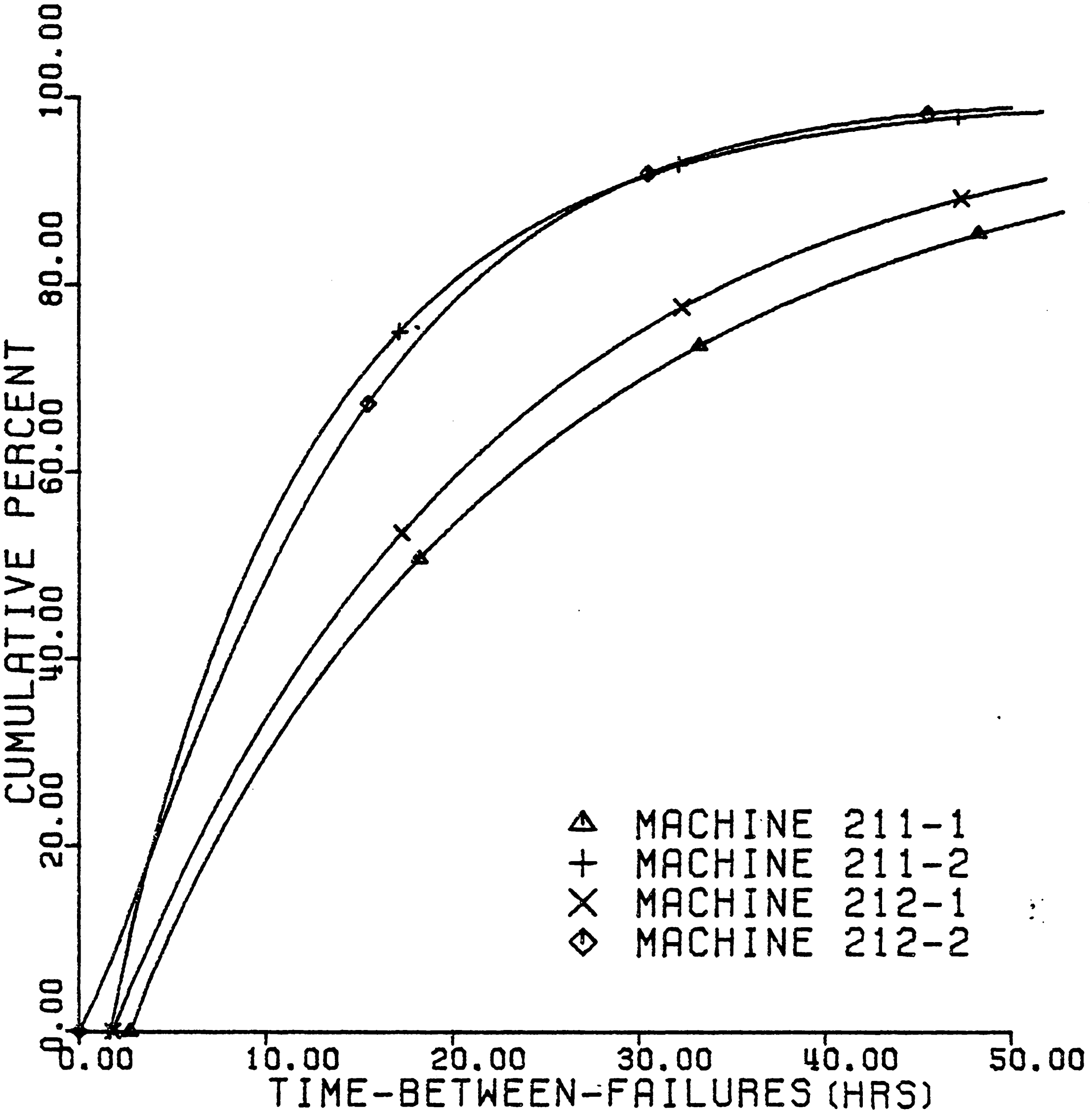
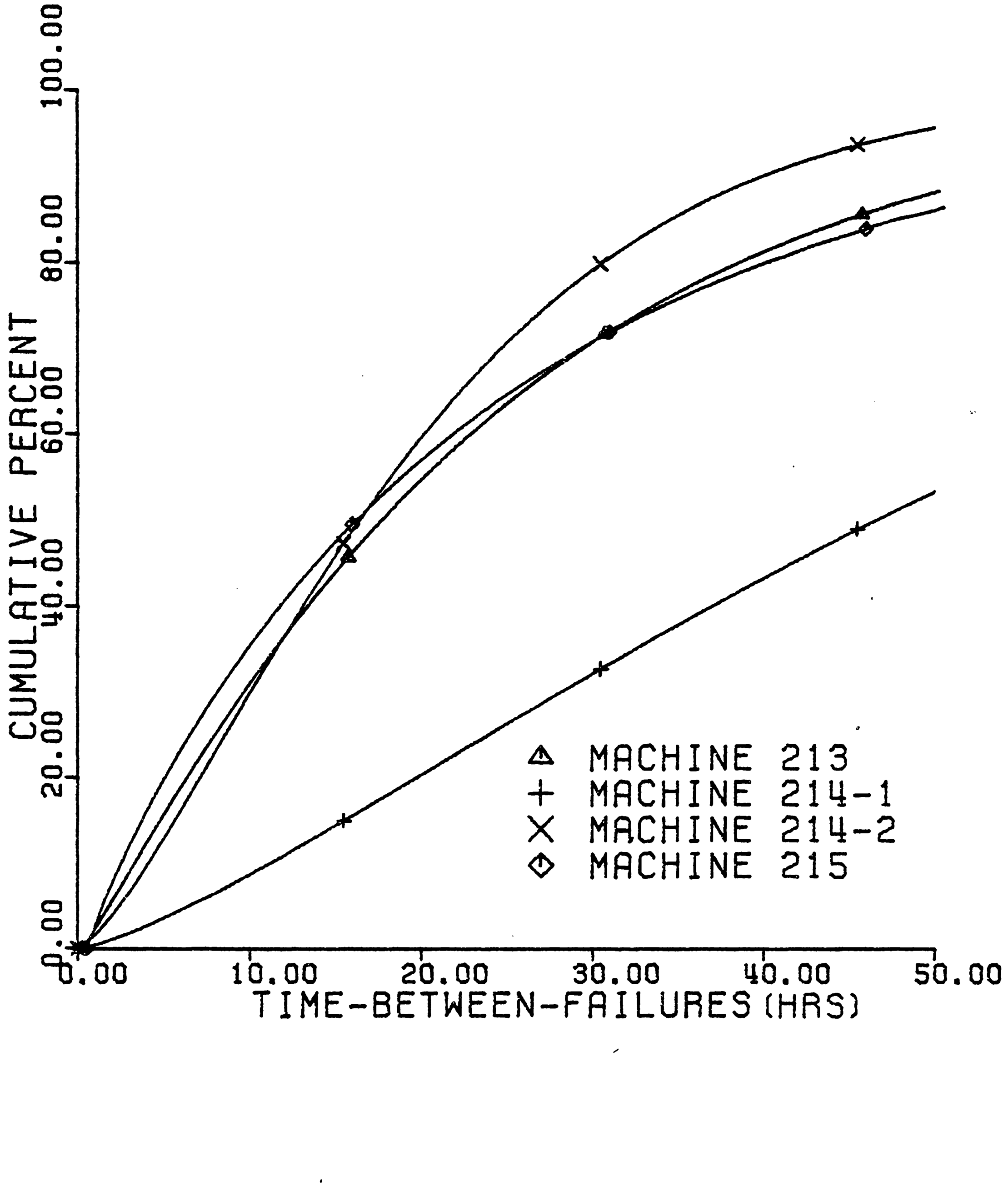
40.00
60.00
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME BETWEEN-FAILURES (HRS)
△ MACHINE 118-1
+ MACHINE 118-2
× MACHINE 119
◇ MACHINE 121


CUMULATIVE PERCENT
0.00
20.00
40.00
60.00
80.00
100.00
TIME-BETWEEN-FAILURES (HRS)
0.00
10.00
20.00
30.00
40.00
50.00
△ MACHINE 122
+ MACHINE 131
× MACHINE 132
◇ MACHINE 133


CUMULATIVE PERCENT
0.00
20.00
40.00
60.00
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 211-1
+ MACHINE 211-2
× MACHINE 212-1
◇ MACHINE 212-2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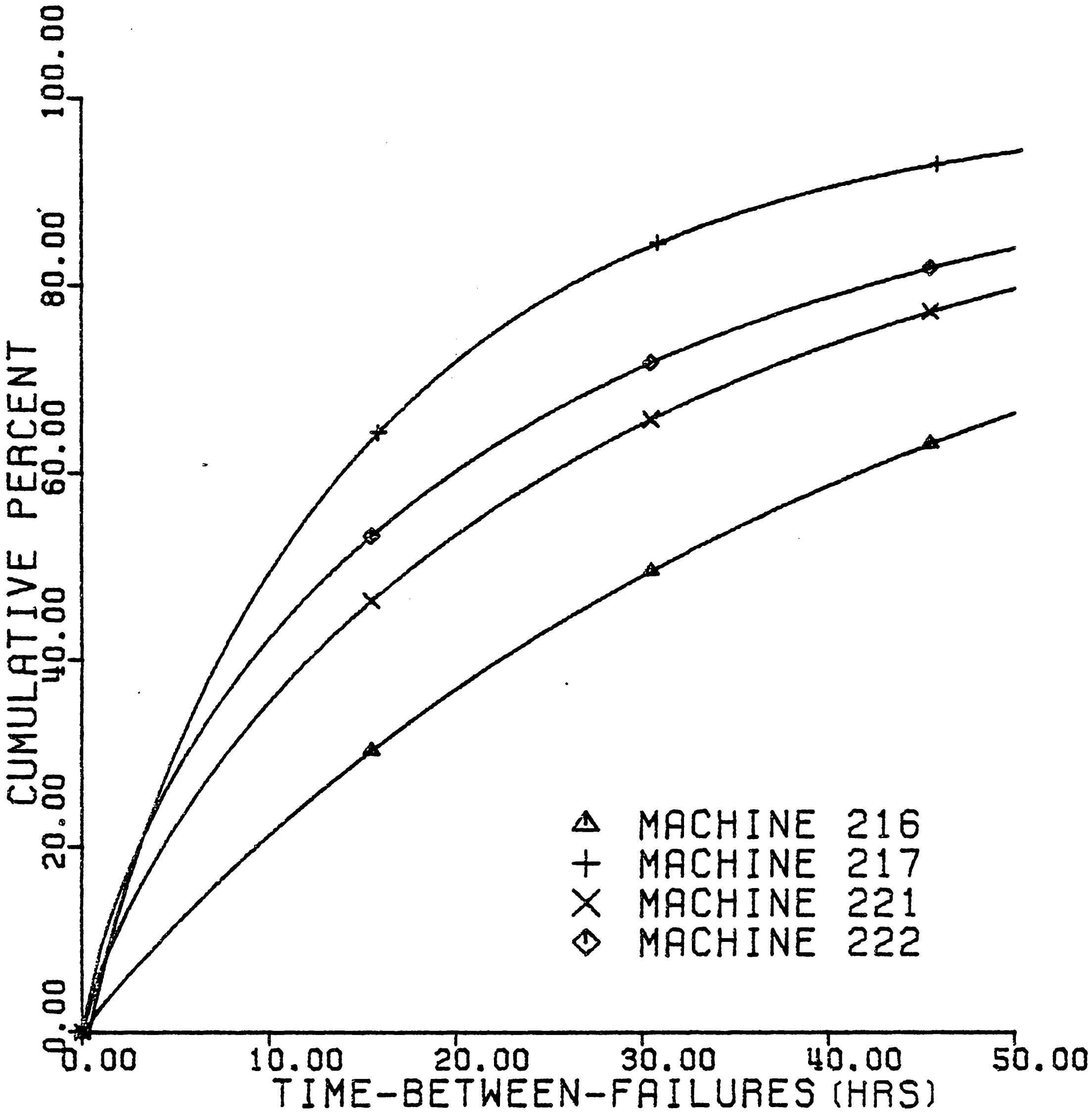
60.00
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 213
+ MACHINE 214-1
X MACHINE 214-2
◇ MACHINE 215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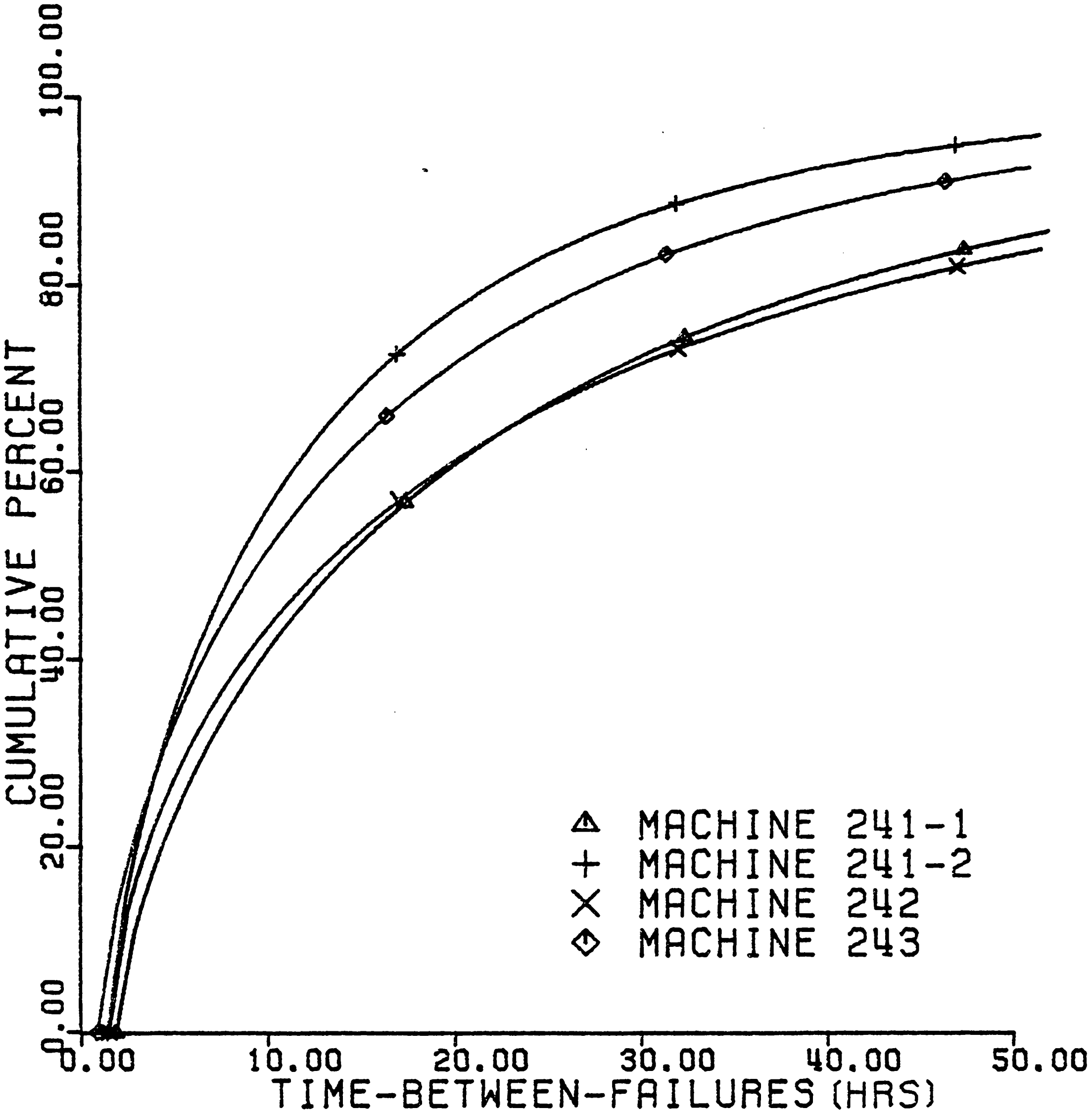
40.00
60.00
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 216
+ MACHINE 217
× MACHINE 221
◇ MACHINE 222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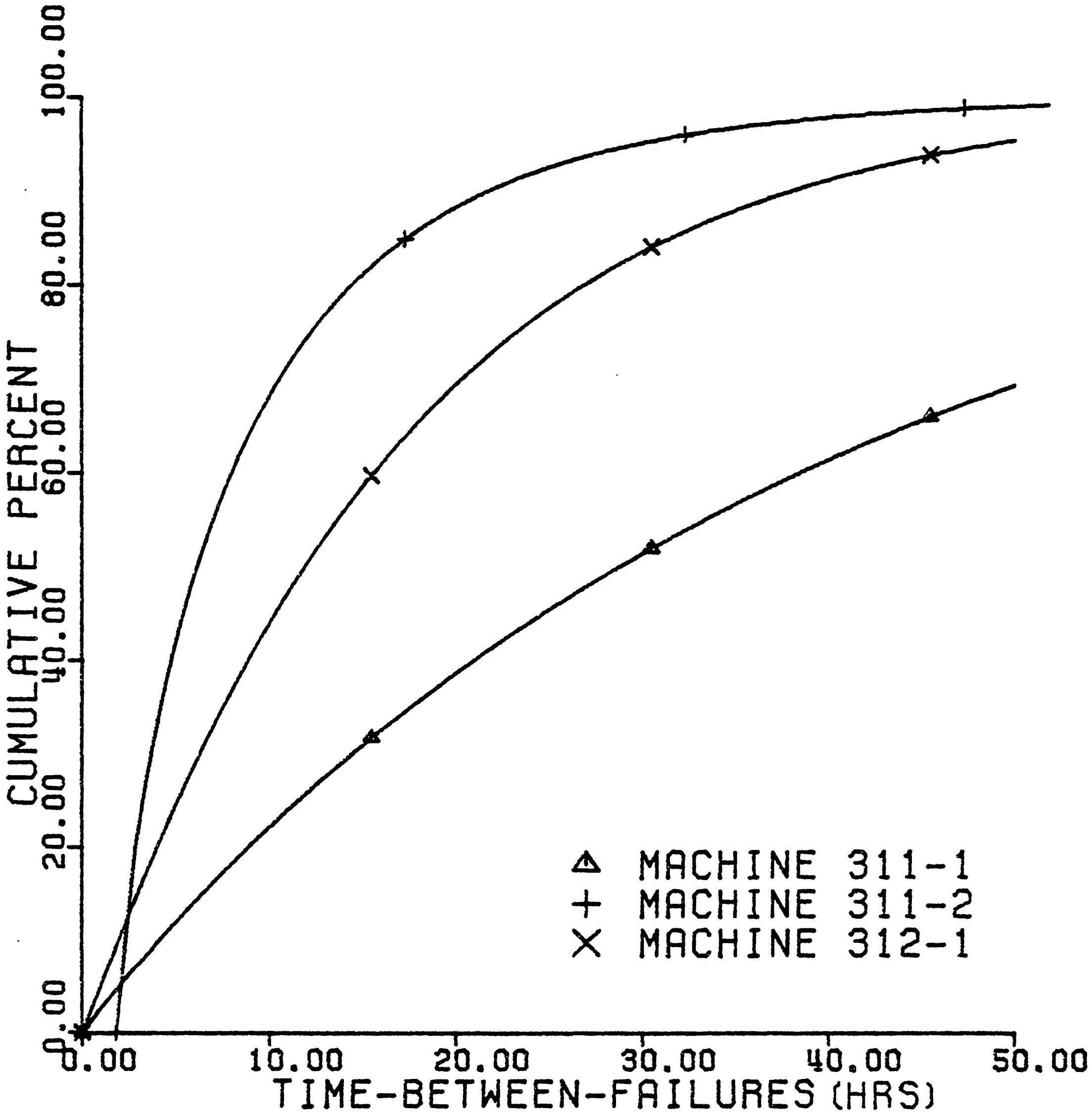
40.00
60.00
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 241-1
+ MACHINE 241-2
× MACHINE 242
◇ MACHINE 243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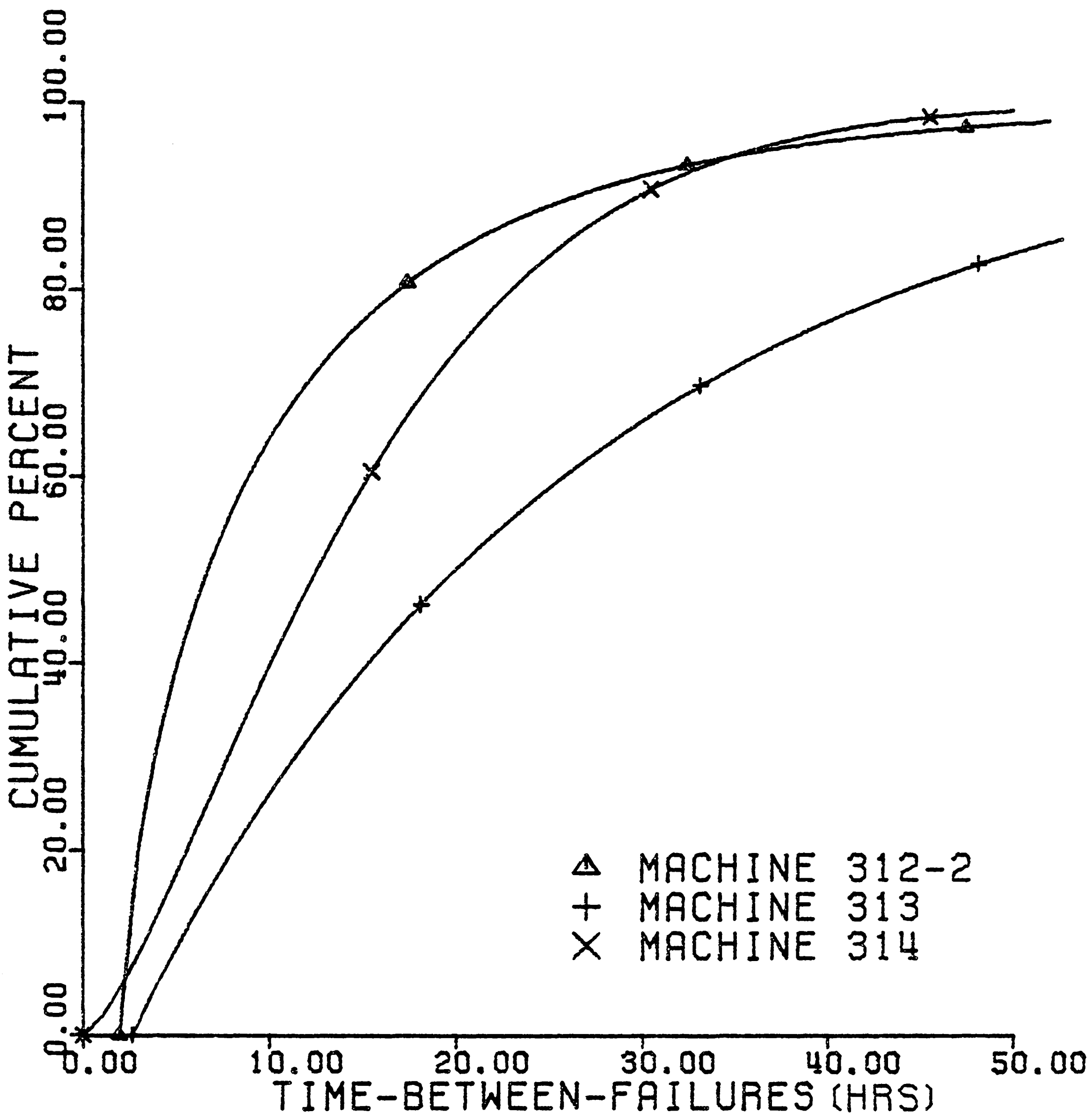
40.00
60.00
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 311-1
+ MACHINE 311-2
× MACHINE 312-1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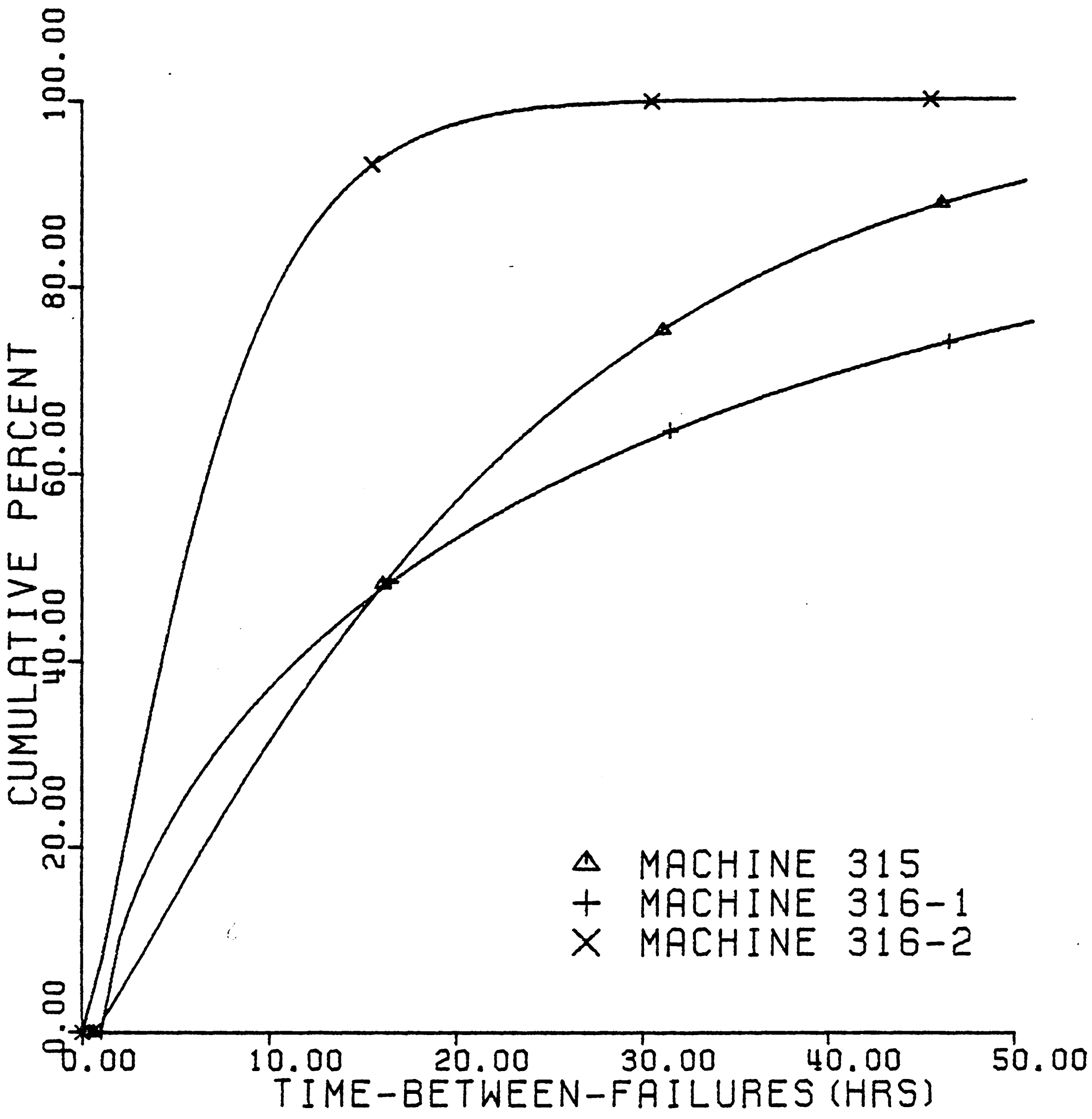
80.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 312-2
+ MACHINE 313
× MACHINE 314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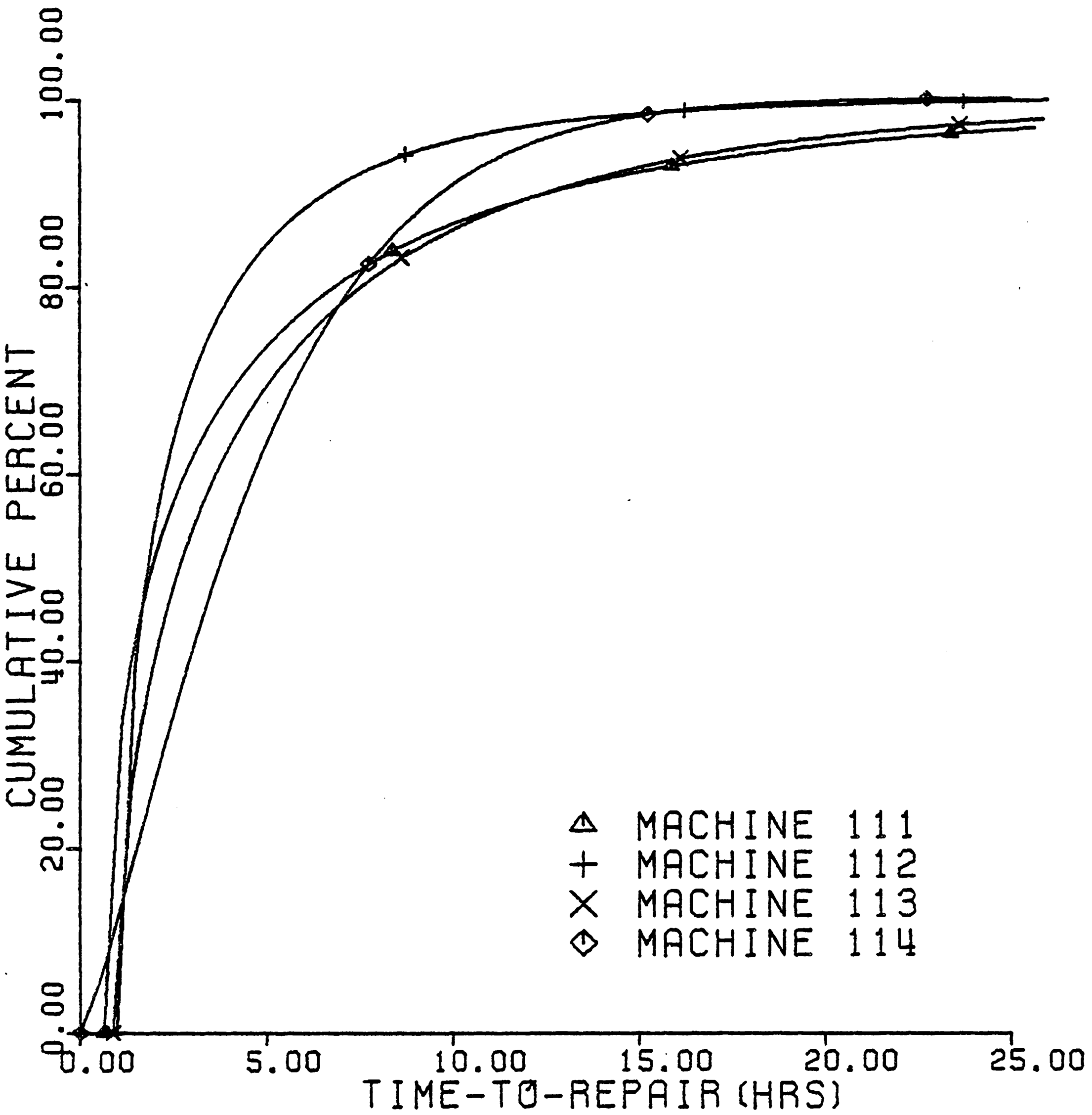
60.00
40.00
20.00
0.00
0.00
10.00
20.00
30.00
40.00
50.00
TIME-BETWEEN-FAILURES (HRS)
△ MACHINE 315
+ MACHINE 316-1
× MACHINE 316-2


CUMULATIVE PERCENT
0.00
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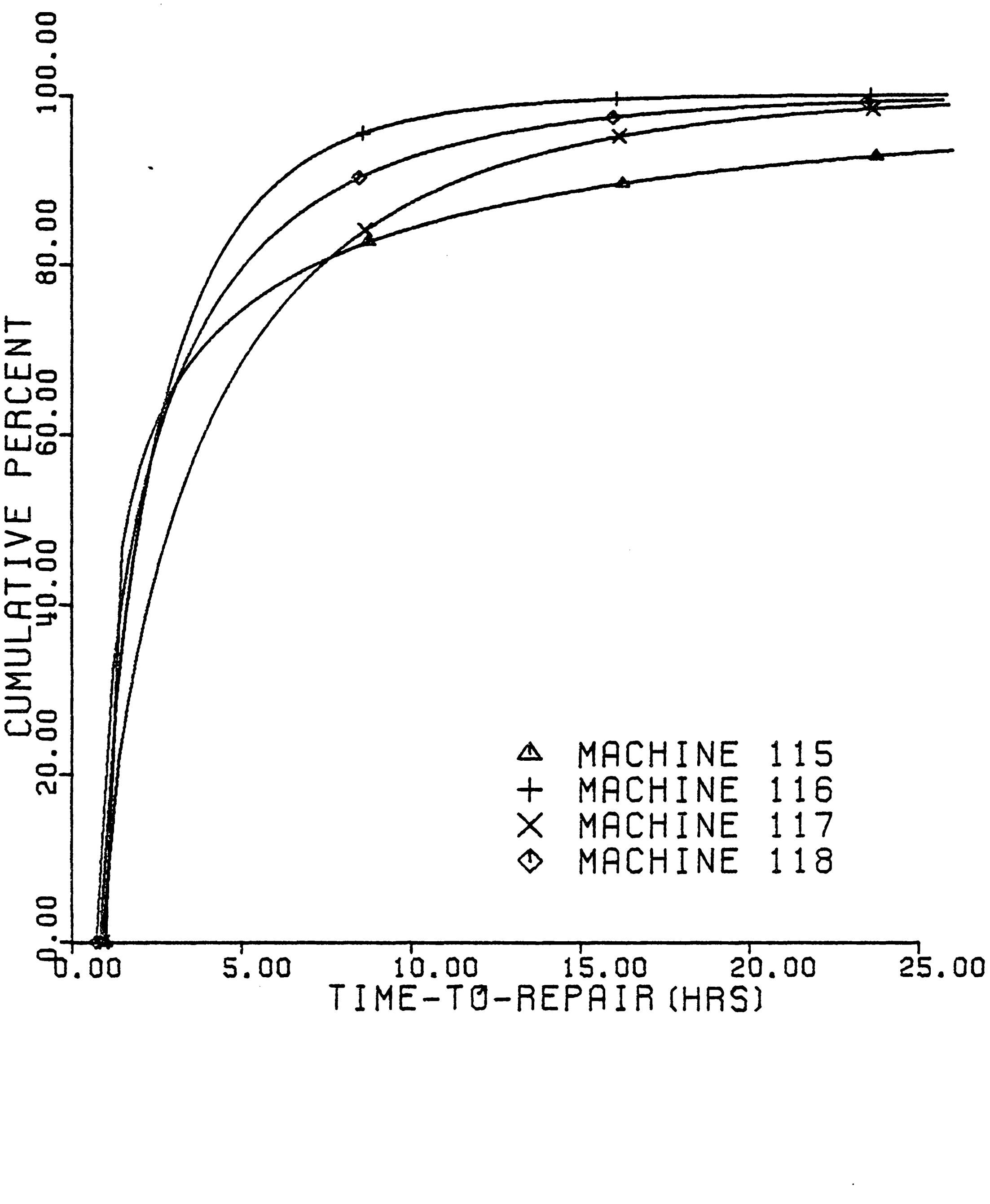
40.00
60.00
80.00
100.00
TIME-TO-REPAIR (HRS)
0.00
5.00
10.00
15.00
20.00
25.00
△ MACHINE 111
+ MACHINE 112
× MACHINE 113
◇ MACHINE 114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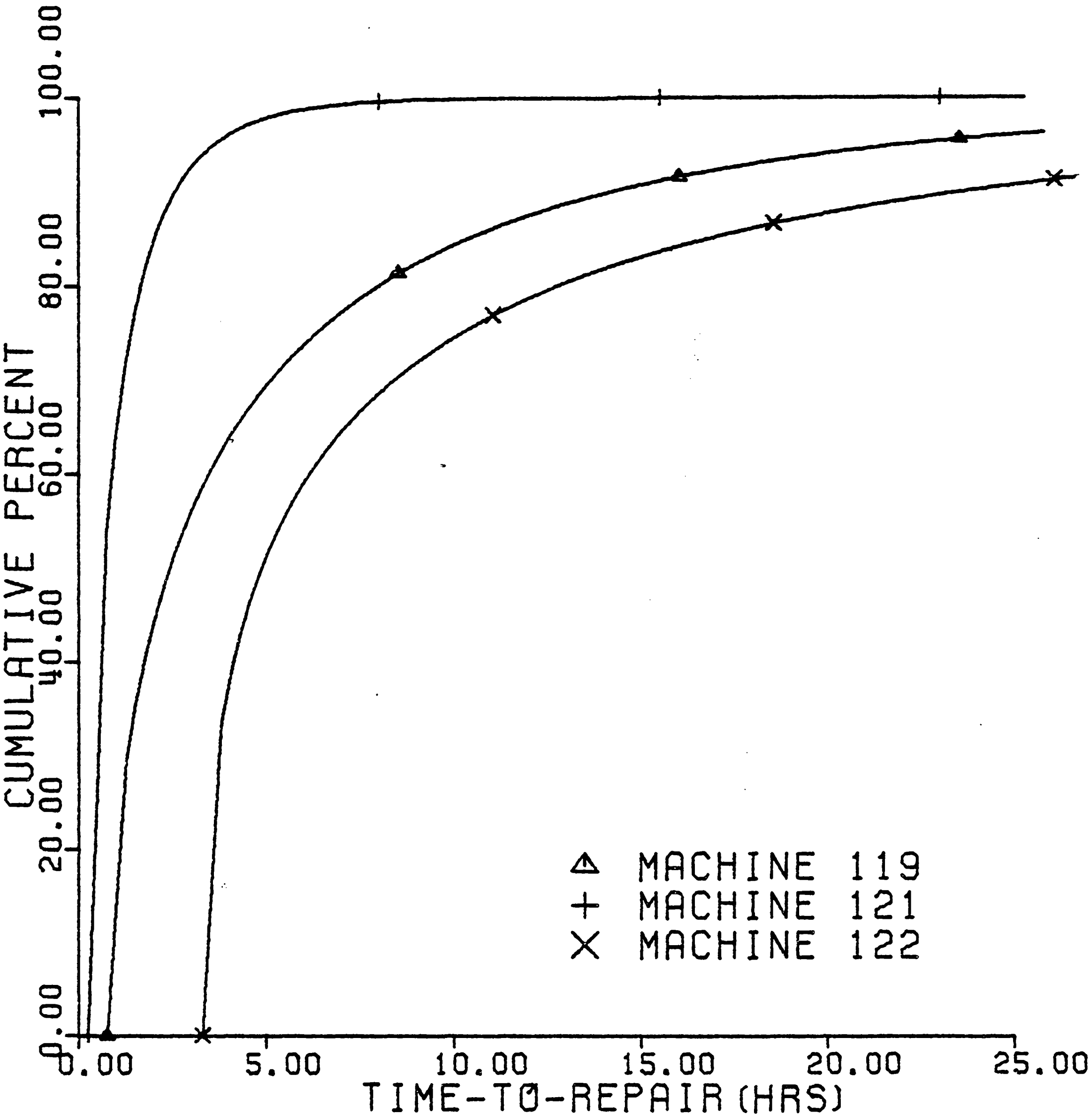
40.00
60.00
80.00
100.00
0.00
5.00
10.00
15.00
20.00
25.00
TIME-TO-REPAIR (HRS)
△ MACHINE 115
+ MACHINE 116
× MACHINE 117
◇ MACHINE 118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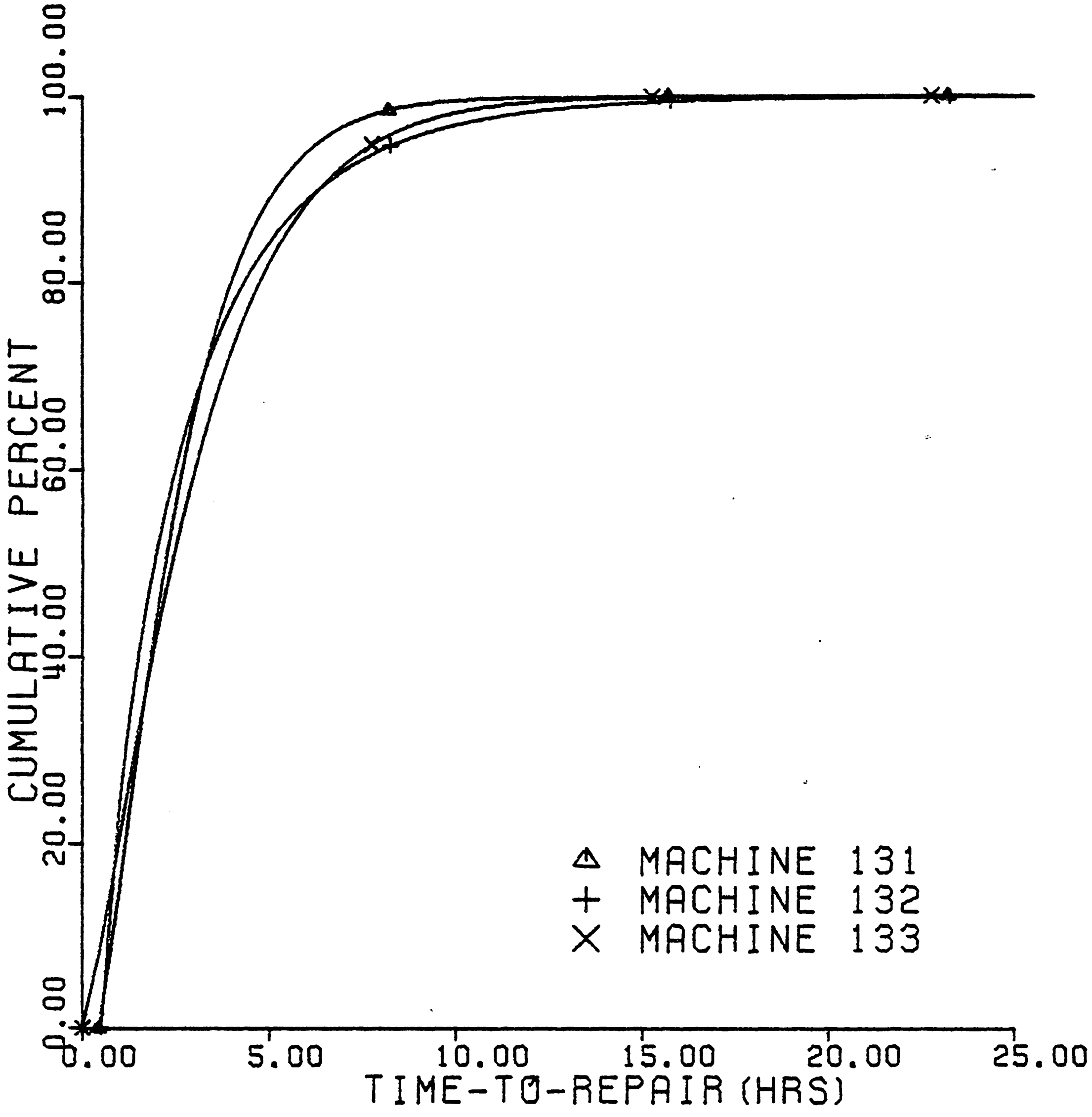
60.00
80.00
100.00
0.00
5.00
10.00
15.00
20.00
25.00
TIME-TO-REPAIR (HRS)
△ MACHINE 119
+ MACHINE 121
× MACHINE 122



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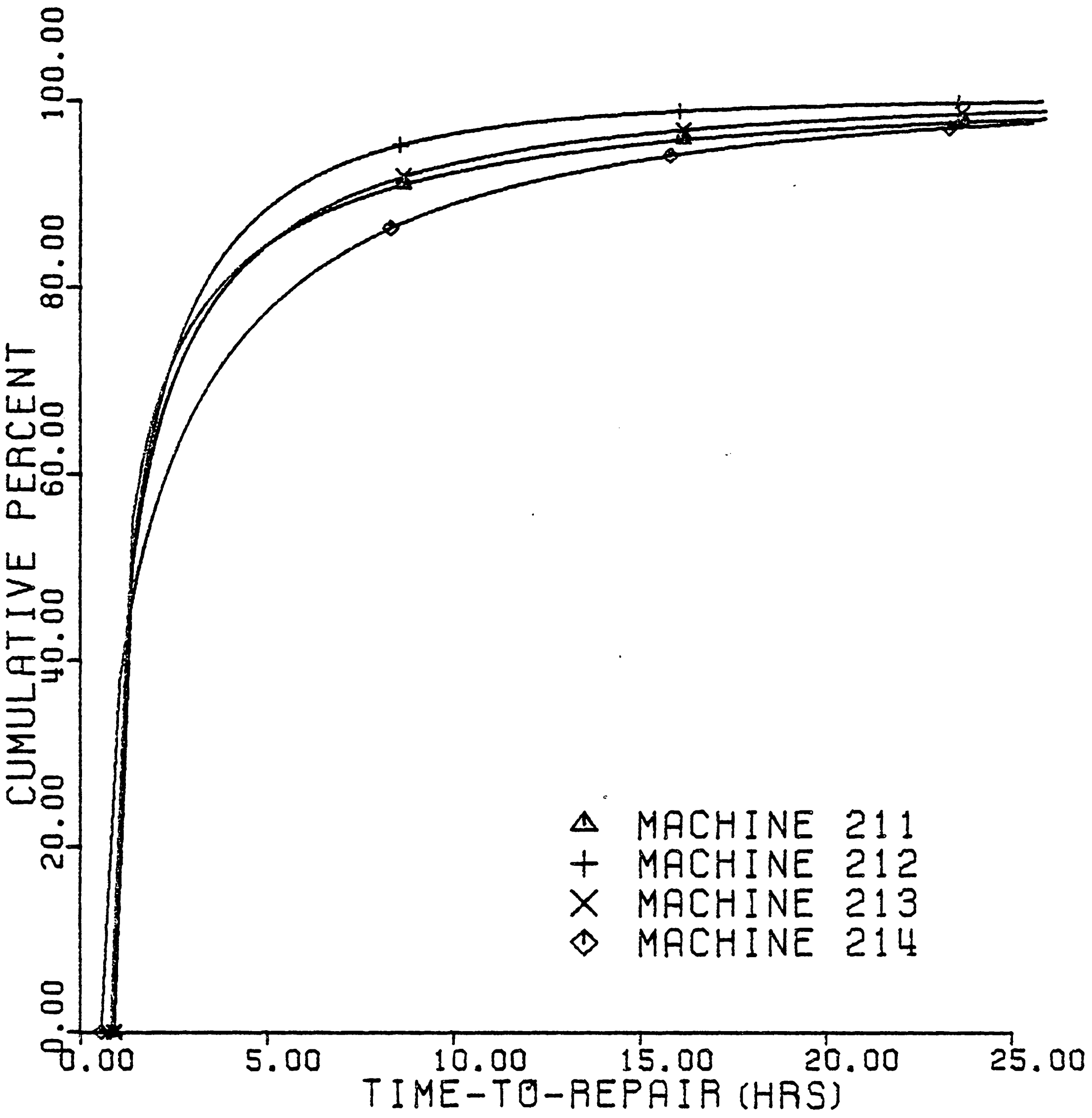
40.00
60.00
80.00
100.00
0.00
5.00
10.00
15.00
20.00
25.00
TIME-TO-REPAIR (HRS)
△ MACHINE 131
+ MACHINE 132
× MACHINE 133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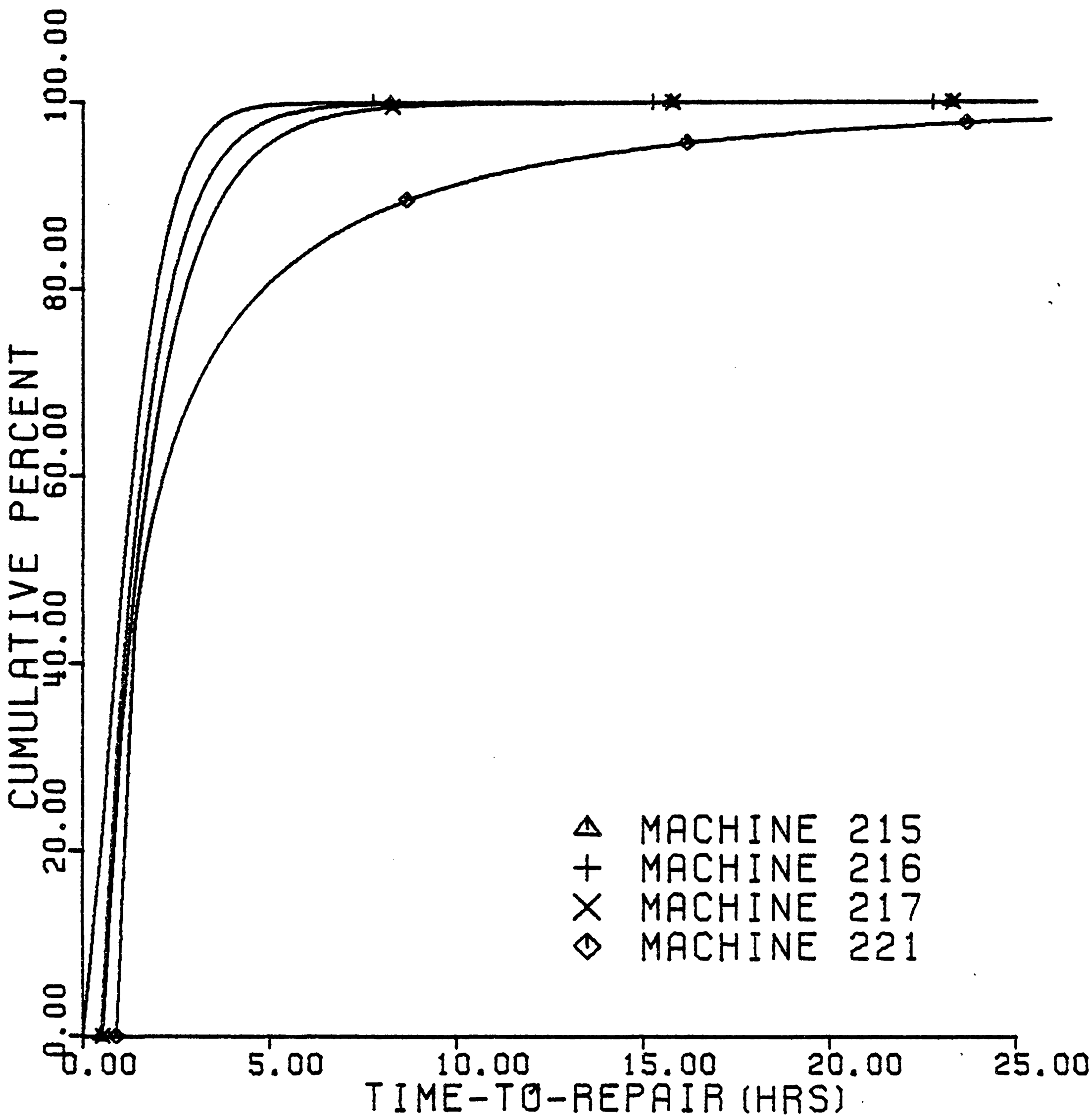
20.00
0.00
CUMULATIVE PERCENT
0.00
5.00
10.00
15.00
20.00
25.00
TIME-TO-REPAIR (HRS)
△ MACHINE 211
+ MACHINE 212
X MACHINE 213
◇ MACHINE 214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5.00
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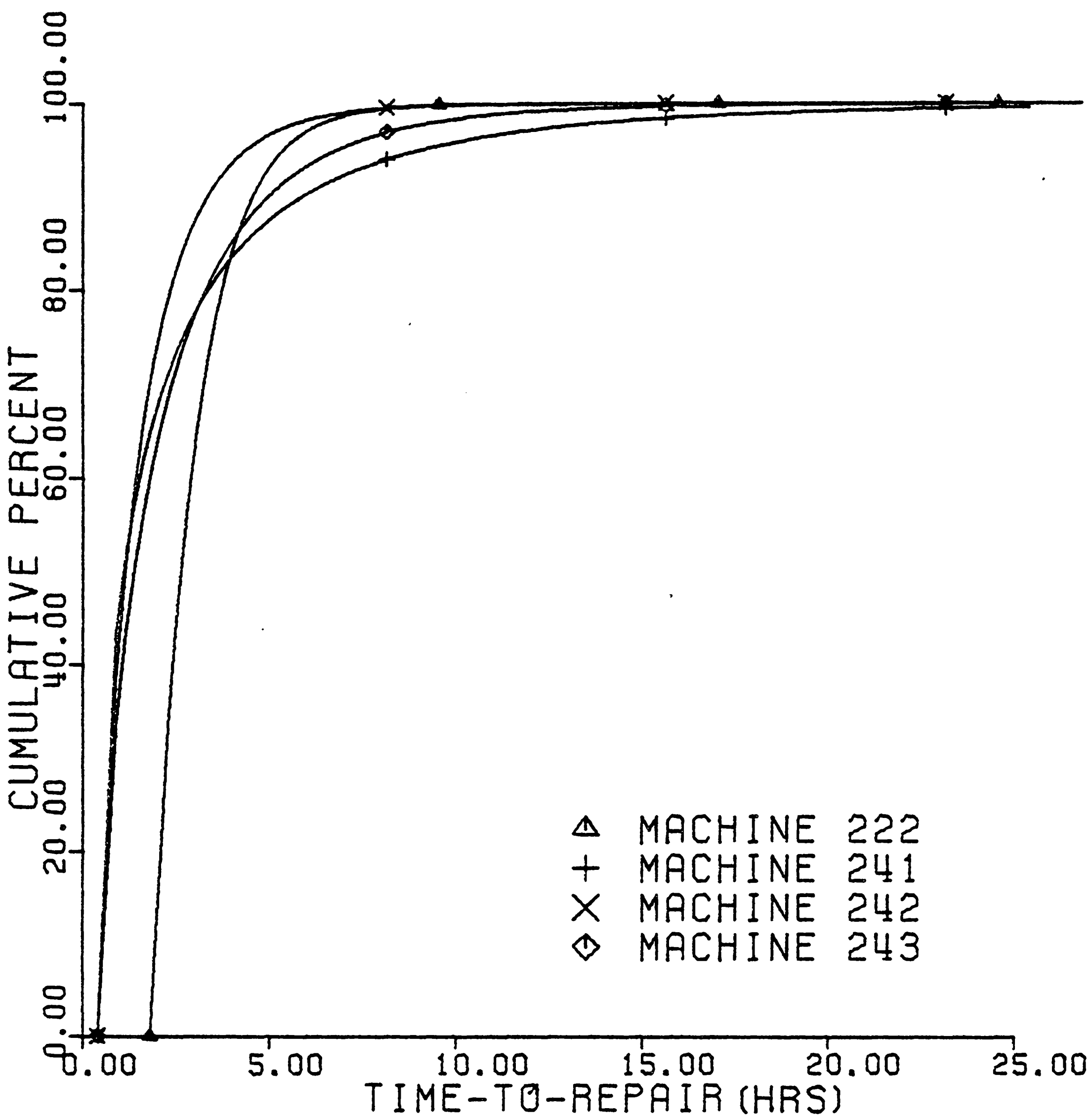
25.00
TIME-TO-REPAIR (HRS)
△ MACHINE 215
+ MACHINE 216
× MACHINE 217
◇ MACHINE 221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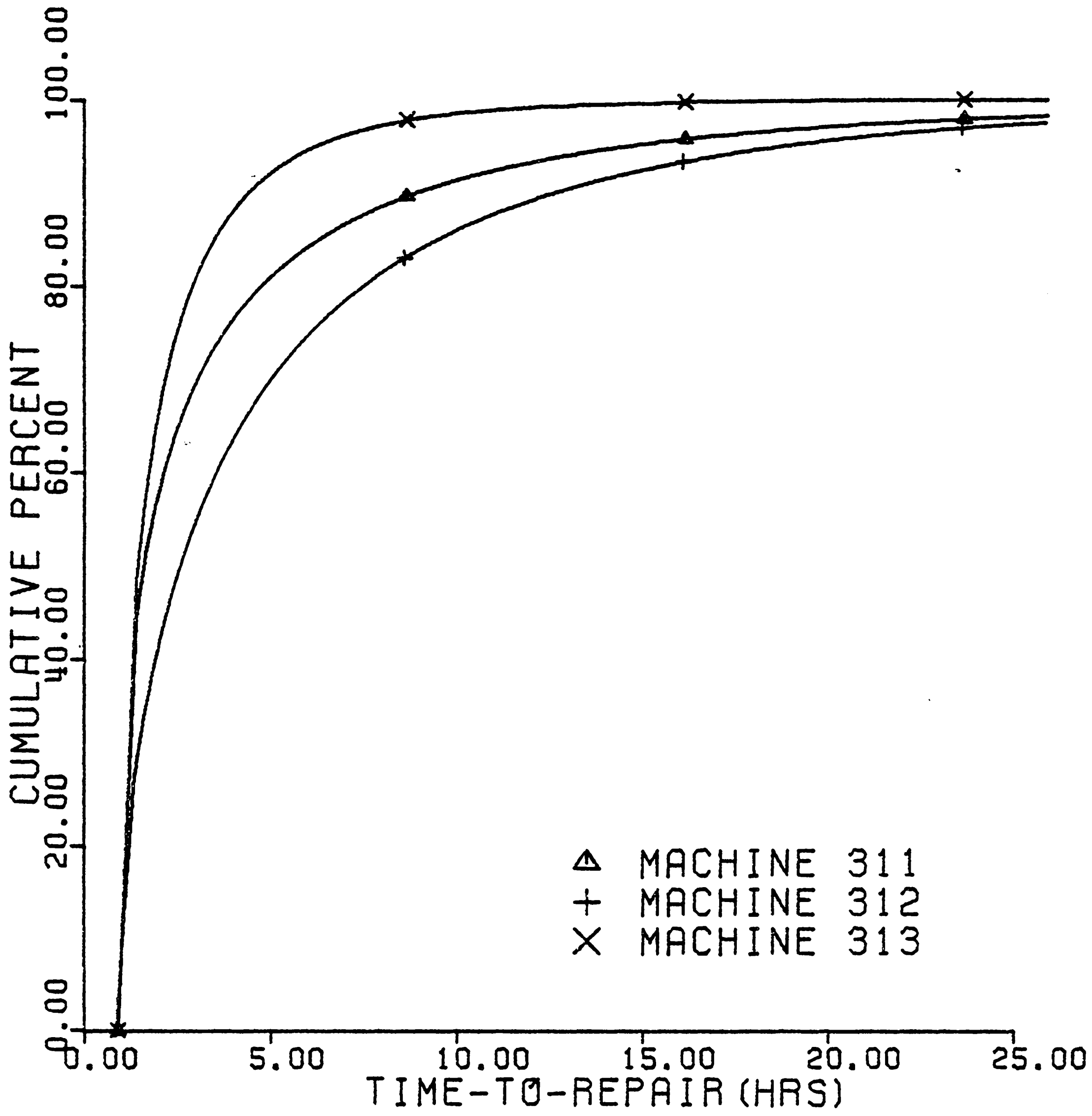
100.00
0.00
5.00
10.00
15.00
20.00
25.00
TIME-TO-REPAIR (HRS)
△ MACHINE 222
+ MACHINE 241
× MACHINE 242
◇ MACHINE 243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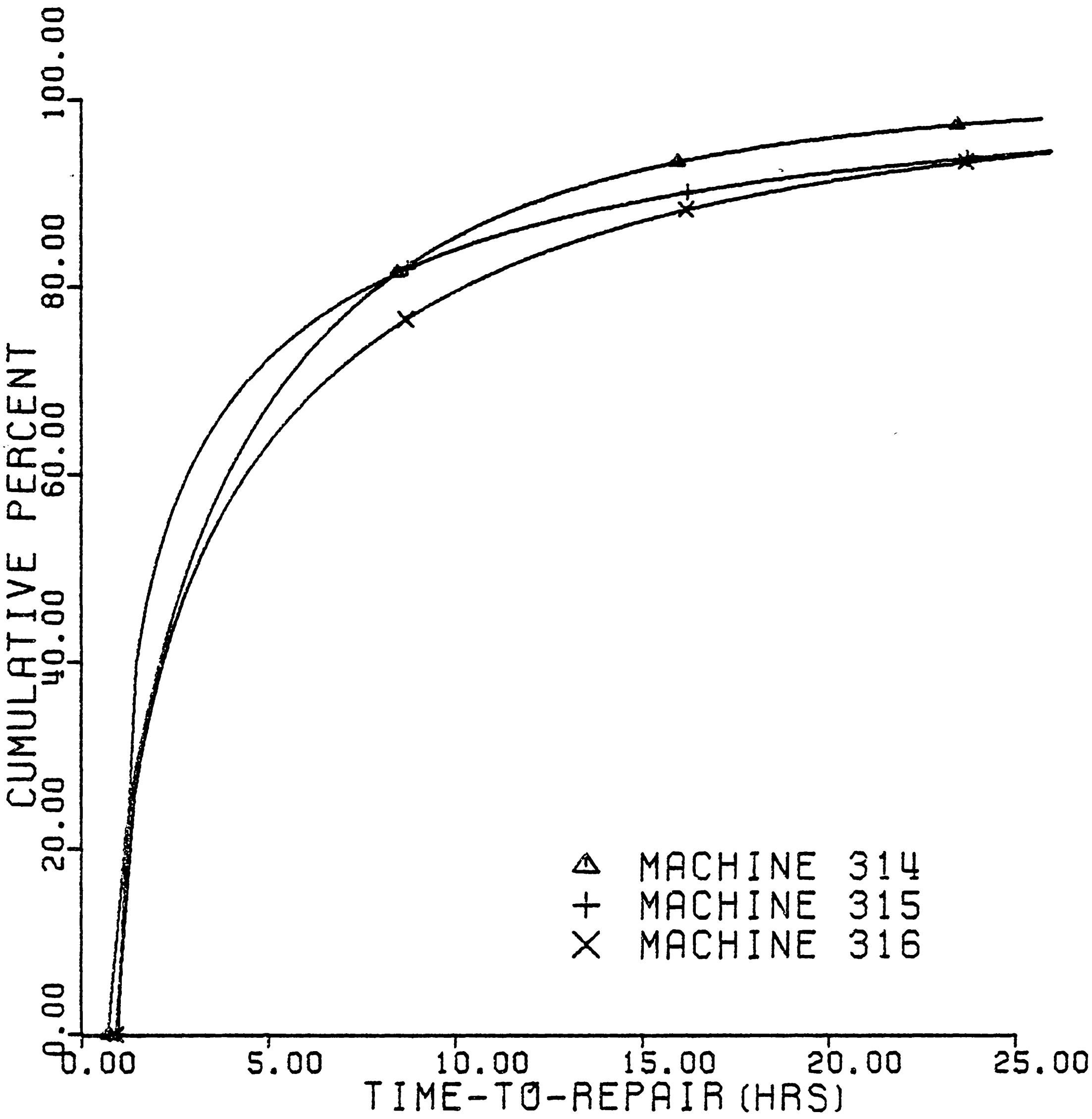
80.00
100.00
0.00
5.00
10.00
15.00
20.00
25.00
TIME-TO-REPAIR (HRS)
△ MACHINE 311
+ MACHINE 312
× MACHINE 313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60.00
40.00
20.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
TIME-TO-REPAIR (HRS)
△ MACHINE 314
+ MACHINE 315
× MACHINE 316

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A RELIABILITY ANALYSIS OF FELLER-BUNCHERS IN USE IN THE SOUTH

Robert A. Tufts

(ABSTRACT)

Maintenance, failure, and repair data on three types of feller-bunchers were analyzed. The data was tested for trends in time between failures as a function of time; time-between-failure and time-to-repair distributions were compared; the effects of changes in reliability, maintainability, and maintenance were analyzed; and a listing of reasons for failures was compiled.

Four different cooperators supplied information on 32 feller-bunchers covering 41,300 operating hours that included 1814 failures.

The time between failures (TBF) does decrease with machine age with the possible exception of an increase when the machine is first put into service. The TBF seemed to decrease rather rapidly during some initial

operating period after which they still decreased, although, at a much lower rate. During this subsequent period some machines exhibited a seasonal fluctuation, longer TBF in the summer and shorter in the winter.

There were no significant differences in TBF among the three types of feller-bunchers. The greatest amount of variability occurred among machines of the same type. A comparison of times to repair (TTR) indicated that the type 2 machines had shorter TTR than the types 1 and 3 which were the same.

Most failures of the shear were minor failures involving only replacing hydraulic fittings and hoses, shimming the cutting blades, or packing a cylinder. Because these are common malfunctions, parts were available and repairs did not require extended periods of time and in many cases could be performed by the operator. Failures of the carrier, on the other hand, covered a wider range. Because of this there were times when the part was not available and the repair usually required the attention of a mechanic. Therefore, failures of the carrier are more crtitical than failures of the shear.

An increase in TBF does increase availability; however, the magnitude of the effect decreases as the TBF increases. There is definitely a point of diminishing returns. However, the longer the average repair or delay time the more pronounced the effect of the TBF. For all three types of feller-bunchers, the point of diminishing returns was less than an average TBF of 40 hours.

Unlike TBF, there is a linear relationship between availability and downtime due to active repair or delay time. And, the shorter the TBF the greater the effect.

The effect of service time is to decrease the effect of the other variables. As the number of failures increase the amount of service time decreases because there will be fewer services. Conversely, as the number of failures decreases the amount of time the machine is down for service increases.

The most common cause of failure for all three types of feller-bunchers was the hydraulic system, accounting for 41.4 percent of all repairs. Other results indicate that a mechanic should have an adequate knowledge of hydraulics and welding.