A STATISTICAL APPROACH TO THE PREDICTION OF COMPONENT FAILURE IN OPEN PIT HAULAGE EQUIPMENT

by

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ABSTRACT

A method of predicting the occurrence of component failures is demonstrated by the application of basic statistical techniques to histories of past component failures. The digital computer is used to simplify the numerous calculations involved for large masses of data.

Results and interpretations are shown for assemblies and components of hauling units used in modern open pit mining.

Recommendations for continuing research in similar areas are offered.

CHAPTER I
INTRODUCTION

General Statement

Dwindling deposits of high-grade ore bodies and the rising costs of mining have necessitated the design and development of specialized equipment by manufacturers to facilitate the moving of very large volumes of material quickly and efficiently in order to yield a profit to the mining companies. Open pit mining equipment particularly has become larger and more complex as improved materials and manufacturing techniques are developed to meet the production demands of mineral producers.

As size and complexity of mining equipment increase the initial capital investment of this equipment also increases at an exponential rate. The mine operator is anxious to reduce this capital cost to a minimum and is, therefore, understandably reluctant to purchase any more equipment than is absolutely necessary. He must consider, however, that periodic equipment breakdowns and component failures will cause a drop in the tonnage output unless spare units are available. For example, it is the accepted practice in the mining industry to provide one spare truck for every eight required to maintain a predetermined production level (Estimating Production and Costs of Material Movement, 1955, p. 15).

An important consideration in the efficient operation of a mine is a maintenance program for equipment. There exists at the present time two distinct schools of thought concerning maintenance of open pit haulage equipment. The first, and perhaps the most accepted practice, is that of establishing a maintenance program whereby trucks are brought into the shop at periodic intervals. Certain maintenance operations are performed on the vehicles, such as welding and replacement of certain components, if it is evident that these parts would fail in the near future. Other maintenance functions would normally include various tests with resulting adjustments when necessary on major assemblies, such as engines or transmissions, to bring their performances up to the manufacturers' standards. Some mining companies have adopted the policy of replacing various major assemblies after a certain number of hours have elapsed. This replacement time is generally based on experience.

The second approach to maintaining haulage equipment is that of no scheduled inspections by the mechanical departments. The driver of the vehicle inspects the truck daily, and if he finds something obviously wrong, it is released for maintenance. While the truck is in the shop it is inspected to determine if other maintenance is required. Those in favor of this maintenance program argue that a truck is going to be in the shop at least once a week for some particular failure and any welding or inspections can be done at that time.

Objective of Study

The objective of this study is to determine the failure frequencies for various major assemblies and their components. By using the various frequency distributions together with some basic concepts of applied statistics the author will show how the "down time" of open pit mining equipment can be predicted. Determination of the desirability of either replacing these components before they fail or waiting until failure occurs will not be pursued in this paper. Such an investigation would be the next logical step in an overall replacement study.

Lloyd and Lipow (1962, p. 41) define failure as "the inability of the equipment to satisfy performance or design specifications once the equipment has experienced successful operation or acceptance or has the expectation of successful performance without adjustment or rework." Failure of equipment also may be defined as the situation in which a component is replaced because of imminent failure of that particular component.

From the concepts of reliability theory these failures or malfunctions (exclusive of failure caused by damage or improper operation) inherent in the equipment can be categorized into three broad classifications (Bazovsky, 1961, p. 3).

The first type of failure is that which occurs early in the life of a piece of equipment or component. These malfunctions or breakdowns are called "early" or "infant" failures by reliability engineers and are due to poor manufacturing processes, quality control, or workmanship. Early failure is often experienced when components have been rebuilt or repaired. These failures can be attributed to poor workmanship during installation or to poor quality replacement parts. The majority of these failures are discovered and corrected during the run-in period used by most manufacturers. However, these testing phases often are not rigid enough to produce a marginal component failure since it is not economically feasible for the manufacturer to put each piece of equipment through tests approximating actual operating conditions for which the equipment is designed. Consequently, during the first few hundred hours of operation of a truck some early failures of components must be expected, and these failures are usually rectified by the manufacturers' warranties. In this study, little emphasis will be placed on this type of failure and no attempt will be made to predict its occurrence; it will be included, however, on the frequency curves to demonstrate its effect on the overall failure rate.

The second type of failure occurs at random intervals irregularly and unexpectedly. These have been classified as "chance" failures and are caused by sudden stress accumulations beyond the design strength of the component. The prediction of chance failures is next to impossible; however, they do obey certain rules of collective behavior so that their frequency of occurrence over a long period of time can be approximated (Bazovsky, 1961, p. 4).

The third type of failure results from wearout of parts. From a reliability point of view these failures occur only if equipment is improperly maintained or not maintained at all. Wearout failures are a symptom of component aging, and this can vary from minutes to years depending on the equipment involved (Bazovsky, 1961, p. 4). In the case of mine haulage equipment the age at which wearout will occur can be expressed in thousands of hours. When wearout failure is due to strength deterioration, the failure rate begins to rise and usually follows a normal distribution.

A major portion of this study is devoted to the examination of chance failures and wearout failures.

CHAPTER II
STATISTICAL CONSIDERATIONS

Probability

In dealing with a problem where predictions are to be made on the basis of some past experience, it is necessary to consider some fundamental concepts of probability.

Volk (1958, p. 2) defines probability in a numerical sense as being a quantitative measure of chance or likelihood. It is expressed in terms of the probability scale as a fraction between 0 (absolute impossibility) to 1 (absolute certainty) and is usually designated P. An impossible event such as having a truck in service for 100,000 hours without a failure of any type would have a probability of 0 (P = 0) while an event which is certain to occur such as that of engine failure due to lack of lubrication would have a probability of 1 (P = 1).

Mathematically the probability of an event occurring is expressed as

$$P(A) = \frac{n}{N}$$

where n = total number of occurrences of the event
N = the total number of trials
and A = the attribute of n

Since the prediction of equipment failures is based on an accumulation of data from past failures the empirical probability concept is used in this study.

Frequency Distribution

Handling large masses of data become rather difficult unless some means of classifying it into groups or categories can be devised. A method commonly used involves grouping the data into class intervals on the basis of maximum and minimum boundaries for each interval and recording the number of variables in each. Such a method of categorizing data is generally referred to as the determination of a frequency distribution.

In determining such a distribution the lowest value of the data is subtracted from the highest value to give the range. The range is then divided by the number (k) of class intervals desired which may be determined from Sturges' rule (Pieruschka, 1963, p. 7) as

$$k = 1 + 3.3 \log_{10}(N)$$

where N is the number of replacements or failures. To keep values from falling on the boundary of two adjacent class intervals, it is necessary to extend the class boundaries by 1/2 a unit beyond their numerical values. In order to use effectively the grouped data in further computations, a representative value for each class interval must be found. Such a value, called the class mark, is determined by taking the average of the difference between the high and low boundaries and adding it to the lower boundary of each class interval. In order to use this method of classifying data an assumption must be made that the times of failure for all the items in any particular interval will be equal to the class mark.

Graphical representations of frequency distributions are often convenient to illustrate the distribution of random variables. Such a representation, a histogram, is of little value as far as giving quantitative information about the distribution. It is useful, however, in showing the relationship between the sample distribution and a theoretical distribution when the theoretical distribution curve is superimposed on the sample curve.

Measure of Central Tendency

In recording data or making measurements, it is not unusual to find clustered about some particular point a group of values whose frequency of occurrence is larger at this point than any other point of the distribution. Any number which shows an indication toward this representation is called an average. There are several specific measures of central tendency; however the numeric value which is used in this investigation is the familiar arithmetic average (mean) and is designated $\overline{x}$. Hoel (1954, p. 49) mathematically defines the mean as being the first moment about the origin which is shown as

$$\overline{x} = \frac{1}{n} \sum_{i=1}^{h} x_i f_i$$

where $n = \sum f$ the total frequency
f = the frequency of the variable x
x = class mark of the interval i

and $\sum_{i=1}^{h}$ = the sum of all x_i's from $i = 1$ to $i = h$

Volk (1958, p. 58) states that

> ". . . the mean is used for two important reasons. When considering the variation of the data it will be done in terms of the square of the deviations from some central value. The mean is the value from which the sum of the squares of the deviations is a minimum. Secondly, and perhaps most important, means of samples of uniform size tend to be normally distributed regardless of the type of distribution of the population from which the samples were drawn; the larger the sample size the more nearly normal the distribution of the means. This characteristic of sample means permits the use of the normal distribution in making probability statements about the population mean even when the population is not normally distributed."

Measures of Variability

The degree to which data vary from the mean is called dispersion or variation. Two groups may have the same mean, yet a considerable difference may exist between the extremes in each group. A convenient test for measuring variability is the standard deviation which is defined as the square root of the mean-squared deviation of the individual measurements from their mean and can be designated as sigma, σ (Volk, 1958, p. 61). Mathematically, the standard deviation for a population can be expressed as

$$\sigma(x) = \sqrt{\frac{\sum (x - \bar{x})^2}{n}}$$

In this study the data are considered as samples of the population since the information available does not represent the failures over the entire life of the subject. Therefore, the equation for finding the standard deviation is modified by dividing the sum of squares of deviation by $n - 1$, instead of by n, to overcome the bias introduced in estimating the population parameters from the sample. Hence, the estimated standard deviation of the population calculated from the sample is denoted as $s(x)$, and is mathematically expressed as

$$s(x) = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}}$$

where $\sum (x - \bar{x})^2$ = the sum of squares of deviation
and $n - 1$ = one less than the total variables in the distribution

It is often convenient to find the standard deviation by first calculating the variance of the sample, then taking the square root of the variance to give the standard deviation. This method was utilized in the computer program written for this study.

The variance is defined as the square of the standard deviation and is equal to the mean-squared deviation of the variable from its mean. Since the variance is defined as the standard deviation squared, it follows that an estimate of the variance of the population from the sample is indicated as $s^2(x)$. Mathematically the estimated variance is calculated

$$s^2(x) = \frac{\sum (x - \bar{x})^2}{n - 1}$$

In this investigation the variance is used primarily as a rapid test to determine whether the sample distribution follows the theoretical Poisson distribution since the variance is approximately equal to the mean of the variables for a Poisson distribution (Moroney, 1963, p. 102).

Poisson Distribution

The Poisson distribution is applicable for situations in which the number of occurrences of an isolated event can be observed in a continuum of time, where the mean expected frequency is small, and the total number of events is large (Moroney, 1963, p. 96).

An example of the observation of the occurrence of an isolated event in a period of time would be the number of failures of a particular component for a given length of time. Consequently, it is logical to compare the sample distribution with a theoretical Poisson distribution determined from the mean of the sample to see if a significant difference is present.

The expected number of failures in a particular interval is determined as

$$\text{(expected failures)} = P(r) \times (\textstyle\sum \text{observed failures})$$

where

$$P(r) = e^{-m} \frac{m^r}{r!}$$

m = the mean of the sample
r = the expected number of occurrences in n trials
and e = 2.718282. . . the base of natural logarithms

From the general shape of the theoretical Poisson curve we would expect a rapid rise in the number of failures occurring early on the time scale with a gradual decrease in number after the peak of the curve has been passed.

The mean used for calculating the probability value is divided by the difference between the high and low boundaries of the first interval of the frequency distribution. This is necessary to reduce the numerical value of the mean so that the computer can determine the value of e^{-m} without an occasional exponent overflow condition which would occur when the limits of the exponential function ($e^{\pm 112.8}$) are exceeded.

Normal Distribution

In determining the theoretical number of expected occurrences of equipment failure the probability of observing a failure in the interval bounded by the lower and upper class boundaries is multiplied by the total number of failures in the sample. Mathematically this can be expressed as

$$(\text{expected failures}) = P(r) \times (\sum \text{observed failures})$$

where

$$P(r) = \frac{1}{s(x)\sqrt{2\pi}} \int_{x_1}^{x_2} e^{-\left[\frac{(x-\bar{x})^2}{2s^2(x)}\right]} dx$$

From the shape of the normal curve we would expect 50% of the failures to occur before the mean life of the component is attained. Further, we would expect to find 99.73% of all failures occurring within plus and minus three standard deviations from the mean (Spiegel, 1961, p. 123).

Bazovsky (1961, pp. 37-42) found that wearout failures tend to be normally distributed; consequently, the tendency toward a normal distribution during the later intervals of the sample distribution is indicative of wearout failures. When this condition is present, the failure rate curve will be bimodal (Figure 2).

Chi-Squared Goodness of Fit Test

The chi-squared test is a convenient measure of the deviation between observed and expected phenomena. In testing the goodness of fit between the sample and a theoretical distribution, the individual chi-squared contributions for each interval are summed to give a value which is compared to a value from a chi-squared table at a particular confidence level. If the calculated chi-squared value exceeds the table value at the selected confidence level, the sample distribution does not follow the theoretical distribution at this level. Mathematically the chi-squared value between the observed and the expected can be determined

$$\chi^2 = \frac{\sum (O - E)^2}{E}$$

where O = observed frequency
and E = expected frequency

A limitation of the chi-squared test curtails its use to situations where the expected frequency is equal to or greater than five. When the value of the frequency of an interval is less than five, the computer program is written to automatically add the frequency value to one or more intervals until the expected value satisfies the above condition.

Failure Rate

Since equipment failures fall into three different categories, it would be anticipated that the failure of equipment and related components would show three different failure rates over a period of time where a large group of the same component is tested or operated under similar conditions. During the early life of a component a relatively high failure rate is expected, declining rapidly to a rate which remains fairly constant over the useful life of the component. Toward the end of the useful life span, the rate of failure again rises indicating the presence of wearout failure (Bazovsky, 1961, pp. 32-33).

In an investigation of this type where the failure history comes from an operating fleet of trucks, it is advantageous to determine, if possible, where the different types of failures occur.

The failure rate for each interval of the distribution is determined mathematically

$$FR_k = \frac{n_k}{(N)(CM_k)}$$

where n_k = number of failures in the interval k
N = number of components in service
CM_k = value of class mark at the k_{th} interval

Confidence Limits

The mean of the sample distribution is only an estimate of the true mean of the population; consequently, the true mean would lie within a certain range from the sample mean. Through the use of Student's "t" test and the following equation the range of the population mean can be determined at various confidence levels (Volk, 1958, pp. 109-110).

$$\mu = \overline{x} \pm t\, s(\overline{x})$$

where μ = true mean
t = value obtained from the t table with the appropriate confidence level and degrees of freedom
and $s(\overline{x})$ = estimated standard deviation of the mean which is determined from

$$\frac{s(x)}{\sqrt{n}}$$

Reliability

Reliability can be defined as the probability of success over a certain period of time. Bazovsky (1961, p. 11) states "reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered."

The reliability of any device which is not subject to infant failures and has not suffered wearout damage of any appreciable amount due to age can be determined with the exponential formula (Bazovsky, 1961, p. 17):

$$R(t) = e^{-\lambda t}$$

where e = base of the natural logarithm (2.71828. . .)
λ = the constant failure rate
and t = operating time in hours

The period for which this equation is valid is referred to as the useful life of the component. The reliability of the component for any time (t) during the useful life can be determined; however it is important that the value of the time (t) never exceeds the useful life of the device since the equation will give an erroneous result (Bazovsky, 1961, p. 17).

Extensive applications of the concepts of reliability are beyond the scope of this thesis. However, this very brief consideration is introduced to show how the down time of open pit haulage equipment could be evaluated in another manner. Where the components analyzed in this study show tendencies toward a constant failure rate over a reasonable period of time, the reliability of the component will be shown for all intervals. This figure will not take into consideration the replacements due to early failure and wearout failure. The assumption here will be that the constant rate of failure prevails throughout the distribution, and the reliability is that expected for a component not subject to either infant or wearout failures.

CHAPTER III
PROCEDURE

Data Background

The information for this thesis was made available by a company operating a medium-size open-pit copper mine located in southern Arizona.

Production requirements for this operation are such that approximately 90,000 tons of ore and waste must be moved out of the pit in a 24-hour period. The truck fleet chosen to fulfill this demand is made up of 35 units each with a rated hauling capacity of 55 to 60 tons. From 24 to 28 units of the fleet are needed to maintain the required production level; the variation in the number of vehicles needed is due to the variable haul distances from the benches in the pit to the primary crusher and the waste dumps.

The hauling units are powered by two 335-HP diesel engines coupled by drive lines to two semi-automatic transmissions, each of which are connected by additional drive lines to separate rear-driving axles. The trucks selected for this study provide an excellent control group in that they are all of the same model with a few minor differences and were purchased at approximately the same time. To date these units have accumulated an average of 17,500 hours per unit over a three and one-half year period.

The maintenance policy of the mining operation is above average with strict adherence to the periodic inspections established by management in accordance with the recommendations of the manufacturer. The management of the corporation has also established a policy of accurate record keeping; therefore the information from these records used for this thesis is assumed to be a true representation of the replacements.

Maintenance Records

When a truck enters the shop for any type of maintenance, a repair card is made out showing the equipment number, the date, and the cumulative hours taken from the truck's hour meter. In addition, the repairs and components to be replaced are recorded together with the number of man hours needed to perform this maintenance. The total number of hours a truck is out of service is indicated on the form after completion of the work.

All major repairs and all component replacements with corresponding dates and hour readings are transferred from the repair cards to a master file for each truck to give a comprehensive history of component failure. The master file for each truck is divided into three major sections: engines, transmissions, and major repairs.

All component replacements pertinent to the engine and transmission groups are recorded in their respective sections, whereas failures of any other type are recorded in the major repair section. The information for this thesis was taken from this master file.

A coding system was established to facilitate handling the data in the IBM 7072 computer by means of punched cards. This code was set up to show the equipment number, date, hours at which replacement took place, the location of the component on the truck (left - right, front - rear), the major assembly, the subassembly, the component, and finally the component position number. The coding system is shown in Appendix A together with an example of how a failure of a particular component was coded for IBM cards.

The coding instructions, written on photostats of the master files, were given to key-punch operators who transferred the information to standard 80-column punch cards. The cards representing the failure of a particular component or assembly were arranged in ascending order by truck number and by time of occurrence, which was the value of the hour-meter reading. This data-arranging procedure was necessary for proper execution of the computer program.

When component parts of a major assembly were under investigation, the cards representing the failures for the major assembly were inserted in sequential order with the component failure cards. This was required since all the component parts in service at the time of a major assembly replacement did not necessarily fail. Therefore the hours in operation from the last failure of the component parts to the time of a major assembly overhaul had to be disregarded. The time between component failures then had to be reset to zero in the computer program since new or rebuilt components were installed at the time of a major assembly replacement.

Computer Program

The program for the IBM 7072 computer was written in Fortran language with the use of an autocoder insert to simplify handling the "table look-up" in the chi-squared subroutine. This program, together with a glossary of the program names, is shown in Appendix B.

The MAIN program and POSCY subroutine were basically data reduction steps in that they read the data and printed out the proper headings for the various components based on control cards placed in front of each block of data. In addition to finding the highest value of hour life of a particular component, the MAIN program arranged the hours-to-failure of the components in ascending order and stored these values for later use. Also included in the MAIN program was an operation to cut off the first interval of the histogram which was assumed to represent the infant failures of a component. Elimination of the first outlier was controlled manually through the use of an alteration switch on the computer console. The POSCY subroutine took all the hour values from the data cards and subtracted the lower values from the higher values giving the life in hours of the particular replacement in question.

The STAT subroutine was perhaps the backbone of the entire program since the sample frequency distribution, as well as the theoretical normal and Poisson distributions, was determined in this step. The mean, standard deviation, and the variance of the sample distribution also were found here for the particular component under investigation. The failure rates for the different intervals of the distribution were determined in the later stages of this program segment.

The CHS subroutine was a curve-fitting routine using the chi-squared test to determine the goodness of fit between the sample distribution and each of the theoretical distributions.

The INTEG subroutine was an integration operation in which Simpson's rule for integrating the function, FY, was used to find the area under the normal curve.

Print-outs of the sample distribution as well as the theoretical frequency distributions occurred during the execution of the STAT subroutine, while the results of the goodness of fit test were printed at the end of the CHS subroutine.

A control card, mentioned earlier, preceded each block of data and contained the following items: number of failures, number of intervals desired in the distribution, number of components in the entire fleet, and headings which were to appear in the print-out. An example of the output obtained from the computer is shown in Appendix C.

The major portion of time devoted to this study was involved in data reduction and programming. Approximately 8,000 individual failures were analyzed, coded, and punched onto 80-column IBM cards. Five separate computer programs were initially written to deal with the various statistical applications and were then combined into the one program shown in Appendix B. Numerous modifications were required to overcome inadequacies and limitations of the initial program in order to accommodate large blocks of data.

In the following chapter the results obtained from blocks of data of varying magnitude for selected assemblies and components are analyzed and conclusions formulated. Since the primary purpose of this thesis is to show a method of predicting failures for any type of equipment, no attempt is made to give the results of all component failures associated with these trucks.

CHAPTER IV
RESULTS AND ANALYSES

Diesel Engines

The diesel engine is the first major assembly investigated for frequency of failure. The engines from 25 trucks are used in this analysis since the power plants of these trucks are all of the same make and model. Two engines for each truck, or a total of 50 engines, are in operation at any one time. A total of 113 failures of this assembly are recorded during the time involved in this investigation.

Using Sturges' rule for determining the number of intervals for grouping data, eight intervals are used in plotting the frequency distribution histogram. The results derived from the computer program are summarized in Table 1 and Figures 1 and 2. The calculated values for the theoretical normal and Poisson distributions for all the tables shown have been rounded to the nearest whole number.

The mean life of these engines is equal to 6,557.4 hours with a standard deviation of 1,020 hours. The calculated chi-squared value for the goodness of fit test between the sample and normal distributions is equal to 59.76. This exceeds the table value of 10.83 at the .001 probability level with one degree of freedom. We can therefore say with 99.9% confidence that the sample distribution is not from a normally distributed population.

TABLE 1
DIESEL ENGINE FAILURES

Interval Number	Class Mark (Hours)	Distributions: Sample	Normal	Poisson	Failure Rate (failures per 1000 hours)
1	838.0	9	--	11	.215
2	2512.5	7	--	17	.056
3	4186.5	8	7	23	.038
4	5861.0	30	55	22	.102
5	7535.5	38	46	27	.101
6	9209.5	10	4	11	.022
7	10883.5	6	--	6	.011
8	12557.5	5	--	3	.008

The results of the chi-squared test between the sample and the Poisson distributions show a calculated value of 44.32 as opposed to 22.46 at the .001 probability level with six degrees of freedom. The sample distribution, therefore, is not representative of a Poisson population.

The difference in the number of degrees of freedom used in the above tests is due to the amount of grouping which is required to overcome the limitation imposed on the chi-squared test. In addition, one degree of freedom is lost in the test for the normal distribution due to the integration routine involved in finding the area under the normal curve.

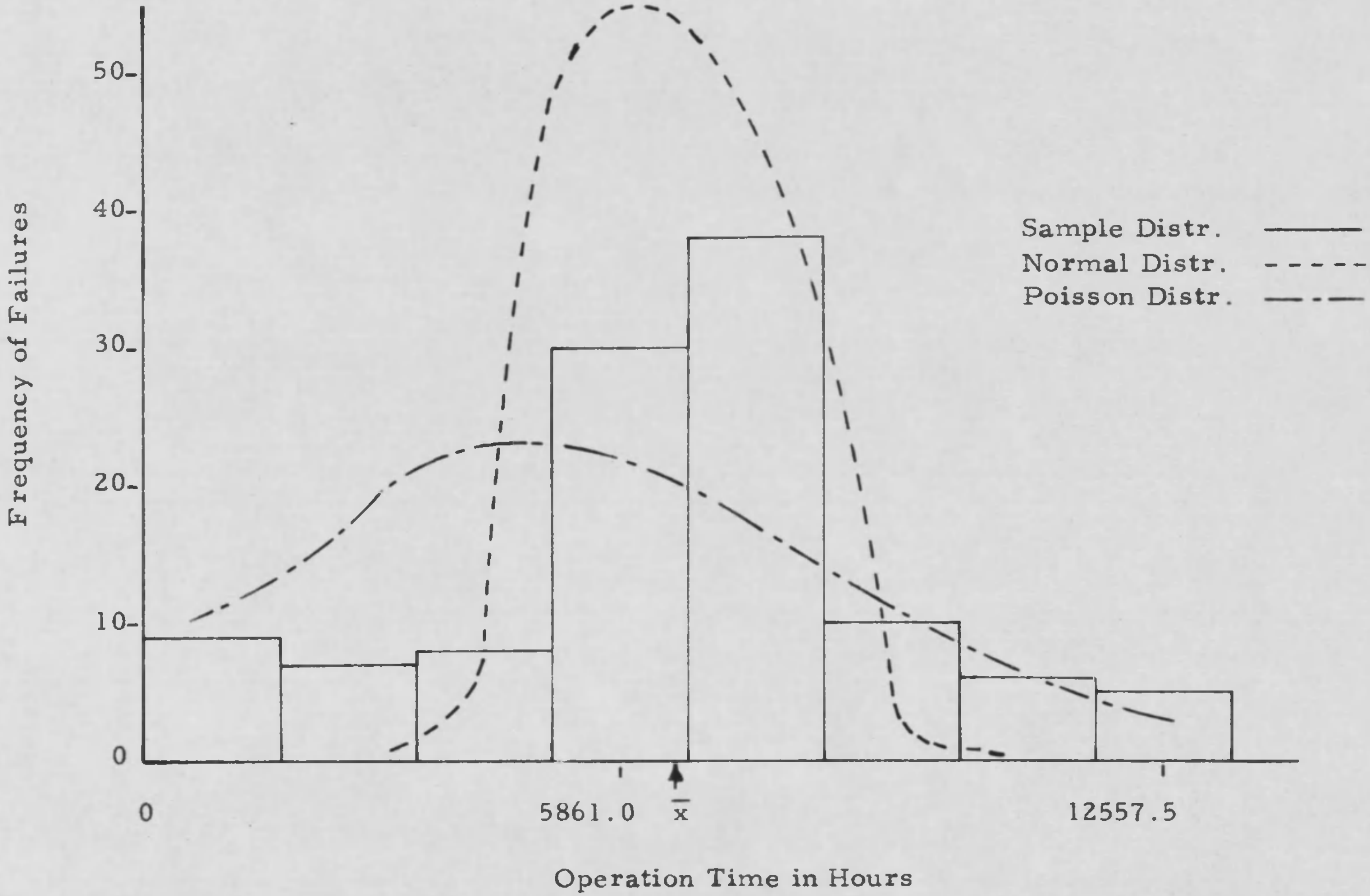

FIGURE 1. DIESEL ENGINE FAILURES

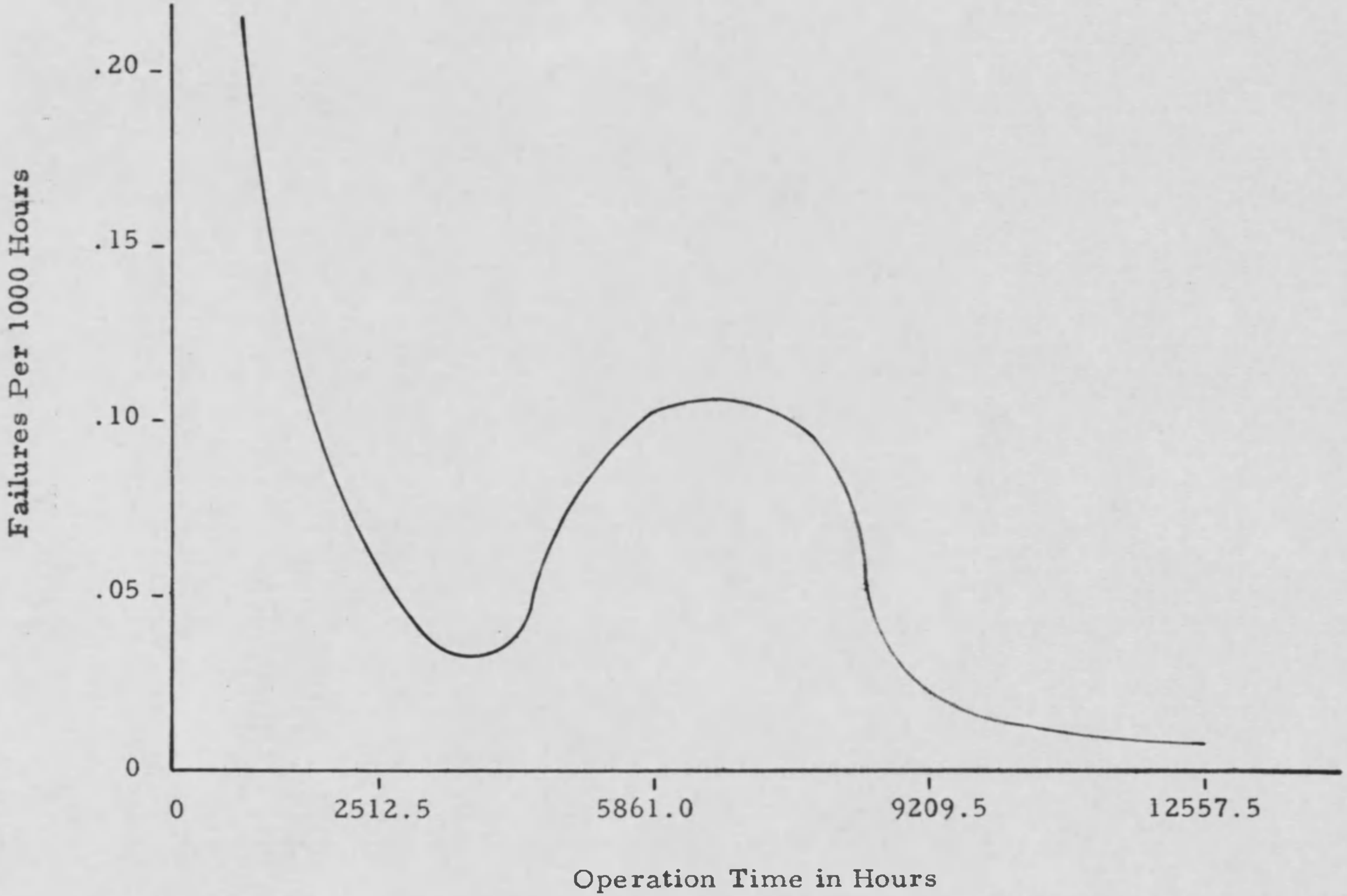

FIGURE 2. ENGINE FAILURE RATE

The failure rate for engines is quite high for the first interval indicating the possible presence of early failures (Table 1 and Figure 2). In the next two intervals the failure rate remains relatively constant. During the latter part of the third interval, the rate of failure begins to rise which indicates possible wearout failures.

In placing confidence limits on the mean at the .99 level, future engine replacements due to failure of the engine as a whole would be expected to occur between 6,278 and 6,836 hours. The reliability for the engine could not be calculated from the frequency distribution since the constant rate of failure does not extend over a long enough period of time. Furthermore, since the engine can be classified as a system composed of many individual components with different levels of reliability, it would not be feasible to predict the reliability on the basis of the failure rate for the system as a whole. A fair estimate of the reliability of a system can be predicted through the use of the product rule based on individual reliabilities of the various components which make up the engine.

Cylinder Heads

The cylinder head of an internal-combustion engine is an integral part of the system in that it contains the fuel injectors, intake and exhaust valves, as well as other functional component parts necessary for operation. The head is also the main constituent of the combustion chamber where the chemical energy contained in the fuel is converted to heat energy necessary for the operation of a reciprocating internal-combustion engine.

The engines from the 25 trucks investigated have a single one-piece head bolted to the top of the engine; therefore 50 cylinder heads are in service at any one time. The data show 327 head replacements over an average of 17,500 truck hours; however only 219 of these component replacements were due to failure while the remaining were changed due to engine replacement.

Ten intervals are necessary to portray the sample frequency distribution according to Sturges' rule. The summary of the results are shown in Table 2 and Figures 3 and 4.

The mean for this sample distribution is 2,312.3 hours with a standard deviation of 811 hours.

The calculated value of the chi-squared goodness of fit test between the sample and the normal distributions is equal to 594.08. This exceeds the table value of 16.27 at the .001 probability level with three degrees of freedom. Therefore the probability that the sample comes from a normal distribution is small.

The calculated value of the chi-squared test between the Poisson and sample distributions yields a value of 32.93 exceeding the table value of 20.52 at the .001 probability level with five degrees

TABLE 2
CYLINDER HEAD FAILURES

Interval Number	Class Mark (Hours)	Distributions: Sample	Normal	Poisson	Failure Rate (failures per 1000 hours)
1	488.5	67	11	69	2.743
2	1463.5	44	61	59	.601
3	2438.0	35	98	45	.287
4	3412.5	30	44	27	.176
5	4387.0	26	5	12	.119
6	5362.0	7	--	5	.026
7	6336.5	5	--	2	.016
8	7311.0	4	--	1	.011
9	8285.5	--	--	--	--
10	9260.0	1	--	--	.002

of freedom. Consequently, there is little likelihood that the sample comes from either a normal or a Poisson population.

By placing confidence limits on the sample mean at the .99 confidence level the true mean would be expected to equal a value between 2,171.9 and 2,454.7 hours if the sample, based on the available data, is a true representation of a population.

The failure rate for this subassembly is very high for the first interval indicating the possibility of poor installation practices. The gradual decline of the failure rate throughout the remaining

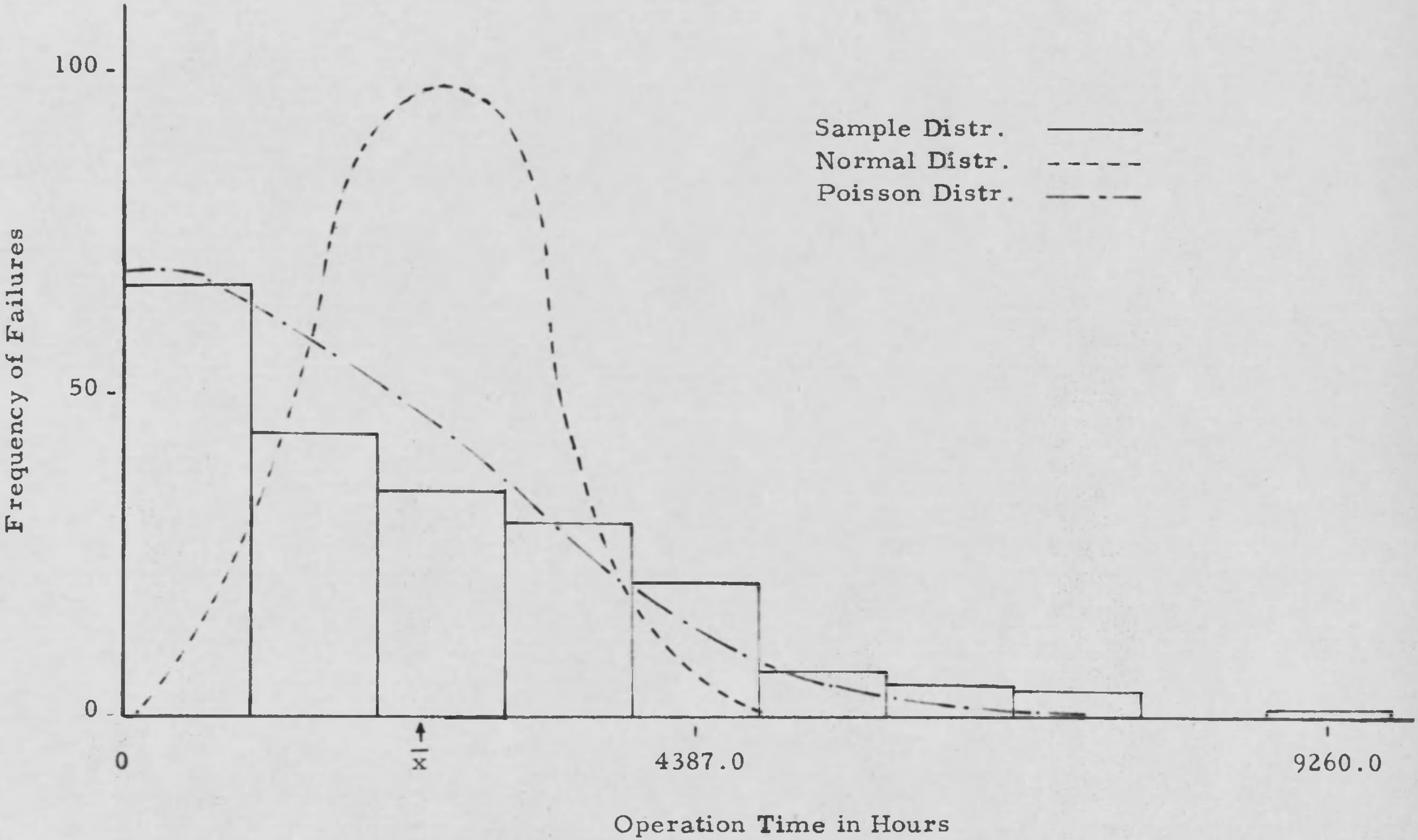

FIGURE 3. CYLINDER HEAD FAILURES

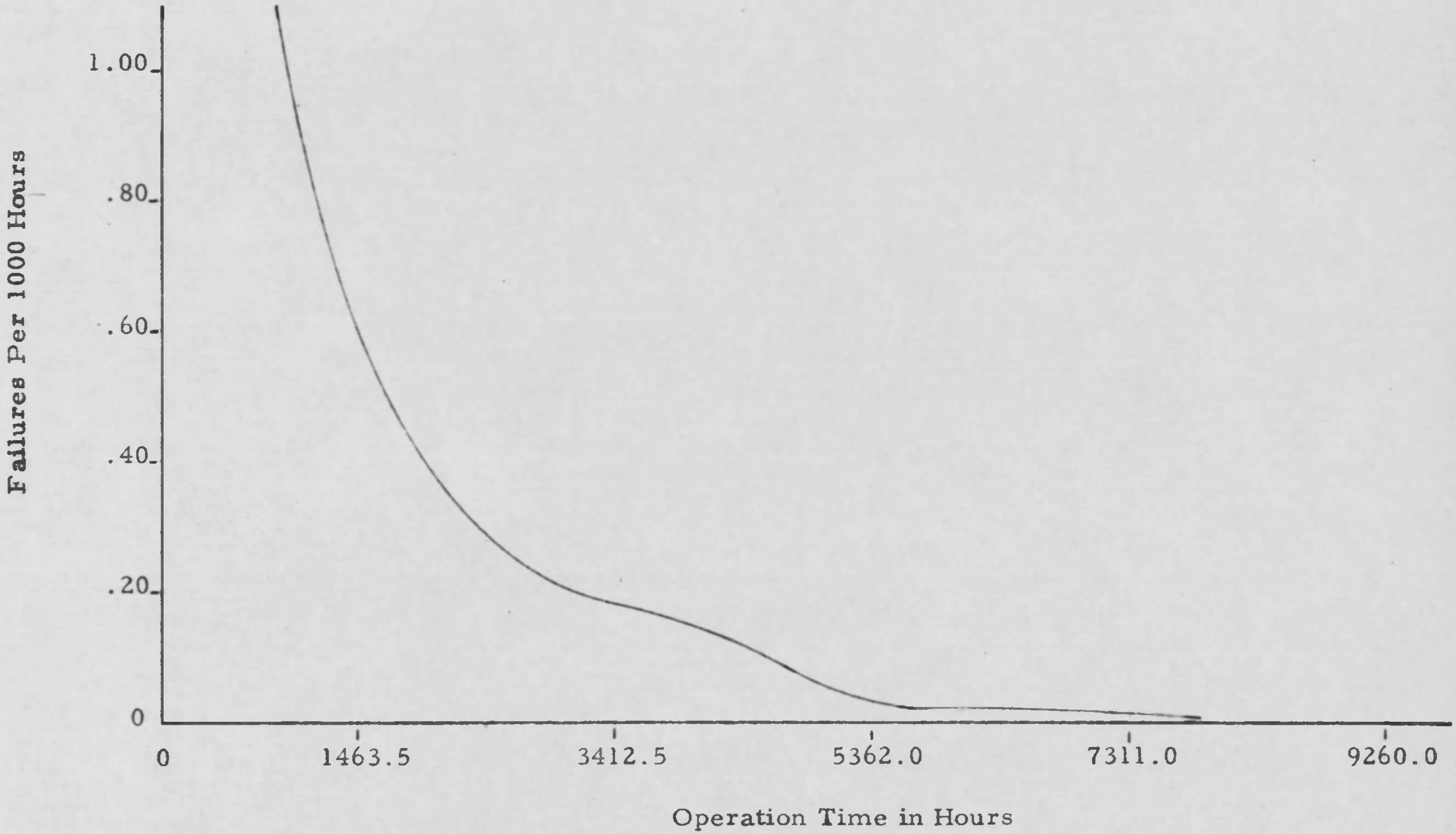

FIGURE 4. CYLINDER HEAD FAILURE RATE

intervals is abnormal and would warrant closer investigation of the causes of failure before any specific conclusions can be drawn. The effects of improper operation of the vehicle must not be ruled out. Since the failure rate does not remain constant over a substantial period of time no attempt is made to predict the reliability of this subassembly.

Fuel Injectors

The fuel injector plays a major role in the proper operation of an engine in that it delivers the required amount of diesel fuel to each cylinder and converts the liquid fuel into a finely atomized spray to insure proper burning in the combustion chamber.

There are six injectors in each engine; therefore 300 injectors are in service for the 25 trucks selected. The data show a total of 913 injector replacements in the 50 engines under consideration. The times-to-failure for only 591 injectors could be used since these had been individually replaced because of either real or assumed failure. It is the policy of this mining company to replace all the injectors when an engine or cylinder head failure is experienced. Therefore, the times-to-failure of the remaining 322 injectors could not be used since these did not actually fail. The computer program is designed to disregard the time in service of all components which were in operation just prior to an engine or head replacement. This is accomplished by placing the data cards for engine and head replacements in the proper sequence with the injector data cards.

Through the use of Sturges' rule ten intervals are used in plotting the sample distribution. The summary of the results from the computer are shown in Table 3 and Figures 5 and 6.

TABLE 3
FUEL INJECTOR FAILURES

Interval Number	Class Mark (Hours)	Distributions			Failure Rate (failures per 1000 hours)
		Sample	Normal	Poisson	
1	397.0	146	--	137	1.226
2	1190.0	112	26	141	.314
3	1982.5	59	367	132	.099
4	2775.0	84	195	92	.101
5	3567.5	113	3	51	.106
6	4359.5	50	--	24	.038
7	5152.0	17	--	10	.011
8	5944.5	8	--	3	.005
9	6737.0	1	--	1	--
10	7529.5	1	--	--	--

The mean life for the injectors equals 2,219.7 hours with an estimated standard deviation of 373 hours.

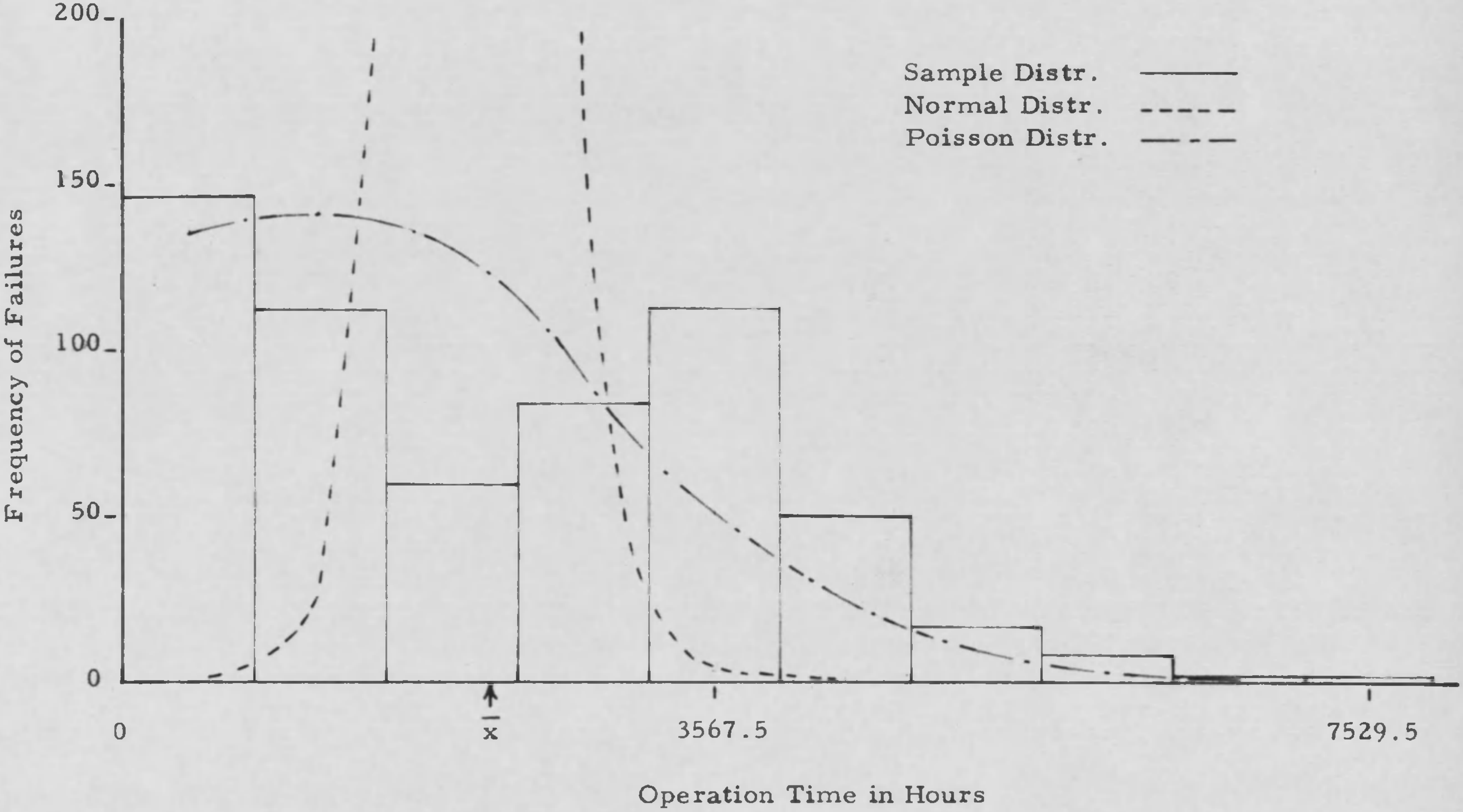

FIGURE 5. FUEL INJECTOR FAILURES

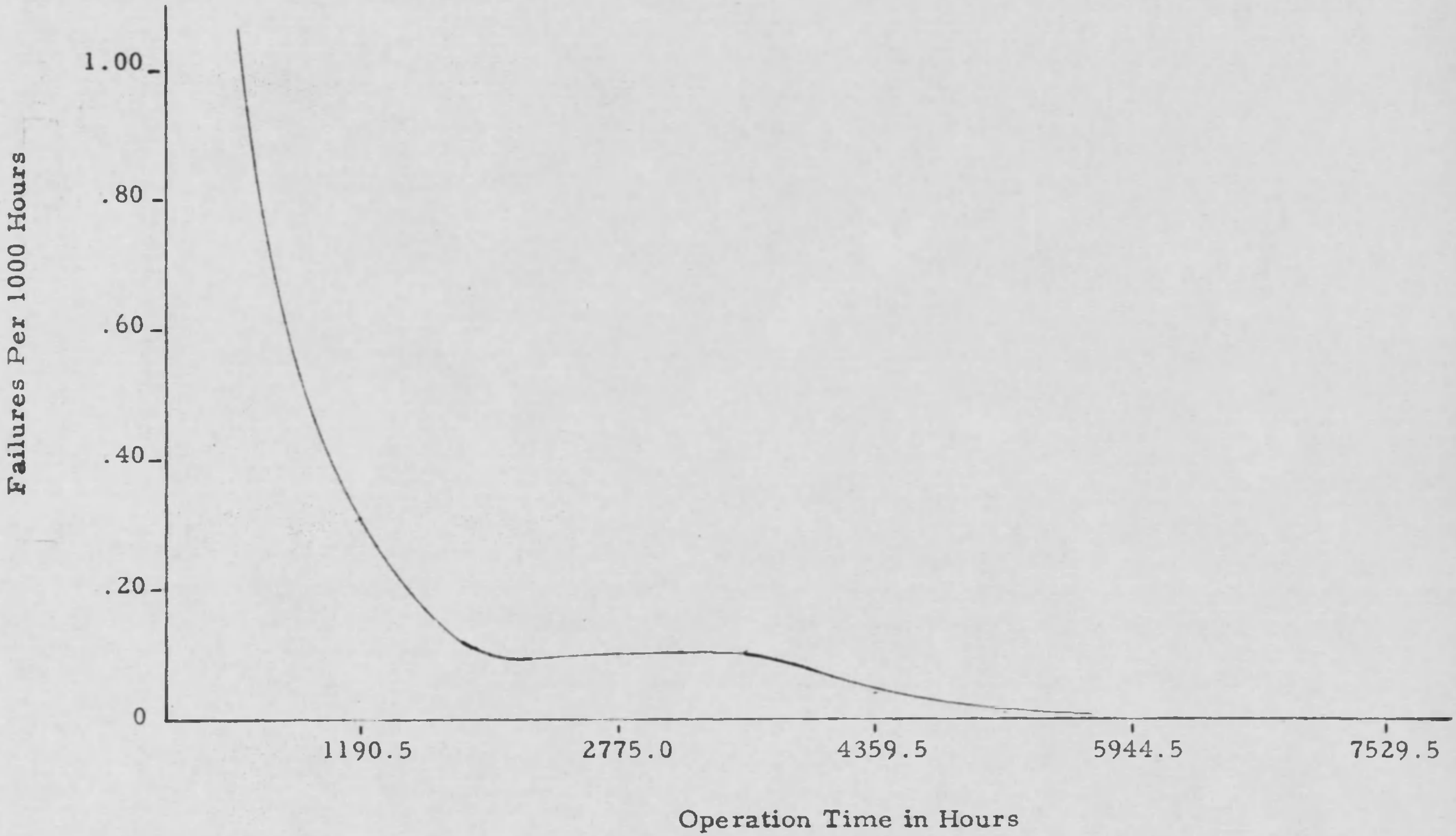

FIGURE 6. FUEL INJECTOR FAILURE RATE

The calculated chi-squared test for goodness of fit between the sample and the normal distributions is equal to 2,729.69, exceeding by a considerable amount the table value of 10.83 at the .001 probability level with one degree of freedom. Therefore the probability that the sample distribution comes from a normal population is small.

Through the application of the chi-squared test between the sample and Poisson distributions the calculated chi-squared value is equal to 160.64. This exceeds the table value of 22.45 at the .001 probability level with six degrees of freedom. Again with less than 0.1% chance of being in error, it is concluded that this sample does not come from a Poisson population.

By placing the confidence limits on the mean at the .99 level the true mean-failure time would be expected to lie within the range of 2,180.12 to 2,259.28 hours if this is a representative sample of the population.

The failure rate for this sample distribution indicates the occurrence of early failures during the first two intervals while the next three intervals show a relatively constant rate of failure indicative of chance failure. In the remaining intervals the failure rate does not follow the upward trend expected for components of this type. The first conclusion that can be drawn from the degeneration of the failure rate curve is that these components are being replaced before any evidence of wearout failure occurs. Since no evidence of wearout failure has been shown one can assume that these components are replaced before their useful life period has expired. The author has observed situations in which all of the injectors in an engine are replaced because the performances of one or two are not up to specifications.

Since the failure rate remains relatively constant over a three-interval period, the reliability of the component can be determined for the various periods of time involved in this analysis as shown in Table 4 and Figure 7. In plotting the reliability an assumption is made that the component will not be subject to early failure and the useful life of the device will not be exceeded.

TABLE 4
FUEL INJECTOR RELIABILITY

Interval Number	Reliability	Interval Number	Reliability
1	.96	6	.64
2	.89	7	.59
3	.82	8	.55
4	.75	9	.50
5	.69	10	.46

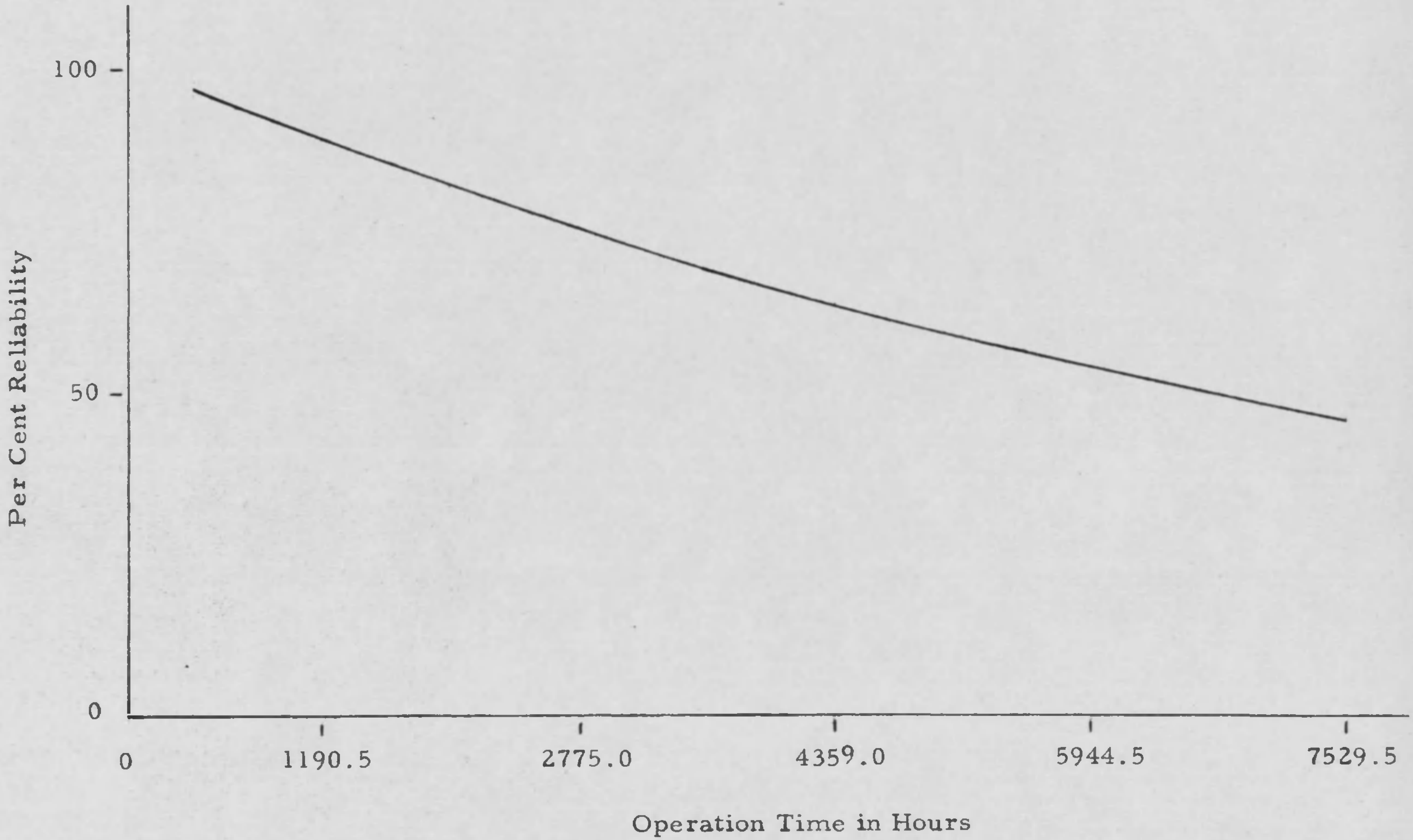

FIGURE 7. FUEL INJECTOR RELIABILITY

Differential Assemblies

The primary function of the differential assembly is to allow the inside set of wheels to rotate at a different rate of speed than the outside wheels whenever the vehicle is turning a corner. In addition, this assembly transfers the energy from the drive shaft to the driving axles through a set of reduction gears. The mining company from which these data were obtained has adopted a policy of replacing the entire assembly whenever individual parts fail. At the time of replacing the defective components, the unit is completely rebuilt with additional new parts which are considered necessary to prevent premature failure. In analyzing the data no information is available to warrant investigation of the individual components which make up this major assembly.

Two differential assemblies are used in each truck; consequently 58 of these units are in operation for the 29 trucks used in this particular analysis. A total of 162 failures are recorded requiring eight intervals for the sample distribution. The summary of the results determined through the use of the computer are shown in Table 5 and Figures 8 and 9.

The mean life for this component is 5,379.7 hours with the estimated standard deviation of the sample equal to 1,230 hours.

TABLE 5
DIFFERENTIAL ASSEMBLIES, ALL FAILURES

Interval Number	Class Mark (Hours)	Distributions: Sample	Normal	Poisson	Failure Rate (failures per 1000 hours)
1	1033.5	44	1	43	.734
2	3098.5	35	24	41	.195
3	5163.0	21	96	35	.070
4	7228.0	25	39	23	.060
5	9292.5	11	2	12	.020
6	11357.0	15	--	5	.023
7	13421.5	7	--	2	.009
8	13486.0	4	--	1	.004

The calculated value of the chi-squared goodness of fit test between the normal and the sample distributions equals 234.73. This exceeds the table value of 10.83 at the .001 probability level with one degree of freedom indicating this sample distribution does not come from a normal population.

The calculated value of the chi-squared test between the Poisson and the sample distributions is equal to 49.90 exceeding the table value of 20.52 at the .001 probability level with five degrees of freedom. It can also be concluded with less than 0.1% chance of being in error that this sample is not representative of the Poisson population.

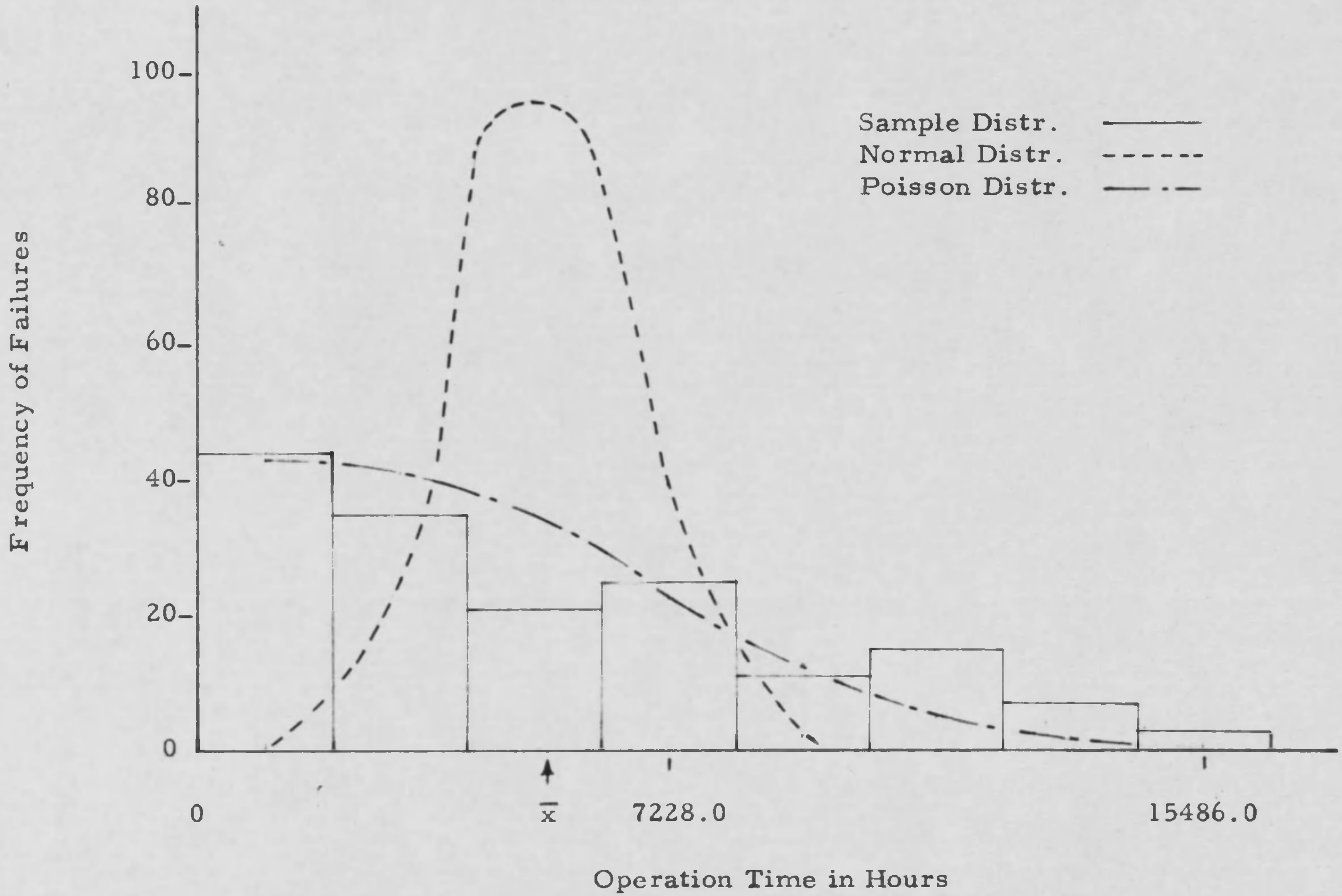

FIGURE 8. DIFFERENTIAL ASSEMBLY, ALL FAILURES

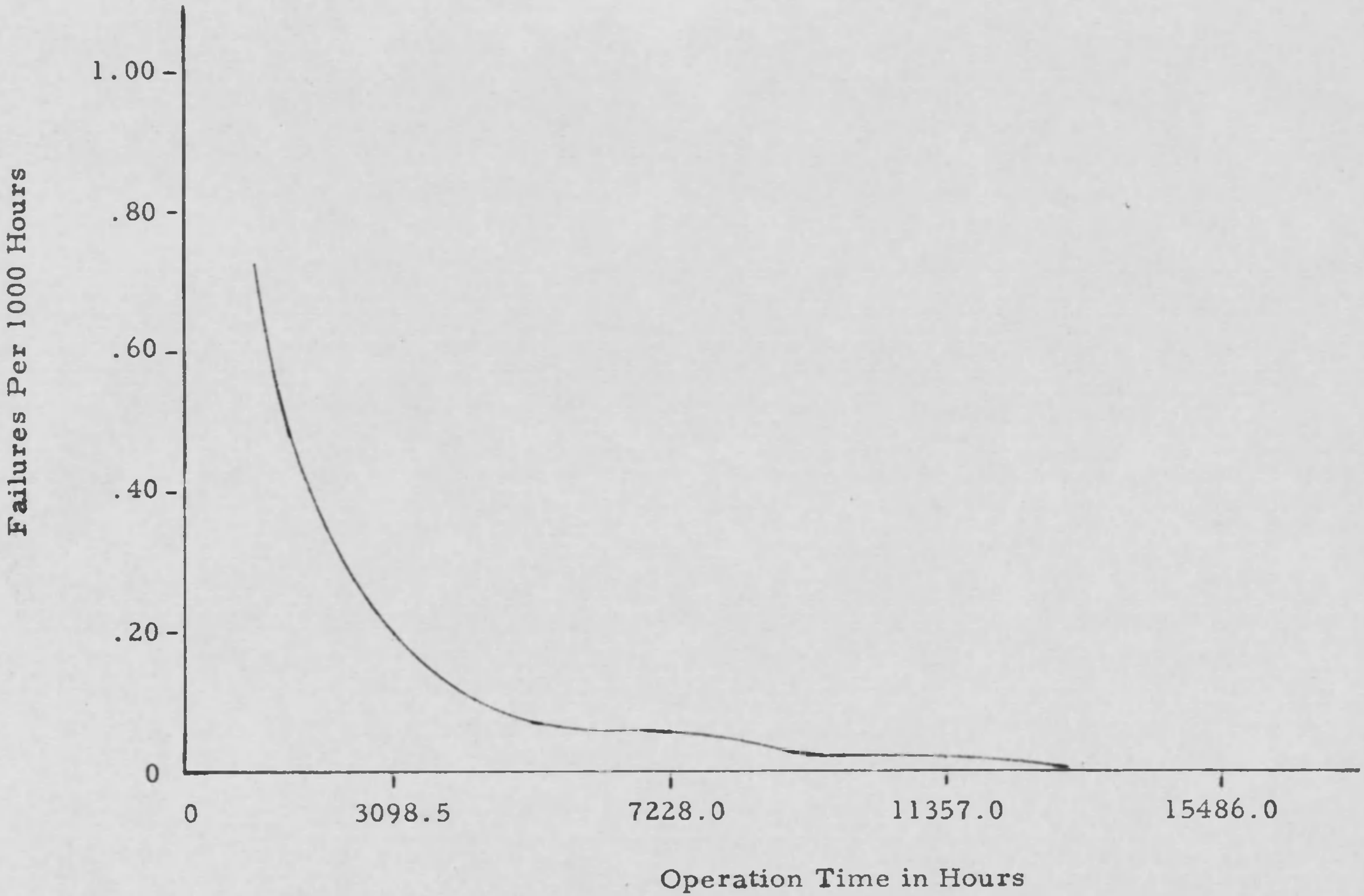

FIGURE 9. DIFFERENTIAL ASSEMBLY FAILURE RATE (ALL)

In placing the confidence limits on the mean of the sample at the .99 level, the true mean time-to-failure would be expected to fall between 5,130 and 5,628 hours providing, of course, that this sample is a true representation of the population.

Based on failure rates at the various intervals of the histogram, this assembly exhibits a tendency toward a high rate of failure during the first interval, decreasing to a fairly constant level during the fourth, fifth and sixth intervals.

An analysis was run on the first failures to determine the presence of any significant differences between the first and succeeding failures. The results of this separate analysis are shown in Table 6 and Figures 10 and 11.

The mean equals 9,419.1 hours with an estimated standard deviation of 1,700 hours. In applying the chi-squared test it is found that the sample is representative of a Poisson population at the .01 probability level.

The primary conclusion that can be drawn from these two distributions is that the samples come from two distinctly different populations. It appears that when these assemblies are rebuilt they are not as reliable as were the original assemblies. Certain other components have shown this tendency toward multi-populations. Further conclusions concerning this situation are developed in Chapter V.

TABLE 6
DIFFERENTIAL ASSEMBLIES, INITIAL FAILURES

Interval Number	Class Mark (Hours)	Distributions: Sample	Normal	Poisson	Failure Rate (failures per 1000 hours)
1	1181.0	--	--	5	--
2	3541.0	7	--	8	.034
3	5900.5	8	5	11	.023
4	8260.0	13	24	11	.027
5	10619.5	13	24	9	.021
6	12979.0	11	4	6	.015
7	15338.5	5	--	4	.006

Transmissions

The transmissions used in the 29 trucks under investigation are eight-speed semi-automatic units located midway between the engine and the rear axles. Power from the engines is brought into the transmissions through the use of torque-tube drive lines where the proper power-to-speed ratio for the immediate operating conditions is determined by the operator with a speed selector lever.

Since each truck uses two transmissions, a total of 58 are in operation during the time represented by this study. A total of 380 replacements are recorded for this period and require ten intervals

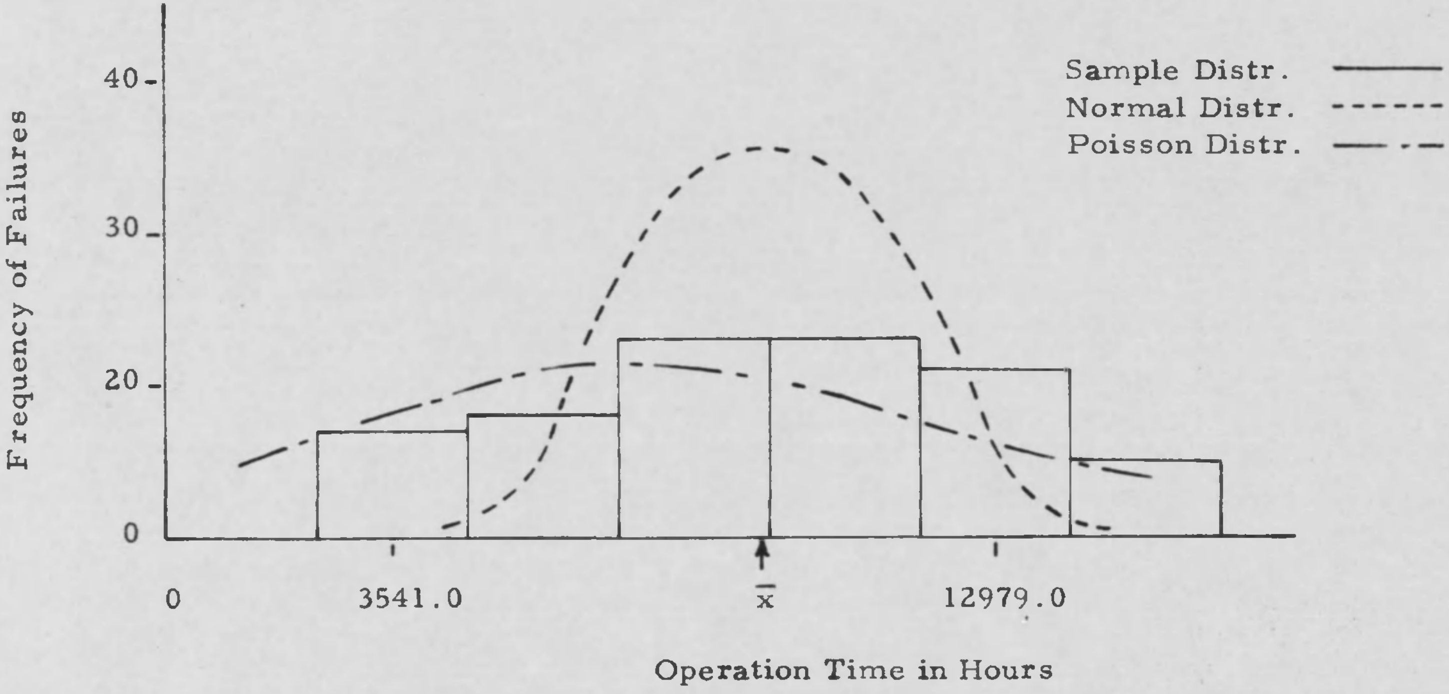

FIGURE 10. DIFFERENTIAL ASSEMBLY, INITIAL FAILURES

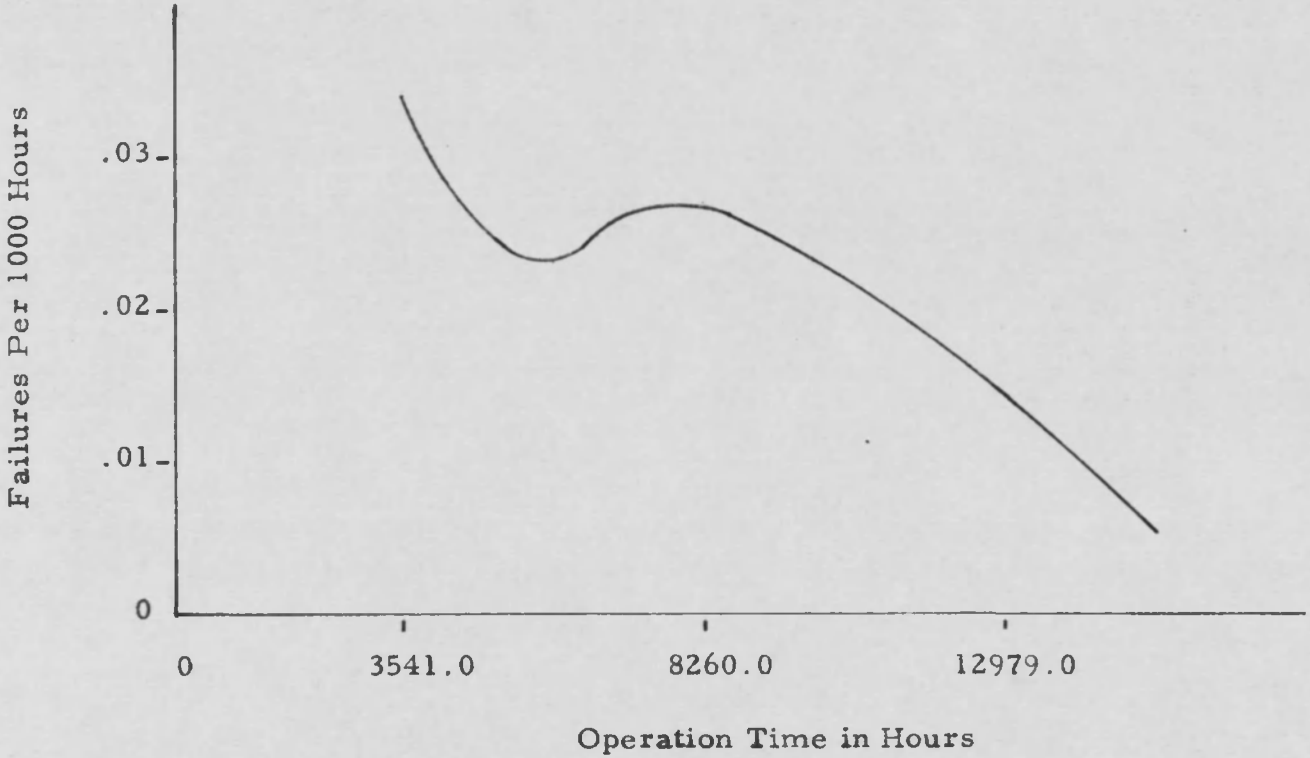

FIGURE 11. DIFFERENTIAL ASSEMBLY FAILURE RATE (INITIAL)

to construct the sample frequency distribution. The summarized results from the computer are shown in Table 7 and with graphical representations in Figures 12 and 13.

TABLE 7
TRANSMISSION FAILURES

Interval Number	Class Mark (Hours)	Distributions Sample	Normal	Poisson	Failure Rate (failures per 1000 hours)
1	401.0	86	--	78	3.698
2	1201.0	80	17	86	1.149
3	2000.5	54	182	85	.465
4	2800.0	45	167	63	.277
5	3599.5	33	13	37	.158
6	4399.0	26	--	18	.102
7	5198.5	44	--	8	.146
8	5998.0	9	--	3	.026
9	6797.5	2	--	1	.005
10	7597.0	1	--	--	.002

The mean is equal to 2,372.8 hours with an estimated standard deviation of 457 hours. In placing confidence limits on the mean at the .99 level, the expected mean of the population would lie between 2,312.3 and 2,433.3 hours if this sample is a true representation of the population.

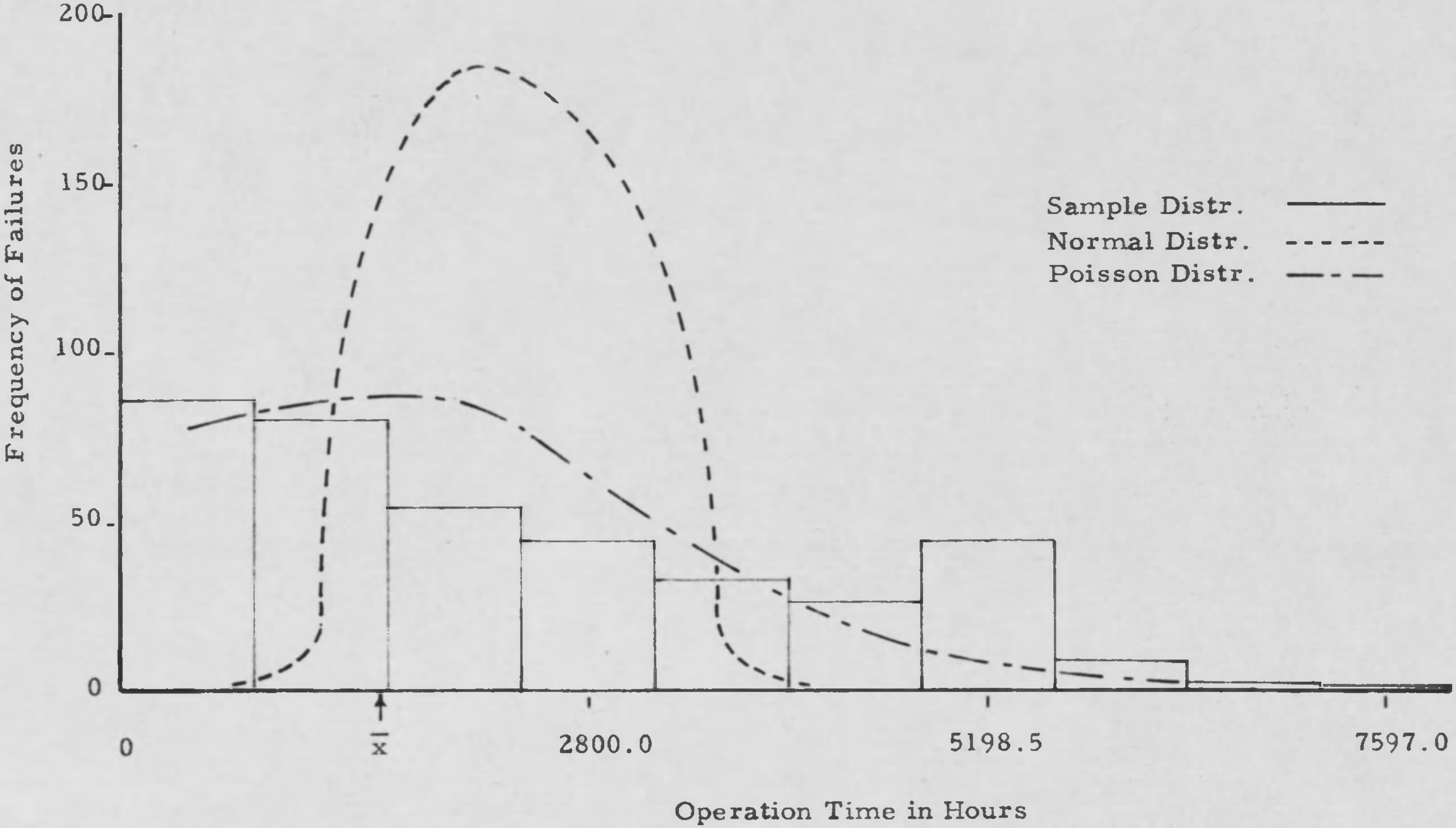

FIGURE 12. TRANSMISSION FAILURES

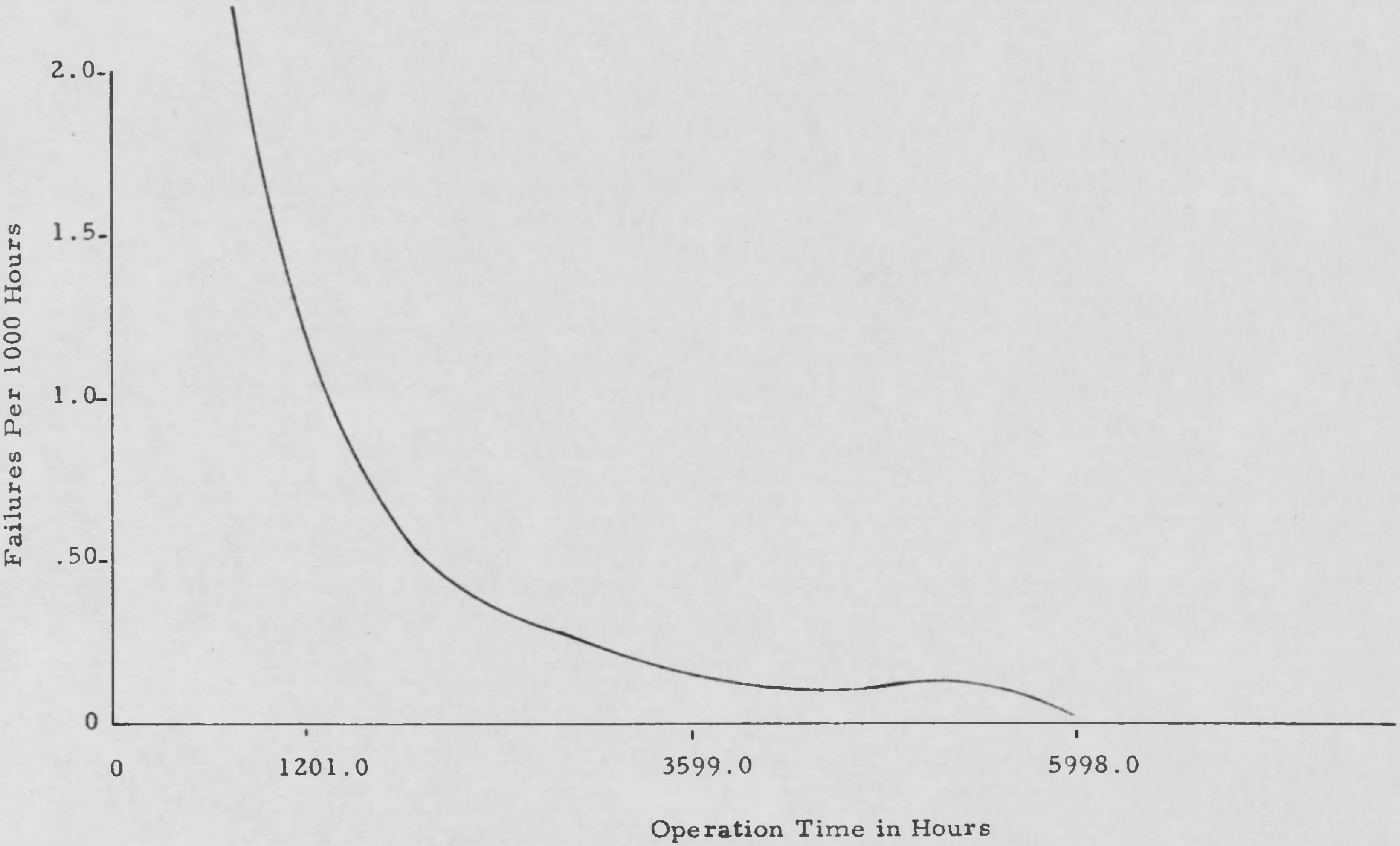

FIGURE 13. TRANSMISSION FAILURE RATE

In applying the chi-squared test between the sample and the normal distributions, the calculated value of 2,239.37 exceeds the table value of 13.28 at the .001 probability level with two degrees of freedom. This is a strong indication that the sample distribution does not come from a normal population.

When the chi-squared test is applied to the sample and Poisson distributions, the calculated value of 185.05 exceeds the table value of 22.46 at the .001 probability level with six degrees of freedom. Therefore, there is little likelihood that the sample distribution comes from a Poisson distribution.

The large number of failures occurring in the first two intervals is indicative of infant failures while the increase in the number of failures during the seventh interval would be an indication of wearout failures. This also might be evidence of a separate population.

During the first two years of truck operation, a condition was recognized where certain components of the transmissions were inadequately designed. The manufacturer redesigned these components, and modifications were made to the existing transmissions at that time. The time between failures was then increased to approximately 5,000 hours. Before any further predictions can be made concerning failures of this assembly, the times at which modifications were made must be determined so that parameters of the two populations can be established.

Steering Booster Pumps

The manual steering operations required to maneuver these ore trucks are assisted by a hydraulic system composed of a pump that supplies the hydraulic oil to two double-acting cylinders which, when activated through a valve connected to the steering wheel, provide the necessary energy needed to turn the front wheels of the vehicle. The power required to run this steering pump is furnished by the left-hand engine of the truck.

One hundred ten steering pump replacements are recorded for 29 trucks; since only one pump is used on each vehicle, the total number of these devices in operation at any one time is 29. Eight intervals are used to determine the sample distribution. Table 8 together with Figures 14 and 15 show the tabulated results with graphical representations of the distributions and failure rates.

The sample mean is equal to 3,665.0 hours with an estimated standard deviation of 2,020 hours.

The results of the calculated chi-squared test between the normal and the sample distributions give a value of 35.53 exceeding the table value of 13.82 at the .001 probability level with two degrees of freedom. Consequently, this sample probably does not come from a normal population.

TABLE 8
STEERING BOOSTER PUMP FAILURES

Interval Number	Class Mark (Hours)	Distributions			Failure Rate (failures per 1000 hours)
		Sample	Normal	Poisson	
1	1133.0	46	27	57	1.400
2	3397.5	35	46	29	.355
3	5661.5	14	30	15	.085
4	7926.0	7	6	6	.031
5	10190.5	5	--	2	.017
6	12454.5	1	--	1	.003
7	14718.5	--	--	--	--
8	16982.5	2	--	--	.004

The application of the chi-squared test to the sample and theoretical Poisson distributions yields a value of 8.21 which is less than the table value of 11.35 at the .01 probability level with three degrees of freedom. This indicates that the sample comes from a Poisson population, and the percentage of failures that would be expected to occur at the various time intervals are shown in Table 9.

The initial failure rate of this component is quite high with 1.3 failures per thousand hours which indicates the occurrence of early failures. Beginning with the fourth interval, the failure rate begins to level off indicating a constant rate of failure. The shape of

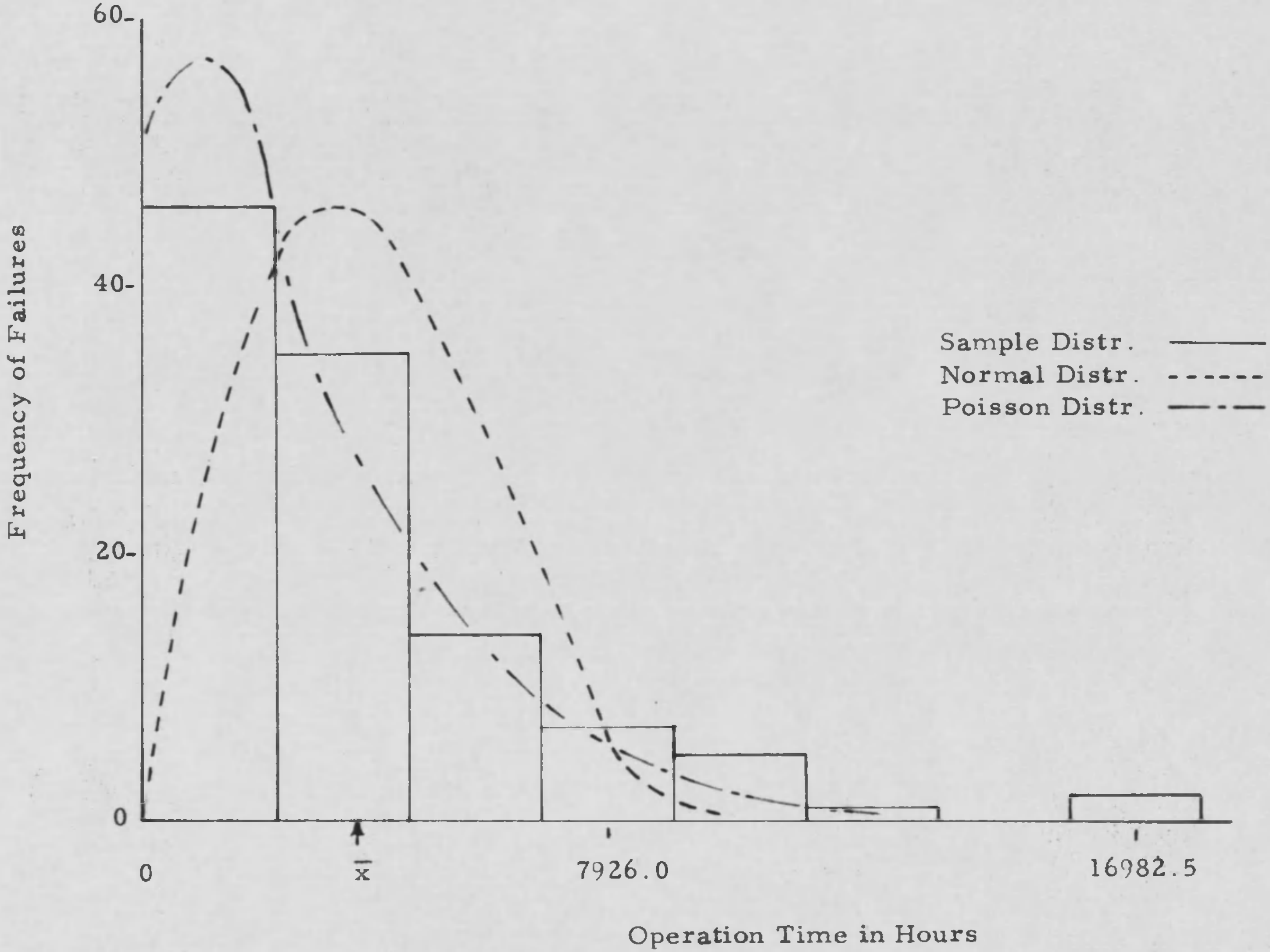

FIGURE 14. STEERING PUMP FAILURES

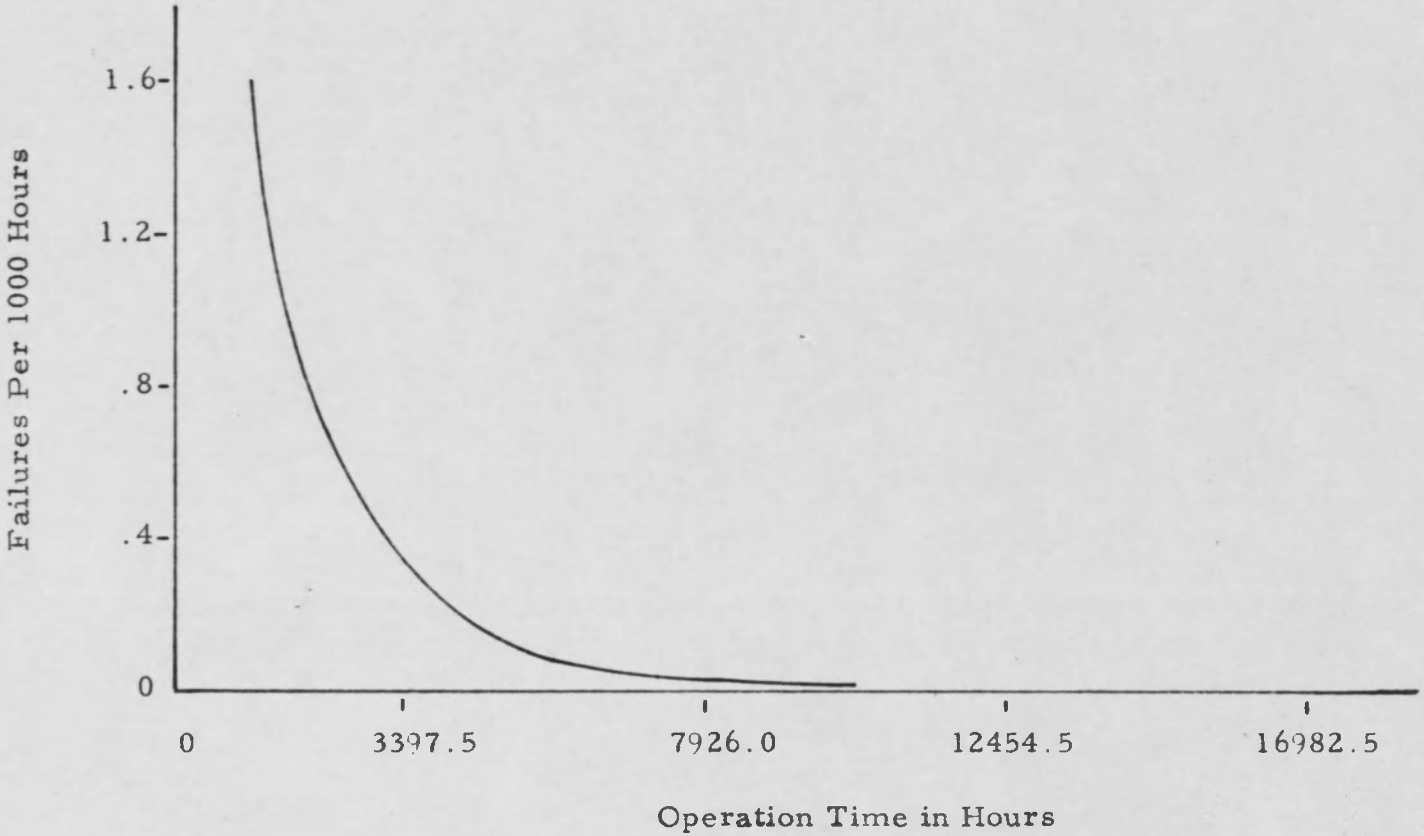

FIGURE 15. STEERING PUMP FAILURE RATE

TABLE 9
STEERING BOOSTER PUMPS
OCCURRENCE OF EXPECTED FAILURES

Range in Hours	Expected Failures in Per Cent
0 - 2300	26.9 - 59.3
2301 - 4500	19.7 - 48.5
4501 - 6800	5.7 - 24.4
6801 - 9100	1.9 - 15.6
9101 - 11300	0 - 4.8
11301 - up	0 - 4.8

the curve during the later intervals gives no evidence of wearout failures.

When confidence limits at the .99 level are placed on the mean, we could expect the average time-to-failure to lie between the limits of 3,145 hours and 4,285 hours.

Since the failure rate does not remain constant over three or more intervals, no attempt is made to predict the reliability of this component. Furthermore, since the sample distribution fits the Poisson distribution at the .99 level, it is felt that this is a more accurate estimate of the occurrence of down time.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

Table 10 shows the various components and assemblies considered in this investigation, the number of recorded failures, and whether the sample distribution fits either theoretical distribution at the .01 probability level. Whenever the sample distribution follows one of the theoretical distributions, the expected frequency of failure can be predicted for the various intervals. In cases where the sample distribution does not follow either the Poisson or normal distribution, only the mean time-to-failure can be predicted based on the assumption that the sample is a true representation of the population.

Three reasons are offered for the nonconformity of the sample distribution to one of the theoretical distributions experienced in this investigation. First, some components initially had certain design inadequacies which were responsible for relatively high early failures. These inadequacies were rectified over a period of time to give acceptable mean times-to-failure. It is obvious, therefore, that two distinct populations must be considered, and the times at which modifications took place must be known in order to separate these populations. If data were available over a long period of time, the effect of these high early failures would become negligible.

Secondly, after certain assemblies have been rebuilt, their mean times-to-failure decrease indicating inadequate overhauling techniques. Included in this area would be poor workmanship; poor judgment as to which component parts of the assembly must be replaced in addition to the defective ones to maintain the original mean time-to-failure; and finally, poor quality replacement parts.

Third, replacement of items may be made without justification, from a statistical point of view, before actual failure occurs. The mining company may prefer to replace these items during scheduled maintenance periods rather than run the risk of failure during production periods. However, this investigation indicates that some components are being replaced too early in their useful life span creating an increase in the number of infant failures.

A continuation of this investigation might take into consideration whether the replacement of components before they fail is economically feasible to maintain a desired level of equipment availability. Such a study might involve the linear programming technique, a method of operations research approach to the solution of problems of this nature.

Further statistical investigations could be carried out to determine whether significant differences of equipment failures exist between various mining operations. Also, tests of correlation may reveal whether a higher rate of failure occurs during any particular time of year.

This study is an example of one of the many ways in which the electronic digital computer can be used as a tool for the solution of routine problems facing mining companies.

TABLE 10
DISTRIBUTION COMPARISONS
FOR ALL COMPONENTS

Component	Number of Failures	Goodness of Fit	
		Poisson	Normal
Engine Assembly			
Replacements	113	No	No
Cylinder heads	219	No	No
Injectors	591	No	No
Fans	116	No	No
Valves	106	No	No
Turbo-blowers	61	No	No
Rods	50	Yes	No
Pistons	64	No	No
Bearings	71	No	No
Injector springs	846	No	No
Water pumps	335	No	No
Cam shafts	74	Yes	No
Liners	153	No	No
Transmission Assembly			
Replacements	380	No	No
Heat exchangers	61	Yes	No
Shift cables	98	No	No
Retarder cables	139	Yes	No
PTO units	78	Yes	No
Differential Assembly			
Replacements	162	No	No
Seals	27	No	No
Axles	87	No	No
Wheel bearings	68	No	No

TABLE 10--Continued

Component	Number of Failures	Goodness of Fit	
		Poisson	Normal
Planetary Assembly			
Wheel seals	206	No	No
Bull gears	80	No	No
Drive Train Group			
Cross bearings	186	No	No
Cross shafts	32	Yes	No
Drive lines	152	No	No
Cross assemblies	869	No	No
Brake System			
Compressors	18	Yes	No
Drums	153	No	No
Lining	1155	No	No
Hoist System			
Pumps	89	Yes	No
Rams	549	No	No
Suspension System			
Spring pads	692	Yes	No
Rear springs	32	Yes	No
Front springs	145	No	No
Steering System			
Rams	69	No	No
Pumps	110	Yes	No

APPENDIX A

CODING FORMAT

Column No.	
1 - 3	Equipment number
4 - 9	Date of failure
10 - 14	Hours from hour meter
17 - 18	Primary assembly
19	Subassembly or component
20	Detail component
21	Position number

COMPONENT FAILURE CODE

Major Assembly or Group	Col. 17-18 Code	Subassembly or Component	Col. 19 Code	Detail Component	Col. 20 Code
Engine	10	General Replacement	0		
		Cooling System	1	Fan	1
				Pump	2
				Radiator	3
				Lines	4
				Thermostats	5
		Cylinder Head	2	Replacement	1
				Injectors	2
				Injector springs	3
				Valves	4
				Cam shaft	5
				Rocker arms	6
				Valve springs	7

Component Failure Code (continued)

Major Assembly or Group	Col. 17-18 Code	Subassembly or Component	Col. 19 Code	Detail Component	Col. 20 Code
		Lubrication System	3	Pump	1
				Lines	2
				Filters	3
		Fuel System	4	Pump	1
				Lines	2
				Filter	3
		Miscellaneous	5	Blower	1
				Cylinder liners	2
				Connecting rods	3
				Pistons	4
				Bearings	5
				Govenor	6
Electrical	20	Generator	1		

Component Failure Code (continued)

Major Assembly or Group	Col. 17-18 Code	Subassembly or Component	Col. 19 Code	Detail Component	Col. 20 Code
		Voltage Regulator	2		
		Wiring	3		
Transmission	30	General Replacement	0		
		Charging Pump	2		
		Lines	3		
		Valves	4		
		Heat Exchanger	5		
		Shifting Cable	6		
		Air Shift	7		
		Retarder Cable	8		
		Power Take Off (PTO Unit)	9		
Drive Train	40	Drive Lines	1	Cross Shaft	6
		Yokes	2		

Component Failure Code (continued)

Major Assembly or Group	Col. 17-18 Code	Subassembly or Component	Col. 19 Code	Detail Component	Col. 20 Code
		Cross Assemblies	3		
		Bearings	4		
Differential	50	General Replacement	0		
		Axles	1		
		Seals	2		
Planetary	60	General Replacement	0		
		Bull Gear	1		
		Pins	2		
		Bearings	3		
Brakes	70	Lining	1		
		Drums	2		
		Linkage	3		
		Air Cylinders	4		

Component Failure Code (continued)

Major Assembly or Group	Col. 17-18 Code	Subassembly or Component	Col. 19 Code	Detail Component	Col. 20 Code
		Lines	5		
		Compressor	6		
		Pilot Valve	7		
Steering	80	Pump	1		
		Rams	2		
		Linkage	3		
Hoist	90	Rams	1		
		Pumps	2		
		Seals	3		
		Lines	4		
		Pins	5		
		Control Valve	6		

Component Failure Code (continued)

Major Assembly or Group	Col. 17-18 Code	Subassembly or Component	Col. 19 Code	Detail Component	Col. 20 Code
Suspension	11	Springs	1		
		Spring Pads	2		
		Bogey Plates	3		

EXAMPLE OF CODED FAILURE

802 122063 18113 108010

802	Truck number
122063	December 20, 1963
18113	Hour meter reading
10	Left-hand side
8010	Steering pump replacement

APPENDIX B

GLOSSARY OF PROGRAM NAMES

CHS	Subroutine for performing the chi-squared goodness of fit test.
FY	Function used in integration subroutine. $$\frac{1}{s(x)\sqrt{2\pi}}\, e^{-\left[\frac{(x-\bar{x})^2}{2s^2(x)}\right]}$$
INTEG	Integration subroutine using Simpson's rule of approximation.
MAIN	Program for reading data cards, printing headings, and arranging hours-to-failure in sequential order.
POSCY	Subroutine for finding time between failures from raw data information.
STAT	Subroutine for performing statistical calculations other than the chi-squared test.

```
**    COMPONENT FAILURE CALCULATIONS
*     COMPILE FORTRAN, EXECUTE FORTRAN

      FUNCTION FY(A,B,C)
      BLX = ((A-B)/C)**2
      IF(BLX-200.)10,10,20
   20 BLX = 200.
   10 FY = EXPEF(-.5*BLX)/(C*SQRTF(6.28316))
      RETURN
      END

      SUBROUTINE INTEG(ANS,A,B, AMEAN,STD)
      AO=0.0
      N=1
      D=0.0
      E=0.0
      C=FY(A,AMEAN,STD)
      G=FY(B,AMEAN,STD)
    1 P=N*2
      E=D*2.0+E
      D=0.0
      H=(B-A)/P
      MA=2*N-1
      DO15K=1,MA,2
      R=K
      X=A+R*H
      Y=FY(X,AMEAN,STD)
   15 D=D+Y
      AN=(H/3.0)*(C+(4.0*D)+(E)+G)
      IF(ABSF(AN-AO)-.0001)7,7,8
    8 AO=AN
      N=N*2
      GO TO 1
    7 ANS=AN
      RETURN
      END

      SUBROUTINE CHS(T,D)
      DIMENSION T(25),D(25),TT(25),DD(25),SCHI(25)
      COMMON NN
      DO 319 K = 1,25
      TT(K) = 0.0
  319 DD(K) = 0.0
      I=1
      DO 6 K = 1,NN
      TT(I)=TT(I)+T(K)
      DD(I) = DD(I)+ ABSF(D(K))
      IF(TT(I)-5.)1,1,5
    5 I=I+1
      GO TO 7
```

```
     1 IF(K-NN)6,3,3
     3 IM1=I-1
       TT(IM1)=TT(IM1)+TT(I)
       DD(IM1)=DD(IM1)+DD(I)
       I = IM1
       GO TO 66
     7 IF(K-NN) 6,8,8
     8 I = IM1
     6 CONTINUE
    66 CHI=0.
       DO 12 L=1,I
       IN = 1
       SCHI(L) = DD(L)*DD(L)/TT(L)
       CHI = SCHI(L)+CHI
    12 CONTINUE
       IF (SENSE LIGHT1) 18, 19
    18 I = I-1
       SENSE LIGHT1
       GO TO 20
    19 I = I-2
    20 HI=0.
       AV=0.
       BO=0.
       FO=0.
       CO = 0.
A                       XL     98,+5
A                       ZA3    I
A                       LE     CTBL(0,1)
A                       B      STMNT96
A                       ZA1    0+X98
A                       SL1    2
A                       ZST1   HI
A                       ZA1    1+X98
A                       SL1    2
A                       ZST1   AV
A                       ZA1    2+X98
A                       SL1    2
A                       ZST1   BO
A                       ZA1    3+X98
A                       SL1    2
A                       ZST1   FO
A                       ZA1    4+X98
A                       SL1    2
A                       ZST1   CO
A                       B      STMNT300
A        CTBL           DC     RDW
A                              +0151663500
A                              +0051541200
A                              +0051384100
A                              +0051270600
```

A	+0051164200
A	+0251921000
A	+0051782400
A	+0051599100
A	+0051460500
A	+0051321900
A	+0352113450
A	+0051983700
A	+0051781500
A	+0051625100
A	+0051464200
A	+0052116680
A	+0051948800
A	+0051777900
A	+0051598900
A	+0552150860
A	+0052133880
A	+0052110700
A	+0051923600
A	+0051728900
A	+0652168120
A	+0052150330
A	+0052125920
A	+0052106450
A	+0051855800
A	+0752184750
A	+0052166220
A	+0052140670
A	+0052120170
A	+0051980300
A	+0852200900
A	+0052181680
A	+0052155070
A	+0052133620
A	+0052110300
A	+0952216660
A	+0052196790
A	+0052169190
A	+0052146840
A	+0052122420
A	+1052232090
A	+0052211610
A	+0052183070
A	+0052159870
A	+0052134420
A	+1152247250
A	+0052226180
A	+0052196750
A	+0052172750
A	+0052146310

A	+1252262170
A	+0052240540
A	+0052210260
A	+0052185490
A	+0052158120
A	+1352276880
A	+0052254720
A	+0052223620
A	+0052198120
A	+0052169850
A	+1452291410
A	+0052268730
A	+0052236850
A	+0052210640
A	+0052181510
A	+1552305780
A	+0052282590
A	+0052249960
A	+0052223070
A	+0052193110
A	+1652320000
A	+0052296330
A	+0052262960
A	+0052235420
A	+0052204650
A	+1752334090
A	+0052309950
A	+0052275870
A	+0052247690
A	+0052216150
A	+1852348050
A	+0052323460
A	+0052288690
A	+0052259890
A	+0052227600
A	+1952361910
A	+0052336870
A	+0052301440
A	+0052272040
A	+0052239000
A	+2052375660
A	+0052350200
A	+0052314100
A	+0052284120
A	+0052250380
A	+2152389230
A	+0052363430
A	+0052326710
A	+0052296150
A	+0452132770

```
A                    +0052261710
A                    +2252402890
A                    +0052376590
A                    +0052339240
A                    +0052308130
A                    +0052273010
  300 IF(CHI-HI)29,29,49
   29 IF(SENSE LIGHT1) 601,602
  601 PRINT 603
  603 FORMAT(/5X,32HFITS POISSON WITH .99 CONFIDENCE)
      GO TO 770
  602 PRINT 129
  129 FORMAT (/5X,31HFITS NORMAL WITH .99 CONFIDENCE)
      GO TO 770
   49 IF(CHI-AV)28,28,48
   28 IF(SENSE LIGHT1) 604, 605
  604 PRINT 606
  606 FORMAT(/5X,32HFITS POISSON WITH .98 CONFIDENCE)
      GO TO 770
  605 PRINT 128
  128 FORMAT (/5X,31HFITS NORMAL WITH .98 CONFIDENCE)
      GO TO 770
   48 IF(CHI-BO) 27,27,47
   27 IF(SENSELIGHT1)607,608
  607 PRINT 609
  609 FORMAT(/5X,32HFITS POISSON WITH .95 CONFIDENCE)
      GO TO 770
  608 PRINT 127
  127 FORMAT (/5X,31HFITS NORMAL WITH .95 CONFIDENCE)
      GO TO 770
   47 IF(CHI-FO)26,26,247
   26 IF(SENSE LIGHT 1) 610,611
  610 PRINT 612
  612 FORMAT(/5X,32HFITS POISSON WITH .90 CONFIDENCE)
      GO TO 770
  611 PRINT 126
  126 FORMAT (/5X,31HFITS NORMAL WITH .90 CONFIDENCE)
      GO TO 770
  247 IF(CHI-CO) 248,248,249
  248 IF(SENSE LIGHT 1) 613,614
  614 PRINT 250
  250 FORMAT(/5X,31HFITS NORMAL WITH .80 CONFIDENCE)
      GO TO 770
  613 PRINT 251
  251 FORMAT(/5X,32HFITS POISSON WITH .80 CONFIDENCE)
      GO TO 770
  249 IF(SENSE LIGHT 1) 252, 253
  252 PRINT 254
  254 FORMAT(/5X,38HDATA DOES NOT FIT POISSON CURVE AT .80)
      GO TO 770
```

```
253 PRINT 255
255 FORMAT(/5X,37HDATA DOES NOT FIT NORMAL CURVE AT .80)
    GO TO 770
 96 PRINT 196
196 FORMAT(/5X,18HVALUE NOT IN TABLE)
770 PRINT    771, I
771 FORMAT (/5X,19HDEGREES OF FREEDOM= I2)
    PRINT 401
401 FORMAT(/5X,36HINDIVIDUAL CHI SQUARED CONTRIBUTIONS)
    PRINT 402,(TT(L),SCHI(L), L = 1,IN)
402 FORMAT( 5X,1PE12.5,3H  = 1PE12.5)
    PRINT 400, CHI
400 FORMAT(/5X,25HCUMULATIVE CHI SQUARED = 1PE12.5)
    RETURN
    END

    SUBROUTINE STAT(CIM, N, ML, CHB)
   0DIMENSION CLB(25), CHB(25),CM(25),FX(25),CFX(25),
   1SFX(25),TFR(25),DIS(25),HRS(2000),FR(25),PR(25),E(25),
   2PDIS(25)
    COMMON NN, HRS, MP
    IF(SENSE LIGHT 1)600,600
600 FNN = NN
    LJ = 1
    FN = N-ML
    CB = CIM/FNN
    BX = 0.
    DX = 0.
    SX=0.
    DO 611 K = 1,25
611 FX(K) = 0.0
    SFX(1)=0.
    T=0.
    P=0.
    TEMP = .5
    DO 217 K = 1,NN
    FK=K
    CLB(K) = TEMP
    CT=CB*FK+1.5
    IT=CT
    CT=IT
    CHB(K)=CT+.5
    CM(K)=(CHB(K)-CLB(K))/2.+CLB(K)
    DO 3J=1,N
    IF(CHB(K)-HRS(J))3,4,4
  4 HRS(J)=99999.
    FX(K)=FX(K)+1.
  3 CONTINUE
    CFX(K)=FX(K)*CM(K)
    SX=SX+CFX(K)
```

```
      T=T+FX(K)
      SFX(K)=T
      TEMP=CHB(K)
      IF(CLB(K)-.5)217,218,217
  218 CLB(K)=0.
  217 CONTINUE
      AMEAN=SX/SFX(NN)
      CE = CHB(1)-CLB(1)
      DO 21 K=LJ,NN
   21 P=P+(CM(K)-AMEAN)**2
      WMEAN = AMEAN/CE
      VAR=P/FN-1.
      STD=SQRTF(VAR)
      PRINT 666
  6660FORMAT(//6X,14HCLASS BOUNDARY,5X,5HCLASS,7X,6HSAMPLE,
     17X,10HCUMULATIVE,7X,6HNORMAL,9X,6HNORMAL,9X,7HPOISSON,
     27X,7HPOISSON)
      PRINT 667
  667 FORMAT(6X,12HLOW      HIGH,7X,4HMARK,7X,9HFREQUENCY,6X,
     19HFREQUENCY,6X,9HFREQUENCY,5X,10HDIFFERENCE,6X,
     29HFREQUENCY,5X,10HDIFFERENCE)
      SDIS=0.
      STS=0.
      SPS=0.
      SPDIS = 0.
      PROD = 1.0
      DELT = -3.9*STD
      BETA = CHB(1)
      DO 5 K = LJ,NN
      CALL INTEG(A,DELT,BETA,AMEAN,STD)
      TFR(K) = A*FN
      BETA = CHB(K+1)
      DELT = CHB(K)
      DIS(K)=FX(K)-TFR(K)
      STS=STS+TFR(K)
      SDIS=SDIS+DIS(K)
      FK = K
      PROD = PROD*FK
      EXXP = EXPEF(-WMEAN)
      PR(K) = ((WMEAN**K)/PROD)*EXXP
    5 CONTINUE
      DO 6 K = LJ, NN
      KP1 = K +1
      E(1) = FN*EXXP+FN*PR(1)
      E(KP1) = PR(KP1)*FN
      PDIS(K) = FX(K)-E(K)
      SPS = SPS+E(K)
      SPDIS = SPDIS+PDIS(K)
    60PRINT334,CLB(K),CHB(K),CM(K),FX(K),SFX(K),TFR(K),
     1DIS(K),E(K),PDIS(K)
```

```
334 FORMAT(3F10.1,1P6E15.4)
    PRINT 335, SFX(NN), STS, SDIS,SPS,SPDIS
335 FORMAT(30X,1PE15.4,15X,1P4E15.4)
    PRINT221,AMEAN
221 FORMAT(/24X,6HMEAN =1PE15.4)
    PRINT222,VAR
222 FORMAT(5X,10HVARIANCE= 1PE10.2/)
    PRINT 223,STD
223 FORMAT(5X,20HSTANDARD DEVIATION= 1PE10.2)
    CALL CHS(TFR,DIS)
    SENSE  LIGHT 1
    CALL CHS(E,PDIS)
    FMP = MP
    PRINT 903
903 FORMAT(//5X,5HCLASS,7X,7HFAILURE)
    PRINT 904
904 FORMAT(   6X,4HMARK,10X,4HRATE)
    DO 906 K = LJ,NN
    IF(FX(K))901,901,902
901 FR(K) = 0.
    GO TO 899
902 FR(K) = FX(K)/(FMP*CM(K))
899 PRINT 907, CM(K),FR(K)
907 FORMAT(F10.1,1PE15.4)
906 CONTINUE
701 RETURN
    END

    SUBROUTINE POSCY(L,LC,TIM,DTIM)
    IF(SENSE LIGHT 2)18,10
 18 SENSE LIGHT 2
    IF(SENSE LIGHT 3)22,24
 24 IF(SENSE LIGHT 4)25,21
 22 TIM1 = TIM
    TIM2 = TIM
    TIM3 = TIM
    TIM4 = TIM
    TIM5 = TIM
    TIM6 = TIM
    TIM7 = TIM
    DTIM = 0.
    GO TO 19
 25 TEM1 = TIM
    TEM2 = TIM
    TEM3 = TIM
    TEM4 = TIM
    TEM5 = TIM
    TEM6 = TIM
    TEM7 = TIM
    DTIM = 0.
```

```
      GO TO 19
   10 TIM1=0.
      TIM2=0.
      TIM3=0.
      TIM4=0.
      TIM5=0.
      TIM6=0.
      TIM7=0.
      TEM1=0.
      TEM2=0.
      TEM3=0.
      TEM4=0.
      TEM5=0.
      TEM6=0.
      TEM7=0.
   21 SENSE LIGHT 2
      LC=LC+1
      IF(L)11,1,11
   11 GO TO (1,2),L
    1 GO TO(3,4,5,6,7,8,31),LC
    3 DTIM=TIM-TIM1
      TIM1=TIM
      GO TO 19
    4 DTIM=TIM-TIM2
      TIM2=TIM
      GO TO 19
    5 DTIM=TIM-TIM3
      TIM3=TIM
      GO TO 19
    6 DTIM=TIM-TIM4
      TIM4=TIM
      GO TO 19
    7 DTIM=TIM-TIM5
      TIM5=TIM
      GO TO 19
    8 DTIM=TIM-TIM6
      TIM6=TIM
      GO TO 19
   31 DTIM=TIM-TIM7
      TIM7=TIM
      GO TO 19
    2 GO TO(12,13,14,15,16,17,41),LC
   12 DTIM=TIM-TEM1
      TEM1=TIM
      GO TO 19
   13 DTIM=TIM-TEM2
      TEM2=TIM
      GO TO 19
   14 DTIM=TIM-TEM3
      TEM3=TIM
```

```
      GO TO 19
   15 DTIM=TIM-TEM4
      TEM4=TIM
      GO TO 19
   16 DTIM=TIM-TEM5
      TEM5=TIM
      GO TO 19
   17 DTIM=TIM-TEM6
      TEM6=TIM
      GO TO 19
   41 DTIM=TIM-TEM7
      TEM7=TIM
   19 RETURN
      END

     0DIMENSION HRS(2000),ISYS(4),ISUB(4),ISUBN(4),
     1AHRS(2000),CCP(25)
      COMMON NN, HRS,MP
  333 READ 100,N,NN,MD,MP,ISYS,ISUB,ISUBN
  100 FORMAT(I4,I2,I1,I3,4A5,4A5,4A5)
      PRINT 21, ISYS
   21 FORMAT(1H1, 50X, 4A5)
      PRINT 111,ISUB
  111 FORMAT(5X,4A5)
   30 PRINT 36, ISUBN
   36 FORMAT(5X, 4A5)
  301 ITE=0
      HV=0.
      MD = MD +1
      DO 88 J=1,N
      READ 101,IK,HP,LOC,M,LC,ID,IDD,IC
  101 FORMAT(I3,6X,F5.0,2I1,I2,3I1)
      IF(SENSE LIGHT3)1002,1002
 1002 IF(SENSE LIGHT4)1003,1003
 1003 GO TO (3,1000,1001),MD
 1000 SENSE LIGHT 3
      GO TO 3
 1001 SENSE LIGHT 4
    3 IF(SENSE LIGHT 3)4,32
   32 LD = LC+ID+IDD
      IF(LD-10)4,20,31
   31 IF(SENSE LIGHT 4)4,33
   33 IF(LD-13)4,20,4
   20 GO TO (1,2),LOC
    1 SENSE LIGHT 3
      GO TO 4
    2 SENSE LIGHT 4
    4 IF(LC-11)10,11,12
   11 IC = M
      GO TO 10
```

```
 12 LC = LC/10
    GO TO (10,10,10,13,11,11,11,11,10), LC
 13 M = M+1
    GO TO (15,15,14,16), M
 14 M = 1
    GO TO 15
 16 M = 2
 15 LOC = M
    IC = IDD
 10 IF(ITE-IK)300,302,300
300 ITE=IK
    IF(SENSE LIGHT 2)302,302
302 CALL POSCY(LOC,IC,HR,HRS(J))
    IF(HV-HRS(J))421,421,88
421 HV=HRS(J)
 88 CONTINUE
    NM1 = N-1
    DO 601 I = 1,NM1
    IP1 = I+1
    DO 601 J = IP1,N
    IF(HRS(I)-HRS(J))601,601,602
602 TEMP = HRS(I)
    HRS(I) = HRS(J)
    HRS(J) = TEMP
601 CONTINUE
    M = 0
    DO 603 J = 1,N
    AHRS(J) = HRS(J)
    CCB(K) = 0.
    IF(HRS(J))603,608,603
608 HRS(J) = 99999.
    M = M+1
603 CONTINUE
    IF(SENSE SWITCH 3 ) 92, 94
 90 HV = 0.
    M = 0
    DO 604 J = 1,N
    HRS(J) = AHRS(J)
    IF(HRS(J)-HV)604,605,605
605 HV = HRS(J)
604  CONTINUE
 92 DO 606 J = 1,N
    IF(HRS(J)-CCB(1))607,607,606
607 HRS(J) = 99999.
    M = M+1
606 CONTINUE
    PRINT 93
 93 FORMAT(1H1)
 94 CALL STAT(HV,N,M,CCB)
    IF(SENSE SWITCH 3)89,612
```

```
 89 TYPE 91
 91 FORMAT(43HALT. SWITCH 3 OFF PLEASE. PRESS START TO GO)
    PAUSE
209 GO TO 333
612 TYPE 613
613 FORMAT(43HALT. SWITCH 3 ON PLEASE- PRESS START TO GO )
    PAUSE
    IF(SENSE SWITCH 3)90,209
    END
```

APPENDIX C

BOOSTER PUMP

CLASS BOUNDARY LOW	HIGH	CLASS MARK	SAMPLE FREQUENCY	CUMULATIVE FREQUENCY	NORMAL FREQUENCY	NORMAL DIFFERENCE	POISSON FREQUENCY	POISSON DIFFERENCE
0.0	2265.5	1133.0	4.6000E 01	4.6000E 01	2.6841E 01	1.9159E 01	5.7115E 01	-1.1115E 01
2265.5	4529.5	3397.5	3.5000E 01	8.1000E 01	4.6399E 01	-1.1399E 01	2.8550E 01	6.4502E 00
4529.5	6793.5	5661.5	1.4000E 01	9.5000E 01	3.0100E 01	-1.6100E 01	1.5395E 01	-1.3953E 00
6793.5	9058.5	7926.0	7.0000E 00	1.0200E 02	6.2456E 00	7.5440E-01	6.2263E 00	7.7367E-01
9058.5	11322.5	10190.5	5.0000E 00	1.0700E 02	4.0628E-01	4.5937E 00	2.0145E 00	2.9855E 00
11322.5	13586.5	12454.5	1.0000E 00	1.0800E 02	8.6743E-03	9.9133E-01	5.4315E-01	4.5685E-01
13586.5	15850.5	14718.5	0.0000E 00	1.0800E 02	5.6453E-05	-5.6453E-05	1.2552E-01	-1.2552E-01
15850.5	18114.5	16982.5	2.0000E 00	1.1000E 02	1.1089E-07	2.0000E 00	2.5383E-02	1.9746E 00
			1.1000E 02		1.1000E 02	-1.1215E-03	1.0999E 02	5.4363E-03

MEAN = 3.6650E 03

VARIANCE= 4.07E 06

STANDARD DEVIATION= 2.02E 03

DATA DOES NOT FIT NORMAL CURVE AT .80

DEGREES OF FREEDOM= 2

INDIVIDUAL CHI SQUARED CONTRIBUTIONS
2.68412E 01 = 1.36752E 01
4.63989E 01 = 2.80037E 00
3.01004E 01 = 8.61196E 00
6.66061E 00 = 1.04416E 01

CUMULATIVE CHI SQUARED = 3.55291E 01

FITS POISSON WITH .99 CONFIDENCE

DEGREES OF FREEDOM= 3

INDIVIDUAL CHI SQUARED CONTRIBUTIONS
5.71146E 01 = 2.16293E 00
2.85498E 01 = 1.45728E 00
1.53953E 01 = 1.26451E-01
8.93488E 00 = 4.46496E 00

CUMULATIVE CHI SQUARED = 8.21162E 00

CLASS MARK	FAILURE RATE
1133.0	1.4000E-03
3397.5	3.5523E-04
5661.5	8.5270E-05
7926.0	3.0454E-05
10190.5	1.6919E-05
12454.5	2.7687E-06
14718.5	0.0000E 00
16982.5	4.0610E-06

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