ACCELERATED LIFE TESTING OF POROUS METAL BEARINGS

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Stephen Joseph Peterson

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ACCELERATED LIFE TESTING OF POROUS

METAL BEARINGS

Approved:

David M. Sanborn, Chairman

Ward O. Winer

Wilton King

Date approved by Chairman: May 28, 1975

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SUMMARY

The porous metal bearing has been widely used for many years, especially in the consumer appliance industry. Although this type of bearing has experienced widespread use, only limited technical information is available. Consumer appliances, which often employ these bearings, require extensive testing before they can be placed on the market. Because life testing is very time consuming, a reliable and accurate method of accelerated life testing would be a valuable tool for users of porous metal bearings. The purpose of this research was to investigate the feasibility of accelerating porous metal bearing life tests.

Although there are many possible methods of accelerated life testing, this research concentrated on two basic approaches. The first was to compare the effect of continuous bearing loading with noncontinuous loading. This effect is important because many appliances and machines are not operated continuously. In addition, appliances often contain cycles during which some components are not in operation. For this reason, the life testing of machines and components, such as the porous metal bearing, can be accelerated through continuous operation if the data can be correlated to actual conditions.

The second approach was to monitor the bearing

operating temperatures. These temperatures were plotted versus the bearing test time, establishing temperature-life curves. If a repeatable temperature-life curve can be recognized, bearing failures may be predicted by knowing when the failure process begins rather than ends.

The research was entirely experimental and most of the effort involved the design and building of test equipment. The data sample obtained in this research was small and should be used primarily as guidance for future research.

The results give some positive indications that the proposed test methods may be feasible. However, further research will be necessary to establish these methods as acceptable test procedures.

CHAPTER I

INTRODUCTION

Background

The problem of life testing of machinery and its components is one shared by many industries. This testing is very time consuming and can delay approval of new designs. In particular the consumer appliance industry has the problem of completing life testing before new products can be introduced in the marketplace. One component which is widely used in this industry is the porous metal bearing. This research explores the feasibility of accelerating the life testing of this bearing.

History of the Problem

The particular bearing used in this investigation is the upper center post bearing found in Whirlpool automatic washing machines. This is one of the bearings which supports the load generated by unbalance forces during the spin cycle of the machine. At present two methods of life testing are available. First, field testing can be used to obtain long range performance data under actual conditions. This test requires approximately ten years to reach the design life of the bearing. (Design life is defined as 5000 machine cycles which is equal to about 1000 hours of bearing operation under load.) Second the entire machine can be run continuously in the laboratory under simulated washing conditions. This test will reach the design life in approximately 20 weeks. However, this still presents a long delay to a designer waiting for performance feedback. Another limitation of current testing is that no data is recorded other than elapsed time to total bearing failure.

A literature search found only limited information available in porous bearing research and design [1,2,3,4]. Since only general design guidelines are available, the importance of life testing to the designer is imperative for mass produced consumer appliances. Successful accelerated testing procedures would aid designers utilizing porous bearings by providing more responsive test feedback.

Proposed Research

There are many types of accelerated test procedures. This research is concerned with two basic approaches. The first approach is related to the operational nature of the machine. In the washing machine the bearing is under load only during the spin cycle. Specifically, the bearing is under load during twelve minutes of the total forty minute machine operation. If the bearing were removed from the machine and tested under simulated conditions, it could be run continuously. It is not known, however, what effect, if any, the start-stop operation and thermal cycling will have on the life of the bearing. A major objective of this research was to compare bearing operation under continuous and noncontinuous load conditions. If a correlation between these load conditions can be established, testing time can be reduced approximately 70 percent.

The second approach was to measure the operating temperature of the bearing in order to monitor the condition of the bearing. Here it is hoped that by establishing a correlation of temperature versus bearing life, failure can be predicted long before it occurs. If this technique can be used in conjunction with continuous testing, the total testing time may be reduced even further, by noting when the failure process begins rather than ends.

The research was entirely experimental and conducted using one specific type of bearing. However, the conclusions may be applicable to other porous bearings and to accelerated testing in general. It should be noted that the emphasis of this research was not to accumulate specific accelerated test results, but to establish the feasibility of the proposed accelerated testing methods.

CHAPTER II

TEST EQUIPMENT DESIGN AND INSTRUMENTATION

General Concept

The major design objective was to build a machine which simulated the type of loading experienced during the spin cycle in the washing machine, and in addition, one that had the flexibility necessary for experimentation. The bearing loads are caused by the unbalance forces which result from uneven distribution of clothes in the washing machine during the high speed spin cycle. This type of loading is unconventional because the loading vector rotates with respect to the bearing at the shaft velocity. (Normally the direction of the loading vector remains constant as in a motor shaft bearing.)

The unbalance forces were simulated in the test machine by an offset weight rotating at the same speed used in the spin cycle. This weight was fixed to a shaft which rotated with respect to two fixed bearings. This basic configuration, which includes the weight fixed to the shaft and the two bearings, will be referred to as a test unit. This test unit is shown in Figure 1. In order to obtain overall balance of the test stand, four test units were combined using flexible couplings. This combination of test

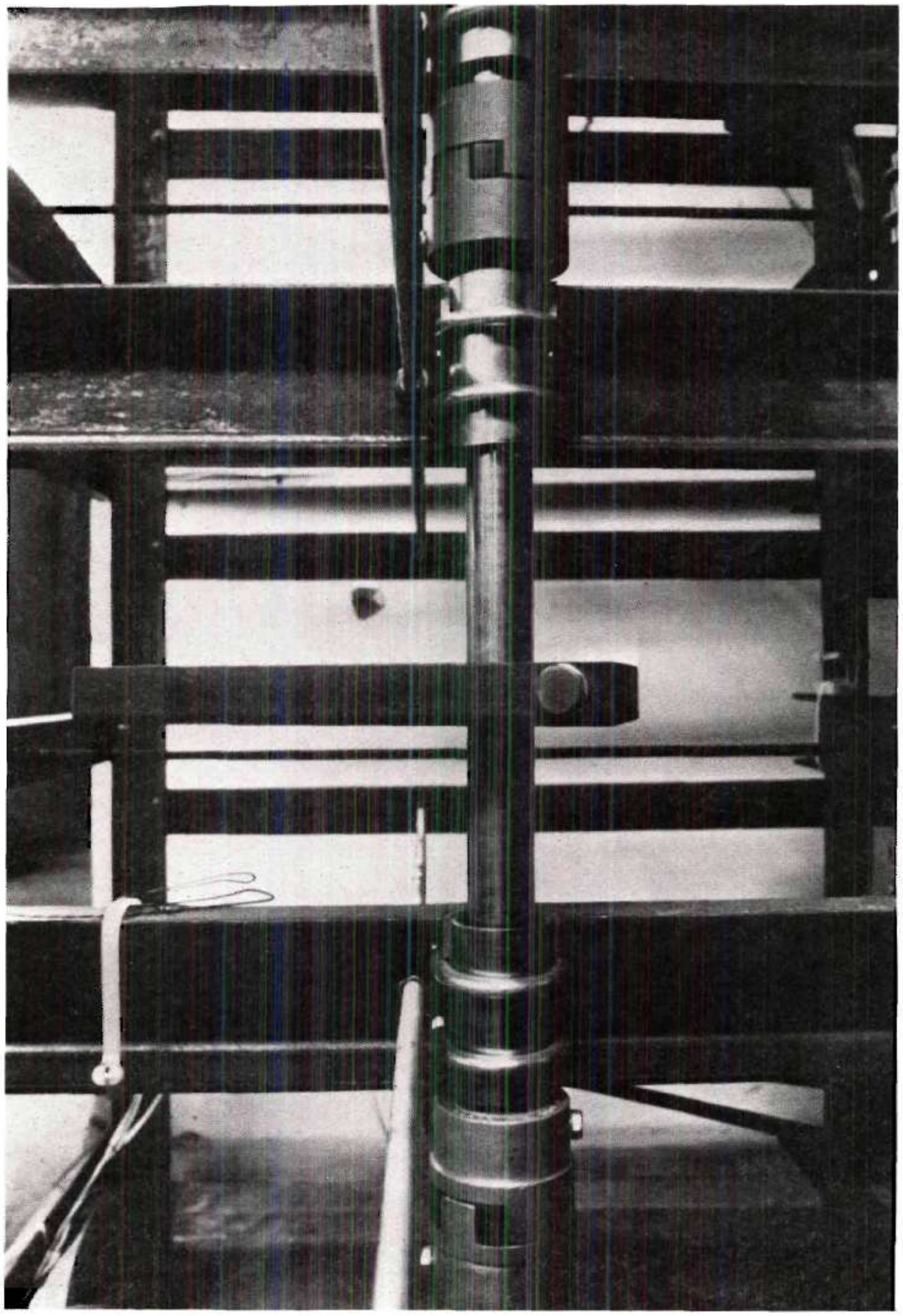


Figure 1. Test Unit

units will be referred to as a test system and is shown in Figure 2. The complete test machine contains four test systems which are combined and supported by a steel superstructure. The photographs in Figures 3 and 4 show two views of the test machine. The machine is able to run 32 bearings simultaneously. A large sampling is desired when testing bearings because the life and performance characteristics exhibit large amounts of scatter. The machine is compactly designed, requiring only 25 square feet of floor area and a total volume of 250 cubic feet. Most of the functional parts are taken directly from the Whirlpool machine with minor modifications in some cases. Part replacement and servicibility is good.

While the machine was specifically designed for these tests and one particular bearing, it could easily be adapted to different experiments. The shaft speed can be changed by using different pulley combinations or using a different motor. The loading due to the offset weight can be changed by repositioning the weight or by modifying its size. By designing a special bearing mount many different bearings, including rolling element types, could be tested with this equipment.

Structural Design

The machine frame and support structure were built entirely from steel members. The basic structural design

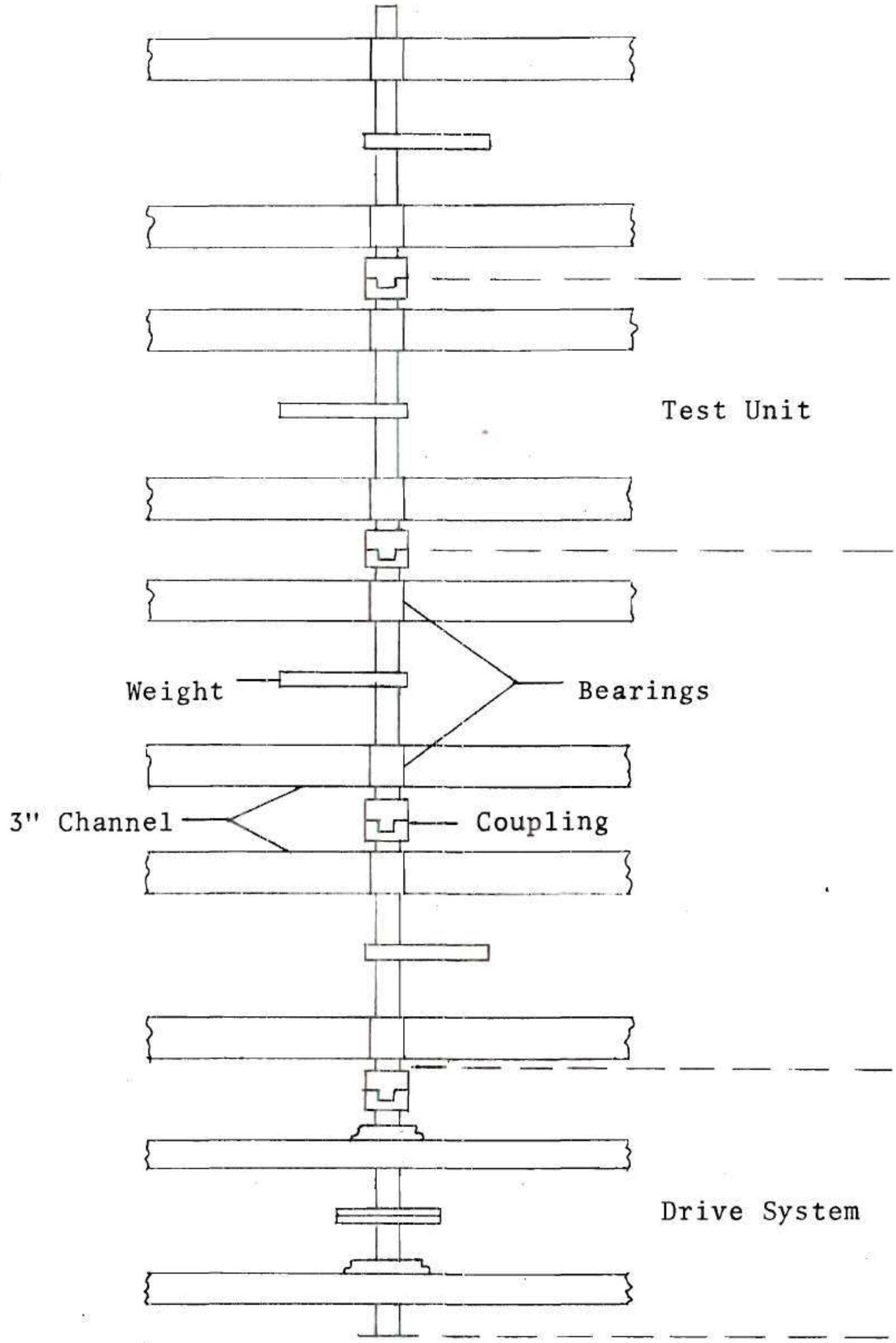


Figure 2. Test System

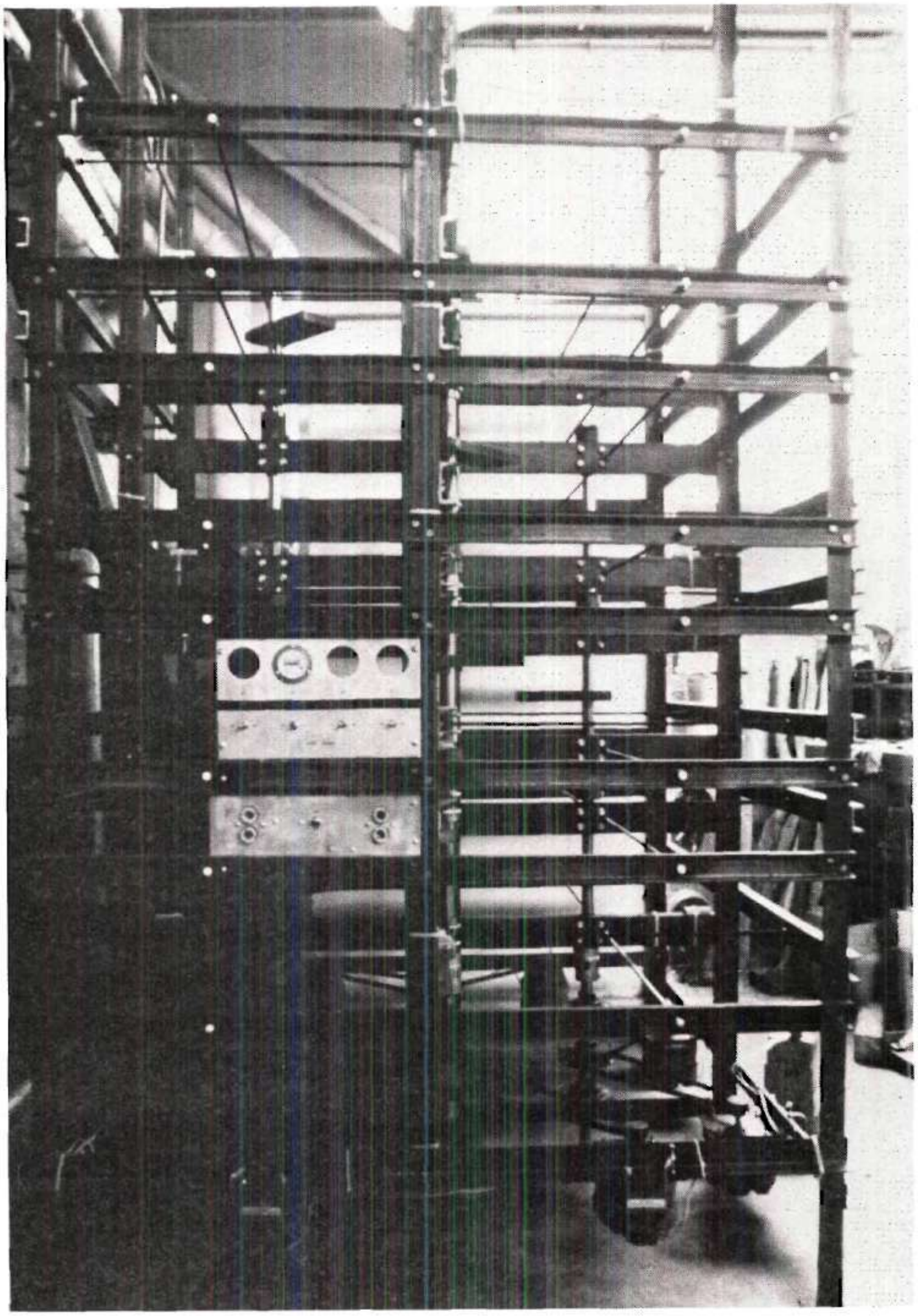


Figure 3. Photograph of Test Machine--Front View

Figure 4. Photograph of Test Machine--Front Angle View

can be seen in the photographs in Figures 3 and 4. The design employs four types of structural members. The outer frame is constructed from two inch bar channel horizontal members and two inch angle vertical support members. The inside members, which contain the bearing mounts, are made from three inch structural channel. These three inch channels are connected to the outer frame with 3/8 inch threaded rod. These rods were used to adjust bearing alignment and also to add rigidity in the direction perpendicular to the three inch channels. Figure 5 shows the plane view of one horizontal level of the frame. The total structure contains eight horizontal planes similar to this which are supported by the two inch angles. The entire structure is bolted using standard 3/8 inch hex bolts and lock washers. A tightening torque of 22 ft-lbs was used. The overall dimensions of the frame are 5 feet by 5 feet by 10 feet.

Mechanical Considerations

Simulation of the clothes unbalance force is accomplished by the rotation of an offset weight. The magnitude of unbalance force transmitted to the upper center post bearing was given by Whirlpool to be 100 pounds. Since the test unit contains two bearings the total force needed is 200 pounds. The magnitude and offset distance of the weight are calculated from:

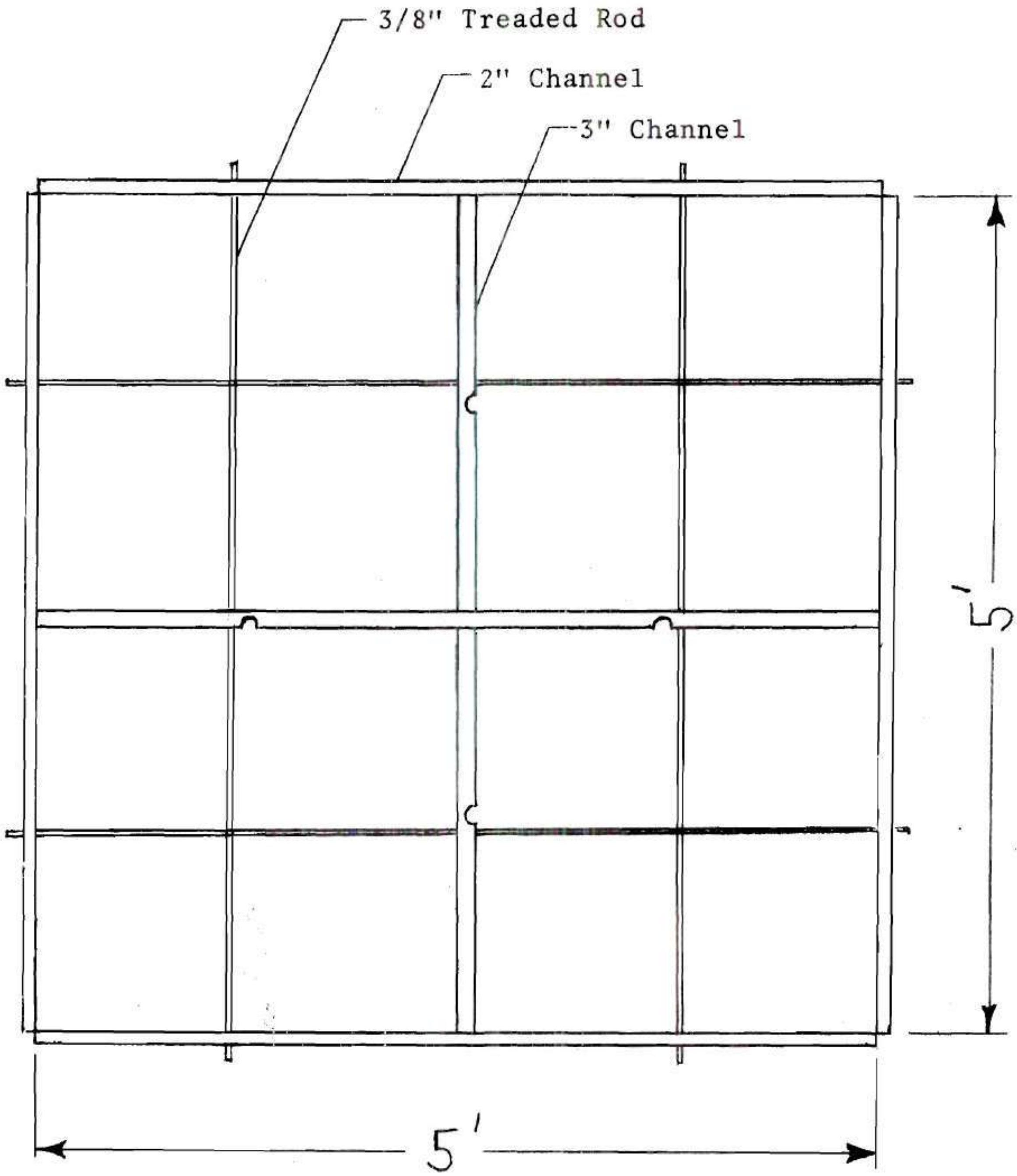


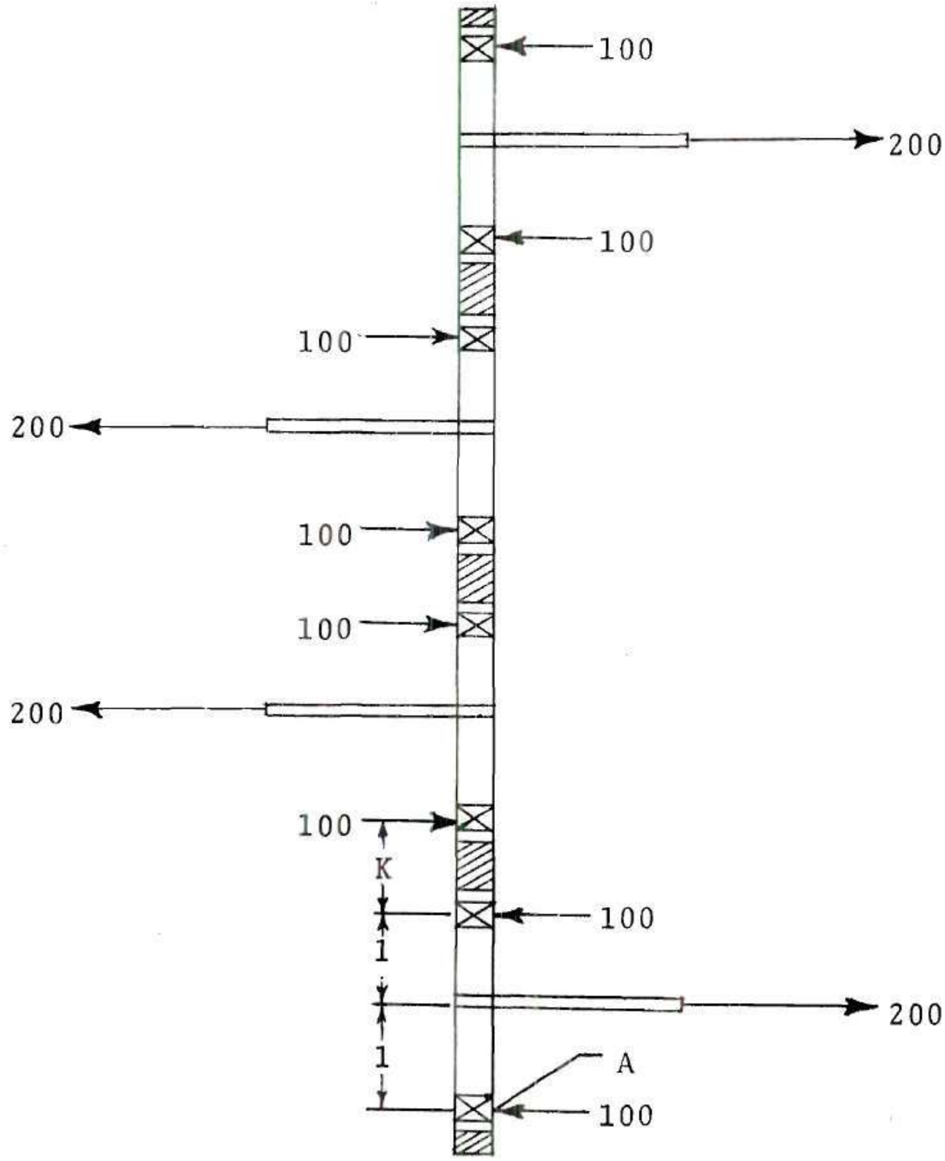
Figure 5. Plan View of Support Structure--One Level

$$F = me\omega^2/gc$$

where F and ω are known and gc is a constant. The quantity (me) can be found leaving the selection of the mass and offset up to the designer. For simplicity and ease of fabrication a one inch by four inch steel flat was used as the offset weight.

Because of the large unbalance forces being generated, it was necessary to counterbalance these forces to maintain overall machine balance and prevent excessive vibration. This was accomplished by combining four test units into a single test system. Figure 6 shows how the test units are arranged to give the sum of the forces and moments equal to zero. The test units are combined with flexible couplings which will transmit the rotational torque, but will not transmit bending moment or shear force. This assures the test units will remain independent.

The final mechanical design necessary is the drive system. Each test system has an independent drive. Figure 7 shows a photograph of the drive system and its components. Two motors are connected to the drive shaft by V-belts through speed reduction pulleys. The drive shaft is supported in two positions by ball bearings (see Figure 8) which carry the thrust loads of the system due to gravity and also the radial driving force of the motors. The drive shaft is connected to the rest of the test system through a



$$\Sigma F = -100+200-100+100-200+100+100-200+100-100+200-100=800-800=0$$

$$\Sigma M_A = 200(1)-100(2)+100(2+K)-200(3+K)+100(4+K)+100(4+2K)-200(5+2K)+100(6+2K)-100(6+3K)+200(7+3K)-100(8+3K) = 3200+1200K-3200-1200K = 0$$

Figure 6. Arrangement of Unbalance Weights for Sum of Forces and Moments Equal to Zero

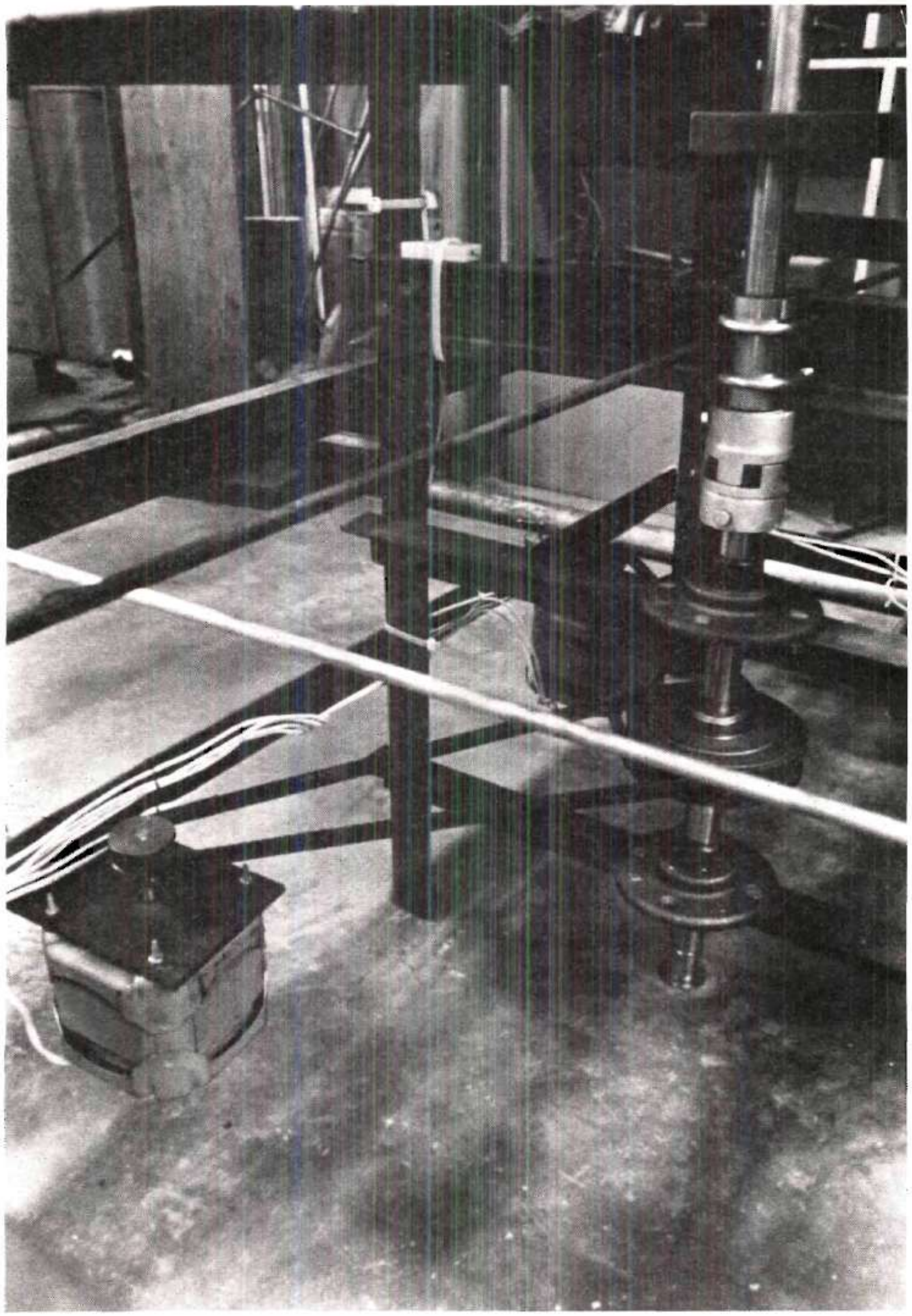


Figure 7. Drive System Components

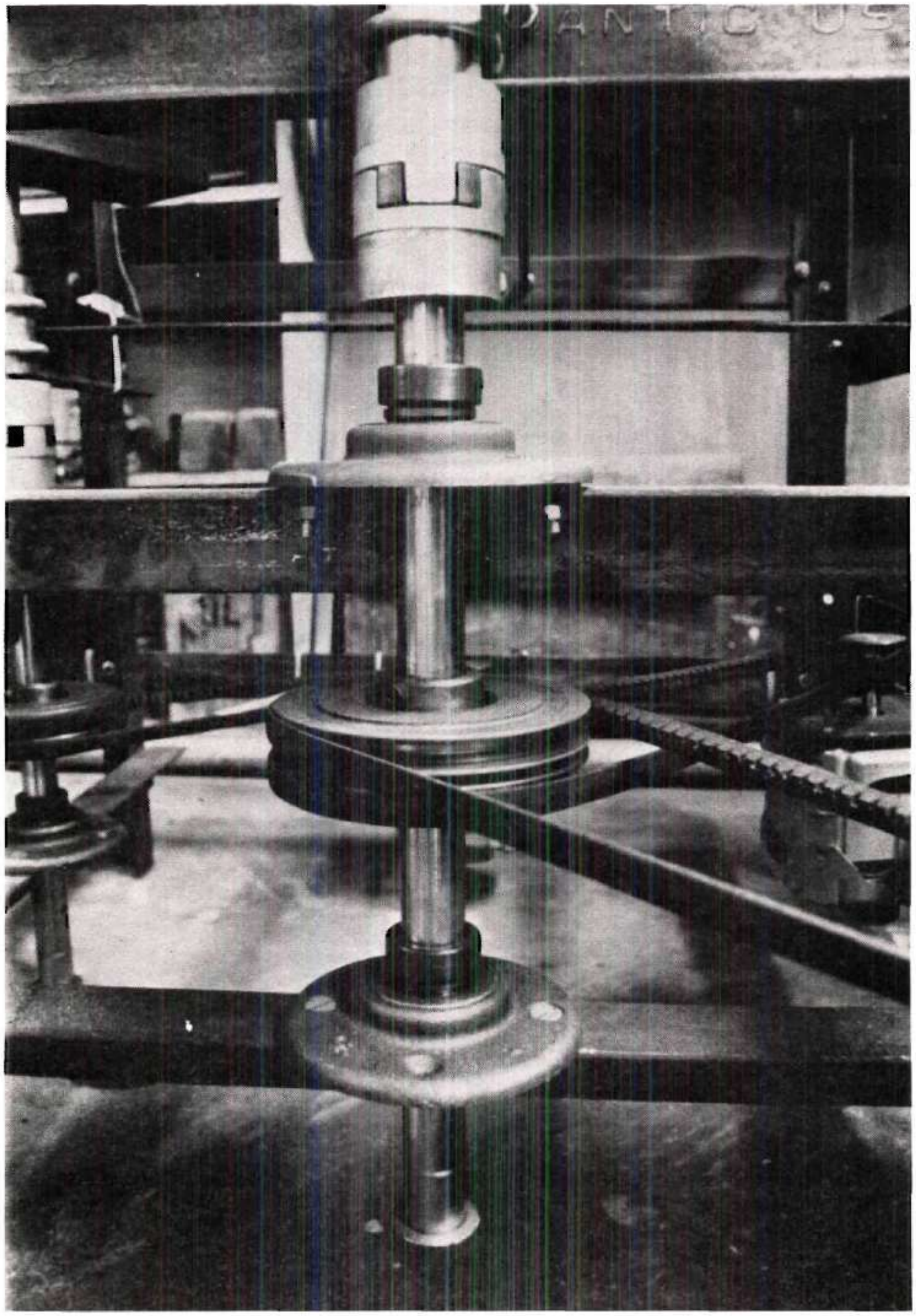


Figure 8. Drive System and Support Bearings

flexible coupling so that only the rotational torque will be transmitted to the test units.

Electrical Control and Instrumentation

Each test system control consists of an on-off switch, a time delay fuse and an elapsed time indicator. The time delay fuse protects the motors from overload due to bearing failure, but allows short overload during start up. The elapsed time indicator records the total test time of each system. Test system #2 which was used for the noncontinuous test, was controlled by a pair of relays and a repeat cycle timer. The timer was adjusted so that the system ran for 40 minutes and then was off for 20 minutes. This cycle was selected to allow the bearing temperature to return to ambient conditions as it would when a washing machine is not in use.

Temperature was measured using chromel-alumel thermocouples with an electronic temperature reference junction. They were inserted in the bearing through a .056 inch hole drilled near the outer edge of the bearing. The thermocouple is located in the center of the bearing longitudinally and about 1/8 inch from the bearing surface. The thermocouple records a bulk bearing temperature rather than the bearing interface temperature. However, this is not critical as the temperature changes and the relative magnitudes are the important parameters.

The data was continuously monitored on a Leeds and Northrup Speedomax multi-point recorder. The recorder print circuit was controlled by the repeat cycle timer in the noncontinuous test system. Each bearing temperature was recorded once each hour.

CHAPTER III

RESULTS AND ANALYSIS

Introduction

The data was collected during a six week test period. Temperature data was obtained from 16 of the bearings which contained thermocouples. The other 16 bearings did not contain thermocouples in order to test for any effects caused by implanting the thermocouples into the bearings. The total time accumulated for each test system ranged from 500 to 900 hours. Of the 32 bearings which began the test, 13 failed. Since the bearing design life is 1000 hours, this is a large number of premature failures. This high premature failure rate is attributed to bearing misalignment problems which were encountered, primarily, in two of the four test systems. This problem was anticipated because the initial bearing alignment was very difficult. In two of the test systems some of the test units could not be adjusted to completely correct the misalignment. The data obtained from these systems is not used in making load system comparisons, but some of the individual data is analyzed. Determining the cause of a failure was based on an examination of the worn bearing after it was removed from the machine. The failure was attributed to misalignment if the bearing displayed an eccentric wear pattern. Uneven wear would be caused by directional overloading which results from misalignment with the shaft. When a failure occurred, the test unit was disassembled and both bearings were removed and inspected. If the good bearing was not damaged as a result of the failure it was returned to the test unit. However, in many cases the failure progressed so far that subsequent shaft wobble and heat transfer through the shaft damaged the other bearing in that test unit.

Bearing test data generally exhibits a wide range of scatter. Accurate data evaluation can usually be obtained through statistical analysis, but it was not used in this research because the data sample was too small. The data analysis is a discussion of the results obtained and their relation to the proposed testing methods. The use of quantitative analysis has been limited because of the small data sample and the limited amount of test time accumulated. A detailed analysis at this stage of the research might only lead to false conclusions. The value of the data is in providing guidance and direction for further research.

The data is presented in plots of temperature versus log time. The data points were plotted every 10 hours during the first 100 hours of testing and once every 100 hours thereafter. The curves are evaluated with respect to the feasibility of the proposed test methods. The curves are presented in two sections. The first compares the results of bearings tested under continuous load with those tested under noncontinuous load. The second section compares individual plots of several of the bearings which failed during the tests.

Comparison of Continuous and Noncontinuous Load Bearings

Figure 9 shows the data obtained from shaft #2 which contained the bearings run under noncontinuous load. The bearing temperature is plotted as a function of log time for each of the four bearings which contained thermocouples. The graph shows most of the data (all but two points) is contained between 120° and 200°F. The initial (10 hours) steady state temperature range was 130° to 180°F. The final (500 hours) temperature range was 125° to 220°F. No failures occurred during the 500 hour test. Individually, the total temperature variations (rounded to nearest five degrees) for each of the four bearings were 25°, 25°, 50°, and 95°F.

Figure 10 shows the data obtained from shaft #4 which contained the bearings run under continuous load. The data is plotted the same as in Figure 9. Again the majority of data (all but seven points) falls between 120° and 200°F. The initial (10 hours) steady state temperature range was 140° to 170°F. The final (500 hours) temperature range was 125° to 230°F. No failures occurred during the 500 hour test. Individually, the total temperature variations

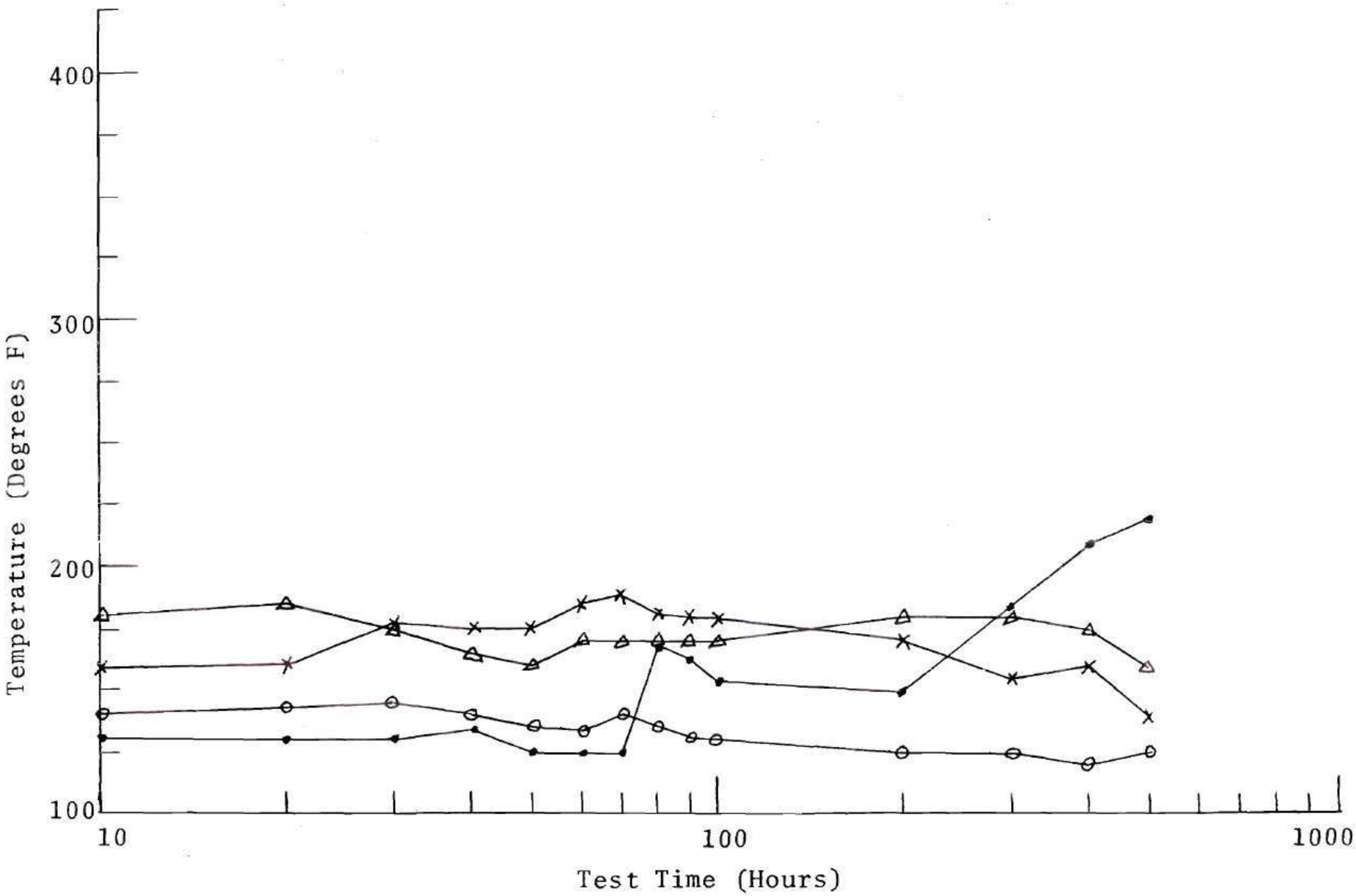


Figure 9. Shaft Number 2 Data--Noncontinuous Loading

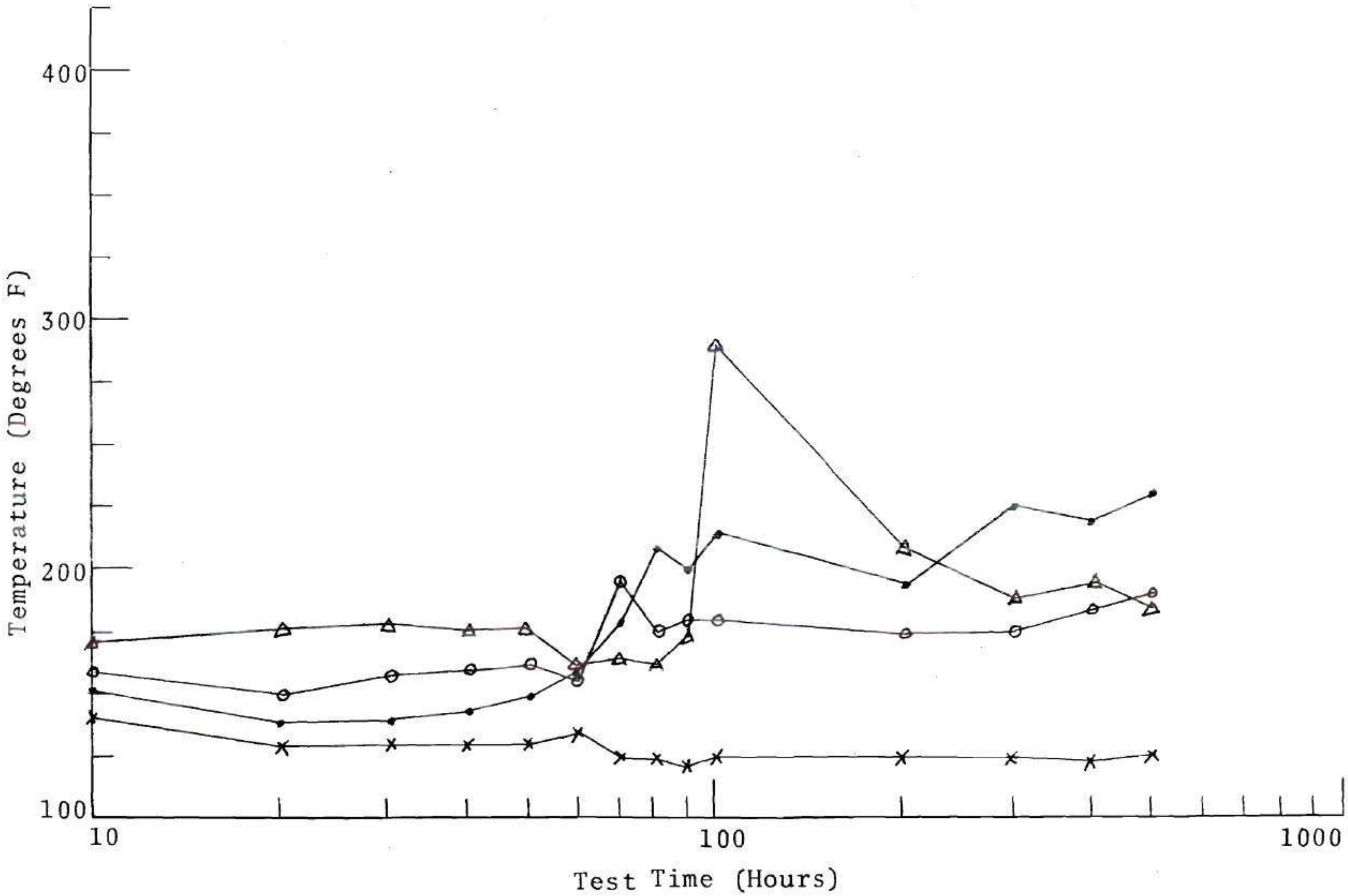


Figure 10. Shaft Number 4 Data--Continuous Loading

(rounded to nearest five degrees) for each of the four bearings were 20°, 45°, 90°, and 130°F. The curve that varied 130° experienced a sharp temporary temperature increase at 100 hours.

A comparison of Figure 9 and 10 finds several similarities. Neither system experienced any failures during the 500 hour test. The total system operating temperature ranges were similar during most of the test. Individual curve comparisons show three of the four pairs with similar temperature variation. The main difference between the two plots is the temperature spike on Figure 10.

Correlation of Temperature and Bearing Life

One of the primary objectives of this research was to find whether there is a relationship between temperature and bearing life. It was hoped that the bearing temperature curve could indicate when the failure process begins or when failure is eminent. This would enable test results to be known before the actual failure occurs. In order to utilize the bearing temperature curve, a repeatable trend must be recognized which will indicate when the bearing failure is likely to occur. Figures 11 through 14 are individual plots of four bearings which failed during the tests. Examination of these curves reveals a similar characteristic in Figures 11, 12, and 13, which is a temperature spike that occurred before the eventual failure. Although this data is too

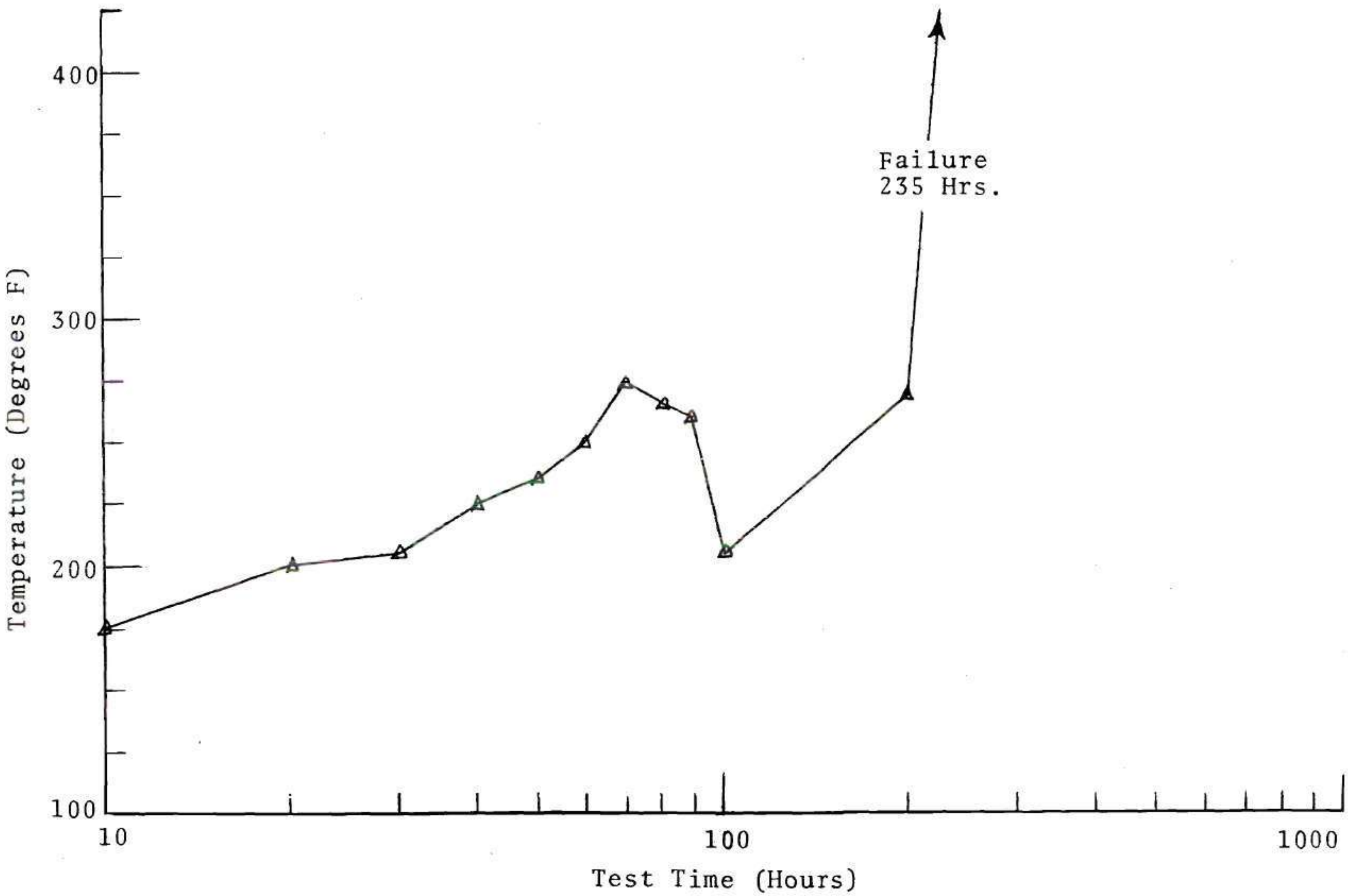


Figure 11. Temperature-Life Curve--Example 1

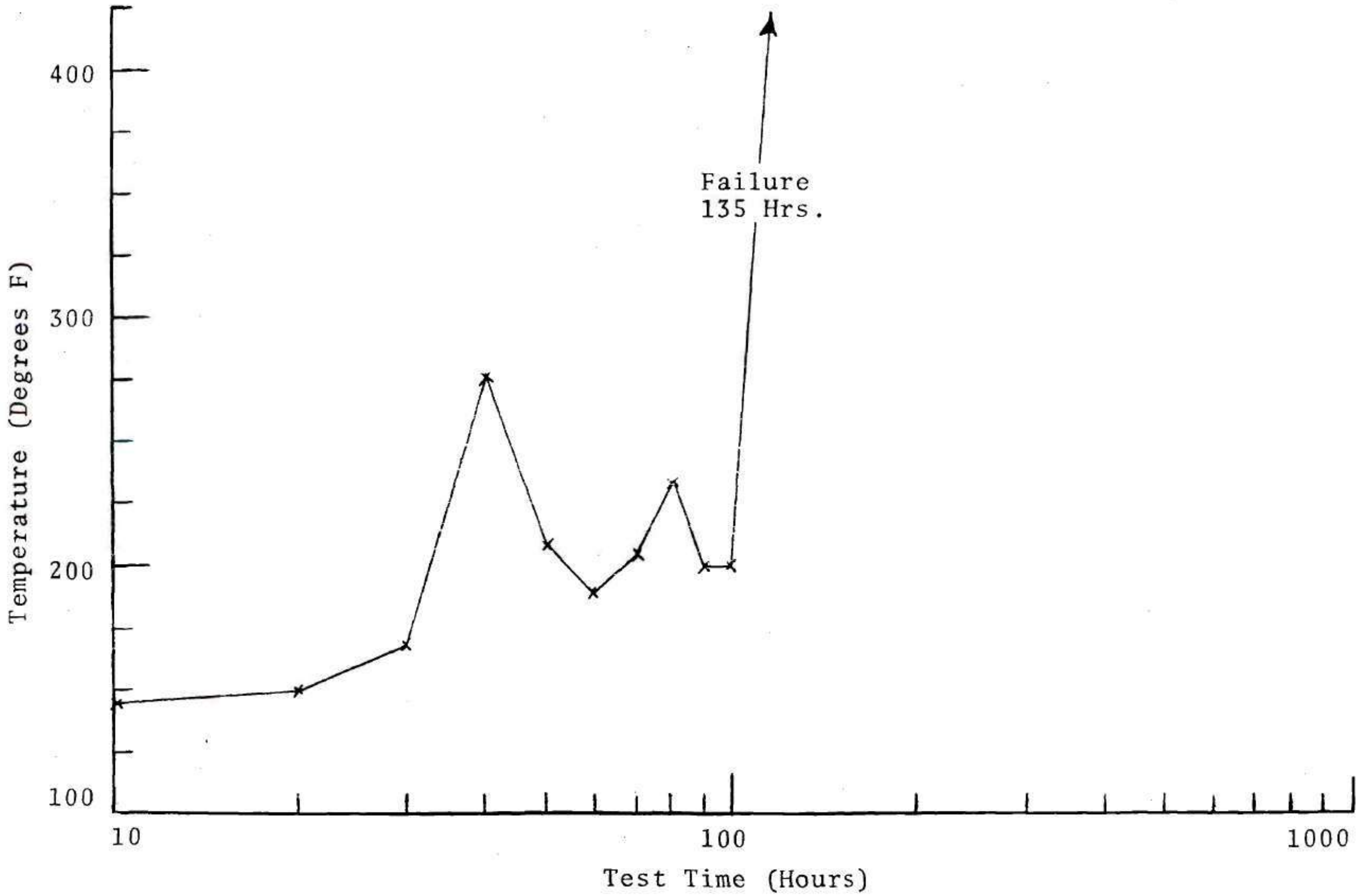


Figure 12. Temperature-Life Curve--Example 2

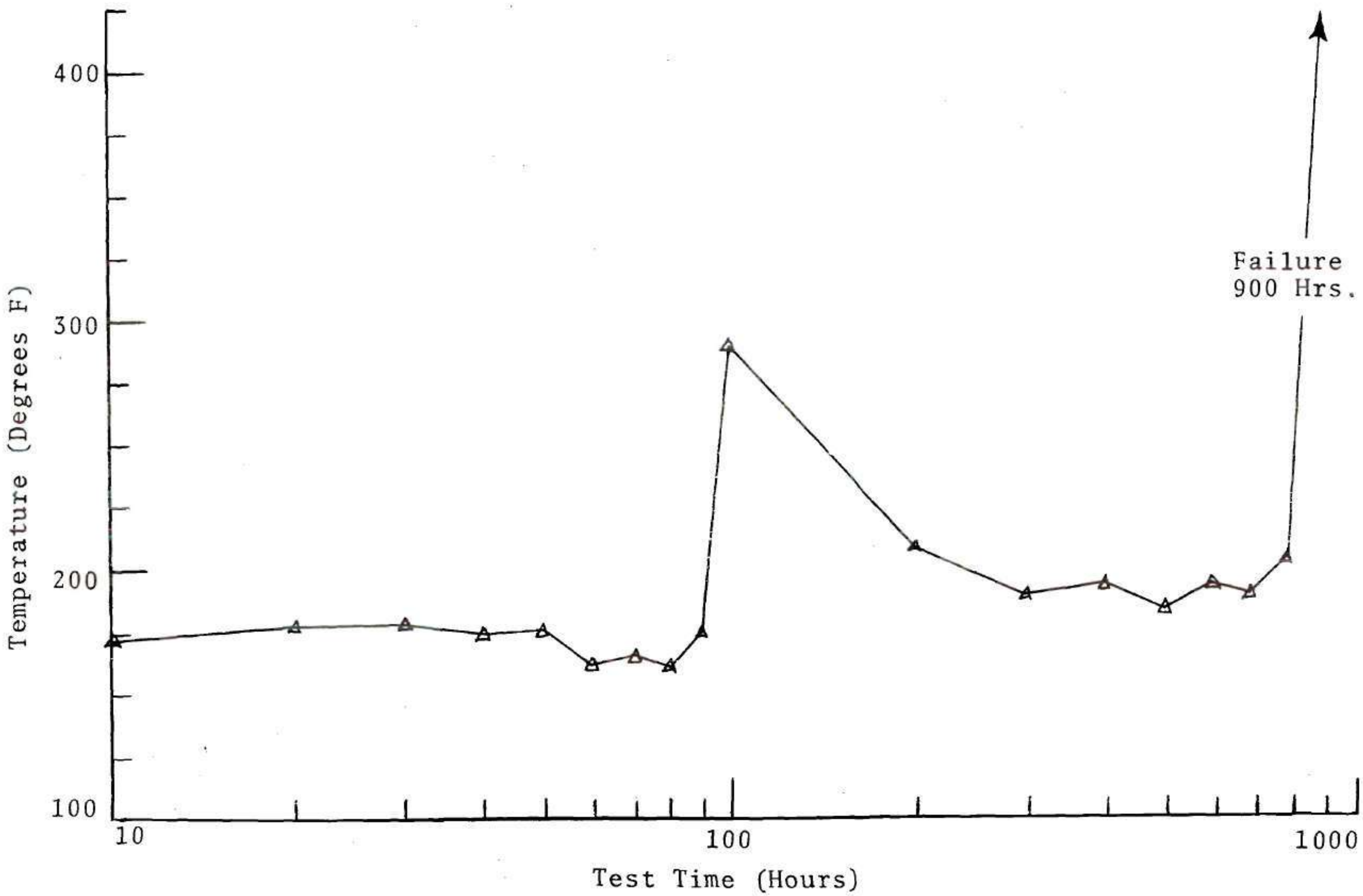


Figure 13. Temperature-Life Curve--Example 3

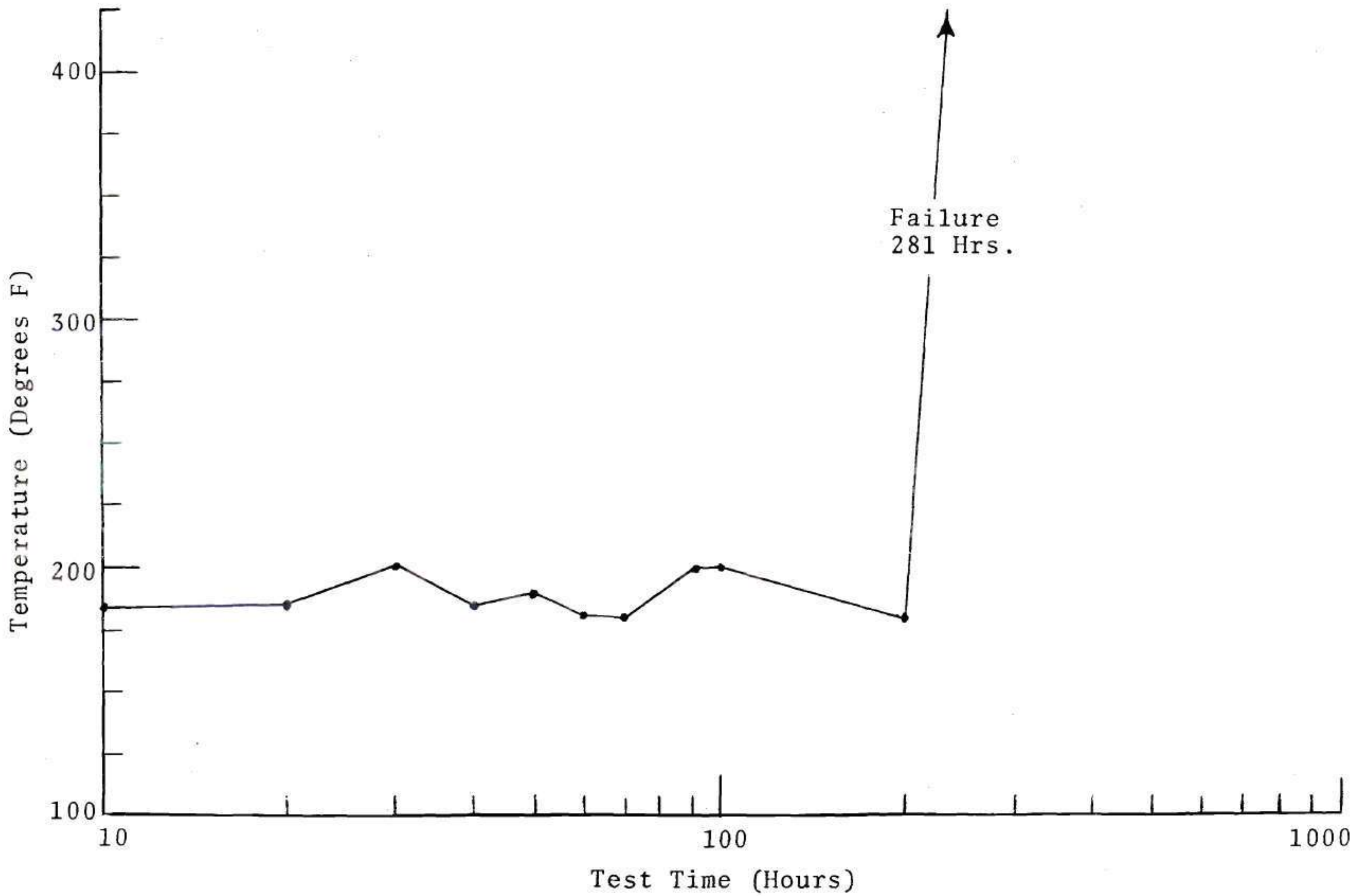


Figure 14. Temperature-Life Curve--Example 4

incomplete to support any conclusions, this characteristic could possibly indicate the origin of the failure process. Other than the temperature spike, the four curves exhibit few similarities. Within the group, Figures 11 and 12 are most similar. In both cases the temperature spike occurs on a steadily increasing curve. Figure 13 also contains a temperature spike, but it occurs on an otherwise stable curve. Figure 14 is a total exception as the temperature curve remains very stable until failure occurs.

General Observations

Some general observations not related to specific data should be mentioned. First, the presence of thermocouples appear to have no effect on the operation of the bearings. Second, the failure process seems to be controlled by the oil content of the bearing. Several spot checks which were made showed that even after several hundred hours of operation bearings showed no signs of wear. However, once a bearing began to fail (temperature begins sharp increase), the entire bearing could be physically destroyed in less than 24 hours. Thus it seems that as long as the bearing maintains a satisfactory oil content, very little surface wear will occur.

CHAPTER IV

ACCELERATED TESTING FEASIBILITY

The data obtained in this research is not sufficient to establish accelerated testing procedures. However, the results give some positive indications that the proposed test methods may be feasible.

With respect to the continuous versus noncontinuous load test, the similar temperature curves suggest that the wear process is similar in both loading conditions. The stop-start conditions and resulting thermal cycling which occurs in the noncontinuous test may have minimal effect on bearing life. If this can be established by additional testing, continuous test time can be directly correlated with actual operational time. If a direct correlation is not valid, additional tests may reveal an accurate conversion factor.

Only four curves were available to investigate the feasibility of predicting bearing failure through temperature curve analysis. With this limited data no conclusions should be made. However, the temperature spike which occurred in several of the curves could be the failure indication which is necessary for application of the proposed test method. Extensive testing will be required to establish that the temperature spike or some other characteristic is common to bearing temperature curves.

In order to explore the possible application of the proposed accelerated test methods, consider the following hypothetical example:

Assume that additional research has established several conclusions. First, continuous test time can be directly correlated to actual operating time. Second, the temperature spike is an indication of bearing failure which occurs, on the average, at 50 percent of total life. A new design has been proposed for the automatic washer which would increase the present bearing load by 25 percent. A group of bearings are put on accelerated test under the proposed loading. After 400 hours of testing the temperature spike had occurred in 30 percent of the test samples. This data would indicate that approximately 30 percent of the bearings used under this load would fail by 800 hours. The 800 hours of continuous test time represents approximately 2600 hours of actual machine operation. Therefore, in this example approximately 2600 hours of machine lab testing was simulated in 400 hours of accelerated testing.

Time savings of this magnitude would be extremely valuable to industry. The accuracy and reliability of accelerating testing will depend upon the extent of research done in this area. The application of statistical analysis and probability theory could help determine the level of confidence for a particular accelerated test. Table 1 shows the time required to run a life test on the present upper center post bearing in the Whirlpool automatic washer by conventional test methods and the proposed accelerated test methods.

Table 1. Time Required to Run a Life Test

Method	Time Procedure	Time Required
Field Testing	Machine operated in the home under actual load conditions	Ten Years
Lab Testing	Machine operated on around-the-clock schedule under simulated load conditions	Twenty Weeks
Continuous Testing	Bearing operated in test apparatus under continuous simulated load conditions	Six Weeks
Continuous Testing with Temperature Data Failure Prediction	Bearing operated in test apparatus under continuous simulated load conditions with temperature being monitored	Less than six weeks actual time depends on how soon prediction can be made

CHAPTER V

RECOMMENDATIONS

Design Changes

The test equipment which was designed and built for this research could be improved for future use by making several design changes. The greatest single problem encountered in this research was bearing alignment. Since each bearing was mounted independently, the alignment was dependent on the accuracy of construction of the machine. Some adjustment was possible by the 3/8 inch threaded rods, but in many cases this was insufficient. Because of the alignment problem, some of the bearings on test shafts number 1 and number 3 were under increased load due to misalignment. Therefore, the data obtained from those systems could not be used for comparison. This problem can be solved by the addition of adjustable bearing mounts to the machine. A three degree of freedom mount would probably correct the problem. However, a four degree of freedom mount, which would allow complete adjustability, could be designed if necessary. A possible three degree of freedom mount is shown in Figure 15.

Another improvement would be the addition of thermocouples to all of the test locations. This was not done in

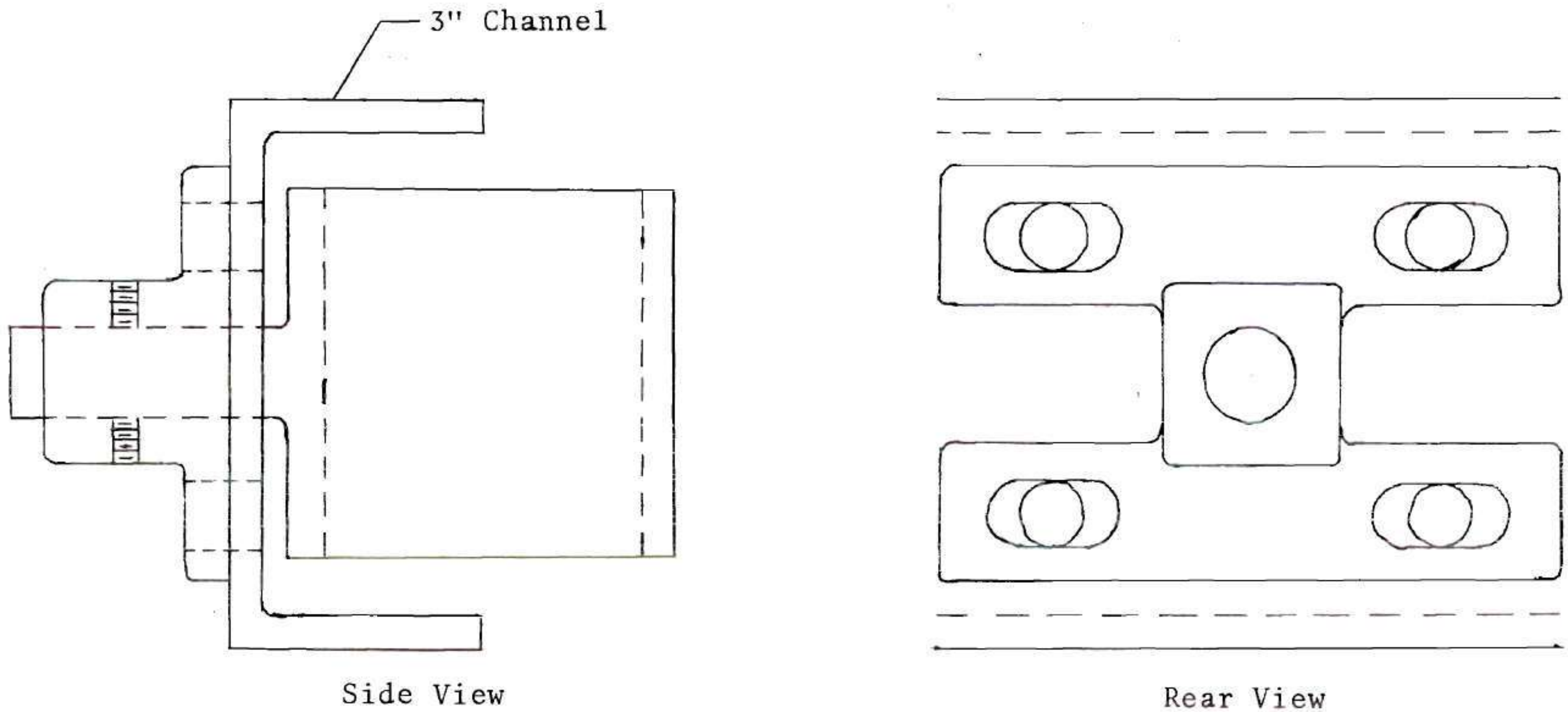


Figure 15. Possible Three Degree of Freedom Bearing Mount

these tests in order to check for any adverse effects caused by the insertion of a thermocouple into a bearing. Since no adverse effects were discovered during this research, the addition of thermocouples to all test sites is recommended.

The implementation of a complete thermocouple network would enable the installation of a more efficient failure shut down system. During the current research, automatic shut down of the system could only be accomplished by overloading the fused circuits. This provided satisfactory electrical protection, but did not respond effectively to bearing failure. Operation of the current system depended on a bearing failure increasing shaft friction, causing the motor to overload and blow the fuse. This was not effective because each shaft contained eight bearings, and a single failure would not cause a sufficient overload. With a complete thermocouple network, a temperature sensitive automatic shut down could be easily incorporated through the multi-point recorder. Since all of the failures which occurred in this research were accompanied by a sharp temperature increase, a temperature sensitive shut down system should be effective.

Continued Research

Both of the accelerated test procedures considered in this research need further development. Final conclusions must be based on an extensive collection and evaluation of test data. If these methods prove successful, further research could include application to other porous bearings and possibly to accelerated testing in general. This research has established the procedures necessary to continue this research.

Data Analysis

Because of the small data sample obtained in this research, the analysis was very limited. However, several considerations are recommended for future research. First, the use of statistical analysis will be an essential tool for evaluating large groups of data and establishing reliability levels for the accelerated tests. Second, several different curve plotting methods should be considered. The sensitivity (time between data points) of the temperature-life curve can be varied and plotted both on semi-log and linear scales. Variation of the plotting technique may find methods that better exhibit key characteristics of the curves.

Proposed Testing

In addition to continued research of the current test methods, there are other possible accelerated test methods which could be considered. The test equipment used in this research was designed to allow experimental flexibility and could be adapted to different test conditions and procedures.

APPENDICES

APPENDIX A

ELECTRICAL CONTROL CIRCUIT

Figure 16 shows a schematic diagram of the run-print control circuit. The continuous systems (1,3,4) controls consist of a switch, a time delay fuse, and an elapsed time indicator. The noncontinuous system (2) control also includes a repeat cycle timer, a power relay, and a time delay relay. The recorder print circuit is activated by the pulse network which is controlled by the repeat cycle timer through the power relay. The operation of the system is as follows:

With the timer in the 40 minute position system number 2 is in operation. When the timer switches to the 20 minute position the power relay switches. This activates the time delay relay (which is now controlling system number 2) and the pulse network. The pulse network activates the recorder print circuit which prints each thermocouple value. Sometime after the print cycle is complete (about 30 seconds) the time delay expires and the relay opens, shutting down system number 2. When the timer returns to the 40 minute position, system number 2 is activated by the power relay and all of the relays are reset in their original position.

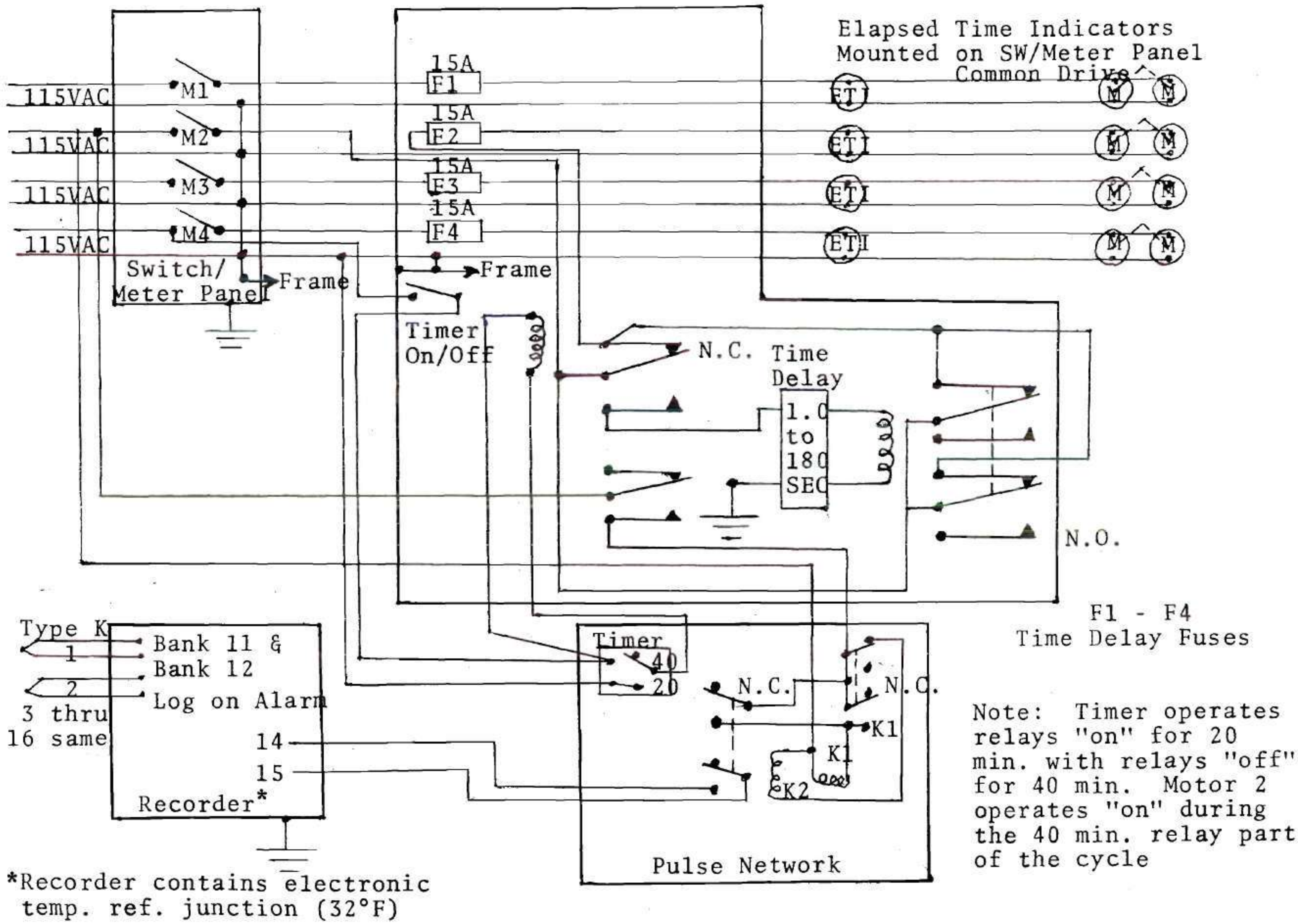


Figure 16. Run-Print Control Diagram

APPENDIX B

DATA-TEST SYSTEMS NUMBERS 1 AND 3

The data obtained from the test systems numbers 1 and 3 is shown in Figures 17 and 18. This data was not used in load system comparisons because of misalignment problems. The erratic patterns, high temperatures, and premature failures clearly illustrate the severe effects of bearing misalignment.

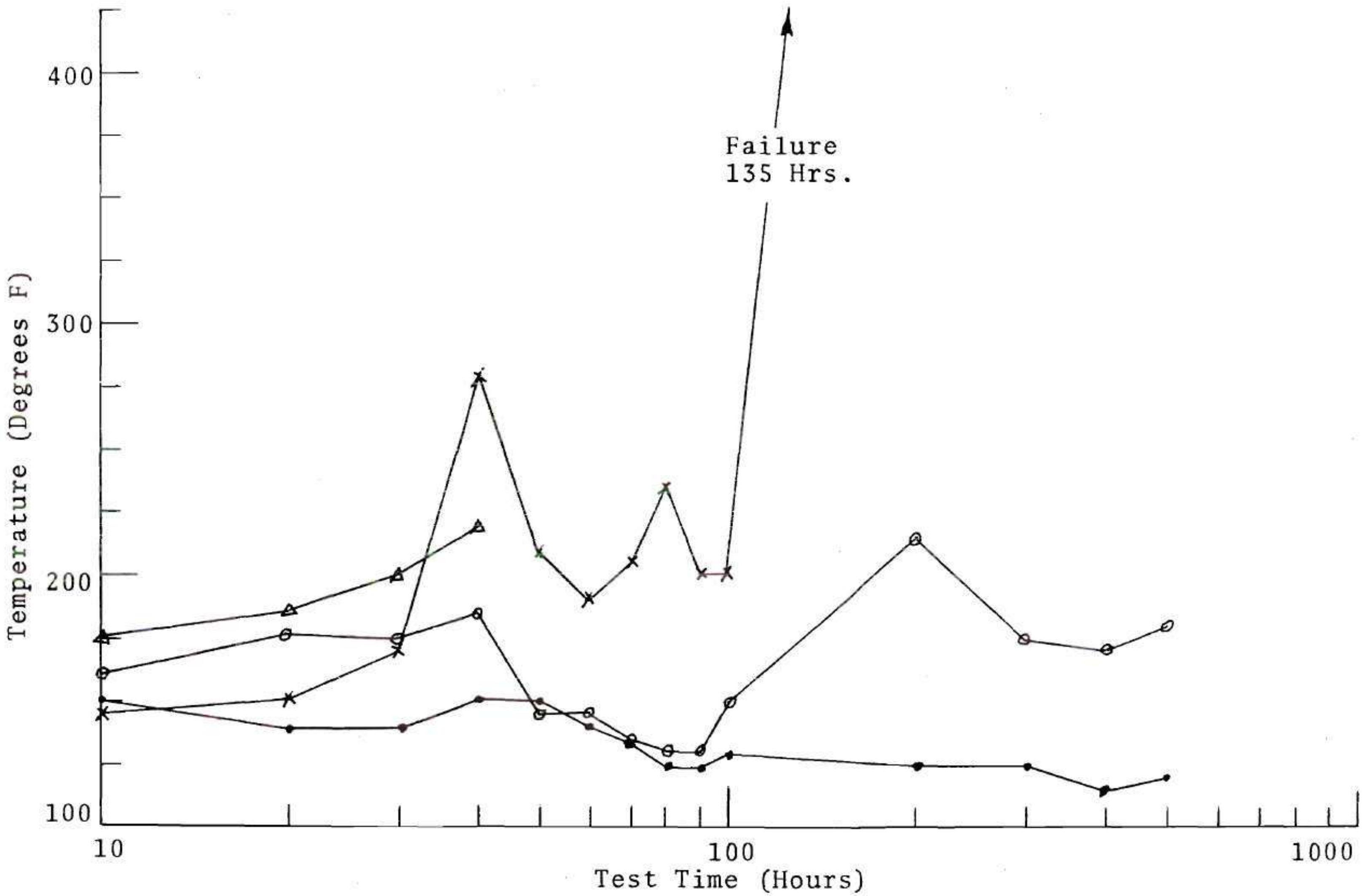


Figure 17. Shaft Number 1 Data

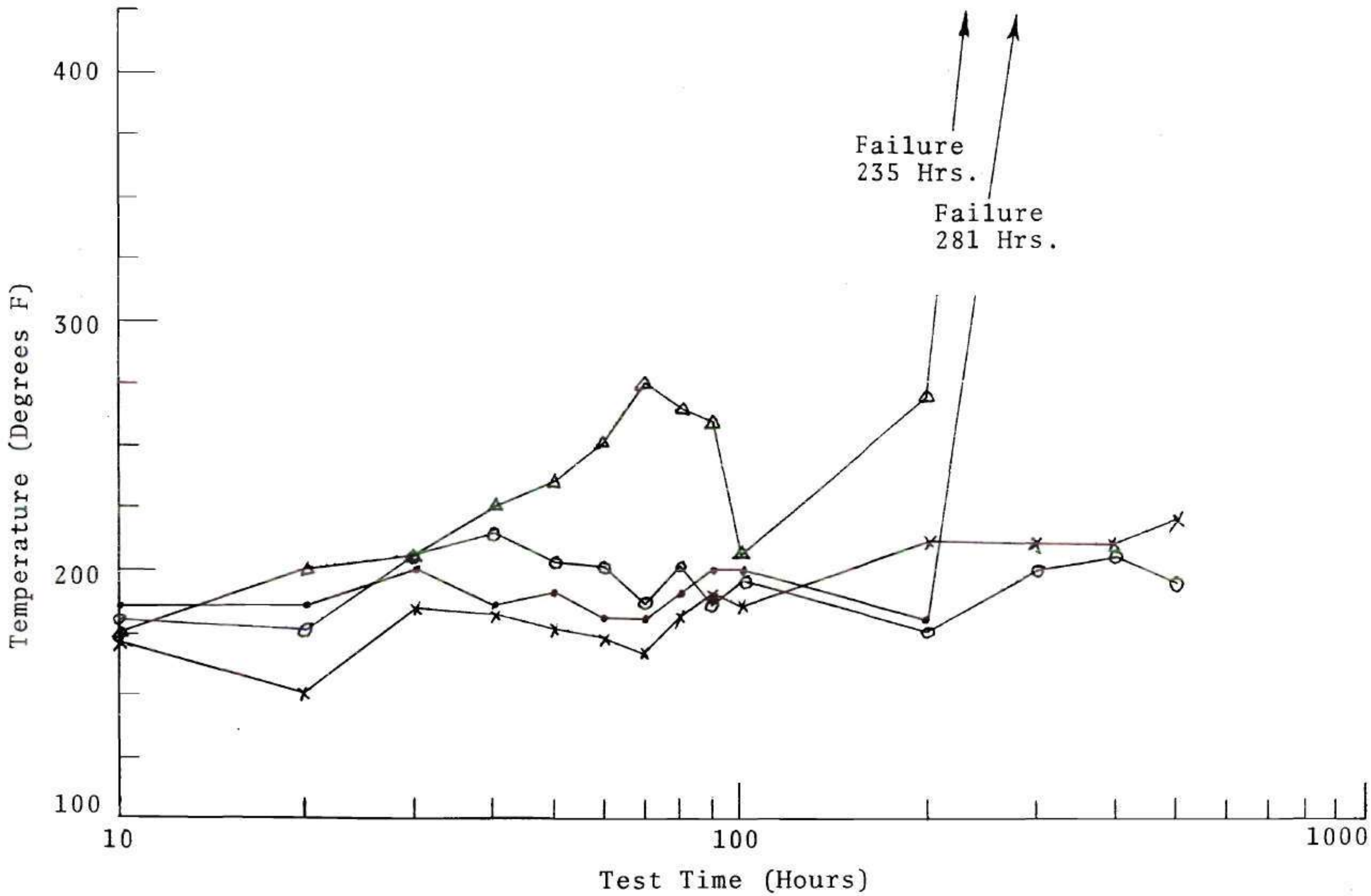


Figure 18. Shaft Number 3 Data

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