Proposal for

DETERMINATION

OF

LIFE CHARACTERISTICS OF ANTI-FRICTION BEARINGS

IN

HELICOPTER ROTOR HUB APPLICATIONS

PR No. 6805

To be conducted by the

DEPARTMENT OF MECHANICAL ENGINEERING

and the

ENGINEERING RESEARCH INSTITUTE

of

THE UNIVERSITY OF MICHIGAN

for the

WRIGHT AIR DEVELOPMENT CENTER

Wright-Patterson Air Force Base

Ohio

November 15, 1955

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1. INTRODUCTION

The use of "anti-friction" bearings in helicopter rotor hubs constitutes a problem area in the design and operation of military aircraft. Relatively short service lives are currently being obtained with the flap-hinge, lag-hinge, and pitch-change bearings. As a result, hub overhauls are necessary at intervals well below the current requirement of 1000 service hours.

The basic difficulty is essentially this: the critical bearings are being operated under conditions for which they were not designed, and for which no ratings and almost no design information are available. The bearings are designed and rated for operation in full rotation or through angles of oscillation greater than the so-called "critical angle," within certain narrow limits of misalignment of the inner and outer races. In the subject helicopter rotor applications, the bearings oscillate through angles less than the critical angle. Moreover, the demands for weight saving in the rotor hub lead to misalignments of the bearing races that are greater than those considered in the standard ratings. These conditions occur in the presence of steady and vibratory radial bearing loads that can reach high values.

As noted, very little information useful in design is available concerning bearing behavior under such conditions.

2. OBJECTIVE

The objective of this program is to study and determine the life characteristics of certain anti-friction bearings under conditions simulating helicopter rotor hub applications. The program essentially becomes an investigation of the behavior and life of selected anti-friction bearings under various conditions of bearing load, race misalignment, and bearing oscillation angle. While the results clearly will have general application and usefulness, the prime intent and focus of the study is to be directed at the subject helicopter rotor hub problem.

The results of the program are to provide design knowledge and criteria for effective modification of existing rotor hub installations, such that the 1000-service-hour requirement can be met and exceeded. In addition, the program shall establish design criteria for future rotor hub designs. Effectively this should lead to achievement of optimum bearing life—installation weight configurations.

3. GENERAL PROGRAM

GENERAL NATURE

The overall program can be considered to encompass two main areas of closely related activity, namely:

(1) Establishment of basic load-rating criteria for anti-friction bearings under conditions involving small angles of oscillation.

(2) Investigation of the effects on bearing life of those installation and environmental factors that are encountered in helicopter rotor hub design and operation.

The first item consists essentially of the establishment of certain base values, thereby providing standards of comparison for evaluating the effects of the various installation and environmental factors of the second item. Thus the activities under the first item will be directed primarily at determining bearing life in the presence of small bearing oscillations, under the idealized conditions of steady load and closely controlled bearing race alignment. This is the equivalent of obtaining standard bearing load ratings, with the exception that the bearings are subjected to small oscillations rather than to full rotation.

The activities of the second item then are directed at examining the effects of such installation and environmental factors as race misalignment, cyclic loadings, and the like—again for the case of small bearing oscillations. Therefore it is the second item which will provide design information directly applicable to the helicopter rotor hub problem, while the first item provides the necessary basic background.

BEARING TYPES TO BE EXAMINED

Similar programs of study and test will be carried out for the following three types of anti-friction bearings:

(1) Needle bearing, caged type

(2) Tapered roller bearing

(3) Spherical roller bearing

The tests are to be carried out on bearings having the following approximate envelope dimensions:

Outside diameter: 3.75 inches

Inside diameter: 2.75 inches (needle bearing)
1.75 inches (tapered and spherical roller bearings)

The bearings tested are to be of standard aircraft quality.

4. OUTLINE OF PROGRAM

The particular areas of activity to be undertaken in the program have been outlined by the Wright Air Development Center in Exhibit A of R and D Exhibit WCLB-27, 21 September 1955, PR No. 6805. Herein, this outline will be referred to merely as Exhibit A.

The overall program may be subdivided into three distinct phases:

Phase I. Detail Study and Analysis

This introductory phase is to be directed at collection and coordination of pertinent information from all interested parties: the sponsoring agency, the helicopter manufacturers, and the bearing manufactuers. This information then shall be used to develop a detailed initial plan for the program.

This initial plan will cover such aspects as test methods, test variables, range of test variables, and the estimated number of specimens which are to be tested in each of the various portions of the program. The activities of this phase, as represented in the resultant plan for the program, will also provide preliminary indications as to which variables and values of variables are particularly pertinent to the current helicopter problem. Then, if desired, these areas may be attacked first in the test program. Thus results useful to the current problem can be obtained at the earliest possible instance.

Phase II. Test Machine Design, Development, and Fabrication

In the light of the results of Phase I, this phase shall involve the design, development, and fabrication of the necessary test fixtures, test machines, and allied instrumentation. While full use should and would be made of any applicable test machines and methods that are currently available, it appears unlikely that this can be done without rather major modification. Indeed, it is likely that new machines will have to be designed and developed.

Phase III. Test Program

This phase consists of the test program proper. As such, it will include basic load-rating tests and tests of the effects of environmental and installation factors on each of the three bearing types stipulated for study. It is convenient for discussion purposes to consider the overall test program as three parts—one for each bearing type; each part then subdivides into investigation of basic load ratings and investigations on installation and environmental factors. As is discussed in later sections, however, there is no fixed intent at this time that the actual test program shall proceed in rigid sequency from one of these areas to another. Rather, the actual program should be geared to providing information useful to the helicopter problem at the earliest opportunity.

* * *

Our proposed activities in each of the above three phases of effort are discussed in detail in sections 8, 9, and 10 of this proposal.

5. TEST REQUIREMENTS

The sponsoring agency has stipulated the general test criteria requirements as follows:

EXHIBIT "B"

R and D Exhibit WCLB-27

21 September 1955

PR No. 6805

General Test Criteria Requirements

A. Load-Rating Tests

1. Cycles - For each type bearing investigated, load ratings for small angle oscillations shall be based on a BL-10 life for 15,000,000 cycles.

2. Type of loading - Constant radial loading shall be used. Loads shall be within the range 1000 lb minimum to 70,000 lb maximum.

3. Angles of oscillation - Angles of oscillation used during the testing shall be within the range of ± 0 to ± 10 degrees. Overlap of adjacent loaded areas on the races of the rolling elements is to be avoided.

4. Bearing Limit load - Bearing limit load is defined as that static load which when applied to the bearing for one-minute duration does not affect the bearing fatigue life.

5. Frequency of oscillation - Frequency of oscillation shall be approximately 600 cpm.

6. Race rotation - The inner race of the bearing shall oscillate with the load applied to the outer race.

7. Frictional torque - Bearing frictional torque shall be continuously monitored during tests for each individual bearing specimen. Failure of the bearing shall be indicated by an increase in friction torque of three times the initial value.

8. Lubricant - One lubricant shall be used throughout the testing. Lubricant will be chosen during the study of Item I, Exhibit "A."

9. Environmental conditions - Environmental conditions such as preload, alignment, atmospheric conditions, etc., shall be controlled and maintained during testing in accordance with the bearing manufacturers recommendations and specifications.

10. Quality control - Factors affecting bearing quality such as surface finish, tolerances, etc., shall be recorded. Bearings shall be standard aircraft quality items.

B. Environmental Tests

1. Factors - At least the following factors shall be considered in establishing the scope and test variables:

a. Housing stiffness

b. Vibratory loading on the bearing

c. Shaft stiffness

d. Variation of load during bearing life.

C. Test Schedule

1. Arrangement of variables - Consideration shall be given to the employment of statistical factorial experiment procedures and regression analysis to control and evaluate interaction effects of major variables.

2. Number of specimens - The precise number of bearings of each type to be tested for the load-rating tests and environmental tests will be determined under the applicable portion of Item I, Exhibit "A."

However, no less than 50 bearings of each type shall be tested for the load-rating tests and no less than 100 bearings of each type for the environmental tests.

D. Test Reports

1. A separate technical report shall be prepared for the load-rating tests and for the environmental tests for each type of bearing. The form of each report shall conform to the requirements of Exhibit WCAP 54-1, as amended.

2. Contents

a. Load-rating tests - The reports covering these tests shall describe the test program, tabulate results, and present recommendations for formulation of load-rating criteria for the respective bearing type.

b. Environmental tests - The reports covering these tests shall describe the test program, tabulate results, and present a summary discussion of the effects of the environmental factors investigated on bearing life.

NOTE: Eight (8) copies, one of which is reproducible by the ozalid process, of all reports shall be furnished.
Two (2) copies of all drawings shall be furnished.

* * *

Certain comments on the above test requirements are presented in section 11 of this proposal.

6. STATISTICAL NATURE OF THE PROBLEM

The entire subject program has a statistical base. In order that reliable results will be obtained in an economical manner, the use of statistical analyses must enter all phases of the investigation: the initial planning, the continuing review of the results being obtained, the ultimate interpretation and presentation of results, and the adaptation of these results to the helicopter problem itself.

Limitations on time have not permitted us to enter into a detailed analysis of this aspect of our proposal. (Indeed, as we shall see, it is somewhat futile to do so prior to the detail study and analysis activities that make up Phase I of the overall program.) Thus the detailed discussions of the following sections may not reflect fully the extent to which the use of statistical analysis is planned. However, as will be discussed in section 12, an applied mathematician practiced in the engineering application of statistics will be a member of the team conducting the program. Statistical methods will be employed to the full required extent.

It is clear that this will be necessary. The individual lives demonstrated by supposedly identical bearings under carefully controlled operating conditions show a very decided "scatter" or distribution, even under ideal conditions of full rotation, steady loading, and carefully controlled race alignment. (Variations in life as great as 50:1 have been observed.) As a consequence, all standard load ratings of anti-friction bearings currently are of a recognized statistical nature. It would be optimistic, to say the least, to expect the scatter obtained under the proposed conditions of this program to be any less than that obtained under the ideal conditions. Indeed it is highly probable that an even greater degree of scatter will result.

As in any program incorporating many variables, regression analysis can be an important tool and should be employed to the fullest useful extent. It should be recognized, however, that the use of regression analysis is somewhat reduced in effectiveness if each variable of itself introduces decided scatter of the end results. As noted, this is likely to be true of the subject program.

7. GENERAL NATURE OF OUR APPROACH

Before entering into the details of our proposal, some introductory remarks are in order concerning our view as to the general manner in which the problem should be attacked. These are aimed at providing information useful in remedying the current helicopter problem at the earliest opportunity.

We would wish to make the overall program one of a continuing interchange of pertinent information between all interested parties: our research team, the sponsoring agency, the helicopter manufacturers, and the bearing manufacturers. Such interchange, of course, would be subject to the approval of the sponsoring agency.

We have no desire to take the program within our walls and then, at infrequent intervals, parcel out minor bits of information until—at long last—the required formal reports are delivered. The pressing demands of the helicopter problem would appear to preclude such an "ivory-tower" approach. While the overall program will be time-consuming, parcels of information useful to remedying the helicopter problem should come available considerably before the preparation and delivery of the last formal report. We would see to it that such information was passed on to the sponsoring agency (and through them to the interested manufacturers) as soon as it was obtained.

It would seem desirable that the time-phasing of the test program would be geared to the same end. On this basis, it would appear undesirable to attack the test program on a strict sequential basis, in which each item of the test program of Exhibit A is completed before the next is begun. It would seem more desirable to make a somewhat simultaneous attack on several of the major variables, and progress through the program in this manner. This should make information useful to the helicopter problem available at an earlier date. This approach is discussed in more detail in a later section of this proposal.

Thus, to the extent requested, we would work with the helicopter and bearing manufacturers both during and after the test program, in order that the results obtained can see maximum use in solution of the helicopter problem.

8. PROPOSED ACTIVITIES—DETAIL STUDY AND ANALYSIS

Clearly the overall program must begin with a period of study and analysis, aimed at the collection and correlation of the knowledge, experience, and thinking of all interested parties: the sponsoring agency, the research team, the helicopter manufacturers, and the bearing manufacturers. This is recognized by the stipulated Detail Study and Analysis phase of the program, as described in section 4.

Out of these activities will come the pattern for the subsequent test activities. In view of the scope of the test program, the importance of this first phase cannot be overestimated. Information will be gathered on:

(1) Loading, alignment, oscillation angle, lubrication, and other environmental and installation characteristics of current representative rotor hubs, as well as the likely trend of these variables in future designs.

(2) Serivce behavior of current representative installations, along with any related laboratory or test-stand experience.

(3) Current recommended ratings and practice in installations subject to the conditions under study.

(4) Existent test equipment or procedures related to the subject study.

Out of this information will be established:

(1) Method of test, test variables, and ranges of test variables for determining

(a) Basic load-rating criteria under small angular oscillations.

(b) Effects of various pertinent installation and environmental factors on the bearing life.

(2) Indications as to which of the variables, and which particular values of the variables, appear most pertinent to the current helicopter problem.

The overall plan for the experimental program can be established from this information. Item (1) defines the nature of the program, item (2) its time-phasing. Clearly this plan must comply to the stipulated requirements of Exhibit B of section 5. Any indicated modifications, additions, or deletions of these requirements must be subject to the approval of the sponsoring agency, as must the formulated plan itself.

The primary sources for the above material will be the Wright Air Development Center, the helicopter manufacturers, and the bearing manufacturers. Through these sources additional prospects for information may be developed; these might include manufacturers (if any) of other products incorporating similar or related oscillating uses of anti-friction bearings. Such additional sources would be explored as well.

The study and analysis phase would begin with a review of the material and information available at the Wright Air Development Center, and of the literature of the field in general. This would be followed by visits (preceded by correspondence) to the pertinent helicopter and bearing manufacturers. WADC personnel might accompany research team members on these trips, at their discretion. At the same time, visits related to the selection and design of the test machine would be made to representative manufacturers.

The resultant planned program of this phase would then be brought into report form. This report would be submitted to the sponsoring agency for approval. It is also recommended that it be circulated to the interested helicopter and bearing manufacturers, for their review and comment. If deemed necessary after such review, a coordinating conference of all interested parties might be called.

In accordance with the general discussion of the preceding section 7, activities in other phases of the program should not necessarily await completion of this detail study and analysis phase. Certainly at least the preliminary work of design and/or selection of the test machines can be carried out concurrently to some extent. Every effort should be made to take advantage of such possibilities for time-saving.

9. PROPOSED ACTIVITIES—TEST MACHINES

The design, or possibly selection, of suitable test fixtures and machines and the necessary allied instrumentation will be a vital phase of the overall program. This is particularly true in view of the number of bearings which must be tested in order to obtain results with the required statistical reliability.

It would be desirable and convenient, of course, if machines were currently available that could be employed for this program with little or no modification; the bearing manufacturers should be the prime source for such items. Certainly this possibility of adapting existing machines should be explored fully from the outset. As noted in the preceding section 8, a survey aimed at this end will be carried out as part of the initial detail study and analysis phase.

At this stage, however, it seems quite unlikely that existing machines can be adapted to this problem with only minor modification. The primary difficulty does not appear to lie in the achievement of the necessary loads, oscillations, race alignments, and the like; these questions are suited to reasonably direct treatment. Rather, the major problem to be faced appears to be that of reliable measurement of the bearing friction torque. (As stipulated in Exhibit B, bearing life or bearing failure is to be based on an increase of bearing friction torque to three times its initial value.) This measurement carries with it certain inherent problems, as will become apparent in the following portions of this section. This is not to say that the problem is insoluble. It certainly is not. But careful thought, ingenuity, and analysis will be required.

Thus the research team is faced with the almost definite requirement of designing, developing, and fabricating special test machines, and adapting the necessary instrumentation to them.

The time pressures on delivery of this proposal have not allowed us to examine the test machine and instrumentation to the extent that we can make at this time a firm recommendation as to the most desirable configuration or approach. (As a matter of fact, such a decision necessarily must await some of the results of the detail study and analysis phase of the overall program.) In this section we shall discuss several alternate possibilities that we have begun to examine; each of these has its own advantages and disadvantages.

The following tentative approaches, along with others, would be examined in detail in the initial portion of the program. Out of this study would be selected machines and instrumentation suited to the program. The eventual design is subject to the approval of the sponsoring agency.

In view of the number of specimens requiring test, and the low stipulated rate of cycling (600 cpm), a considerable number of machines will be required to complete the program in a reasonable time. This implies that a single type of machine need not be adaptable or used for examination of all variables. For example, relatively simple machines might be constructed for certain aspects of the testing, and perhaps somewhat more complex ones adapted for certain of the environmental investigations. This would be in line with our earlier viewpoint that the overall program perhaps should consist of a simultaneous examination of several variables, rather than a strict sequential completion of each phase of testing in turn.

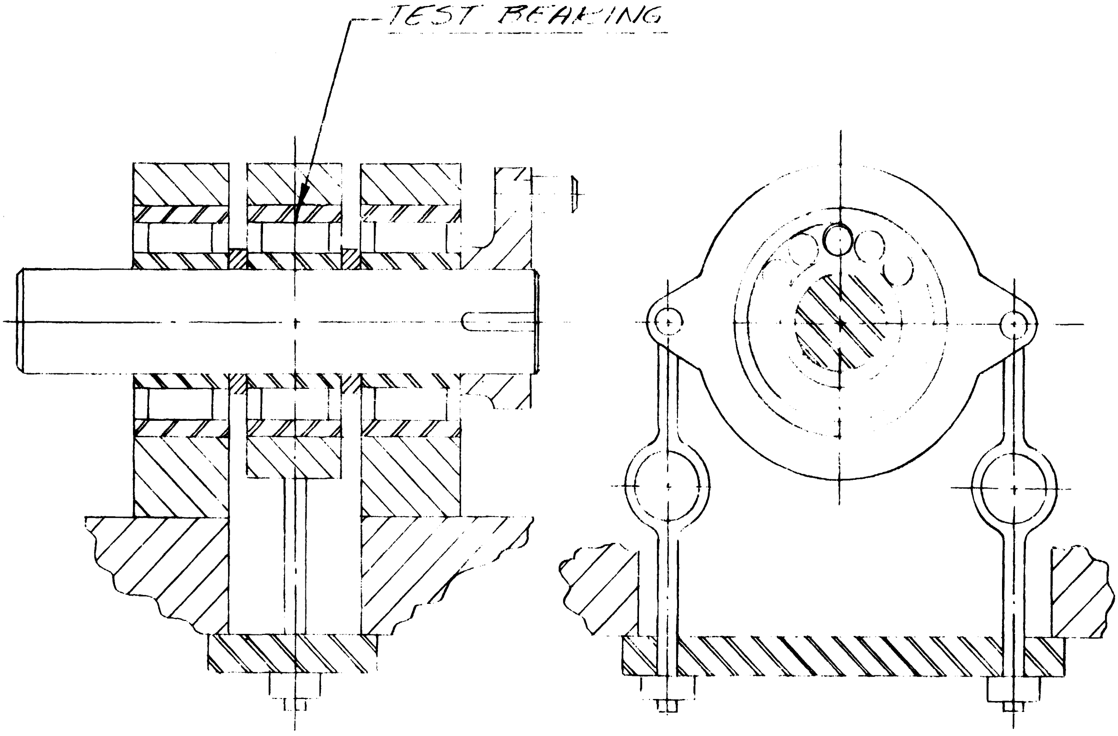
As has been inferred earlier, it will be relatively simple to design and fabricate basic machines capable of loading the outer race, oscillating the inner race, and permitting the introduction of controlled misalignments of the races. The constant reliable monitoring of the friction torque of the test bearing presents the primary probelm.

The following paragraphs outline some of our preliminary thinking on various methods for achieving the desired machines and instrumentation. As noted, we are far from a decision as to which of these methods—or whatever other method—should and will be adopted. Actually such a decision cannot be made prior to the detail study and analysis phase. Thus the following possibilities are tentative only.

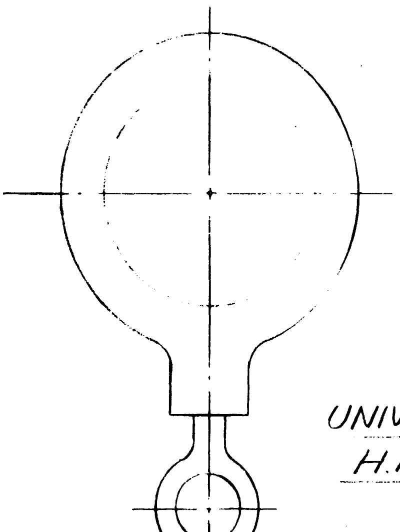
POSSIBILITY NO. 1

The construction shown schematically in Figure 1, page 20, is relatively simple. The bearing to be tested is mounted on a shaft between two supporting bearings. The required radial loading is applied through proving rings in either of the two arrangements shown, by tightening a nut (with careful control that extraneous torques are not applied to the outer race), or by similar means. A lever system might be incorporated to facilitate the loading.

As the shaft is oscillated by the crank, the friction torque induced in the test bearing changes the loading on the proving rings. In the two-ring case in the upper right-hand portion of Figure 1, the friction torque induces cyclic changes in the tension loads in the two rings, the load in one increasing slightly while the load in the other decreases simultaneously by the same amount. In the single-ring configuration at the bottom of Figure 1, the friction torque imposes a small cyclic bending moment on the proving ring. In either case the resultant cyclic stresses and strains can be sensed by means of strain transducers, such as, for example, wire strain gages. Some form of recording these outputs would then be provided.



SCHEMATIC LAYOUT



ALTERNATE METHOD OF LOADING

PROPOSED BEARING
TEST MACHINE
UNIVERSITY OF MICHIGAN
H.A. 11-2-55

FIGURE 1

The primary difficulty will lie in the small magnitude of the signal provided, as a result of the small magnitudes of the friction torques that might be expected. This does not seem insurmountable, however. Note that in each case tensile and compressive stress and strain variations are obtained simultaneously. Thus, in the customary Wheatstone bridge arrangement, all four arms of the bridge may be made "active," effectively increasing the sensitivity of the system by a factor of four.

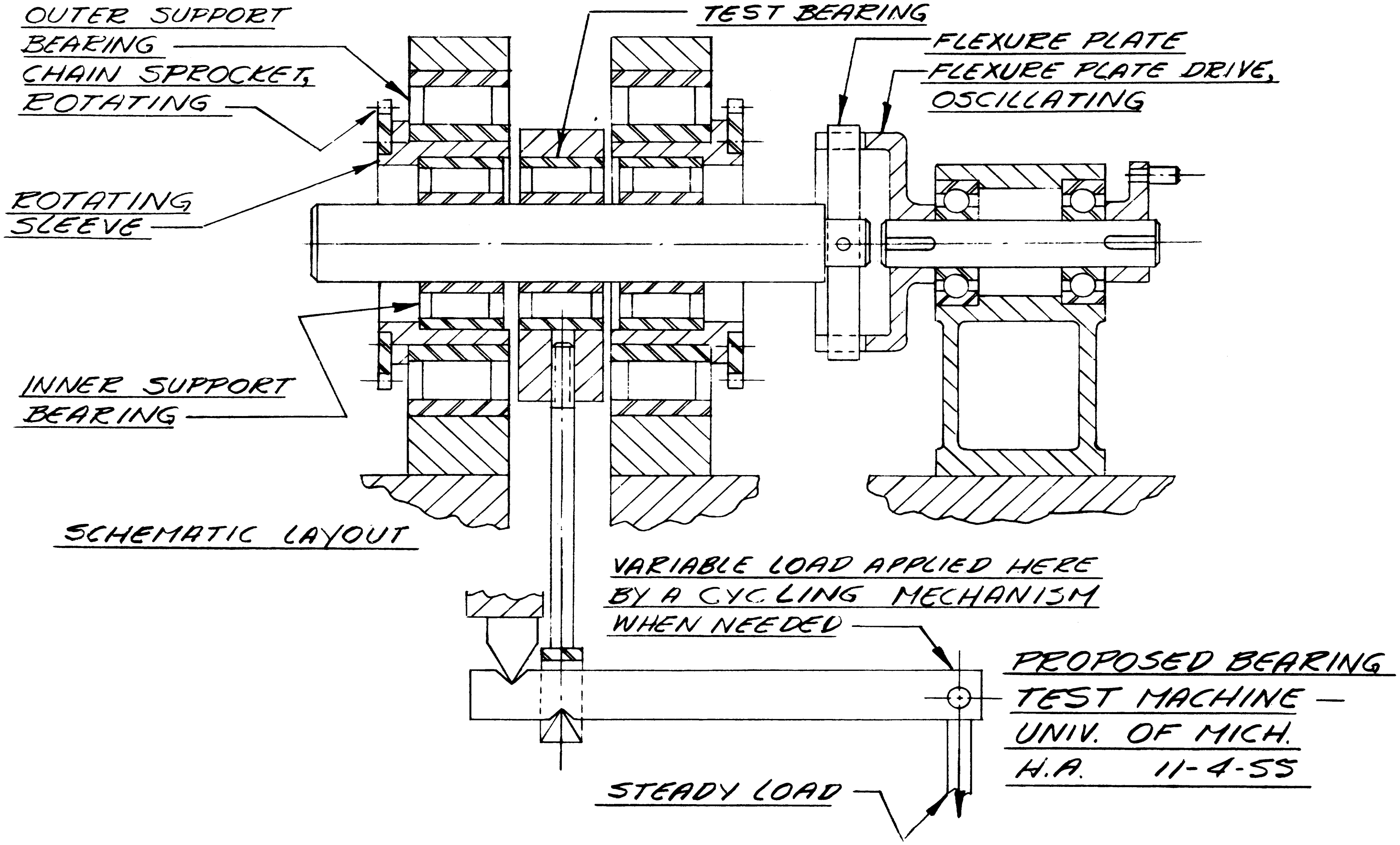
Other difficulties lie in the elimination of unwanted eccentricities in the applied loadings. The design can provide for this.

Note that this system is not well adapted to cyclic loading of the bearings, since these would also travel through the proving rings and tend to obscure the signal resulting from the friction torque, unless the frequencies of the cyclic load and the oscillation of the bearing were markedly different.

POSSIBILITY NO. 2

Another possibility is illustrated in Figure 2, page 22. Insofar as loading is concerned, this machine is similar to that of Figure 1. Here the use of a lever is illustrated schematically; in practice this lever would operate in a plane perpendicular to the shaft axis rather than as shown. Proving rings or strain gages could be used to establish the applied loads, which could include vibratory components.

The primary modification is in the measurement of the friction torque. The inner support bearings, holding the shaft carrying the test bearing, are in turn mounted in sleeves supported in auxiliary outer bearings. These sleeves can be rotated at constant speed in one direction, perhaps by a chain drive. The outer races of the inner support bearings then rotate with the sleeves.



PROPOSED BEARING
TEST MACHINE —
UNIV. OF MICH.
H.A. 11-4-55

FIGURE 2

The shaft carrying the test bearing is oscillated at the required 600 cpm by a crank, through the flexure-plate drive shown in Figure 2. The flexure plate is a tight fit in both the shaft and the driving crank member. Wire strain gages on the flexure plate provide a measure of the torque required to oscillate the shaft in either direction.

Then the oscillating motion of the inner shaft alternately will be in the same direction and the opposite direction as the rotation of the chain-driven sleeves. Consider these two possibilities separately:

1. Shaft and sleeve move in same direction

   If the sleeves turn at an angular velocity exceeding the maximum angular velocity of the oscillating shaft, friction in the inner support bearings will tend to drive the oscillating shaft, helping to overcome the friction of the test bearing. If the friction torque of the test bearing is greater than the combined friction torques of the two inner support bearings, the flexure-plate drive will provide the necessary additional torque required to overcome the test bearing friction. If the friction torque of the test bearing is less than the combined friction torques of the two inner support bearings, the flexure plate will be driven by the shaft.

   In either case, the flexure-plate gages will indicate the difference between the test bearing friction torque and the inner support bearing friction torque.

2. Shaft and sleeve move in opposite directions

   When the shaft and sleeve move in opposite directions, the friction torque of the inner support bearings will oppose the motion of the shaft. Then the flexure-plate drive must overcome the friction torque of the test bearing plus the friction torque of the two inner support bearings.

In this case the flexure-plate gages indicate the sum of the test bearing friction torque and the friction torque of the inner support bearings.

Since the flexure-plate gages alternately indicate the sum and the difference of the friction torques of the test bearing and the inner support bearings, the desired test bearing friction torque can be determined. Note that the signal can be made as large as desired, by the design (and hence stresses) of the flexure plate.

A drawback of secondary importance is present. It is clear that the relative speed of the inner and outer races of the inner support bearings are somewhat different when the sum of the torques is being measured from when the difference is being measured. However, previous work on roller bearings indicates that the friction torque is largely independent of speed; thus this effect should not seriously influence the test results.

A similar procedure can be created in which the sleeves are oscillated at the same frequency as the shaft itself. This approach introduces additional mechanisms, and therefore does not seem as desirable as that outlined above.

As noted earlier, this possibility no. 2 lends itself readily to vibratory, or cyclic, loadings. Cyclic loading of the lever produces cyclic loading of the bearings. Since all friction torque readings are obtained from the flexure plate, these readings are unaffected by the cyclic loadings.

Controlled race misalignments can be obtained readily with both of the possibilities outlined above. Consider the entire left-hand support bearing moved to the left, without changing the position of the test bearing. Then the test bearing is no longer centrally located, and the shaft takes an angular aspect at the test bearing, and a controllable misalignment is obtained.

Hollow shafting can be used, if required, to increase this effect.

In a similar sense, either of the two machines illustrated above can be used with bearing support configurations directly simulating actual helicopter rotor applications.

Preliminary layouts indicate that the machine described above would probably have overall dimensions of approximately 24" x 15" x 15", independent of the loading device.

POSSIBILITY NO. 3

A third possible machine is shown schematically in Figure 3, page 26, incorporating a cradle-type loading device. Load is applied through a lever and cradle arrangement pivoted on knife edges at the centerline of the bearing. As the bearing shaft is oscillated, the resultant friction torque will tend to turn the outer race of the test bearing, thus rotating the cradle on its knife edge pivots. Suitable signaling devices will indicate the forces necessary to restrain the cradle against such rotation; thus indicating the magnitude of the friction torque.

This type of machine relies upon the knife edge pivot remaining essentially free of friction, and upon close alignment of the knife edge pivots and the center of rotation of the test bearing. Such a machine probably would be larger than the others. It also introduces the problem of balancing the cradle on the bearing so that it would not tend to rotate due to its own weight; the signaling devices could be used in achieving this balance.

Loading of the bearing could be attained by the various means noted in the two preceding possibilities. However, the ability of this machine to indicate bearing torque accurately under cyclic loading might be questionable.

Controlled misalignment of the races might be introduced by having the top surface of the test bearing holder—on which the cradle bears—machined

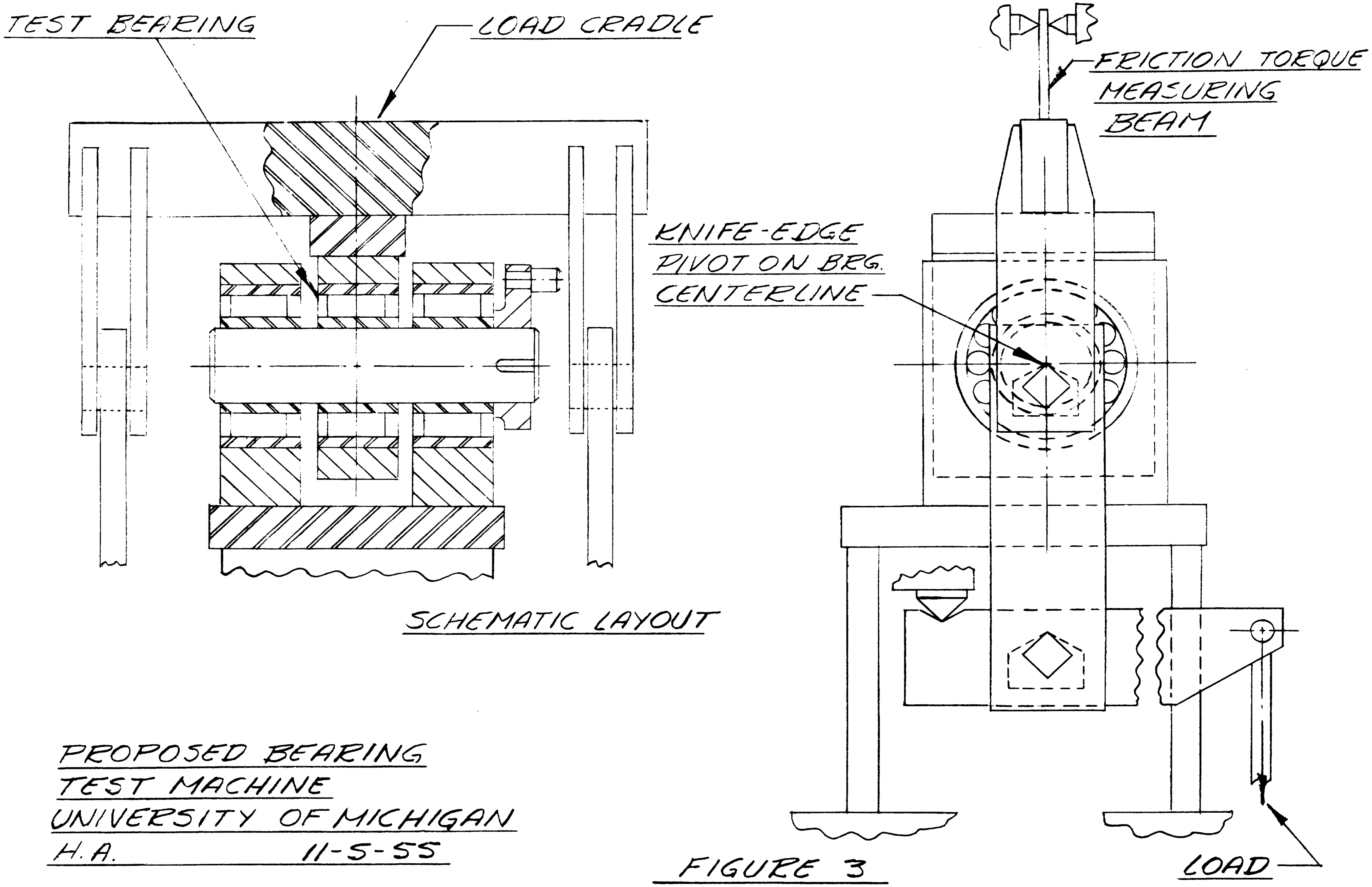

TEST BEARING
LOAD CRADLE
FRICTION TORQUE MEASURING BEAM
KNIFE-EDGE PIVOT ON BRG. CENTERLINE
SCHEMATIC LAYOUT
LOAD
PROPOSED BEARING
TEST MACHINE
UNIVERSITY OF MICHIGAN
H. A. 11-5-55

FIGURE 3

in such a way as to be nonparallel to the bore holding the outer race of the bearing. Application of the load would tend to deflect the bearing holder, providing the necessary misalignment.

OTHER POSSIBILITIES

Other possibilities for loading and instrumentation remain to be explored.

The measurement of bearing friction torque, for example, might be accomplished by the measurement of the torsional stresses in the bearing shaft on either side of the test bearing. These stresses can be related to the torques in the shaft at the positions of stress measurement. Consequently the difference in the stresses at the two sections provides a means of determining the friction torque. This very direct approach has much merit in principle; the primary question to be answered is whether a signal of sufficient magnitude can be obtained. Other electrical means of measuring the relative displacements of shaft sections on either side of the test bearing would also suffice. Again the magnitude of the available signal becomes significant. These and other means will be explored.

The general nature of the continuous monitoring of the friction torque, over and above the actual measurement of the torque, will also require consideration and study. Automatic cut-off devices will be given special attention. The intent, of course, will be to accomplish the monitoring in the most economical manner that provides reliable results.

Insofar as loadings themselves are concerned, we have begun to examine means of loading and testing several bearings in a single package. Our thoughts in this area are not sufficiently advanced to merit inclusion in this proposal. In general, direct approaches to the load problem are not difficult to find; our proposed sketches should be considered as schematic only.

We have included no direct discussion of means of programming and measuring planned or resultant changes in bearing load during the progress of the tests. This area should present no particular problem.

10. PROPOSED ACTIVITIES—TEST PROGRAM

Phase III of the overall investigation will consist of the test program proper. In this phase, then, will be carried out the experimental work called for in the initial plan developed during the detail study and analysis of Phase I, using the test machines and instrumentation evolved in Phase II.

The experimental program must begin with certain exploratory testing aimed at verifying that the adopted machines and instrumentation do indeed perform their intended function. Such exploratory work will be required in the case of each of the major variables. Once these activities are completed, the remaining test work becomes essentially routine. Clearly, in view of the slow frequency of cycling (600 cpm), the testing must proceed on an around-the-clock basis if the program is to be completed within a reasonable time.

Certain detailed comments relating to both the test requirements and the test program are discussed in the following section 11, which examines the stipulated test requirements.

The overall test program will encompass the following areas:

(1) Needle bearings
    a. Load-rating tests
    b. Installation and environmental tests

(2) Tapered roller bearings
    a. Load-rating tests
    b. Installation and environmental tests

(3) Spherical roller bearings

a. Load-rating tests

b. Installation and environmental tests

The time-phasing of the examination of these six areas can be handled in either of two distinct manners. At one extreme, the testing might be carried out in an essentially sequential manner. Thus, for example, the testing might begin with emphasis directed to the fullest possible extent on the tests of area (1)a. When the data for this area are essentially complete, the testing would shift to another area, for example, either (1)b or (2)a. Thus, as far as practicable, each area is completed before the next is begun. This would be true of work within a single area as well; a particular installation factor would be examined completely before another is begun.

In a second approach, the test program from the outset would examine several areas and variables simultaneously, in the order of their estimated importance to the early solution of the helicopter problem.

Each approach has its advantages and disadvantages. The results obtained at the completion of each portion of the program by the first method would have the full desired statistical reliability, but no information would be available on some items until the end of the entire program. In the second method, information would be coming available continually on all facets, with the statistical reliability increasing as the program progresses.

As noted earlier, it is our opinion that the second approach should be employed; it may provide an answer to the helicopter problem at an earlier date. Nonetheless, either method can be adopted; this would remain at the discretion of the sponsoring agency. The information gathered in the detail study and analysis phase should provide the basis for decision.

The test program phase will not consist of experimentation alone.

The continuing results obtained must be subjected to constant examination and analysis. This can well point out desirable shifts in the program outline, with consequent economies in time and money. The program must be kept flexible to permit such modification, if found desirable. Furthermore, both throughout the program and at its conclusion, the information obtained will be related directly to the particular questions of the helicopter problem.

11. DISCUSSION—TEST REQUIREMENTS

The detailed test requirements are outlined in Exhibit B. Concerning these, one general comment might be made: as in all other aspects of the problem, these requirements should be regarded as somewhat flexible at this time. The detail study and analysis phase, and the results obtained from the earlier portions of the testing, may indicate desirable modifications. These would be subject to the approval of the sponsoring agency.

Certain of the requirements merit brief discussion at this time.

1. Frequency and number of cycles

The stipulated 600-cpm cycling and the associated requirement of a BL-10 life of 15 million cycles automatically makes for a long-term test program, or one utilizing a large number of test machines.

2. Frictional torque

It is stipulated that failure of the bearing will be indicated when the friction torque has increased to 3 times its original values. Usual bearing-rating tests customarily have employed the appearance of the bearing as the criterion of failure. While the subject tests will be conducted with the friction-torque criterion, correlations will be made with the bearing appearance as well. This may well prove useful to the service maintenance problem.

3. Continual monitoring of friction torque

The test requirements demand a continual monitoring of the friction torque during the test period. This should prove feasible of accomplishment. Nonetheless, a periodic monitoring of the torque should also be considered during the test machine design phase, with the stipulation, of course, that the period between checks would be sufficiently small that no significant error or variation is introduced into the results. This seems readily attainable; the slow build-up of total cycles at 600 cpm would permit periodic monitoring at considerable time intervals with only a small percentage change in the overall accumulated cycles. (Note that even a 24-hour interval between monitoring would correspond to an accumulation of less than 1 million cycles, approximately ± 3% error in the 15-million-cycle definition of life.)

4. Lubricant

The test requirements stipulate that only a single lubricant is to be employed during the testing. This appears somewhat surprising, at this stage. The scanty available literature relating to bearing life under small oscillations indicates that the lubricant itself, and the state of lubrication, are major variables of the problem. This relates to the pitting-corrosion—subsurface-fatigue nature of bearing race wear and failure. Thus it would appear that the initial detail study and analysis phase should give further careful consideration to the present limitation on the lubrication factor. In the same sense, the degree of oxidation may prove significant—another factor meriting careful thought in the program planning and the machine design.

5. Misalignment

As noted in the section on the test machine, there are a number of possibilities for achieving varying degrees of race misalignment. The actual rotor hub configurations can be used directly, to give a very direct simulation of service conditions. As other approaches, misalignment can be built in by deliberate mismachining, by permitting controlled shaft deflections, and similar manners, using standardized forms of shaft and housing elements.

Both methods should certainly be employed, and the results correlated. This is another area which cannot be foreseen in advance, but must be worked out during the detail study and analysis phase.

6. Number of specimens

The number of specimens required in the test program to obtain a particular level of reliability cannot be estimated closely in advance. This is not merely a matter of definition of variables and the ranges over which they are to be examined. These aspects can be established during the detail study and analysis phase. At least equally important, the pronounced statistical nature of bearing failure means that the number of specimens required for a given reliability of the results depends on a statistical interpretation of the "scatter" obtained in the test results themselves. Thus the required number of specimens can only be determined as the tests progress. Moreover, it may well develop that certain portions of the ranges of the variables are completely excessive in terms of bearing life, and that this becomes apparent early in the testing. This would modify the numbers of test specimens significantly.

In any case, the stipulated minimum requirement of 450 test bearings (150 of each type) appears definitely to be on the low side of the number which will actually be required.

12. PERSONNEL AND FACILITIES

The conduct of the proposed program would be a joint effort of a team selected from the teaching faculty of the College of Engineering and from the full-time research staff of the Engineering Research Institute of the University.

This "team-work" approach is one of the greatest assets the University can bring to any particular problem, when considered against the diversity of knowledge and interests represented by the combined faculty and the Institute. Thus the knowledge of faculty and Institute members in all fields of engineering and science can be applied to any given question. In a similar sense, all the laboratory and instrumentation facilities of all the engineering and science departments, as well as those of the Institute itself, can be directed at any given problem. In addition, the selected team enjoys that independence and freedom from production demands that is so desirable in the conduct of fundamental investigations.

OPERATIONS OF THE ENGINEERING RESEARCH INSTITUTE

The Engineering Research Institute of The University of Michigan provides for an effective integration of the research activities of the University with its educational function. Sponsored research activities are carried on in the manner noted above, as joint efforts of the teaching faculty and the full-time research staff of the Institute. Thus the members of the faculty have the necessary opportunities for continuing practice and growth in their respective fields. Moreover, the University is able to make the most effective use of the many talents within it, in rendering its research services to the state and to the country.

A few remarks concerning the magnitude of the Institute's operations may be pertinent. During the fiscal year 1954-55, the Engineering Research Institute carried on industry- and government-sponsored research amounting to over 8.5 million dollars. This was distributed over 408 projects, comprising work in 22 broad areas. During this period, over 200 members of the teaching faculty participated on a part-time basis. Over 900 students were employed; of these approximately 270 were graduate students. The full-time professional research staff of the Institute totaled approximately 400 members, plus the usual complement of nonprofessional supporting staff.

In addition to the reports to sponsors, Institute research during the year was described in nearly 150 papers written by participating faculty and research-staff members and published in various journals, transactions, and similar media.

PROJECT TEAM FOR THIS PARTICULAR PROGRAM

As noted above, the program will be conducted by a selected team of faculty and Institute members.

The continuing technical and administrative responsibility for the program will be carried jointly by Associate Professor Rune Evaldson and Assistant Professor Herbert H. Alvord of the Department of Mechanical Engineering. They will carry on the program under the broad guidance of Professor Wyeth Allen, Chairman of the Mechanical Engineering Department. Professor Charles W. Good of the Mechanical Engineering Department will serve in a continuing consultive capacity. The Institute research staff will provide for the day-by-day conduct of the test program proper.

Professors Evaldson and Alvord will draw upon the specialized talents of other members of the faculty and the Institute as required, to form *a flexible overall team geared directly to all aspects of the problem.* Thus, for example, an applied mathematician from the Department of Engineering Mathematics will be called on to assist with the statistical aspects of the problem, from the planning stage onward. In a similar manner, other specialists can and will be called on; these might include, for example, metallurgists, aeronautical design engineers, electronic engineers specializing in instrumentation, and specialists in experiment design.

In the operating procedure of the Institute, personnel charges against the budget are related directly to the time a man spends on the project. Thus personnel services are billed against the program on an hours-worked basis.

BIOGRAPHICAL DATA ON STAFF

Summary biographical data on faculty members who will play major roles in the program are presented in the Appendix, as well as for faculty members representative of those who will be called in as specialists. However, a few additional remarks are in order highlighting those aspects of their experience that are particularly pertinent to this program.

Professor Evaldson's experience and interests are in the fields of experimental and analytical analyses of stress, strength, and vibration. As a faculty member at the University, his courses are directed at these aspects of the machine design problem. As a past employee of the Hamilton Standard Propellers Division of the United Aircraft Corporation, his duties consisted primarily of carrying out experimental investigations of the stresses and deformations in propeller blades, hubs, and other components—both in simulated laboratory tests and during actual operation—and in the conduct of fatigue tests on the same items. These programs are, of course, directly related to the installation and environmental aspects of the subject investigation. As a subsequent member of the management consulting virm of Booz, Allen, and Hamilton, Professor Evaldson worked on a number of programs—including a number in the guided missile field—which involved coordination of data obtained from many industrial and governmental sources. This activity is directly of the type required in the Detail Study and Analysis portion of the subject program. A number of the projects he directed for Booz, Allen, and Hamilton were of an "operations-research" type, effectively the determination of optimum configurations in the presence of many variables. This too parallels closely some of the demands of the helicopter problem.

Professor Alvord's experience and interests are in the field of machine design, as are his teaching duties. His industrial and research experience relate primarily to gearing and bearing applications. As a research and development engineer at Fairbanks-Morse and at Cummins Engine Company, he has directed his efforts at the design and experimental development of these aspects of the engines. Currently, in a consultive capacity, he serves as engineering advisor of a Michigan firm designing and manufacturing auxiliary transmissions of various types; again bearings and gearing are primary topics. It is interesting to note that his activities at Fairbanks-Morse included a program of development of a unit in which ball bearings were required to carry loads in the presence of oscillation. Another item of particular pertinence is his work on an Institute research project currently nearing completion. This project is an investigation of the life of plastic gears under various loadings; an integral part of the monitoring of these tests consists of the measurement of friction losses in the gears themselves and in the bearings of the test fixture.

Professor Charles W. Good is a mechanical engineer of long and diverse experience, practicing and teaching in the areas of machine design and internal combustion engines since 1918. His outstanding reputation is attested by his election as a Fellow in the American Society of Mechanical Engineers. Until recently he has been Acting Director and Associate Director of the Engineering Research Institute. Particularly pertinent to this proposal, he has directed research, and in a consulting capacity has designed test equipment, for testing of plain bearings and of gears.

As noted, Professors Evaldson and Alvord will carry out the program under the broad guidance of Professor Wyeth Allen. Professor Allen has only recently joined the University faculty as head of the Department of Mechanical and Industrial Engineering; prior to this he was president of the Globe-Union Company of Milwaukee, Wisconsin.

We feel that these men, in combination with selected specialists from all required fields of engineering and science, present a team that is admirably suited to the proposed project, and should give excellent performance and results.

FACILITIES FOR RESEARCH

As noted earlier, we can bring to this project all the diverse facilities and equipment of the College of Engineering and the Engineering Research Institute.

In all likelihood, the program would be housed in the 60,000-square-foot Automotive Laboratory which is to be completed on our North Campus by January, 1956. The facilities of the Engineering Research Institute at the Willow Run Airport provide an alternate possibility.

The laboratories of the University and the Institute provide a wide range of standard and specialized equipment and instrumentation which can be applied to the problem. Among these, as an example, the Gage Laboratory provides the items which might be required in the sampling control of the quality of the test bearings.

The construction of the test machines and fixtures is scheduled to be carried out in the shops of the College of Engineering and the Engineering Research Institute. However, full advantage will be taken of opportunities for time-savings possible in subcontracting certain aspects of this manufacturing to non-University sources.

13. REPORTS

Exhibit A calls for the preparation of certain reports. These would be provided, as called for in the exhibit.

Additional methods of reporting can be arranged to fit the sponsor's needs. In any case, a brief work report is made monthly. More complete periodic progress reports can be arranged if desired; in this particular case such reporting would appear to be justified.

14. BUDGET DISCUSSION

GENERAL REMARKS

The preceding discussions of this proposal have highlighted a number of areas of the problem that cannot be evaluated or defined with any strong degree of finality until the detail study and analysis phase is well under way. These include such significant aspects as the nature of the test machines and instrumentation, and the number of specimens that must be tested to obtain reliable results.

Clearly these are factors which have a major impact on the necessary budget. Thus the following proposed budget necessarily has a strong element of estimation in it.

We present it as our estimate of the expenditure of time and money we believe necessary to carry out a program geared to providing results consistent with the objective of the overall program. Two rather flexible prime variables are present: the number of specimens to be tested and the overall time for completion of the project. We are definitely amenable to modification and negotiation on these, subject of course to mutual agreement of the sponsoring agency and the Engineering Research Institute.

The following subsections define the primary bases on which the presented budget is predicated, and serve to illustrate the aformentioned flexibility.

NUMBER OF BEARINGS TO BE TESTED

As noted earlier in section 11, the number of bearings which must be tested in order to obtain a particular level of reliability cannot be estimated closely in advance. This is not merely a question of establishing the test variables and their ranges during the detail study and analysis of Phase I. The pronounced statistical nature of bearing failure means that the number of specimens required for a given reliability of results will depend on the "scatter" of the results themselves. Thus the number of bearings requiring test can be established only as the tests progress.

Unfortunately, the number of test specimens required is the prime variable in estimates of the budget for the program. *The following budget is based on an estimate that 600 bearings will be tested.* We believe this number will provide an *engineering* answer to the helicopter problem.

A total of 600 specimens is likely to be insufficient for a completely statistical examination of all the variables and the relations between them. Indeed, it would be possible to make an entirely legitimate estimate of as many as three times this number. The results of such an expanded program would have much greater statistical reliability. Such results would be more proper in terms of fundamental design criteria for all bearing problems of this type. We believe, however, that 600 specimens can serve the immediate needs of the helicopter problem.

Extensions of the program to improve the basic design criteria characteristics of the data can be made subsequently, if desired. Then the earlier results of the 600-bearing program will serve as a useful base for the extended program. Tentative budget estimates of an approximate nature are also presented for expanded programs of 1200 and 2000 bearings, should such programs be more representative of the plans and desires of the sponsoring agency.

TIME REQUIRED FOR COMPLETION OF PROGRAM

The overall time required to complete the program also has considerable flexibility. We believe three years would provide a desirable time period, and would make the expenditures for machines and instrumentation both effective and economical. Thus the following proposal is predicated on a three-year period. As noted in earlier discussions, partial results useful to the helicopter problem might well become available considerably before the end of this overall time period.

It is clear that a longer time period could also be established. This would lead to a more economical utilization of the test machines and instrumentation. However, a period longer than three years would appear unrealistic in view of the current demands of the helicopter problem. It would also be possible to reduce the time period somewhat, but only at the expense of additional test machines and instrumentation. Two years would be a bare minimum for the 600 tests; this period would require what would appear to be an excessive number of machines. A two-and-one-half-year period would perhaps be the shortest feasible time.

As noted, the question of the time period is open to discussion and negotiation.

TIME REQUIREMENTS FOR INDIVIDUAL PHASES OF THE PROGRAM

The following time estimates are geared to our proposed three-year program. Our estimates for the individual phases are:

1. Detail Study and Analysis. We will begin this phase directly on receipt of contract. All information should be gathered well within 3 months, and the required formal report on this phase should be available within 4 months of receipt of contract.

2. Machine and Instrumentation Design. Certain aspects of this phase will begin directly on receipt of contract; however, the final design will be dependent on the information gathered during the detail study and analysis phase. With this approach, designs for machines and instrumentation for certain portions of the test program, for example, the basic load-rating tests, should be developed within 4 months of receipt of contract. All designs and instrumentation should be formulated within 10 months.

   On this basis, it is expected that some machines will have been built and will be ready for verification testing within 7 months of receipt of contract. If desired, the fabrication program can begin with the construction of one or two machines of each general required category. Then their performance can be explored before the overall proposed total of 15 machines is completed. On this basis, it is estimated that the 15 required machines would come available at the end of the first year.

   These estimated time limits might be reduced somewhat if the construction of all machines is begun more or less simultaneously. The designs should prove quite direct and obvious. Very little gamble would be involved by their simultaneous construction. At best some slight modification might prove necessary. Thus it is entirely possible that sizable time-savings might accrue with a limited additional dollar cost.

3. Test Program. On the basis of the above, the testing program proper should be well under way at the end of the first year.

   Time limits for completion of various aspects of the program cannot be set until the most desirable sequence of testing is established by the detail study and analysis phase. For discussion purposes, however, assume that all testing of the needle bearings would be completed before that of the tapered roller bearings was begun, and so forth. On this basis, we would expect the load-rating and environmental testing of the needle bearings to be completed during the twentieth month, the tapered roller bearings during the twenty-eighth month and the spherical roller bearings during the thirty-fourth month. This leaves two months for overall coordination and report preparation; note, however, that the examination, correlation, and dissemination of the data would be a continuing process throughout the test program.

As noted earlier in the section 7, we believe that the above sequential test program is not the approach best suited to obtaining results useful to the helicopter problem at the earliest possible instance. Rather, we would recommend that the program investigate several variables simultaneously. However, the above time estimates should serve to demonstrate our expected time performance on our proposed program.

The above can be taken as our considered estimates only, and not as guarantees of delivery.

PERSONNEL BUDGET

This section presents the estimated requirements on personnel time. The corresponding dollar budget, complete with overhead, is summarized in a separate section. Following are our estimates of the personnel time required, in man-months, to carry out the overall specified program for a three-year period (36 months). Individuals already selected for the team are presented by name; specialists to be called in for particular facets of the work are designated merely by the area of their specialty.

1.	Associate Professor Rune Evaldson (Overall planning, design, technical direction, analysis, and interpretation of results, reporting.)	12 man-months
2.	Assistant Professor Herbert H. Alvord (Overall planning, design, technical direction, analysis, and interpretation of results, reporting.)	12 man-months
3.	Professor Charles W. Good (Continuing consultation.)	4 man-months
4.	Applied Mathematician (Statistician) (Statistical aspects of planning, monitoring of continuing results, analysis of final results.)	4 man-months
5.	Specialists in Design and Instrumentation (Assistance in design of test machines and allied instrumentation.)	4 man-months
6.	Specialists and Miscellaneous Professional Staff (Specialists in various areas as required. Areas are likely to include metallurgy of corrosion and wear, lubricants, aeronautical design, and the like. Also includes professional personnel used as required to expand test team in periods of maximum effort.)	3 man-months
7.	Supervisor of Test Program (Permanent full-time staff member of the Engineering Research Institute, in responsible charge of the continuing day-by-day testing.)	24 man-months
8.	Technicians and Mechanics (Full-time personnel handling the detailed test setups, tests, and the like.)	30 man-months
9.	Student Assistants or Equivalent (Monitoring of tests, analysis of data, and the like.)	50 man-months

The above estimates do not include man-power charges associated with the direct fabrication and assembly of the machines. These are included in the total dollar cost estimates of these systems.

The estimates for laboratory personnel are tenuous indeed, depending on the degree to which the tests must be monitored by personnel rather than by instrumentation. This must await completion of the design phase. Thus the man-power estimates for items 8 and 9 may be reduced significantly in the final outcome.

COST ESTIMATES FOR TEST MACHINES AND INSTRUMENTATION

It is certainly clear that no more than tentative estimates can be made of the ultimate costs of machines and instrumentation whose basic natures have not as yet been established. The following cost estimates, made under this condition, are based primarily on our composite experience or other test and research projects whose complexities appear to parallel those of the subject problem.

We estimate that a total of 15 machines will be required to conduct the above program in a calendar time of 3 years. Ideally these machines would all be modifications of a basic model, the modifications serving to adapt the machines to the examination of the various variables. In actuality, it may become necessary to design and fabricate more than one basic type of machine. Suitable instrumentation will also be required. In addition, a number of special test fixtures will be necessary to the conduct of the program. Our cost estimates for this equipment is itemized with other costs in a separate section. The test machines and fixtures will be manufactured in the shops of the Engineering College and the Institute unless outside sources provide savings in time.

BEARING COSTS

Even the cost of the test bearings themselves introduces a sizable source of error in the proposed budget. The test requirements specify bearings "of aircraft quality." This can have many meanings. In one sense, "aircraft quality" becomes the quality of whatever bearings are being used in the current helicopter applications. In another sense, it implies a particularly high level of quality. In such items as bearings, a relatively slight change in the level of quality can introduce great price differentials.

We understand from certain bearing manufacturers that the bearings currently used in the helicopter applications (and hence termed "of aircraft quality") have a cost somewhat less than $5.00 per bearing. On this basis, we estimate the bearing costs to total approximately $3500.00, allowing a certain number of spares for sampling and miscellaneous usage. An upgrading of the quality level from that represented by the $5.00 figure could easily raise this cost to four times the above value.

SUMMARY DOLLAR BUDGET

The summary dollar budget for our three-year, 600-specimen proposed program, complete with overhead charges, is presented in the following section.

In view of the many uncertainities noted above, this proposed budget can be nothing more than a proposal for time and services to be rendered, directed against a program which we believe to be capable of accomplishment.

As noted, we are completely amenable to discussion and modification of the scope of the program, the time period for accomplishment, and the division of the program into various budget-year bases.

The particular points meriting such discussion are the scope of the program—as measured by the numbers of bearings to be tested—and the overall time duration of the program. Our selected values, 600 specimens and 3 years, are tentative estimates of what we believe to be satisfactory.

The urgency of the program, in terms of time, may make a shorter time period necessary to the sponsoring agency. In such a case, we can modify our present estimates to suit the actual demands; as noted the program can be condensed somewhat at the expense of a somewhat increased cost per bearing tested.

In a similar sense, we have pointed out earlier that a legitimate argument could be made for expanding the program to include many more specimens than the 600 on which we are basing our proposal. We can expand our program to meet such a condition, should the sponsoring agency so desire. Tentative cost estimates for three-year expanded programs of 1200 and 2000 bearings are presented in the following section, along with the proposed three-year, 600-specimen budget. It will be noted that the dollar cost per bearing tested diminishes significantly as the scope of the program is expanded. This is due to the elements of more-or-less fixed cost that remain essentially constant despite the magnitude of the program; these include such cost items as planning, design, analysis, and so forth.

APPENDIX

General Bibliographies of the Proposed Key Personnel

ALVORD, HERBERT H. Assistant Professor of Mechanical Engineering

Education: B.S. (M.E.) Mich. College of Mining and Tech., 1942. M.S. (M.E.) Univ. of Mich., 1950.

Employment: Academic
Univ. of Mich.: Inst. 1947-51; Asst. Prof. 1951-present.
Other Professional
Elec. Design Engr., Culter-Hammer, Inc., Milwaukee, Wis., 1942-43; Diesel Eng. Devel. Engr., Fairbanks-Morse and Co., Beloit, Wis., 1943-45; Diesel Eng. Devel. Engr., Cummins Engine Co., Columbus, Ind., 1945-47; Design Engr., Chelsea Products Co., Chelsea, Mich., 1951-present (part time).

Experience: Design and layout of electrical control devices; design and redesign of engines and parts; conducting and supervising tests and test programs to improve power output, combustion efficiency, life of parts, etc.; mechanical design of parts for a gas turbine used as a heating device; testing of combustion improving devices on an automobile engine; gear design; design of geared power takeoffs and auxiliary geared transmissions for heavy-duty trucks.

Professional and Honorary Societies: Am. Soc. for Engr. Education; Am. Soc. of Automotive Engrs. (Aeronautical Drafting Manual Committee, S-1).

CARVER, HARRY C. Professor

Education: B.S., Univ. of Mich., 1915.

Employment: Academic
Univ. of Mich.: Inst., 1916-18; Asst. Prof., 1918-25; Assoc. Prof., 1925-36; Prof., 1936-.
Other Professional
Operations Analyst, U.S. Air Force, 1944-45.

Experience: Research on various subjects shown under "Publications."

Publications: Books, Bulletins, etc.--Statistical Tables, Edwards, Ann Arbor, 1940. Introduction to Air Navigation, Edwards, Ann Arbor, 1943. Tables of Compound Interest Functions and Logarithms of Compound Interest Functions, Wahr, Ann Arbor, 1944. Introduction to Mathematical Statistics, 1949. Mathematical Statistical Tables, 1950.
Articles--Several on applications of statistical and actuarial methods.
Editor of Journal: Editor of Annals of Mathematical Statistics, 1930-38.

Professional and Honorary Societies: Am. Statistical Assn.; Czechoslovakian Statistical Soc.; Institute of Mathematical Statistics.

Listed in: American Men of Science; Who's Who in America.

DARLING, DONALD A. Assistant Professor

Education: A.B., Univ. of Calif. at Los Angeles, 1940; Ph.D., Calif. Inst. of Tech., 1947.

Employment: Academic
Rutgers Univ.: Asst. Prof., 1948-49. Univ. of Mich.: 1949-.
Other Professional
Statistical Supervisor, U.S. Army Air Force, Calif. Inst. of Tech., 1941-45; Statistician, U.S. Naval Ordnance Test Station, Calif., 1946-47; Research Assoc., Cornell Univ., 1947-48; Consultant, RAND Corp., Santa Monica, Calif., for 12 summers.

Experience: Mathematical statistics; probability and applications; stochastic processes.

Professional and Honorary Societies: Am. Mathematical Soc.; Institute of Mathematical Statistics; Mathematical Assn. of America.

Listed in: American Men of Science.

DWYER, PAUL S. Professor

Education: A.B., Allegheny College, 1921; M.A., Penn. State College, 1923; Ph.D., Univ. of Mich., 1936.

Employment: Academic
Penn. State College: Inst., 1921-26. Antioch College: Asst. Prof., 1926-29; Assoc. Prof., 1929-33; Prof., 1933-36. Univ. of Mich.: Research Asst., Research Assoc., and Consultant, Office of Educational Investigations, 1936-45; Asst. Prof., 1937-42; Assoc. Prof., 1942-46; Prof., 1946- ; Consultant, Statistical Research Laboratory, 1947-.
Other Professional
Research Assoc., Princeton Univ., 1942; Consultant, Adjutant General's Office, Dept. of Army, (part time) 1950-.

Experience: Mathematics and educational statistics; use of Hollerith machines in statistical work; statistical computation techniques, specifically on fire control, matrix inversion, and linear programming.

Publications: Books, Bulletins, etc.--A Study of the Geographic Distribution of Students in 363 American Colleges and Universities (with coauthor), Rutgers Univ. School of Educ., New Studies in Educ. No. 1, 1931. A Statistical Summary of the Records of Students Entering the University of Michigan in the Decade 1927-36 (with 2 coauthors), Univ. of Mich. Adm. Studies, I, No. 4, 1940. Linear Computations, Wiley, 1951.

Articles--36 (a few with coauthors) in the field of statistics, sampling, computing machines, matrices, correlation coefficients, etc.

Professional and Honorary Societies: Am. Assn. for the Advancement of Science; Am. Mathematical Soc.; Am. Statistical Assn.; Biometric Soc.; Econometric Soc.; Institute of Mathematical Statistics (Secy.-Treas., 1943-49; Pres.-Elect, 1950; Pres., 1951); Mathematical Assn. of America; Psychometric Soc.

Listed in: American Men of Science; Who's Who in American Education; Who's Who in the Midwest; Who's Who in America.

EVALDSON, RUNE L. Associate Professor of Mechanical Engineering

Education: B.S., (M.E.), Univ. of Illinois, 1941; Ph.D. (E.M.), Stanford Univ., 1950.

Employment: Academic

Stanford Univ.: Research Asst. and Teaching Asst., 1947-50; Univ. of Mich.: Associate Professor, 1953-present.

Other Professional

Senior Analytical Engineer, Hamilton Standard Div., United Aircraft Corporation, East Hartford, Conn., 1941-47; Engineering Consultant, Booz, Allen and Hamilton, Chicago, Ill., 1950-53.

Experience: Experimental and theoretical stress and vibration analysis, fatigue-strength studies of materials, components, and assemblies; management consulting surveys of organizations, operations, and personnel of engineering and research organizations; classified "Operations-Research" studies of cost, effectiveness, and characteristics of weapon systems.

Publications: Articles--1 (with coauthors) on dynamic response of nonlinear systems to transient disturbances.

Professional and Honorary Societies: Soc. of Automotive Engineers; Inst. of American Society of Mechanical Engineers; Sigma Xi; Tau Beta Pi.

GOOD, CHARLES W. Professor of Mechanical Engineering

Education: B.S.E. (M.E.), Univ. of Mich., 1918.

Employment: Adademic
Univ. of Mich.: Inst. in Automotive Mechanics, 1918; Inst. in Mechanical Engineering, 1918-25; Asst. Prof., 1925-33; Assoc. Prof., 1933-43; Prof., 1943-(on leave 1951-53).
Other Professional
Eng. Res. Inst.: Asst. to Director, 1923-36; Asst. Director, 1936-51. Member, Engineering College Research Council, Univ. of Mich.; Atomic Energy Commission, 1951-53.

Experience: Internal-combustion engines; study of various internal-combustion-engine fuels at high compression ratios; effect of valve timing and other factors on volumetric efficiency; effect of hydrogen as a fuel when used alone and in combination with other fuels; design of clutches and development of equipment to test clutches; mechanical research on bearings, etc.

Publications: Books, Bulletins, etc.—Internal Combustion Engines (with coauthors), Edwards, rev. ed., 1944.
Articles—"Theoretical Consideration of Power Loss Caused by Combustion Knock."

Professional and Honorary Societies: Am. Soc. for Engineering Education; Am. Soc. of Mechanical Engineers; Engineering Soc. of Detroit; Soc. of Automotive Engineers; Tau Beta Pi.

Listed in: American Men of Science; Who Knows - And What; Who's Who in America; Who's Who in Engineering; Who's Who in the Midwest.

HALL, KEITH W. Associate Professor of Mechanical Engineering

Education: B.S. (M.E.), Univ. of Alabama, 1933. (Reg. Mech. Engr.)

Employment: Academic
Univ. of Mich.: Asst. Prof., 1949-51; Assoc. Prof., 1951-present.
Other Professional
Detroit Edison Co., 1930-31; Toledo Scale Co., 1933-46; Defiance Machine Works, 1946-49; Assoc., Delos M. Palmer and Assoc., 1949-present; Consultant, Baldwin-Lima-Hamilton Corp., 1949; Ohio Plate Glass Co., 1951-52; Wyandotte Chem. Corp., 1951.

Experience: Experimental work on new scale developments; research and development to improve storage of living produce; machine-tool design; design and development of hydraulic and mechanical presses and special production machines.

Publications: Books, Bulletins, etc.—"Performing Presses," in Mod. Plas. Ency., 1948; articles - 1 on molding process.

Professional and Honorary Societies: Soc. of Plastic Engineers; Am. Soc. for Engineering Education; Am. Soc. of Mech. Engineers; Tau Beta Pi.

ISAKSON, GABRIEL   Associate Professor

Education: B. Eng. (M.E.), Magill Univ., 1942; S.M. (Ae.E.), M.I.T., 1947, Sc.D. (Ae.E.), M.I.T., 1953.

Employment: Academic
M.I.T.: Research Asst., 1946-47, 1952-53. Univ. of Mich.: Assoc. Prof., 1955-present.
Other Professional
Junior Research Engineer, National Research Council (Canada) 1942-45. Senior Stress Analyst, Canadian Limited, Montreal, Canada, 1945-46. Staff member, Div. of Industrial Cooperation, M.I.T., 1947-52. Staff Engineer - Preliminary Design, Kaman Aircraft Corp., Bloomfield, Conn., 1953-55.

Experience: Aircraft structural research, analysis and design; research in structures dynamics, aero-elasticity, and thermal stress; analysis and design of rotary wing aircraft.

Publications: Books, Bulletins, etc.---Ten research reports (nine with coauthors) submitted by the Aero-Elastic and Structures Lab., M.I.T., to U.S. Air Force, in the field of gust loads, structural dynamics and aero-elasticity.
Articles--Four papers (three with coauthors) published by the Journal of the Aero. Sciences on gust loads, structural dynamics, and aero-elasticity.

Professional and Honorary Societies: Institute of the Aeronautical Sciences, American Helicopter Society, Sigma Xi.

JONES, LESLIE M.   Research Engineer

Education: B.S.E. (Phys.), Univ. Of Mich., 1940.

Employment: Sound Engineer, Woodall Industries, Detroit, Mich., 1940-41; Production Engineer, Western Electric, Kearny, N.J., 1941-42; Industrial Electronics Instrument Engineer, Physicists Research Co., Ann Arbor, Mich., 1942-46; Research Engineer, Eng. Res. Inst., 1947- present.

Experience: Application of electronics and end-organ design to industrial and research measurements in such fields as acoustics, surface finishes, aircraft-engine performance, rocket performance, and upper-atmosphere physics; supervision of upper-atmosphere research program.

SCHAFFER, EDWARD J. Research Engineer

Education: B.E.E., Cooper Union, 1943; M.S., Univ. of Mich., 1948.

Employment: H.O. Boehme, New York, N.Y., 1941-43; Asst. Electrical Engineer Princeton Univ., 1943-46; Research Engineer, Eng. Res. Inst., 1946- .

Experience: Production testing and inspection in industrial plant; design, construction, and maintenance of field electronic equipment for scientific investigations; design and field testing of fm-fm telemetering system for pilotless aircraft (now known as Raymond Rosen FM-FM System); design and field installation of rocket-borne instruments for upper-atmosphere research.

Professional and Honorary Societies: Am. Institute of Electrical Engineers; Institute of Radio Engineers; Sigma Xi.

SIEBERT, CLARENCE A. Professor of Chemical and Metallurgical Engineering

Education: B.S.E., Wayne Univ., 1930; M.S.E., Univ. of Mich., 1931; Ph.D., Univ. of Mich., 1933. (Registered Chemical Engineer)

Employment: Academic
Wayne Univ.: Inst. in Metallurgical Engineering, 1934-36; Univ. of Mich.; Asst. Prof. of Met. Engr. 1936-42; Assoc. Prof., 1942-47; Prof. of Chem. and Met. Engr., 1947-present.
Other Professional
Research Engineer, Motor Prod. Div., U.S. Rubber Co., 1933-34; Consulting Eng. to Houdaille-Hershey Corp. and Muskegon Motor Specialties, 1937-present; Work on Manhattan Proj., 1943-44 (on leave from Univ. of Mich.).

Experience: Thermodynamic studies of metal reactions; physical metallurgy studies in the ferrous field; work on Manhattan Proj.

Publications: Books, Bulletins, etc.--Literature Survey of the Low-Temperature Properties of Metals (with coauthor), Government Printing Office, 1946 (republished, Edwards, 1947).

Articles--7 (with coauthors) on properties of low-carbon steels, quenching oils and heat transfer in circulating furnaces.

Professional and Honorary Societies: Am. Inst. of Mining and Metallurgical Engineers; Am. Soc. for Engr. Education; Am. Soc. for Metals; Am. Soc. for Testing Materials; Nat'l. Assn. of Corrosion Engineers; Phi Lambda Upsilon; Sigma Xi.

SINNOTT, MAURICE J. Associate Professor of Chemical and Metallurgical Engineering

Education: B.S.E. (Ch.E.), Univ. of Mich., 1938; M.S. (Ch.E.), Univ. of Mich., 1941; Sc.D. (M.E.), Univ. of Mich., 1946.

Employment: Academic
Univ. of Mich.: Inst., 1944-47; Asst. Prof., 1947-50; Assoc. Prof., 1950-present.
Other Professional
Plant Metallurgist, Great Lakes Steel Corp., 1938-40; Univ. of Mich., Eng. Res. Inst., 1940-43; Senior Res. and Devel. Engr., Goodyear Aircraft Corp., 1943.

Experience: Heat transfer; high-temperature metallurgy; metallurgical thermodynamics; physical metallurgy.

Publications: Books, Bulletins, etc.--Structure and Properties of Solids, Edwards Bros., Ann Arbor, Mich.

Articles--9 (with coauthors) on creep in titanium, nodular irons, salt quenching and recirculating furnaces.

Professional and Honorary Societies: Am. Inst. of Mining and Metallurgical Engrs., Am. Soc. for Metals; British Inst. of Metals; Alpha Chi Sigma; Phi Kappa Phi; Sigma Xi.

SPENCER, NELSON W. Research Engineer

Education: B.S.E. (E.E.), Univ. of Mich., 1941; M.S.E. (E.E.), Univ. of Mich., 1953.

Employment: Sciaky Bros., Chicago, 1941-44; U.S.N.R., 1944-46; Research Engineer, Eng. Res. Inst., 1946- .

Experience: Electronics, specifically design, development, construction, rocket instrumentation, and supervision.