CORRELATION OF FATIGUE DATA TO DETERMINE STRESS CONCENTRATION FACTORS IN 76S-T ALUMINUM ALLOYS

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SUMMARY

The purpose of this study was to determine the stress concentration factor in a shoulder under a cyclic tensile load. The test specimens were models of a propeller blade root section similar to the blade design now employed in the fans of the Cooperative Wind Tunnel. All specimens were given a 5 microinch finish and all were made of 76S-T aluminum alloy taken from an actual propeller blade forging. Two series of tests were conducted. One series consisted of a cyclic tensile load varying from zero to maximum over a nominal stress range from 21,000 psi to 28,000 psi. The other series consisted of a cyclic load, wherein the amplitude of the cyclic stress was varied from 20 to 50 percent of the maximum developed stress. These two conditions would correspond respectively to the "start-stop" cycle of wind tunnel operation and to constant speed tunnel operation.

It was found that the stress concentration factor determined from the fatigue test results closely approximated the results obtained from the three dimensional static tests of the actual blade.

This work was carried out by the authors at the Guggenheim Aeronautical Laboratory, California Institute of Technology, under the supervision of Dr. E. E. Sechler.

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I. INTRODUCTION

The failure of metals by fatigue has long posed interesting and difficult problems for both the structural engineer and the metallurgist. The general analytical solution of fatigue failures has yet to be developed, but much empirical and experimental data has been compiled on the subject over a period of years. Through experiment and experience optimum design shapes and surface finishes have been found to increase the fatigue life of certain metals. The metallurgist has developed many new alloys with improved mechanical properties but he has not been able as yet to increase materially the endurance limit of these new alloys. It has been left to the engineer to find ways and means of minimizing stress concentrations in particular structures subjected to repeated cyclic loadings.

This study is one particular attempt to determine stress concentration values in a tension specimen loaded at a shoulder. The initiation of the study was prompted by a fatigue failure of a propeller blade in the Cooperative Wind Tunnel, Pasadena, California, which resulted in extensive damage to the tunnel itself as well as a loss of valuable time while the tunnel was under repair. The failed wind tunnel propeller blade is shown in Fig. 1. The specimens tested were scaled after the present blade design used in the Cooperative Wind Tunnel and the loading cycles were taken to approximate the start-stop cycle of wind tunnel operation and also the fluctuating tensile load caused primarily by the bending load due to aerodynamic interference between blades and nacelle supports.

This study then is an attempt to correlate the model fatigue studies with the actual propeller blade operation, but in particular it is an attempt to determine stress concentration values in a particular metal of a particular structural shape, under particular loading patterns. The investigation therefore is of a very specialized nature and the results thereof must necessarily be limited in their application.

The study was conducted by the authors in the Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California under the supervision of Dr. E. E. Sechler during the period from November 1949 to May 1950.

II. EQUIPMENT AND PROCEDURE

Specimens:

All specimens were machined from 76S-T aluminum alloy taken from an actual wind tunnel propeller blade forging; the axis of symmetry of the specimens was taken with the grain of the propeller forging. The blade root section was constructed to one-tenth scale, the specimen dimensions being taken from the Cooperative Wind Tunnel blueprint of the actual propeller blade. Certain minor features of the actual blade could not be reproduced because of the very small dimensions of the specimen. The major dimensions and features of the actual blade were retained in the model and the specimen under fatigue could reasonably be expected to duplicate the actual blade so far as shape factors were concerned. Because of the great importance of surface finish on fatigue life, all specimens were finished to approximately five microinches. Great care was taken to insure that no surface scratches or marks were introduced which might cause local stress concentrations at the surface and subsequent failure. Detail drawings and dimensions of the specimens tested are shown in Figs. 2 and 3. As a check on the dimensional accuracy of the machining operations, an actual specimen was checked in a Jones and Lamson optical comparator. The results of this optical check are shown in Fig. 4.

Specimen Fixture:

The specimens were mounted in a jig designed by the authors and constructed in the GALCIT Machine Shop. The jig, shown in Figs. 5 and 6, closely approximated the method by which the actual wind tunnel blades were fixed in the wind tunnel except that in the actual blade fixture a clamp was used above the flange section to restrain the blade in bending. However, the introduction of tensile loads in the model and the actual blade was the same. The jig applied the tensile load to the upper flange surface over the same proportionate area as experienced by the full size blade.

During testing in the Sonntag machine one of the hold-down bolts on the jig failed with consequent warping of the split-ring section of the jig. The split ring was then replaced by a new one made of 3/8 inch thick heat-treated steel. The old bolts were replaced by AN heat-treated 1/4 inch steel bolts. No further difficulty was experienced with the jig after this modification, although it is believed that the old bolts would not have failed had they been tightened periodically during the fatigue tests. It was later found that these hold-down bolts slowly worked loose under the cyclic loading. In practice the bolts were tightened before the jig was placed in the testing machine. When the cyclic loading was placed on the specimen and fixture, the specimen quickly seated itself in the jig and the initial tension on the bolts relaxed. An offset screwdriver was then used to re-tighten the bolts. Because of the difficulty involved in tightening the slotted head machine bolts, this type of bolt was finally replaced by an Allen head bolt of the same diameter. The Allen head bolts proved most satisfactory and speeded up the fixture of the specimen in the jig.

Stress Measurements:

To determine actual stresses at some reference section in the specimen, three strain gages were mounted on each specimen at 120 degree intervals around the circumference. These gages were Baldwin-Southwark SR-4 electrical strain gages, type A1, and carried lot number MZ. Stresses were calculated according to the following formula:

$$\sigma = \frac{\mu V \times 40}{BV \times GF}$$

where μv was the gage reading in microvolts, BV the battery voltage in volts, and GF was the gage factor. The gage factor for this lot of strain gages was listed as 2.04.

The first major problem which had to be resolved was the accurate determination of this gage factor. If the gage factor varied widely with each individual gage it would be necessary to determine the extent of this variation so that correct values of stress would be reported by each gage. The manufacturer listed the gage factor for this MZ lot as 2.04 plus or minus 1 %, but a verification of this figure was needed to insure the accuracy of subsequent procedure.

The gages were mounted on the test specimens according to the manufacturer's instructions, air dried for 24 hours, and then baked under infra-red lamps for an additional 8 hours at 150 degrees F. The baking process insured the complete polymerization of the adhesive. Without baking, the cement would remain in an unstable condition for several days and any strain gage readings taken during this period would be inconsistent.

The location of the strain gages on the specimen is shown in Fig. 2. The 120 degree intervals around the circumference of the specimen at the gage reference section were obtained by marking the specimen in a lathe where accurate interval measurement was possible. The marking was done with a soft lead pencil so as not to mar the surface finish in the vicinity of the test section. The plastic covered lead wires to the strain gages were carefully soldered to the gage wires to assure good electrical contact. After the baking operation all gages were tested for shorts and current leakage. All the gages were found to be satisfactory in this respect.

The verification of the gage factor was accomplished in the following manner. The specimen was mounted in a Riehle beam balance tensile testing machine and loaded in 500 pound increments to a maximum load of 2500 pounds. The strain gages were connected to a switching panel which connected one gage at a time to a Leeds and Northrup Potentiometer. Three dummy strain gages mounted on a solid block of 76S-T alloy were coupled into the switching panel to compensate for temperature effect on the active gage microvolt readings. Microvolt readings were then taken on all three gages at each tensile load level. From the cross-sectional area at the gage reference section and the value of the tensile load as read from the beam balance, the tensile stress at this section was computed by the usual formula P/A. Using the formula $\sigma = \frac{40 \times \mu V}{BV \times GF}$ and solving for GF, values of the gage factor for each gage were determined. It was found that the method of gripping the specimen in the machine introduced a considerable amount of bending into the specimen. To cancel the effects of bending it was necessary to rotate the specimen 120 degrees three times until each gage occupied the position formerly occupied by the others. In this way the effect of the bending was eliminated and an average gage factor for each gage was found. In this manner the gage factor was determined to be within 2% of 2.05. This value of 2.05 was used in all subsequent strain gage calculations. This value for gage factor agrees closely with that found by Campbell in a random sampling of the SR-4 type A1 gages. (See ref. 2). A standard 6 volt wet cell storage battery was used as a power supply for these calibrations.

Dynamic Stress Measurements:

To determine the dynamic stresses in the specimens due to cyclic loadings two methods were available. One means was provided within the Sonntag testing machine itself. Here a self-contained dial micrometer could be used to measure the preload on the specimen, while the dynamic loading could be obtained from the reading on the displacement scale of the eccentric weight which causes the oscillating force. These two measurements were provided within the Sonntag testing machine and were stated by the manufacturer to be accurate within 2% throughout the range of the machine. The other means of checking the dynamic loading was through the electrical strain gages coupled with a recording oscillograph. To accomplish this result electrical components were designed and built in the following manner. A three channel test panel was designed to be used in conjunction with the potentiometer to measure static stresses, and with a recording oscillograph to measure the dynamic stresses. A Heiland recorder was used to measure the dynamic stresses as reported by the strain gages. The Heiland gives a visible record of the fluctuating loads on the specimen by means of a photographic tape that runs through the device at a constant speed providing a time-amplitude trace for each of the three strain gages. The arrangement of this electrical set-up is shown in Figs. 7, 8. A typical Heiland trace is shown in Fig. 13. To provide a means of measuring the amplitudes of the traces a calibration signal was imposed on the Heiland record corresponding to a known load intensity. This calibration trace then could be used as a measuring scale for the strain gage records. The introduction of this calibration trace was accomplished in the following manner: From the calibration tests of the strain gages and using the gage factor of 2.05, the microvolt reading corresponding to an applied tensile load of 2000 pounds could be determined. Then using a standard resistance box and the storage battery power supply the correct value of resistance necessary to give this microvolt reading on the potentiometer was found. Precision resistors of this value were then wired into the switching panel to give the 2000 pound microvolt signal. A pushbutton switch cut this signal into the Heiland circuit to produce the 2000 pound deflection in each of the three strain gage traces. The test panel was so designed that a selector switch could be turned to give static potentiometer readings on all three gages, and variable resistances were provided in each channel so that each gage could be zeroed for the no load condition. In measuring loads the operation of these components was as follows: With the specimen fixed in the Sonntag machine but with no load of any kind upon the specimen, the strain gages were zeroed by means of the variable resistances in the test panel. The test panel was connected to the Heiland recorder. The preload was set on the specimen; the dynamic load set on the machine which was then set in operation. Switches on the test panel were set to the GAGE position. In this position only the zero readings of the gages were transmitted to the Heiland recorder and, since all gages had been previously zeroed, no deflection of the Heiland galvanometer occurred. (The galvanometer action of the Heiland occurs as the deflection of a dot of light, the amplitude of the deflection being proportional to the current flow through the gages.) The trace in this position gave a straight line for all three gages representing the zero load level. Next, the gages were switched to HEILAND position. Here the trace deflections corresponded to the fluctuating tensile loads experienced at each strain gage, and the time trace on the Heiland tape was a sinusoidal curve, the amplitude of which represented the amplitude of the loading cycle. Next, with the test panel switches set at the HEILAND position the fatigue testing machine was turned off. The strain gages now experienced only the preload tension set in the testing machine and the Heiland trace again showed three straight lines. The displacement of these lines from the zero traces indicated the amount of preload at each strain gage. Next, the pushbutton on the test panel was depressed,which introduced the calibration step in the trace (the 2000 pound measuring signal). With this step the Heiland record was now complete. Using the 2000 pound step as a scale, the magnitudes of the preloads and the amplitudes of the cyclic loadings for each of the three strain gage locations could be determined. A wiring diagram of the test panel is shown in Fig. 10. A comparison of the amplitudes of the sinusoidal traces gave an indication of the amount of bending introduced into the specimen by its fixture in the fatigue testing machine. If these amplitudes were all the same then no bending existed and the specimen was loaded in pure tension. In all specimens tested it was found that the amount of bending was negligible, amounting to 3 or 4 per cent at the most. The Heiland record also provided a check on the accuracy of the Sonntag machine's preload micrometer and dynamic load scale. Here again the 2% accuracy of the machine as stated by the manufacturer was borne out.

Method of Loading:

The study was conducted in two main parts. In the first, the specimens were loaded in tension only and the load was made to vary from zero to some maximum value. To accomplish this it was necessary first to set a preload into the specimen of approximately one half the value of the maximum load desired. The dynamic load was then set on the eccentric weight mechanism at a value slightly less than the preload. The cycle then would vary from approximately zero to maximum when the machine was operating. The preload was always maintained slightly higher than the dynamic load setting to prevent the possibility of the load cycle passing through zero and causing chattering or hammering of the specimen in its jig. Such action would result in a form of impact loading which could readily nullify any results of a tension test. The second part consisted of testing specimens which were loaded to some nominal maximum value where the cyclic load was taken from 20 - 50% of the maximum load value. The resultant pattern was then one of a variable cyclic load maintaining the maximum stress value constant.

Procedure:

The procedure followed for both types of test was practically the same. The specimen was first mounted in the jig and the hold-down bolts tightened as evenly as possible. The gages were then zeroed by adjusting the variable resistances in the test panel using the Leeds and Northrup potentiometer at a zero indicator. It usually took the gages about 1/2 hour to warm up to the extent that the zero values no longer drifted. The jig with its specimen was then mounted in spherical seats and fixed in the jaws of the testing machine. (See Fig. 9). Originally the specimen was clamped in the machine so that it could be tested in both tension and compression, but this method of fixture introduced large bending moments which were almost impossible to remove. In the reported tests the compression heads on the testing machine were removed and the specimen was held in place only by the tensile load upon it. A description of this mounting system as well as the operation of the Sonntag testing machine can be found in ref. 5. When the strain gage zeros had steadied, the specimen was preloaded in tension by a jack-screw adjustment within the Sonntag machine. The amount of the preload was determined from a dial micrometer graduated in a scale proportional to the preload. (For this particular machine one-one thousandth of an inch deflection represented 4.17 pounds of preload). Next the dynamic load was set on the rotating weight scale and the machine was turned on for a minute or so to allow the spherical seats to become adjusted and to allow the specimen to seat itself in the jig. Potentiometer readings were then taken of each strain gage to determine the amount of bending present. If the readings were not all equal, a ring on the upper spindle of the testing machine was adjusted until all three gages had approximately the same reading. After each adjustment the machine was run a short while to allow for alignment of the mounting fixtures. When the gage readings were equalized the preload value was again checked and adjusted if necessary.

The machine was then turned on and the test commenced. With the machine in operation a Heiland tape was taken to check the loading on the specimen and a final counter reading was taken of the number of cycles run when the specimen failed. Micro switches on the testing machine normally would shut the machine off at specimen failure but to insure a clean break with no abraded surfaces due to failure of the machine to stop immediately after fracture of the specimen, an electronic triggering circuit was set up using the specimen as the sensitive element. When the specimen broke a relay immediately cut off the power to the testing machine. Typical specimen fractures are shown in Figs. 11, 12, while a typical Heiland Record is shown in Fig. 13.

With the known loading value, the cycles to failure, and an appropriate S/N curve for the material it was then possible to determine stress concentration values at the fractured cross-section.

Testing Difficulties:

Several problems arose during testing which led to the loss of a good deal of valuable time which might be avoided in subsequent similar tests.

1. Jig design. The jig design as modified (see page 4) proved quite satisfactory but difficulty was encountered at first in removing the base of the specimen from the jig after a fracture. This difficulty was removed by increasing the clearance between the

specimen base and the well in the jig to a free fit. A one-quarter inch diameter hole was drilled up through the jig so that a drift pin could be used to drive out a specimen base which had become jammed. Before assembling the specimen in the jig all pieces were given a liberal coating of spindle oil. A graphite lubricant was used once but discarded because it seemed to alloy with the specimen and jig, making removal very difficult. At intervals while the tests were in progress the hold-down bolts on the jig were tightened as they had a tendency to work loose under cyclic loading. It is believed that the early bolt failures were due to loosening of the bolts rather than inadequate strength of the bolts.

2. Mounting in the test machine. The removal of the compression heads in the tension fixture of the testing machine practically eliminated all bending from the specimen. With the compression heads in place the removal of bending was a long and tedious process. If, however, a specimen were to be tested in compression or under any loading cycle, passing through zero load, it would be necessary to use the compression head. Here again a liberal amount of spindle oil was used on the spherical seats of the fixture to decrease friction and allow the specimen to align itself.

3. Pre-load and dynamic indicators. The preload indicator and

dynamic load indicator on the Sonntag machine were found to be within the 2% accuracy limits stated by the manufacturer. However, the use of strain gages would still be necessary on future tests to determine the amount of bending in the specimen and for presenting a graphic picture of the cyclic load as recorded by the Heiland oscillograph.

III. RESULTS AND DISCUSSION

In the presentation of experimental test data and curves it would be well to include if possible theoretical values or empirical data for comparison purposes. Theoretical values of stress concentration factor,defined as the ratio of local or apparent stress to nominal stress,have been determined for some simple plane figures but three dimensional analyses are very complex. Much information however is available through photoelastic measurements of geometrical shapes under various loadings. Here again the values of stress concentration are experimental rather than theoretical and in most cases apply only to two dimensional figures. It has been found that two dimensional stress concentration values are in general higher than the three dimensional values.

In ref. 6 values of stress concentration factor from photoelastic measurements are given for shoulders with circular fillets. For the ratio of fillet radius to specimen diameter of .15 corresponding to the blade models tested in this investigation, the stress concentration factor is given as 2.15. It should be noted that this value is listed for a specimen loaded in tension uniformly over the cross-section and does not exactly correspond to the flange loading experienced by the propeller blade models. It might be expected however that the stress concentration value for the dynamically loaded three-dimensional models would be approximately of this order.

Static tension tests of the actual propeller blade were conducted by CIT for the Cooperative Wind Tunnel (cf. ref. 7). Actual stress measurements were made at the minimum section of the blade by the use of electrical strain gages located over the fillet radius. From these local stress measurements and the computed nominal stress the stress concentration factor was determined to be approximately 1.9 for a nominal stress at this section of 9,000 psi.

In order to obtain stress concentration values, it was necessary to obtain S-N curves for the material tested. For this purpose two separate S-N curves were run,using smooth specimens free from stress-rising detail. One curve was obtained from test data using the R. R. Moore Rotating Beam machines. Standard R. R. Moore specimens (cf. ref. 3) were used and all test specimens were surface finished to 5μ. The results of this test are shown in Table III. A plot of this data appears in Fig. 14. Because the R. R. Moore test data is based upon complete reversal of the stress and the actual propeller blade model was to be tested in tension only, an S-N curve was obtained from the Research Laboratories of the Aluminum Company of America (Appendix). To corroborate this information, several smooth tension specimens were tested in the Baldwin-Southwark fatigue machine. These test points were found to lie very close to the ALCOA S-N curve. The ALCOA curve as well as the check points run in the B. S. machine are shown in Fig. 14.

The results of this study are completely represented in the curves of Figs. 14-15 and in Tables I, II, III and IV. It was found that the endurance limit for 76S-T aluminum alloy in reversed bending was approximately 22,000 psi. This result closely checks the values given by Cooley in Ref. 1, Dolan in Ref. 4, and the Aluminum Company of America (cf Appendix) for small, polished, unnotched specimens.

The three smooth specimens tested in the Sonntag machine gave S-N values which very closely approximated the direct tension test results given by ALCOA (Appendix). Because of the coincidence of these check points with the ALCOA information, the ALCOA curve (Fig. 14) was taken as the S-N curve for 76S-T alloy in tensile fatigue.

The comparison of propeller model S-N values with the ALCOA curve indicated the stress concentration factors at various nominal stress levels. These factors are given in Table IV from which an average stress concentration factor was found to be 1.8 for the nominal stress range from 21,000 to 28,000 psi.

The stress concentration factor from the fatigue tests was determined by comparing the values of stress at the minimum section of the blade model and the smooth specimen at the same number of cycles to failure. The stress concentration factor then was taken as the ratio of the stress for the unnotched specimen to the nominal stress for the propeller model at the same number of cycles to failure.

It can be seen that there exists very good agreement between the stress concentration values obtained from photoelastic measurements, static tensile tests, and actual fatigue tests in this particular case. The photoelastic value of 2.15 is slightly higher than the actual value of 1.8 which is to be expected inasmuch as the two-dimensional values have been found to be higher than the three-dimensional values (ref. 6). The static tensile test stress concentration value of 1.9 (ref. 7) agrees very closely with that found by this study. This comparison, however, may not prove of much value inasmuch as the static tests were conducted on a full scale propeller blade whereas the fatigue test value was obtained from a 1/10 scale model. Available information on fatigue studies has indicated that rate of loading has little effect upon endurance limits of the aluminum alloys, but scale effects may be important when models over two inches in diameter are used.

For small polished specimens past experience has indicated that there is little size effect in models up to two inches in diameter under fatigue loadings. In this study the static stress concentration value for the full size blade agrees very well with the values obtained from fatigue measurements on the 1/10 scale model. Using the static stress concentration value of 1.9 a predicted S-N curve for the propeller could be made using the experimentally determined S-N curve for unnotched specimens. This predicted curve, which would pass through stress values approximately 53% of the stress values for the smooth specimens, would agree very closely with the actual S-N curve developed from model tests. This can be seen more readily by the close agreement between static and fatigue stress concentration values of 1.9 and 1.8 respectively.

If there were no size effect between the full size blade and the 1/10 scale model then this value of 1.8 in fatigue would hold for the full-size blade under the dynamic tensile loading. Here again past experience indicates that size effect may be important in fatigue. As a specific example Sachs (ref. 8) determined the endurance limit on small polished specimens of a magnesium alloy propeller material to be 18,000 psi, but on using a 4 1/2 inch diameter specimen of the same material mounted as an actual propeller is clamped, the endurance limit was reduced to about 6,000 psi. Here size effect decreased the endurance limit by a factor of three. If this effect holds true in the present case, then stress concentration in fatigue loading of the actual propeller blade (which had a minimum diameter of 4.95") might be expected to reach values higher than the indicated 1.8.

It should be noted however that the estimated fatigue life of the original propeller blade which failed would not indicate stress concentration values of the magnitudes found by Sachs. The results obtained by Sachs were based on a single series of tests and should not be generalized to other materials or methods of loading. It is because of size effect that accurate correlation of fatigue data between models and full scale specimens is difficult. At present a quantitative determination of this effect has not been made. Qualitatively it appears that the endurance limit or fatigue strength is reduced in a given material as the size increases over a minimum value found to be about 2 inches in diameter.

Fig. 15 shows the effect of variation of the cyclic amplitude on the cycles to failure for a given maximum nominal stress. In this test four specimens were run at a maximum stress value of 28,000 psi. The loading varied from 0 to $\sigma_{max.}$, from 20% to $\sigma_{max.}$, from 40% to $\sigma_{max.}$, and from 60% to $\sigma_{max.}$. A sketch of the loading amplitudes as well as the results of this test are shown in Fig. 15. The test indicates in a qualitative manner the effect of reducing the vibration amplitude of a specimen subjected to some maximum stress in tension. As might be expected the cycles to failure increased with reduction in cyclic amplitude.

The results obtained from this study are subject to errors due to the material itself, methods of testing and inaccuracies of equipment. Among the major sources of error are:

a) Non-homogeneity of material. Examination of several of the specimen fractures indicated fractures along planes containing inclusions or impurities in the metal. In any metal it is impossible to obtain homogeneity of structure in sizes larger than single crystals of the metal. It is believed that this factor is primarily responsible for the wide variation in test results and makes necessary the selection of a large number of random samples before test results can be used with confidence.

b) Minor machining defects. Careful final machining and polishing tend to reduce stress concentration factors at the surface of a material but failure can still develop from microscopic scratches at a metal's surface.

c) Deformation and wear of the jig. The deformation and wear of the clamping ring on the jig could easily introduce variations in the loading of the specimen which would be difficult if not impossible to determine.

d) Failure to completely remove bending. Although the strain gage readings indicated a low percentage of bending in the specimen the effect of even small bending moments could change the stress concentration values found.

e) Variation of clamping pressure in the jig. Inasmuch as the specimen was loaded on the flange by the split ring, and because the ring was held against the specimen by hand-tightened bolts, large variations in the compressive stresses in the flange might be expected. These stresses could very possibly influence the stress field at the minimum section of the model because of the proximity of the flange loading area to the fillet.

f) Errors in electrical measuring components. These errors undoubtedly would influence the validity of the results but should be regarded as secondary in comparison with the others mentioned previously.

IV. CONCLUSIONS

The following conclusions are drawn from the results obtained in this study:

1. The endurance limit of 76S-T aluminum alloy with a 5 μ surface finish was verified to be approximately 22,000 psi in reversed bending.

2. Three specimens of 76S-T aluminum alloy with 5 μ surface finish corroborated the S-N curve furnished by ALCOA for tension fatigue tests where the stress cycle ranged from zero to maximum.

3. The average stress concentration factor for a 1/10 scale model of the C.W.T. propeller blade was determined to be approximately 1.8 under a zero to maximum tension stress cycle.

4. A reduction in the amplitude of a cyclic stress imposed on a specimen under a constant value of peak stress results in an increase in the number of cycles to failure of the specimen.

5. Because of size effect no direct correlation can be made between stress concentration factors in fatigue between the model and the full scale propeller except to state that the full scale stress concentration factor may possibly be higher than that of the model.

It is recommended that if future studies be conducted on this particular problem the following suggestions be followed if possible:

1. Replace the Baldwin Southwark Testing Machine with one designed primarily for true axial loading tests and one in which the rate of loading can be increased considerably over that of the present machine which operated at 1800 cycles per minute. The present loading rate is too slow to permit a large number of specimens to be tested in a reasonable time period.
2. A redesign of the holding jig to make it more massive. The present design has adequate strength but is not exceptionally rigid. The jig should be made of hi-strength steel and bearing surfaces should be fully hardened so as to minimize wear under loading.

It is further recommended that an investigation be carried out to determine the effect of size in this particular test. Inasmuch as the actual blade minimum diameter is 4.95 inches it would be practically impossible to conduct full scale fatigue tests with standard testing machines. The size effect correlation is needed before small scale tests can be made useful, but how this correlation can be obtained for such large specimens will present a very difficult problem if developed experimentally.

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TABLE I

Propeller Blade Specimens

$$\frac{\text{Min. stress}}{\text{Max. stress}} = 0$$

(Loads in lbs.)

Specimen No.	Machine Load Dyn.	Static	Total	Heiland Trace Gage No. 1	2	3	Cycles to Failure
1	2500	2500	5050	5150	4960	5120	30,000
2	2500	2535	5035	No record			64,000
3	2430	2460	4890	4750	4780	4850	91,000
5	2250	2290	4540	4600	4460	4540	175,000
4	2000	2050	4050	4020	4110	4060	257,000
8	1980	2000	3980	No record			300,000
9	1960	1980	3940	No record			400,000
6	1880	1920	3800	3900	3850	3850	14,500,000 did not fail

TABLE I-A (Stresses)

All stresses in psi (tension)

Specimen No.	Machine indicated (P/A)	Heiland Trace Gage No. 1	Heiland Trace Gage No. 2	Heiland Trace Gage No. 3	Variation from Machine indicated (%) 1	Variation from Machine indicated (%) 2	Variation from Machine indicated (%) 3
1	27900	28450	27400	28285	3.0	1.8	3 1.3
2	27820		No record			No record	
3	27020	26240	26440	26800	2.8	2.2	1.0
5	25080	25410	24640	25080	1.0	1.7	neg.
4	22380	22210	22710	22430	1.0	1.5	neg.
8	21990		No record			No record	
9	21760		No record			No record	
6	20990	21550	21270	21270	2.6	1.3	1.3

TABLE II

PROPELLER BLADE MODELS

CONSTANT MAXIMUM TENSION STRESS WITH VARYING MINIMUM STRESSES

Test Machine:	Sonntag Universal Fatigue Testing Machine
Specimens:	1/10th scale propeller blade models
Surface Finish:	5 microinches
Speed of Loading:	1800 cycles per minute

TEST RESULTS

Specimen No.	Machine Load (lbs) Static	Machine Load (lbs) Dynamic	Max. Stress (psi)	Min. Stress (psi)	Stress Range (psi)	Cycles to Failure
1	2535	2535	28,000	0	28,000	30,000
2	3040	2030	28,000	5580	22,420	60,000
3	3550	1520	28,000	11,200	16,800	816,000
4	4060	1010	28,000	16,840	11,160	did not fail at 35,000,000

TABLE III

R. R. MOORE ROTATING BEAM

FATIGUE TEST

Material:	76S-T Aluminum alloy
Machine:	R. R. Moore Fatigue Testing Machine
Machine Speed:	10,000 RPM
Specimen Design:	Standard R. R. Moore (Ref. 3)
Surface Finish:	5 microinches

No.	Tare lbs.	Added lbs.	Total "W" lbs.	Stress (psi) "S"	Cycles to failure "N"
1	10	43	53	40,000	72,000
2	10	43	53	40,000	88,000
3	10	40	50	37,700	140,000
4	10	36	46	34,700	300,000
5	10	33	43	32,400	500,000
6	10	30	40	30,200	810,000
7	10	26.5	36.5	27,500	4,400,000
8	10	23	33	25,000	8,200,000
9	10	22	32	24,200	30,000,000
10	10	18	28	21,000	82,000,000

Stress = 755 x W

TABLE IV

STRESS CONCENTRATION FACTORS

$$SCF = \frac{\text{Max. stress}}{P/A}$$

Specimen No.	Cycles to Failure	Nominal Stress (P/A)	Apparent Max. Stress	SCF
1	30,000	27,900	54,000	1.935
2	64,000	27,800	50,500	1.816
3	91,000	27,020	47,750	1.767
5	175,000	25,080	45,000	1.794
4	257,000	22,380	43,500	1.943
8	300,000	21,990	43,000	1.955
9	400,000	21,760	41,600	1.911

Average SCF = 1.8

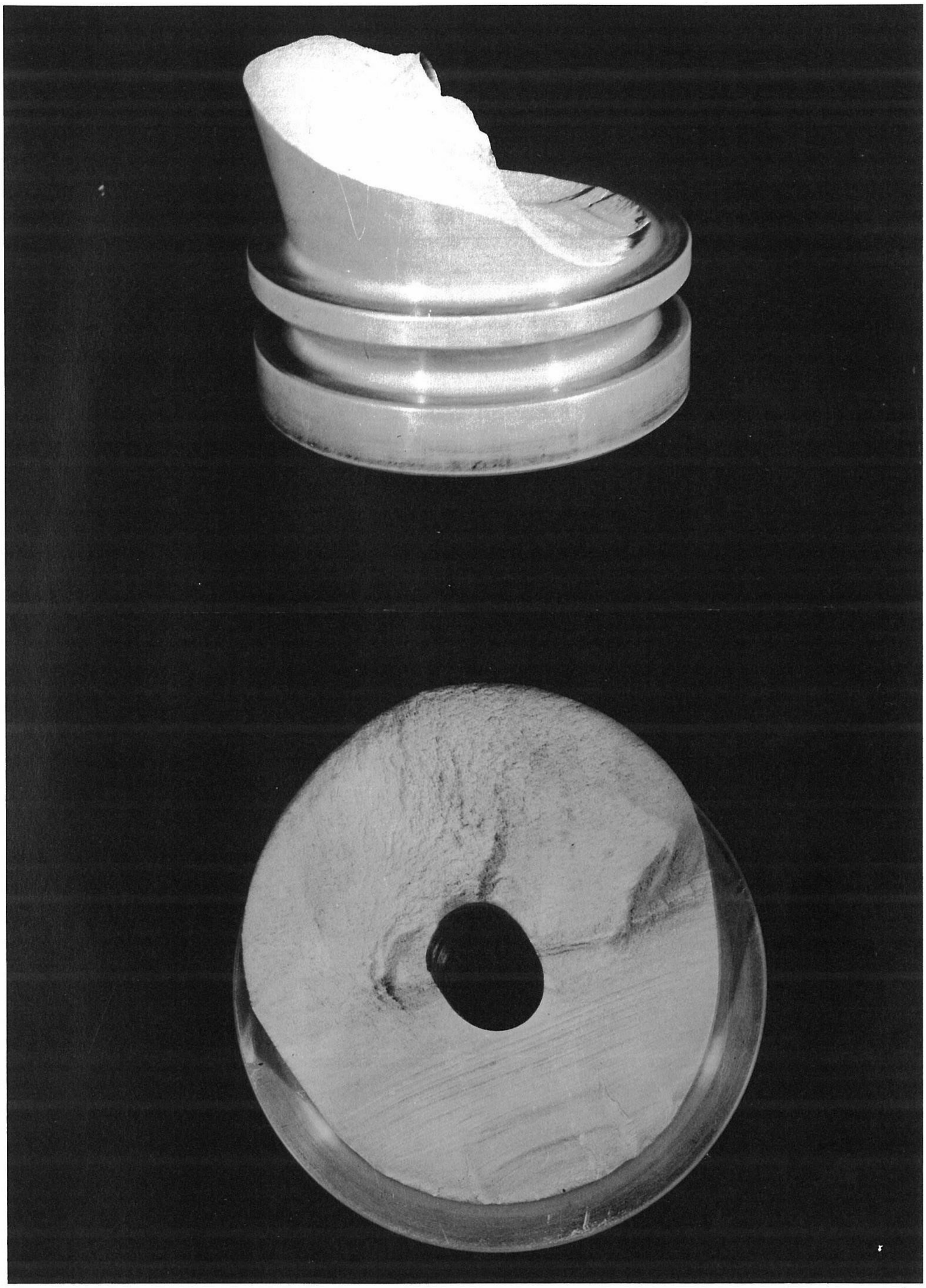
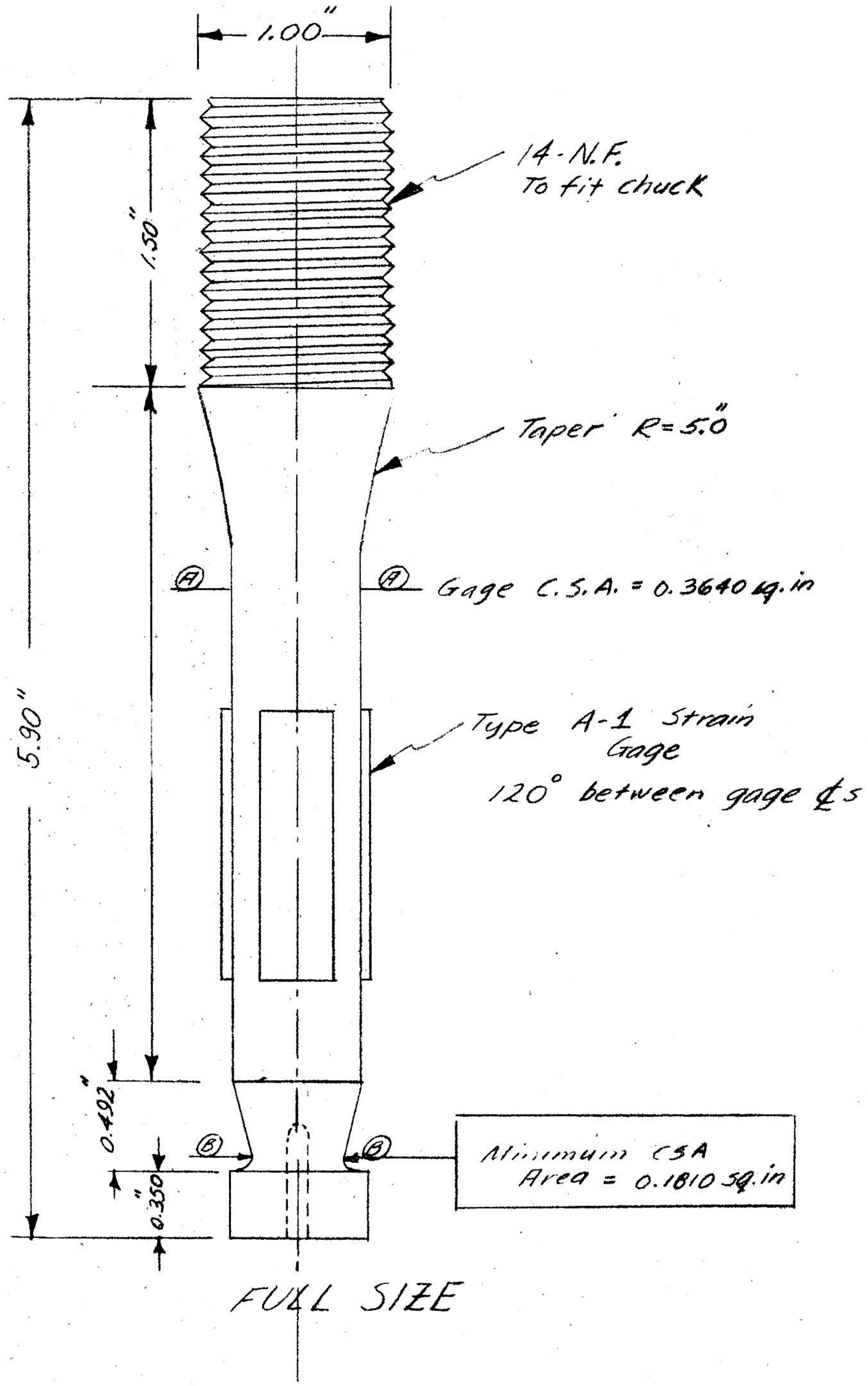


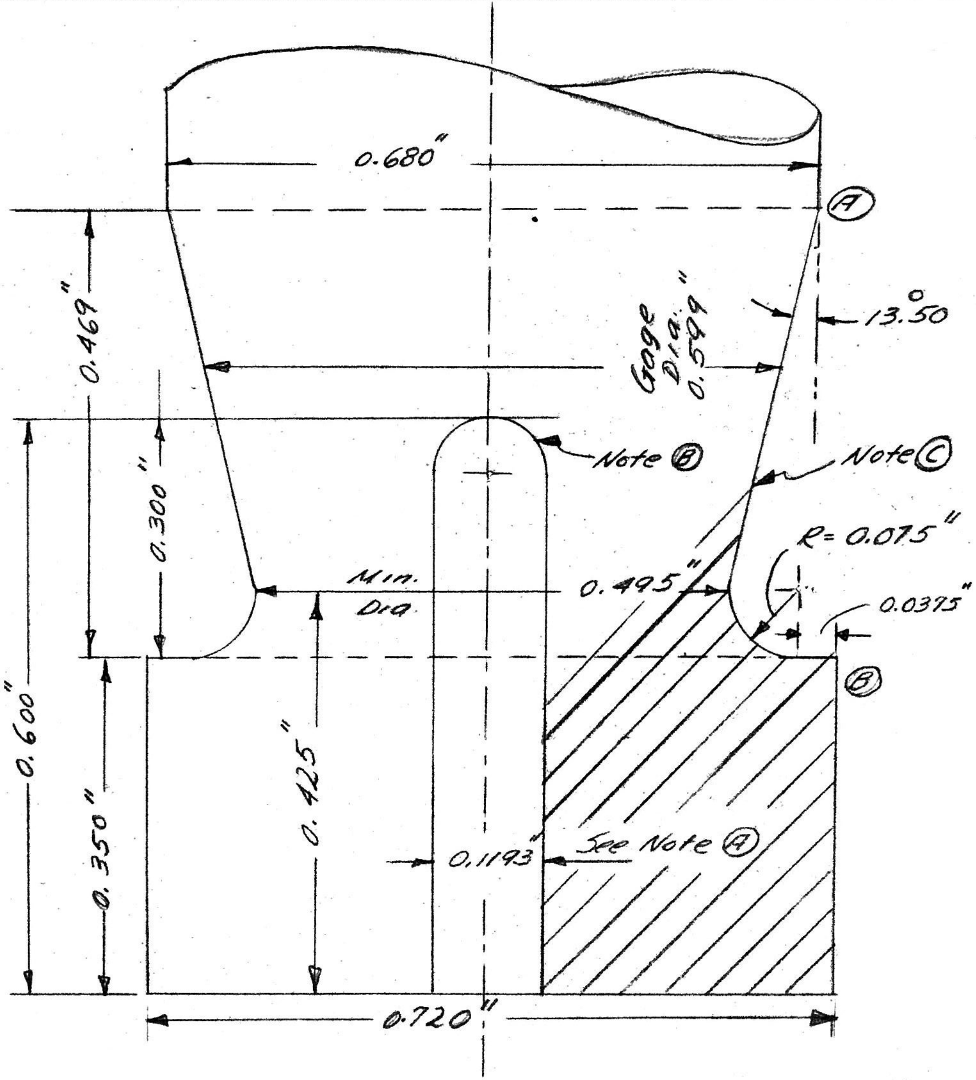
Figure 1. Failure of Wind Tunnel Propeller Blade.



FATIGUE SPECIMEN

Showing gage locations

Figure 2



FATIGUE SPECIMEN

Ref: Ham. Std. Dwg. #SK16000
(SCALE: x 5)

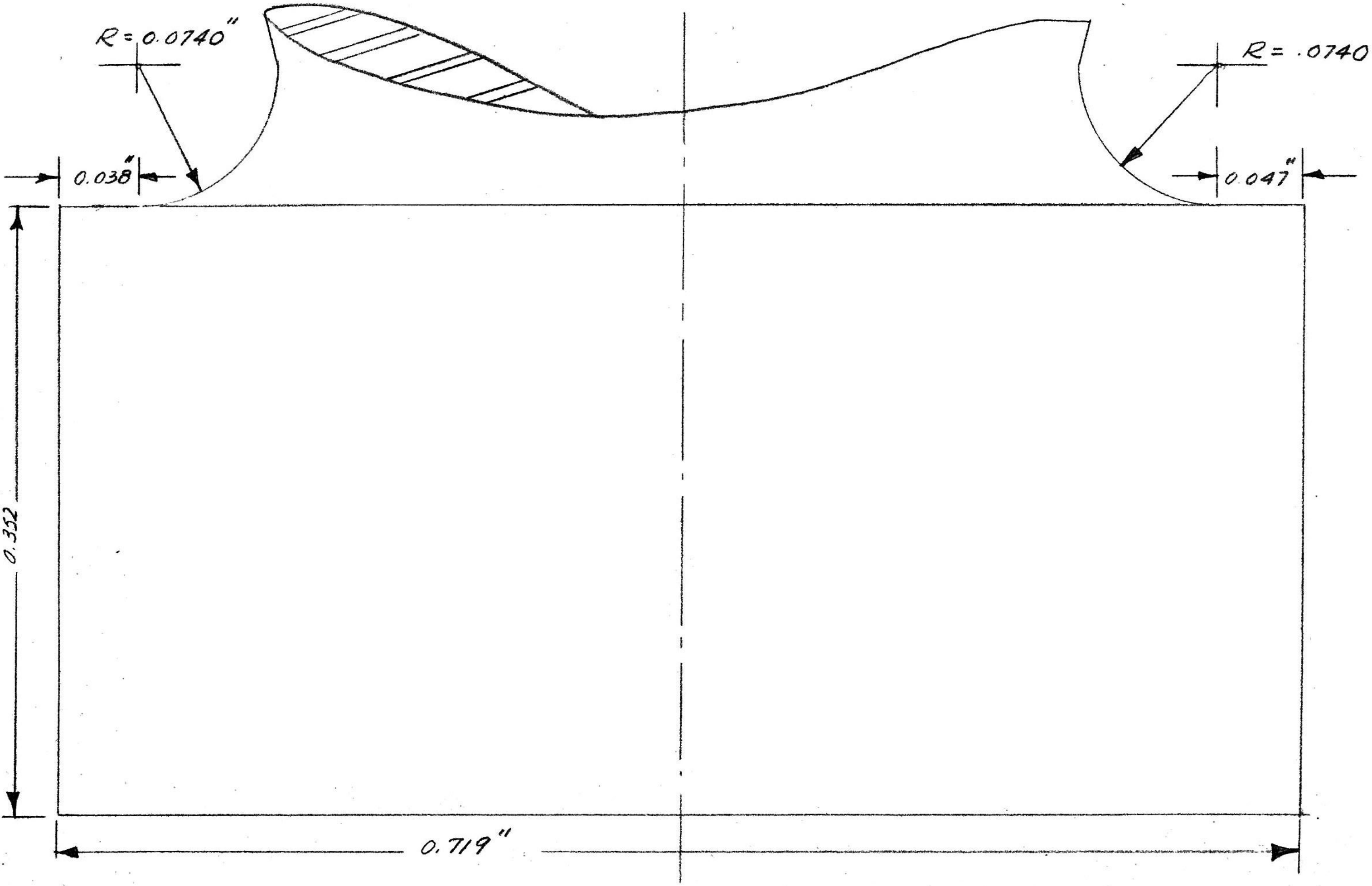
NOTES:

Ⓐ Drill with #32 and hand lap.

Ⓑ Central hole spherical at bottom

Ⓒ Finish surface to 5μ inches.
between points A and B

Figure 3



Dimension Check with
Jones & Lamson Optical Comparator
Figure 4

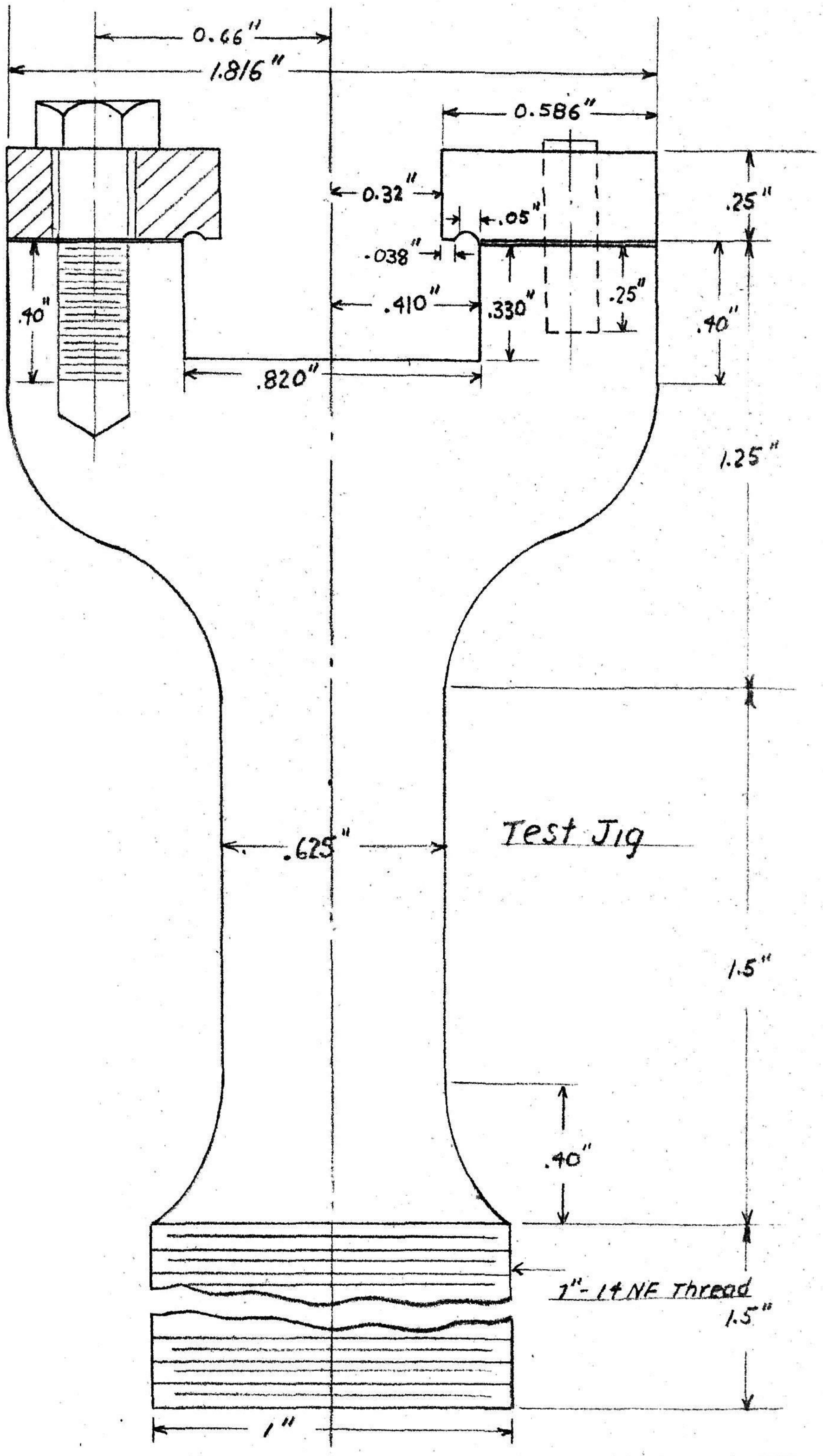

0.66"
1.816"
0.586"
0.32"
.05"
.038"
.25"
.410"
.330"
.25"
.40"
.40"
.820"
1.25"
Test Jig
.625"
1.5"
.40"
1"- 14 NF Thread
1.5"
1"

Fig. 5

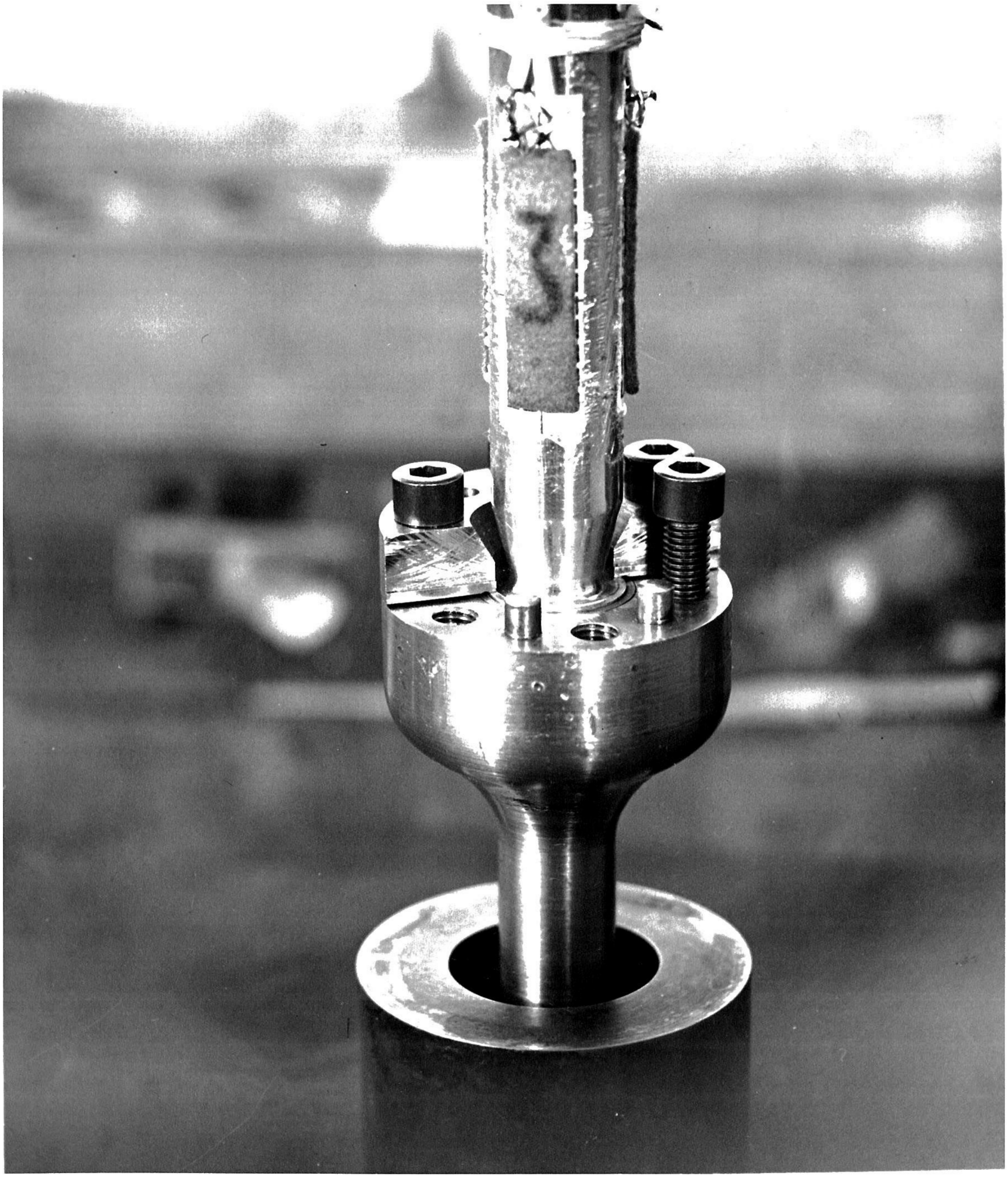


Figure 6. Specimen Mounted in Holding Jig.

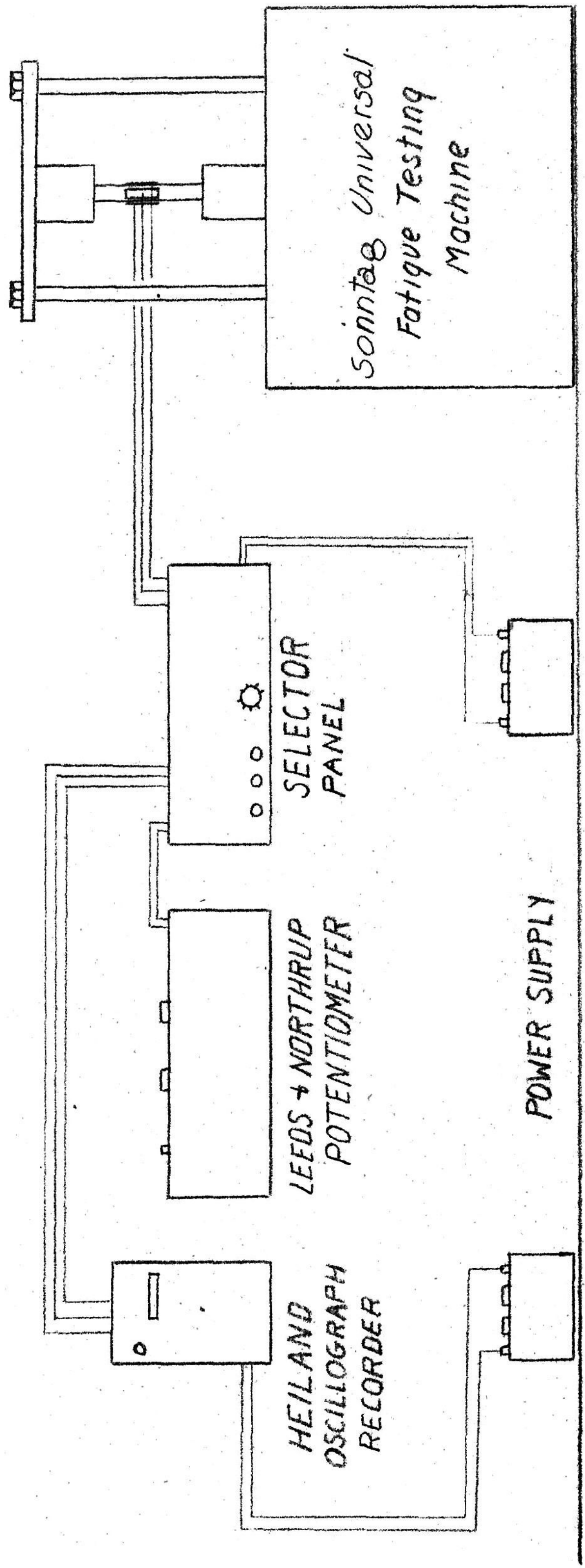


Fig. 7
Schematic Diagram
of
Test Equipment

Figure 8. Test Set-up.

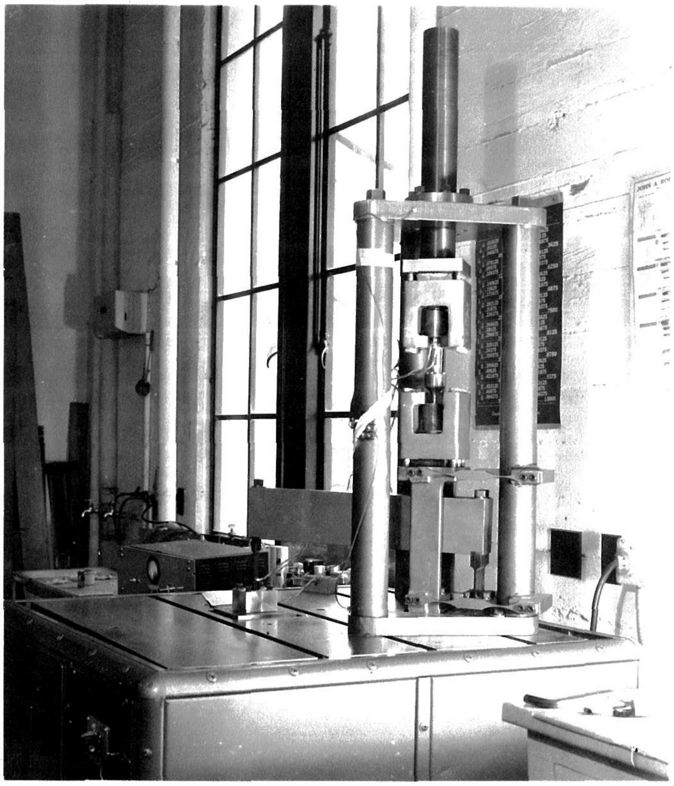


Figure 9. Specimen Mounted in Multiplying Fixture

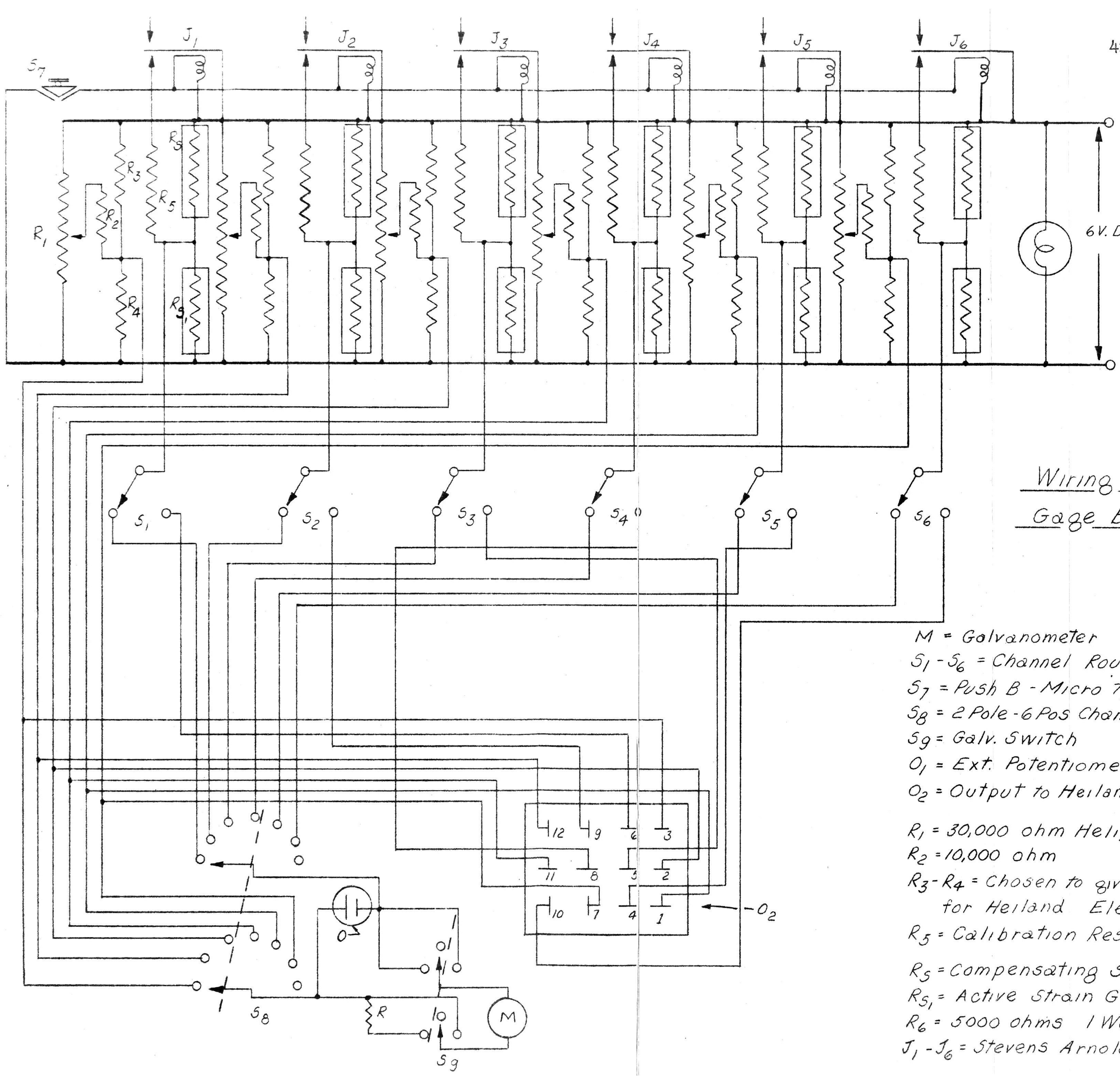


Fig. 10

Wiring Diagram of Strain Gage Balance Panel

M = Galvanometer

S_1 - S_6 = Channel Routing

S_7 = Push B - Micro Type (Norm. Open)

S_8 = 2 Pole - 6 Pos Channel Selector

S_9 = Galv. Switch

O_1 = Ext. Potentiometer

O_2 = Output to Heiland

R_1 = 30,000 ohm Helipot
R_2 = 10,000 ohm
} Same on all channels

R_3 - R_4 = Chosen to give critical damping for Heiland Element used

R_5 = Calibration Resistor

R_s = Compensating Strain Gage

R_{s_1} = Active Strain Gage

R_6 = 5000 ohms 1 Watt

J_1 - J_6 = Stevens Arnold Millisec Relay #172 (Norm. Open)

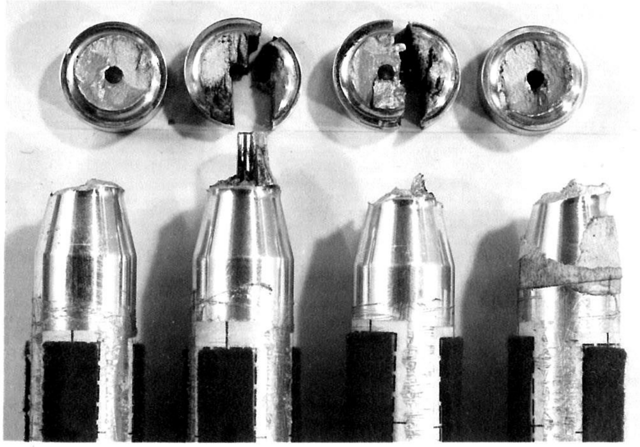


Figure 11. Specimens After Failure. (Top View).

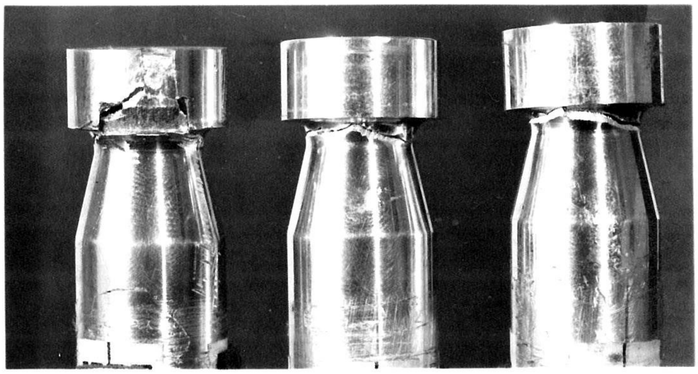


Figure 12. Specimens After Failure. (Side View).

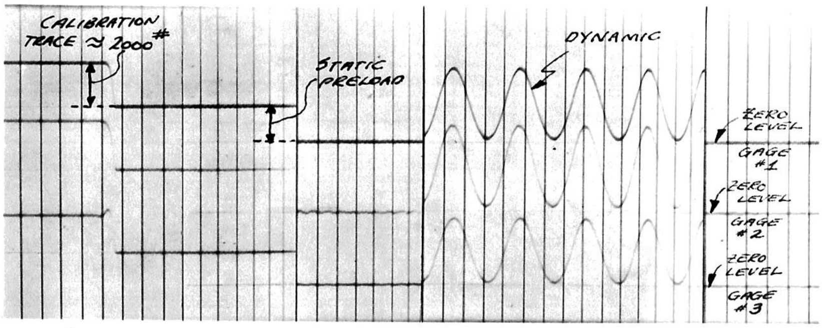


Figure 13 -- Typical Heiland Record

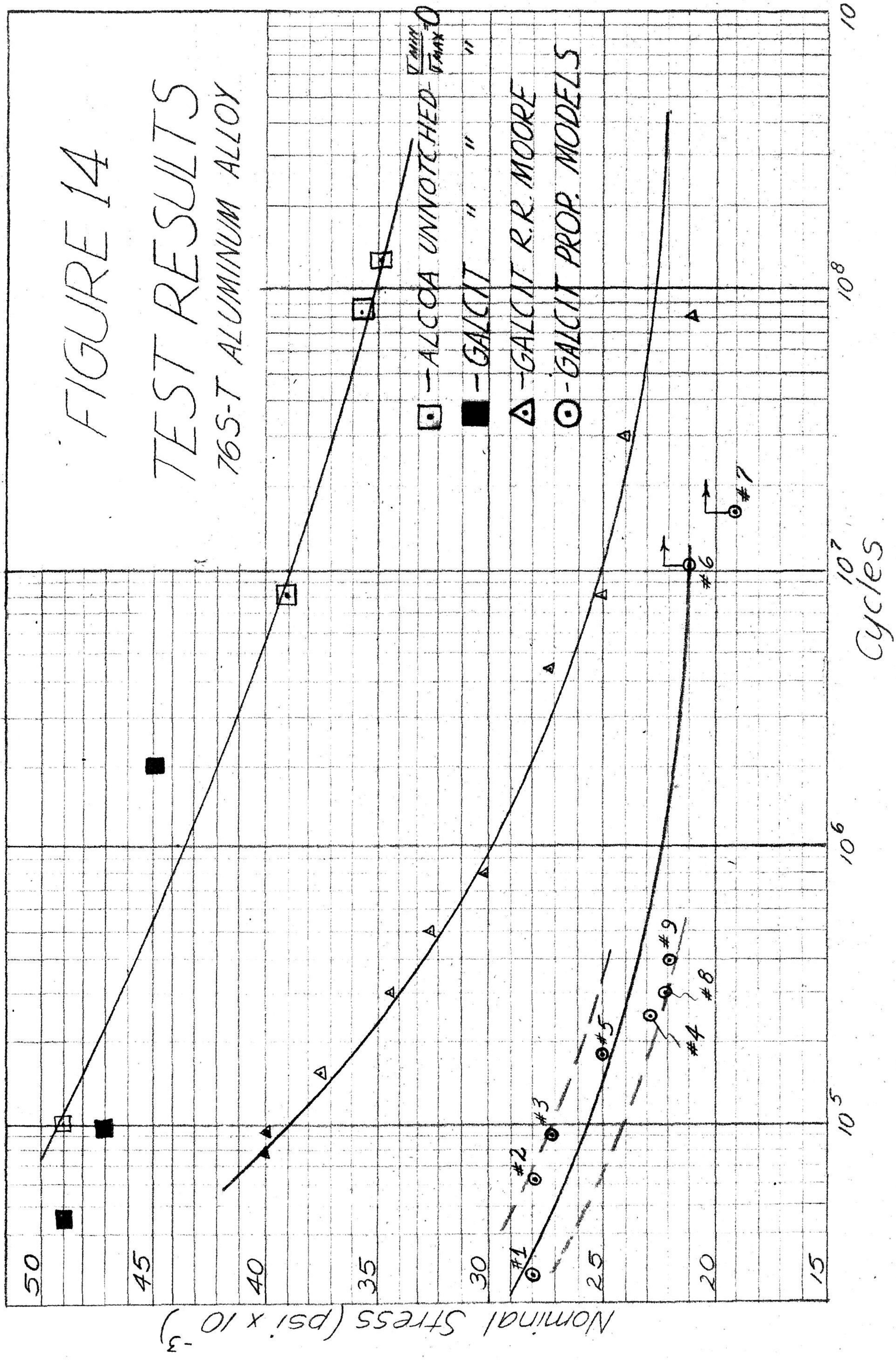


FIGURE 14
TEST RESULTS
76S-T ALUMINUM ALLOY

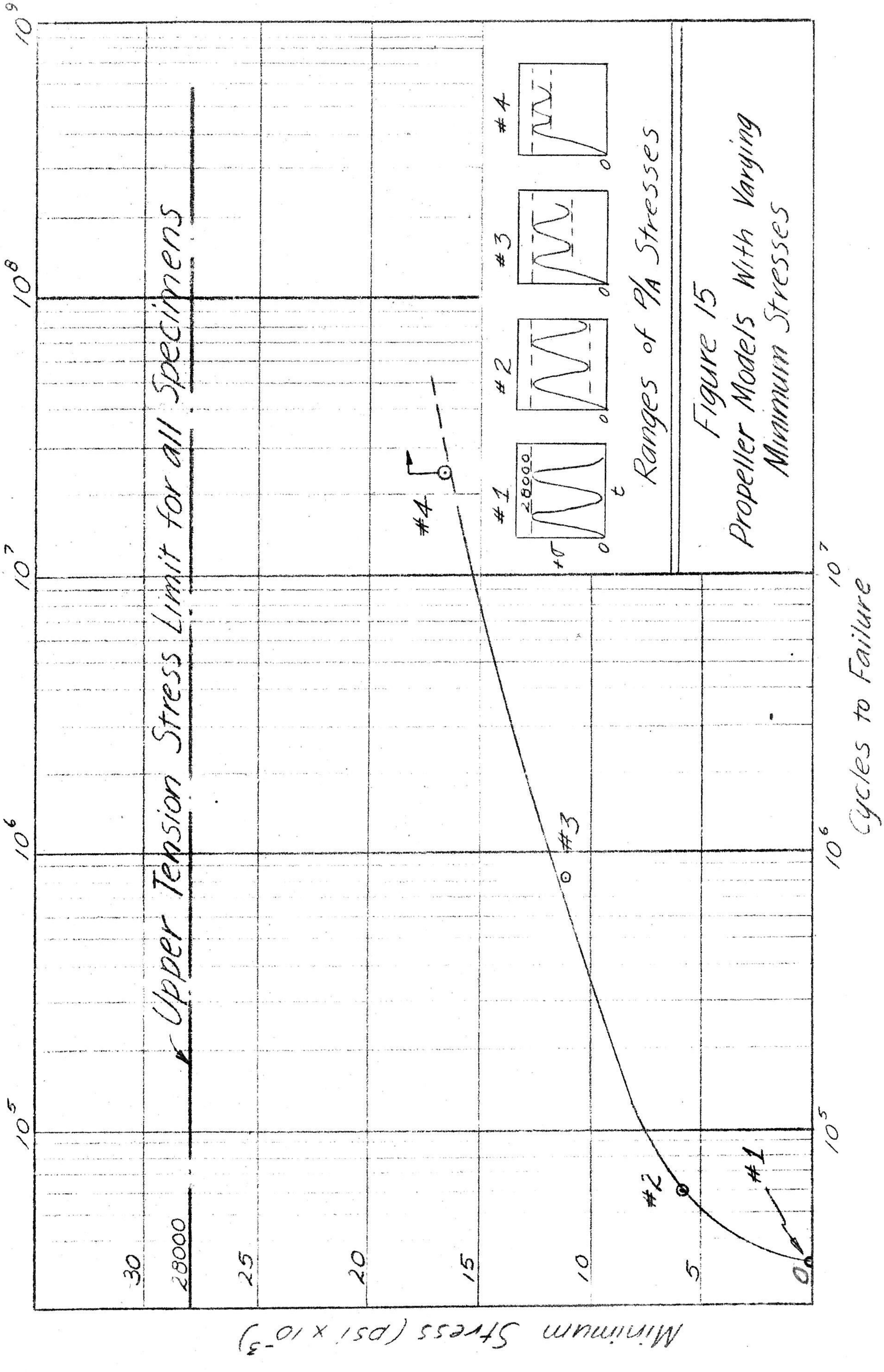


Figure 15
Propeller Models With Varying Minimum Stresses

VIII. APPENDIX

Fatigue Information on 76S-T Aluminum Alloy from the Aluminum Company of America.

Released by

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Assistant Director of Research
Aluminum Company of America