ACOUSTIC EMISSION,

AN EXPERIMENTAL METHOD

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Paul S. Shoemaker

1961

This is to certify that the

thesis entitled

ACOUSTIC EMISSION,

AN EXPERIMENTAL METHOD

presented by

PAUL S. SHOEMAKER

has been accepted towards fulfillment
of the requirements for

MASTER OF SCIENCE degree in APPLIED MECHANICS

C. A. Tatro
Major professor

Date June 5, 1961

ABSTRACT

ACOUSTIC EMISSION, AN EXPERIMENTAL METHOD

by Paul S. Shoemaker

Acoustic emissions are sound pulses emitted from crystalline materials subjected to an applied stress. The purpose of this investigation is to examine an experimental method that would enable one to study acoustic emission and to show some experimental results. These acoustic emissions are at such low energy levels that amplification is necessary to detect them. Great care must be taken in the method of detection so that any experimental process that generates mechanical or electrical vibrations will not interfere or be confused with the actual acoustic emission signals. The transducer employed for sound pulse detection is an ammonium-dihydrogen phosphate piezoelectric crystal. The loading mechanism used to subject a specimen to stress must be completely silent. This silent load is produced by cooling contraction of a pre-heated aluminum rod. The results presented are in the form of histograms with acoustic emissions per minute versus specimen strain. There is ample verification that emission signals are detected and that the experimental method is quite satisfactory. An analysis of the results indicates that there is an obvious difference in acoustic emission between different engineering materials; and some evidence that there could be a difference in the same engineering materials. There are obvious patterns present in the histograms that indicate possible correlation between acoustic emission and engineering design properties. Certainly, there is evidence present that indicates a relation between acoustic emission and metallurgical and crystal properties in metals.

ACOUSTIC EMISSION,

AN EXPERIMENTAL METHOD

By

PAUL S. SHOEMAKER

A THESIS

Submitted to the School of Graduate Studies of
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

Department of Applied Mechanics

1961

ACKNOWLEDGEMENTS

The author is indebted to Dr. Clement A. Tatro for his guidance and assistance throughout this research. It is certain that this investigation would have been almost impossible without his abilities. Mention must be made of the fact that the thermal loading method is an idea conceived by Dr. Tatro, and was developed by the writer.

The author is also grateful to the Applied Mechanics Department, Dr. Charles O. Harris and the Division of Engineering Research for help in many ways.

Appreciation is also expressed to the author's wife, Beth, for her typing and proofreading.

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NOTATION

a	extensometer beam radius
A	attenuation
Å	angstroms
ADP	ammonium dihydrogen phosphate
c	speed of sound
cm	centimeters
°C	degrees centigrade
E	modulus of elasticity
°F	degrees fahrenheit
G	amplifier gain
in.	inches
kg	kilograms
ksi	kips per square inch
L	critical section length
m	meters
mm	millimeters
psi	pounds per square inch
r	acoustic mismatch or impedence ratio
RMS	root-mean-square
sec.	seconds
S	piezoelectric crystal sensitivity
SKL	Spencer Kennedy Laboratories
t	extensometer beam thickness
V	signal voltage
w	piezoelectric crystal stack element width

Δ	deformation
ϵ	strain
μ	micro (10^{-6})
π	pi (3.14)
ρ	density
σ	stress
Ω	ohms

CHAPTER I

INTRODUCTION

Acoustic emissions are sound pulses emitted from crystalline materials subjected to an applied stress. For many years it has been known that the metal tin, when stressed, emits sounds that can be heard by the unaided ear. However, only quite recently has there been any investigation to study the sound pulses emitted from stressed crystalline metals such as steel, aluminum, copper, lead, zinc, etc. In 1950, Dr. Josef Kaiser (Ka 50), in Germany, presented a doctorate thesis on the subject and showed that these materials exhibited acoustic emission. The emissions, however, were at such low energy levels that amplification was necessary for detection.

Since Dr. Kaiser's initial investigation, there has been a great deal of research in the acoustic emission phenomenon carried out by B. H. Schofield of Lessells and Associates, Incorporated, Boston, Massachusetts (Sch 58, PR 1-11) and by Dr. C. A. Tatro at Michigan State University (ER 57, Ta 59, Ta 60).

Because the acoustic emissions are at such low energy levels, great care must be taken in the detection of the sound pulses so as not to confuse them with mechanical and electrical noise that may be present in the experimental apparatus. It was for this reason that a silent loading mechanism and noise isolation of the specimen had to be developed. It is the purpose of this investigation to examine an experimental method that would enable one to study acoustic emission and to show some experimental results.

CHAPTER II

EXPERIMENTAL METHOD

1. NECESSITY OF SILENCE

To further impress on the reader the necessity of mechanical and electronic silence in the vicinity of the specimen under test, an approximation will be made of the magnitudes of stress and strain that accompany a detectable acoustic emission.

The piezoelectric transducer chosen for this experiment was a 45° Z-cut ADP (ammonium dihydrogen phosphate) crystal stack composed of eight elements in parallel. The crystal sensitivity is:

$$S = .177 \frac{\text{volts/meter}}{\text{newton/meter}^2}$$

The noise inherent in the electronic recording mechanism shown in Fig. 6 was approximately 5×10^{-3} volts at the oscilloscope output. The smallest acoustic emission level judged detectable at the oscilloscope was about two times this or 10^{-2} volts. The pre-amplifier gain was 800 and the signal loss (attenuation) in cabling from the crystal stack to the pre-amplifier was approximately .5. Another loss in signal detection was the acoustic mismatch or impendence ratio at the interface between the crystal stack and the specimen. This is determined as follows (HuBo 55):

$$r = \frac{\rho c \text{ (crystal)}}{\rho c \text{ (specimen)}}$$

where: r = impedence ratio at interface

ρ = density of material

c = speed of sound in material

$$\rho c \text{ (ADP)} = 6.1 \times 10^6 \frac{\text{kg}}{\text{m}^3} \times \frac{\text{m}}{\text{sec.}}$$

$$\rho c \text{ (aluminum)} = 13.8 \times 10^6 \frac{kg}{m^3} \times \frac{m}{sec.}$$

$$\rho c \text{ (steel)} = 39.1 \times 10^6 \frac{kg}{m^3} \times \frac{m}{sec.}$$

then,

$$\text{Aluminum:} \quad r = \frac{6.1}{13.8} = .442$$

$$\text{Steel:} \quad r = \frac{6.1}{39.1} = .156$$

In continuing, one would choose the aluminum specimen as an optimistic approach in stress detectability. The stress pulse received by the crystal stack from the specimen head is then given by:

$$\sigma = \frac{V}{(Sw)AGr}$$

$$\sigma = \frac{10^{-2}}{(.177)(1.59 \times 10^{-3})(.5)(800)(.422)}$$

$$\sigma = 21.2 \times 10^{-2} \text{ newtons/m}^2$$

$$\sigma = 30.8 \times 10^{-6} \text{ pounds/in.}^2$$

where

σ = stress pulse at specimen head

S = crystal stack sensitivity per element width = $.177 \dfrac{\text{volts/meter}}{\text{newton/meter}^2}$

w = element width = 1/16 inch = 1.59×10^{-3} meters

V = smallest detectable voltage level = 10^{-2} volts

A = Cable Attenuation = .5

G = pre-amplifier gain = 800

r = impedence ratio = .442.

The stress pulse at the specimen head is, however, a smaller pulse than is actually coming from the specimen critical section. Referring to the specimen detail, Fig. 10, one may see that the pulse traveling from the critical section toward the head will either spread over the entire head or will be kept focused to the one half inch shank diameter. Assuming the critical section stress pulse spreads over the entire head, the critical section stress is:

$$\sigma_{c.s.} = \sigma \times \frac{\text{head area}}{\text{critical section area}}$$

$$\sigma_{c.s.} = 30.8 \times 10^{-6} \times \frac{(1)^2}{(.1875)^2} = 8.74 \times 10^{-4} \text{ psi}$$

Assuming the critical section stress pulse is kept focused to the one half inch shank diameter, the critical section stress is:

$$\sigma_{c.s.} = \sigma \times \frac{\text{shank area}}{\text{critical section area}}$$

$$\sigma_{c.s.} = 30.8 \times 10^{-6} \times \frac{(.5)^2}{(.1875)^2} = 2.18 \times 10^{-4} \text{ psi}$$

Again using an optimistic approach, a stress of 8.74×10^{-4} psi in the critical section would lead to a strain of:

$$\varepsilon = \frac{\sigma}{E} = \frac{8.74 \times 10^{-4}}{10^7} = 8.74 \times 10^{-5} \ \mu \text{ in./in.}$$

Assuming all of this strain occurs in the specimen critical section, which is approximately .75 inches long, the total deformation due to one detectable acoustic emission is:

$$\begin{aligned} \Delta &= \varepsilon L \\ &= (8.74 \times 10^{-11})(.75) = 6.55 \times 10^{-11} \text{ inches} \\ &= 16.65 \times 10^{-11} \text{ cm} \\ &= .01665 \text{ Å} \end{aligned}$$

which is approximately one two-hundredths of an aluminum atomic diameter. It should be apparent that the above analysis is a rough approximation and should be valued accordingly. There is some question as to whether the elastic modulus used to obtain strain from the critical section stress should be Young's modulus of elasticity (10^7 psi) or another elastic constant which more closely describes inter-crystal action. An acoustic emission does not originate from a plane in the cross section but originates in a single crystallite of a polycrystalline specimen, and is thus effectively a point source. The sound pulse emitted from the point source should, however, develop into a plane wave within the length it travels. The relative magnitudes arrived at above do, however, serve to point out the need for proper sound isolation of the crystal stack and specimen. Imagine the confusion in detecting an acoustic emission when the noise level inherent in the most quiet conventional testing machine is forty millivolts (Ta 59) or four times the magnitude of the smallest detectable acoustic emission.

2. SILENT LOADING MECHANISM

Basically and simply, the silent load is produced by cooling contraction of a pre-heated aluminum rod. The thermal loading apparatus is shown in detail in Fig. 1. The one inch diameter thermal bar is suspended by a ball and socket arrangement from a derrick-like framework fixed to the upper stationary head of the Riehle testing machine. Aluminum was chosen for the thermal bar because of the relatively large coefficient of thermal expansion, and was hung from a ball and socket joint to minimize effects of moments produced on the specimen (assuring an uniaxial tension).

The thermal bar is heated over approximately six feet of its length by a cylinder-like furnace or heat tube which surrounds it. The heat tube contains two electric strip heaters, each three feet

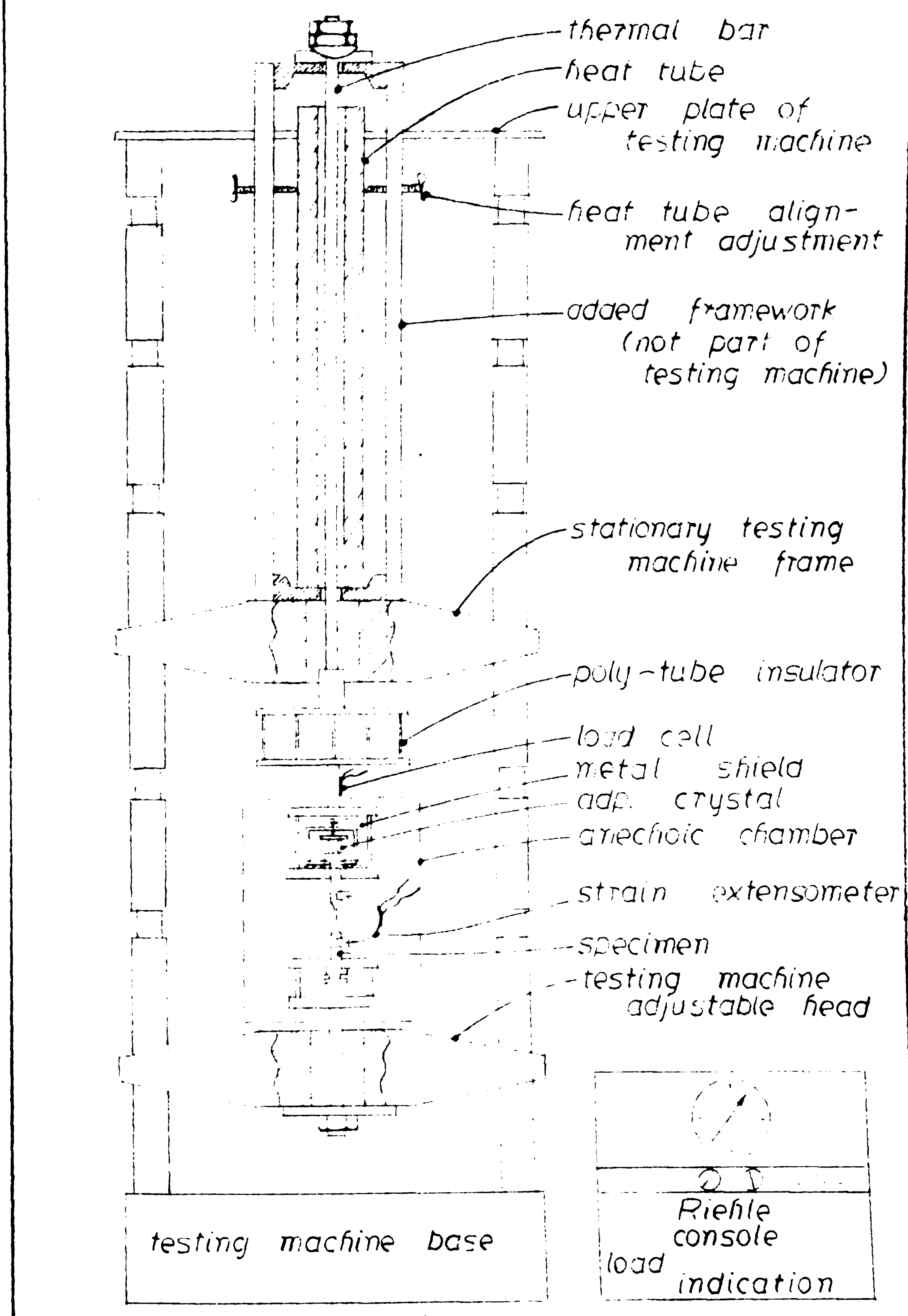
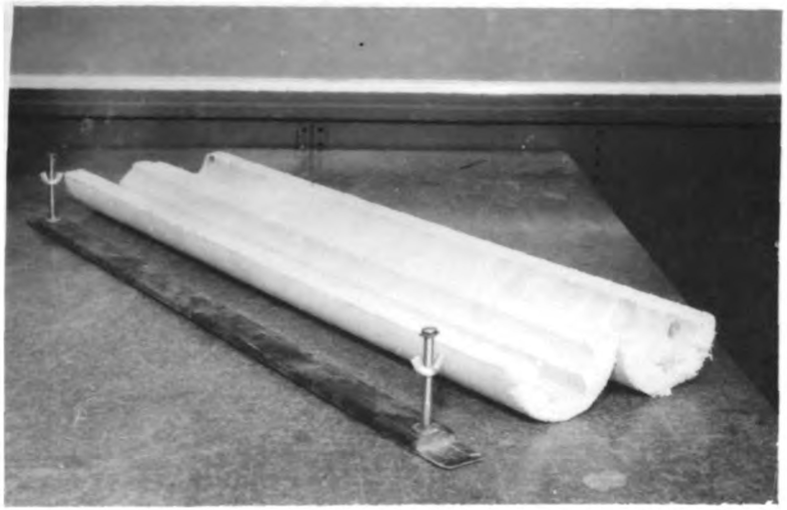


FIGURE 1 – Mechanical Apparatus

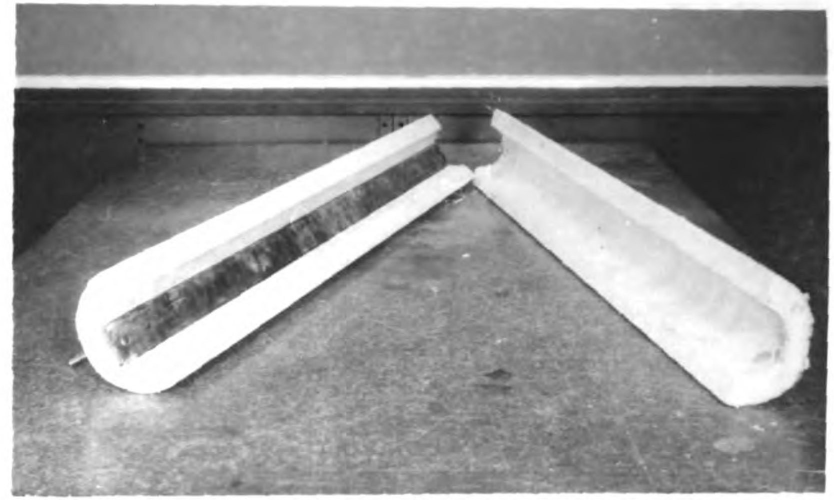
long, that run end to end along the entire length of the six foot furnace. The heat tube itself is constructed of two layers of steam pipe insulation secured rigidly by cheesecloth and wheat paste. Refer to Fig. 2.

The properties of piezoelectric materials vary considerably with temperature and the least percent change in these properties occurs around room temperature (20° C, 68° F)(Br 53). For this reason, it is necessary to insulate the crystal stack from the heat produced by the thermal loading mechanism. The insulator shown in Fig. 3 consists of thirteen quarter inch diameter by six inches long by .008 inch wall thickness stainless steel tubes equally spaced between two ten-inch diameter steel plates. The upper plate, attached closest to the heat source, is one inch thick and has six pie-like sections removed. The spoke-like upper plate minimizes radiation to the lower plate and serves to dissipate heat as it is conducted radially outward along the spokes. The stainless steel tubes provide the necessary strength properties required to support the loading, yet have a relatively low thermal conductivity. The lower plate is a solid disc, three quarters of an inch thick. This poly-tube arrangement adequately provides the necessary surface area to dissipate the heat. The massiveness of this insulator is not to insure adequate heat transfer, but to provide strength qualities necessary for minimum deflection under an applied load. It must be kept in mind that deflection is at a premium because it is the principle load producing mechanism. In other words, any deflection absorbed in the tension linkage is not imposed on the specimen as it should be.

Controlled deflection as opposed to controlled loading, is



a



b

c

d

FIGURE 2: Heat Tube Assembly

FIGURE 3: Poly-Tube Insulator

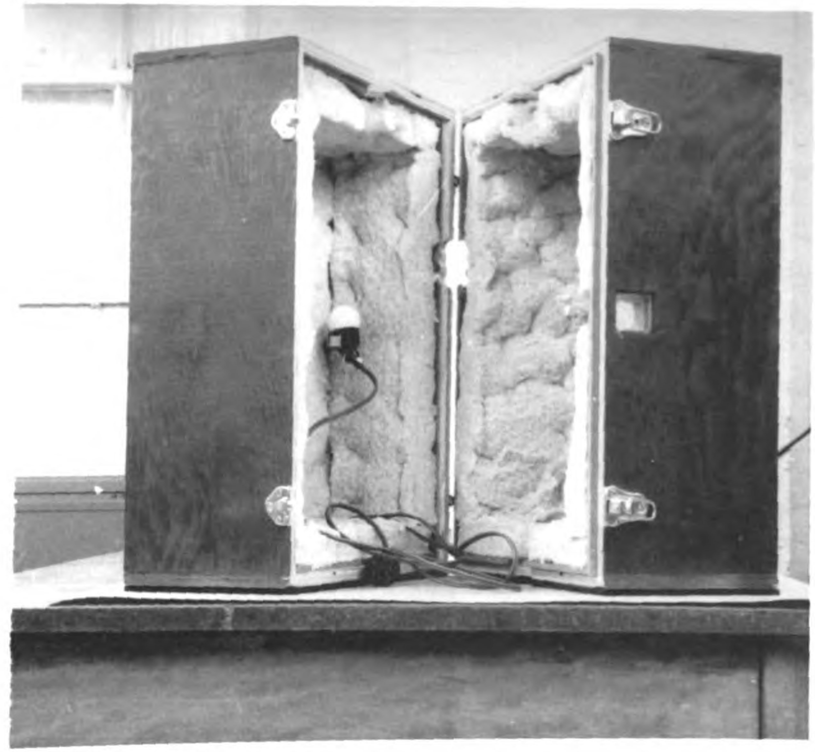
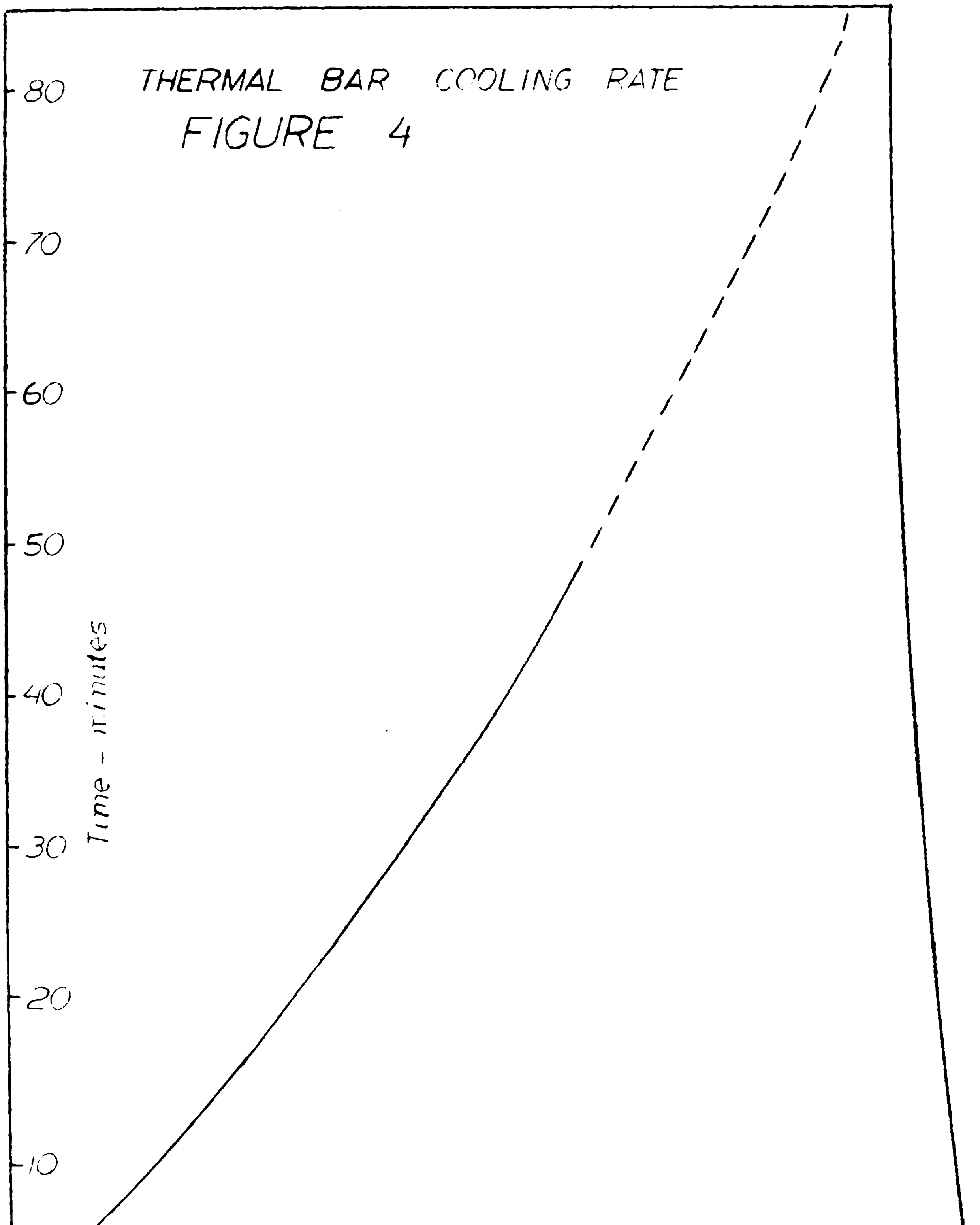


FIGURE 9: Anechoic Chamber

a unique advantage which the thermal loading mechanism has over a dead weight silent loader. Once a weight is applied to a dead weight loader, the stress is immediately changed. This stress range is moved through so rapidly, that acoustic emission recordings are almost impossible. One could conceivably move through the yield point (an interesting area for acoustic emission study) instantaneously with one load application. The thermal loader applies the load very much the same way as a conventional testing machine, although the straining rate is somewhat less. The lowest conventional testing machine deflection speed available is .012 inches per minute, while that of the thermal loader is approximately .004 inches per minute. The thermal loader straining rate is taken from the cooling rate curve shown in Fig. 4, and is calculated, assuming a constant slope. It may be seen that this curve is exponential, but is approximately linear over the cooling range necessary to produce the required loads. The straining rate can be varied by simply varying the cooling rate. The controlled deflection and low straining rate make it possible to record the yield point region of steel over a period of about three minutes. This enables one to obtain a very accurate picture of the stress-strain curve right up to fracture without fracturing the specimen.

The magnitude of the load produced varies with specimen material, critical cross section, critical length and amount of thermal contraction. For example, a steel specimen of .25 inches critical cross section and 2.5 inches critical length results in a load of about 3000 pounds when subjected to approximately .15 inches of thermal contraction. This is well into the plastic region of this particular steel.

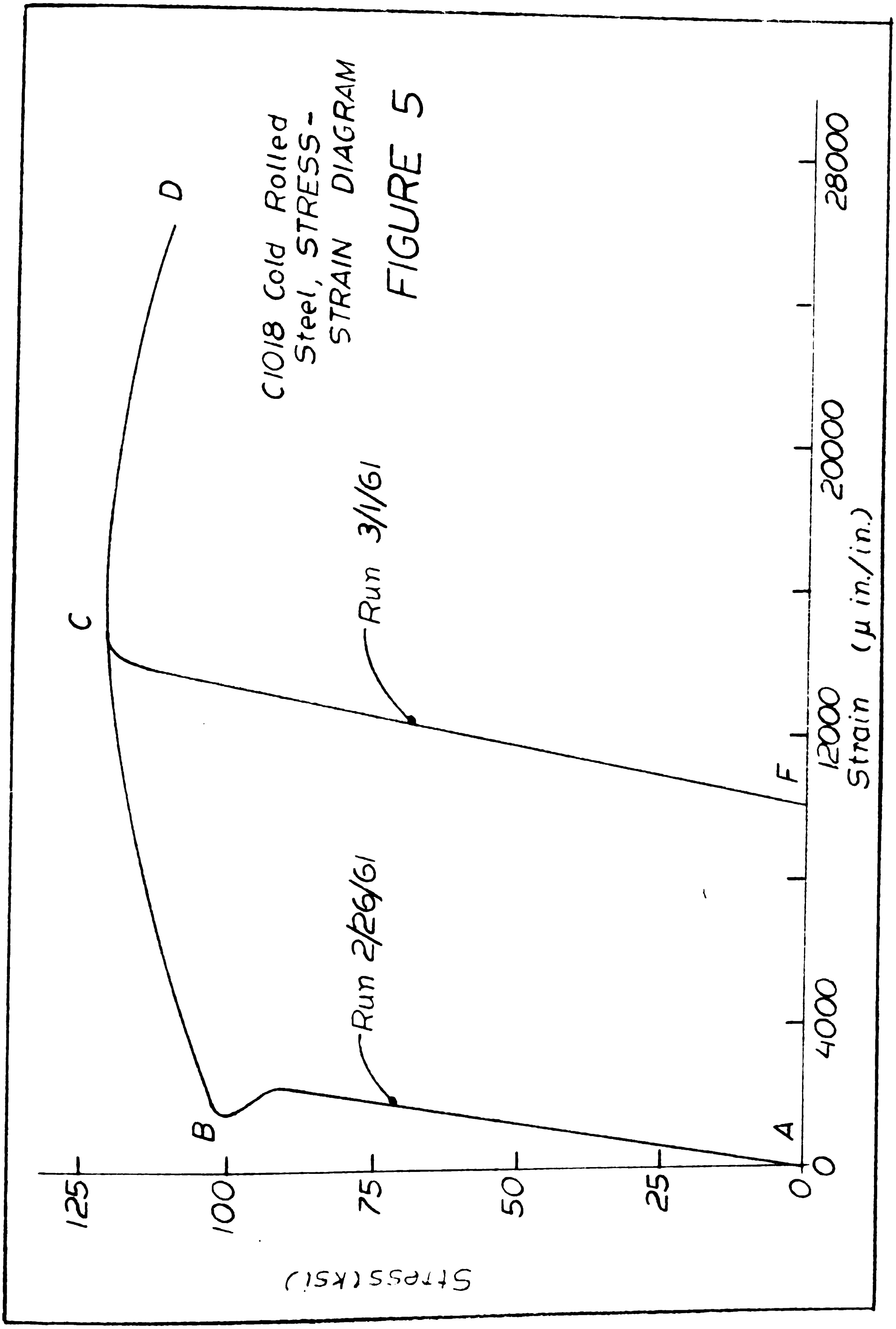

THERMAL BAR COOLING RATE
FIGURE 4
80
70
60
50
40
30
20
10
Time - minutes
0
.05
.10
.15
.20
.25
.30
Cooling Contraction - inches

The noise inherent in the thermal loading mechanism is practically nil. A stress-strain curve for a steel specimen is shown in Fig. 5. This specimen was initially loaded through the curve ABC and exhibited acoustic emissions without any particular noise interference. The specimen was then reloaded from F to C to D. Acoustic emissions do not occur in a specimen over the pre-loaded portion (F to C) and there could be no confusion in this loading region as to whether the signals were loading mechanism noise or acoustic emissions. In this loading region, no signals of any kind were encountered. However, immediately upon reaching point C, the acoustic emissions began and continued to point D.

The peculiar nose in the yield point region, (point B) of Fig. 5, is not material for this report and no attempt will be made to explain it.

3. ELECTRONIC MECHANISM

The electronic recording mechanism which is necessary for collecting data is shown in Fig. 6. This instrumentation is shown photographed in Fig. 21. The stress pulse from the specimen is received by an ammonium dihydrogen phosphate piezoelectric crystal stack. This crystal stack is composed of eight one-sixteenth by one half by one inch plates that form into a one half by one half inch square by one inch high transducer (See Fig. 11). The signal from the transducer is amplified approximately 800 times by a Tektronix type 122 pre-amplifier. The amplified signal passes through a Spencer Kennedy Laboratories frequency wave filter where all frequencies below 1500 - 2000 cycles per second are eliminated. The acoustic emission signal is thus available for viewing with an oscilloscope and for permanent recording with a tape recorder. The acoustic signals are recorded on



C1018 Cold Rolled Steel, STRESS-STRAIN DIAGRAM

FIGURE 5

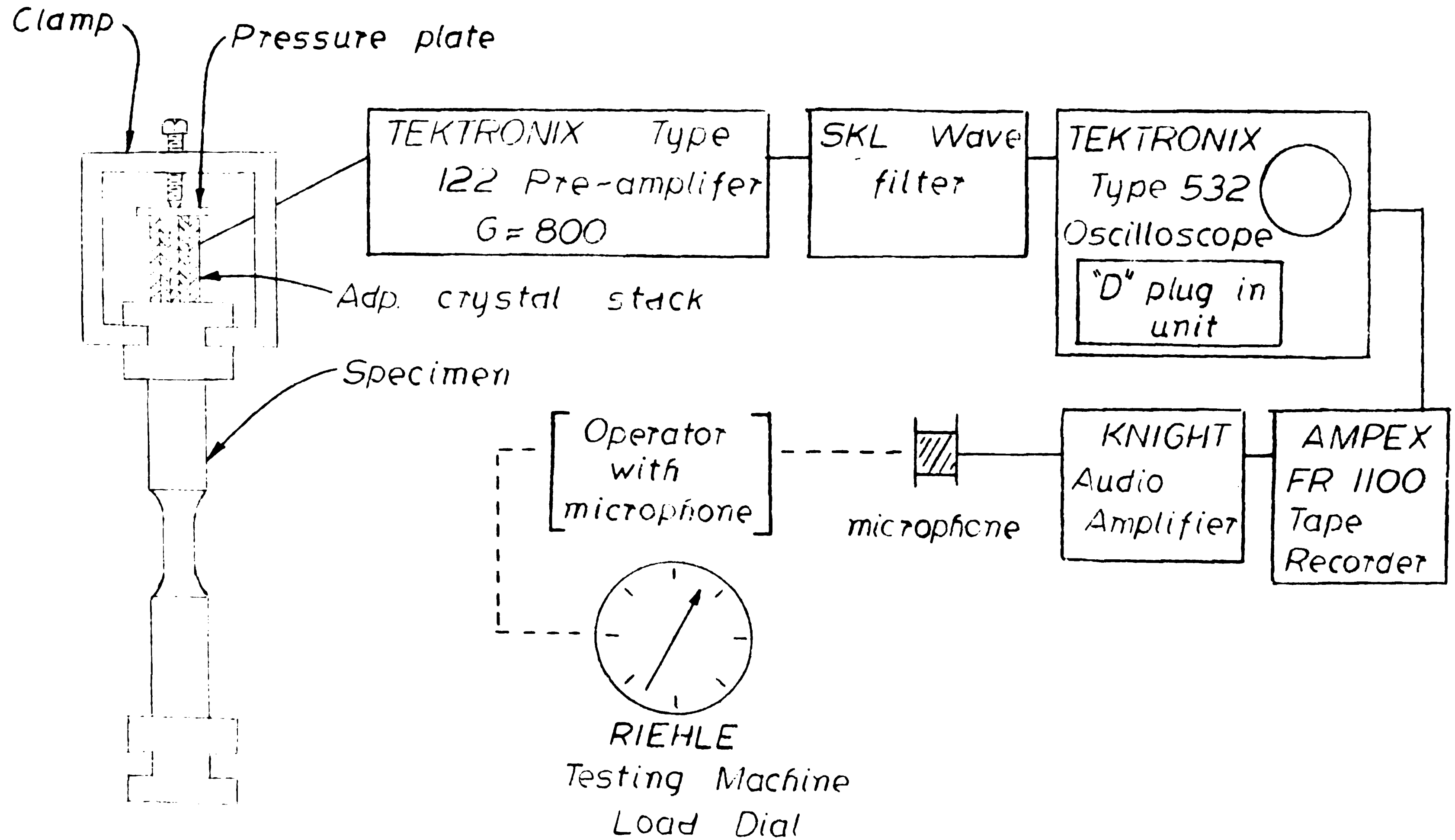


FIGURE 6 -Electronic Recording Mechanism

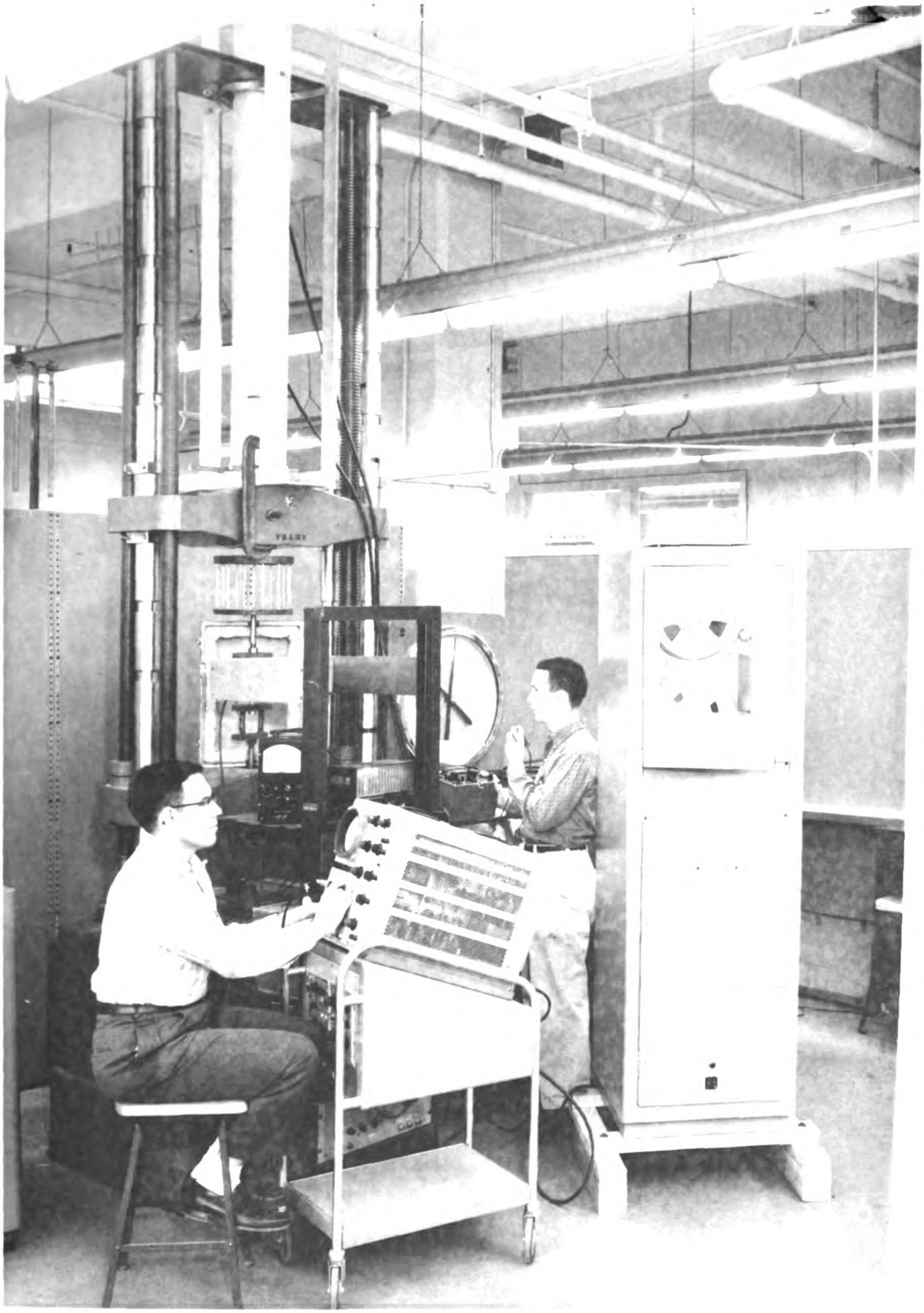


FIGURE 21: Experimental Apparatus

the even channels (2, 4, 6) and voice comments and specimen loading data are recorded on the odd channels (1, 3, 5, 7) of a seven-channel Ampex (FR-1100) tape recorder. A Bell & Howell microphone and Knight audio amplifier are used for voice recording. The oscilloscope used in this experiment was a Tektronix type 532 with a "D" type plug-in unit.

Two types of playback or counting mechanism were used in analyzing the recorded data, as shown in Fig. 7. In one case, the tape recorded acoustic signal is played through the oscilloscope (for visual viewing) into a Hewlett-Packard model 523-B electronic counter. Simultaneously, voice recording is played back through the audio amplifier and loudspeaker. In this manner, the loads recorded on the voice channel are synchronized with the acoustic signals being counted. The other method of data analysis employs a Ballantine model 320 true root-mean-square voltmeter. The acoustic signal from the tape recorder is directed into the RMS meter where it may be visually observed as an RMS meter reading or recorded on a Sanborn oscillograph. Again, the loudspeaker announces the applied loads to the specimen in order that synchronization is available between acoustic signals and specimen stress properties. In both cases of data analysis, the SKL wave filter may be used for refiltering.

4. NOISE ISOLATION

The loading linkage is capable of introducing noise interference if the specimen is not acoustically isolated from these sources. For this reason, acoustic mismatch materials are provided between the specimen heads and the loading mechanism as shown in Fig. 8. Washers of clay-impregnated Bakelite one sixteenth of an inch thick are glued to the loading frames and provide the necessary noise absorption

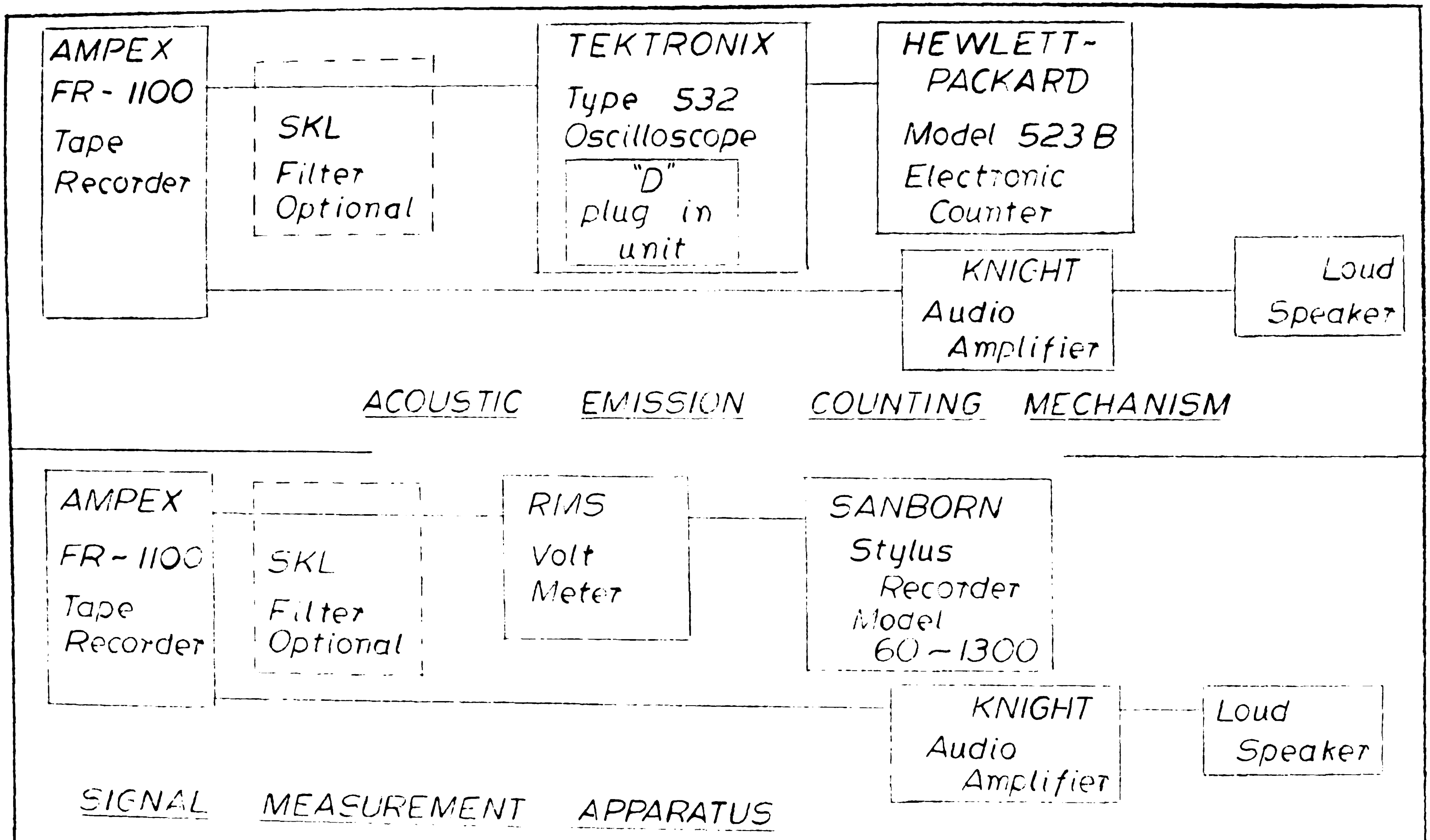


FIGURE 7 -Electronic Playback Mechanism

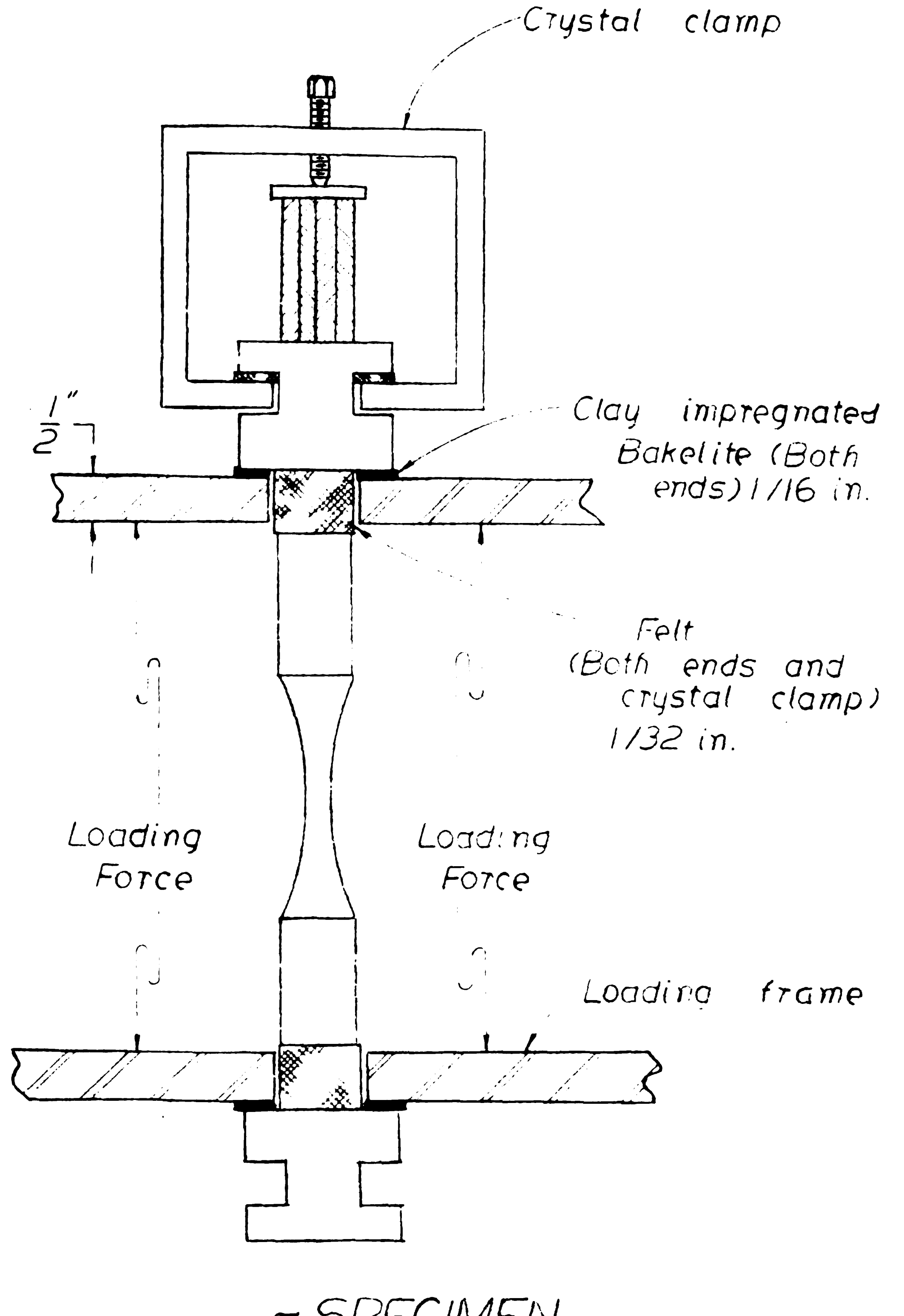


FIGURE 8 NOISE ISOLATION

originating in nut and bolt assemblies in the loading linkage. This clay-impregnated Bakelite provides an attenuation of approximately .60 (Wo 61).

A good grade of one thirty-seconds of an inch thick felt is glued to the specimen shank close to the heads where the shank goes through the loading frame. The felt is also glued to the specimen head in the notches provided for mounting the crystal clamp. The felt provided in these places eliminates any possible metal to metal contact which could be a noise generator.

The transducer crystal stack is very sensitive to electrostatic pick-up and it becomes necessary to construct an electrostatic shield around it. The electrostatic shield consists of two nested metal boxes completely surrounding the crystal stack as shown in Fig. 1.

An anechoic chamber was constructed (Sc 50) which encloses the specimen and crystal in order to minimize any noise interference from general laboratory activity. Shown in Fig. 9 is a close-up of the chamber and Fig. 1 shows its placement among the apparatus. A foam rubber pad is placed between the anechoic chamber and its resting place to eliminate any mechanical vibration that may be transmitted from the ground or the testing machine. A small window has been placed in the chamber wall to allow a view of the specimen.

Experimental tests were conducted during the early morning (between 12:00 midnight and 6:00 a.m.) to eliminate any possible mechanical or electrical noise which would be present during normal laboratory activity hours.

5. SPECIMENS AND STRESS-STRAIN RECORDING MECHANISM

Specimen geometry is shown in detail in Fig. 10 and in the

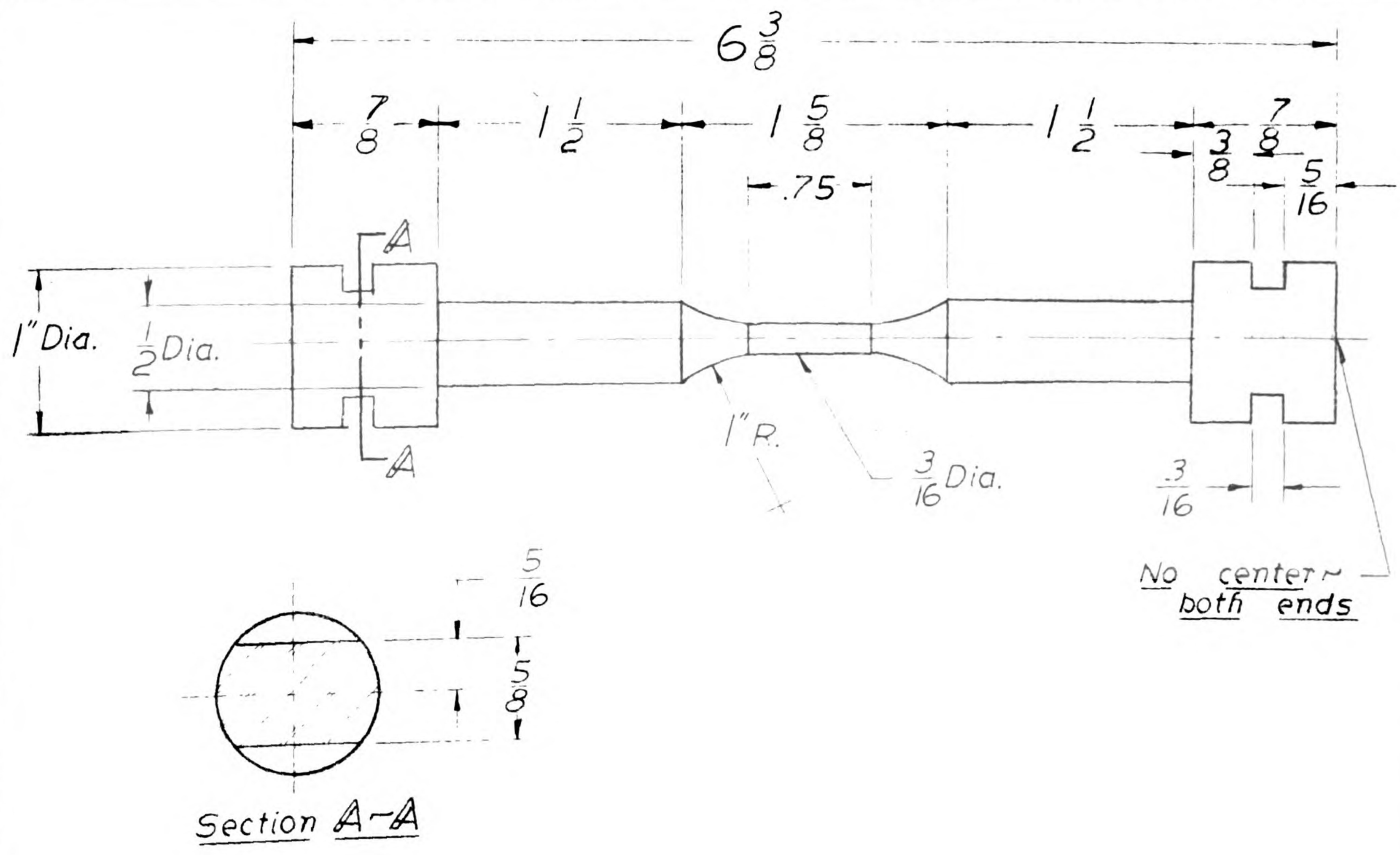


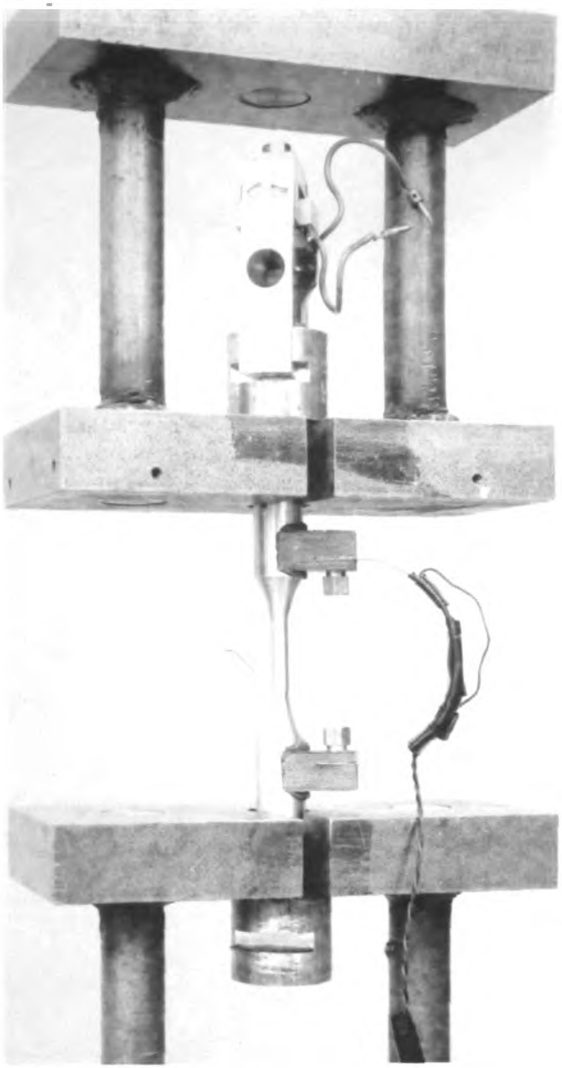
FIGURE 10 -DETAIL OF SPECIMEN

photographs, Fig. 11. The specimens were machined from one inch diameter bars and the center mark was removed to provide a smooth surface for piezoelectric crystal mounting. Only one crystal was used in this experiment. However, provisions were made for crystal mounting at each end.

The specimen used for Run 4/1/61 was aluminum (2024-T4) with a critical length of .750 inches and a critical section diameter of .1876 inches. The specimen used for Run 4/3/61 was annealed cold rolled steel (C1018) with a critical length of .768 inches and a critical section diameter of .1850 inches. The heat treatment for annealing the steel specimen was as follows:

45 minutes at 1600° F
70 minutes at 1150° F
Cool in still air from 1150° F (Approximately thirty minutes).

A continuous load record was charted on one channel of a dual channel Sanborn stylus oscillograph. A signal was sent from a semi-conductor strain gage (gage factor of 118) mounted on a rod within the tension linkage, to the Sanborn recorder. The strain gage bridge circuit for this load cell is shown in Fig. 12. Shown in the top two arms are the active strain gage (sixty-five ohms) and a temperature compensating gage (sixty-five ohms). A 5000 ohm potentiometer was placed in shunt with the compensator gage to provide a means of re-zeroing the oscillograph. The oscillograph was calibrated to give approximately three pounds per chart line and the chart was fifty lines wide. Because specimen load ranges were approximately zero to 3000 pounds, it was necessary to employ a re-zeroing technique. In this bridge circuit, it was necessary to put an 800 ohm resistance



a

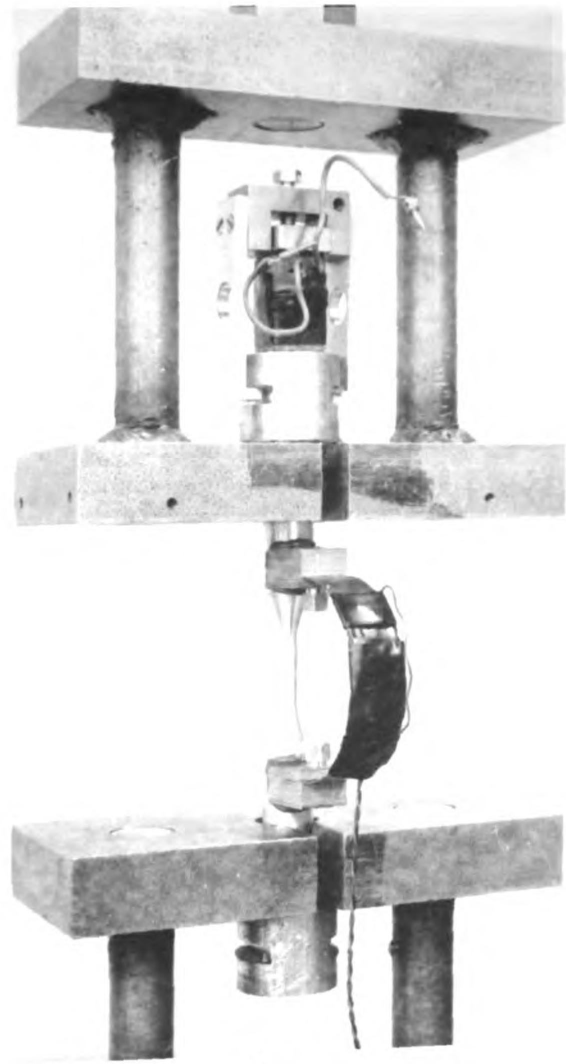


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FIGURE 11: Specimen, Strain Extensometer And Crystal Assembly

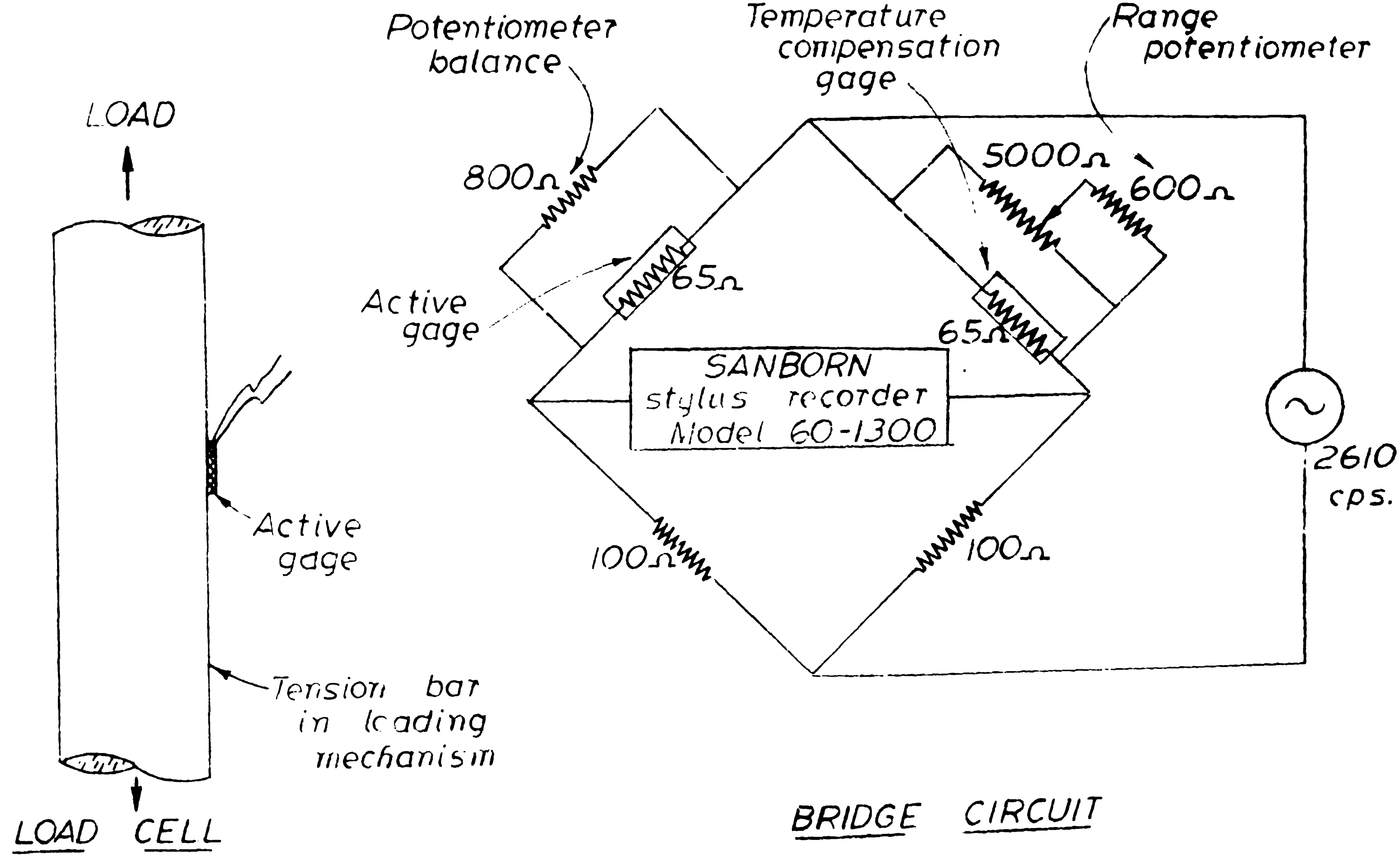


FIGURE 12 -Load Cell and Wheatstone Bridge

in shunt with the active gage to balance the bridge. Stresses were then calculated from the load data, depending on the critical area of the specimen.

Strain measurements were made with a unique extensometer shown in Fig. 11. This strain measuring device consists of a semi-conductor strain gage (gage factor of 118) mounted on a spring steel beam formed into a semi-circular arc of one inch radius. The beam width is one half inch and the thickness is one thirty-seconds of an inch. The beam is fastened to small Bakelite blocks which are glued to the specimen. The Bakelite blocks allow an acoustic mismatch so that the strained beam does not transmit a vibration into the specimen. The extensometer is flexible enough that it will introduce only negligible moments or additional stresses on the specimen. It also permits strain to be recorded without physically hampering the specimen by mounting a strain gage directly upon it. This method of measurement furnishes excellent strain data throughout the elastic and plastic ranges where a conventional strain gage application could not withstand a yielding specimen.

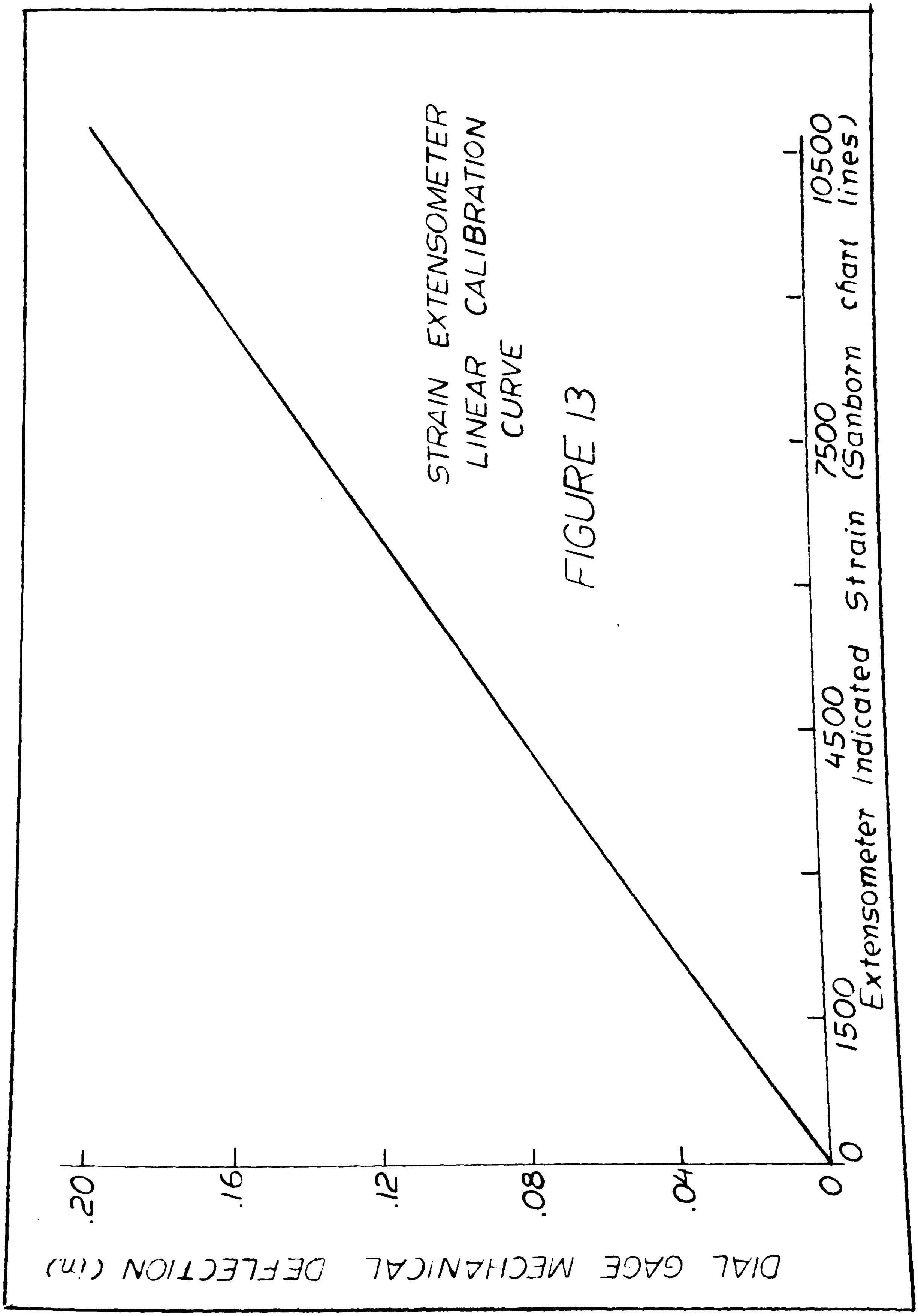
An analysis of strain in the specimen versus strain in the beam shows the following relationship;

$$\frac{\varepsilon_b}{\varepsilon_s} = \frac{2t}{\pi a}$$

Where ε_b = strain in beam
ε_s = strain in specimen
t = beam thickness
a = beam radius

provided the higher order terms are neglected. The above equation shows a linear relationship. However, the higher order terms that have been dropped would theoretically introduce a small degree of non-linearity. Fig. 13 shows that experimentally there is a linear relationship between strain in the beam and actual specimen strain. The curve was constructed by actual measurement of extensometer indicated strain that accompanied the mechanical deflection of a calibrating frame.

The continuous strain recording is made on one channel of the dual channel Sanborn oscillograph (with continuous load recording on the other channel). The bridge circuit for the strain extensometer is shown in Fig. 14. This circuit is approximately the same as that for the load cell except that a fifty-five ohm resistor was added in series with the active gage to act as a desensitizer. It was found that the strain gage was too sensitive and this resistor, placed in series with it, reduces the gage factor by approximately one half. The fifty-five ohm resistor placed in series with the compensator gage is a balance for the desensitizer. Strain measurements ranged from zero to 40,000 μ in./in. and again it was necessary to provide a means of re-zeroing the oscillograph. This was accomplished with a 10,000 ohm potentiometer. The oscillograph was calibrated to give approximately fourteen μ in./in. of strain per chart line.



STRAIN EXTENSOMETER
LINEAR CALIBRATION
CURVE

FIGURE 13

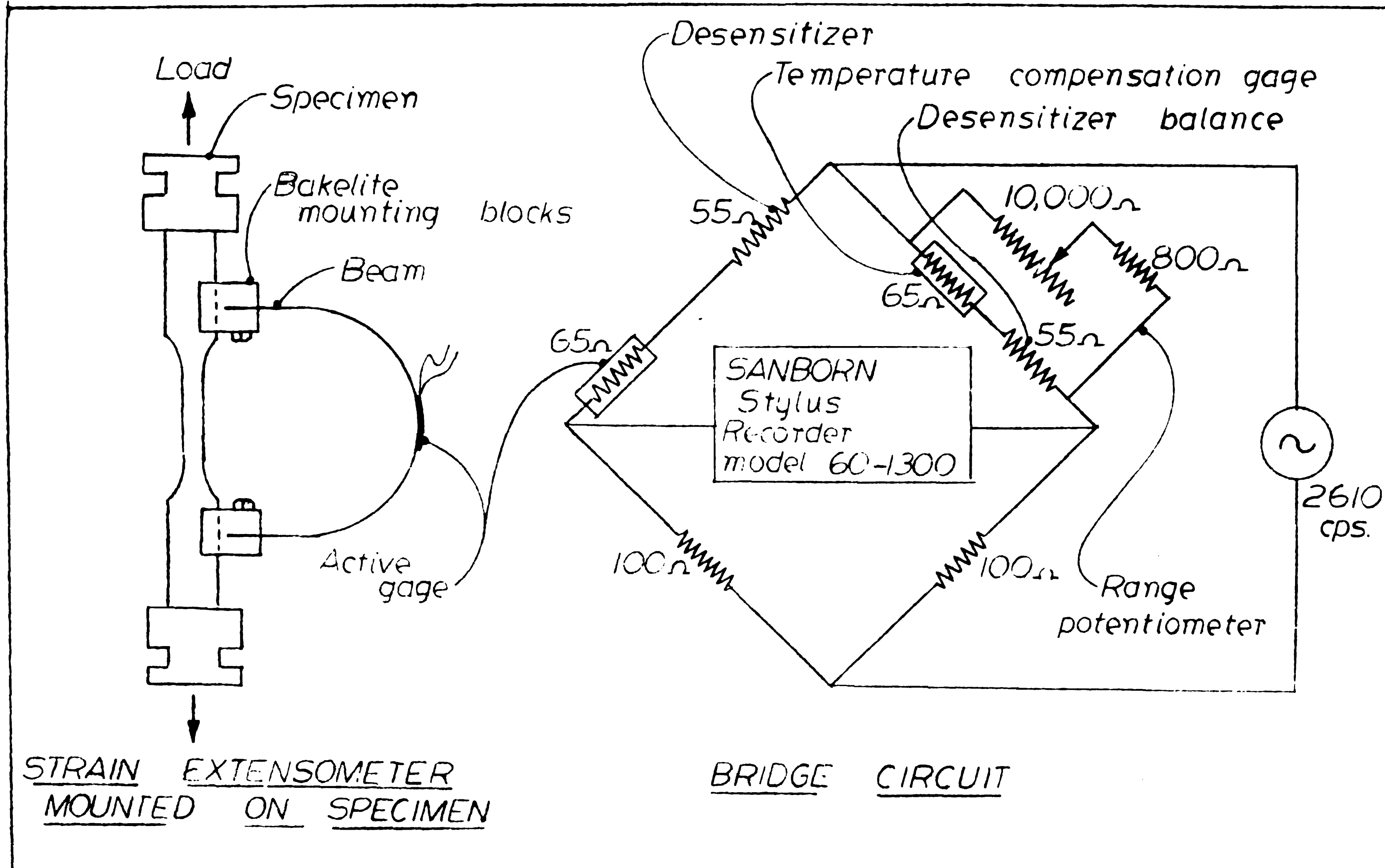


FIGURE 14–Strain Extensometer and Wheatstone Bridge

CHAPTER III

EXPERIMENTAL PROCEDURE

The initial experimental procedure begins by expanding the thermal bar. The heat tube is turned on and allowed to heat the thermal bar until an elongation of approximately .30 inches is reached. This is about the maximum elongation attainable with this particular heating furnace. This amount of elongation indicates an average temperature of the thermal bar of approximately 450° F. As the bar expands, the adjustable head on the Riehle testing machine is moved down to maintain a predetermined tension on the specimen. (The reader may wish to refer to Fig. 1.) When the full expansion of the thermal bar is reached, the testing machine and heat tube are turned off. The contraction of the heated bar being cooled now begins to produce a load on the specimen. The actual test begins at this point and the tape recorder is turned on. The acoustic signal is being viewed on the oscilloscope (see Fig. 20) and simultaneously recorded on an even channel of the tape recorder. The loads produced may be observed at any time directly from the load indication dial of the testing machine. The laboratory is in complete silence, with the exception of these loads being monitored into an odd channel of the tape recorder every minute. Occasionally voice comments are added on the voice channel in the event of an interesting occurrence. Normally, thirty-five to forty minutes of natural cooling produces sufficient load (approximately .15 inches of contraction) to put any specimen well into the plastic region. The tape recorder is stopped and the testing machine is turned on when yielding is so great that fear of fracture is present. Specimen fracture is avoided to preserve expensive apparatus. There is now a permanent record of acoustic emissions that may be replayed at any convenient time for careful inspection.

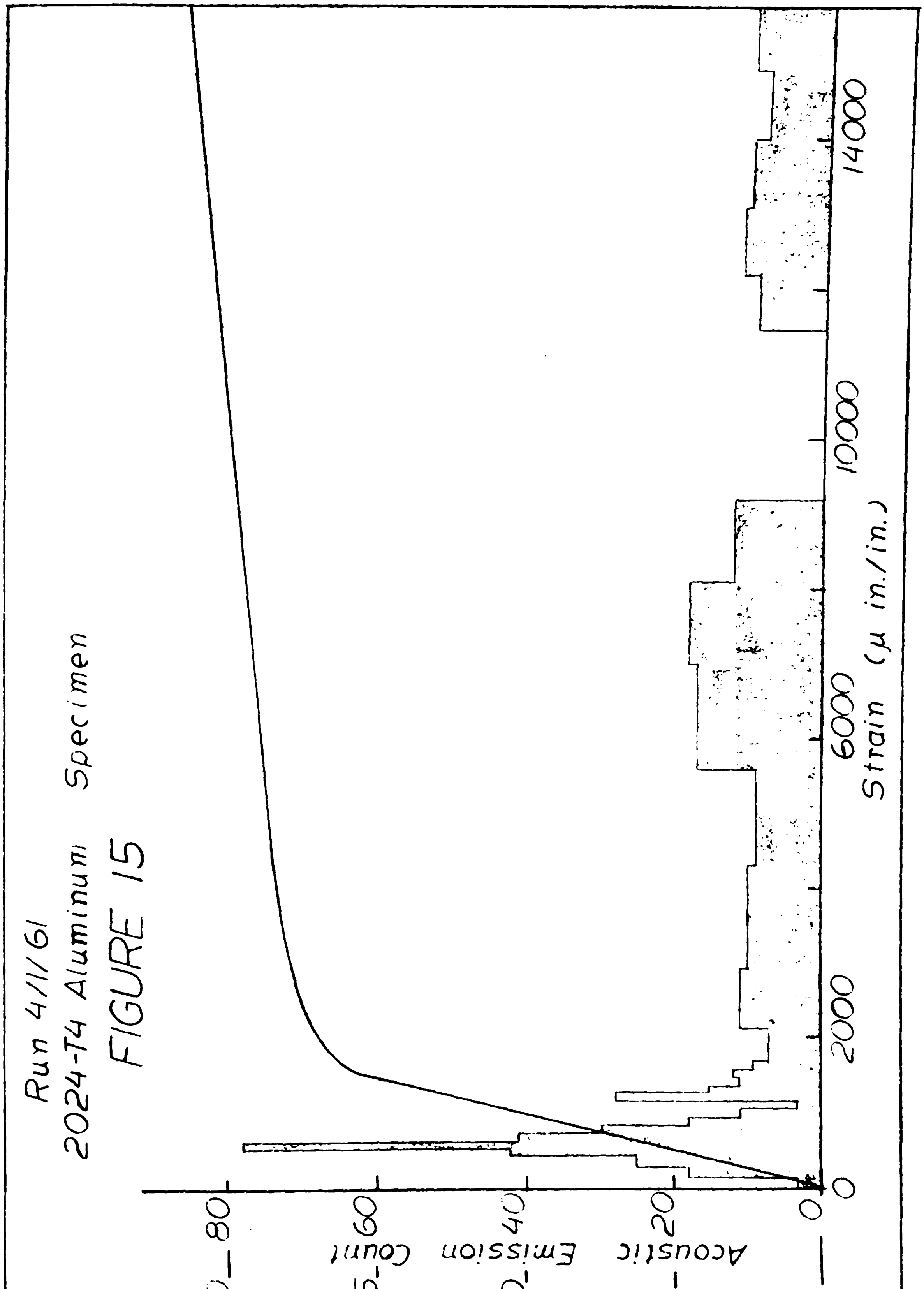
Stress-strain data is available from the Sanborn recording which has been synchronized with the tape recorder by a remote timing switch. At the precise time the minute interval loads are monitored on the tape recorder, a mark is placed on the oscillograph chart. This easily enables one to correlate stress-strain data with acoustic data.

The smallest acoustic signals, judged detectable, are two times amplifier noise. This is attained by trigger level setting on the oscilloscope. The tape recorder records everything that comes through the SKL filter. The filtering frequency on the SKL is variable, and its choice of setting depends a good deal on acoustic experience with various specimen materials. Frequencies below 2000 cycles per second were filtered for this particular experiment. In general, one must gain experience and become quite familiar with acoustic emission and the electronic apparatus to thoroughly understand all of the range settings.

CHAPTER IV

PRESENTATION OF EXPERIMENTAL RESULTS

Significant results are presented in the form of stress-strain curves superimposed on acoustic emission histograms. The results of the 2024-T4 aluminum specimen (Run 4/1/61) are shown in Fig. 15, and the annealed C1018 steel specimen (Run 4/3/61) in Fig. 16. The stress-strain diagrams are self-explanatory. However, to understand the histograms, some explanation may be required. The stress-strain curve and the histogram share a common abscissa, which is strain. Keeping in mind that the loads are recorded in one minute intervals, the specimen strain is also related to time (via the stress-strain curve). The electronic counter is arranged to count the total number of acoustic emissions per minute (per load recording interval) that are greater than two times noise. The electronic counter is arranged so that it gives one square wave signal (to be counted) per oscilloscope sweep and the oscilloscope is arranged so that one acoustic emission will occur in one sweep length. Assuming, then, that only one acoustic emission occurs during a sweep and that the emission is greater than two times noise, all emissions are counted. This is not so however, and it must be kept in mind that some emissions are missed (Those that are less than two times noise and those that occur more than one per sweep). The acoustic emission counts per minute, or per strain interval corresponding to a minute, are then plotted as the ordinate in the histogram. The steps in the histogram represent one minute intervals and are represented as strain intervals corresponding to one minute on the abscissa. This method of plotting is very descriptive because it represents relative acoustic emissions as



Run 4/1/61
2024-T4 Aluminum Specimen
FIGURE 15
Stress (ksi)
Acoustic Emission Count
0
15
30
45
60
0
20
40
60
80
0
2000
6000
10000
14000
Strain (μ in./in.)

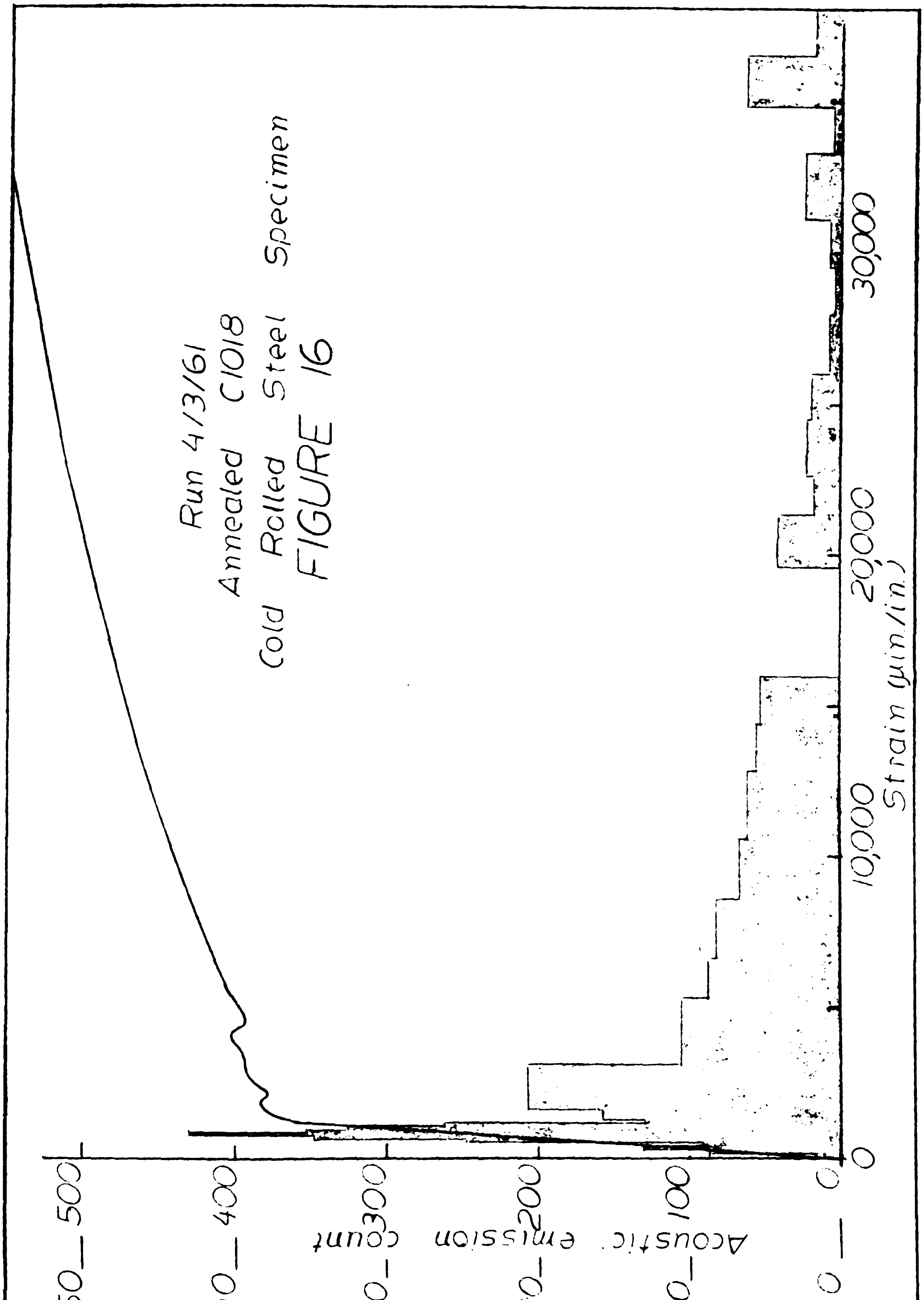
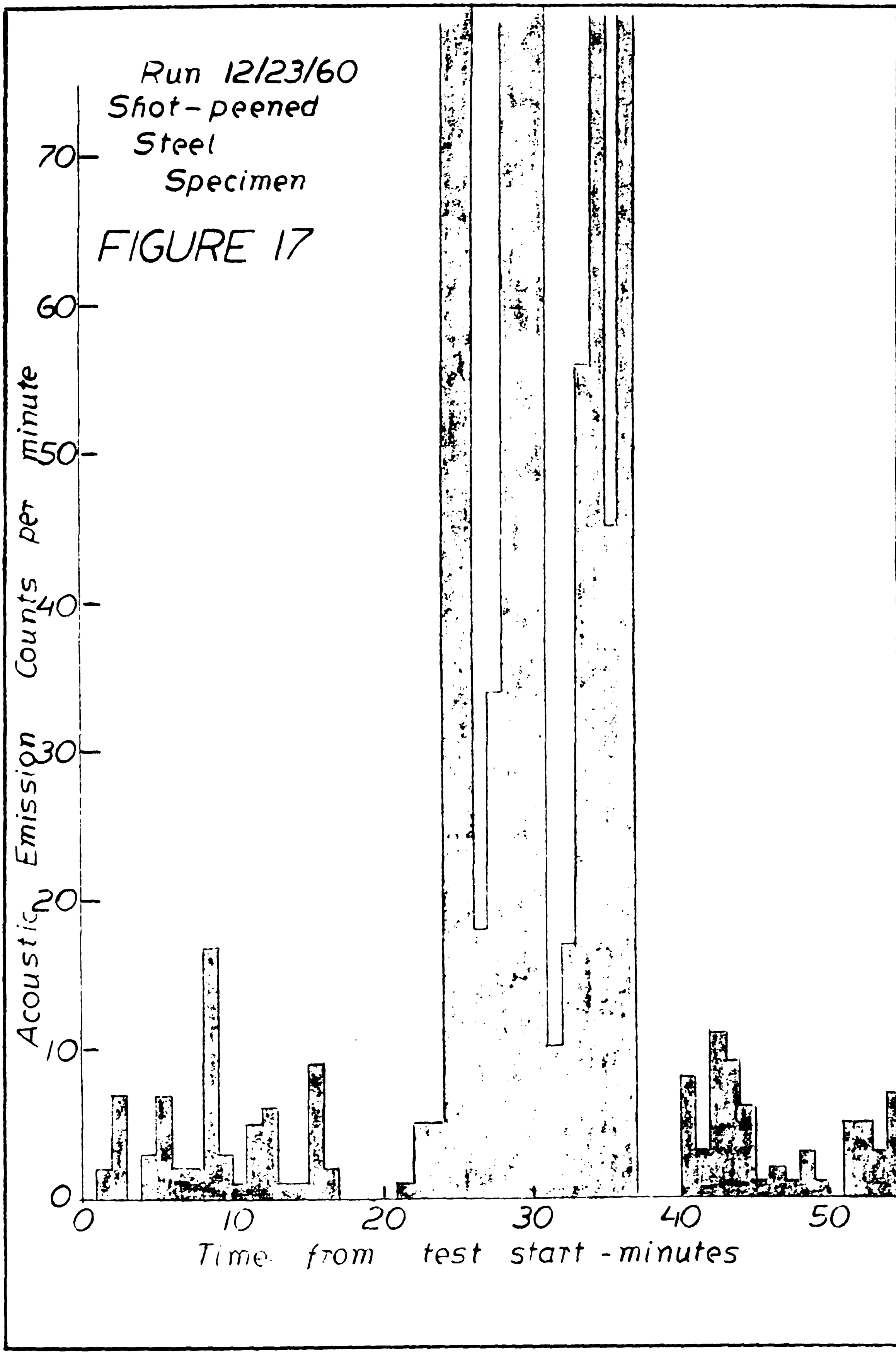

Run 4/3/61
Annealed C1018
Cold Rolled Steel Specimen
Strain (μin/in)
0
10,000
20,000
30,000
Stress (ksi)
Acoustic emission count
0
10
20
30
40
50
0
100
200
300
400
500

FIGURE 16

they occur on the stress strain diagram. The portions of the histogram where counts are not recorded are merely portions where data was not available because changes in recording tape track were made at this time. Although one cannot be certain, one is relatively sure that there is no outstanding phenomenon occuring in these void areas because of the trend of the plot.

The histogram shown in Fig. 17 is plotted with time in minutes as the abscissa and again acoustic emission counts per minute as the ordinate. The data for this run was obtained in exactly the same way as was the data for Runs 4/1/61 and 4/3/61. Strain measuring instrumentation was not available at the time this test was made. However, the time from test start may be correlated with specimen loads. The counts that disappear off the scale of the plot continue to a magnitude of 700 to 900 acoustic emissions per minute. This histogram appears to be more descriptive plotted to this scale rather than one that ranges from zero to 900. The specimen for Run 12/23/60 was steel that had been shot peened over approximately one and seven sixty-fourths of an inch of its critical length. The critical length was two inches and the critical diameter was one quarter inch.

A relative description of the acoustic emission pulses are presented in a somewhat different form in Figs. 18 and 19. These oscillograph recordings are for the aluminum 2024-T4 specimen (Fig. 18) and for the annealed steel C1018 specimen (Fig. 19). These charts were obtained by oscillograph recordings of the acoustic emission signals as seen by a root-mean-square voltmeter. The baseline of the chart represents the relative noise magnitude and the peaks or pulses represent relative acoustic emission voltage signals. Because of the


Run 12/23/60
Shot-peened
Steel
Specimen
FIGURE 17
Acoustic Emission Counts per minute
0
10
20
30
40
50
60
70
Time from test start - minutes

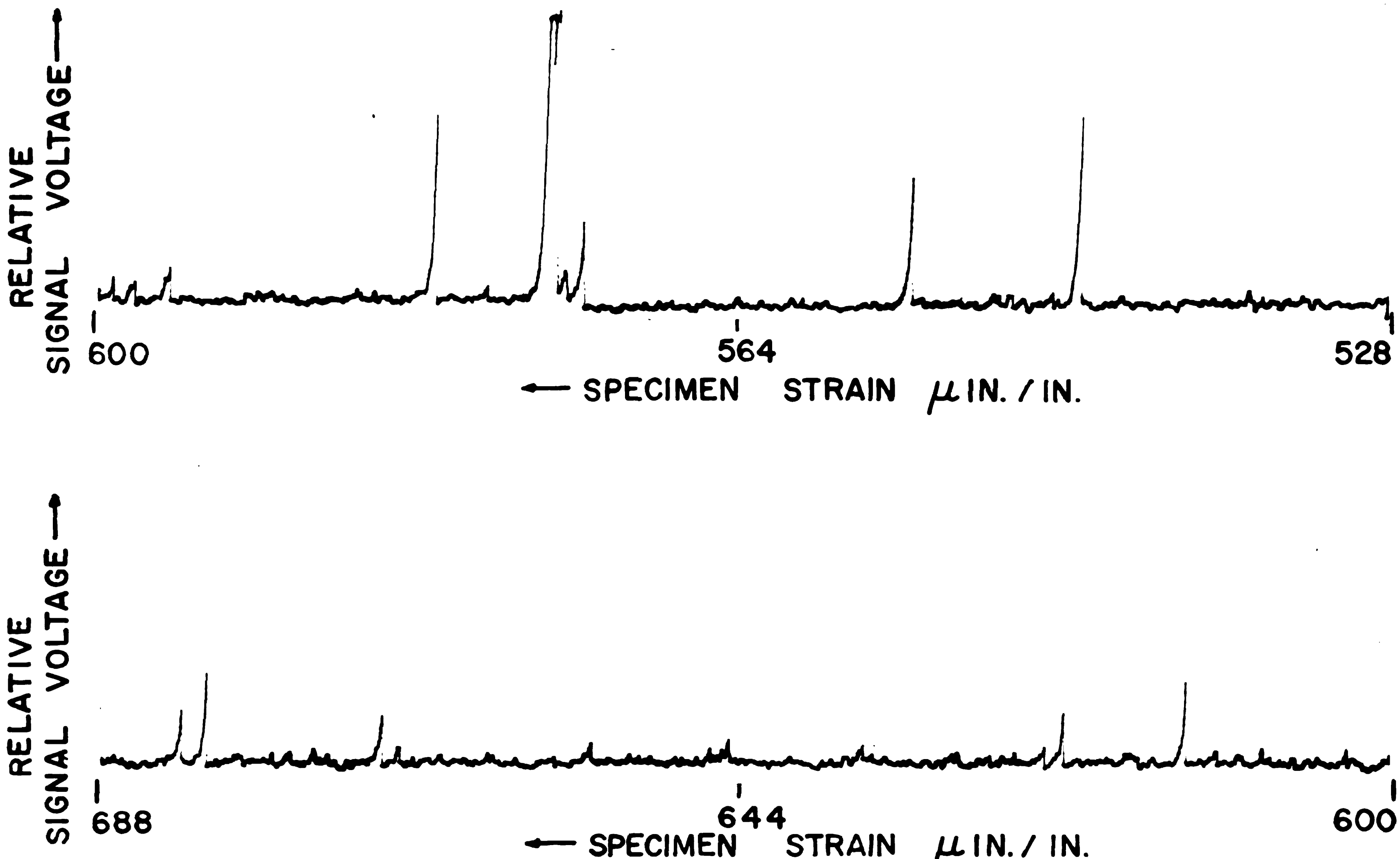


FIGURE 18 - RELATIVE SIGNAL VOLTAGE OF RUN 4/1/61, 2024-T4 ALUMINUM SPECIMEN

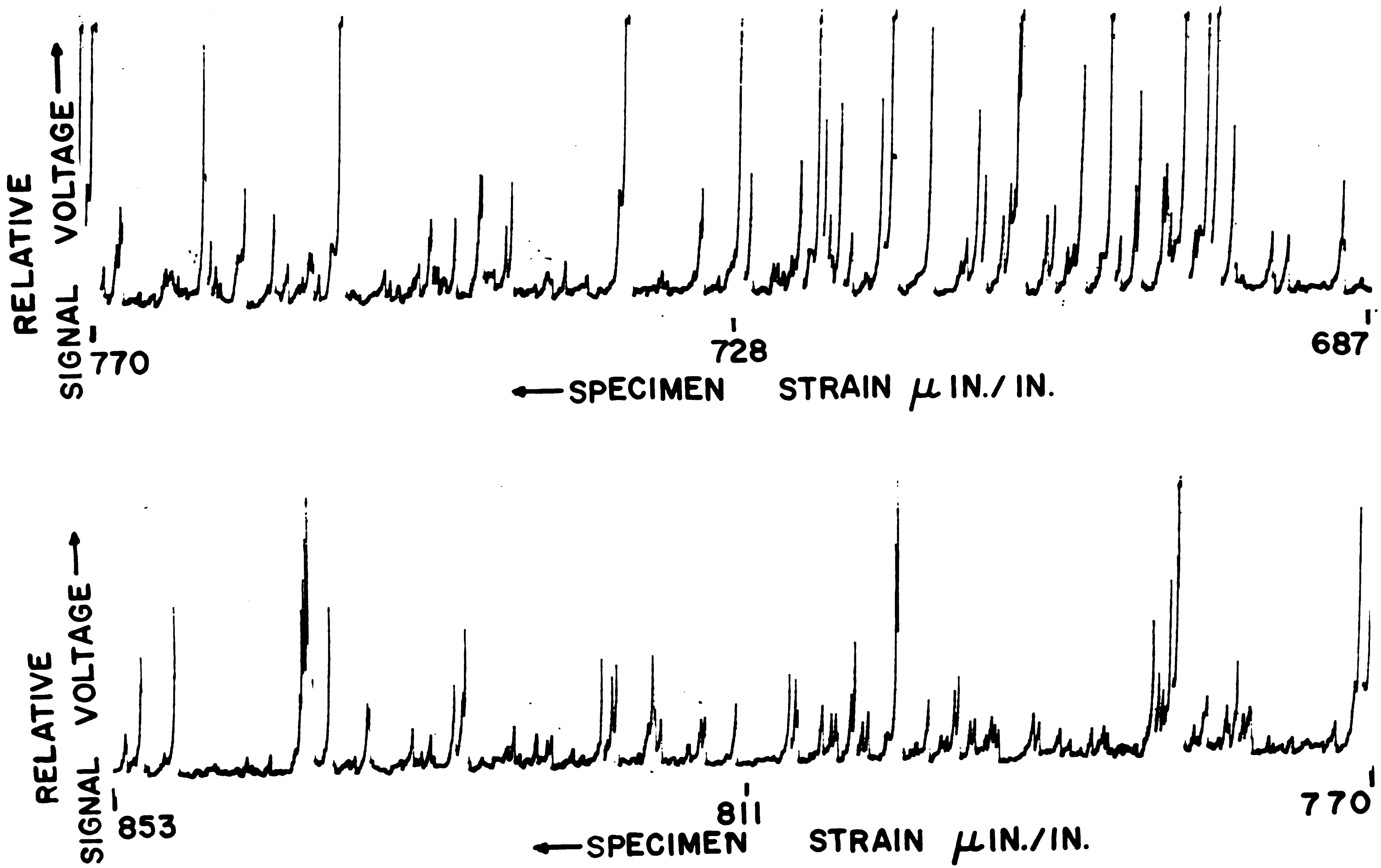


FIGURE 19 - RELATIVE SIGNAL VOLTAGE OF RUN 4/3/61, ANNEALED C1018 COLD ROLLED STEEL SPECIMEN

great length of oscillograph chart required to record a complete run, only the most acoustically active portions of the runs have been shown. It should be noted that the strain intervals presented for the oscillograph charts correspond to the strain intervals indicating the most activity (most number of counts per minute) in the histograms for these particular specimens (Refer to Figs. 15 and 16). The relative voltage signals are correlated with strain intervals in the same manner indicated previously for histogram data analysis.

The photographs shown in Fig. 20 are a portion of a reel of film which photographed the acoustic emissions that accompanied a yielding region in the shot peened steel specimen mentioned above (Run 12/23/60). The tape recording of this run was played into the oscilloscope and approximately five seconds of a yielding region was photographed on fifty feet of film with a DuMont type 321-A, 35 mm oscillograph record camera. Approximately three inches of this film was magnified five times and reproduced as Fig. 20. Approximately 900 oscilloscope sweeps occurred during this five seconds of filming which would indicate ideally that 900 acoustic emissions occurred. The timing marks shown on the photograph are one one hundred twentieth of a second apart.

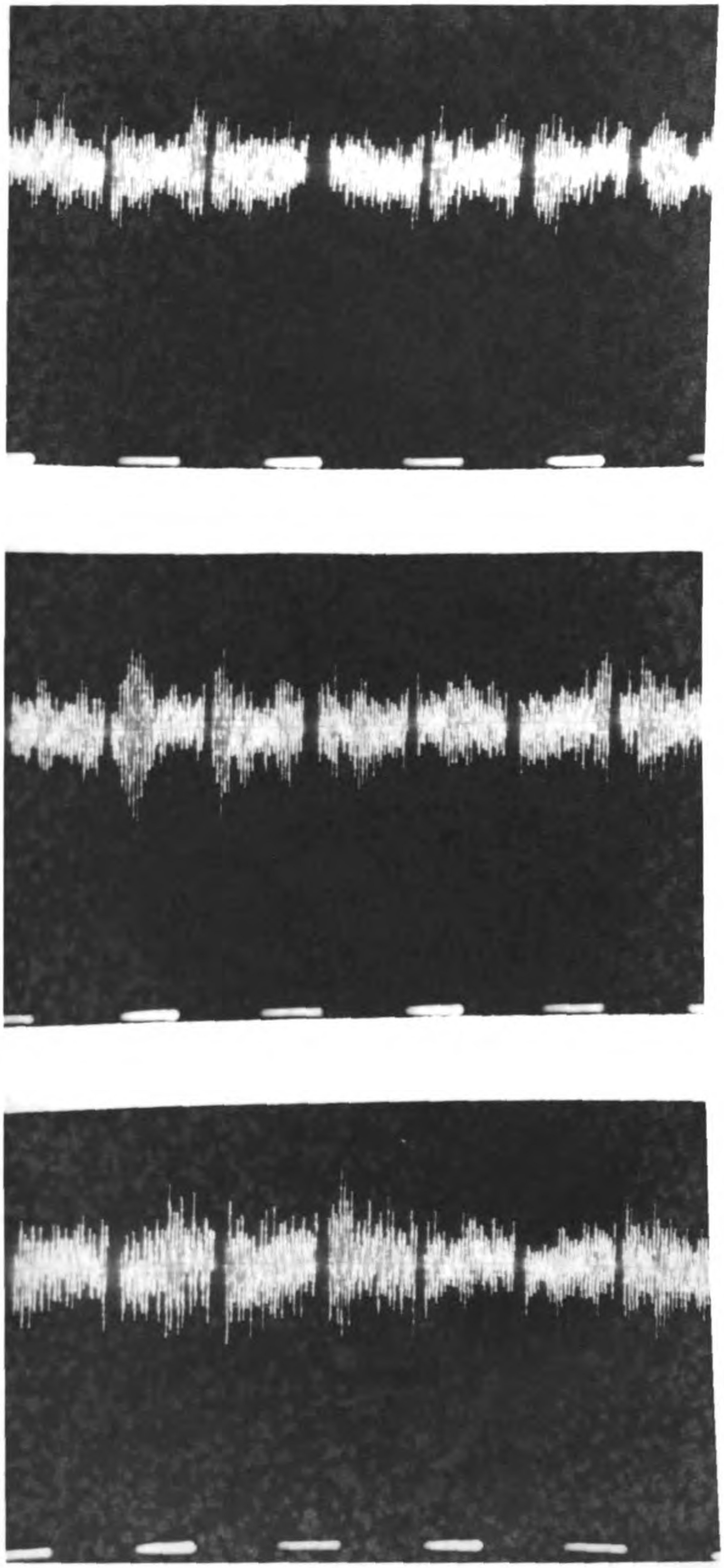


FIGURE 20: Photograph Of Oscilloscope Image For A Yielding Region Of Run 12/23/60, Shot Peened Steel Specimen

CHAPTER V

SUMMARY AND CONCLUSIONS

The thermal loading mechanism developed for research in acoustic emission meets the necessary design requirements more than adequately. This loading device is certainly quiet enough to eliminate confusion between acoustic signals and extraneous noises that are encountered in ordinary testing machines. Load magnitudes produced were sufficient to yield any specimen tested, and the loading operation is simple.

The electronic recording and data analyzing mechanism was not infallible. However, at the present time, it offers the only known solution to instrumentation in some cases, and in others, it is the only available instrumentation. The instrumentation and analysis methods used in this experiment were certainly more than sufficient for a complete preliminary study in acoustic emission.

It is very difficult to draw any concrete conclusions from the results presented. However, they are certainly worthy of considerable discussion. It is fairly obvious that there is a definite difference between steel and aluminum as far as acoustic emissions are concerned. One might note the difference in the magnitude of counts per minute. The acoustically active regions of steel reveal counts as high as 430 per minute while the aluminum active region is approximately eighty counts per minute (Fig. 15 and 16). This point is further emphasized by comparing the relative signal voltage oscillograph of aluminum (Fig. 18) with that of steel (Fig. 19). The emission occurrence of steel is obviously greater. It might also be pointed out that the relatively inactive portions indicated on the histograms (regions past yield) were verified on the RMS relative signal voltage charts (not shown).

Although it is not so obvious from the results presented, it is fairly certain that there is quite an acoustic emission difference between specimens of similar material. The shot peened steel specimen (Fig. 17) exhibited acoustic counts as high as 900 per minute as compared with the annealed steel specimen's (Fig. 16) 430 per minute.

There seems to be an obvious pattern present in both the aluminum and annealed steel histograms. These histograms indicate a large amount of activity just before yield and then seem to become less active in the plastic region. This is also verified from the results obtained with the shot peened steel specimen. Although strain data was not available for this specimen, the initial yield was recorded on the voice channel of the tape recorder. The shot peened steel specimen began to yield twenty-one minutes after test start. The pattern developed in these histograms would lead one to believe there could be a correlation between acoustic emissions and engineering design properties.

It is an engineer's hope that acoustic emission research will ultimately lead to some new criteria for engineering design. It is possible that acoustic emission studies may be an aid in those areas where more insight into the physical nature of engineering materials is needed. Two possible areas could be design for optimum creep and fatigue behavior.

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