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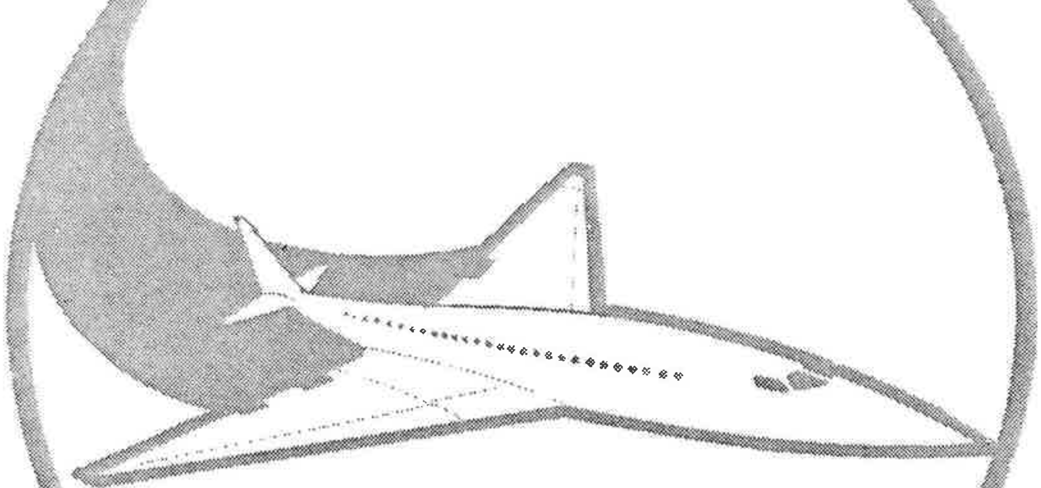
Development of Alternating Current Potential Drop (ACPD) Procedures for Crack Detection in Aluminum Aircraft Panels



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13. ABSTRACT (Maximum 200 words)

The Alternating Current Potential Drop (ACPD) method is investigated as a means of making measurements in laboratory experiments on the initiation and growth of multiple site damage (MSD) cracks in a common aluminum alloy used for aircraft construction. Procedures for instrumenting MSD test specimens are recommended. The ACPD method is found to be capable of (1) detecting crack initiation at a crack length of the order of 1 mm; (2) monitoring crack propagation at a resolution of the order of 5 μm; and (3) providing an indirect measurement of crack extension in R-curve type tests of fastener hole details.

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AC potential drop, crack growth, fatigue, fracture, R-curve, stable crack extension

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PREFACE

This report describes an investigation of the application of the alternating current potential drop method (ACPD) to the study of Multiple Site Damage (MSD) cracks in common aluminum alloy. The report was prepared by D.A. Jablonski of Instron Corporation, under contract to the U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center. It was sponsored by the U.S. Department of Transportation, Federal Aviation Administration Technical Center, Propulsion and Structures Branch.

METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

$[(x - 32)(5/9)]$ °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

$[(9/5)y + 32]$ °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES: 0 1 2 3 4 5 6 7 8 9 10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

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LIST OF ABBREVIATIONS AND SYMBOLS

a	crack length
b	intercept in linear fit
D	hole diameter
f	current frequency
m	slope in least squares fit
r	correlation coefficient
Pd	AC potential
Pd_o	initial AC potential
Xoff	vertical distance from edge of hole to potential lead
δ	AC field skin thickness
Δ	spacing between potential probes
σ	electrical conductivity
μ	magnetic permeability

EXECUTIVE SUMMARY

This report summarizes the results of a study to determine the strengths and the weakness of the AC potential drop technique for measuring multiple site crack initiation and crack propagation in aluminum aircraft test specimens. This technique is easily automated; thus long term multi-site test specimens can be tested without the constant stopping of the test by an operator to visually measure the crack sizes. This will reduce the time it takes to generate multi-site test data, improve the quality of the data, and reduce the cost of running a test.

The principles of the AC potential drop technique are that a high frequency current (3 to 100 kHz) is injected into the specimen. The current field is confined to the surface of the specimen by the so called "skin effect." Because of the skin effect, only small currents are required (generally less than 2 amps). The potential is measured by phase sensitive amplifiers which results in high sensitivity and the ability to reject noise. The current field is focussed only on the area of interest to improve sensitivity.

This ACPD technique was applied to test specimens under fatigue cycling conditions as well as static R-curve testing. Aluminum ALCALD 2024 test specimens with three holes and those with a row of three rivets were examined. Optimum current and potential lead geometries were determined for each specimen geometry. Correlations between crack length and potential were determined. It was found that a simple linear relationship between the measured potential and crack length existed for both specimen types. The sensitivity of the technique for measuring crack length increased with increasing current frequencies up to 30 kHz. The sensitivity of ACPD at 30 kHz was 32 $\mu m/\mu V$ for the three-hole specimens and 77 $\mu m/\mu V$ for the riveted specimens. The ACPD system could resolve 0.1 μV. Crack initiation experiments showed that the increase in AC potential prior to finding a visible crack was due to crack growth. R-curve tests showed that the AC potential was not affected by the large scale deformation which occurs in this testing mode. Crack length potential relationships determined by fatigue testing can be used to predict crack length from the AC potential in an R-curve test.

In applying ACPD to the measurement of multi-site crack growth it was discovered that the current and potential leads should be separated as much as possible and the leads should be attached rigidly. In order to obtain repeatable crack length potential relationships it was necessary to subtract the initial AC potential of the uncracked hole or rivet. This initial potential was found to vary widely from specimen to specimen. This problem would make the technique inapplicable to the inspection of cracking on aircraft, yet the technique is still a very useful tool for laboratory testing.

1. INTRODUCTION

The characterization of multiple site damage by use of laboratory test specimens is an important precursor to the understanding of multiple site damage in aging aircraft. As the number of damage sites in the laboratory specimen increases, it becomes more time consuming to measure crack initiation and growth from the various sites. Typically the crack initiation and crack growth would be measured either visually or with a low power microscope. This technique is accurate, but it is very labor intensive.

In order to reduce the time necessary to obtain multiple site crack growth rate data, an automated crack length measuring technique is needed. There are a variety of possible automated crack length techniques available. The most popular are compliance, DC potential drop, and AC potential drop. The compliance technique relates the specimen's normalized compliance to crack length by a complex polynomial relationship. The accuracy of this technique decreases as the specimen's compliance decreases. Aluminum aircraft panels are not very compliant; therefore this technique would not be able to accurately measure crack length. Another drawback is that the attachment of displacement gages to an aircraft panel would be difficult. For more information about the compliance technique the reader should consult references 1 and 2.

The DC potential drop technique applies a constant DC current to the specimen and measures the resulting potential. The potential increases as the crack grows. The magnitude of the current necessary to produce repeatable and accurate potential readings depends upon the specimen geometry, size, and the material's resistivity. Materials with relatively high resistivity, such as alloy steels, require currents of the order of 10 to 50 amps. Materials with low resistivity, such as aluminum alloys, require currents of the order of 50 to 250 amps. Low resistivity materials require such high current densities for accurate potential measurements that there is a serious problem of specimen heating. The DC potential drop technique is not very sensitive to crack initiation and the measurement of short cracks. For more information about the DC potential drop technique the reader should consult references 3 and 4.

The AC potential drop technique applies a high frequency (3 to 100 kHz) current to the specimen and measures the resulting potential. ACPD uses phase sensitive detection to measure the small voltages involved. The phase sensitive detection is responsible for the high sensitivity and ability to reject most noise. In ACPD the high current frequencies cause the current to be concentrated on the surface of the specimen, and it is this so called "skin effect" which is responsible for the high sensitivity and low currents required (1 amp). The skin thickness (δ) can be calculated by the following equation.

$$\delta = \frac{1}{\sqrt{(\pi \mu \sigma f)}}$$

Where:

μ = magnetic permeability

σ = electrical conductivity

f = current frequency

The skin depth for an alloy steel with current frequencies of 3, 10, and 30 kHz would be approximately 0.60, 0.15, and 0.08 mm. The skin depth for an aluminum alloy with the same current frequencies would be 2.0, 1.0, and 0.60 mm respectively.

With the ACPD technique it is possible to concentrate the current to only the area of interest by routing the current leads in a line directly above the area of interest; this is the so called current focusing technique. This intensifies the current field and increases the sensitivity of the technique. A possible problem with this technique is that the potential can be affected by plastic deformation. Reference 5 discusses this problem with alloy steel. The reader is referred to reference 6 for more detail on the ACPD technique.

This report describes the benefits and problems of applying ACPD to aluminum aircraft panels. Two specimen types, multi-hole and riveted panels were studied. Current and potential lead geometry was experimented with to obtain high sensitivity. Duplicate specimens were run to determine repeatability of the technique.

2. EXPERIMENTAL PROCEDURE

2.1 HARDWARE SETUP

In this study three types of specimen were used. The specimen types are single hole, three hole and riveted panels. Pictures of these three specimens are shown in Figures 1 to 3. The specimens were tested with an Instron 8502 digital servohydraulic test machine. The crack length was measured visually with a Questar QRMS-M optical microscope system. The AC potential measuring equipment consisted of a Matelect CGM5 ACPD unit, SC1 scan controller, SCM1 8 channel potential scanner, and SCM2 8 channel current scanner. The test was controlled and data was collected using a Compaq-386 computer. A special program was written for this task. The details of the program will be described in the next section. A picture of the test setup is shown in Figure 4. A close-up of the ACPD equipment is shown in Figure 5. A schematic representation of the system and the data communication connections are shown in Figure 6. A brief description of the various pieces of test equipment used will be given below.

The Matelect ACPD system is a multiple frequency AC potential drop crack length measuring device. The available frequencies are 0.3, 3.0, 10.0, 30.0, and 100 kHz. The maximum output current is 2.0 amps. The voltage is measured with an automatic phase detection circuit with gains of 50, 60, 70, 80 and 90db. The amplified potential may be read from the 4 1/2 digit display, by computer with an RS-232 interface or from an analog output. The current and potentials can be scanned with a multiplexing arrangement. The multiplexing devices each handle 8 channels. The multiplexing is controlled by switches on the SC1 scan controller or through a separate RS-232 connection on the SC1.

The Questar QRMS-M system is a high resolution long distance microscope. The system consists of a QM-100 microscope with a 1 μm resolution, an instrumented X-Y-Z stage, a floor stand, CCD camera, high resolution black and white monitor, video cross hairs and a fiber optics illumination device. The X-Y-Z stage has a digital read-out for X and Y position and has a resolution of 0.01 mm. The digital meter can also be read by an RS-232 interface.

The Instron 8502 is a digital servohydraulic test machine. It has a capacity of 250 kN with a maximum frequency response of 20 Hz. The system is capable of measuring position, load and two strain channels with an accuracy of 0.2% of full-scale. This particular system was fitted with a 25 kN load cell for this series of tests. The fatigue tests were run in load control and the R-curve tests were run in position control. The computer interface on the machine is IEEE. Control functions as well as test data can be sent and received over the IEEE interface.

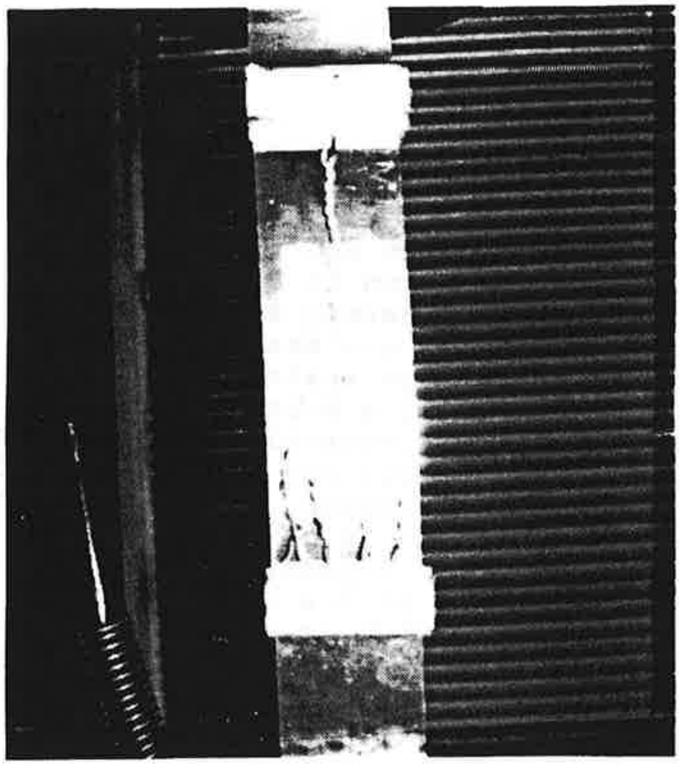


FIGURE 1. PICTURE OF SINGLE HOLE ALUMINUM SPECIMEN

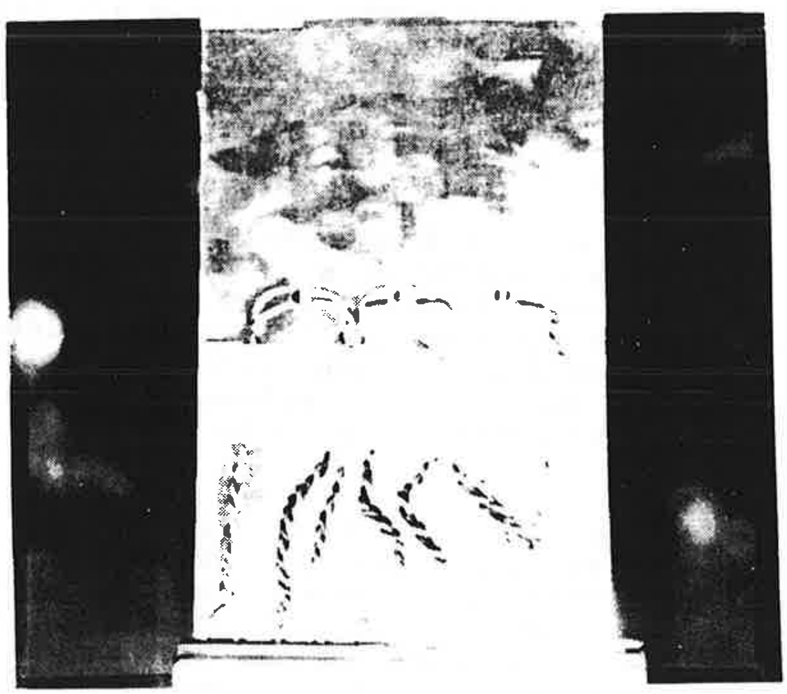


FIGURE 2. PICTURE OF THREE HOLE ALUMINUM SPECIMEN

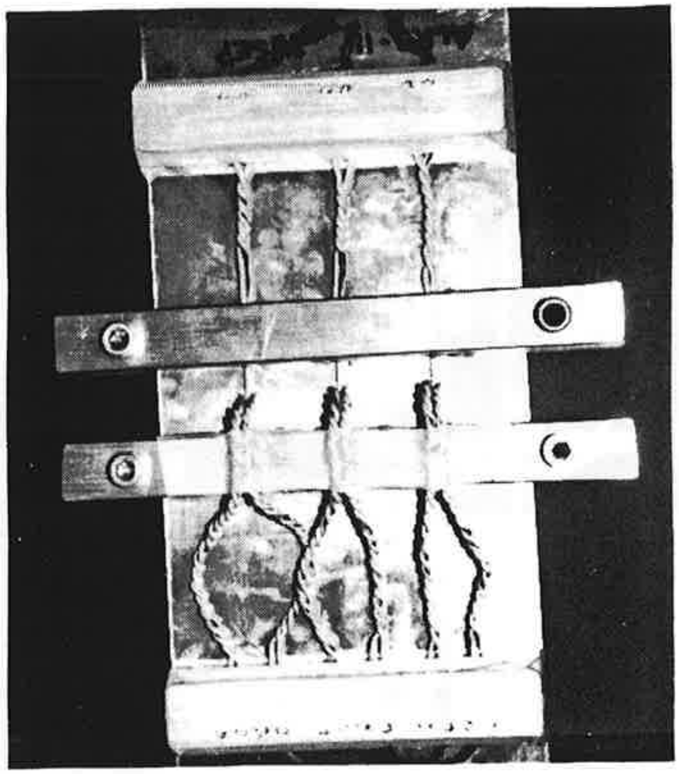


FIGURE 3. PICTURE OF RIVETED ALUMINUM PANEL

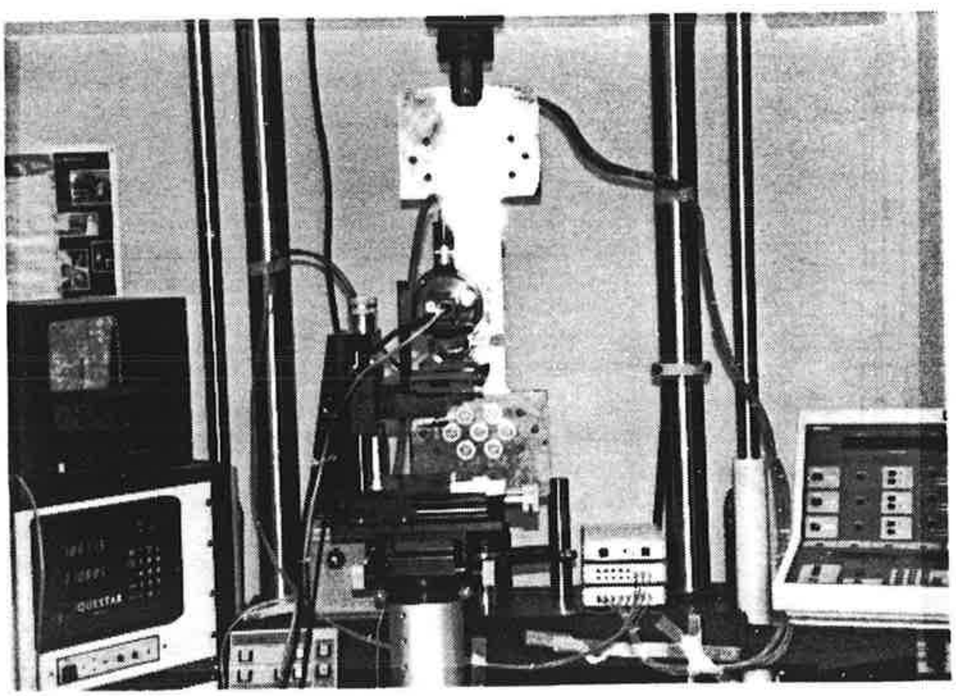


FIGURE 4. PICTURE OF EXPERIMENTAL TEST SETUP

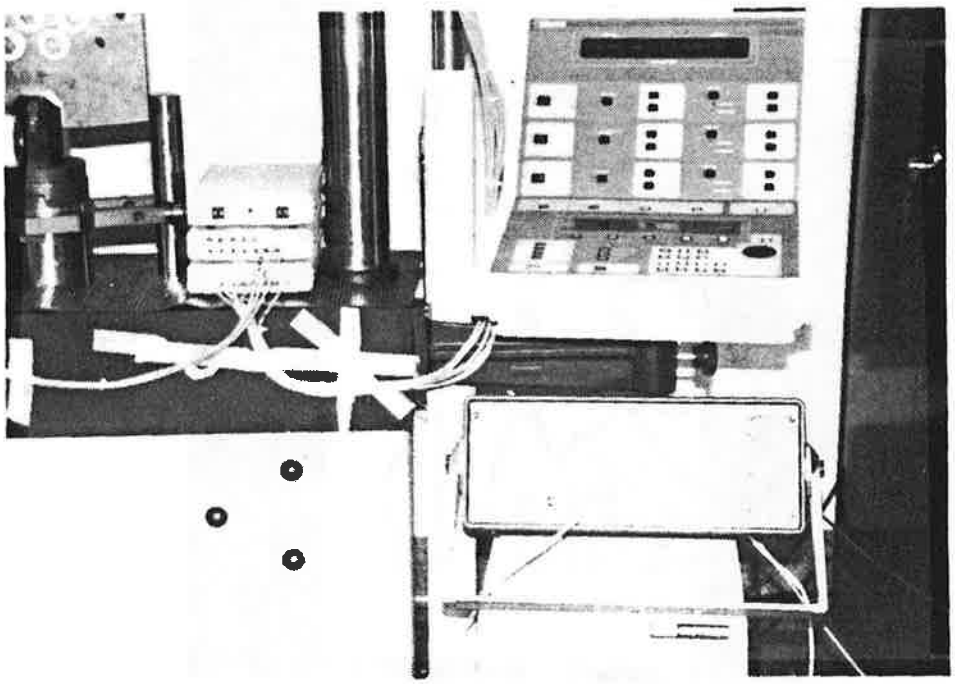


FIGURE 5. PICTURE OF ACPD EQUIPMENT

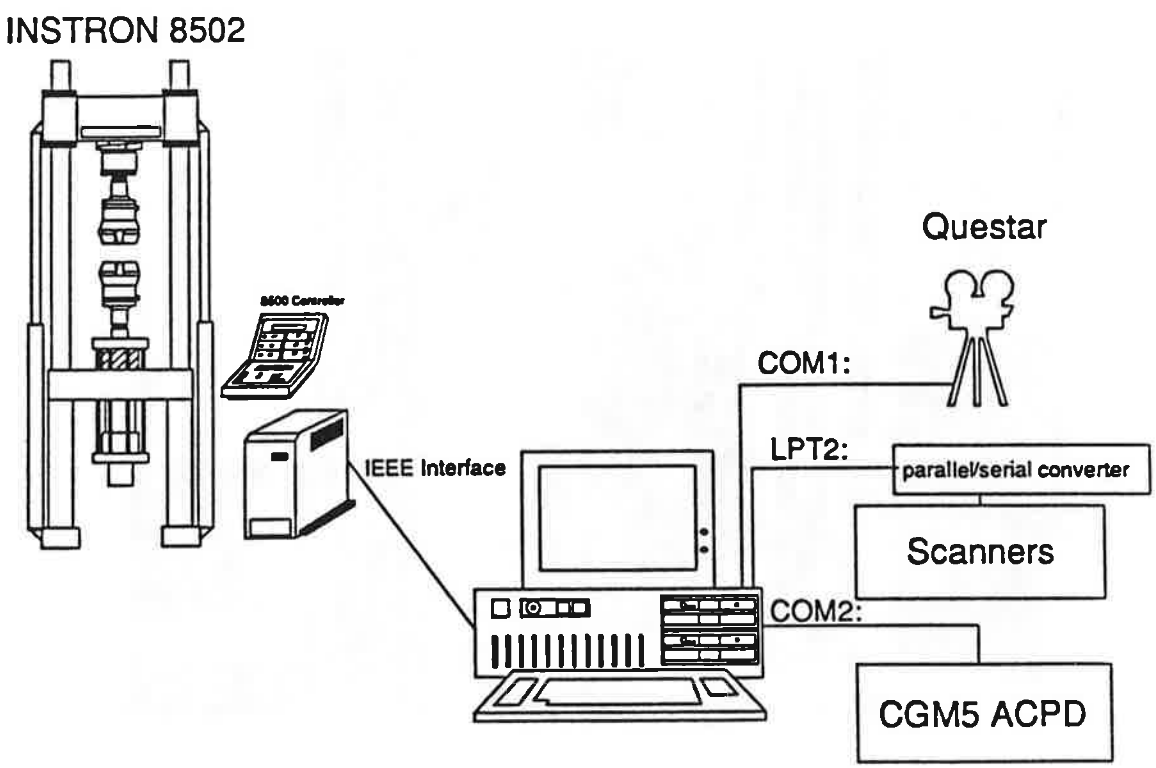


FIGURE 6. SCHEMATIC OF TEST SETUP SHOWING DATA COMMUNICATIONS CONNECTIONS

2.2 SOFTWARE DESCRIPTION

A software program called "ACPDCYC" was written to control the fatigue test and to collect test data and store it in an ASCII file for post test analysis. The program was written in Microsoft Quick Basic version 4.5 and ran under DOS 3.31. A listing of the source code is given in Appendix B. Data communication between the Instron 8502 and the PC was performed by an IEEE interface. A National instruments PC-2A IEEE card was installed inside the PC for this purpose. The Questar and Matelect data communication was performed by RS-232. Microsoft Quick Basic can only address two communications ports, COM1: and COM2:. In order to address the 3rd serial device, the 2nd parallel port on the PC , LPT2:, was converted to a serial port using a parallel to serial converter from Black Box. With this configuration the software program sends the data to LPT2: and the converter converts the data to serial data for the attached device.

The software was designed to cycle the test specimen at a user defined frequency, stress amplitude, and stress ratio for a specified number of cycles. When the specified number of cycles is reached, the Instron machine stops cycling and ramps to the maximum load in the cycle. Once maximum load is reached, the potential at the various locations is measured. Prior to running the test the user enters the number of locations for potential measurement required for the particular specimen. The user specifies for each individual potential measurement the current channel used and the potential channel to measure. The user also specifies how many crack length locations are to be measured. After the potential measurements are made, the results are displayed on the screen and the user has the option of repeating the measurement. A measurement is repeated if a lead fails and requires rewelding before continuing. After the potential readings are accepted, the program measures the crack lengths with the Questar. This was an interactive procedure which requires the user to first aim the microscope at the center of the hole and press the return key on the computer to zero the digital XY position readout, and then aim the microscope at the crack tip and press the return key so that the computer can read the digital XY readout. This procedure is repeated for every hole or rivet. At the end of the crack length measurements, the crack lengths are displayed on the screen and the user has the option of accepting the measurements or repeating them. Once the measurements are accepted, the potentials, crack lengths, stress amplitude, stress ratio, and cycle number were stored in an ASCII file and sent to the printer. After this is done, the specimen is subjected to cyclic loading until the next cyclic interval is reached and the measurements are repeated again.

While a specimen is being cycled there is a variety of options available. If the operator sees that the crack is growing rapidly, the test parameters can be changed and an immediate measurement of AC potential and crack lengths can be made. A test can be halted temporarily and the program shells to DOS;

when DOS is exited the cycling is automatically resumed. At any time during the testing the cycling can be stopped and the program exited.

A separate program called "ACPDRAM" was written for the R-curve testing. This program was based upon "ACPDCYC" and operated in much the same manner. This program subjected the specimen to a tensile position ramp at an operator specified rate and measured load, position, and AC potential at one location, and crack length at another location. The data was collected at one-second intervals and stored in an ASCII file.

2.3 SPECIMEN TYPES AND SPECIMEN PREPARATION

Three types of specimens were tested. The specimens were one hole, three hole, and riveted panels. Pictures of the specimens are shown in Figure 1 to 3 and detailed drawings are given in Appendix A. The one hole specimens were manufactured at Instron from 1 mm thick ALCLAD 2024 aluminum sheet. The three hole specimens and riveted panels were manufactured by Arthur D. Little from 1 mm thick ALCLAD 2024 aluminum sheet.

The potential leads were 0.50 mm dia aluminum 99.9999% wire and the current leads were 1.0 mm dia aluminum 99.9999% wire. Both leads were attached to the specimens by spot welding. Spot welding aluminum wire to aluminum sheet is difficult. A good weld requires the right amount of pressure and power. Too little pressure results in a spark which burns the wire, whereas too much pressure crushes the wire. Conversely too little power results in no weld being made and too much power results in a spark which burns the wire. The spot welder used was a Unitek model 125 which has 125 watt-seconds of stored energy and a 2.3 msec pulse width. The weld heads used were a Unitek model 80F fixed weld head and a model THF small welding hand piece. The 80F weld head had adjustable firing force, which made it easy to repeatedly weld wires. The THP was a hand held unit and firing force control was poor. This unit is quite portable and was used to repair broken leads for specimens which were under test. Good welds were obtained with the THP if the welding was done in three steps. For 0.50mm wire, start at 30% power, then weld again at 40% power and finally weld at 50% power. For 1.0mm wire start at 50% power, then weld again at 80% power and finally weld at 100% power.

2.4 NOISE SOURCES AND NOISE REDUCTION

During the testing programs the experiments were constantly monitored and sources of noise pick-up and drift were investigated. The two largest problems which were found will be described below. The Matelect scan controller has three programing modes. The first mode scans current and potential channels simultaneously, the second mode scans only current or potential channels, and the third mode allows for random programing of current and potential channels. The initial tests used the first programing mode of the scanner because it was the easiest to program. In this mode the number of current connections to the scanner had to be equal to the number of potential connections. For example, for a specimen with two potential leads and one current lead, the two current cables from the scanner to the terminal strip on the specimen would be tied together at the terminal strip. After tests with this arrangement had gone on for approximately one month, it was discovered that connecting two cables into one terminal strip affected the measured potentials. The attachment of the second current cable created an alternative current field path which changed the measured AC potential. This problem was corrected by using the random programing mode of the scanner which allow the use of fewer current cables. In the previous example only one current lead would be required. A second source of noise was the routing of the potential and current cables from the scanner to the specimen. If the current cables were too close to the potential cables, then the current cables would induce a potential in the potential cables. It was important to keep the two sets of cables as far away from each other as possible and to keep them rigidly tied down.

3. RESULTS AND DISCUSSION

Two different types of test were run: cyclic and static. The cyclic test was run to determine how well ACPD could measure crack initiation and crack growth in specimens with holes and rivets. The static test was used to measure R-curve behavior. The goal of these tests were to determine if the AC potential was affected by the plastic deformation that occurs with this type of test. Three types of specimens were used for the cyclic test: one hole, three hole, and riveted specimens. The one hole specimens were used to learn about the ACPD technique and to experiment with different lead geometries. The other two specimens were used to determine the sensitivity of ACPD in measuring multi-site crack initiation and growth. The R-curve tests were run only with the one hole specimens, since the goal of this experiment was only to measure the effect of plastic deformation on AC potential.

3.1 ONE HOLE SPECIMEN CYCLIC TESTS

The one hole specimens were used to learn about the sensitivity of various potential and current lead geometries and to experiment with various ACPD parameters. In the one hole experiments sources of noise and inconsistent data were determined as described in the previous section. Because many of these experiments had the previously described noise sources, the reader should not scrutinize the data for exact relationships, but rather use it to observe general trends. A summary of the one-hole tests is given in Table 1. The details of the lead attachment geometry can be found in Appendix A, which contains the individual specimen drawings. This table lists the current frequency used, has a description of the potential and current lead geometry, and contains a comment about the test and, where applicable, the fitting parameters used to describe the crack length AC potential relationship. The crack length relationship used was a linear one given by the following equation.

$$a=m\cdot(Pd-Pd_o)+b$$

The initial potential of the uncracked hole, Pd_o, was found to vary from specimen to specimen with identical lead geometries, for some unknown reason. It was determined that the crack length potential relationship for identical specimens was consistent when the initial potential, Pd_o, was subtracted from the actual potential, as in equation 1. The crack length was measured from the edge of the hole.

Potential leads were attached at both sides of the holes to monitor crack initiation and growth. All specimens had these leads attached at the same location. Some of the specimens had reference leads attached below the hole. A few specimens also had potential leads attached at the center line of the hole at top and bottom locations. Two different current lead locations were experimented with. The first geometry consisted of two leads per hole with the leads attached at the center line of the hole at a distance of ether "3D" (D = hole diameter) or "6D" from the center of the hole. The second geometry consisted of 4 leads per hole, with leads attached to the left and right sides of the hole at distances of "3D" and "6D" from the center of the hole. The current lead were placed so that the current path was in line with the potential leads; this maximizes the current focusing effect.

The effect of potential lead placement on crack length sensitivity was studied with specimen ALH1_4. The potential leads were placed on either side of the hole and also in the middle of the hole. The middle location should average the crack growth from both sides of the hole, whereas the side locations measure growth from each side of the hole. The results are shown in Figure 7. The results show that the side locations are more sensitive, in that they show greater potential increase for a given amount of crack growth. The side locations show more scatter, but this is to be expected since this data is from two sets of potential leads compared with one set for the middle location. The least squares fitting parameters are:

Location	Slope (μm/μV)	Intercept (mm)	Correlation coefficient
side	59	2.379	0.89
middle	151	3.964	0.978

The effect of current leads spacing was examined in the same specimen. The middle current leads were placed at distances of "3D" and "6D" from the hole centerline. The results showed that a spacing of "3D" was more sensitive, 114 μm/μV versus 151 μm/μV, which is a 25% increase in sensitivity for the "3D" spacing. A disadvantage of the "3D" spacing is that the slope sensitivity factor would change more when the leads were placed slightly off from the "3D" spacing than would the "6D" spaced leads. A close examination of reference voltages from specimens with both 3D and 6D spaced current leads showed that the reference voltages were less noisy and more constant for the "6D" spaced current leads. The current lead geometry which had two leads per hole produced more consistent reference voltages. Initially it was thought that an expression derived from the work of Collins Dover and Michael [6] which relates the ratio of active to reference voltage could be used to correlate the potential drop data. This expression when applied to the geometry of the one hole specimens is as follows.

$$a = \frac{\Delta}{2}\left[\cdot\frac{P_{dact}}{P_{dref}} - \left[\frac{\pi}{2} - \mathrm{Sin}^{-1}\cdot\left[\frac{\Delta - 2\cdot X_{off}}{\Delta}\right]\right]\right]$$

Where:

Δ	=	spacing between potential probes
Pd_{act}	=	active potential
Pd_{ref}	=	reference potential
Xoff	=	vertical distance from edge of hole to potential lead

Appendix C gives a derivation of this equation. This expression was applied to the test data from various specimens. Figure 8 shows a comparison of predicted and actual crack length versus cycle number for one of the best cases. The prediction gives the right trend of increasing crack length with cycle number, but there is a large difference between calculated and actual crack lengths.

One test was run in which the current leads were placed at a distance of 20D from the center of the hole. The current leads were routed so that they would not induce an additional current field. This was done by making the leads run perpendicular to the loading axis. The results showed that this lead geometry was not very sensitive. The sensitivity was 3455 μm/μV, which is poor compared to 59 μm/μV, for a specimen with a 6D current spacing and current focusing by routing the leads parallel to the loading axis.

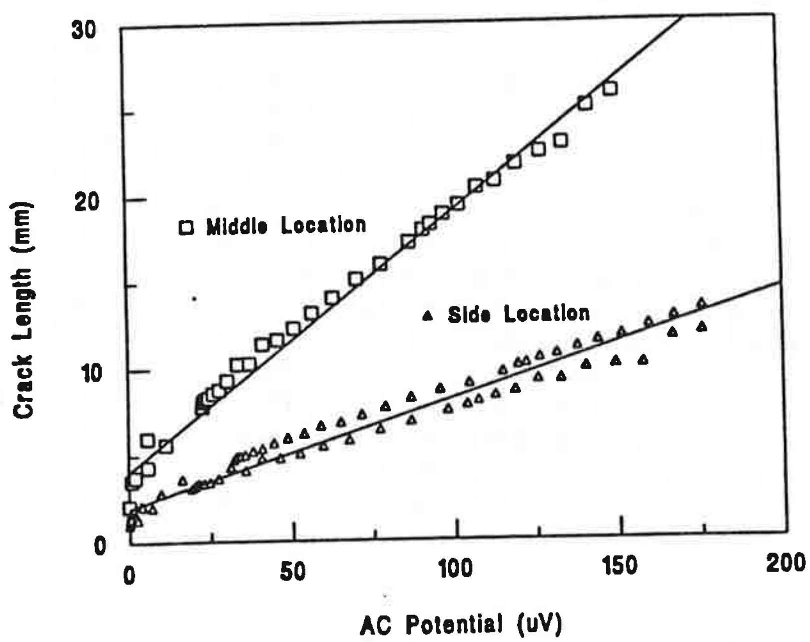


FIGURE 7. EFFECT OF POTENTIAL LEAD PLACEMENT ON CRACK LENGTH SENSITIVITY

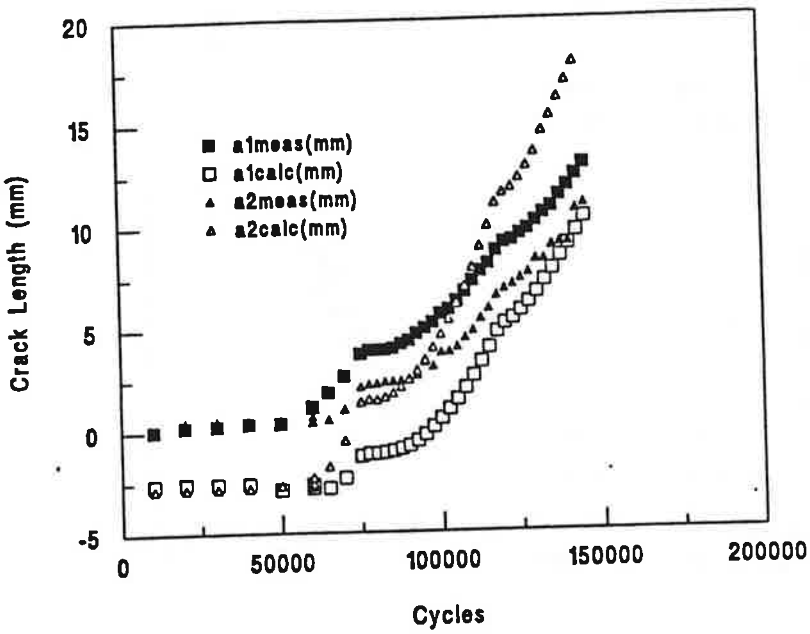


FIGURE 8. PREDICTION OF CRACK LENGTH FROM RATIO OF POTENTIALS

Another variable which was examined was the effect of having the current leads on the same side as the potential leads or on the opposite side. This was examined with specimen ALH1_6 in which each potential was measured with the current applied on the same and opposite sides of the specimen. The results are shown in Figure 9. The potentials are higher when the current leads are on the same side as the potential leads, but both readings seem to give the same increase in potential with crack length. The data in Figure 9 was re-plotted with the initial potential readings subtracted. This is shown in Figure 10, which shows that the results are identical when the side to which the current is injected is changed. The only effect of changing the side of the specimen to which current is injected is that it changes the initial potential with no crack. The geometry in which the current leads are on the opposite side from the potential leads is more convenient since there are fewer leads on the side where visual crack length measurements are made.

The effect of current frequency was investigated by measuring the potentials with the current frequency at 3, 10 and 30 kHz. The results are shown in Figure 11. The key observation from this plot are that the sensitivity of ACPD technique increases with current frequency and that the scatter in the results also increases with current frequency.

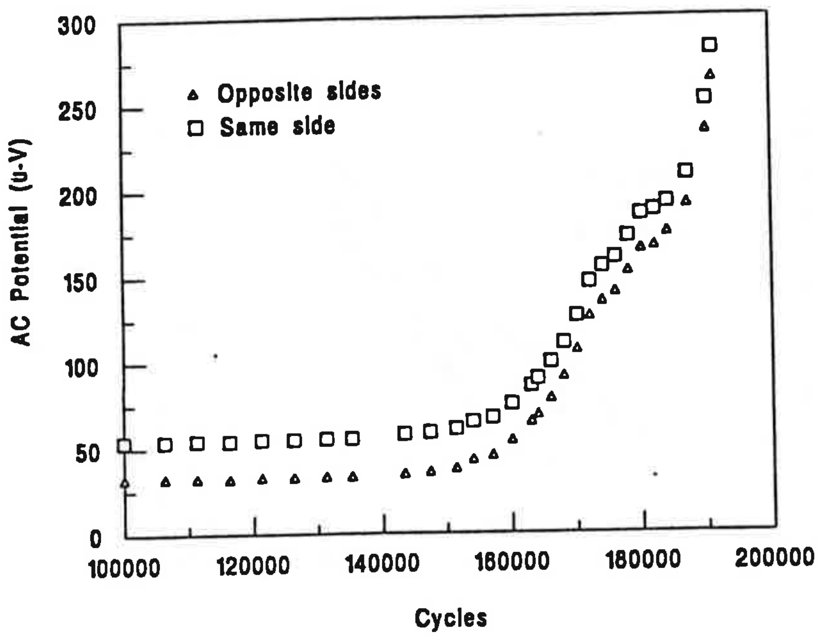


FIGURE 9. EFFECT OF CURRENT LEADS BEING ON SAME OR OPPOSITE SIDE AS POTENTIAL LEADS

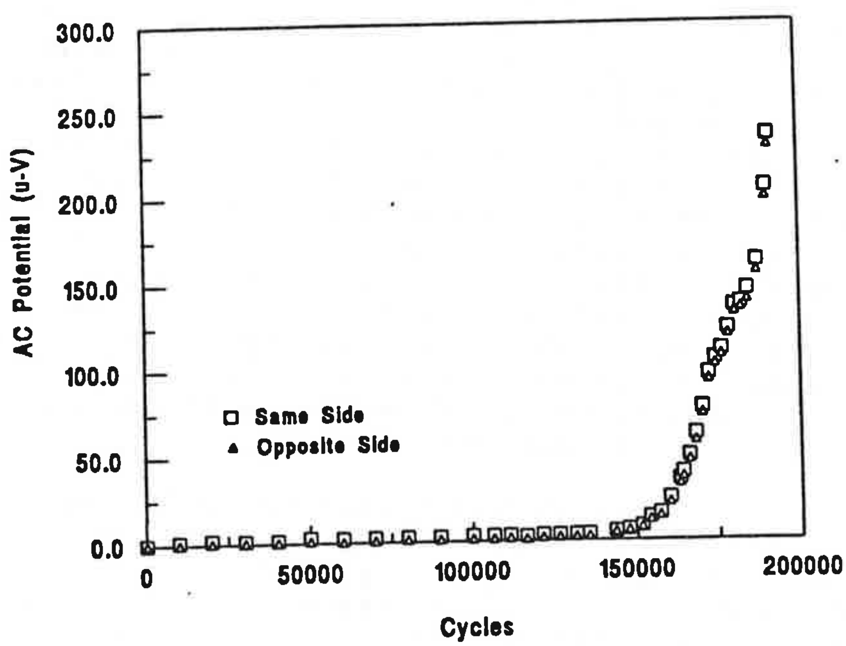


FIGURE 10. DATA OF FIGURE 9 RE-PLOTTED WITH INITIAL POTENTIAL SUBTRACTED

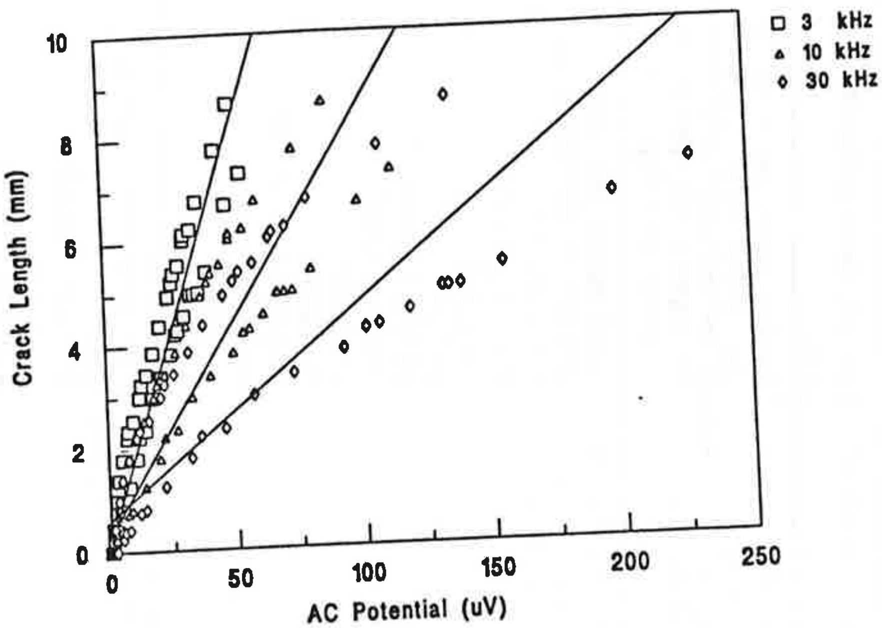


FIGURE 11. EFFECT OF CURRENT FREQUENCY WITH ONE HOLE SPECIMEN

TABLE 1. SUMMARY OF ONE HOLE SPECIMEN CYCLIC TESTS

Specimen Number	Frequency (kHz)	Potential lead location	Current lead location	Comments
ALH1_1	10	2 leads, left and right sides, no reference	2 leads on either side of hole, spacing 3D	1st test, many problems. Used starter slot.
ALH1_2	10	4 leads, left and right side, and references	2 leads on either side of hole, spacing 3D	2nd test, many problems. Used starter slot. Reference Pds poor.
ALH1_3	10	6 leads; left, right and middle and 3 references	3 leads; left, middle and right.	No starter notch. Results noisy. Had problems resolving crack visually.
ALH1_4	10	6 leads; left, right and middle and 3 references	4 leads; left, middle and right with 3D spacing. 1 in middle with 6D spacing	Good results. 6D current spacing gives best results. Reference Pds look good. Side Location m = 59 μm/μV b = 2.379 r= 0.899 Middle Location "3D" m = 114 μm/μV b = 3.273 r= 0.999 Middle Location "6D" m = 151 μm/μV b = 3.964 r= 0.978
ALH1_5	30	6 leads; left, right and middle and 3 references	1 current lead with spacing of 20D and no current focusing.	Very poor results. Current lead location poor. m = 3455 μm/μV b = 8.479 r= 0.976

TABLE 1. SUMMARY OF ONE HOLE SPECIMEN CYCLIC TESTS (continued)

Specimen Number	Frequency (kHz)	Potential lead location	Current lead location	Comments
ALH1_6	3, 10, 30	4 leads; left and right sides and 2 references.	2 current leads with 6D spacing. Leads were on both front and back sides	Compared the effect of having current leads on same and opposite sides of potential leads. Specimen also used for R-curve test. 30 kHz $m = 42\ \mu m/\mu V$ $b = 0.616$ $r = 0.857$
ALH1_7	30	2 leads; left and right sides.	1 current lead with 6D spacing.	Specimen pre-cracked for R-curve. $m = 44\ \mu m/\mu V$ $b = 0.347$ $r = 0.978$
ALH1_8	30	4 leads; left and right sides and 2 references.	1 current lead with 6D spacing.	Specimen pre-cracked for R-curve. Final lead geometry. $m = 55\ \mu m/\mu V$ $b = 0.172$ $r = 0.955$

3.2 THREE HOLE SPECIMEN CYCLIC TESTS

A total of seven three-hole specimens were tested. The goals of these experiments were to investigate two different current lead geometries, to observe the effect of current frequency, and to determine the repeatability of the technique. A summary of the three-hole tests is given in Table 2. The details of the lead attachment geometry can be found in Appendix A, which has the individual specimen drawings. Table 2 lists the current frequency used, has a description of the potential and current lead geometry, and contains a comment about the test and, where applicable, the fitting parameters used to describe the crack length AC potential relationship.

One thing which needed to be done was to evaluate the difference between the effect of two sets of current leads per hole versus one set which is placed in the middle of the hole. Based upon the one hole test results is was decided that the current spacing should be "6D." The first two specimens ALH3_1 and ALH3_2 attempted to determine the difference between the two current lead geometries. The results showed that the single set of current leads were more sensitive: 78 μm/μV versus 86 μm/μV. This result was in contradiction to the one hole results, which showed the opposite effect. A later investigation of the results showed that these experiments had two problems. First the tests were run with multiple connections into the current scanner ports and the current and potential leads were not separated enough to give adequate isolation. The two problems were corrected in tests with specimens ALH3_4 and those following it, including all the riveted tests and tests on one hole specimens ALH 1_6 and those following it. Test specimen ALH3_4 was instrumented to examine the effect of current lead geometry within a single specimen. Figure 12 shows a plot of crack length versus AC potential for current lead geometries with one set of current leads in the middle of the hole and for the case with a set of current leads on either side of the hole. The current frequency in this test was 10 kHz. The results with two sets of current leads gave greater sensitivity, 53 μm/μV, versus 59 μm/μV, which is a 10% change. This same comparison was made with specimens ALH3_5 and ALH3_6, except that the current frequency was 30 kHz. The results are shown in Figure 13. The specimen with only one set of current leads per hole was less sensitive to measuring crack growth. The slope sensitivity factors were 24 μm/μV versus 29 μm/μV, a 17% change.

The results from both one hole and three hole specimens show that by placing two sets of current leads per hole, there is an increase in the sensitivity of ACPD to measuring crack growth. The amount of the increase, however, is quite small. It was decided to only use one set of current leads per hole since there was very little sacrifice in sensitivity, and specimen preparation was greatly simplified. The final potential and current lead geometry consisted of potential leads on either side of each hole, and one set of current leads in the middle of each hole with a current lead spacing of "6D."

Specimens ALH3_6 and ALH3_7 were prepared with the final lead geometry. These specimens were tested under identical conditions to determine the repeatability of the ACPD technique. The results for specimen ALH3_6 are shown in Figure 14. The 30 kHz current frequency gives the greatest sensitivity for measuring crack growth, whereas the 3 kHz current frequency gives the least sensitivity. The amount of data scatter has been reduced from previous experiments. This is due to a combination of improved experimental technique and experience. Figure 15 shows a comparison between duplicate test specimens. There is excellent agreement between the two specimens for the 3 and 10 kHz test data. The test data at 30 kHz shows a small difference between the two test specimens.

The crack length versus AC potential test data was fit mathematically using both linear and non-linear equations. Figures 16 shows the data from specimen ALH3_6 with a linear fit and Figure 17 shows the data with a 5th order polynomial fit. The fitting coefficients are listed in Table 3. The linear fit does a poor job for crack lengths less than 1.5 mm. The 5th order polynomial does a good job fitting the data over the entire range of crack lengths studied. The r^2 values are better for the 5th order fit than those for the linear fit; which again reinforces the fact that a 5th order polynomial fits the data better.

Visually it was difficult to measure cracks which were less than 0.50 mm. This was due to the rough finish around the hole and the ensuing plastic deformation which would develop during fatigue cycling. A close examination of the ACPD data showed that the potential would increase before any cracks were measured visually. An example of this is shown in Figure 18. There is a steady increase in potential until a visual crack is seen. This plot shows that crack initiation can be detected by AC potential drop.

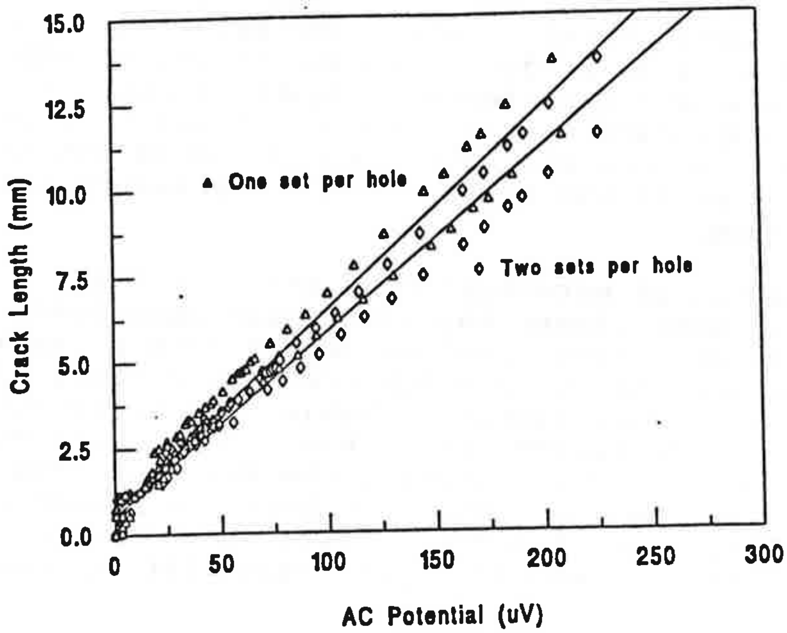


FIGURE 12. COMPARISON OF ACPD SENSITIVITY AT 10 KHZ FOR TWO CURRENT LEAD GEOMETRIES

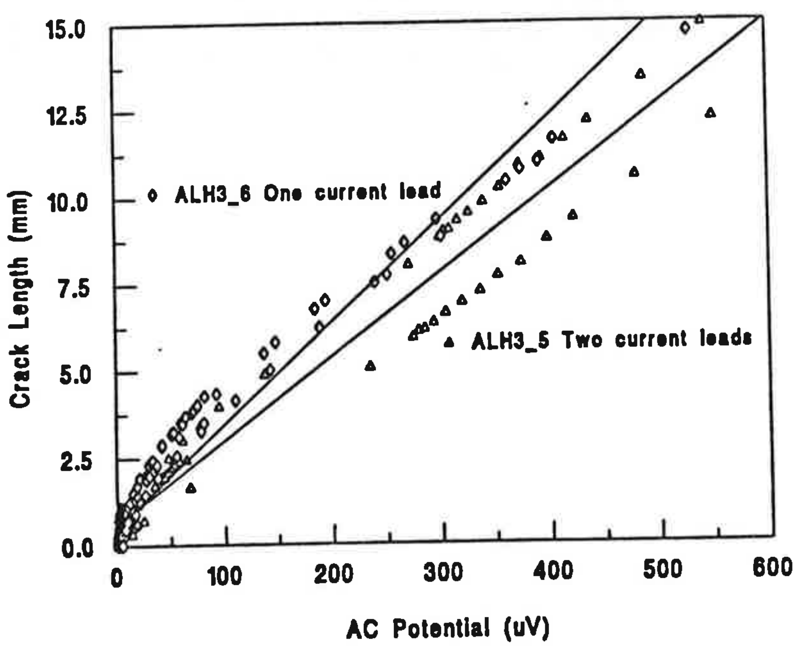


FIGURE 13. COMPARISON OF ACPD SENSITIVITY AT 30 KHZ FOR TWO CURRENT LEAD GEOMETRIES

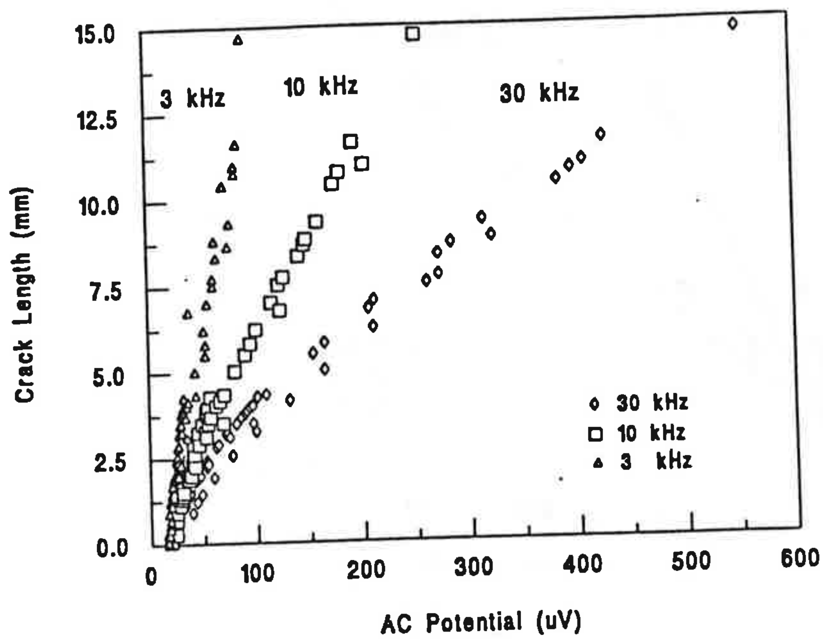


FIGURE 14. COMPARISON OF ACPD SENSITIVITY AS FUNCTION OF CURRENT FREQUENCY

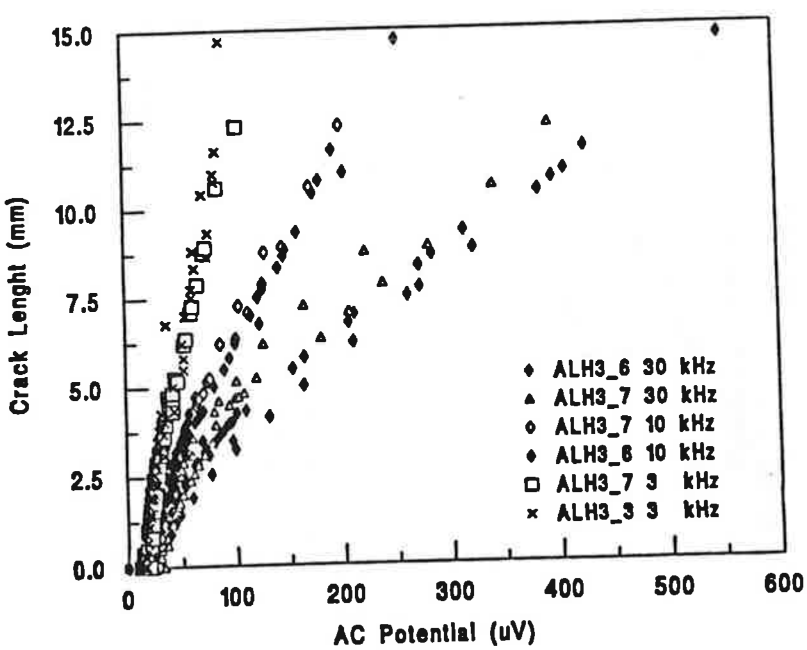


FIGURE 15. COMPARISON OF ACPD DATA ON DUPLICATE THREE HOLE TESTS

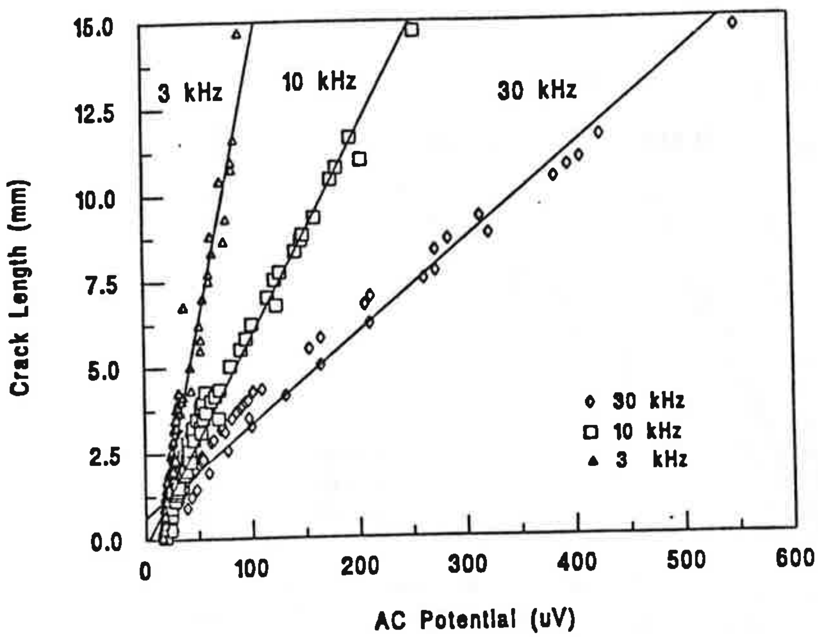


FIGURE 16. COMPARISON OF LINEAR FIT OF ACPD DATA

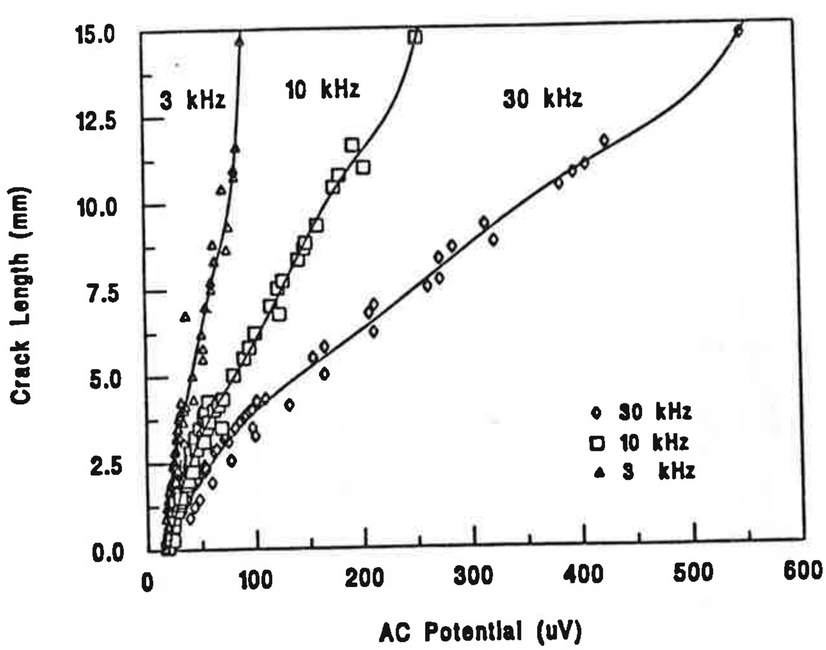


FIGURE 17. COMPARISON OF 5TH ORDER POLYNOMIAL FIT OF ACPD DATA

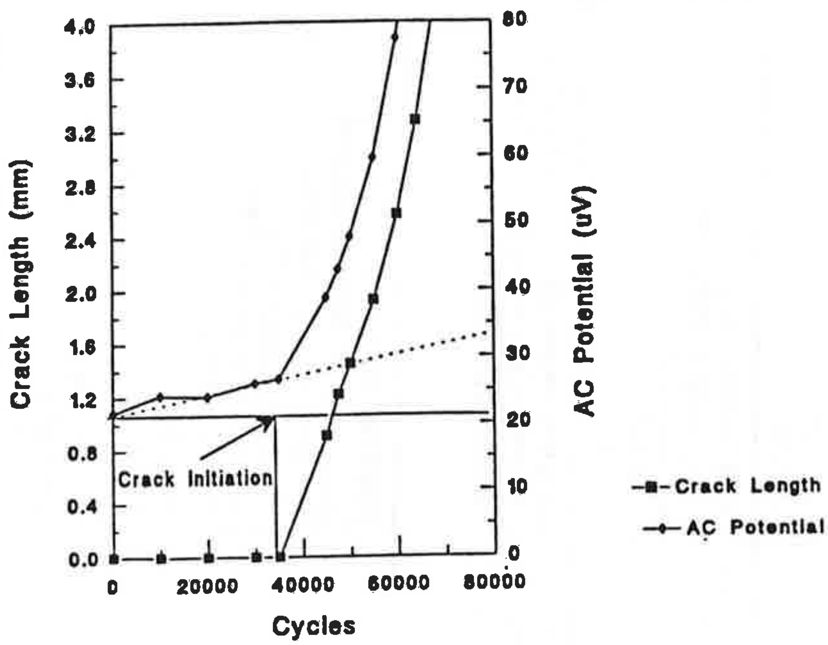


FIGURE 18. PLOT OF POTENTIAL AND CRACK LENGTH VERSUS CYCLES FOR THREE HOLE TEST

TABLE 2. SUMMARY OF THREE HOLE TESTS

Specimen Number	Frequency (kHz)	Potential lead location	Current lead location	Comments
ALH3_1	10	8 leads; left and right side on each hole; 2 reference leads on middle hole.	3 leads, one on centerline of each hole; spacing 6D	Good results; only left and right holes cracked. Crack length correlations: m = 78 μm/μV b = 0.972 r= 0.997
ALH3_2	10	8 leads; left and right side on each hole; 2 reference leads on middle hole.	6 leads one on each side of each hole; spacing 6D	Good results. Slope Crack length correlations: m = 86 μm/μV b = 0.701 r= 0.99
ALH3_3	10	8 leads; middle location each hole; center hole has additional leads on left and right sides; 3 reference leads on middle hole.	5 leads; left and right hole lead in middle; center hole has left, middle and center leads.	Data was inconsistent because of noise problems when multiple leads were connected to same scanner port.
ALH3_4	10	8 leads; 2 each on left and right sides of left and right holes; none on middle hole.	6 leads; left, middle and right locations on left and right holes; none on center hole.	Specimen compared in-line currents leads to center hole current leads. In-line leads gave greater sensitivity, but effect was small (10%) Current leads in-line (2/hole) m = 53 μm/μV b = 0.545 r= 0.99 Current leads in middle (1/hole) m = 59 μm/μV b = 0.653 r= 0.986

TABLE 2. SUMMARY OF THREE HOLE TESTS (continued)

Specimen Number	Frequency (kHz)	Potential lead location	Current lead location	Comments
ALH3_5	30	8 leads, left and right side on each hole; 2 reference leads on middle hole.	6 leads one on each side of each hole; spacing 6D	Crack length correlations: m = 24 μm/μV b = 0.58 r= 0.985
ALH3_6	3, 10, 30	8 leads, left and right side on each hole; 2 reference leads on middle hole.	3 leads, one on centerline of each hole; spacing 6D	Final lead locations. 30 kHz m = 29 μm/μV b = 0.51 r= 0.976 10 kHz m = 64 μm/μV b = 0.36 r= 0.985 3 kHz m = 160 μm/μV b = 0.21 r= 0.981
ALH3_7	3, 10, 30	8 leads, left and right side on each hole; 2 reference leads on middle hole.	3 leads, one on centerline of each hole; spacing 6D	Duplicate of ALH3_6 to determine repeatability. 30 kHz m = 35 μm/μV b = 0.63 r= 0.951 10 kHz m = 73 μm/μV b = 0.40 r= 0.975 3 kHz m = 150 μm/μV b = 0.26 r= 0.981

TABLE 3. LINEAR AND FIFTH DEGREE FITTING COEFFICIENTS FOR SPECIMEN ALH3_6

Fit	Frequency (kHz)	r^2	C0	C1	C2	C3	C4	C5
5th	3	0.974	-13.1963	1.5373	-6.114E-2	1.305E-3	-1.341E-5	5.324E-8
5th	10	0.994	-4.0676	0.2845	-4.198E-3	3.525E-5	-1.366E-7	1.9687E-10
5th	30	0.992	-1.5627	9.8363E-2	-6.429E-4	2.5426E-6	4.66E-9	3.18E-12
linear	3	0.962	0.21	0.160				
linear	10	0.970	0.36	0.064				
linear	30	0.952	0.51	0.029				

$$a = C0 + C1 \cdot Pd + C2 \cdot Pd^2 + C3 \cdot Pd^3 + C4 \cdot Pd^4 + C5 \cdot Pd^5$$

3.3 RIVETED SPECIMEN CYCLIC TESTS

A total of ten riveted panel specimens were tested. The goals of these experiments were to investigate the sensitivity of ACPD for measuring crack growth and crack initiation. A summary of the riveted panel tests is given in Table 4. The details of the lead attachment geometry can be found in Appendix B, which has the individual specimen drawings. This table lists the current frequency used, has a description of the potential and current lead geometry, and contains a comment about the test and, where applicable, the fitting parameters used to describe the crack length AC potential relationship.

The first two specimens ALR3_1 and ALR3_2 failed from the inside of the lap joint towards the surface of the panel. There was practically no change in AC potential during the test. Visually only the surface deformation caused by the internal cracking was seen. The cracks propagated from back of the lap joint towards the surface of the panel because of excessive bending due to the fact that there was only one row of rivets. A pair of aluminum clamps was manufactured and they were placed at either end of the lap joint. Appendix B for specimens ALR3_3 to ALR3_10 shows a schematic of this clamping arrangement. A piece of mylar film was placed between the clamp and the specimen to electrically isolate the clamp from the specimen. The bolts on the clamps were tightened finger tight. Specimen ALR3_3 was tested with this new arrangement and cracks were easily initiated from the rivets.

Figure 19 shows the results for riveted panel ALR3_5. The results show the same trends as for the three hole tests. The key differences appear to be that the sensitivity of potential drop for measuring crack advance in riveted panels is less than that of the three hole tests. It also appears that the riveted panel results have more data scatter. The potential leads for specimen ALR3_5 were attached to the specimen at the locations shown in Appendix B. The potential leads were laid flat on the surface of the specimen and were routed perpendicular to the loading axis for approximately 5 mm and were bent at right angles and then traveled parallel to the loading axis. Specimens ALR3_6 to ALR3_10 had potential leads attached at the same location as specimen ALR3_5, but the wires were routed differently. The wires were routed so that they extended about 10 mm up perpendicular from the surface of the specimen and then were bent at right angles and traveled parallel to the loading axes. Figure 2 shows a picture of how the potential leads were routed for specimen ALR3_5 and Figure 3 shows how it was routed for specimens ALR3_6 to ALR3_10. The routing of the potential leads for specimens ALR3_6 - ALR3_10 has the advantage that the potential leads do not get in the way of visual crack length measurements. When specimen ALR3_6 was tested there were two surprises in the results. First the potential measured with no crack was substantially higher for ALR3_6. With a 30 kHz test frequency the potentials with no crack were 52 μV versus 180 μV. The second surprise was that the potential lead routing of ALR3_6 was more sensitive. This is shown in Figure 20. The reasons for these differences remains unclear.

The crack length potential drop data was found to be adequately represented by a linear fit as shown in Figure 21. A duplicate specimen to ALR3_6 was run, ALR3_7, to determine the repeatability of the results. The results are shown in Figure 22. The ACPD data for the riveted panels show similar repeatability as the three hole results (Figure 15), however the scatter is somewhat greater. The minimum detectable visual crack is 1.0 mm versus 0.50 mm for the three hole tests. The data in Figures 21 and 22 indicates that the potential increases even though there is no visible crack growth. This is shown more clearly in Figure 23 which is a dual y axis plot of potential and crack length versus cycles.

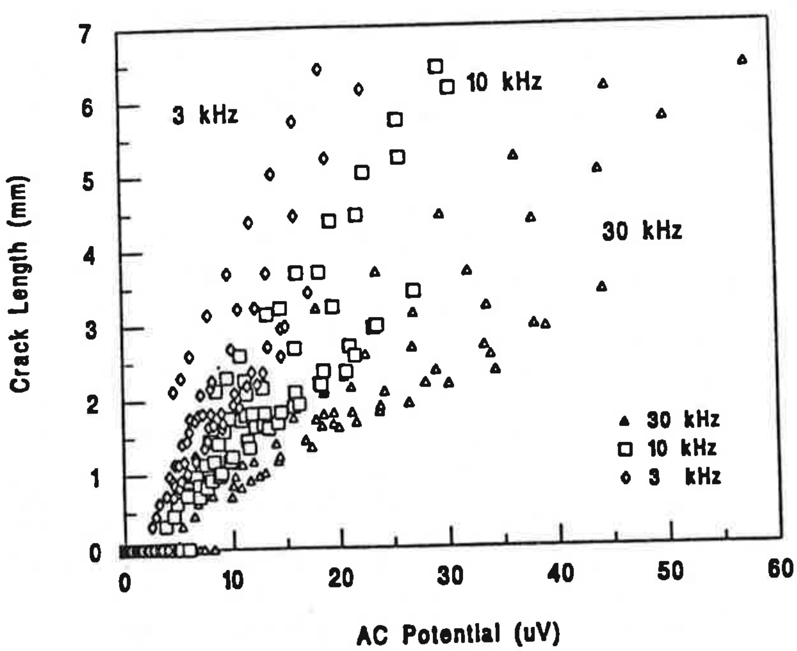


FIGURE 19. PLOT OF CRACK LENGTH VERSUS POTENTIAL FOR RIVETED PANEL ALR3_5

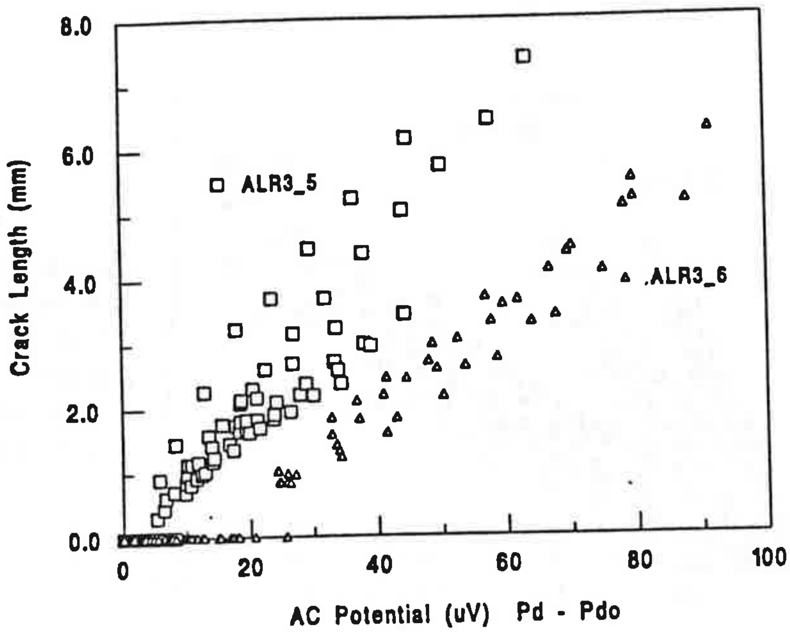


FIGURE 20. COMPARISON OF DIFFERENT POTENTIAL LEAD GEOMETRIES OF RIVETED PANEL

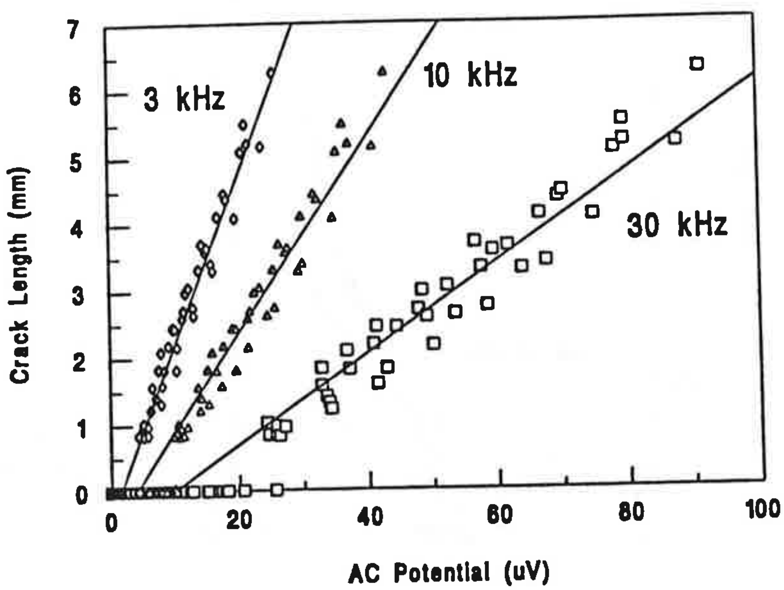


FIGURE 21. PLOT OF CRACK LENGTH VERSUS POTENTIAL FOR RIVETED PANEL ALR3_6

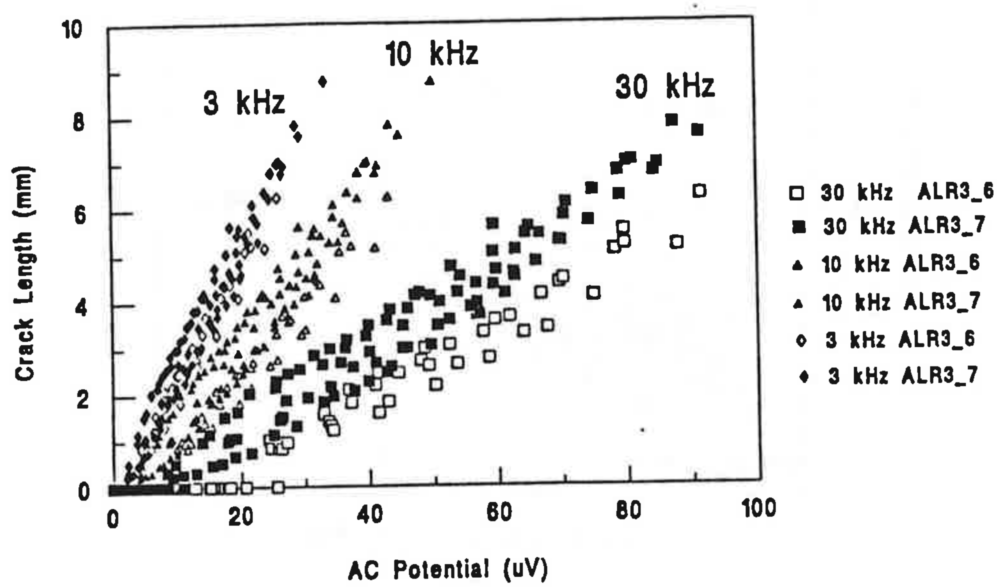


FIGURE 22. PLOT OF CRACK LENGTH VERSUS POTENTIAL FOR RIVETED PANELS ALR3_6 AND ALR3_7

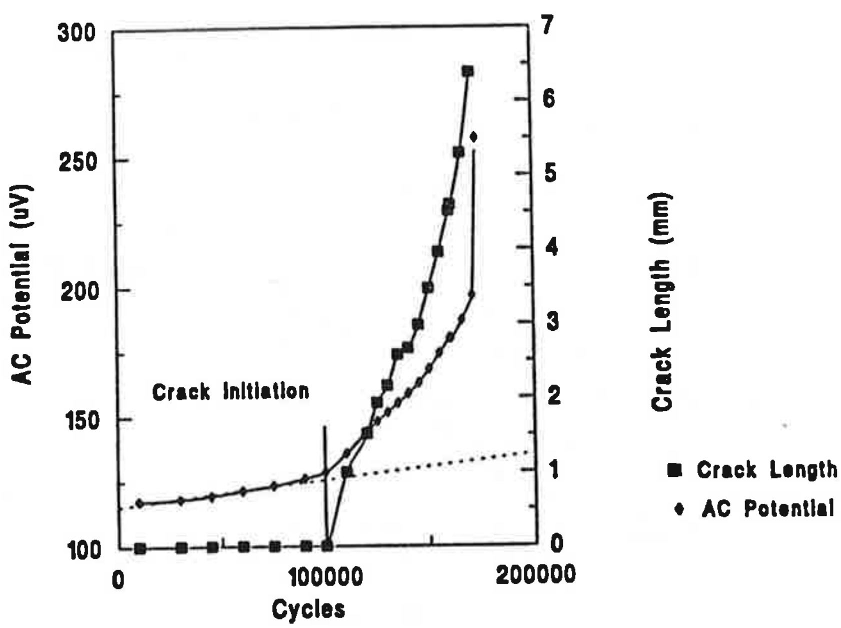


FIGURE 23. PLOT OF CRACK LENGTH AND AC POTENTIAL VERSUS CYCLES

TABLE 4. SUMMARY OF RIVETED PANEL TESTS

Specimen Number	Frequency (kHz)	Potential lead location	Current lead location	Comments
ALR3_1	3, 10, 30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	Poor results, specimen failed from underneath lap joint due to excessive bending.
ALR3_2	3, 10, 30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	Poor results, specimen failed from underneath lap joint due to excessive bending.
ALR3_3	3, 10, 30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	No data collected, this specimen was used to evaluate the effectiveness of the clamps.
ALR3_4	3, 10, 30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 3D.	added support bars to eliminate bending 30 kHz m = 107 μm/μV b = 0.00995 r = 0.880 10 kHz m = 194 μm/μV b = -0.217 r = 0.941 3 kHz m = 277 μm/μV b = -0.317 r = 0.968

TABLE 4. SUMMARY OF RIVETED PANEL TESTS (continued)

Specimen Number	Frequency (kHz)	Potential lead location	Current lead location	Comments
ALR3_5	3, 10, 30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	30 kHz m = 109 μm/μV b = -0.2118 r = 0.955 10 kHz m = 181 μm/μV b = -0.290 r = 0.949 3 kHz m = 268 μm/μV b = -0.249 r = 0.946
ALR3_6	3, 10, 30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	Crack length correlations: 30 kHz m = 68 μm/μV b = -0.651 r = 0.975 10 kHz m = 145 μm/μV b = -0.561 r = 0.979 3 kHz m = 251 μm/μV b = -0.368 r = 0.986

TABLE 4. SUMMARY OF RIVETED PANEL TESTS (continued)

Specimen Number	Frequency (kHz)	Potential lead location	Current lead location	Comments
ALR3_7	3, 10, 30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	30 kHz m = 86 μm/μV b = -0.4186 r = 0.983 10 kHz m = 174 μm/μV b = -0.3866 r = 0.984 3 kHz m = 267 μm/μV b = -0.202 r = 0.987
ALR3_8	30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	Used for crack initiation study. Stress ratio alternated between 0.10 and 0.50
ALR3_9	30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	Used for crack initiation study. Stress ratio alternated between 0.10 and 0.60
ALR3_10	30	6 leads, left and right side on each rivet.	3 leads, one on vertical centerline of each hole, spacing 6D.	Used for crack initiation study. Stress ratio alternated between 0.10 and 0.70

A series of experiments was conducted to determine if ACPD could detect crack initiation. The data in Figure 23 showed that the potential increased before visible cracks were detected. The increase in potential seen does not necessarily have to be due to crack growth; other factors such as deformation or a change in the conduction through the rivet could cause a similar effect. In order to determine the cause of the potential increase, riveted aluminum panels were subjected to alternating cycles of low to high stress ratio cycling with the maximum load keep constant. The idea being that the crack would grow during the low stress ratio cycling and the high stress ratio cycling would mark the crack front of the fracture surface with a band. Three different stress ratio combinations were tried: (0.10,0.50), (0.10, 0.60), (0.10,0.70). The first two stress ratio combinations did not produce visible bands. The last stress ratio combination produced fracture surface bands. A SEM picture of the fracture surface bands are shown in Figure 24. A comparison of crack length measured from the SEM picture and that measured optically was made. The data is shown in Table 5, which lists the two crack lengths and the measured potential increases. The data shows that the potential increase is due to crack growth. The ACPD technique can measure crack initiation but it is difficult to correlate the potential to crack growth. More experiments like that run on ALR3_10 are needed to quantify the crack initiation stage. The data from these experiments indicates that a 10 μV change in potential translates into a 0.5 mm crack and that the crack has to be between 1 to 2 mm before it is seen.

TABLE 5. COMPARISON BETWEEN SEM AND VISUAL CRACK LENGTHS IN CRACK INITIATION STUDY ON ALR3_10

Band	SEM a(mm)	Visual a(mm)	P_d-P_{do} (uV)
1	0.559	0	10.5
2	1.168	0	16.3
3	1.803	1.956	44.0
4	2.743	3.150	62.6

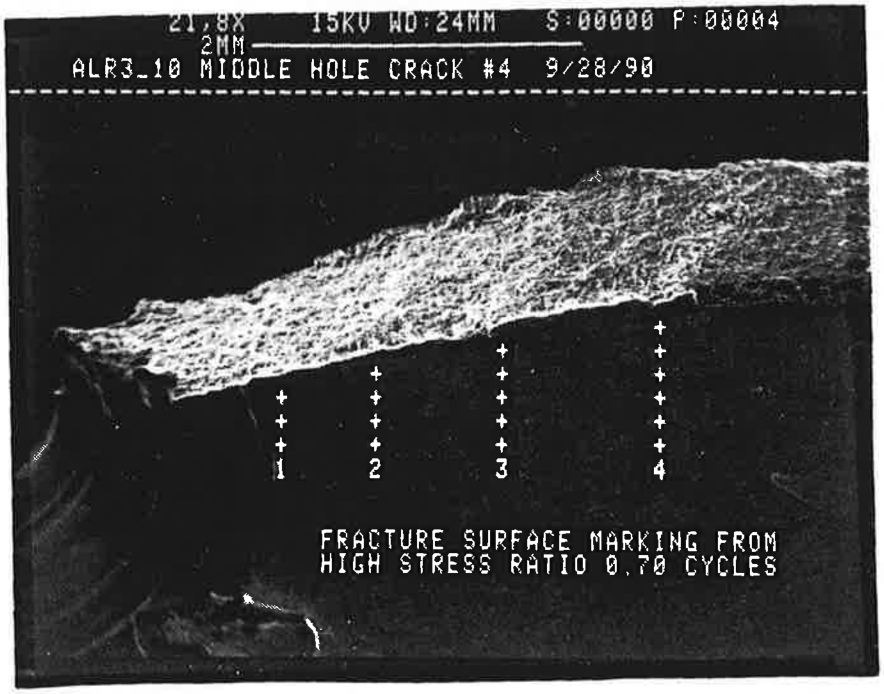


FIGURE 24. SEM PICTURE SHOWING BANDING ON FRACTURE SURFACE OF RIVETED PANEL PRODUCED BY HIGH LOW STRESS RATIO CHANGES

3.4 RISING LOAD R-CURVE TESTS

The R-curve tests were run using single hole specimens. The specimens were instrumented with potential leads on either side of the hole and a single current lead was attached at the center of the hole on the opposite side using a spacing of 6D from the center of the hole. The current frequency was 30 kHz. Test specimens were fatigue pre-cracked to obtain cracks in the range of 7 to 9 mm. The specimens were tested in position control using a ramp with a rate of 0.127 mm/min. Load, position, AC potential, and crack length was measured at one-second intervals and stored into an ASCII file. The longest crack was the crack that was monitored visually and whose AC potential was measured. Figure 25 shows the load displacement plot for a typical test. Figure 26 shows a plot of AC potential and crack length versus position. Initially the potential increases rapidly; this is due to opening of the crack which eliminates surface shorting. After the crack is open enough to eliminate surface shorting the potential does not change until the crack starts to grow. The crack length was monitored visually with the Questar and the stage was moved manually as the crack grew. Steps in the crack length versus position plot are observed because it was difficult to resolve the crack tip continuously. Careful examination of Figures 25 and 26 shows that the crack grows before maximum load is reached. After maximum load is reached the crack propagates rapidly. Figures 27 to 29 shows plots of AC potential versus crack length for the three specimens tested. The R-curve data are simply a linear extension of the fatigue precracking results. The plastic deformation of the R-curve test does not appear to have any effect on the crack length potential relationship. Crack length during an R-curve test can be measured with AC potential drop using the correlations obtained by fatigue cracking experiments. The mode of loading does not affect the relationship between crack length and potential.

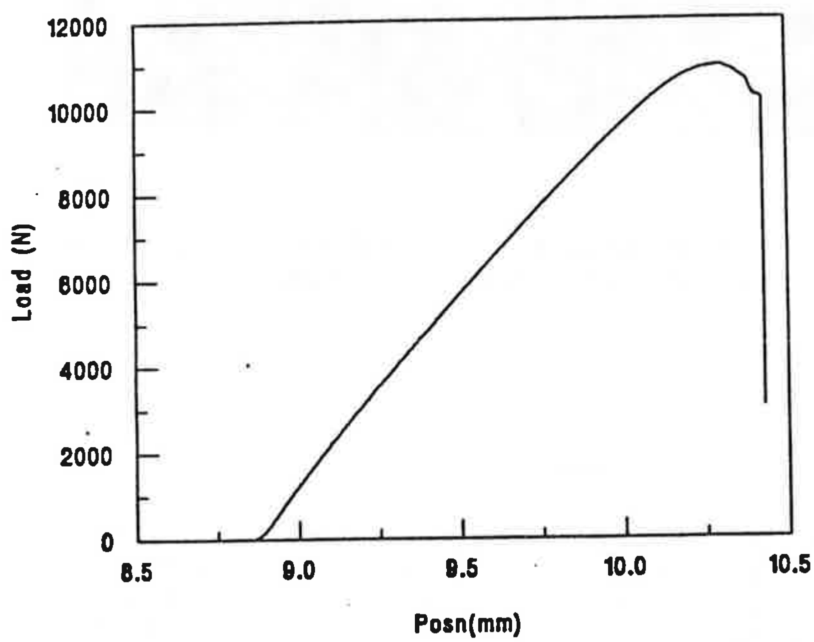


FIGURE 25. LOAD DISPLACEMENT CURVE FOR R-CURVE TEST

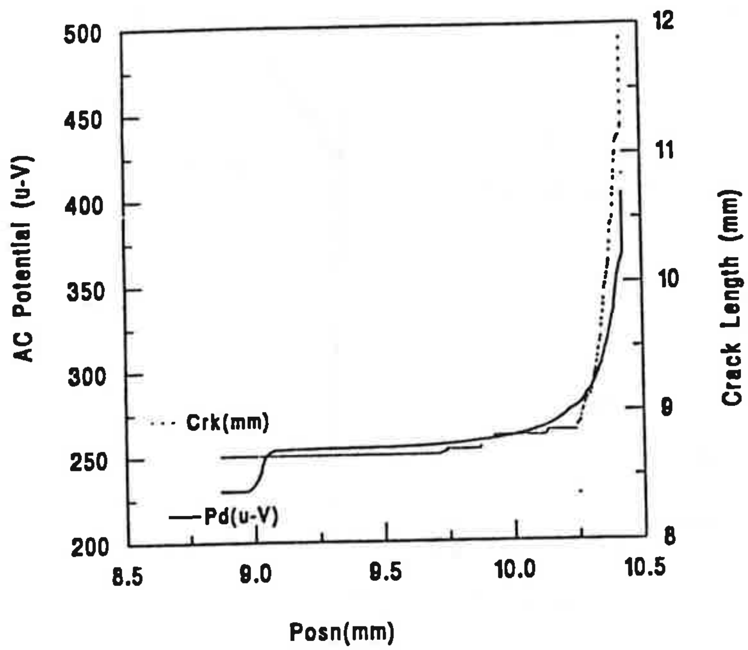


FIGURE 26. AC POTENTIAL AND CRACK LENGTH VERSUS POSITION FOR R-CURVE TEST

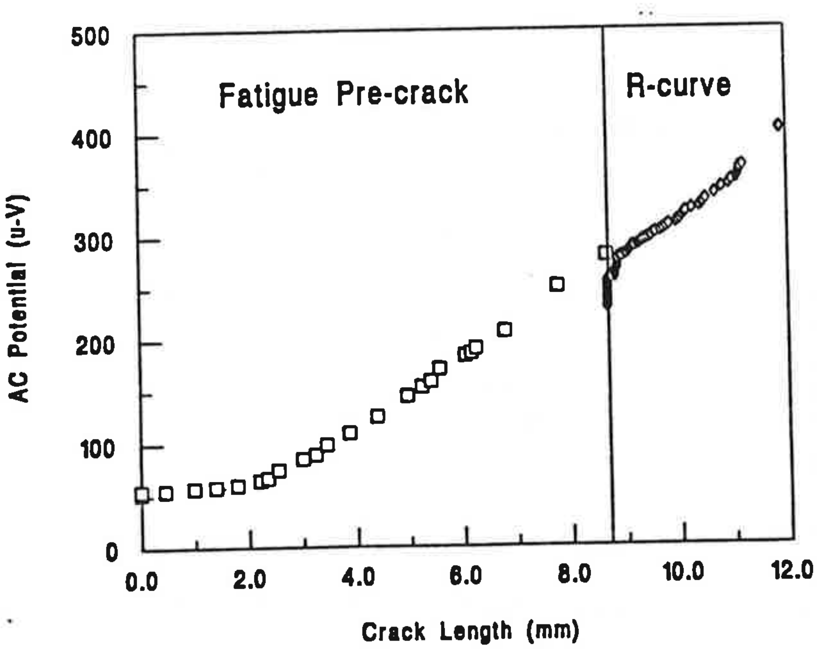


FIGURE 27. R-CURVE TEST FOR ALH 1_6. CRACK LENGTH VERSUS POTENTIAL

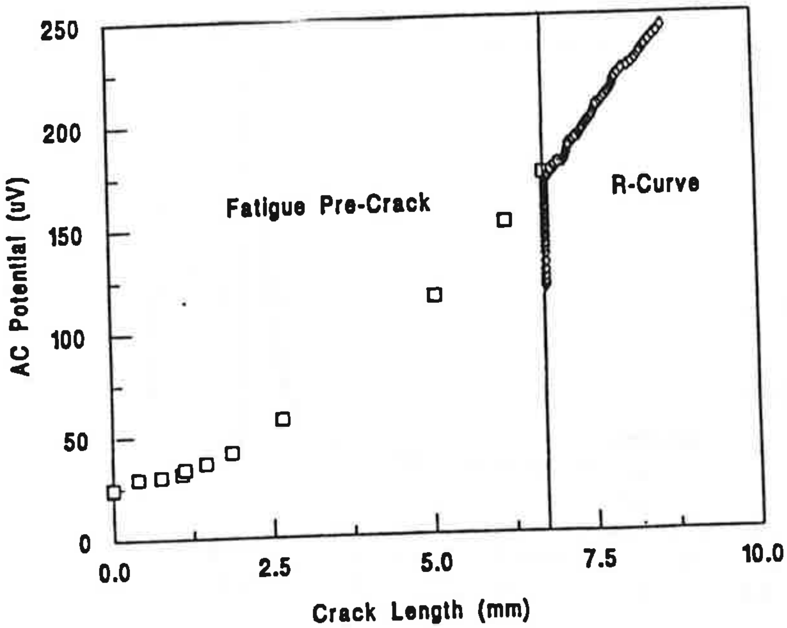


FIGURE 28. R-CURVE TEST FOR ALH1_7. CRACK LENGTH VERSUS POTENTIAL

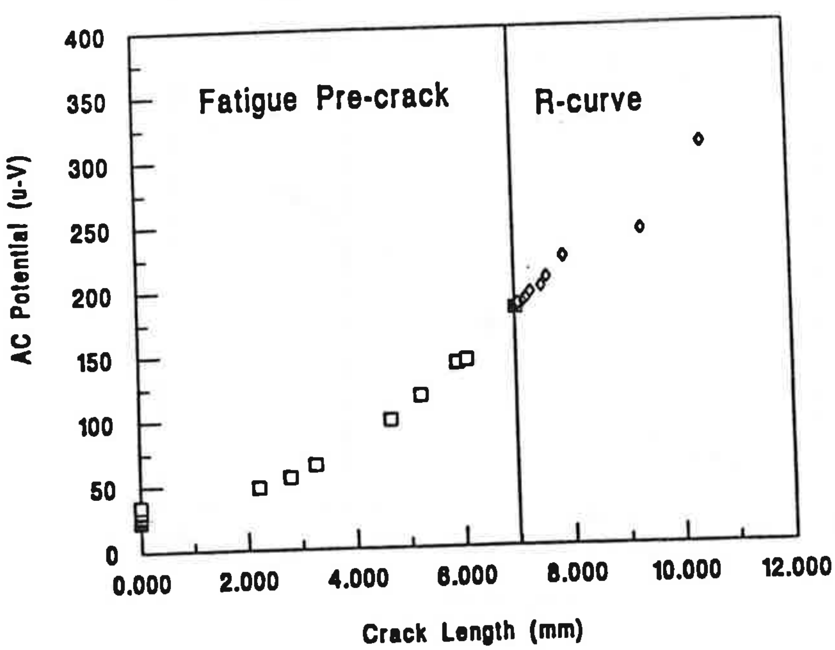


FIGURE 29. R-CURVE TEST FOR ALH1_8. CRACK LENGTH VERSUS POTENTIAL

4. SUMMARY

The technique of AC potential drop was applied to typical aluminum aircraft panel test specimens. The technique was evaluated to determine its sensitivity for measuring multiple site crack initiation and growth under cyclic fatigue conditions. The technique was also evaluated for static R-curve testing. The optimum locations for attaching both potential leads and current leads were determined for three hole specimens and for specimens with a single row of three rivets. The effect of current frequency on the sensitivity of the technique to measure crack growth was also examined.

The results of the cyclic test are as follows. The AC potential can be used to measure crack growth in three hole and riveted panels. Both theoretical and empirical correlations of AC potential with crack length were examined. The theoretical relationships predicted crack length from the ratio of active to reference potential. The theoretical relationship worked poorly. An empirical relationship which relates the crack length to the potential by a simple linear expression worked well. The expression used was:

$$a=m\bullet(Pd-Pd_0)+b$$

It was found that the initial potential measured on an uncracked hole or rivet varied from specimen to specimen and from hole to hole. In riveted panels this potential varied at 30 kHz from a low of 50 μV to a high of 200 μV. It was found that if this initial potential was subtracted, a simply linear equation could be used to correlate the data. The sensitivity of the technique is determined by the slope "m." A lower slope means greater sensitivity. The slope decreased as the current frequency was increased. The three hole specimens had average slopes of 32,68, and 1 μm/μV at current frequencies of 30,10 and 3 kHz respectively. The riveted panels had average slopes of 77,159, and 259 μm/μV at current frequencies of 30,10 and 3 kHz respectively. The ACPD technique was more sensitive for specimens with holes than those with rivets.

The minimum detectable visual crack was 0.5 mm for three hole specimens and 1.0 mm for riveted panels. Before cracks were detected visually, an increase in the potential was observed. Test specimens were subjected to low to high stress ratio cycling which produces bands on the fracture surface. When these specimens were examined in the SEM, the width of the bands was measured and was correlated with the measured AC potentials. It was shown that the AC potential increase was due to crack advance.

R-curve testing was done on one-hole specimens. These experiments showed that the AC potentials were not affected by the deformation in these tests. Correlations of crack length to potential measured by fatigue accurately predicted the crack advance in the r-curve tests. The crack length potential relationships are not affected by the loading mode.

APPENDIX A

TEST CONTROL PROGRAM LISTING

```
DEFINT A-Z
DECLARE SUB TextIn2 (T$, Max%, Exit.Code%)
DECLARE SUB Crkvisual (N, Crk!(), Pdchans)
DECLARE SUB Setpoint (Chan, Mean!, status, Unitcon!(), fullscale!())
DECLARE SUB Ramp (Chan, Amp!, Time!)
DECLARE SUB ACPD (Pdchans, Acpds!(), DEL!, Scantype$, Crntchan!(), Crntpot!
())
DECLARE SUB Cycles (Chan, Freq!, Meanlev!, Amp!, Ncycles!)
DECLARE FUNCTION bitset% (Value, bit)
'
'*****************************************************
'*                                                   *
'*        Program ACPDCYC9.BAS                       *
'*                                                   *
'*****************************************************
'
DIM Units$(3), Unitcon!(3), fullscale!(3), Acpds!(30), Crkvis!(30), Acpdrea
l!(30)
Unitcon!(1) = .0254: Unitcon!(2) = 4.44822: Unitcon!(3) = 25.4
DIM Crntchan!(30)
DIM Crntpot!(30)
'
'*************************************************************'
'
ON ERROR GOTO CheckError
Chan = 2                                          ' Position Control Channe
l
R! = .1                                           ' Stress Ratio
Scantype$ = "CUS": P5$ = "6"
Time! = 51: Pdchans = 2: Prtflg = 1
T1$ = "4.00": T2$ = "0.040": Stype$ = "Three Hole": Snumber$ = "xxxxx"
P1$ = "8": P2$ = "20":  P4$ = "80"
R1$ = "1000.00": R2$ = "0.10": R3$ = "10.0": R4$ = "1000"
Ans$ = " ": Filename$ = "TEST": Version$ = "1.7"
Sp$ = "                                                       "
CLS : COLOR 7, 1
LOCATE 10, 15: PRINT "Aging Aircraft Multi-site Fatigue Program    "
LOCATE 12, 15: PRINT "For Use with Instron 8500 and Matelect CGM5  "
LOCATE 14, 15: PRINT "Sponsored By US. Department of Transportation"
LOCATE 16, 15: PRINT "Transportation Systems Center Cambridge, MA. "
LOCATE 18, 29: PRINT "Version  "; Version$
LOCATE 20, 23: PRINT "Type any Key to Continue"
DO
LOOP UNTIL INKEY$ <> ""
COLOR 7, 0
'
'*************************************************************'
'
CLS : GOSUB SPparams
CLS : GOSUB PDparams
CLS : GOSUB RTparams
CLS : Filered$ = Filename$ + ".PRN": File$ = Filename$ + ".DAT": COLOR 7, 1
IF FQ$ = "FYES" THEN Filered$ = Filename$ + "C.PRN"
F.Exist: CALL Exist(File$, X)
IF X THEN                                    ' File Exists
```

```
   LOCATE 2, 10
   PRINT "The Data File : "; File$; "  Already exist on disk"
   LOCATE 4, 10: PRINT "Purge File (Y/N)  ";
   INPUT Fans$
   IF Fans$ = "Y" OR Fans$ = "y" THEN
      LOCATE 6, 10: PRINT "File "; File$; " will be purged"
      PRINT "File "; File$; " will be purged"
      KILL File$: OPEN Filered$ FOR OUTPUT AS #5: CLOSE #5
      IF FQ$ = "FYES" THEN
           FK$ = Filename$ + "A.PRN": OPEN FK$ FOR OUTPUT AS #5: CLOSE #5
           FK$ = Filename$ + "B.PRN": OPEN FK$ FOR OUTPUT AS #5: CLOSE #5
      END IF
      OPEN File$ FOR OUTPUT AS #3
   ELSE
      IF (Fans$ = "N" OR Fans$ = "n") THEN
           LOCATE 6, 10: PRINT "The file  "; File$; "  will be appended"
           Fileprm$ = Filename$ + ".PRM"
           OPEN Fileprm$ FOR INPUT AS #4
           INPUT #4, Pdchans.tmp, MaxCrks.tmp
           CLOSE #4
           OPEN File$ FOR INPUT AS #3
           FOR I = 0 TO 10000
Readfile: INPUT #3, X$
           IF (FileEnd = 1) THEN EXIT FOR
           NEXT I
Readfile2: OPEN File$ FOR INPUT AS #3
           FOR kk = 0 TO I - 2
              INPUT #3, A$
           NEXT kk
           FOR J = 1 TO Pdchans.tmp
              INPUT #3, X!
             'PRINT "PDs ", X!
           NEXT J
           FOR K = 1 TO MaxCrks.tmp
              INPUT #3, X!
              'PRINT "Crks ", X!
           NEXT K
           INPUT #3, CurntCycle!
           LastCycle! = CurntCycle!
           LOCATE 10, 1: PRINT "Current Cycle ", CurntCycle!
           CLOSE #3
           LOCATE 11, 1
           PRINT "Enter Current Cycle :   ": LOCATE 11, 25
           Cycle$ = STR$(CurntCycle!)
           CALL TextIn2(Cycle$, 10, Exit.Code)
           CurntCycle! = VAL(Cycle$)
           OPEN File$ FOR APPEND AS #3
           OPEN Filered$ FOR APPEND AS #4
      ELSE
        LISTEN$ = "T180 o2 P2 P8 GGG L2 E-"
        FATE$ = "P24 P8 L8 FF L2 D"
        PLAY LISTEN$ + FATE$
        LOCATE 4, 40: PRINT "Please Type (Y/N)"
        LOCATE 4, 27: PRINT "       "
        GOTO F.Exist
```

```
      END IF
   END IF
ELSE
  OPEN File$ FOR OUTPUT AS #3
  OPEN Filered$ FOR OUTPUT AS #4
END IF
CLOSE #3, #4
'
' ---------- Create test parameter file ---------------'
'
Fileprm$ = Filename$ + ".PRM"
OPEN Fileprm$ FOR OUTPUT AS #3
PRINT #3, Pdchans + 1; "   "; MaxCrks
PRINT #3, Snumber$; "   "; Stype$; "   "; W!; "   "; B!
PRINT #3, Scantemp$; "   "; DEL!; "   "; Pdgain!
CLOSE #3
'
'*************************************************************'
'
Ncycinc! = Ncycinc4! * 4!
AmpPhys! = (STamp! / 2!) * W! * B!
'
'*****************************************************'
'
CALL gpib.setup(3, 15, status)                    ' initialize gpib.
CALL gpib.clear(status)                           ' clear interface.
'                                                 '
COLOR 7, 1
GOSUB take.control                                ' take computer contr
ol.
'
'*****************************************************'
'
GOSUB Full.scales                                 ' read fullscale valu
es
Amp! = (AmpPhys! * Unitcon!(Chan)) / fullscale!(Chan) ' convert to fraction
 of
                                                  ' fullscale
Mean! = Amp! * ((1! + R!) / (1! - R!))
fac! = fullscale!(Chan) / Unitcon!(Chan)
PRINT "The Load Amplitude  (lbs) is "; Amp! * fac!
PRINT "The Load Mean Level (lbs) is "; Mean! * fac!
q: LOCATE 5, 1: INPUT "Is this okay (Y/N) "; Ans$
IF Ans$ = "Y" OR Ans$ = "y" THEN GOTO C3
IF Ans$ = "N" OR Ans$ = "n" THEN GOTO Stop.test
GOTO q:
C3: COLOR 7, 0: CLS
'
'*****************************************************'
'
Key.on: KEY ON
KEY 1, "Stop"
KEY 2, "Print"
KEY 3, "ACPD"
KEY 5, "Change"
```

```
KEY 8, "End Pg"
KEY 10, " DOS"
KEY(1) ON:  KEY(2) ON: KEY(3) ON:  KEY(5) ON: KEY(8) ON: KEY(10) ON
ON KEY(1) GOSUB Stopcyc
ON KEY(2) GOSUB Printer
ON KEY(3) GOSUB ACPD.imediate
ON KEY(5) GOSUB RT.Change
ON KEY(8) GOSUB Stop.test
ON KEY(10) GOSUB Dos.shell
'
'*****************************************************'
'
Cmd$ = "C300," + STR$(Chan)
'                                          ' Transfer to channel
CALL Gpib.cmd(Cmd$, status)                ' number "Chan"

Cmd$ = "C211," + STR$(CurntCycle! * 4)
                                           ' set total cycle cou
CALL Gpib.cmd(Cmd$, status)
nt                                         ' Current Cycle

                                           ' set total segment
CALL Gpib.cmd("C33,0", status)             ' count to zero

'
CALL Setpoint(Chan, Mean!, status, Unitcon!(), fullscale!())
          ' Force new setpoint
'
Restart:  COLOR 7, 1
LOCATE 1, 12: PRINT "Test summary and Status"; " Date : "; DATE$; " Time :"
; TIME$
LOCATE 2, 1
PRINT "Stress Amplitude : "; STamp!; " Psi "; "  Stress Ratio : "; R!;
PRINT "  Test Frequency : "; Freq!; " Hz"
LOCATE 3, 1
PRINT "Crack Length Measurement Interval : "; Ncycinc! / 4; " Cycles";
PRINT "  Data File : "; File$; "      "
LOCATE 4, 1: PRINT "Last Cycle Measured : "; CurntCycle!; "
 "
LOCATE 4, 40
IF (Prtflg) THEN
   PRINT "Printer is ON"; Sp$
ELSE
   PRINT "Printer is OFF"; Sp$
END IF
COLOR 7, 0
KEY 1, "Stop"
KEY 2, "Print"
KEY 3, "ACPD"
KEY 5, "Change"
KEY 8, "End Pg"
KEY 10, " DOS"
KEY(1) ON:  KEY(2) ON: KEY(3) ON:  KEY(5) ON: KEY(8) ON: KEY(10) ON
ON KEY(1) GOSUB Stopcyc
ON KEY(2) GOSUB Printer
```

```
ON KEY(3) GOSUB ACPD.imediate
ON KEY(5) GOSUB RT.Change
ON KEY(8) GOSUB Stop.test
ON KEY(10) GOSUB Dos.shell
GOSUB Startcyc
DO
  Cmd$ = "Q212"
  CALL Gpib.cmd(Cmd$, status)                          ' request cyclic stat
e
  CALL Gpib.rpt(rpt$, 10, status)                      ' read report
  state = VAL(rpt$)
  GOSUB Cycle.Count
LOOP UNTIL state = 4                                   ' wait for tripped
                                                       ' state (cycles done)
Cmd$ = "C219,0"                                        ' Turn constant
CALL Gpib.cmd(Cmd$, status)                            ' Amplitude control
                                                       ' off
Cmd$ = "C212,0"
CALL Gpib.cmd(Cmd$, status)                            ' turn off cycle coun
ter
CALL Gpib.cmd("C200,4", status)                        ' finnish waveform.
'
GOSUB ACPD
'
CALL Gpib.cmd("C33,0", status)                         ' set total segment
'                                                      ' count to zero
COLOR 7, 0: CLS
GOTO Restart
DO                                                     ' LOOP Until "ESC"
LOOP UNTIL INKEY$ = CHR$(27)                           ' is pressed
'
END
'
'*****************************************************************'
'
Full.scales:
Units$(1) = "m": Units$(2) = "N": Units$(3) = "mm"
FOR N = 1 TO 3
    Cmd$ = "Q308," + STR$(N)
    CALL Gpib.cmd(Cmd$, status)
    CALL Gpib.rpt(rpt$, 10, status)
    fullscale!(N) = VAL(rpt$)
    'PRINT "Channel No "; N; " Fullscale : "; fullscale!(N); " "; Units$(N)
NEXT N
RETURN
'
'*****************************************************************'
'
take.control:
  CALL Gpib.cmd("C909,1", status)                      ' request control.
  CLS                                                  ' display instruction
s.
  PRINT "Press REMOTE button on 8500 console to take"
  PRINT "computer control."
  DO                                                   ' wait to be in contr
```

```
ol.
    CALL Gpib.cmd("Q909", status)                      ' request control sta
te.
    CALL Gpib.rpt(rpt$, 10, status)                    ' read report.
    in.control = VAL(rpt$)                             ' convert status.
  LOOP UNTIL in.control = 1                            ' wait to be in contr
ol.
  CALL Gpib.cmd("C904,0", status)                      ' disable watch dog.
  CALL Gpib.cmd("C23,1", status)                       ' turn actuator on.
  CALL Gpib.cmd("C314,0", status)                      ' reset emergency sto
p.
  CALL Gpib.cmd("C913,0", status)                      ' disable GPIB SRQ's.
RETURN
'
'****************************************************'
'
Return.control:
  CLS
  CALL Gpib.cmd("C200,4", status)                        ' finish waveform.
  CALL Gpib.cmd("C909,0", status)                        ' Return control.
END
RETURN
'
'****************************************************'
'
Cycle.Count:
    DO
    CALL Gpib.cmd("Q211", status)                      ' Request cycle numb
er
    CALL Gpib.rpt(rpt$, 10, status)                    ' Read cycle number
    CurntCycle! = INT(VAL(rpt$) / 4)
    LOOP UNTIL CurntCycle! > 0
    COLOR 7, 1: LOCATE 7, 27
    PRINT "Cycle Number : "; CurntCycle!; "    ": COLOR 7, 0
RETURN
ACPD.imediate: CLS
CALL Gpib.cmd("C200,4", status)                        ' finish waveform.
Cmd$ = "C219,0"                                        ' Turn constant
CALL Gpib.cmd(Cmd$, status)                            ' Amplitude control
                                                       ' off

Cmd$ = "C212,0"                                        ' turn off cycle coun
CALL Gpib.cmd(Cmd$, status)
ter
CALL Gpib.cmd("C200,4", status)                        ' finish waveform.
'
GOSUB ACPD
'
CALL Gpib.cmd("C33,0", status)                         ' set total segment
'                                                      ' count to zero
KEY 1, "Stop"
KEY 2, "Print"
KEY 3, "ACPD"
KEY 5, "Change"
KEY 8, "End Pg"
KEY 10, " DOS"
```

```
KEY(1) ON:  KEY(2) ON: KEY(3) ON:  KEY(5) ON: KEY(8) ON: KEY(10) ON
ON KEY(1) GOSUB Stopcyc
ON KEY(2) GOSUB Printer
ON KEY(3) GOSUB ACPD.imediate
ON KEY(5) GOSUB RT.Change
ON KEY(8) GOSUB Stop.test
ON KEY(10) GOSUB Dos.shell
COLOR 7, 0: CLS
GOTO Restart
'
'*******************************************************'
'
ACPD: COLOR 7, 0: CLS : COLOR 7, 1: KEY(5) OFF          ' Read ACPD from C
GM5
     CALL Ramp(Chan, Amp!, Time!)                    ' Ramp to maximum
     CALL Gpib.cmd("Q211", status)                          ' Request cycle num
ber
     CALL Gpib.rpt(rpt$, 10, status)                        ' Read cycle number
     LastCycle! - VAL(rpt$) / 4
StartACPD:
     LOCATE 1, 1: PRINT "ACPD Readings at Cycle Number "; LastCycle!
     IF FQ$ - "FNO" THEN GOTO GETacpd
     LOCATE 20, 10: PRINT "
    "
     LOCATE 20, 10: PRINT "SET FREQUENCY AT "; KHZ; "KHZ AND SET CURRENT TO
 ONE"
     LOCATE 21, 18: PRINT "                              "
SETfq: LOCATE 21, 20: PRINT "Press Return When Ready"
     DO
     LOOP UNTIL INKEY$ - CHR$(13)
     IF FQ$ - "FYES" THEN
         LOCATE 21, 1: PRINT SPACE$(79): LOCATE 21, 10: PRINT "PD GAIN: ":
Max - 3
         LOCATE 21, 20: CALL TextIn2(P4$, Max, Exit.Code)
         Pdgain! - VAL(P4$)
     END IF
     BEEP
     LOCATE 21, 1: PRINT SPACE$(79)
GETacpd: CALL ACPD(Pdchans, Acpds!(), DEL!, Scantype$, Crntchan!(), Crntpot
!())    ' Read ACPD's
     Sp$ - "                                                   "
     Data$ - ""
     FOR I - 0 TO Pdchans
     LOCATE I + 2, 1
     Acpdreal!(I) - Acpds!(I) / (10! ^ (Pdgain! / 20)) * 1000000!
     PRINT "Chan # : "; I + 1; "  ACPD : "; Acpdreal!(I); " (u-Volts)"
     Data$ - Data$ + MID$(STR$(Acpdreal!(I)), 1, 10) + "  "
     NEXT I
     IF FQ$ - "FYES" THEN LOCATE Pdchans + 4, 1: PRINT " CURRENT FREQ -"; K
HZ; "KHZ  "
Rep: LOCATE 20, 1: PRINT SPACE$(79): LOCATE 22, 20
     TONE$ - "L55 CDEFABCDEFABCDEFAB"
     PLAY TONE$
     PRINT "Repeat measurement "; : INPUT Meas$
     IF Meas$ - "Y" OR Meas$ - "y" THEN LOCATE 22, 1: PRINT SPACE$(79): GOT
```

```
O StartACPD
     IF Meas$ = "N" OR Meas$ = "n" THEN LOCATE 22, 1: PRINT SPACE$(79): GOT
O Pd.exit
     GOTO Rep
Pd.exit:
     IF FQ$ = "FNO" THEN GOTO Crkvis
     IF CSET = 3 THEN GOTO SETstep
     LPRINT "Cycle Number : "; CurntCycle!; "  Stress Amplitude : ";
     LPRINT STamp!; " Stress Ratio : "; R!; "  Current Freq : "; KHZ
     LPRINT "Pds :";
     FOR I = 0 TO Pdchans
        LPRINT TAB(10 + 10 * I); MID$(STR$(Acpdreal!(I)), 1, 8);
     NEXT I
     LPRINT CHR$(13)
SETstep:
     IF CSET = 1 THEN KHZ = 10: Filefq$ = Filename$ + "A.PRN"
     IF CSET = 2 THEN KHZ = 30: Filefq$ = Filename$ + "B.PRN"
     CSET = CSET + 1: IF CSET = 4 THEN CSET = 1: GOTO Crkvis
     OPEN Filefq$ FOR APPEND AS #3
     PRINT #3, Data$
     CLOSE #3
     GOTO StartACPD
Crkvis: CALL Crkvisual(MaxCrks - 1, Crkvis!(), Pdchans)'   Enter visual cra
ck
                                                       '   lengths
     FOR I = 0 TO MaxCrks - 1
     Data$ = Data$ + MID$(STR$(Crkvis!(I)), 1, 10) + "  "
     NEXT I
     Data$ = Data$ + STR$(CurntCycle!) + "   " + STR$(STamp!) + "   " + STR$(
R!)
     Comment$ = ""
     LOCATE 3 + Pdchans, 2: PRINT " Comments"
     LOCATE 3 + Pdchans, 13: CALL TextIn2(Comment$, 60, Exit.Code)
     OPEN Filered$ FOR APPEND AS #3
     PRINT #3, Data$
     CLOSE #3
Data$ = Data$ + "   " + "'" + Comment$ + "'"
File.out: LOCATE 22, 10: Ans$ = "Y"
    ' PRINT "Save data to disk (Y/N) ";
    ' INPUT Ans$
     IF Ans$ = "y" OR Ans$ = "Y" THEN
        OPEN File$ FOR APPEND AS #3
        PRINT #3, Data$
        CLOSE #3
        GOTO Cont.ramp
     ELSE
        IF Ans$ = "N" OR Ans$ = "n" THEN GOTO Cont.ramp
     END IF
     GOTO File.out
Cont.ramp:
     IF (Prtflg) THEN                              ' send data to printer
     'LPRINT CHR$(27)                               ' set print to condenced
     LPRINT "Cycle Number : "; CurntCycle!; "  Stress Amplitude : ";
     LPRINT STamp!; " Stress Ratio : "; R!; "  Current Freq : "; KHZ
```

```
      'LPRINT "  Time :  "; TIME$
      LPRINT "Pds :";
      IF FQ$ = "FYES" THEN KHZ = 3
      FOR I = 0 TO Pdchans
         LPRINT TAB(10 + 10 * I); MID$(STR$(Acpdreal!(I)), 1, 8);
      NEXT I
      LPRINT " "
      LPRINT "Crk : ";
      FOR I = 0 TO MaxCrks - 1
        LPRINT TAB(10 + 10 * I); MID$(STR$(Crkvis!(I)), 1, 8);
      NEXT I
      LPRINT " "
      LPRINT CHR$(13): LPRINT CHR$(13): LPRINT CHR$(13)
      END IF
      CALL Ramp(Chan, 0! * Amp!, Time!)              ' Ramp to mean level
      Cmd$ = "C219,1"                                ' Turn constant
      CALL Gpib.cmd(Cmd$, status)                    ' Amplitude control
                                                     ' on
      CALL Cycles(Chan, Freq!, Meanlev!, Amp!, Ncycles!)' Restart Function
                                                     ' Generator
      COLOR 7, 0
      KEY(5) ON
      RETURN
'
'*****************************************************'
'
Startcyc:

'
   Ncyc! = Ncycinc! - 4! * (CurntCycle! - LastCycle!)
   CALL Cycles(Chan, Freq!, Meanlev!, Amp!, Ncyc!)    ' Start cycling
'
   KEY 1, "Stop"
   ON KEY(1) GOSUB Stopcyc
'
RETURN
'
'*****************************************************'
'
Stopcyc:
    CALL Gpib.cmd("C200,4", status)                    ' finish waveform.
'
    Cmd$ = "C219,0"                                    ' Turn constant
    CALL Gpib.cmd(Cmd$, status)                        ' Amplitude control
                                                       ' off
    CALL Gpib.cmd("C200,4", status)                    ' finish waveform.

'
    KEY 1, "Start"
    ON KEY(1) GOSUB Startcyc
RETURN
'
'*****************************************************'
'
Stop.test:
```

```
    CALL Gpib.cmd("C200,4", status)                          ' finish waveform
;
    Cmd$ = "C219,0"                                          ' Turn constant
    CALL Gpib.cmd(Cmd$, status)                              ' Amplitude contr
ol                                                           ' off

   GOSUB Return.control
RETURN
'
'*****************************************************'
'
SPparams:
COLOR 7, 1: LOCATE 1, 20
PRINT "Specimen Parameters"
LOCATE 3, 1: PRINT "Specimen Width              "
LOCATE 3, 35: Max = 10
CALL TextIn2(T1$, Max, Exit.Code)
W! = VAL(T1$)
LOCATE 5, 1: PRINT "Specimen Thickness          "
LOCATE 5, 35
CALL TextIn2(T2$, Max, Exit.Code)
B! = VAL(T2$)
LOCATE 7, 1: PRINT "Specimen Type               "
LOCATE 7, 35: Max = 10
CALL TextIn2(Stype$, Max, Exit.Code)
LOCATE 9, 1: PRINT "Specimen Number             "
LOCATE 9, 35: Max = 10
CALL TextIn2(Snumber$, Max, Exit.Code)
FQin: LOCATE 11, 1: PRINT "Multiple Current Frequencies? (Y/N)    "
LOCATE 11, 44: Max = 1
CALL TextIn2(F$, Max, Exit.Code)
IF F$ = "Y" OR F$ = "y" THEN FQ$ = "FYES": KHZ = 3: CSET = 1: GOTO Inl
IF F$ = "N" OR F$ = "n" THEN FQ$ = "FNO": KHZ = 30: GOTO Inl
GOTO FQin
Inl: LOCATE 20, 1: PRINT "Continue with Edit (Y/N)  "; : INPUT Ans$
IF Ans$ = "Y" OR Ans$ = "y" THEN GOTO SPparams
IF Ans$ = "N" OR Ans$ = "n" THEN GOTO Fml
LOCATE 20, 1: PRINT "                                    "
         LISTEN$ = "T180 o2 P2 P8 GGG L2 E-"
         FATE$ = "P24 P8 L8 FF L2 D"
         PLAY LISTEN$ + FATE$
GOTO Inl
Fml: COLOR 7, 0
RETURN
'
'*****************************************************'
'
PDparams:
COLOR 7, 1: LOCATE 1, 20
PRINT "ACPD Parameters"
LOCATE 3, 1: PRINT "Number of Channels          "
LOCATE 3, 35: Max = 5
CALL TextIn2(P1$, Max, Exit.Code)
Pdchans = INT(VAL(P1$)) - 1
```

```
LOCATE 5, 1: PRINT "Channel Delay Time           "
LOCATE 5, 35
CALL TextIn2(P2$, Max, Exit.Code)
DEL! = VAL(P2$)
Scantype$ = "CUS"
LOCATE 7, 1: PRINT "ACPD Gain (DB)               "
LOCATE 7, 35: Max = 5
CALL TextIn2(P4$, Max, Exit.Code)
Pdgain! = VAL(P4$)
LOCATE 9, 1: PRINT "Number Crack Measurements "
LOCATE 9, 35: CALL TextIn2(P5$, 5, Exit.Code)
MaxCrks = VAL(P5$)
In2: LOCATE 17, 1: PRINT "Continue with Edit (Y/N)  "; : INPUT Ans$
IF Ans$ = "Y" OR Ans$ = "y" THEN GOTO PDparams
IF Ans$ = "N" OR Ans$ = "n" THEN GOTO Fm2
LOCATE 17, 1: PRINT "                                        "
        LISTEN$ = "T180 o2 P2 P8 GGG L2 E-"
        FATE$ = "P24 P8 L8 FF L2 D"
        PLAY LISTEN$ + FATE$
GOTO In2
Fm2:
IF Scantype$ = "CUS" THEN GOSUB Custom
COLOR 7, 0
RETURN
'
'*****************************************************'
'
RTparams:
COLOR 7, 1: LOCATE 1, 20
PRINT "8500 Control Parameters"
LOCATE 3, 1: PRINT "Stress Amplitude (Psi)      "
LOCATE 3, 35: Max = 10
CALL TextIn2(R1$, Max, Exit.Code)
STamp! = VAL(R1$)
LOCATE 5, 1: PRINT "Stress Ratio                "
LOCATE 5, 35
CALL TextIn2(R2$, Max, Exit.Code)
R! = VAL(R2$)
LOCATE 7, 1: PRINT "Test Frequency (Hz)         "
LOCATE 7, 35: Max = 10
CALL TextIn2(R3$, Max, Exit.Code)
Freq! = VAL(R3$)
LOCATE 9, 1: PRINT "Number of Cycles            "
LOCATE 9, 35: Max = 10
CALL TextIn2(R4$, Max, Exit.Code)
Ncycinc4! = VAL(R4$)
LOCATE 11, 1: PRINT "Data File Name              "
LOCATE 11, 35
CALL TextIn2(Filename$, Max, Exit.Code)
In3: LOCATE 17, 1: PRINT "Continue with Edit (Y/N)  "; : INPUT Ans$
IF Ans$ = "Y" OR Ans$ = "y" THEN GOTO RTparams
IF Ans$ = "N" OR Ans$ = "n" THEN GOTO Fm3
LOCATE 17, 1: PRINT "                                        "
        LISTEN$ = "T180 o2 P2 P8 GGG L2 E-"
        FATE$ = "P24 P8 L8 FF L2 D"
```

```
        PLAY LISTEN$ + FATE$
GOTO In3
Fm3: COLOR 7, 0
RETURN
'
'******************************************************'
'
RT.Change:
     CLS :
     GOSUB Stopcyc
     GOSUB RT.CHparams
     Ncycinc! = Ncycinc4! * 4!
     AmpPhys! = (STamp! / 2) * W! * B!
     Amp! = (AmpPhys! * Unitcon!(Chan)) / fullscale!(Chan)
                                                    ' convert to fraction
 of                                                 ' fullscale
     Mean! = Amp! * ((1! + R!) / (1! - R!))
'
'******************************************************'
'
CLS
COLOR 7, 1
LOCATE 1, 12: PRINT "Test summary and Status"; " Date : "; DATE$; " Time :"
; TIME$
LOCATE 2, 1
PRINT "Stress Amplitude : "; STamp!; " Psi "; "  Stress Ratio : "; R!;
PRINT "  Test Frequency : "; Freq!; " Hz"
LOCATE 3, 1
PRINT "Crack Length Measurement Interval : "; Ncycinc! / 4; " Cycles";
PRINT "  Data File : "; File$
LOCATE 4, 30
IF (Prtflg) THEN
   PRINT "Printer is ON"
ELSE
   PRINT "Printer is OFF"
END IF
COLOR 7, 0
KEY 1, "Stop"
KEY 2, "Print"
KEY 3, "ACPD"
KEY 5, "Change"
KEY 8, "End Pg"
KEY 10, " DOS"
KEY(1) ON:  KEY(2) ON: KEY(3) ON:  KEY(5) ON: KEY(8) ON: KEY(10) ON
ON KEY(1) GOSUB Stopcyc
ON KEY(2) GOSUB Printer
ON KEY(3) GOSUB ACPD.imediate
ON KEY(5) GOSUB RT.Change
ON KEY(8) GOSUB Stop.test
ON KEY(10) GOSUB Dos.shell
'
'******************************************************'
'
     CALL Setpoint(Chan, Mean!, status, Unitcon!(), fullscale!())
```

```
                ' Force new setpoint
     GOSUB Startcyc
RETURN
'
'*****************************************************'
'
RT.CHparams:
COLOR 7, 1: LOCATE 1, 20
PRINT "8500 Control Parameters"
LOCATE 3, 1: PRINT "Stress Amplitude (Psi)     "
LOCATE 3, 35: Max = 10
CALL TextIn2(R1$, Max, Exit.Code)
STamp! = VAL(R1$)
IF STamp! > 20000 THEN GOTO RT.CHparams
LOCATE 5, 1: PRINT "Stress Ratio               "
LOCATE 5, 35
CALL TextIn2(R2$, Max, Exit.Code)
R! = VAL(R2$)
LOCATE 7, 1: PRINT "Test Frequency (Hz)        "
LOCATE 7, 35: Max = 10
CALL TextIn2(R3$, Max, Exit.Code)
Freq! = VAL(R3$)
LOCATE 9, 1: PRINT "Number of Cycles           "
LOCATE 9, 35: Max = 10
CALL TextIn2(R4$, Max, Exit.Code)
Ncycinc4! = VAL(R4$)
In5: LOCATE 17, 1: PRINT "Continue with Edit (Y/N)  "; : INPUT Ans$
IF Ans$ = "Y" OR Ans$ = "y" THEN GOTO RT.CHparams
IF Ans$ = "N" OR Ans$ = "n" THEN GOTO Fm5
LOCATE 17, 1: PRINT "                                "
        LISTEN$ = "T180 o2 P2 P8 GGG L2 E-"
        FATE$ = "P24 P8 L8 FF L2 D"
        PLAY LISTEN$ + FATE$
GOTO In5
Fm5: COLOR 7, 0
RETURN
'
'*****************************************************'
'
Printer:                                       ' turn printer on or off
IF (Prtflg) THEN                               ' printer is currently o
n
    Prtflg = 0                                 ' set printer flag to of
f
    COLOR 7, 1: LOCATE 4, 40: PRINT "Printer is OFF": COLOR 7, 0
ELSE                                           ' printer is currently o
ff
    Prtflg = 1                                 ' set printer flag to on
    COLOR 7, 1: LOCATE 4, 40: PRINT "Printer is ON ": COLOR 7, 0
END IF
RETURN
'
'*****************************************************'
'
Custom:
```

```
COLOR 7, 0: CLS
COLOR 7, 1
DIM W$(30), V$(30), CUR$(60), POT$(60)
OPEN "CUSTOM.DAT" FOR INPUT AS #5
FOR J = 0 TO 59
INPUT #5, CUR$(J)
NEXT J
CLOSE #5
FOR J = 0 TO Pdchans
Crntchan!(J) = VAL(CUR$(J))
W$(J) = LTRIM$(STR$(Crntchan!(J) +.1))
NEXT J
FOR J = 0 TO Pdchans
J1 = J + 30
Crntpot!(J) = VAL(CUR$(J1))
V$(J) = LTRIM$(STR$(Crntpot!(J) + 1))
NEXT J
CUS1:
LOCATE 1, 30: PRINT "Custom Scan Cycle"
FOR J = 0 TO Pdchans
   LOCATE 3 + J, 1
   PRINT "READING"; J + 1; ":": LOCATE 3 + J, 14: PRINT "POTENTIAL = "
   LOCATE 3 + J, 26: Max = 2
   CALL TextIn2(V$(J), Max, Exit.Code)
   Crntpot!(J) = (VAL(V$(J)) - 1)
   LOCATE 3 + J, 32: PRINT "CURRENT = "
   LOCATE 3 + J, 42:  Max = 2
   CALL TextIn2(W$(J), Max, Exit.Code)
   Crntchan!(J) = (VAL(W$(J)) - 1)
NEXT J
In10: LOCATE Pdchans + 4, 1: PRINT "Continue with Edit (Y/N)  "; : INPUT An
s$
IF Ans$ = "Y" OR Ans$ = "y" THEN GOTO CUS1
IF Ans$ = "N" OR Ans$ = "n" THEN GOTO Fm10
LOCATE 17, 1: PRINT "
        LISTEN$ = "T180 o2 P2 P8 GGG L2 E-"
        FATE$ = "P24 P8 L8 FF L2 D"
        PLAY LISTEN$ + FATE$
        GOTO In10
Fm10:
FOR J = 0 TO 29
CUR$(J) = STR$(Crntchan!(J))
NEXT J
FOR J = 0 TO 29
J1 = J + 30
CUR$(J1) = STR$(Crntpot!(J))
NEXT J

OPEN "CUSTOM.DAT" FOR OUTPUT AS #5
FOR J = 0 TO 59
PRINT #5, CUR$(J)
NEXT J
CLOSE #5: COLOR 7, 0
RETURN
'
```

```
'*****************************************************'
'

Dos.shell:
          GOSUB Stopcyc
          CLS
          SHELL
CLS
COLOR 7, 1
LOCATE 1, 12: PRINT "Test Summary and Status  "; " Date : "; DATE$; " Time
:"; TIME$
LOCATE 2, 1
PRINT "Stress Amplitude : "; STamp!; " Psi "; "  Stress Ratio : "; R!;
PRINT "  Test Frequency : "; Freq!; " Hz"
LOCATE 3, 1
PRINT "Crack Length Measurement Interval : "; Ncycinc! / 4; " Cycles";
PRINT "  Data File : "; File$
LOCATE 4, 30
IF (Prtflg) THEN
   PRINT "Printer is ON"
ELSE
   PRINT "Printer is OFF"
END IF
COLOR 7, 0
KEY 1, "Stop"
KEY 2, "Print"
KEY 3, "ACPD"
KEY 5, "Change"
KEY 8, "End Pg"
KEY 10, " DOS"
GOSUB Startcyc
RETURN
CheckError:
IF ERR = 62 THEN
   FileEnd = 1
   CLOSE #3
   RESUME NEXT
ELSE
   ON ERROR GOTO 0
END IF

END

SUB ACPD (Pdchans, Acpds!(), DEL!, Scantype$, Crntchan!(), Crntpot!())
IF Scantype$ = "C+S" THEN
   S$ = "M"
ELSE
   S$ = Scantype$
END IF
CH! = 0: MAXCH = Pdchans
'                                                  *
' *** Setup LPT2: for control of scanner ***
'                                                  *
OPEN "lpt2:" FOR OUTPUT AS #2
```

```
REM OPEN "COM2:300,N,8,2,CS1000,DS,CD" FOR RANDOM AS #2
FOR I = 0 TO MAXCH
PRINT #2, "C"; Crntchan!(CH!) 'Switch to proper current channel
TIME$ = "00:00:00":
Tim1:
IF (TIMER - 1! < 0) THEN GOTO Tim1
PRINT #2, "S"; Crntpot!(CH!)  'Switch to proper potential channel
TIME$ = "00:00:00":
Tim:
IF (TIMER - DEL! < 0) THEN GOTO Tim
'                                                  *
' *** Setup COM2: for reading voltages from CGM5 ***
'                                                  *
OPEN "COM2:9600,N,8,1,CS,DS,CD" FOR RANDOM AS #1
Cgm.init: A$ = INPUT$(1, #1): B! = ASC(A$)
D! = B! AND 15: IF D! <> 0 THEN GOTO Cgm.init
POL! = B! AND 32: DP! = B! AND 64: ORR! = B! AND 128: B! = (B! AND 16) / 16
: DPM$ = CHR$(48 + B!)
FOR NPM = 1 TO 4
    A$ = INPUT$(1, #1): B! = ASC(A$)
    DPM$ = DPM$ + CHR$(48 + (B! AND 240) / 16)
NEXT NPM
IF ORR! = 1 THEN DPM$ = "99999": GOTO Cgm.value
IF POL! < 1 THEN DPM$ = "-" + DPM$:
                                  ELSE DPM$ = "+" + DPM$
IF DP! > 0 THEN DPM$ = LEFT$(DPM$, 3) + "." + MID$(DPM$, 4, 10)
IF DP! = 0 THEN DPM$ = LEFT$(DPM$, 2) + "." + MID$(DPM$, 3, 10)
Cgm.value: Acpds!(I) = VAL(DPM$)
           CLOSE #1
           CH! = CH! + 1            ' Increment Channel Number
NEXT I
CH! = 0!
PRINT #2, "M"; CH!
CLOSE #2
END SUB

SUB Crkvisual (N, Crk!(), Pdchans)
DIM Crktmp$(8)
Sp$ = "
     "
Method$ = "Auto"
SELECT CASE Method$
CASE "Manual"
Man.input:
FOR I = 0 TO N
    LOCATE I + 9, 10
    PRINT "Enter Crack Length at Location Number "; I + 1; " :  ";
    LOCATE I + 9, 60
    CALL TextIn2(Crktmp$(I), 10, Exit.Code)
    Crk!(I) = VAL(Crktmp$(I))
NEXT I
Crk.input:
LOCATE 20, 10
PRINT "Continue with edit (Y/N)  ";
INPUT Ans$
```

```
IF Ans$ = "Y" OR Ans$ = "y" THEN GOTO Man.input
IF Ans$ = "N" OR Ans$ = "n" THEN GOTO Crk.exit
GOTO Crk.input
CASE "Auto"
' *                                                          *
' ***  Code For RS232 Input From Questar ******
' *                                                          *
RS232.read:
OPEN "COM1:9600,N,8,1,CS,DS,CD" FOR RANDOM AS #1
PRINT #1, "G90"                                    ' Set to absloute mode
PRINT #1, "G70"                                    ' Set to english units
INPUT #1, A$                                       ' Read status fron "G90"
FOR I = 0 TO N STEP 2
    LOCATE 20, 1: PRINT Sp$: LOCATE 20, 1
    PRINT "Measurement number "; I + 1; " move stage to zero location and p
ress return "
    LOCATE 20, 70: CALL TextIn2(Z$, 1, Exit.Code)
    GOSUB zero: BEEP
    FOR J = 0 TO 1
       LOCATE 20, 1: PRINT Sp$: LOCATE 20, 1
       PRINT "Measurement number "; J + I + 1; " move stage to crack tip an
d press return "
       LOCATE 20, 70: CALL TextIn2(Z$, 1, Exit.Code)
       GOSUB Readxy: BEEP
       LOCATE I + J + 1, 53
       PRINT "Crack "; I + J + 1; ": "; ABS(VAL(Ydata$))'; "    "; ABS(VAL(
Xdata$))
       Crk!(I + J) = ABS(VAL(Ydata$))
    NEXT J
NEXT I
CLOSE #1
Question: LOCATE 20, 1: PRINT Sp$
LOCATE 22, 1: PRINT SPACE$(79): LOCATE 22, 20
PRINT "Repeat measurement "; : INPUT Meas$
IF Meas$ = "Y" OR Meas$ = "y" THEN LOCATE 22, 1: PRINT SPACE$(79): GOTO RS2
32.read
IF Meas$ = "N" OR Meas$ = "n" THEN LOCATE 22, 1: PRINT SPACE$(79): GOTO Crk
.exit
GOTO Question
END SELECT
GOTO Crk.exit
zero:                                              ' Zero X,Y axis
  PRINT #1, "CA"
RETURN                                             ' Read X,Y Position
Readxy:
  PRINT #1, "DA"
  INPUT #1, Ans$
  Signx$ = MID$(Ans$, 2, 1): Xvalue$ = MID$(Ans$, 4, 7)
  Xdata$ = Signx$ + Xvalue$
  SignY$ = MID$(Ans$, 13, 1): Yvalue$ = MID$(Ans$, 15, 7)
  Ydata$ = SignY$ + Yvalue$
RETURN
Crk.exit:
END SUB
```

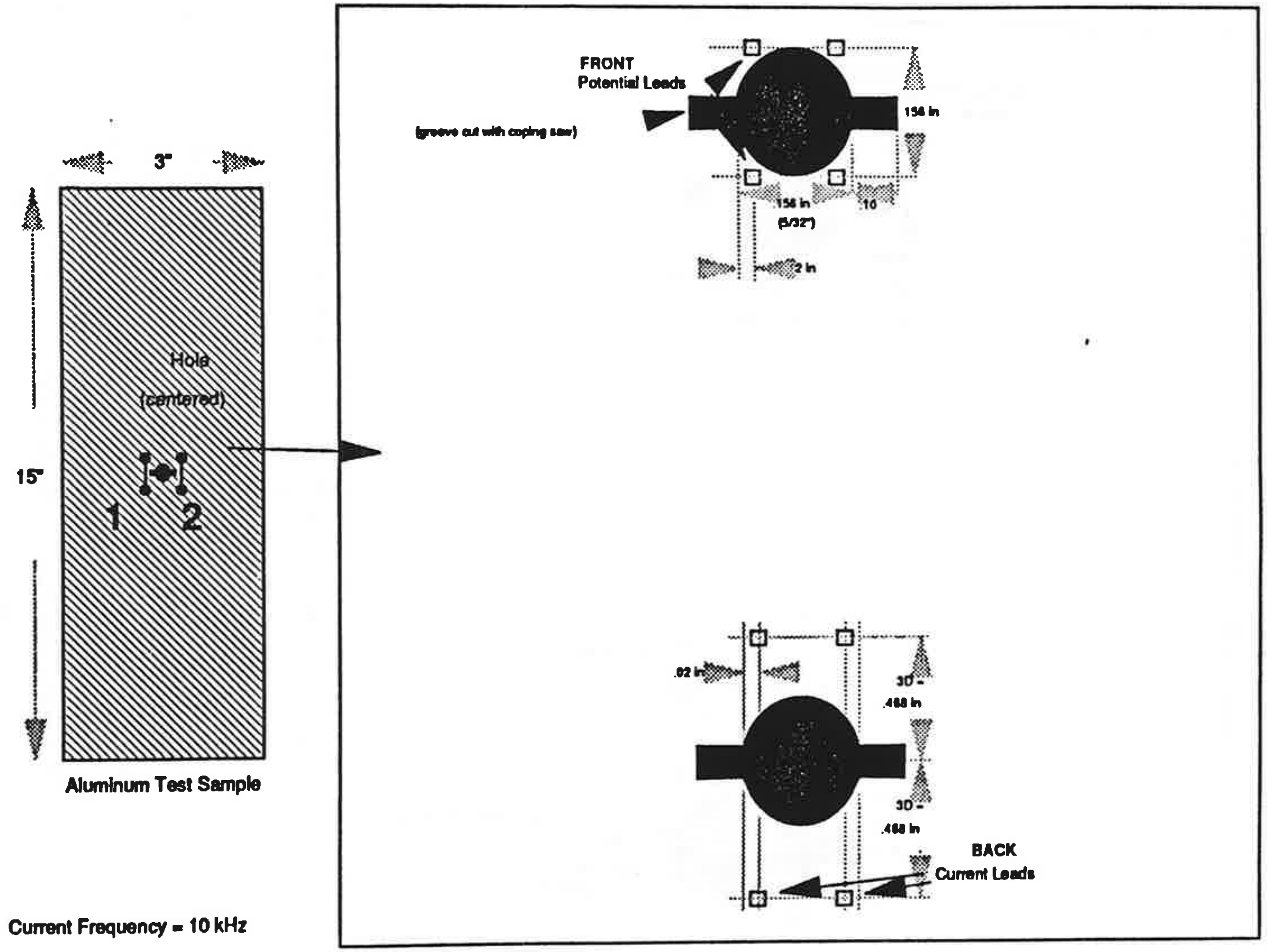
```
SUB Cycles (Chan, Freq!, Meanlev!, Amp!, Ncycles!)
'-----------------------------------------------'
' Setup waveform, Frequency "Freq" Amplitude at "Amp %" of full scale,
' using stroke mode of control and the current
' starting level. The 8500 will cycle indefinately
' until the ESC key is pressed.
'-----------------------------------------------'

Cmd$ = "C201," + STR$(Chan) + ",0"
CALL Gpib.cmd(Cmd$, status)                          ' sine wave type
                                                     ' on channel Chan

Cmd$ = "C202," + STR$(Chan) + "," + STR$(Freq!)
CALL Gpib.cmd(Cmd$, status)                          ' set frequency to
                                                     ' Freq!(Hz).

Cmd$ = "C203," + STR$(Chan) + "," + STR$(Amp!)
CALL Gpib.cmd(Cmd$, status)                          'set amplitude to Amp
!
Cmd$ = "C212,0"
CALL Gpib.cmd(Cmd$, status)                          'cycle comparator off
Cmd$ = "C209," + STR$(Ncycles!)
CALL Gpib.cmd(Cmd$, status)                          'set # of cycles
Cmd$ = "C213,3"
CALL Gpib.cmd(Cmd$, status)                          'hold at end of cycli
ng
Cmd$ = "C214,0"
CALL Gpib.cmd(Cmd$, status)                          'no data logging
Cmd$ = "C212,2"
CALL Gpib.cmd(Cmd$, status)                          ' Arm cycle counter
CALL Gpib.cmd("C200,1", status)                      ' start waveform.
Cmd$ = "C219,1"                                      ' Turn constant
CALL Gpib.cmd(Cmd$, status)                          ' Amplitude control
                                                     ' on

END SUB

SUB Ramp (Chan, Amp!, Time!)
state = 1
CALL Gpib.cmd("C200,4", status)                         ' finish waveform
.
Cmd$ = "C2," + STR$(Chan) + ",0"
CALL Gpib.cmd(Cmd$, status)                             ' Set to single r
amp
Cmd$ = "C4," + STR$(Chan) + "," + STR$(Amp!)
CALL Gpib.cmd(Cmd$, status)                             ' Set ramp amplit
ude
Cmd$ = "C6," + STR$(Chan) + STR$(ABS(Amp! / Time!))
CALL Gpib.cmd(Cmd$, status)                             ' Set ramp rate
Cmd$ = "C1,1"
DO
  CALL Gpib.cmd(Cmd$, stas)                             ' Start ramp
  Cmd$ = "Q1,"
  CALL Gpib.rpt(rpt$, 10, status)
  state = VAL(rpt$)
LOOP UNTIL state = 0
END SUB
```

```
SUB Setpoint (Chan, Mean!, status, Unitcon!(), fullscale!())
Meanreal! = (Mean! * fullscale!(Chan)) / Unitcon!(Chan)
Cmd$ = "C3," + STR$(Chan) + "," + STR$(Mean!)
CALL Gpib.cmd(Cmd$, status)                              ' Set setpoint to new valu
e
                                                         ' new value is "Mean!"
Readval:
    Cmd$ = "C134," + STR$(Chan) + ",7,1"                 ' Set single point read of
                                                         ' feedback
    CALL Gpib.cmd(Cmd$, status)
    Cmd$ = "Q134," + STR$(Chan) + ",0"
    CALL Gpib.cmd(Cmd$, status)                          ' Read feedback value
    CALL Gpib.rpt(rpt$, 10, status)
    Value! = (VAL(rpt$) * fullscale!(Chan)) / Unitcon!(Chan)
'   PRINT "Setpoint , Feedback is "; Meanreal!, Value!
    IF (ABS((Meanreal! - Value!) / Meanreal!) < .01) THEN
      GOTO Exit.sub
    ELSE
      GOTO Readval
    END IF
Exit.sub: 'PRINT "Setpoint reached"
END SUB
```

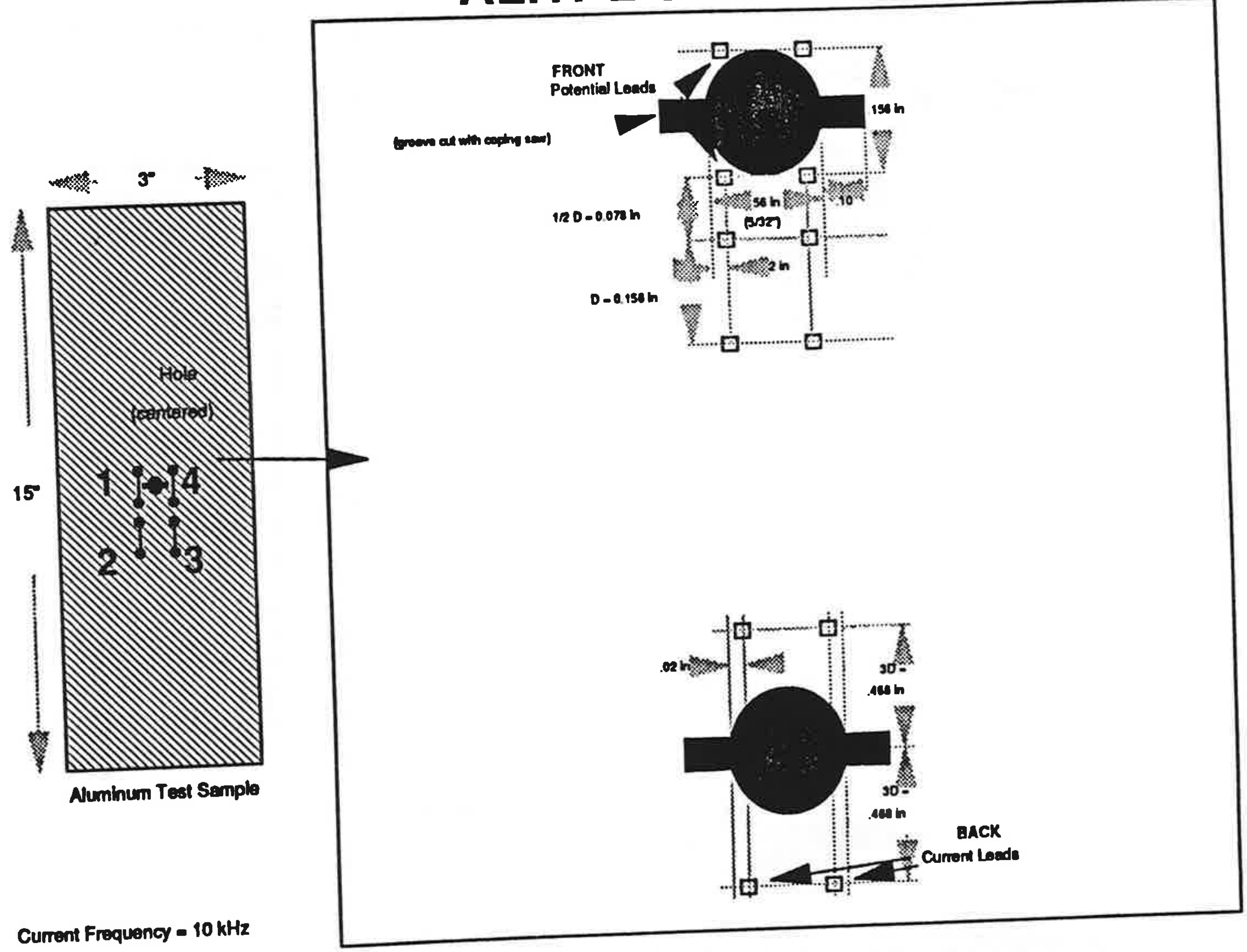
APPENDIX B

TEST SPECIMEN DRAWINGS

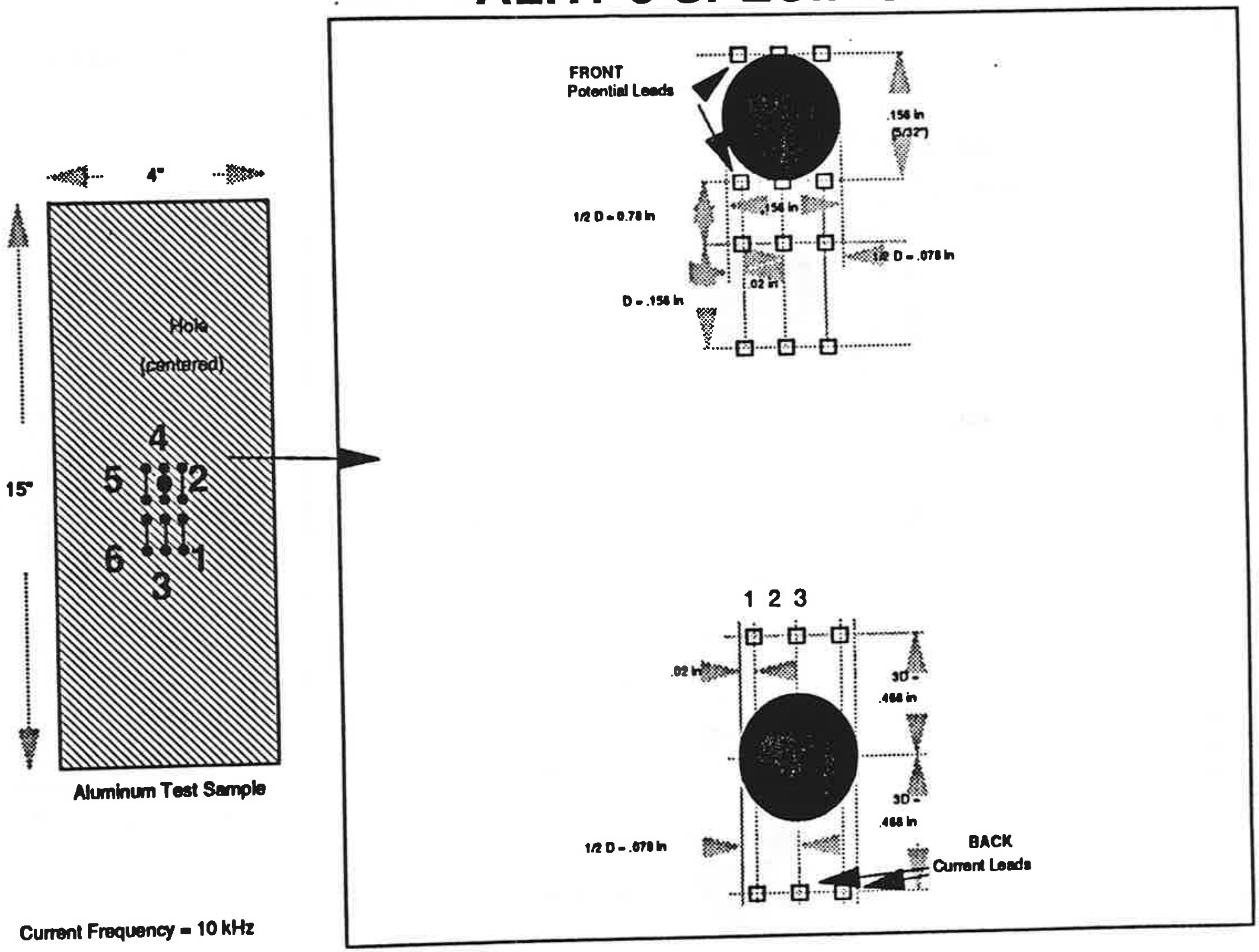
ALH1-1 SPECIFICATIONS



ALH1-2 SPECIFICATIONS

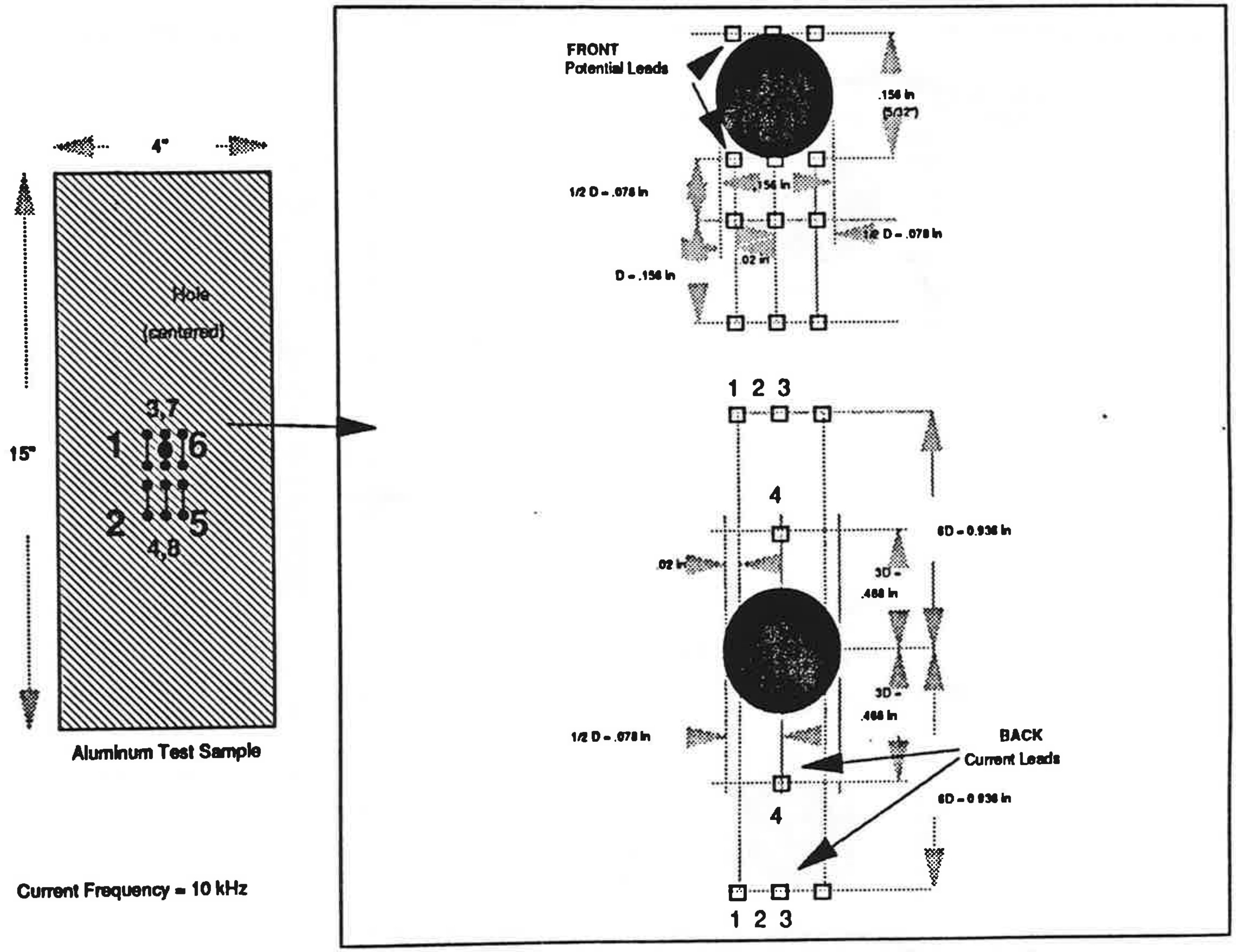


ALH1-3 SPECIFICATIONS

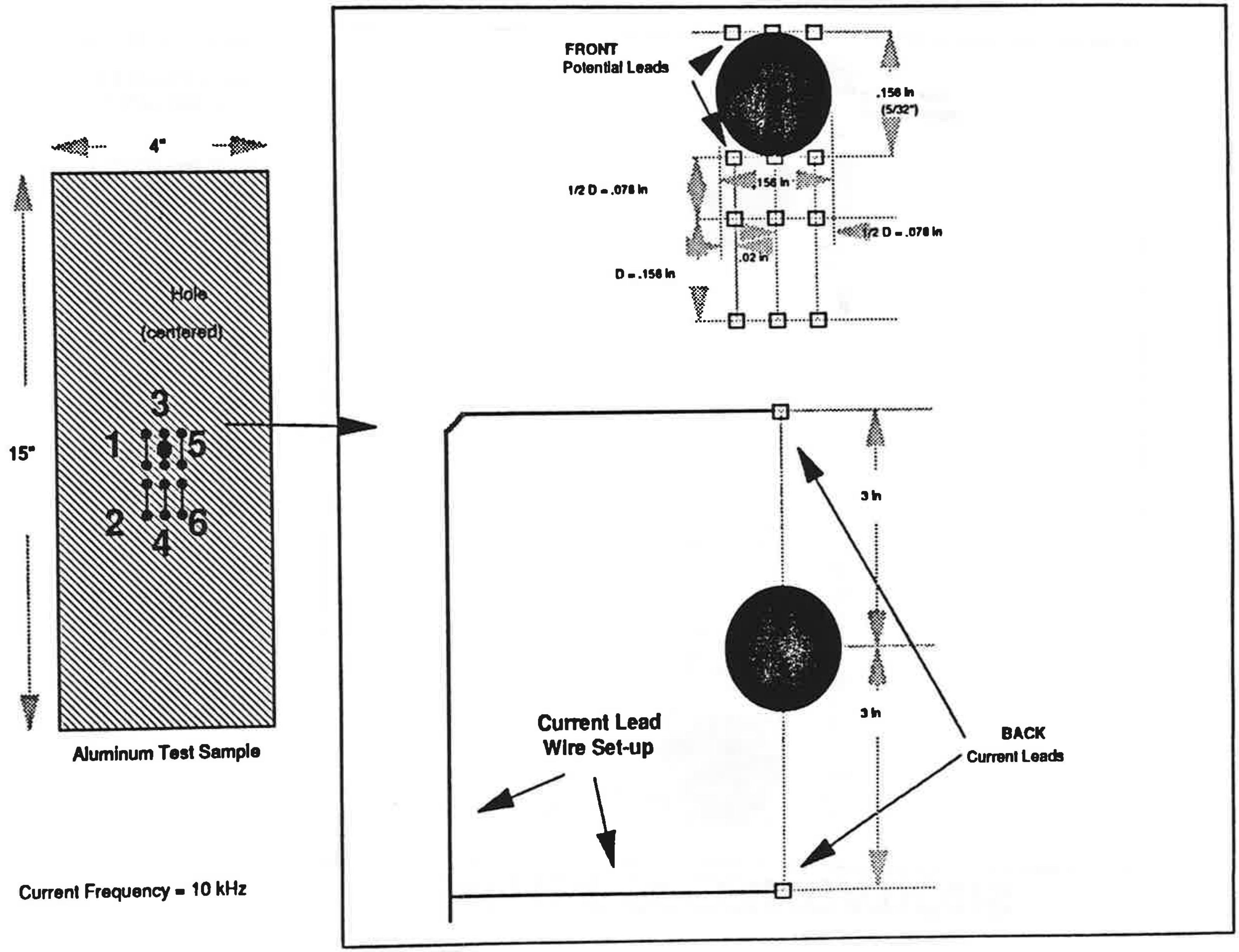


Current Frequency = 10 kHz

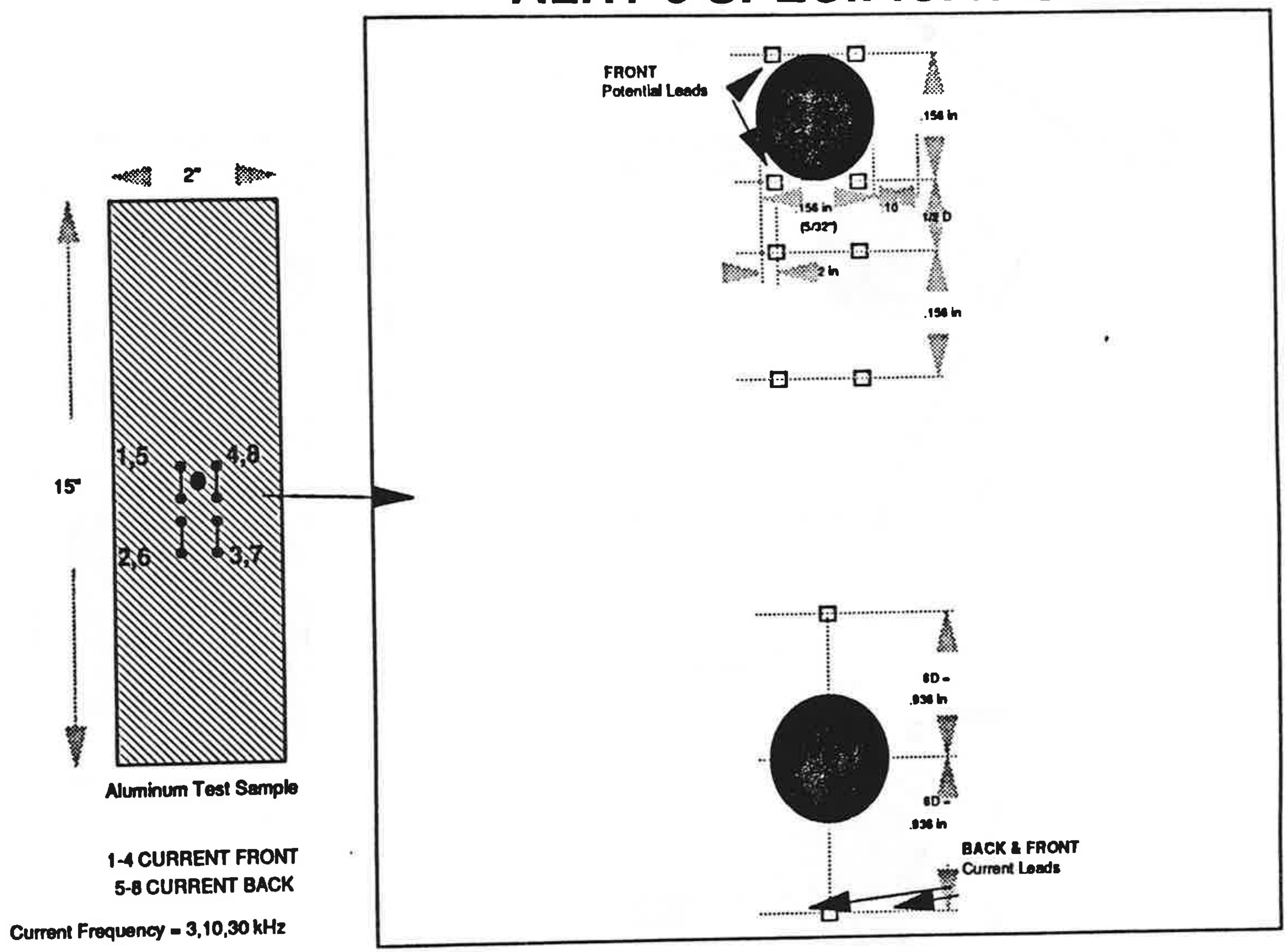
ALH1-4 SPECIFICATIONS



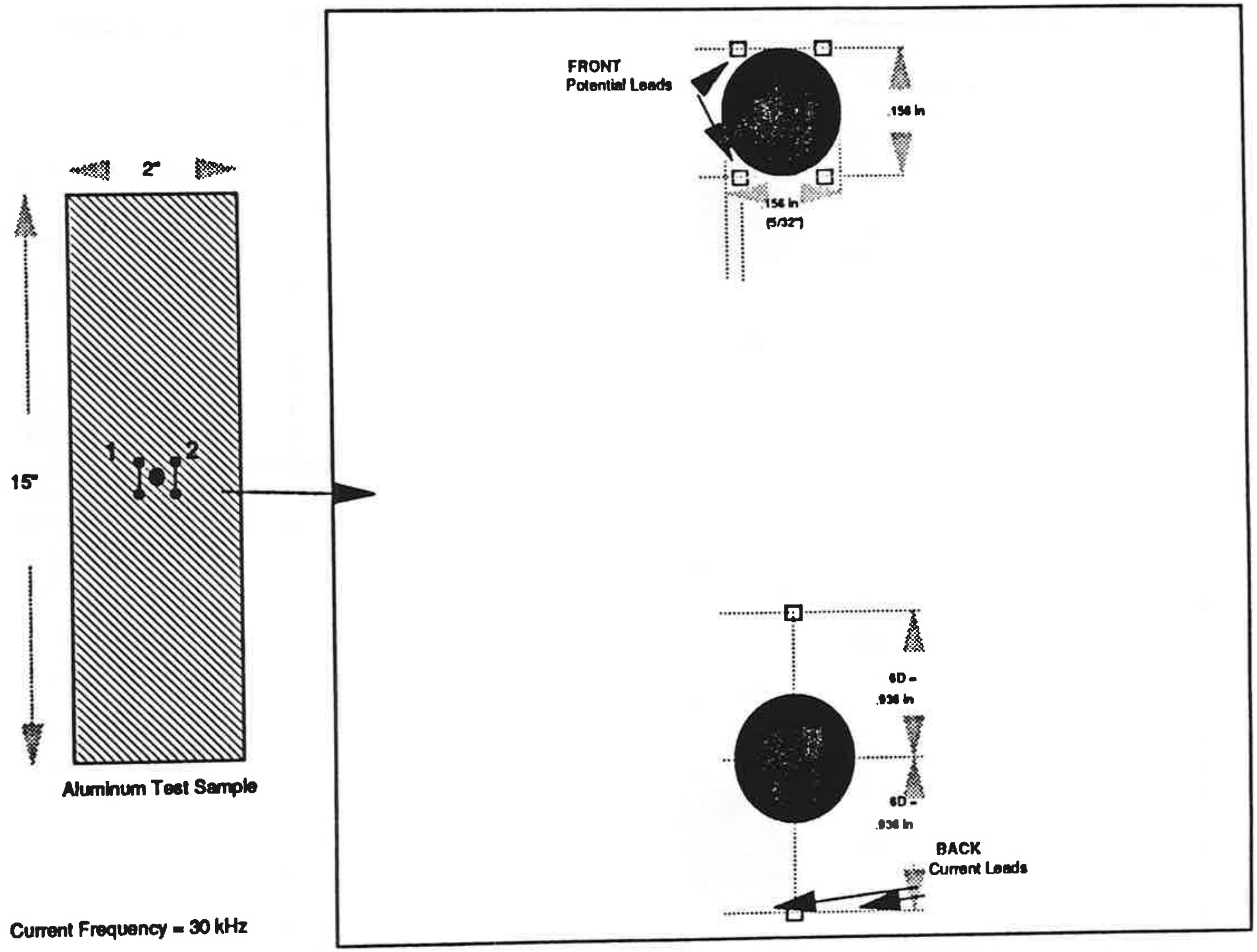
ALH1-5 SPECIFICATIONS



ALH1-6 SPECIFICATIONS

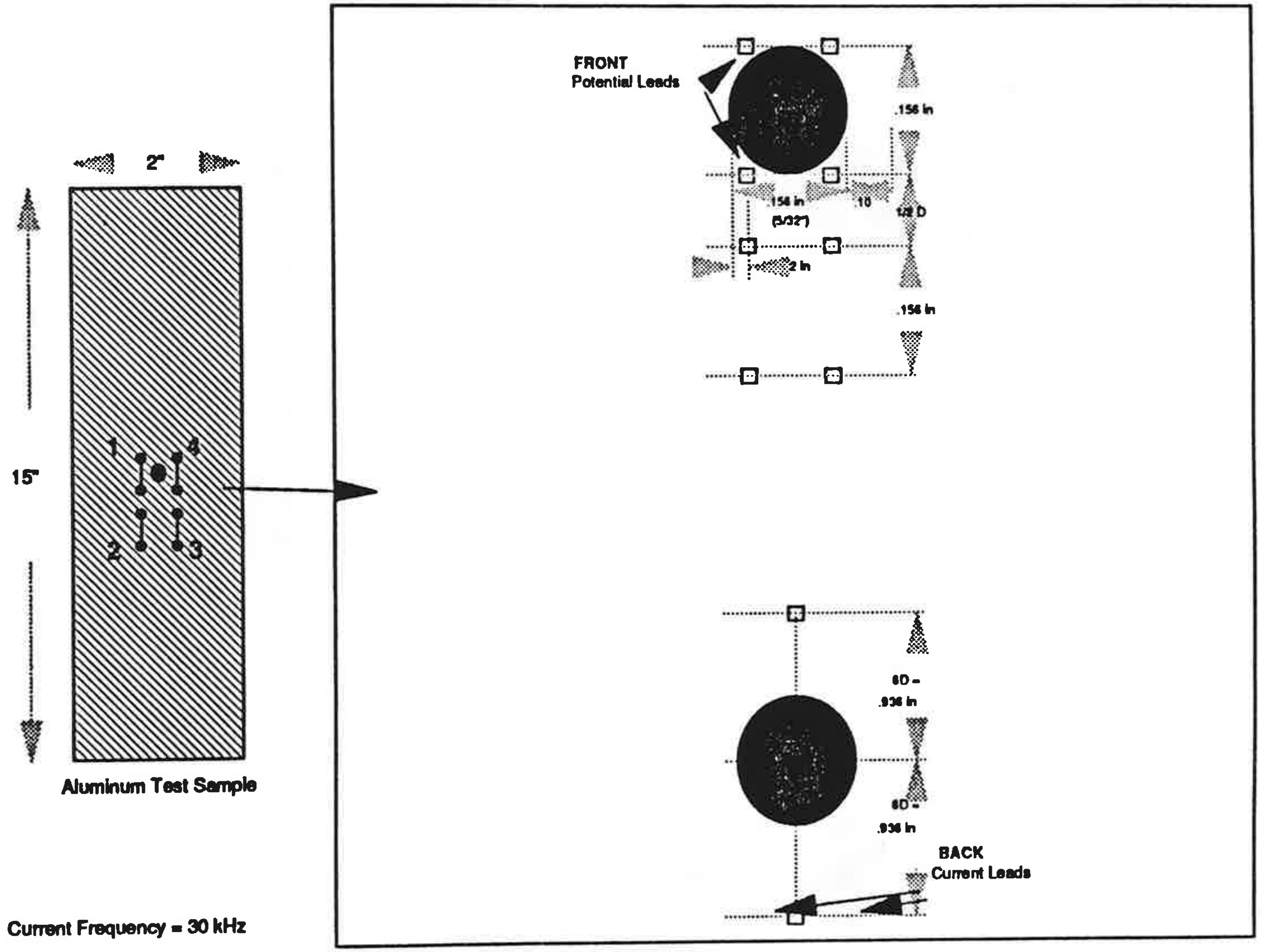


ALH1-7 SPECIFICATIONS

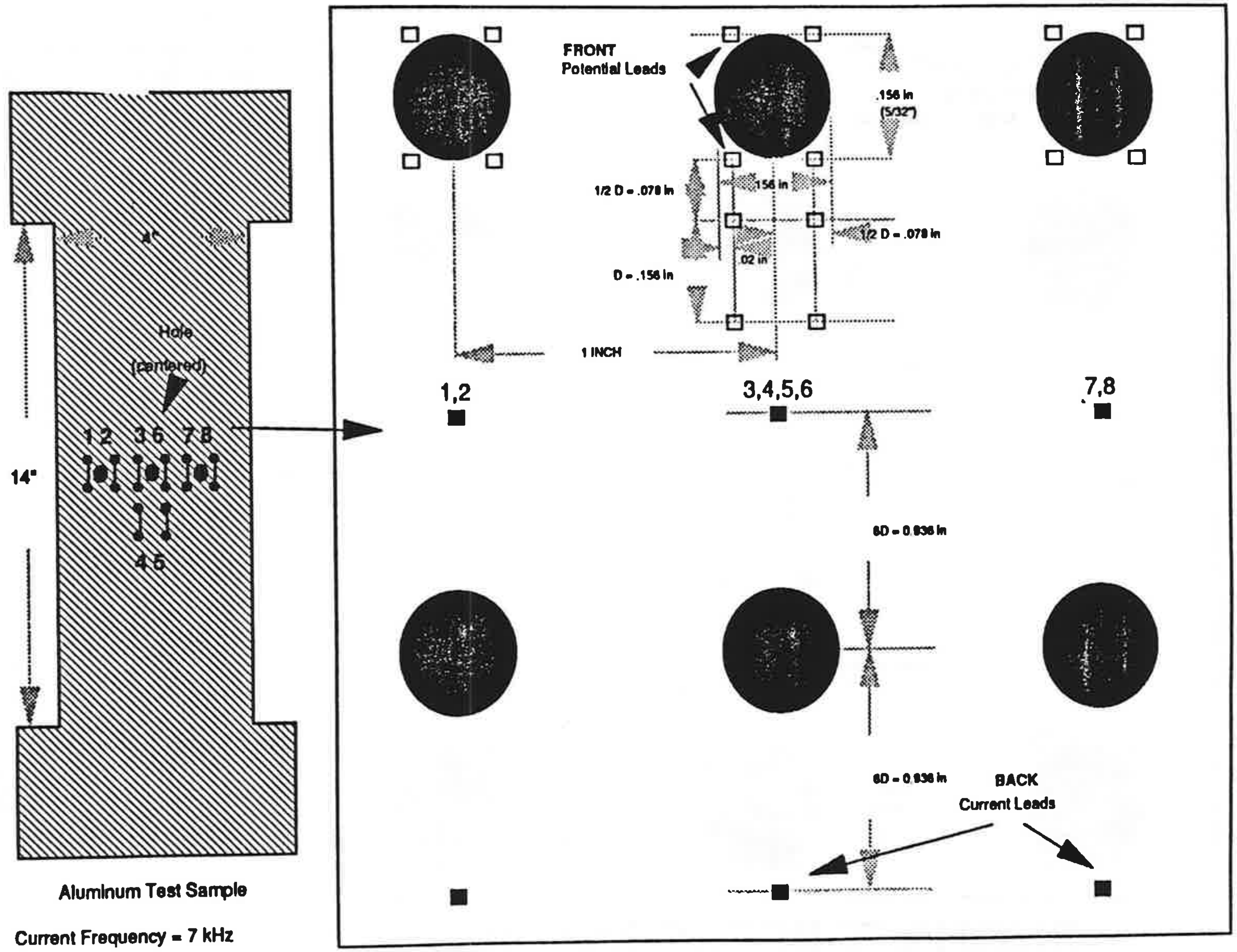


Current Frequency = 30 kHz

ALH1-8 SPECIFICATIONS



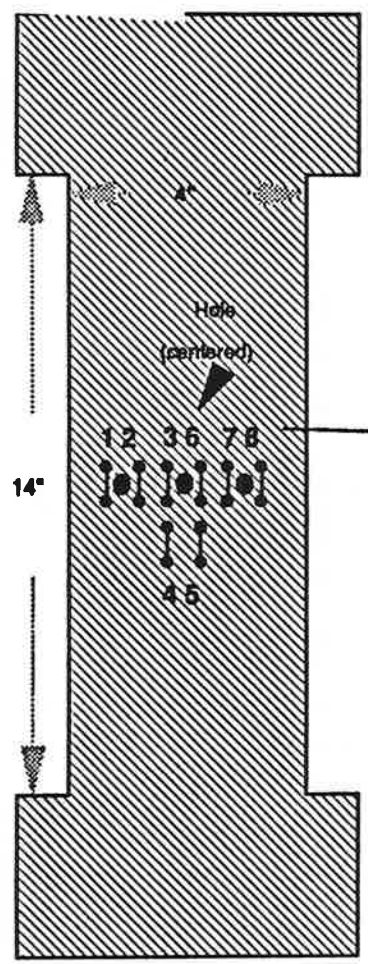
ALH3-1 SPECIFICATIONS



Aluminum Test Sample

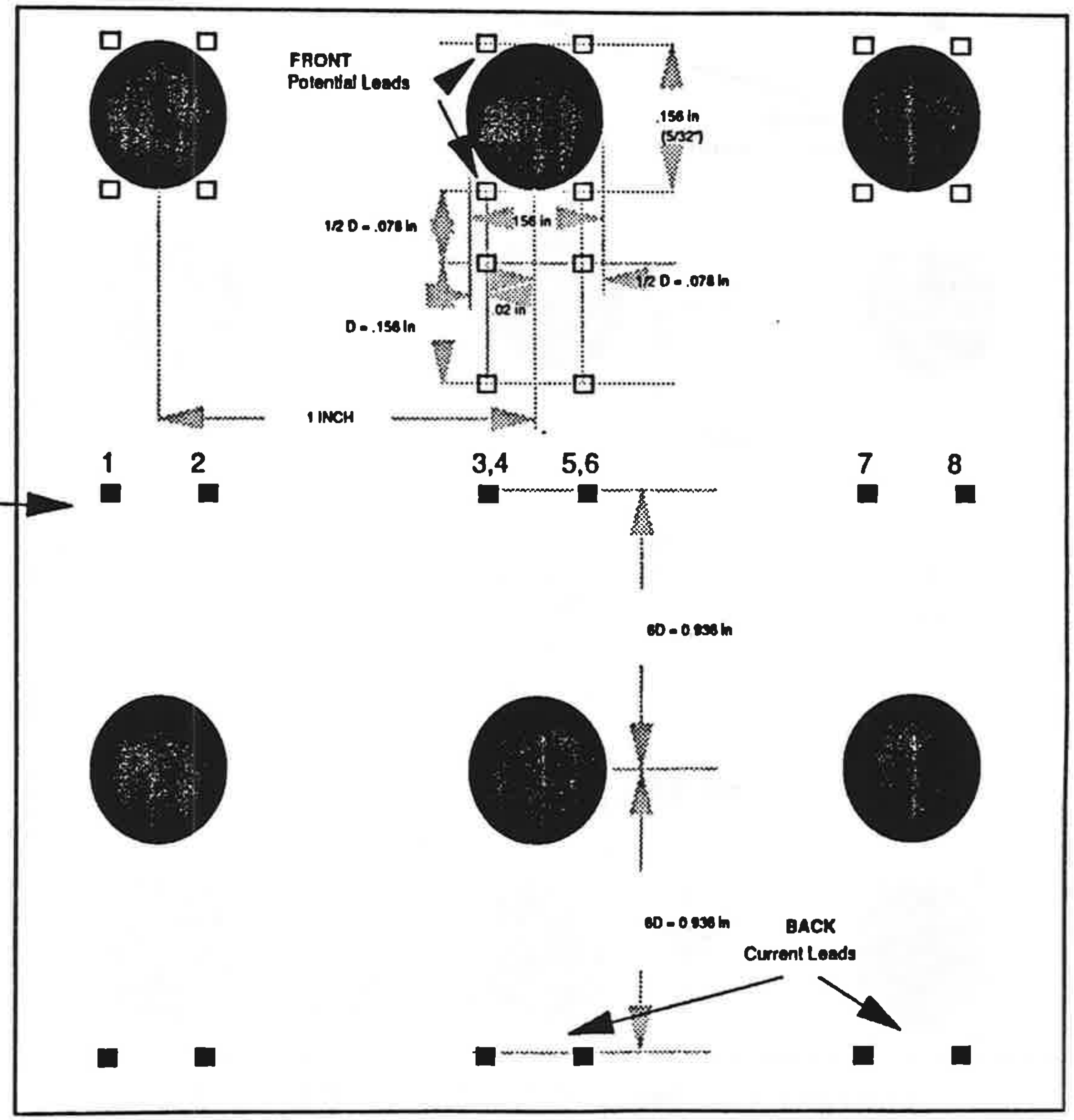
Current Frequency = 7 kHz

ALH3-2 SPECIFICATIONS

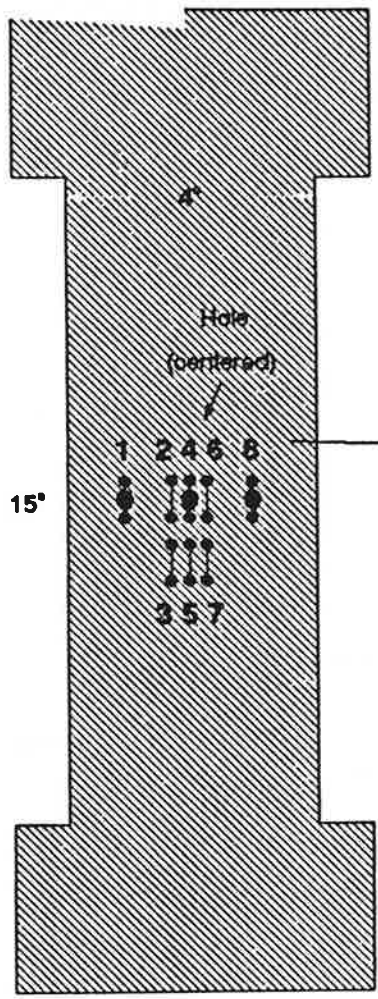


Aluminum Test Sample

Current Frequency = 7 kHz

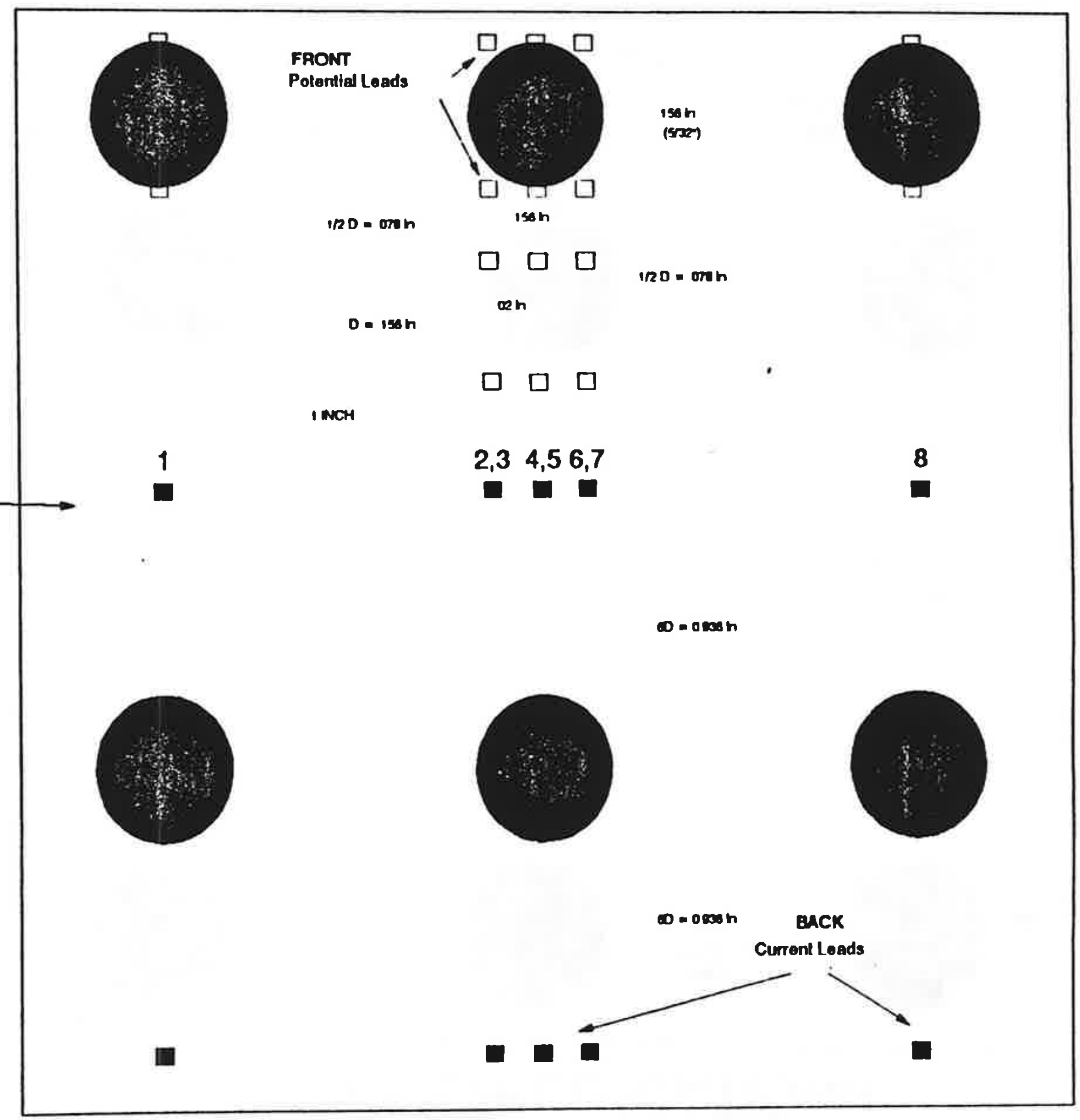


ALH3-3 SPECIFICATIONS

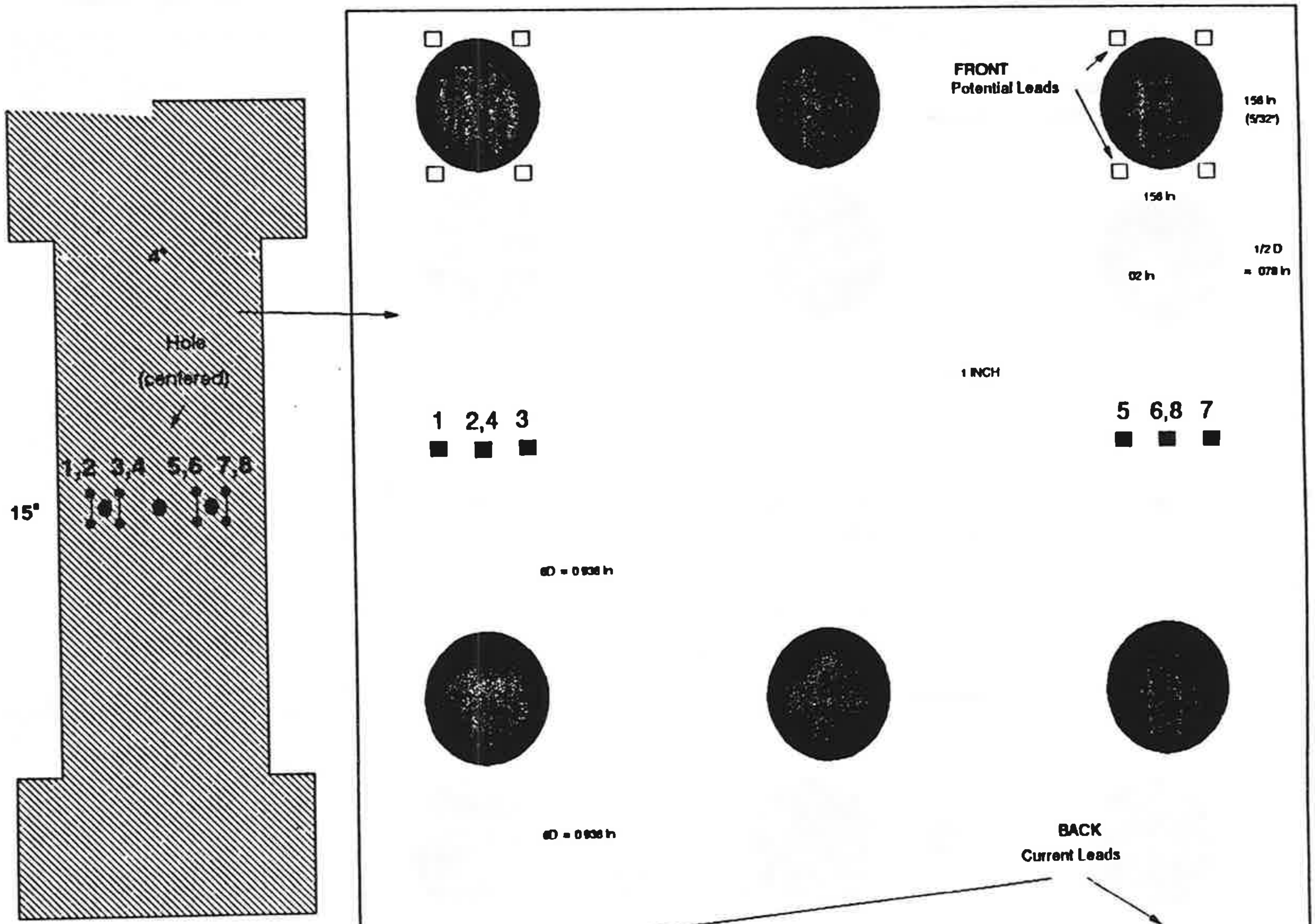


Aluminum Test Sample

Current Frequency = 10 kHz



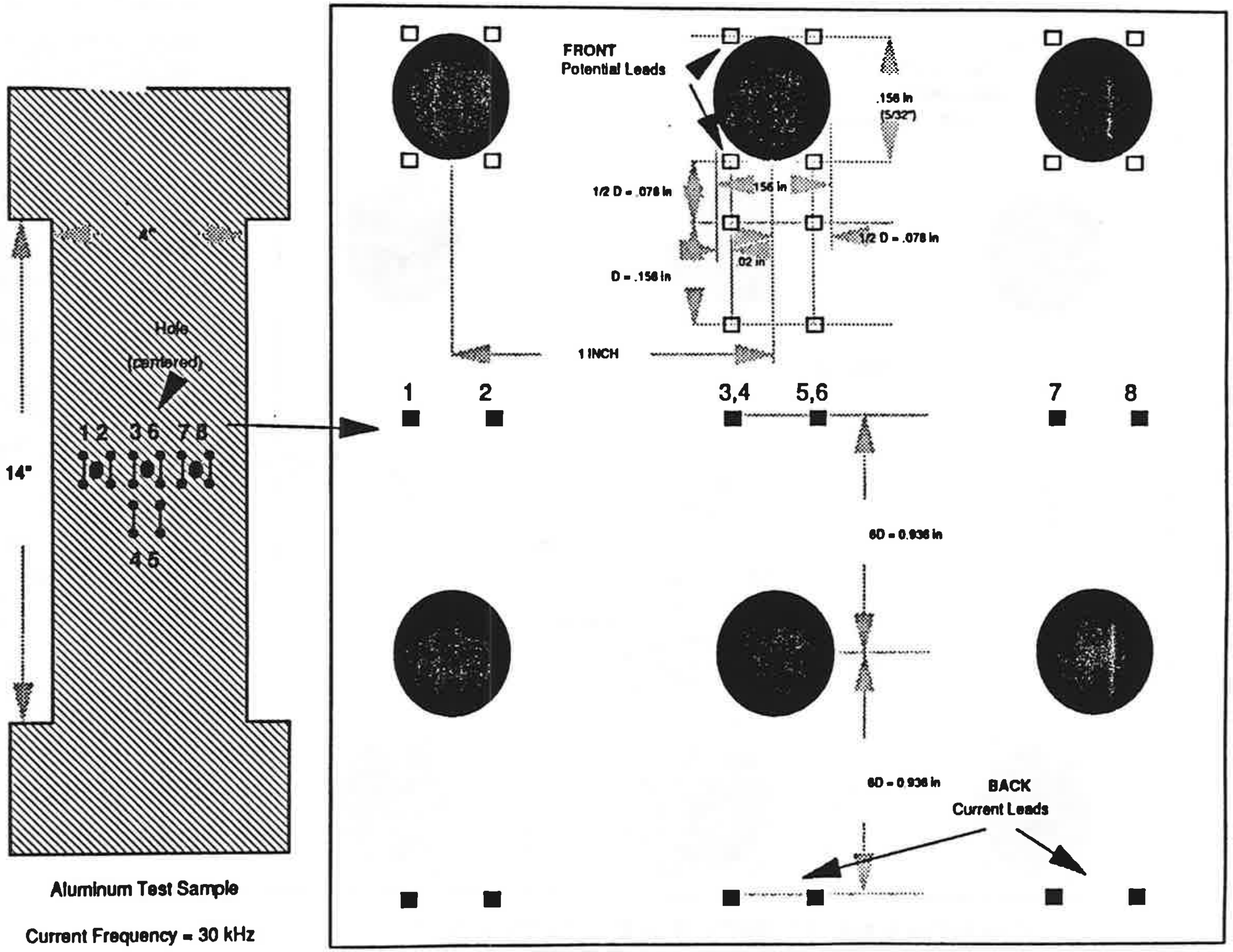
ALH3-4 SPECIFICATIONS



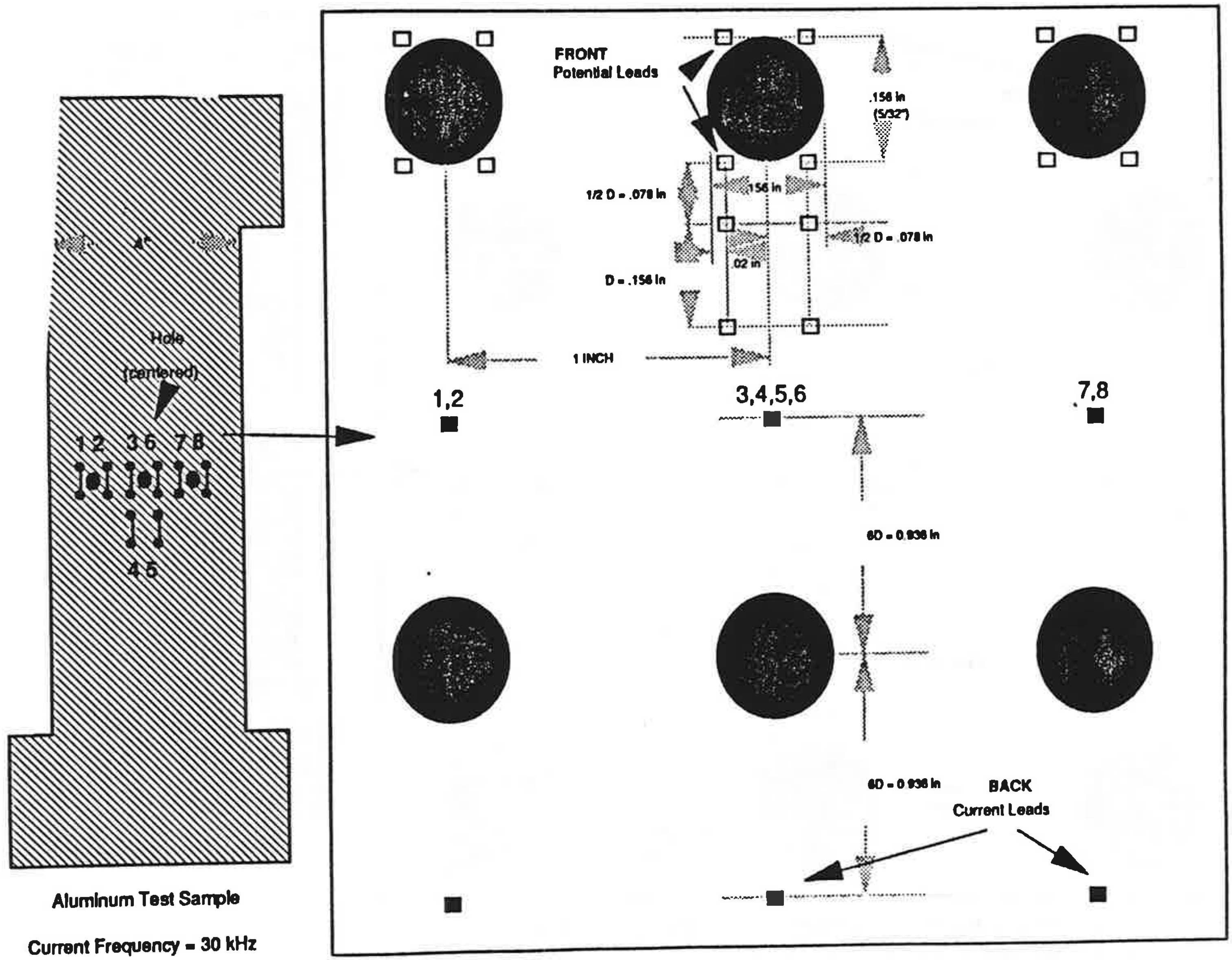
Aluminum Test Sample

Current Frequency = 10 kHz

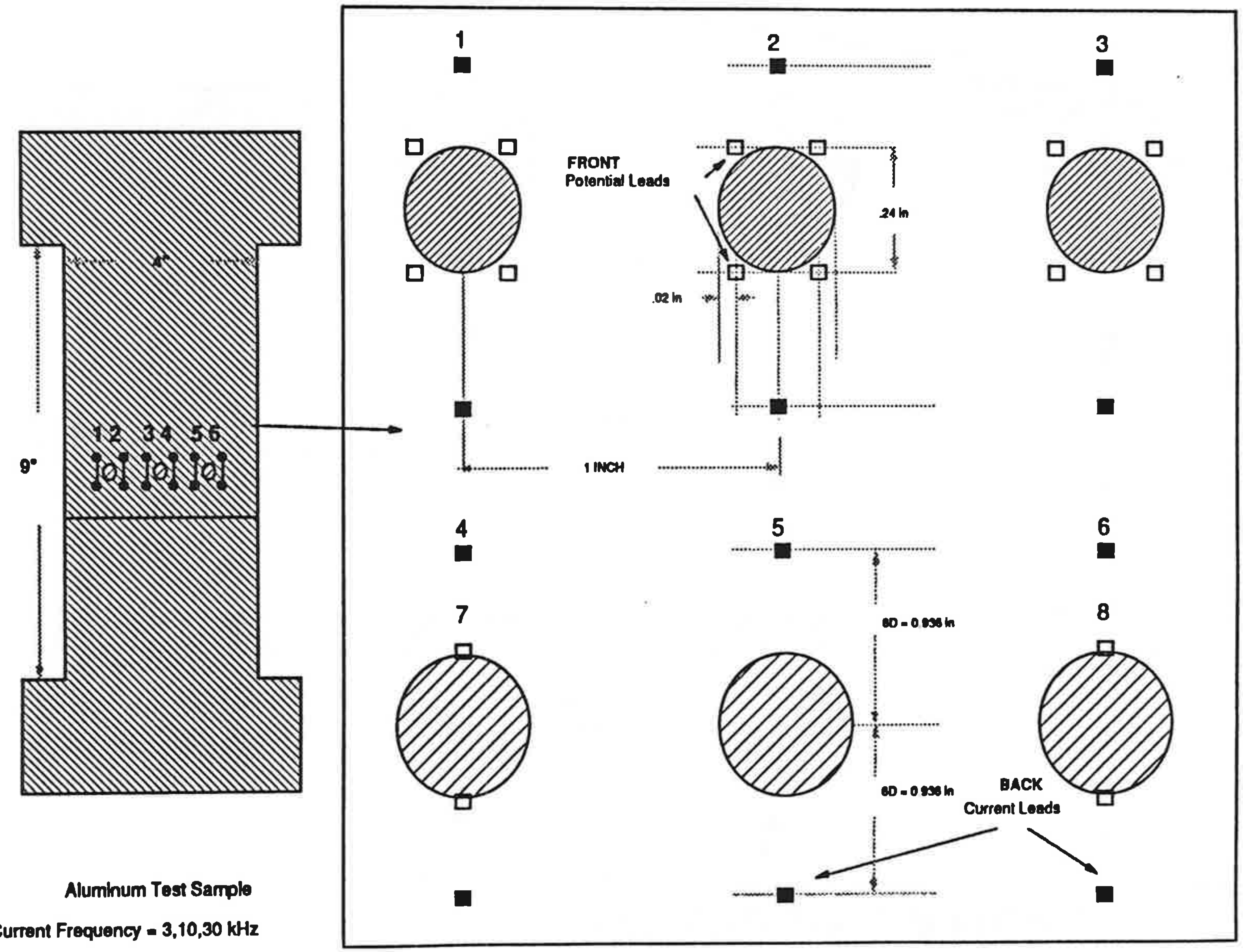
ALH3-5 SPECIFICATIONS



ALH3-6 SPECIFICATIONS



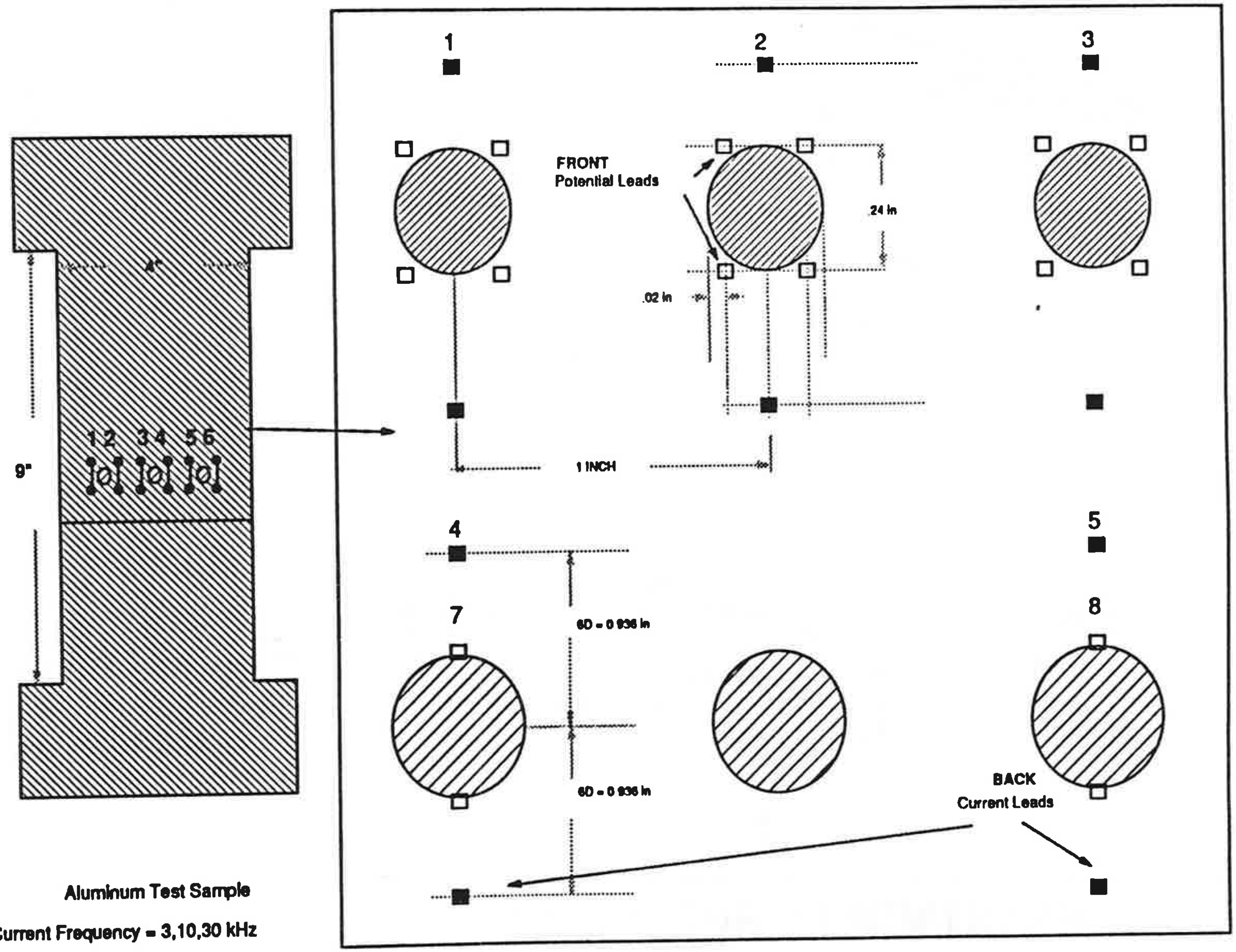
ALR3-1 SPECIFICATIONS



Aluminum Test Sample

Current Frequency = 3,10,30 kHz

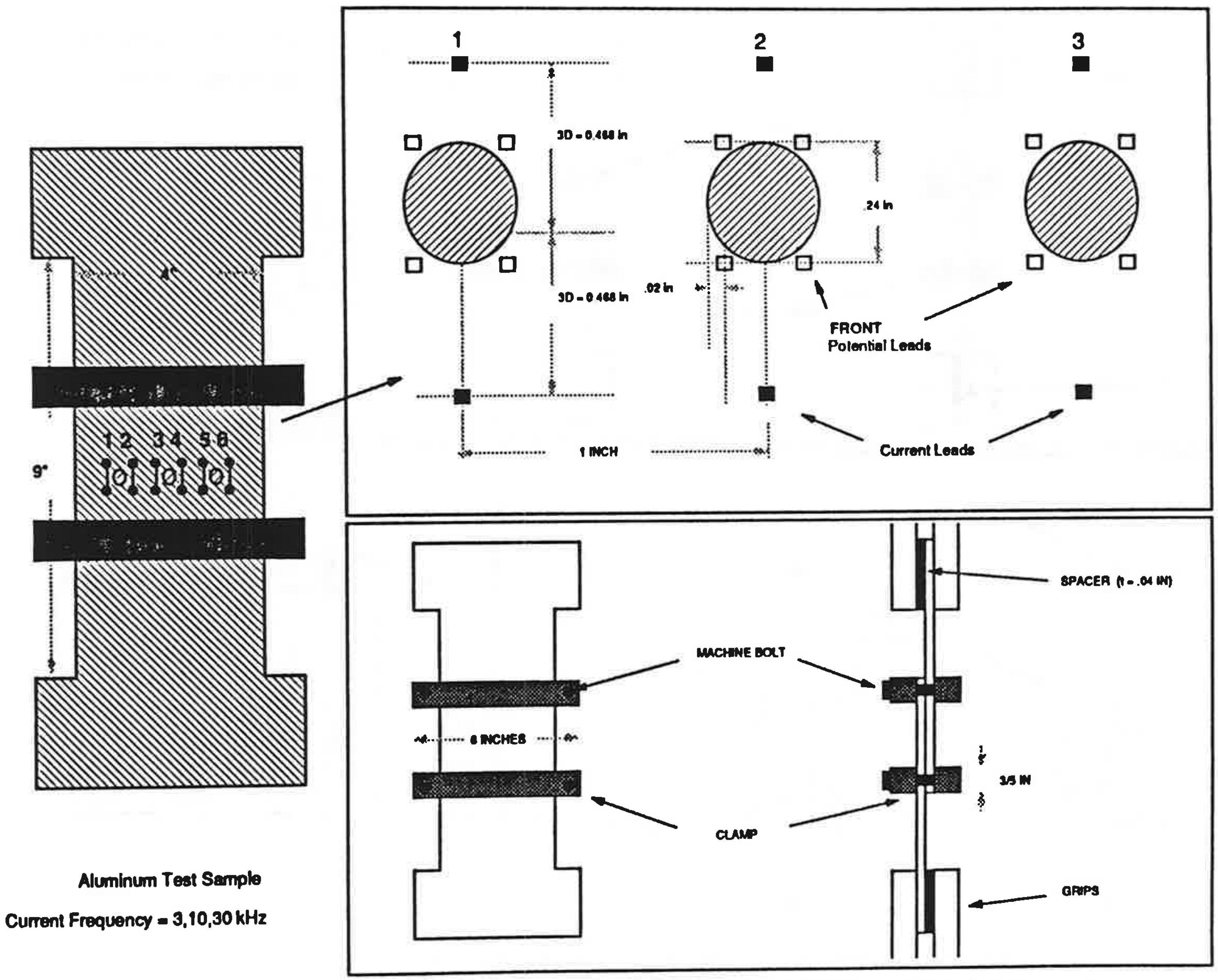
ALR3-2 SPECIFICATIONS



Aluminum Test Sample

Current Frequency = 3,10,30 kHz

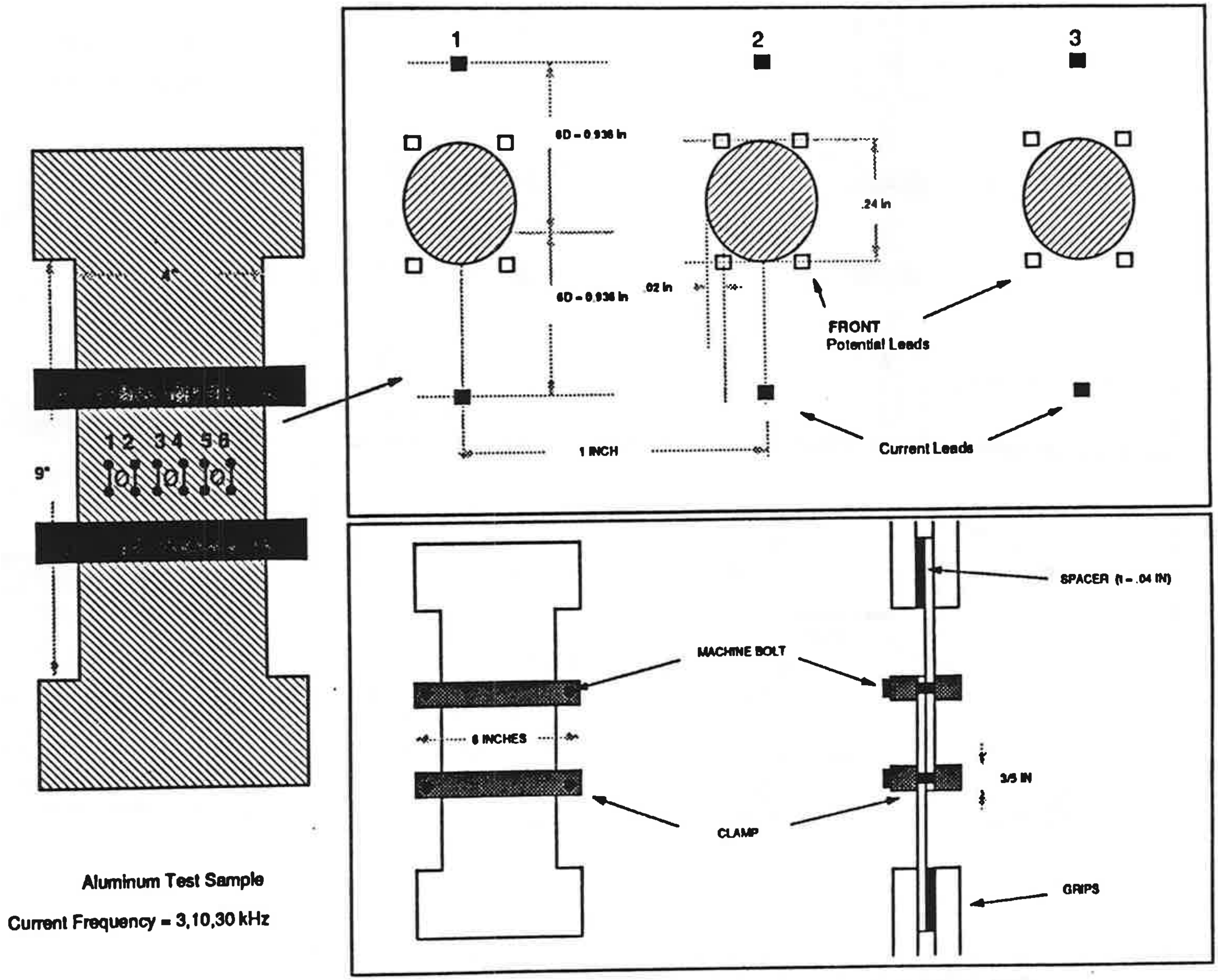
ALR3-3 SPECIFICATIONS



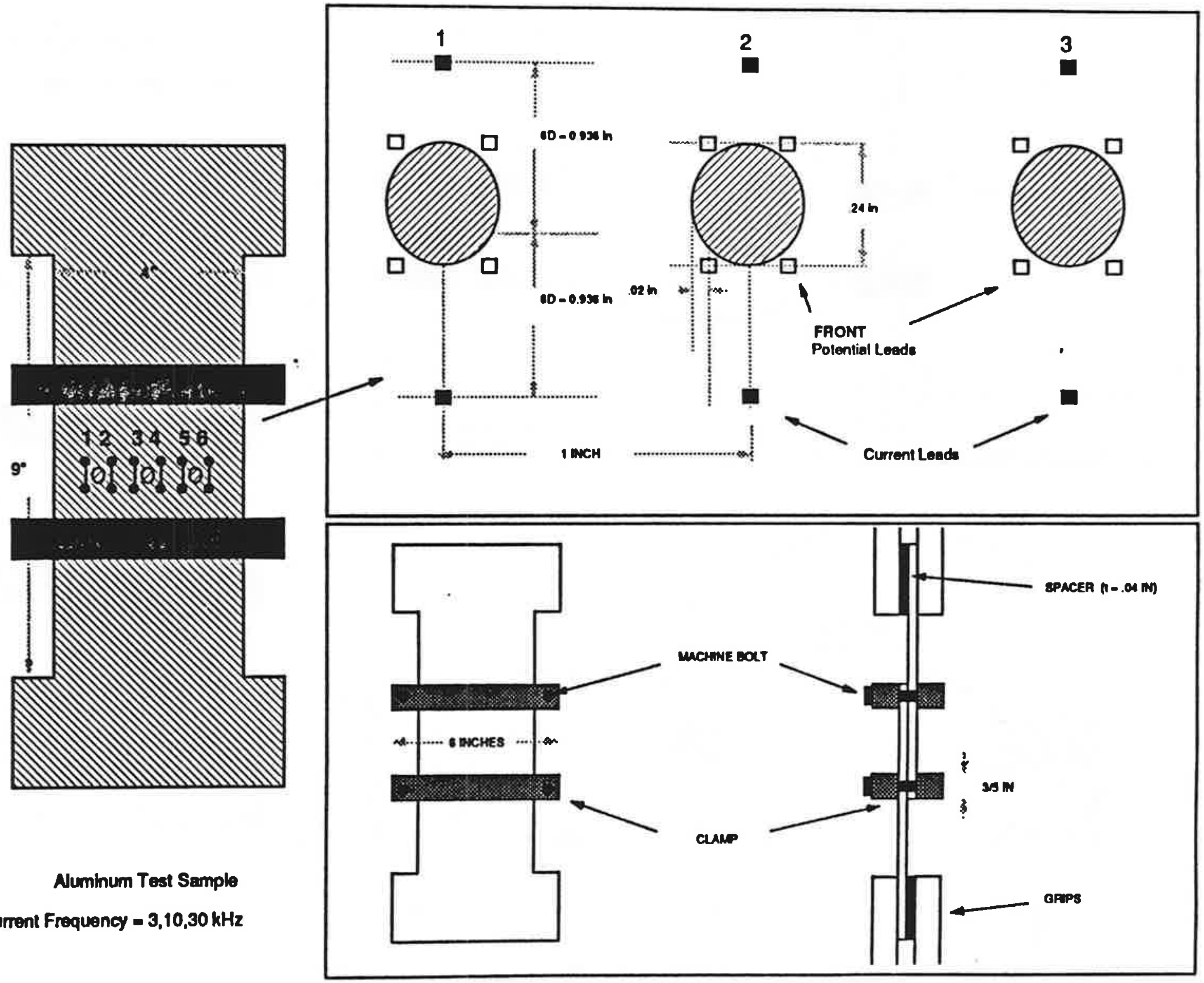
Aluminum Test Sample

Current Frequency = 3,10,30 kHz

ALR3-4 SPECIFICATIONS



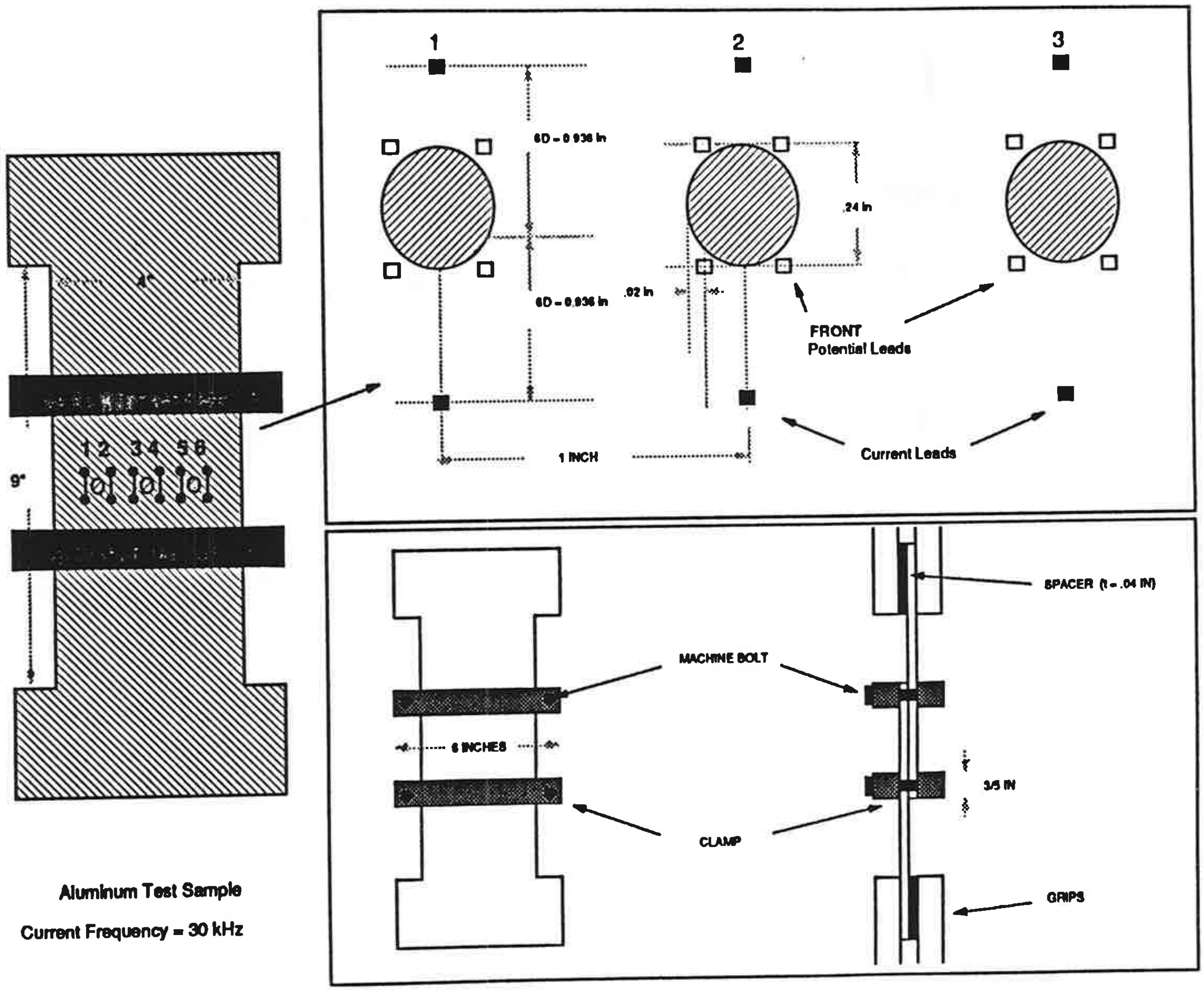
ALR3-7 SPECIFICATIONS



Aluminum Test Sample

Current Frequency = 3,10,30 kHz

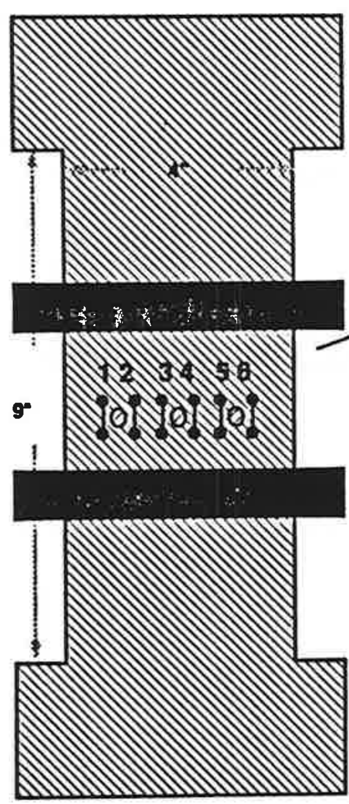
ALR3-8 SPECIFICATIONS



Aluminum Test Sample

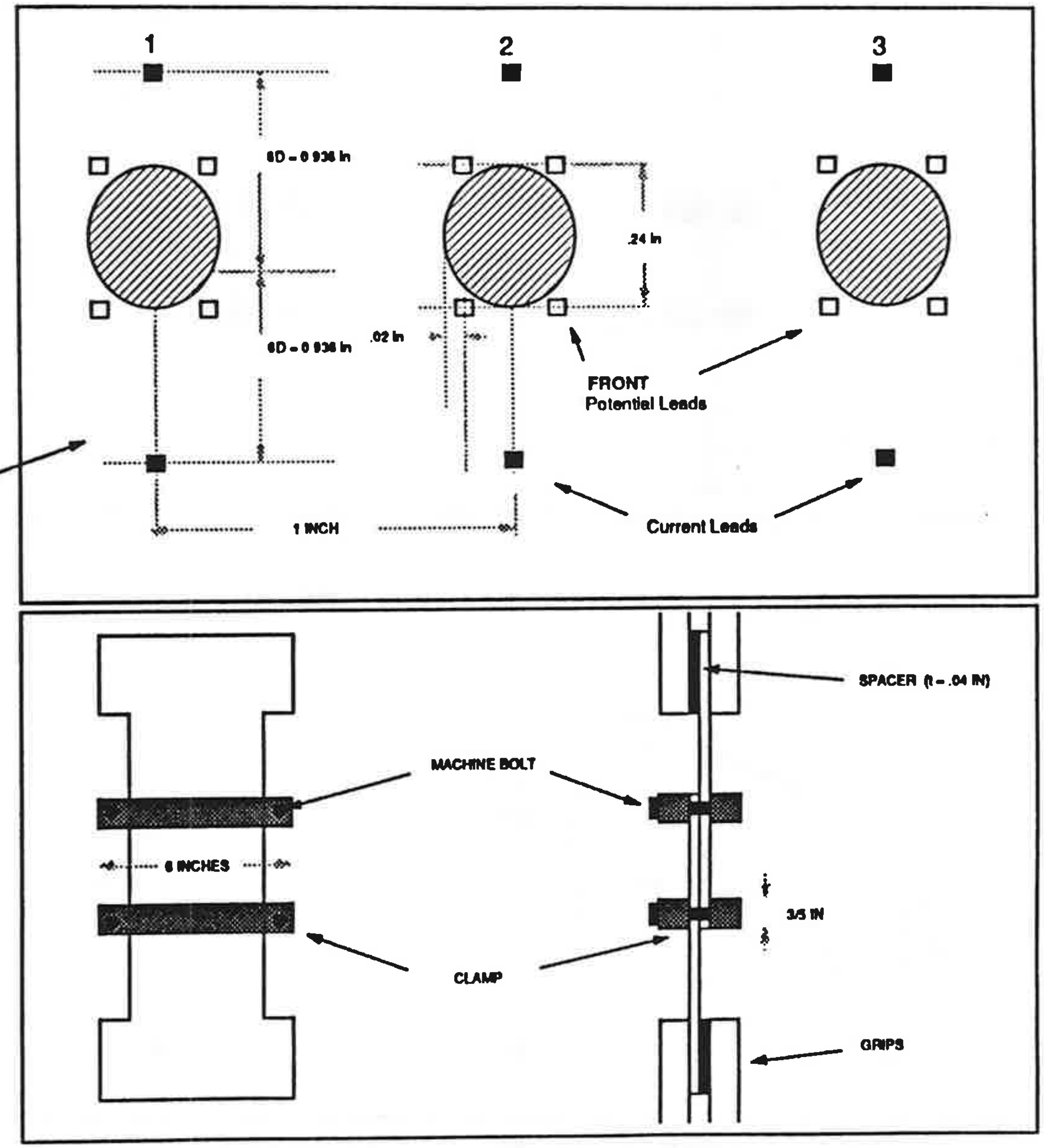
Current Frequency = 30 kHz

ALR3-9 SPECIFICATIONS

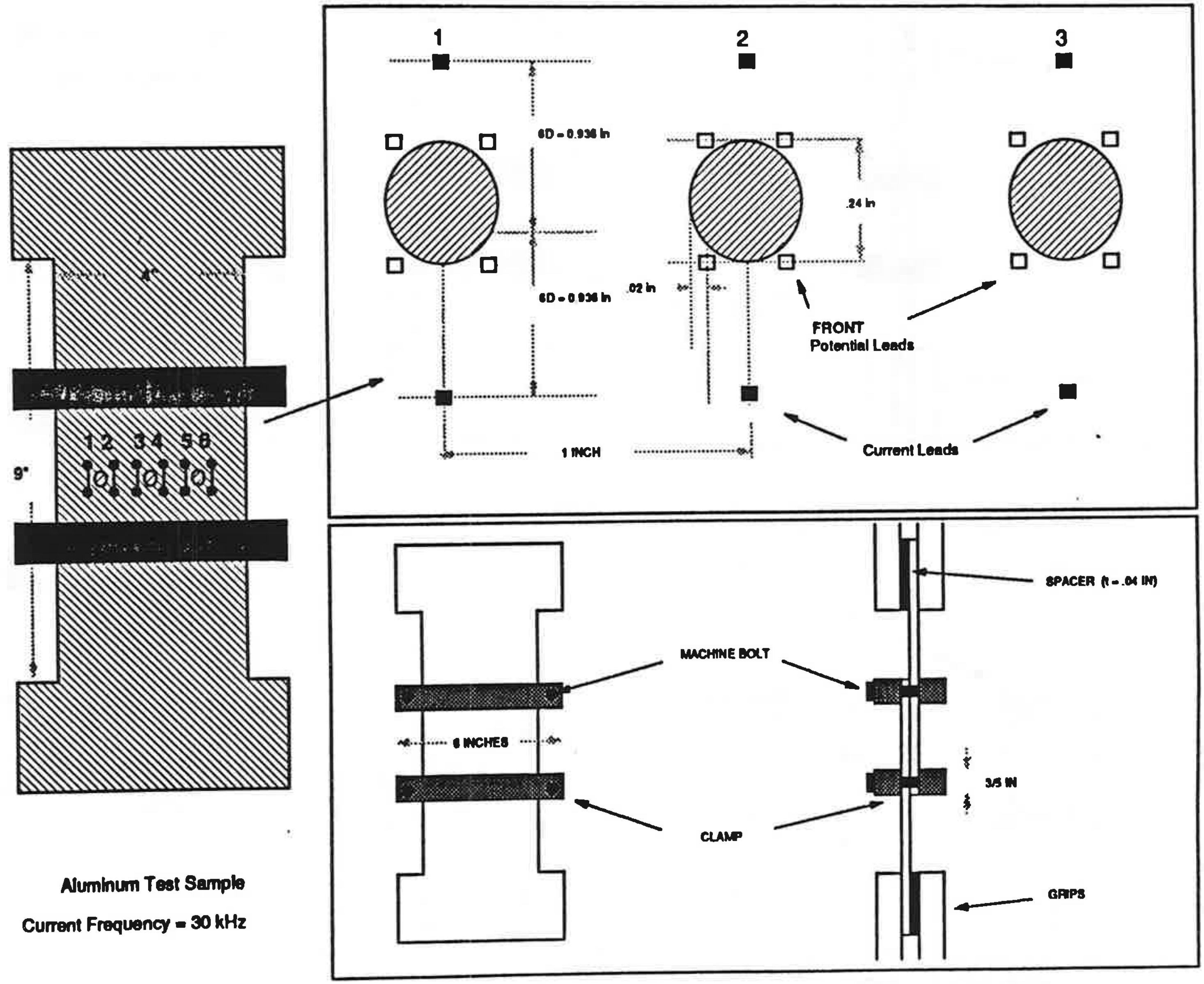


Aluminum Test Sample

Current Frequency = 30 kHz



ALR3-10 SPECIFICATIONS



Aluminum Test Sample

Current Frequency = 30 kHz

APPENDIX C

DERIVATION OF CRACK LENGTH POTENTIAL DROP RATION EQUATION

The crack length can be calculated from the ratio of the potential measured around the cracked section, Pd_{act}, to the potential measured at a reference location below the hole, Pd_{ref}. Let the active and reference leads be a distance of Δ apart. The distance the active potential lead is placed from the edge of the hole is X_{off}. The crack length is calculated from the following equation.

$$a = \frac{\Delta}{2}\left[\cdot\frac{Pd_{act}}{Pd_{ref}} - 2\cdot\left[\frac{\pi}{2} - \mathrm{Sin}^{-1}\left[\frac{\Delta - 2\cdot X_{off}}{\Delta}\right]\right]\right]$$

The derivation of this equation is given below. Refer to Figure C1 for the geometry and symbols used.

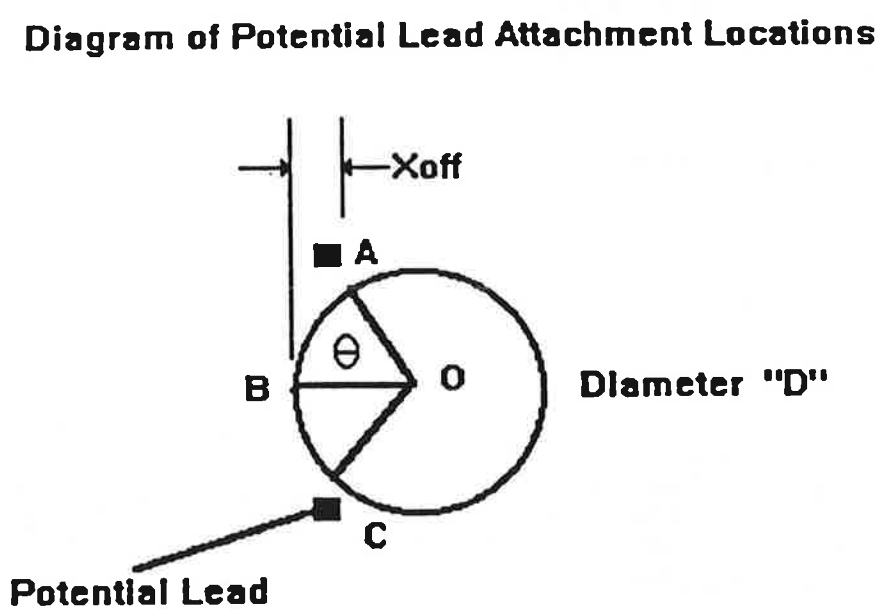


FIGURE C1. GEOMETRY OF POTENTIAL PROBE PLACEMENT AND SYMBOL DEFINITION

$$Arc\ \ AB = \frac{D}{2}\cdot\Theta$$

$$\Theta = \frac{\pi}{2} - \mathrm{Sin}^{-1}\cdot\left[\frac{D-2\cdot X_{off}}{D}\right]$$

In these experiments D = Δ. Therefore the equation for θ reduces to

$$\Theta = \frac{\pi}{2} - \mathrm{Sin}^{-1}\cdot\left[\frac{\Delta-2\cdot X_{off}}{\Delta}\right]$$

Rearranging gives

$$Arc\ \ AB = \frac{\Delta}{2}\cdot\left[\frac{\pi}{2} - \mathrm{Sin}^{-1}\cdot\left[\frac{\Delta-2\cdot X_{off}}{\Delta}\right]\right]$$

The total length the current flows is Arc AC + 2a.

$$\Delta\cdot\left[\frac{\pi}{2} - \mathrm{Sin}^{-1}\cdot\left[\frac{\Delta-2\cdot X_{off}}{\Delta}\right]\right] + 2\cdot a$$

The electrical field is arranged to be uniform in the region of interest. The potential difference, Pd_{ref}, is proportional to the probe length Δ. The potential difference, Pd_{act}, includes the probe length, Arc AC, plus twice the crack length, 2a. The following equation holds:

$$\frac{Pd_{ref}}{\Delta} = \frac{Pd_{act}}{Arc\ AC + 2\cdot a}$$

Substituting in values for this equation gives:

$$\frac{Pd_{ref}}{\Delta} = \frac{Pd_{act}}{\Delta \cdot \left[\frac{\pi}{2} - \mathrm{Sin}^{-1} \cdot \left[\frac{\Delta - 2 \cdot X_{off}}{\Delta} \right] \right] + 2 \cdot a}$$

rearranging gives:

$$\Delta \cdot \frac{Pd_{act}}{Pd_{ref}} = \Delta \cdot \left[\frac{\pi}{2} - \mathrm{Sin}^{-1} \cdot \left[\frac{\Delta - 2 \cdot X_{off}}{\Delta} \right] \right] + 2 \cdot a$$

Solving for 2a:

$$2a = \Delta \cdot \frac{Pd_{act}}{Pd_{ref}} - \Delta \cdot \left[\frac{\pi}{2} - \mathrm{Sin}^{-1} \cdot \left[\frac{\Delta - 2 \cdot X_{off}}{\Delta} \right] \right]$$

Rearranging this equation gives

$$a = \frac{\Delta}{2} \left[\cdot \frac{Pd_{act}}{Pd_{ref}} - 2 \cdot \left[\frac{\pi}{2} - \mathrm{Sin}^{-1} \cdot \left[\frac{\Delta - 2 \cdot X_{off}}{\Delta} \right] \right] \right]$$

REFERENCES

[1] Saxena, A. and Hudak, S., International Journal of Fracture, Vol. 14, Oct. 1978, pp. 453-467.

[2] Jablonski, D., Journet, B., Vecchio, R., and Hertzberg, R., Engineering Fracture Mechanics, Vol. 22, No. 5, 1985, pp. 819-827.

[3] Newby, J. ed., Metals Handbook, Vol. 8, (Mechanical Testing) 9th ed., American Society For Metals, Metals Park, Ohio, pp. 386-391.

[4] Ritchie, R. O., Garrett, G. G., and Knott, J. F., International Journal of Fracture, Vol. 7, 1971, pp. 462-467.

[5] Gibson, G. P. Engineering Fracture Mechanics, Vol. 32, No. 3, 1989, pp 387-401.

[6] Collins, R., Dover, W. D., and Michael, D. H. Nondestructive Testing, Vol. 8, Academic Press, London, U.K., 1985, pp 211-267.