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Technical Report

R 535

RADIO-FREQUENCY SHIELDING
PROVIDED BY BOLTED SEAMS
CONNECTING ARMORED--
PLYWOOD PANELS

June 1967

NAVAL FACILITIES ENGINEERING COMMAND



NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

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RADIO-FREQUENCY SHIELDING PROVIDED BY BOLTED SEAMS CONNECTING ARMORED-PLYWOOD PANELS

Technical Report R-535

Y-F006-09-02-211

by

H. A. Lasitter

ABSTRACT

Rooms shielded against radio-frequency (RF) signals are essential to the Navy's research and development and operational use of equipment sensitive to RF interference. A series of shielding-effectiveness measurements of armor-clad plywood sections representative of those used in the construction of radio-frequency shielded rooms has been conducted. Five sections and their bolted seams were subjected to wet cycles of 70°F, 100% RH and to dry cycles of 200°F, 10% RH. The percent moisture content, thickness variability, DC resistance, and surface currents at 12.8 kHz were observed during the wet-dry cycles. DC surface resistance of the seams increased monotonically throughout the test period. Standard deviation of the surface current measurements reached a peak at approximately 12 days. Another series of tests indicated that seams caulked with silver-loaded compounds had distribution of surface currents similar to those of solid armored sheets.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

CONTENTS

	page
INTRODUCTION	1
DESCRIPTION OF TEST SAMPLES	1
TESTING	4
Humidity Exposure	4
Electrical Resistance	12
Radio-Frequency Skin Currents	14
Effect of Bolt Torque on Distribution of Skin Currents	21
Other Investigations of Surface Currents	27
CONCLUSIONS	28
RECOMMENDATIONS	35
REFERENCES	36
LIST OF SYMBOLS	37

INTRODUCTION

Many manufacturers' types of demountable rooms shielded against electromagnetic radiation are modular and utilize armored-plywood panels mated with bolted metal seams. The greatest difference in available shielded room types is in the design of the metal seams used to secure adjacent panels. The electromagnetic shielding obtained using bolted seams depends largely on the quality of the electrical bond in the seam joining the adjacent armored-plywood panels.

This report covers a study made to determine the effects of controlled exposure to temperature and moisture on the continued quality of the electrical bond between adjacent panels and the bolted seams. The effects of bolt torque on the distribution of surface currents and the use of various schemes to improve the bond between the seam and panel are also reported.

DESCRIPTION OF TEST SAMPLES

Manufacturers of bolted armored-plywood shielded rooms were asked for cut samples of wall and corner seams. Three manufacturers delivered samples suitable for testing in a humid environment. Samples from these three manufacturers are considered typical of bolted armored-plywood construction.

Five sample wall and corner sections (Figures 1 and 2) were exposed in a controlled-humidity chamber for periods of from 1 to 30 days at 100% relative humidity (RH). The three corner sections and two wall sections were cut to size (18x12 inches) to fit the available drying oven. Each sample was fitted with a bolted seam that was typically used by the manufacturer to fasten sections of the paneling together. Each section was made of 5-ply Douglas-fir plywood (3/4 inch thick) bonded on two sides with 24-mil zinc-coated steel sheet metal. All of the seam samples made use of pairs of steel strips (1/8 to 3/16 inch thick). The seams consisted of a cover and backing seam plate bolted together at 3- to 4-inch intervals. The cover and backing plates under spring tension firmly clamped both edges of the panel to be joined. Copper tabs were soldered to the edges of the samples to provide the low-resistance connections which were used in measurements of the DC resistance and surface currents.

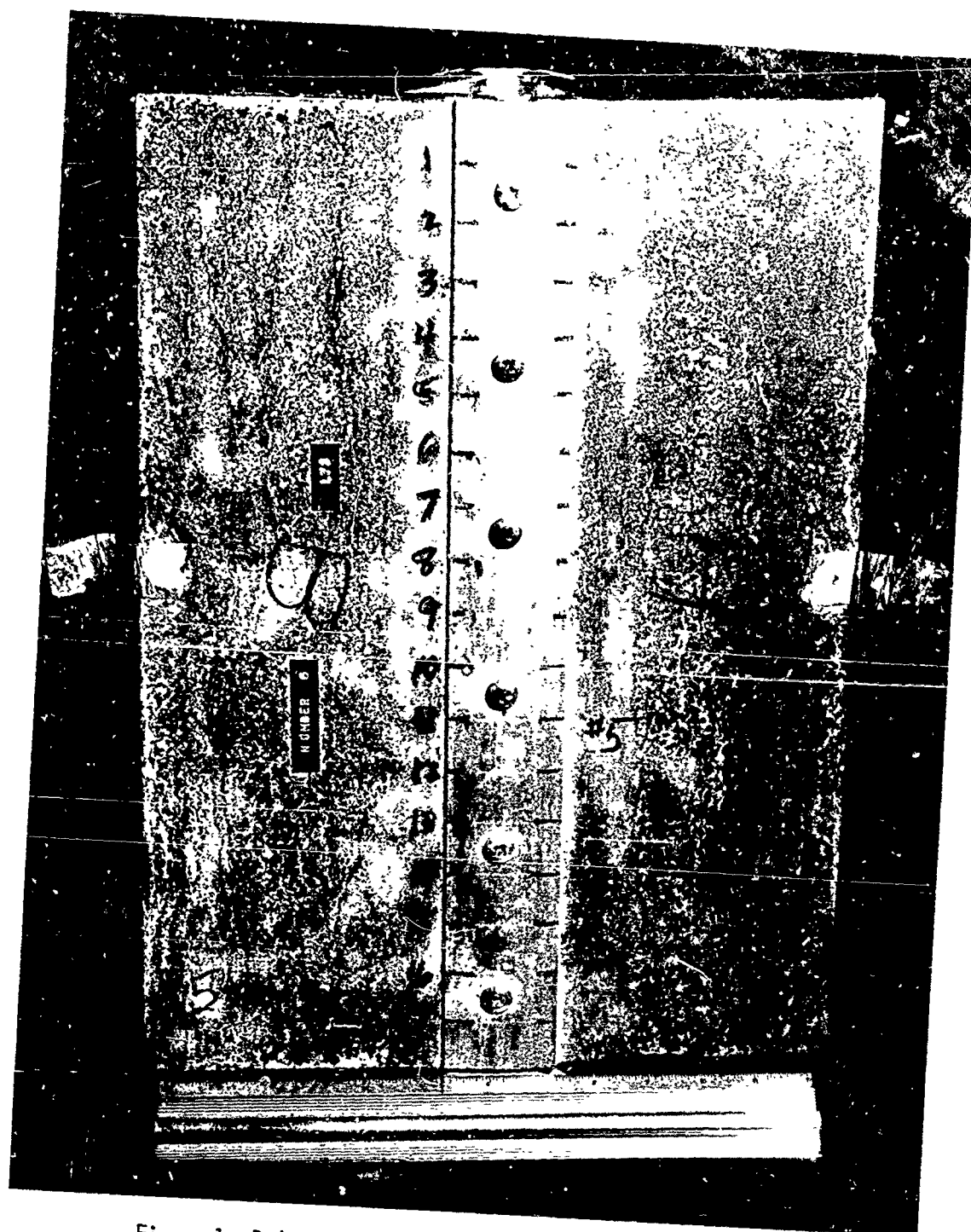


Figure 1. Bolted seam of flat armored-plywood test panels.

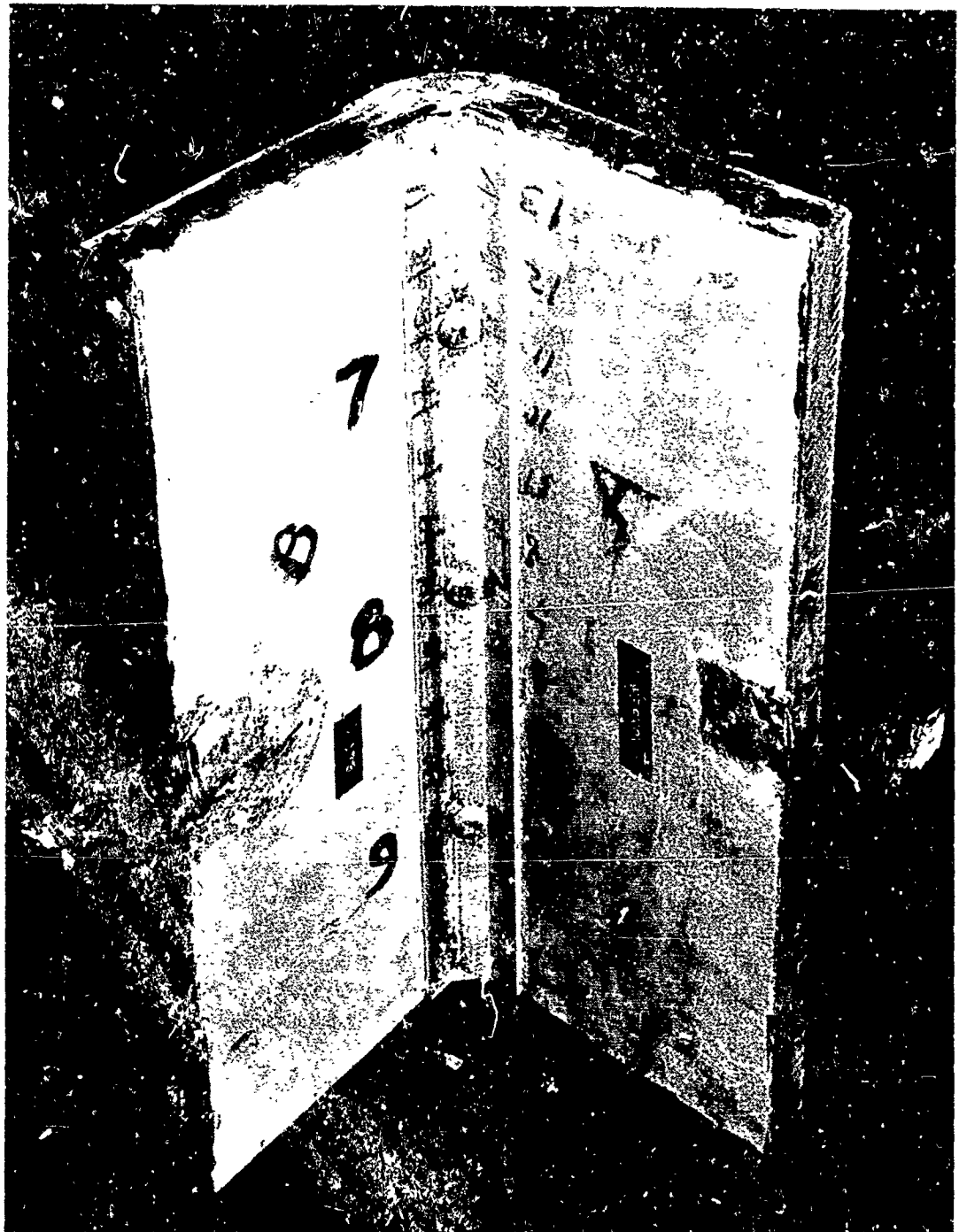


Figure 2. Bolted seam of corner test section.

TESTING

Humidity Exposure

Since untreated wood shrinks or expands noticeably when subjected to variable humidity and temperature, it is important to determine the extent of these dimensional variations in the wood of a bolted seam that holds armored-plywood panels together. Coast-type Douglas-fir plywood shrinks 7.8% parallel to the grain when dried from green wood to zero percent moisture content. It also shrinks approximately 5% transverse to the grain under the same circumstances.¹ The transverse shrinkage during dry cycles is of greatest interest in this study since this results in a change in the thickness of the plywood and tends to loosen the bolted seams.

In a humid environment, wood will give up or take in moisture from the surrounding atmosphere until the moisture in the wood is in equilibrium with that in the atmosphere. This equilibrium moisture content (M), expressed as a percentage of the oven-dry weight of the wood, can be derived by the equation $M = 100(W_c - W_o)/W_o$, where W_c is the weight of the cut wood sample before drying, and W_o is the oven-dry weight. Curves for moisture absorption and loss by the samples are shown in Figure 3. Each sample exhibits approximately the same rate of moisture absorption as evidenced by the similar shapes of the curves. This is particularly true at the beginning of the exposure period (between the 1st and 11th days), when there is a linear, constant-slope increase in weight. At the end of 11 days, the rate of moisture absorption dropped to about one-half the initial rate, and moisture absorption continued at a lower constant rate for the next 17 days. During the 100% RH exposure period, none of the samples reached a saturated state. Saturation occurs at about 30% moisture content (when the wood becomes water logged), since only slight swelling takes place after this point is reached.^{2,3} The maximum moisture content observed (16.9%) was for one of the flat wall panels.

Since in an actual installation only the edges of the plywood underneath the clamps would be exposed to a changing environment, the penetration of moisture was limited to the exposed edges of the measured samples underneath the clamped seams. The outside cut edges of the samples were coated with glyptol to inhibit moisture penetration. The locations of the coated and uncoated edges of the sample are shown in Figure 4.

At the completion of the 100% RH, 73°F exposure tests, the samples were dried for 18 hours at an accelerated rate. The resulting changes in moisture content are shown in Figure 3. The samples were dried by placing them in an oven heated to 200°F; they were weighed to determine moisture content at 1, 2, and 18 hours during the drying cycle. Two of the flat wall sections shrank until they could easily be pulled out of the seam. (The initial torque on each of the seam bolts was between 60 and 70 inch-pounds.) The shrinkage in the wood was 0.034 inch as determined by a series of measurements of average thickness during dryout of the samples (Figure 5).

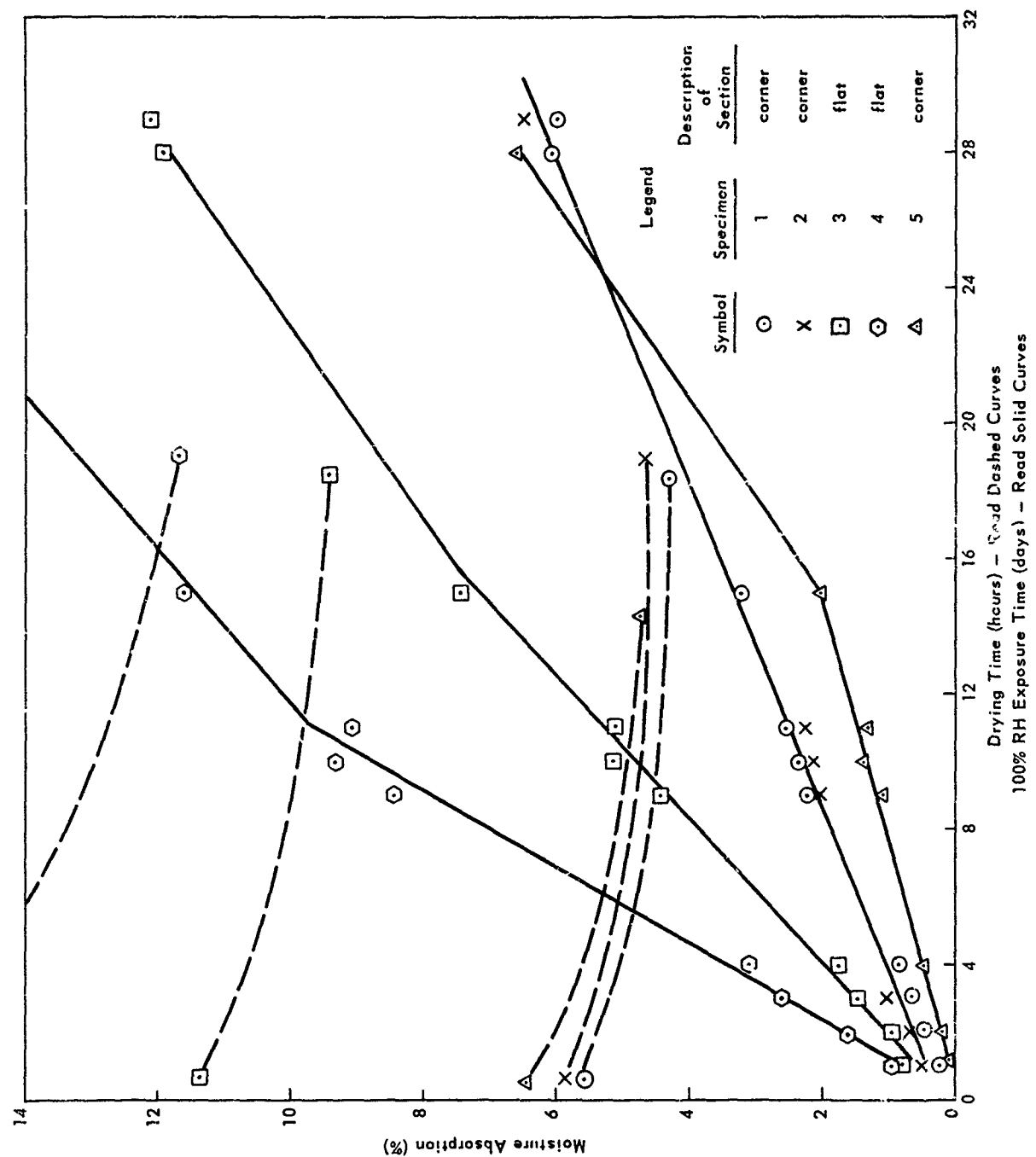


Figure 3. Moisture absorption or loss by test panels exposed to wet-dry cycles.

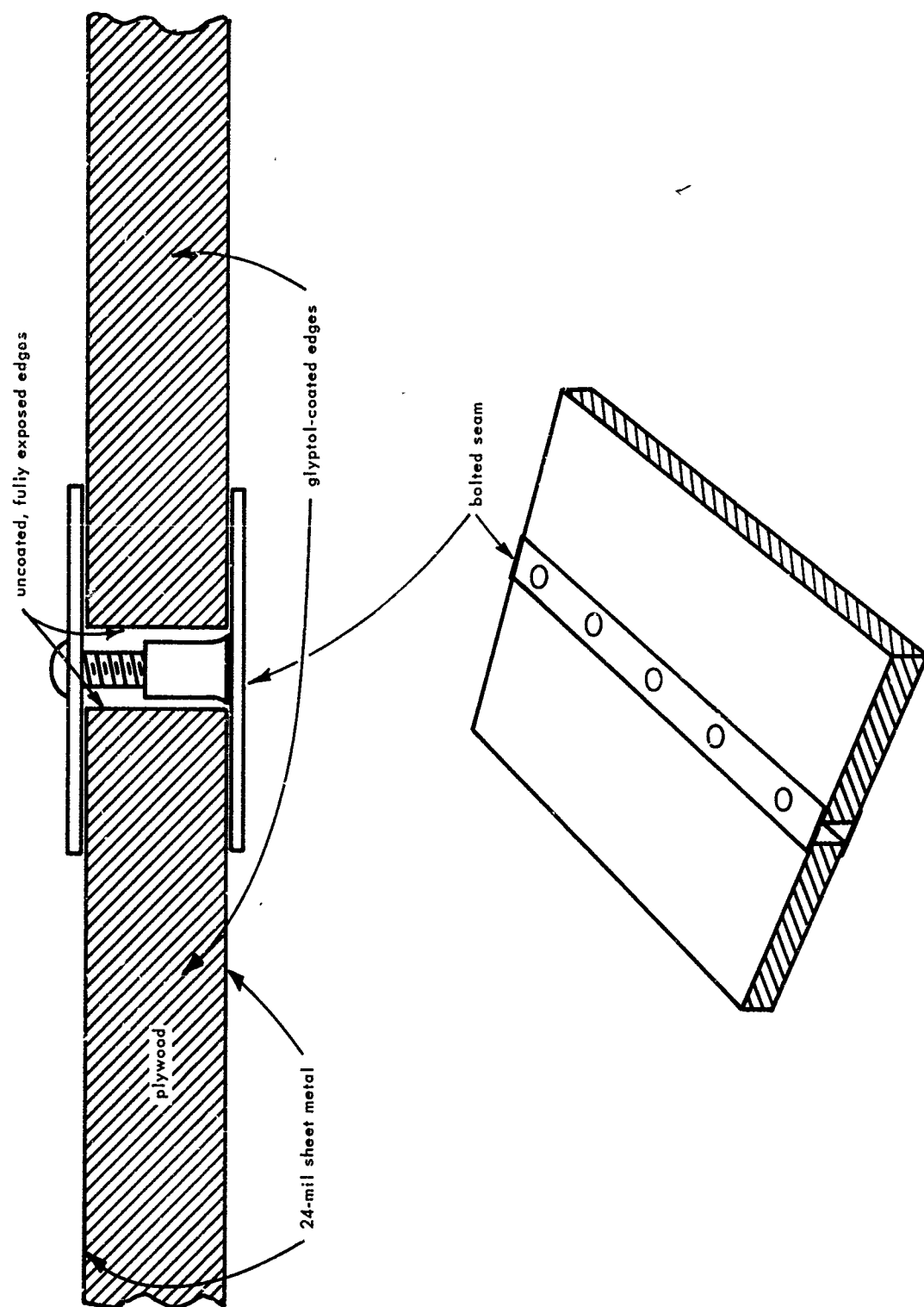


Figure 4. Cross section and isometric views of bolted flat armored-plywood panels.

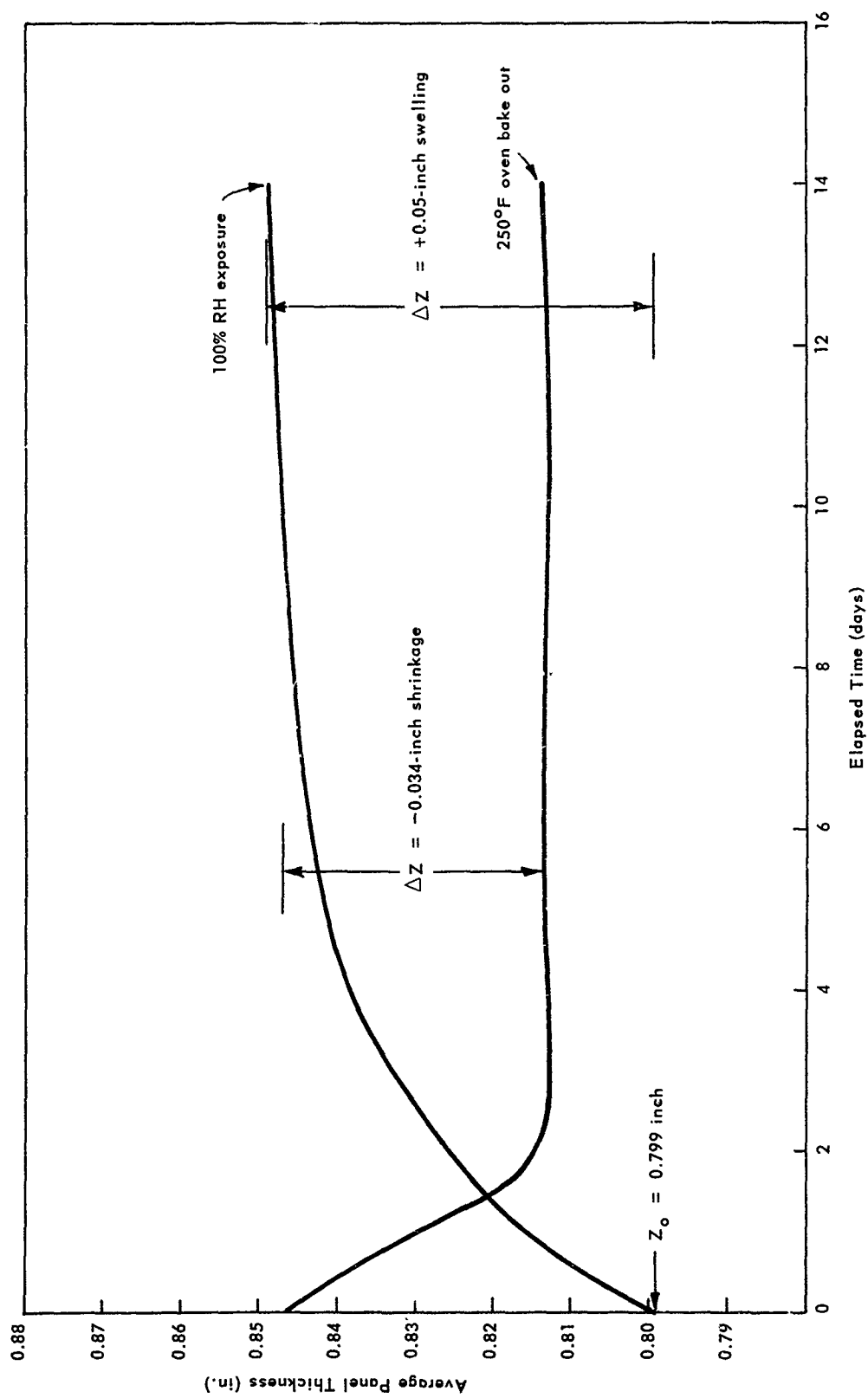


Figure 5. Shrinking and swelling of armored-plywood panels exposed to wet-dry cycles.

The differential equation describing the relationship between thickness Z and percent moisture content M is ^{2,4}

$$\frac{dZ}{dM} = K - JZ \quad (1)$$

where K and J are constants to be determined from experimental observations. The solution to this equation is straightforward,⁵ and is similar to that describing a capacitor charging up to an electrical potential. Evaluation of the constants is based on three points obtained from the experimental data. The expression for the solution to Equation 1 with constants evaluated is

$$Z = 0.85 - 0.0372e^{-0.4852M} \quad (2)$$

This theoretical curve is plotted in Figure 6 and shows a good fit to the measured data. The 0.799-inch sample swelled rapidly during the initial portion of the wet exposure period and then approached a maximum thickness of 0.85 inch asymptotically (Figure 5). This change in thickness occurred during the first 12 days of exposure. During the dryout period, the rate of shrinkage was quite rapid (the linear rate was 17 mils per day), but quickly reached a constant value after 2 days. The weight and dimensional changes experienced by the samples caused rather extensive deterioration of the edges of the samples after the end of the wet and dry tests. This deterioration was characterized by splitting of the plywood and a general pulling away of the sheet metal from the wood. Figures 7 and 8 show these effects on the edges of the panels.

In addition to determining moisture-content changes and dimensional changes, it was felt that another quantity, the moisture gradient, would be useful in determining how far from an exposed edge the moisture actually penetrates the armored plywood. Therefore, the moisture penetration in an armored-plywood panel (42 x 144 inches) which had been immersed in water for about 6 months was measured. At each of 17 positions on the panel the moisture content was determined at four depths in the wood: 1/2 inch, 5/8 inch, 3/4 inch, and 7/8 inch. Since the moisture content measured showed no dependence on depth, moisture content was determined at an average depth (0.6875 inch) along parallel lines 6 and 12 inches from one edge of a panel (Figure 9). Measurements were made with a commercial moisture meter designed for measuring wood moisture by means of a variable depth probe. Holes were drilled in the sheet metal covering to provide access to the plywood for probing. As plotted in Figure 9, near the edge of the panel the moisture gradient is linear with a slope of 0.35% per inch. The moisture content reaches a minimum value of approximately 13.5% at the center of the panel. The slopes of the curves are almost equal at 6 and 12 inches from the edge of the panel, indicating that the rate of penetration is almost uniform along the edge of the panel. Water immersion probably represents by far the worst possible case for moisture absorption.

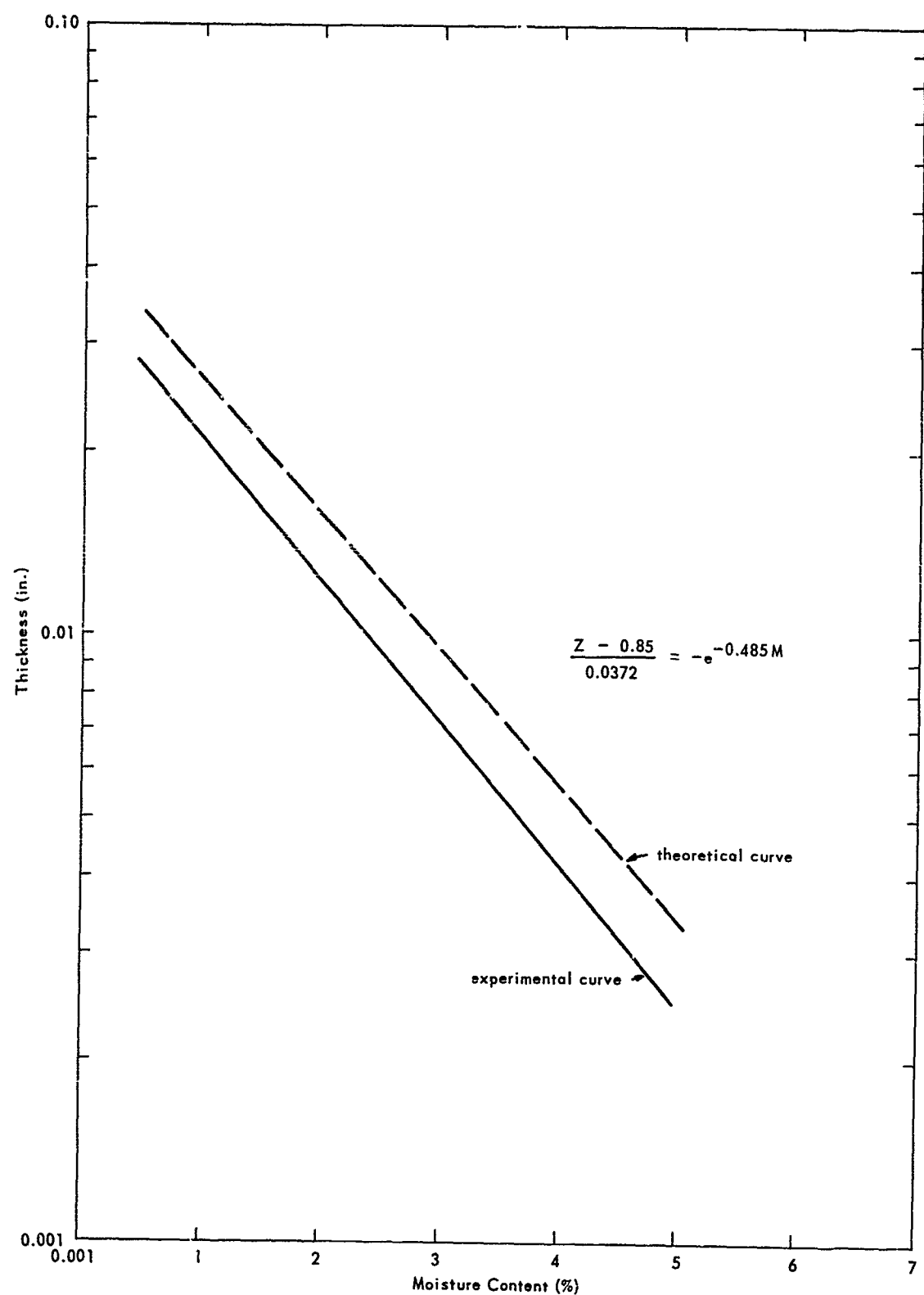


Figure 6. Experimental and theoretical thickness of armored-plywood panels versus percent moisture content.

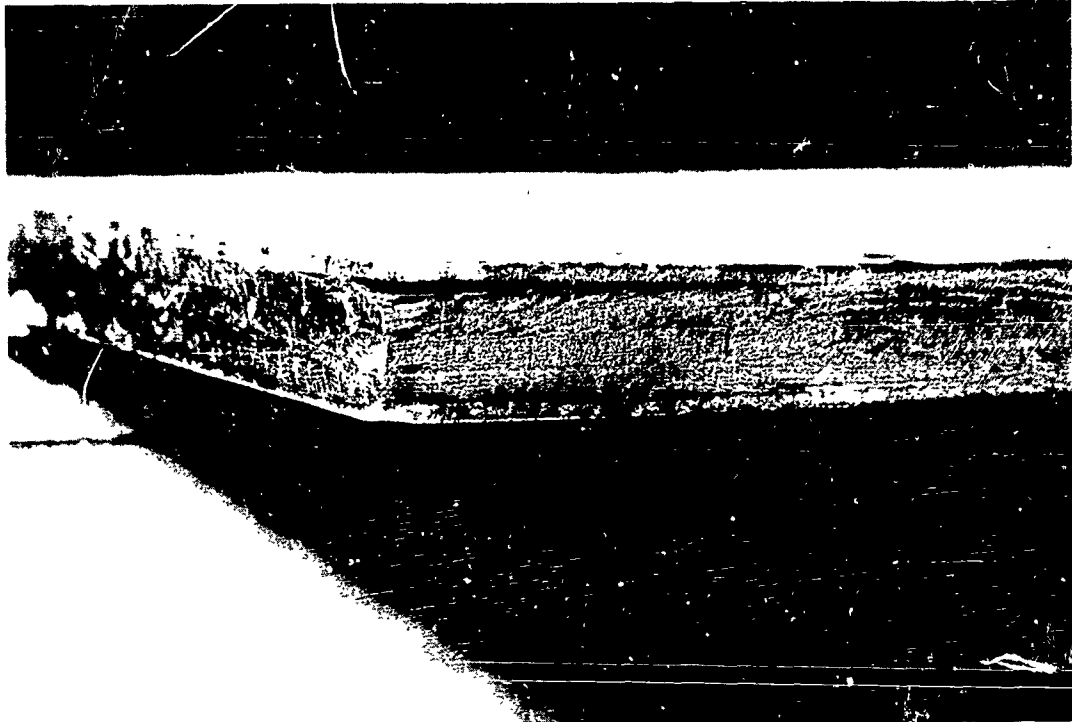


Figure 7. Deterioration of panel edge after dry cycle.

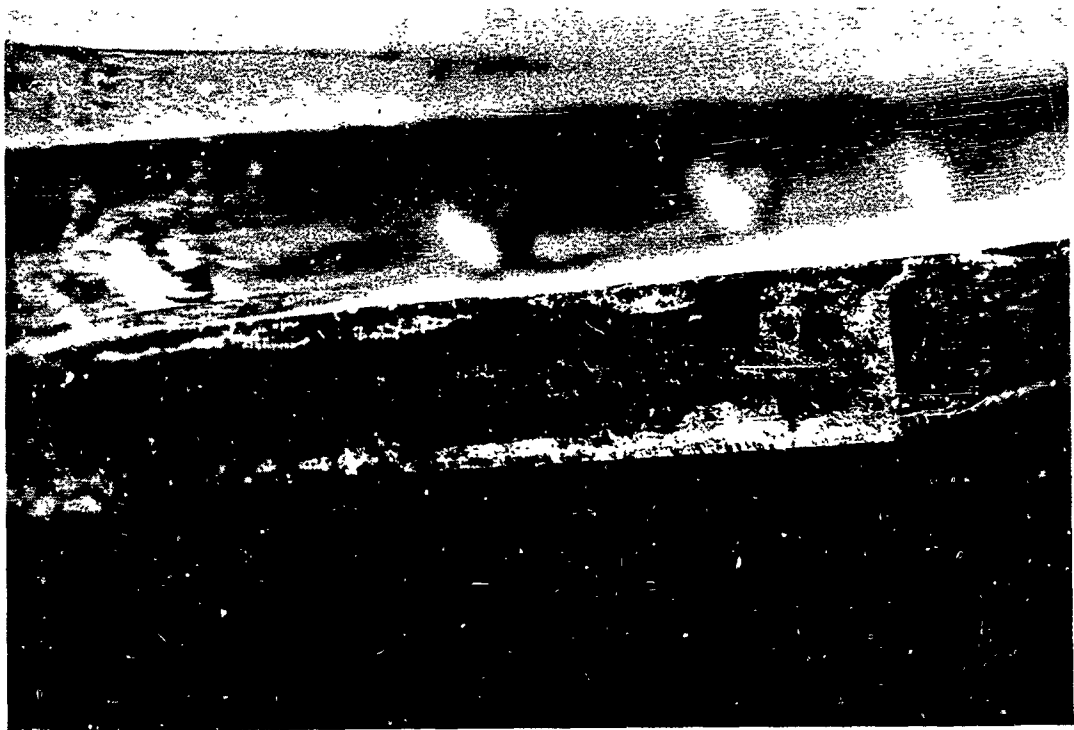


Figure 8. Deterioration of panel edge during 100% RH cycle.

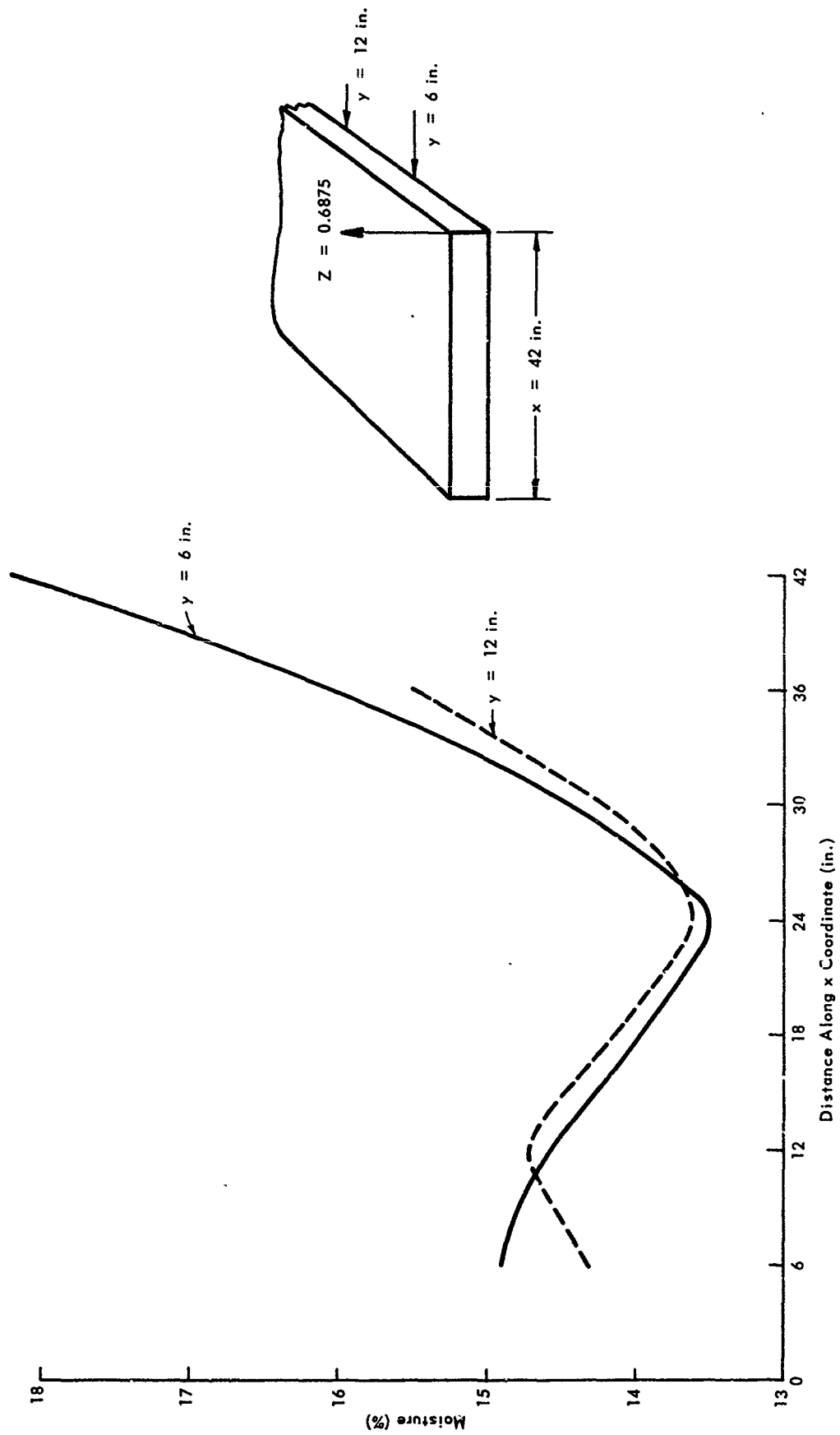


Figure 9. Measured moisture penetration in armored-plywood panel.

In considering the results of moisture absorption tests, there are several points that should be kept in mind. The rate of moisture absorption will vary widely, depending on relative humidity, temperature, air currents circulating around or near the panel, and the pressure applied near the panel edges by the bolted seam plates. Absorption will be greatest, of course, when the exposed edge is constantly wet so that the wood fibers adjacent to the edge of the panel have a constant source of moisture.

Electrical Resistance

During the same period that moisture absorption tests were being made on the samples, a series of electrical resistance and surface current tests were also made.

The setup used to determine DC resistance of the sample is shown in Figure 10. A direct current is passed through the sample transverse to and through the bolted seam section. The resulting voltage drop is measured across the sample. The ratio of voltage to current then determines the resistance of the sample. Current is measured using an ammeter with calibrated shunts (1% full-scale accuracy). Voltage is measured using a null-type potentiometer voltmeter with high impedance input. Use of this type of measurement (i.e., making a four-terminal resistor of the sample) and an accurate ammeter as well as a high impedance voltmeter gave the accuracy needed for measurement of DC resistance ranging from 0.7 to 70 m Ω . A continuous record of resistance with time obtained during the wet and dry cycles is plotted in Figure 11.

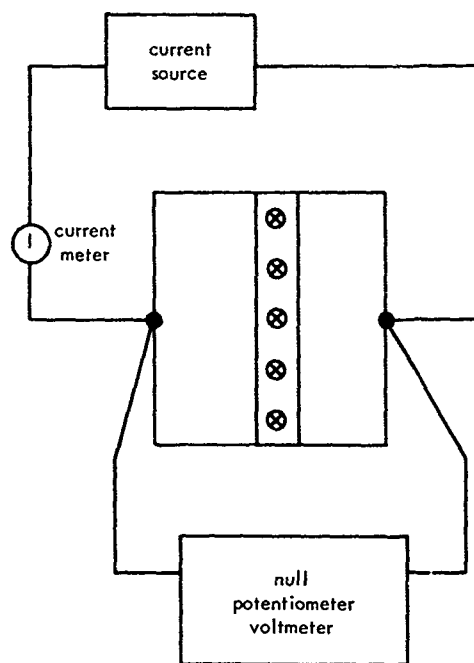


Figure 10. Diagram of equipment setup for measurement of direct current resistance in armored-plywood panels.

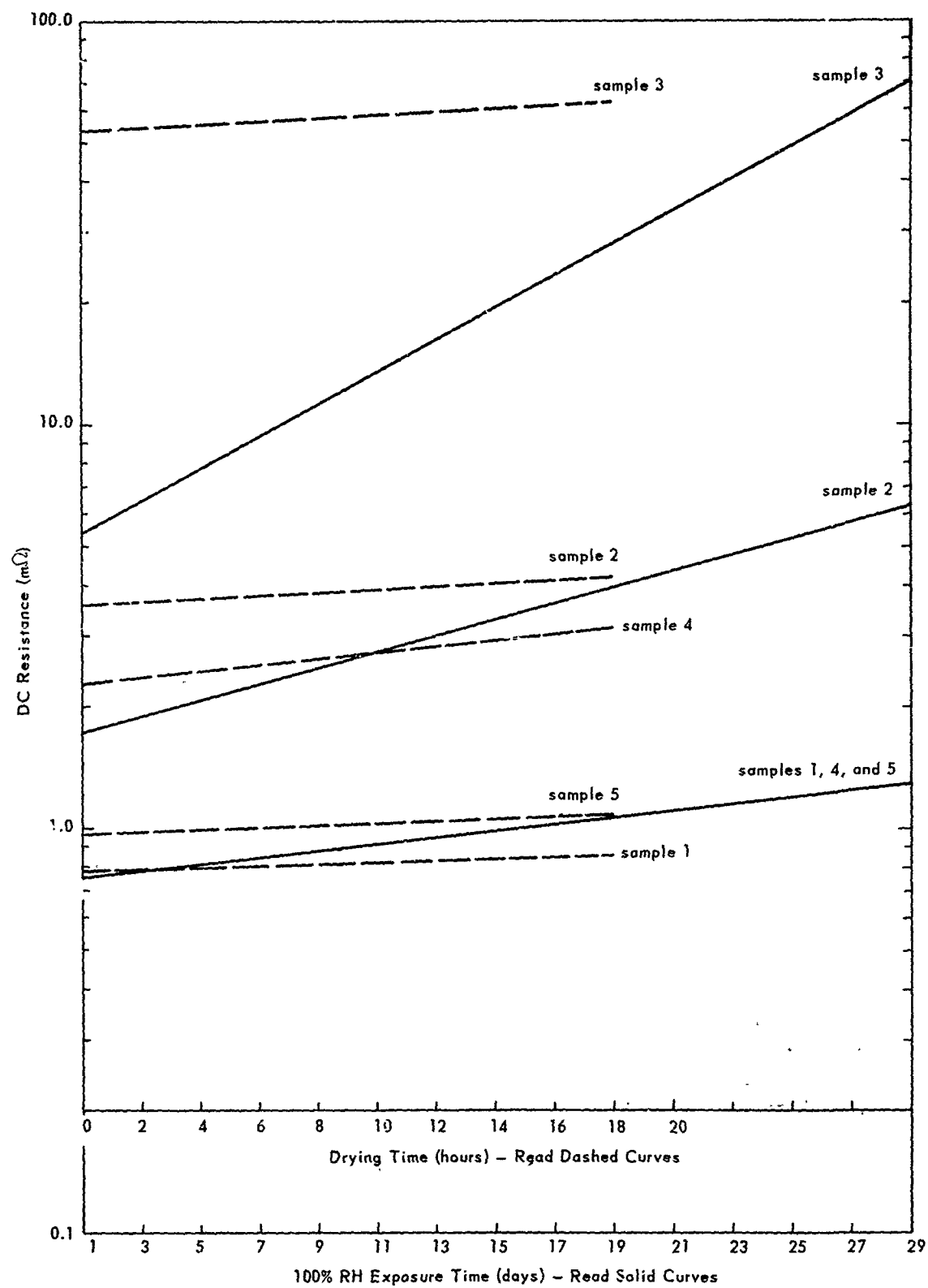


Figure 11. DC resistance of samples versus exposure and drying time.

The resistance of the samples increased with greater exposure to 100% RH (Figure 11), even though the clamping force increased due to expansion of the plywood. The resistance did not decrease as a result of the drying cycle. Examination of the metallic surface underneath the seam clamps at the conclusion of the tests indicated that a metallic oxide had formed which could be removed by mechanical means (hand rubbing with steel wool or wire-wheel buffing). This would indicate that the ultimate resistance of the seam will depend on the amount or continuity of the clean metal-to-metal bonding surfaces in contact under the seam.

Radio-Frequency Skin Currents

The distribution of radio-frequency currents induced in a metallic sheet depends on the electrical properties and physical configuration of the sheet. Current lines formed along the surface can be mapped with a multiturn loop probe to sense the magnetic field generated by these lines.⁶ The mapping of induced currents in the skin of shielded rooms has formed the basis for devices and techniques used to search the room for small cracks and imperfections along seams of the room.⁷ Discontinuities in the metal skin of the shielded room distort the distribution of the induced current and give rise to local variations in the magnetic field strength as sensed by the magnetic probe. By mapping the magnetic field measured along a seam connecting any two panels of a bolted armored-plywood shielded room, an indication of the location of RF leaks can be made. The voltage V developed by a current probe of inductance L sensing such a current distribution along the x axis is^{8, 9}

$$V = L \frac{di_z}{dt} = j2\pi f L i_z \quad (3)$$

where i_z is the desired distribution of current, t is time, j is $\sqrt{-1}$, f is frequency, and $2\pi f L$ is a proportionality factor. The magnitude of the voltage will be

$$|V| = 2\pi f L |i_z| \quad (4)$$

An empirical relationship for the observed distribution of current along each of the seams has been developed. Graphical analysis indicates that distribution of current is exponentially related to distance along the seam. A fit of the experimental data is obtained by consideration of the function

$$i_z = i_o e^{-\left(\frac{x_o - x}{k}\right)} \quad (5)$$

where i_0 is the initial current at position x_0 , x is the position at any point on the sheet, and k is an arbitrary constant to be determined. The value of k is found to be 0.05856, based on $x_0 = 0.229$, $i_z/i_0 = 0.0199$, and $x = 0$. The final form of Equation 5 is rewritten as

$$\frac{i_z}{i_0} = 0.0199 e^{17.07x} \quad (6)$$

The theoretical values are compared with experimental data in Figure 12.

The characteristics of the sensing probe proved to be a determining factor in selecting the test frequency. The frequency response of the probe used is shown in Figure 13. The resonant frequency is 12.6 kHz and the Q is calculated as 28.46. The proportionality constant $2\pi fL$ directly relates the voltage developed across the sensing probe described by Equation 4 to the distribution of current. The measured value of L is 800 μH , and at a frequency of 12.6 kHz, the constant $2\pi fL$ (inductive reactance) is 63.3 ohms. This calculation has assumed that losses in the probe are negligible. Although the response of the probe is down more than 20 db at 20 kHz, other parameters (signal levels and meter sensitivity) permitted its use at a frequency as high as 20 kHz.

Another important requirement for using the probe at frequencies other than at resonance is to know the transfer impedance over a wide frequency range (Figure 14). The impedance at resonance (12.6 kHz) is on the order of 1 ohm, and falls to 5.6 $\text{m}\Omega$ at 100 kHz and 1 $\text{m}\Omega$ at 430 Hz.

A diagram of the equipment used to determine the current distribution along surfaces of various samples is shown in Figure 15. A current is passed through the test sample from the signal source and amplified by coupling through a standard RF current probe modified by the addition of low-resistance secondary turns. This modification makes the probe a matching transformer. This driving probe was used between the amplifier and sample to obtain a more satisfactory impedance match to the low-impedance sample so that greater power could be delivered to the sample. The turns ratio of the matching transformer was 10:1. The current into the primary winding and the voltage across the primary of the driving probe were monitored continuously by means of the two high impedance voltmeters shown in Figure 15. These readings indicated the rms value of current and voltage. The real power delivered to the probe and test sample was calculated using a measurement of the phase shift between the voltage and current. Since the phase shift is relatively constant for given circuit conditions, only one measurement of this quantity was made and the power P was computed using the equation $P = |I||V|\cos\theta$, where θ is the phase shift. For most samples the power delivered to the probe was 9 watts. The efficiency of the probe is on the order of 10% at the test frequency so that 0.9 watt was available at the sample. Since the resistance of the samples varied from 1 to 100 $\text{m}\Omega$ (see Figure 11), the current through these samples varied between 30 and 3 amperes.

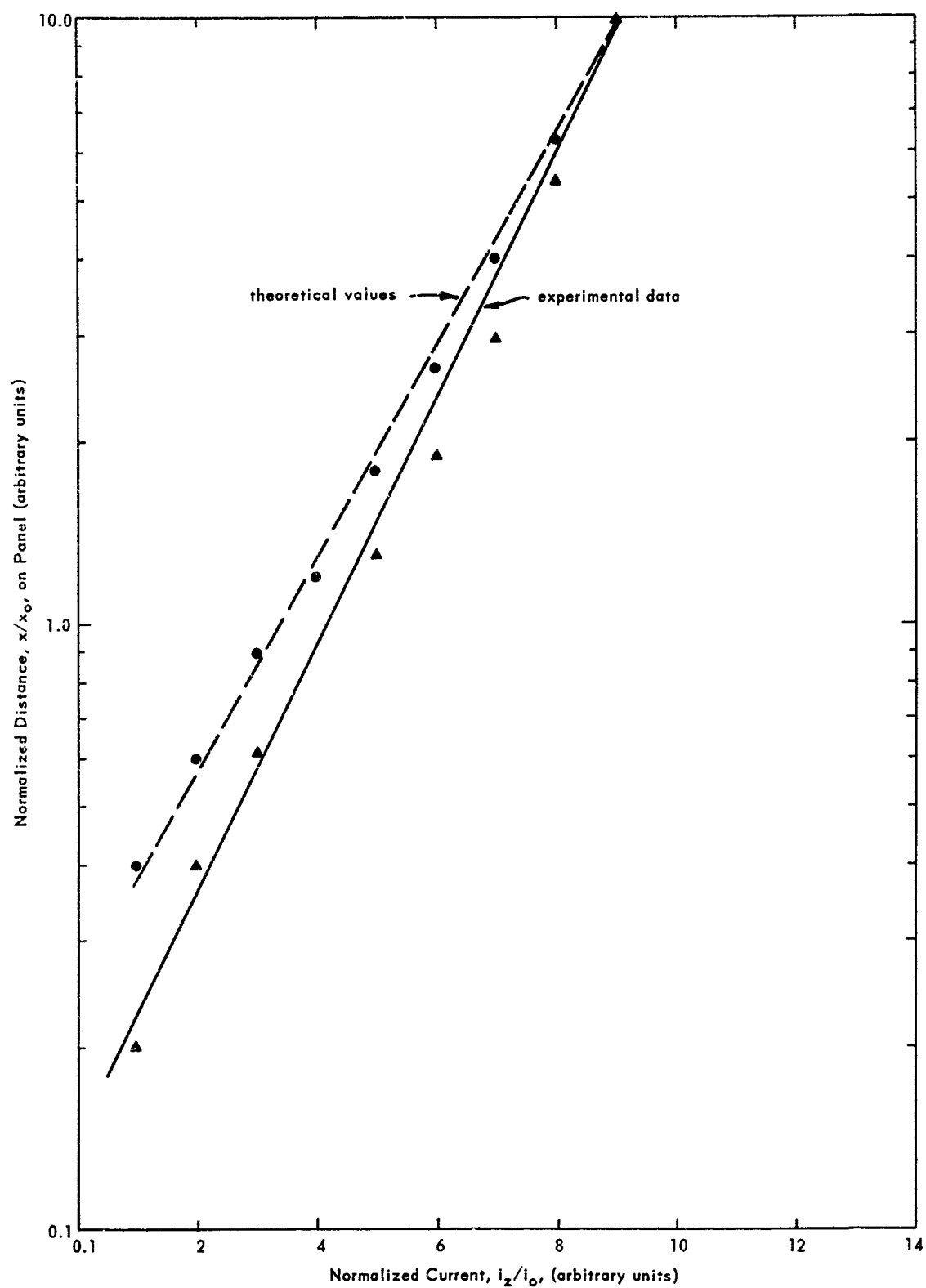


Figure 12. Comparison of experimental and theoretical values for surface current.

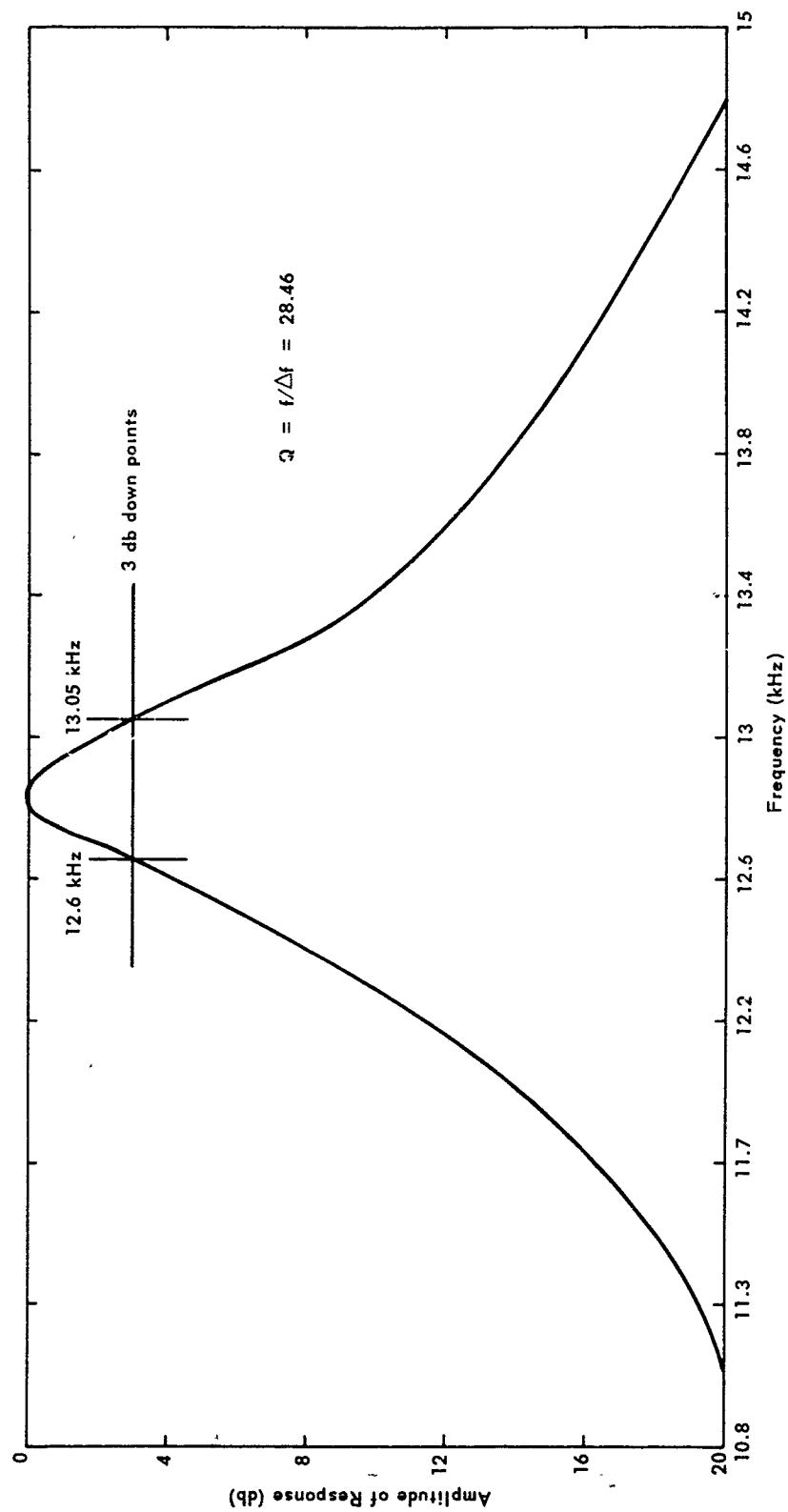


Figure 13. Amplitude versus frequency plot for surface current probe.

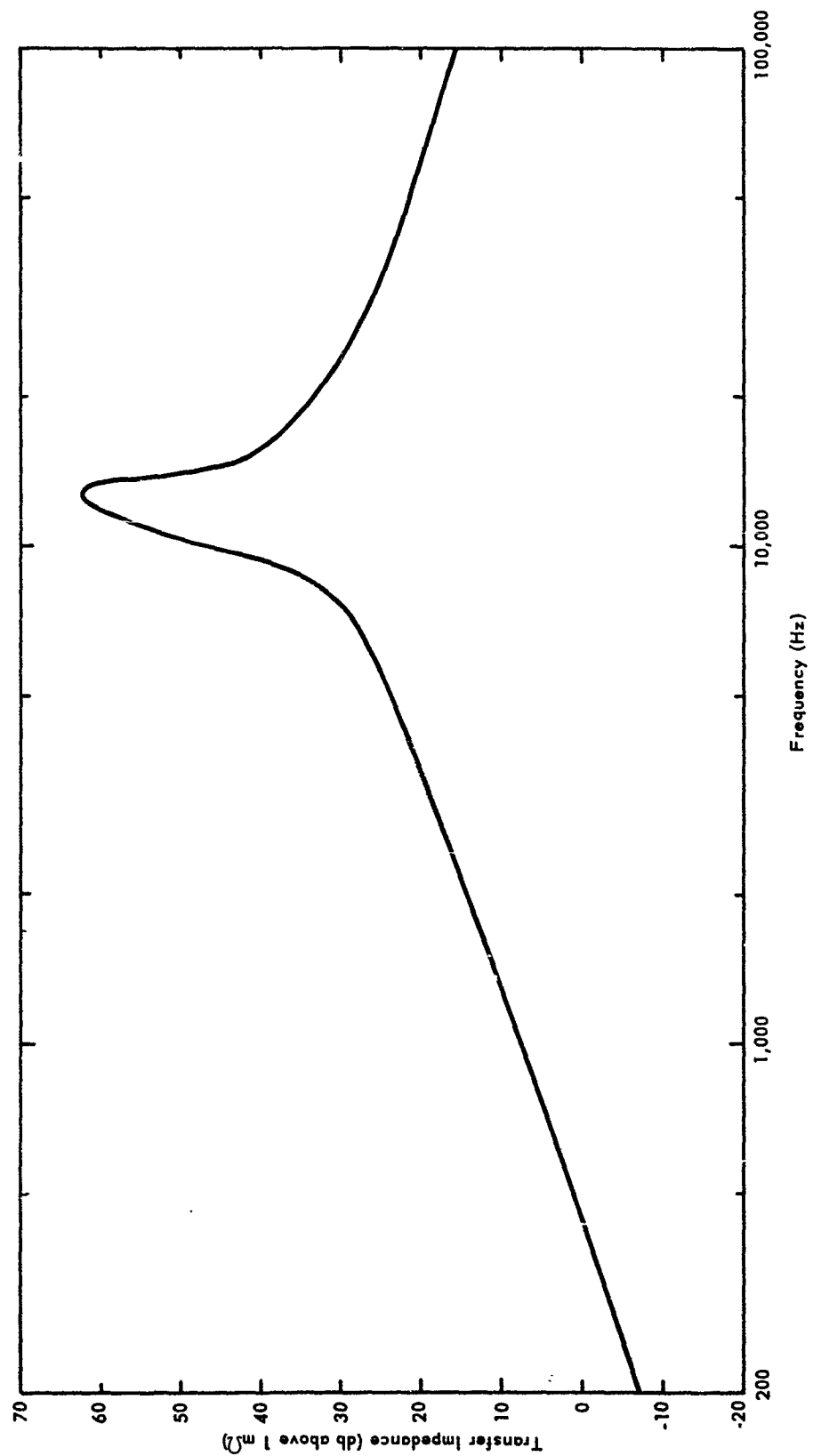


Figure 14. Transfer impedance versus frequency for surface current probe.

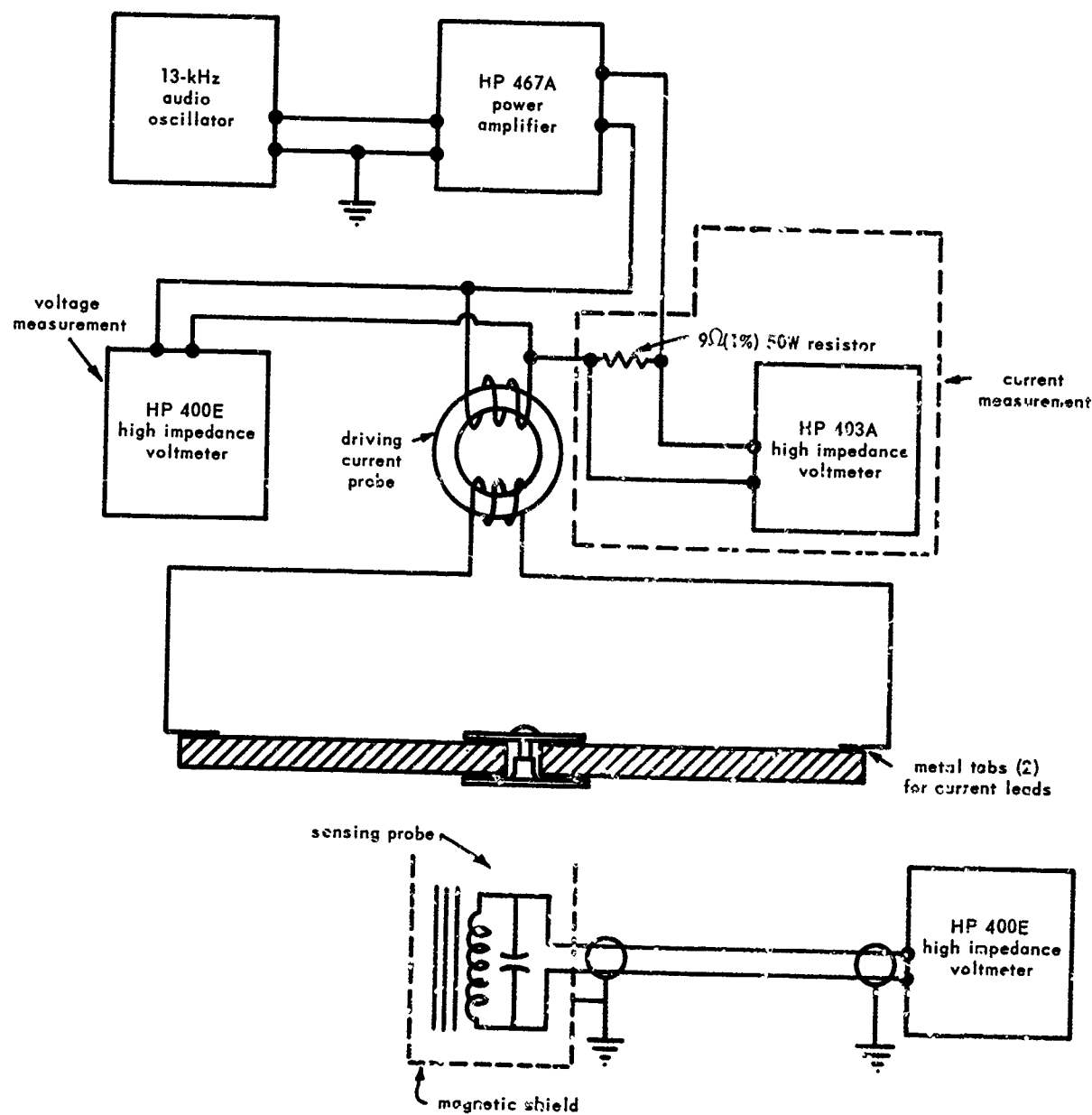


Figure 15. Equipment setup for measurement of surface currents.

The distribution of current described by Equation 5 is for a solid, seamless sheet. Therefore, to form an experimental comparison with the calculations used with Equation 5, initial measurements were made on a solid sheet of the same dimensions as the remainder of the samples. The departure of the experimental curve from the calculated curve as the edge of the sheet was approached (between 6 and 7 on the abscissa of Figure 12) was first attributed by the author to the fact that since the dimension of the sample in the direction of current flow was very short (12 inches), an abnormal distortion of the distribution of current was occurring along the edges. However, it was found that the same general distribution curve was obtained from a solid sheet which was 18 inches wide but approximately 8 feet long in the direction of current flow. The data obtained from examination of seams using this technique has shown remarkable consistency between sets of measurements. The principal value of tests on samples of this type is repeatability of the tests and the opportunity of comparing one type sample to the next. It is felt that the techniques developed by this approach will be very useful in determining relative values of various means of bonding adjacent sheets of metal by metal seams.

Five samples were used in the test series. Skin current measurements (recorded as voltages induced in the measurement loop probe) were made at 1-inch intervals along an 18-inch panel on both sides of the seam. These 18 measurements comprised a set of readings. During the wet (100% RH) portion of the cycle, 11 complete sets of data were taken; during the drying portion of the cycle, three sets were taken. The total number of readings taken was $5 \times 18 \times 2 \times 2(11 + 3) = 5,040$. In order to analyze this amount of data in a reasonable time, a statistical approach toward a solution was attempted. The most important comparison of measurements was to determine the change in readings which occurred during the wet test cycles, since a change in a reading represents a change in the distribution of currents across the sample. This change in currents can only be caused by a variation in the electrical resistance — which in turn is influenced by variations in seam contact. For each measurement time and each sample, a set of readings was taken, and an arithmetic average was calculated for the set. In this way, an average value was obtained for each of the five samples 13 times during the wet cycle. The deviation from the mean value is a measure of the dispersion of the readings and is indicative of a change in the distribution of currents over a period of time. The mean and standard deviation for a group of data can be obtained¹⁰ from

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{18} x_i f_i \quad (7)$$

$$S = \sqrt{\frac{\sum_{i=1}^{18} x_i^2}{n-1} - \bar{x}^2} \quad (8)$$

where $\bar{x}$ = the mean value

x_i = the value of the individual data points

n = the number of data points

f_i = the frequency of data points (in this case, 1)

S = the standard deviation

This calculation is easily programmed on a computer and the solution can be obtained quickly. The data obtained in this fashion is shown in Figures 16 through 20. Except for sample 2, the greatest deviation occurred 12 to 15 days after the beginning of the tests. In general, all of the standard deviation curves had an upward trend, indicating the distribution of skin currents became worse as exposure time increased.

Effect of Bolt Torque on Distribution of Skin Currents

One of the samples used in the previous tests was refurbished by complete dryout and seam cleanup. It was then subjected to another set of tests to determine the relationship between torque on each of the bolts and the resulting distribution of currents in the skin. The seams were supplied with 1/4-20 x 3/8-inch bolts, each having a phillips screwhead. The sample used had five bolts spaced approximately 3 inches apart. Because it was impossible to obtain a torque over 70 inch-pounds with these phillips type bolt heads using a hand torque wrench, these bolts were replaced with hexagonal head bolts to reduce slippage of the torque wrench under high torque. With the hex head bolts it was possible to attain well over 100 inch-pounds and each bolt could be tightened to accurate values of torque. It was also found that if the torque exceeded 90 inch-pounds, the seam clamp warped and thereby reduced its effective clamping pressure along the seam.

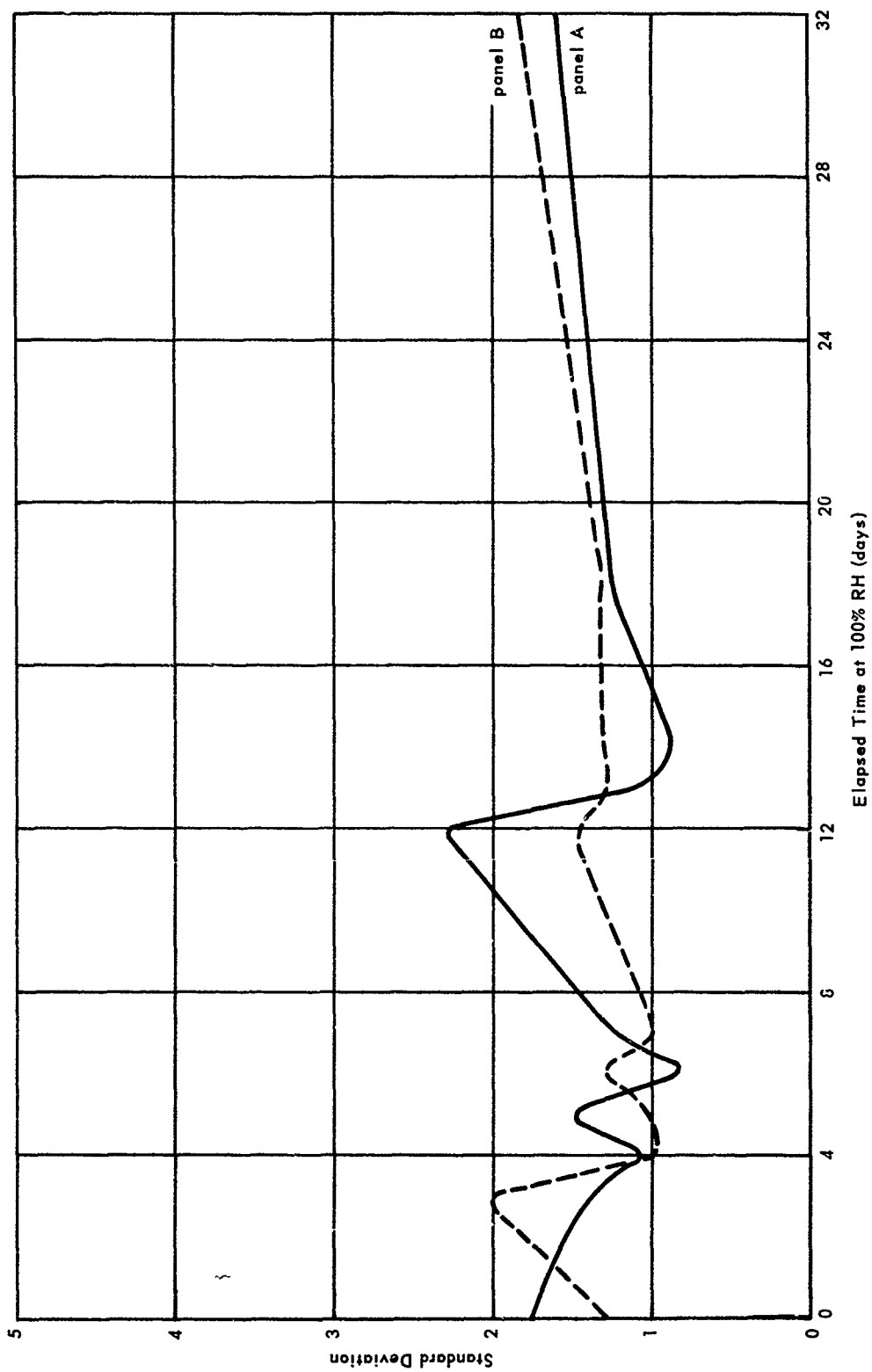


Figure 16. Standard deviations from average surface current readings versus time for sample 1.

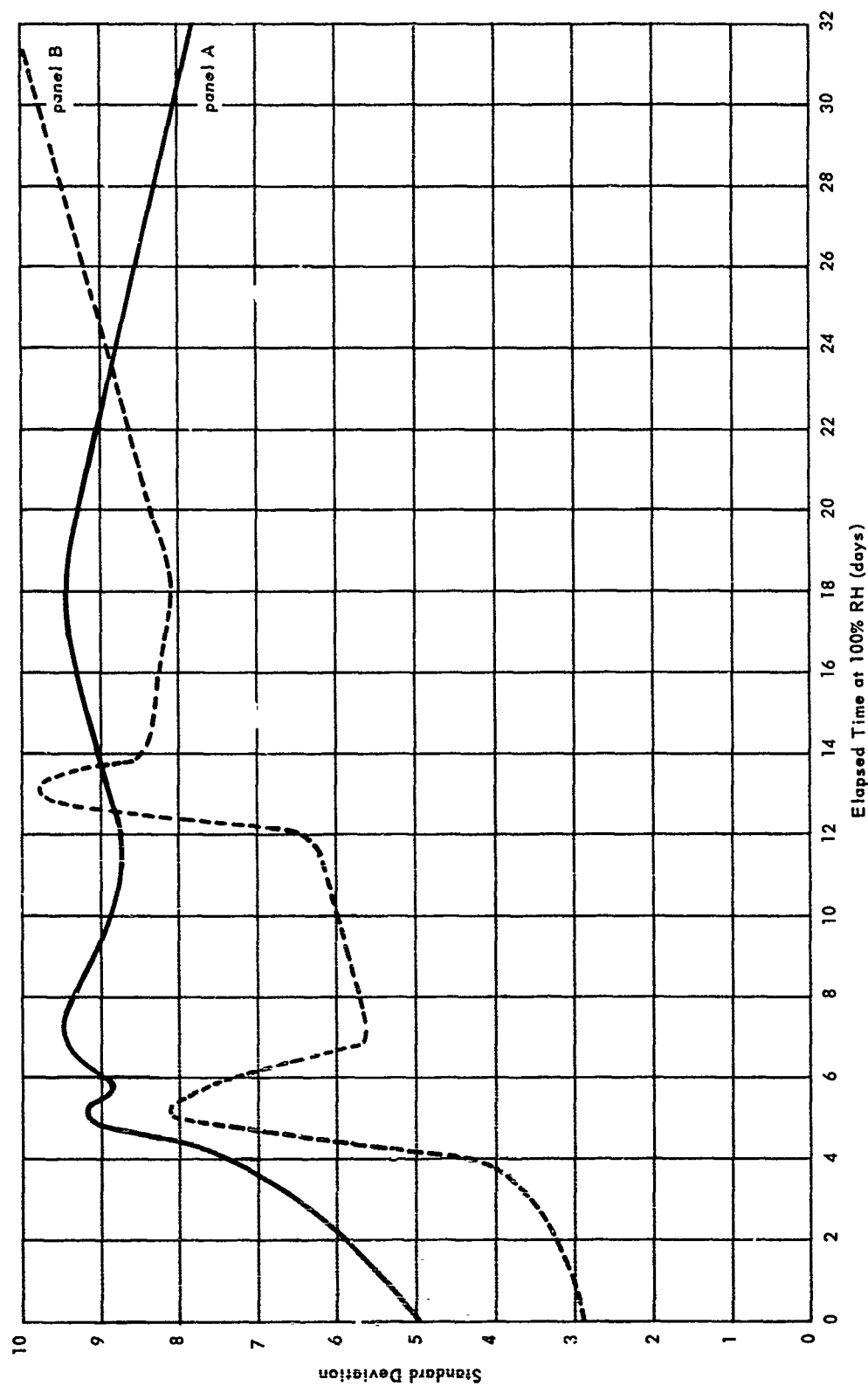


Figure 17. Standard deviations from average surface current readings versus time for sample 2.

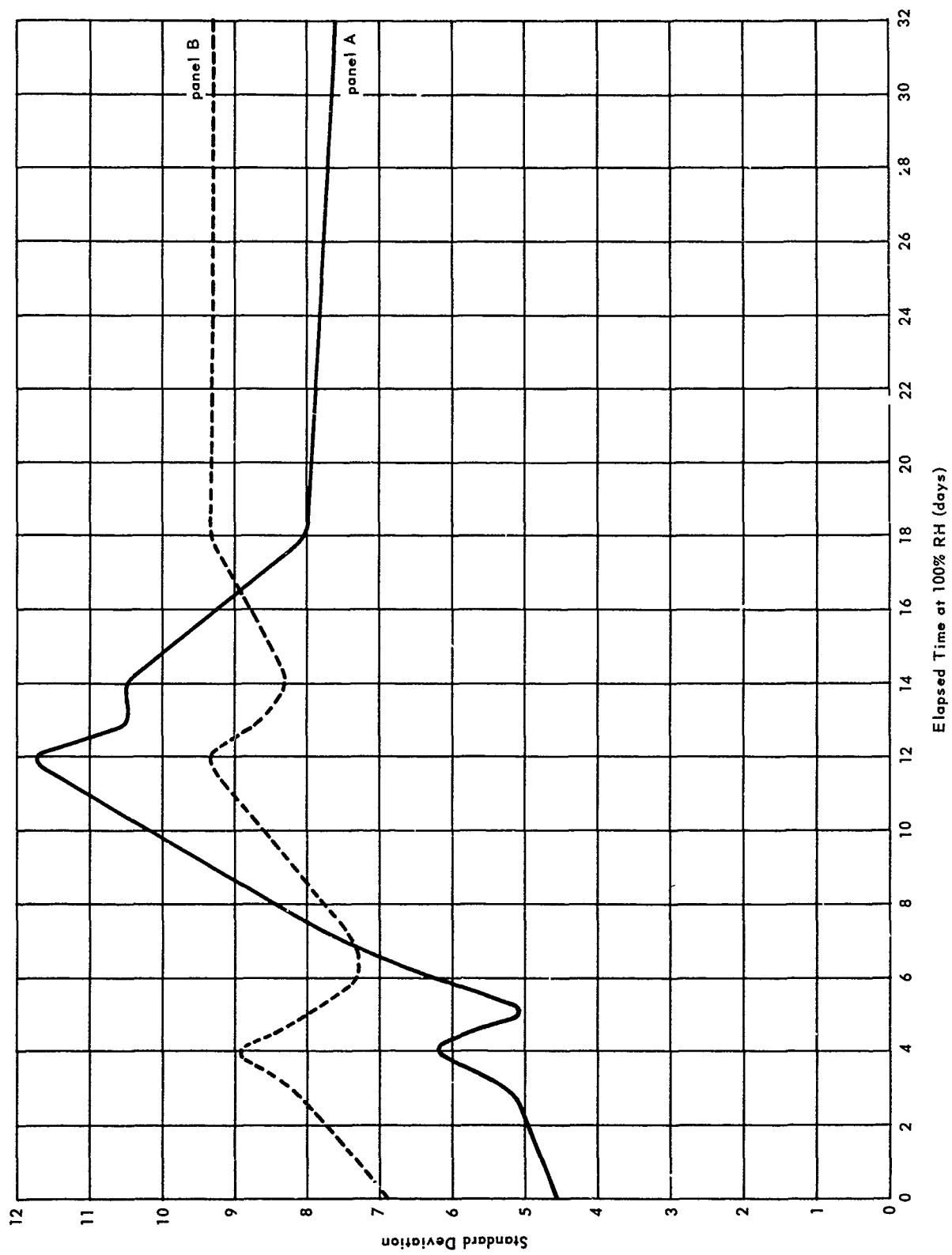


Figure 18. Standard deviations from average surface current readings versus time for sample 3.

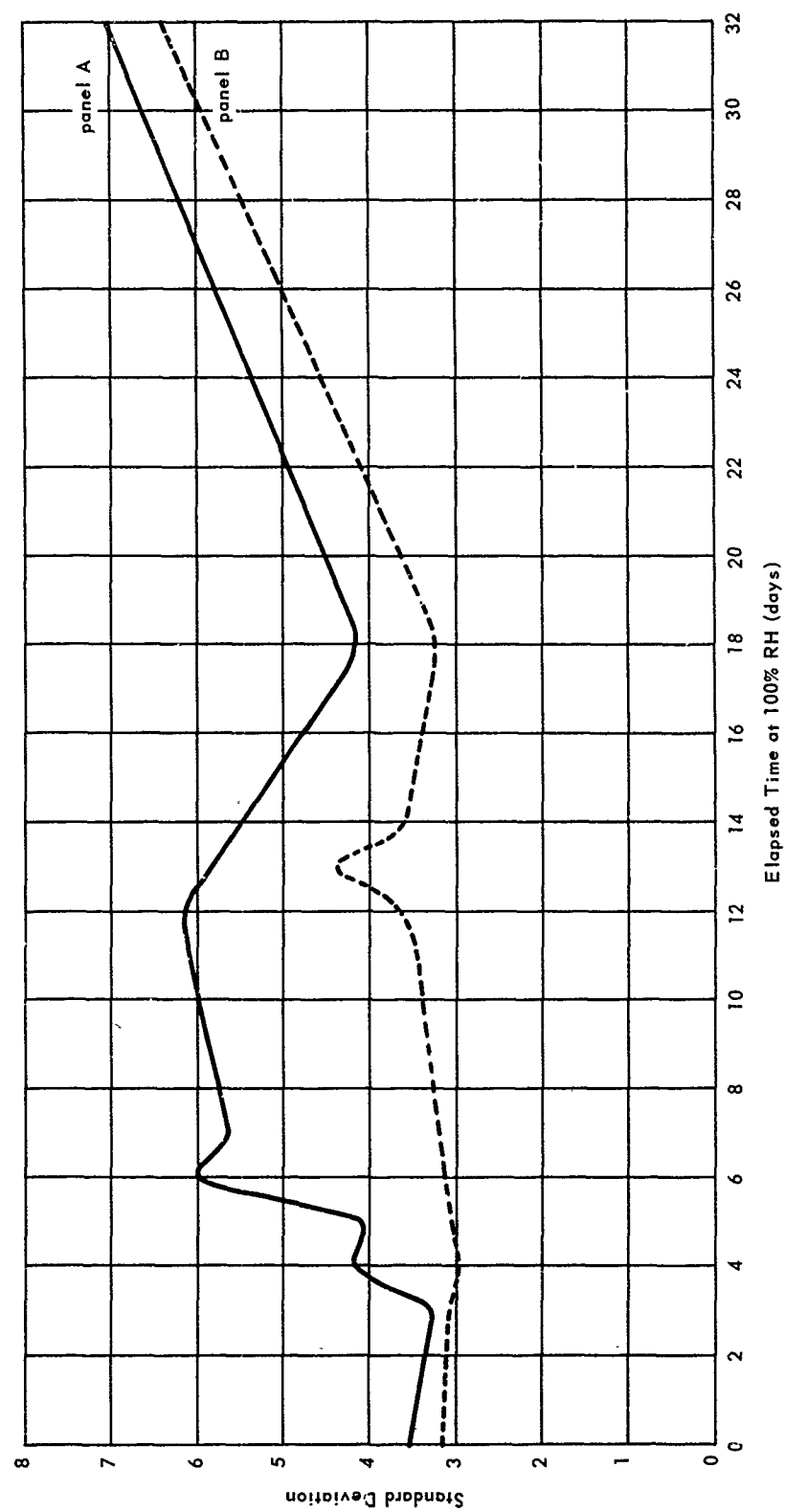


Figure 19. Standard deviations from average surface current readings versus time for sample 4.

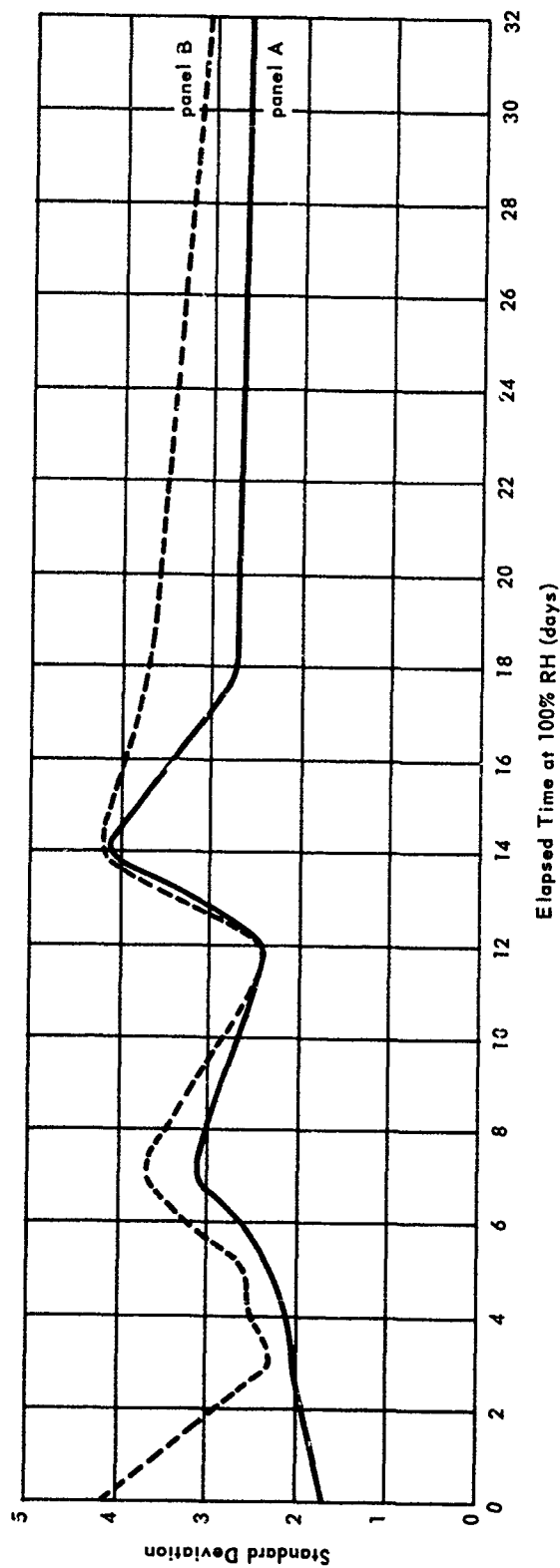


Figure 20. Standard deviations from average surface current readings versus time for sample 5.

The same equipment setup used for the moisture tests was used to determine skin currents for this test (Figure 15). A composite set of curves (one for each of the torque settings of 50, 70, and 100 inch-pounds) showing the current measurements appears in Figure 21. Along with this set of curves is a curve for bolt settings of irregular, but low torque values. The effect of uniform torque between 50 and 100 inch-pounds can be readily seen from the graph. Once the torque exceeds 40 inch-pounds, the location of each bolt can almost be pinpointed by observing the peaks and valleys of the indicated current distribution as the probe is moved along the sheet. Data for these curves were obtained by recording the value at 1-inch intervals while observing the location of the maximum and minimum values as the probe traversed the seam edge. In this way, no significant changes in current level went unobserved.

Still another group of readings was made on both panels connected by a bolted seam (see Figure 22 for data on panel A and panel B). The surface current readings were averaged over the entire seam and correlated with the torque used for that set of readings. The torque in this case was varied from 10 to 100 inch-pounds. At about 50 to 60 inch-pounds, the average current begins to level off to a nearly constant value.

Other Investigations of Surface Currents

Several other determinations of surface currents were made that utilized existing test facilities and the samples which were available.

The following were compared: (1) a solid sheet (no seam), (2) a seam where the joining surfaces have been cleaned with steel wool, (3) a clean seam with a commercially available conductive silver paint applied to mating surfaces, and (4) a clean seam with a silver-loaded caulking compound applied. The resulting surface current distribution for each of the above conditions is shown in Figure 23. It is interesting to notice that the curve for the conductive caulking compound is almost identical with the curve for a solid sheet, except near the edges of the sheet. This would indicate that a good electrical bond can be obtained if clean seams are caulked with a conductive compound before assembly. The cost of the caulking material compound (on the order of \$24 per pound) would be a limiting factor. Such compounds are composed almost entirely of tiny spheres of silver, silver coated copper spheres, or silver on tiny spheres of some other material — all in an epoxy binder.

The fact that the improved metal-to-metal bond resulting from cleanup of a joint by removing oxides and contamination causes the surface current distribution to approach that of a solid sheet suggested an effective and economical method of achieving seam cleanup in large rooms. It is very costly to clean each seam of a shielded room by disassembling the supporting strips and clamps, even if these are accessible. It was decided to mechanically vibrate a panel within its clamped joint and determine the resultant effects within the seam on the distribution of RF current and the quality of the electrical bond. For this purpose a sample section (two panels

and seam plates) was corroded on an accelerated basis by using a dilute acid on all mating surfaces. The section was then reassembled and the seam plate was vibrated with a chisel bit in an air hammer. Then the sample was disassembled and examined visually. The vibration caused a number of bright longitudinal scratches to appear in the corroded surface of the panels, as shown in Figure 24.

The vibration technique was then extended and used on an actual shielded room. A heavy duty electromechanical shaker was bolted securely to one of the wall seams of the room (Figure 25). Before and after shaking the wall, shielding effectiveness (SE) tests were made along one wall and on a large elevator door. These SE tests were made at 400 MHz since this frequency represents one of the more critical frequencies used in testing shielded rooms to meet MIL-STD-285. If a room will pass the 400 MHz plane wave tests, it will more than likely meet specifications for shielding effectiveness at lower frequencies. Figures 26 and 27 show measurement locations and values obtained before and after the application of the mechanical shaker to the wall and elevator door. Included in each of these figures is a table showing the improvement in the electrical bond of the seam after vibration. The wall had only one point at which the electrical bond was degraded by vibration (-6 db), while six other points along the wall indicated a marked improvement (a high value of +13 db). Out of 13 points at the elevator door only three indicated a decrease in shielding effectiveness.

CONCLUSIONS

Although the tests reported here are not exhaustive, sufficient data has been accumulated to warrant a number of conclusions at this time.

1. The exchange and cycling of moisture between the surrounding atmosphere and the plywood panels used in shielded room construction are sufficient to cause premature loosening of bolts along the seam connecting any two panels. A wet period followed by hot dry conditions could produce this effect in a relatively short period of time. The rate of moisture exchange can only be retarded by the use of a moisture barrier or inhibitor applied along each plywood edge exposed to the variable environment.
2. DC resistance measurements of samples have indicated that the resistance of the seam joints generally increases with time and is related to percent moisture absorption only indirectly; that is, through the extra pressure applied to the seam during swelling of the seam. When the seam dries out, oxidation and contamination on the interface of the joint cause high electrical resistance through the joint. One corrective action is to disassemble the high-resistance seams, clean the parts, and reassemble. Another corrective method is to mechanically vibrate the high-resistance seams as described in this report.

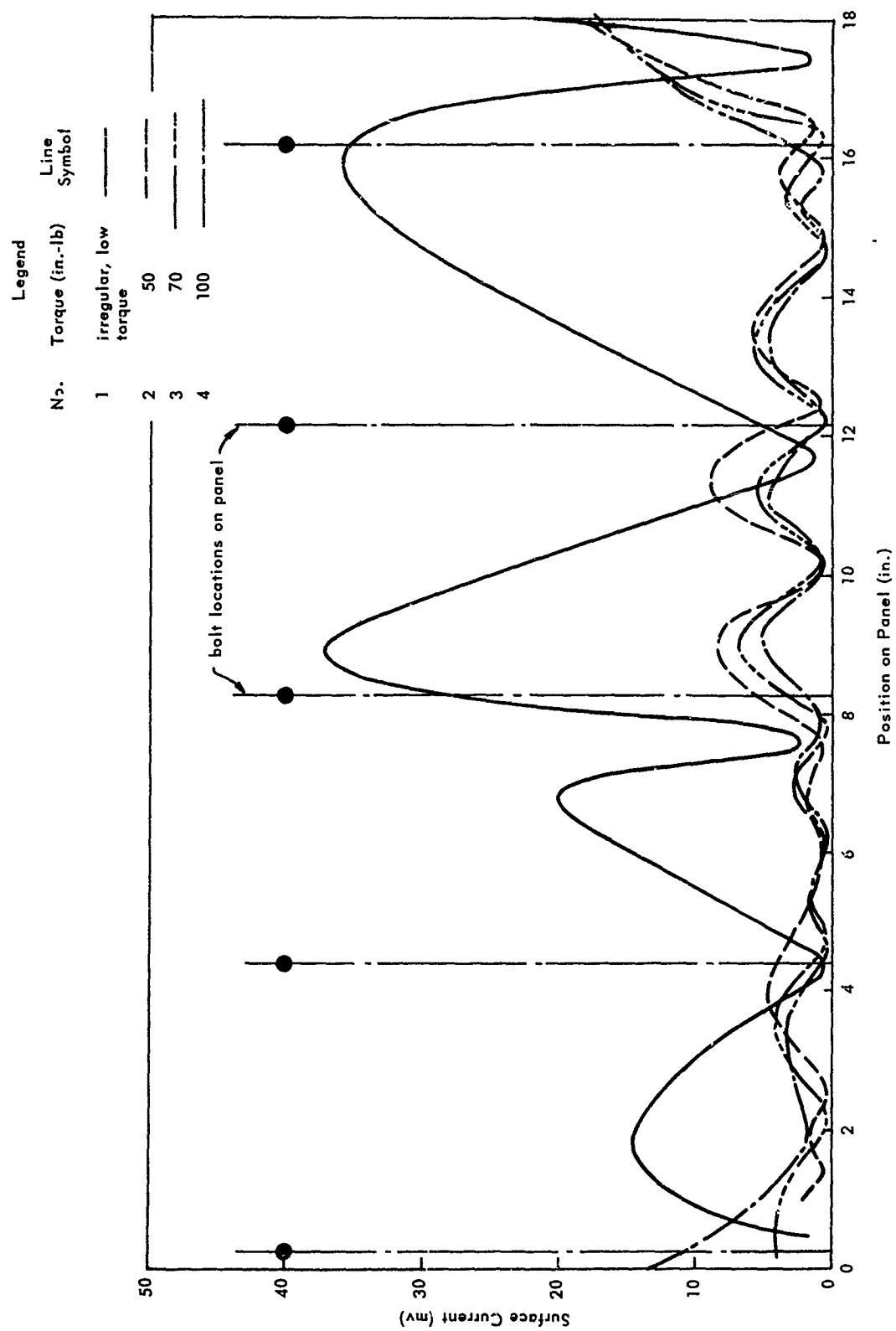


Figure 21. Surface current values for bolted-seam torques of 50, 70, and 100 inch-pounds.

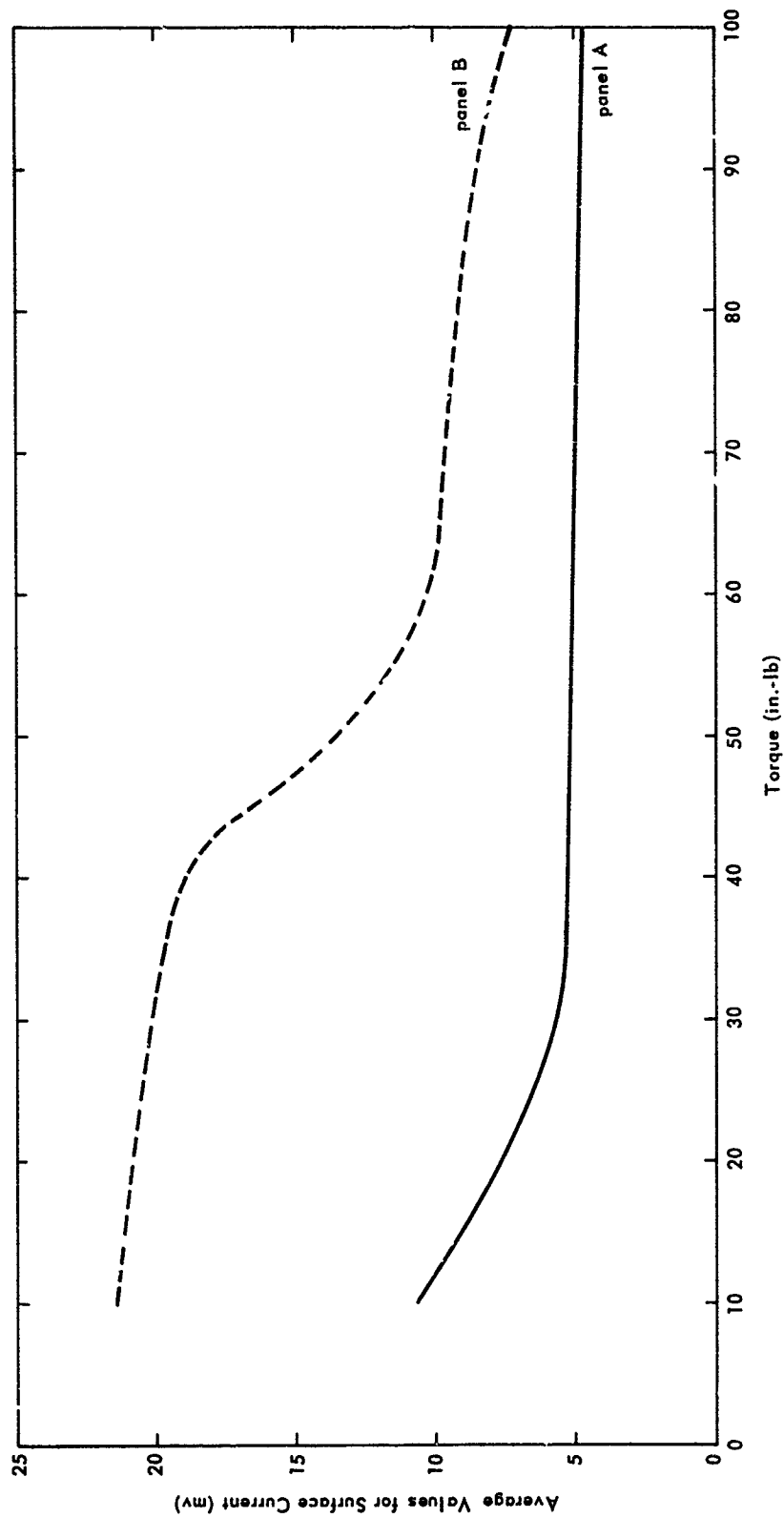


Figure 22. Bolted-seam torque versus average surface current readings.

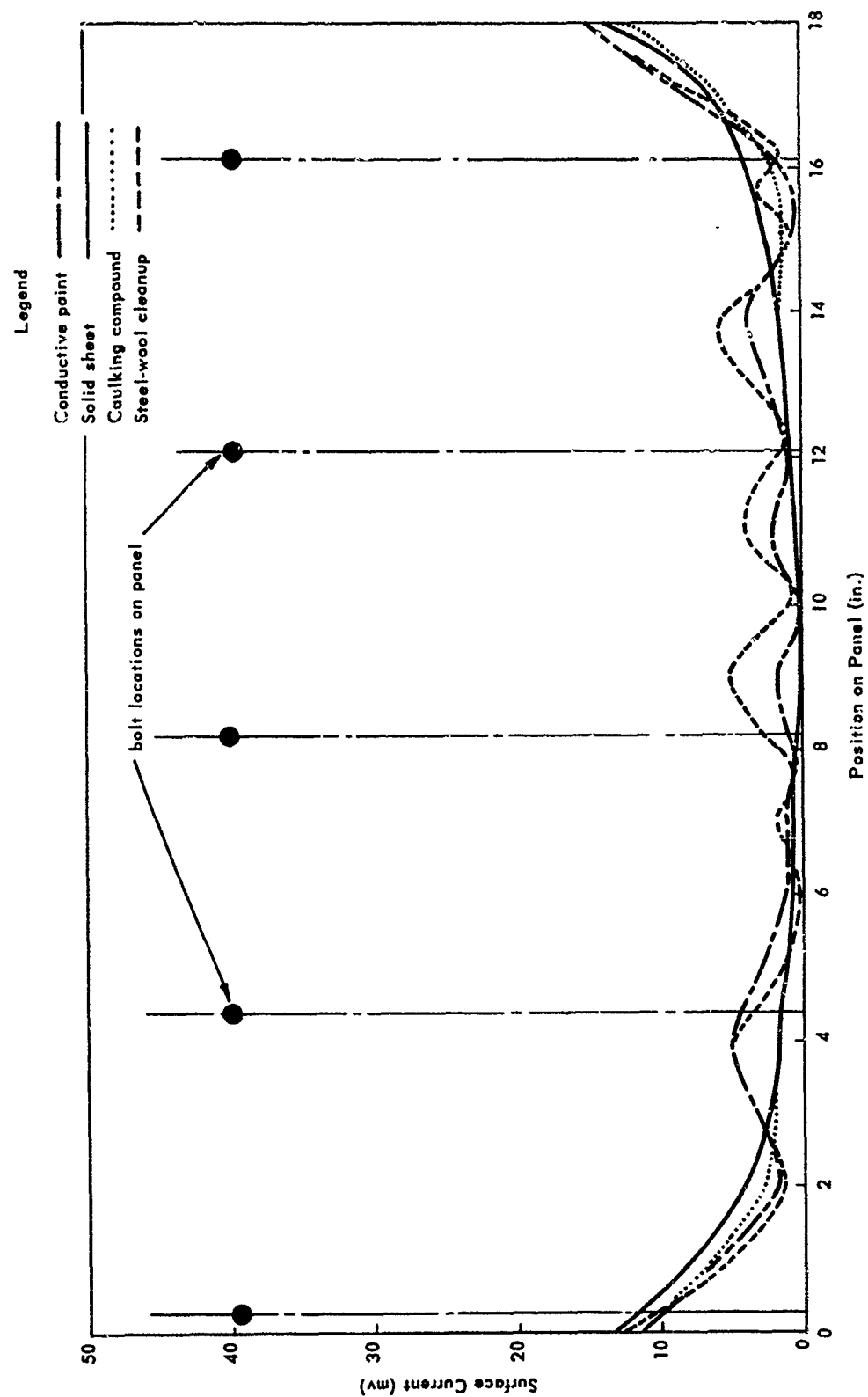


Figure 23. Comparison of distribution of surface current for four seam types and solid armored plywood sheet.



Figure 24. Bright metal shows in seam contact area as a result of panel vibration.

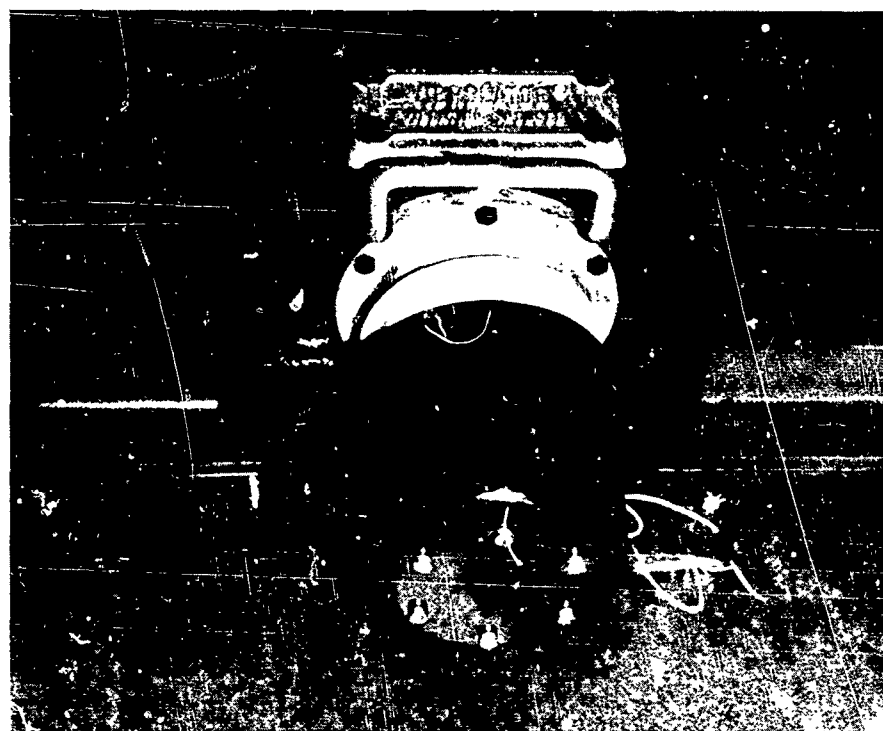


Figure 25. Seam shaker in operation.

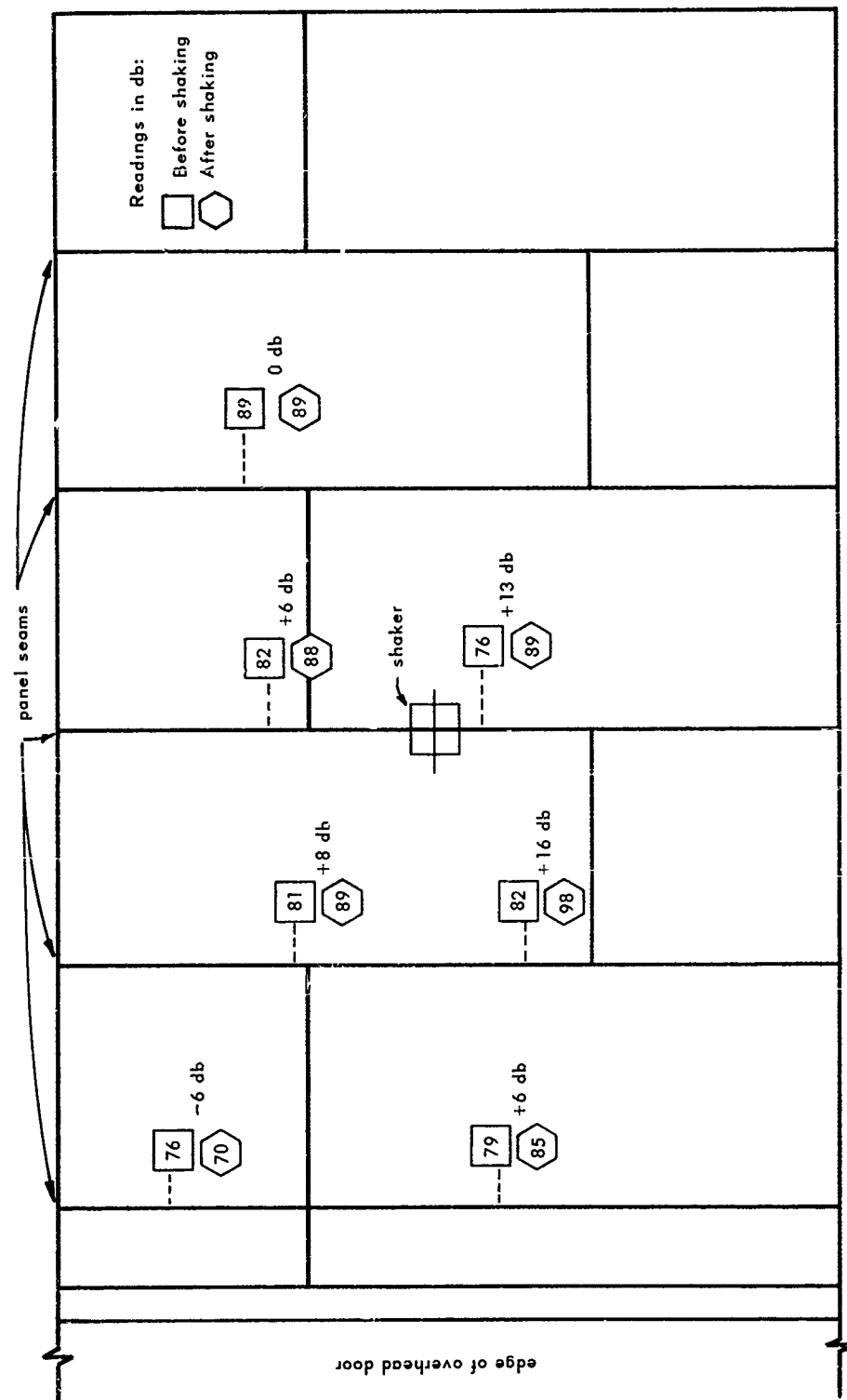


Figure 26. Shielding effectiveness values before and after shaker treatment of south wall, room 201, building 761, Point Mugu. Dynamic range of test signal was 120 db at 400 MHz.

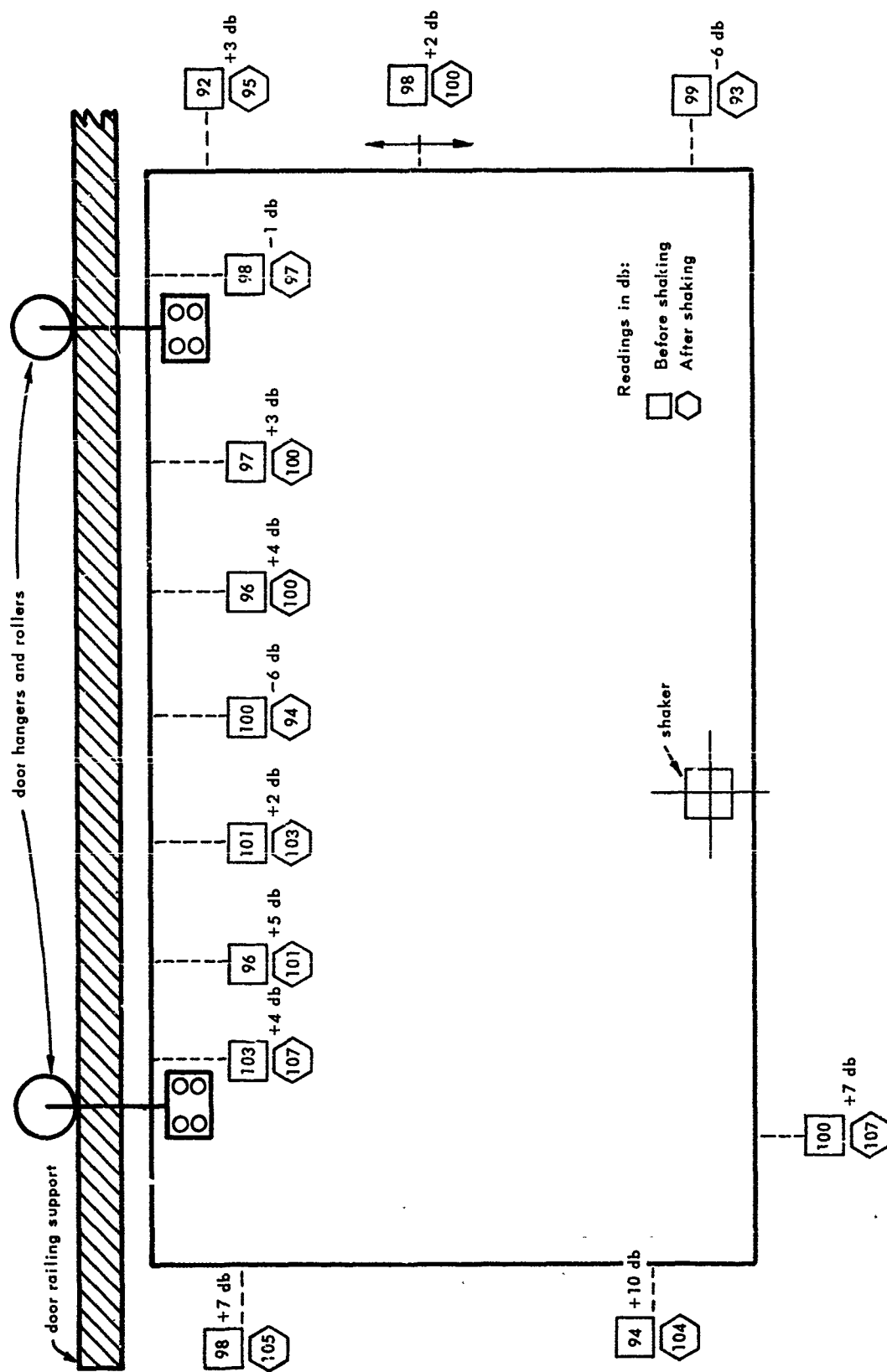


Figure 27. Shielding effectiveness values before and after shaker treatment of elevator door 206, room 201, building 761, Point Mugu. Dynamic range of test signal was 120 db at 400 MHz.

3. Surface current tests have indicated that a conductive caulking compound (silver base) applied to clean mating surfaces modifies the distribution of current until it is very similar to the ideal distribution observed with a solid sheet. Although the cost of initial application of silver-base caulking compounds is quite high, the cost would be insignificant in comparison to disassembling and cleaning and reassembling all seams of a shielded room after it had been assembled. However, the long-term electrical conductivity of bolted seams caulked with conductive compound is not known at this time.

RECOMMENDATIONS

1. Bolted-seam construction of shielded rooms should not be utilized if the rooms are to be subjected to extreme temperature-moisture cycles.
2. As a first measure for refurbishing existing bolted-seam shielded rooms which have lost shielding effectiveness, the seams should be vibrated by attaching a shaker to several positions on each wall, ceiling and floor, after which all bolts should be tightened to approximately 80 inch-pounds of torque (based on 1/4-inch bolts with 3- to 6-inch intervals).
3. The long-term electrical conductivity of bolted seams caulked with conductive materials should be experimentally determined.

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LIST OF SYMBOLS

f	frequency, Hz	W_c	weight of wood sample at time of cutting, grams
f_i	frequency of data points	W_o	weight of wood sample (oven dry), grams
I	transformer current, amperes	x	distance along seam, meters/inches
i_o	initial current, amperes	$\bar{x}$	mean value, same units as x_i
i_z	current in panel, amperes	x_i	value of individual data points
J	constant	x_o	distance along seam, where $i_z = i_o$, meters/inches
j	$\sqrt{-1}$	Z	thickness, inches
K	constant	Z_o	initial value, inches
k	constant	θ	phase shift, degrees
L	inductance of probe, henries		
M	moisture content, %		
n	number of data points		
P	power, watts		
Q	tuned circuit figure of merit		
RH	relative humidity, %		
S	standard deviation		
t	time, seconds		
V	voltage across probe, volts		

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Bolted seams						
Caulked seams						
Silver-loaded caulking compounds						
Armored plywood						
DC resistance						
Surface currents						