NON-DESTRUCTIVE TESTING

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APPLIED RESEARCH PROGRAM FOR NONDESTRUCTIVE METHODS DEVELOPMENT

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Paralleling the omnidirectional advances in materials technology is progress in nondestructive methods development. As a category of test procedures, nondestructive techniques have been used successfully for centuries. Originally such tests were developed for gross detection capabilities, that is, separation of the good and bad. Gradually, through various improvements, these techniques were developed to measure a degree of acceptability. This trend has continued producing techniques of greater precision and accuracy in terms of meaningful information. Recent progress has added the potential of property measurements, and capabilities to measure material behavior and response to environmental variations. Therefore, nondestructive methods provide a scientific contribution to materials research, and assurance of reliability and integrity. The most outstanding single attribute of a nondestructive test is that it is economically advantageous.

In the development of methods for measuring the qualities or properties of materials in a non-injurious fashion, the Directorate of Materials and Processes directs an integrated program for providing nondestructive techiques for the Air Force.

From the study of material behavior or properties, this undertaking extends from that of exploring the unknown, to the development of new or improved techniques and their direct application to material problem areas. This concept or approach is ideal, and provides the necessary basis for future research and application programs.

Much of the nondestructive methods development has been after-the-fact in nature, by devising techniques to cope with specific problems as they arise. This will continue to be one of the more important contributions of the techniques. Of equivalent importance, is the general improvement of procedures and the creation of those with new or unique capabilities. Beyond this lies the lightly investigated region of using several forms of energy in a nondestructive manner to study various properties of materials and their behavior under a variety of environmental conditions. Through this type of research has come nondestructive techniques for measuring grain size, and the ability to measure or observe phase transformation and similar phenomena nondestructively.

To present a clear picture of these concepts in terms of the basic purpose, direction and progress, several programs will be related with future technical requirements cited.

For the past two years there has been an active program for the ultrasonic determination of actual flaw size in materials. While anomalies in materials have been detectable ultrasonically for over a decade, their exact physical location, size and other characteristics have been defined by comparison to various types of calibrated standards. These qualitative comparisons are normally adequate but certainly subject to considerable criticism. The standard blocks usually have flat bottomed holes, with the holes normal to the path of the sound waves. During actual material evaluations, the flaw is seldom normal to the sound beam, but at an angle and the amplitude of the signal is decreased. A curved flaw surface will give a smaller signal than an equivalent flat bottomed hole normal to the sound path. The result is obvious since smaller signals are readily interpreted as smaller discontinuities and could result in the use of unsatisfactory materials.

Improvement in past ultrasonic developments have logically and correctly followed electronic advances. The required information has largely been associated with appropriate electronics in terms of transmitting, receiving and displaying a propagated sound wave. Important as this is, the most critical factor is a fundamental understanding of the sound beam. The acoustic properties are paramount in successful inspection, with all electronics serving only as a media for information display.

Currently, three basic methods of presentation are in use for displaying the ultrasonic information existing within materials. These are A, B, and C scans, which are shown in figure 1. A-scan is a single line display in which time is measured on the horizontal axis and the amplitude of the echo from internal flaws on other material surfaces is measured on the vertical axis. By measuring the position of the echo on the time scale the depth of a discontinuity below the surface may be determined. The B-scan presentation gives a cross sectional view and displays the depth and extent on the horizontal axis as shown in figure 2. Physical position of the transducer is represented by the horizontal axis and is translated to an electrical signal by a data potentiometer. The C-scan, is the presentation which shows a plan view of flaw or flaws within a part and is analogous to a radiograph, as illustrated in figure 3. The result is a picture of the scanned surface area and location of flaws within this area without regard to depth. This is accomplished using two data potentiometers to record transducer position. Each of these presentations has advantages and in each there is a limitation in the ability to show volume and to give a complete picture. If we combine B and C scans, thereby deriving information in both the vertical and horizontal planes, we will be able to more fully describe the contents of a given material.

This was done using a single transducer with an electronic combination of the B and C-scan systems. Basically the system consisted of the transducer scanning horizontal back and forth across the part, with the transducer being stepped over mechanically after each length of travel. This displacement is electrically synchronized through the use of data potentiometers to the displacement on the oscilloscope screen. Summation of all cross sectional scans on an oscilloscope results in an isometric projection of a section of a material and its internal inhomogeneities. Figure 4 illustrates the principle. The problem is still not solved. The single transducer views in only one direction and while depth, location and extent are shown, this is in part the result of data potentiometer translation. Information with respect to discontinuity volume is still not available. Therefore, while a single transducer can be effectively employed to produce isometric views it is still limited in a practical realistic sense because a single transducer can only receive responses from surfaces relatively normal to the path of the sound beam defining only one or part of one dimension of the flaw.

The solution to this problem is viewing a material from more than one direction. The first approach was through the use of a multiple transducer system. A complex of three or more matched transducers were used. A schematic of the system is shown in figure 5. Part A shows the information from the normal transducer, No. 1. Part B shows the data derived by transducer No. 2. Part C is the information from the third transducer, and Part D is the composite scans of all three transducers. Combining this with the previously discussed scanning will produce an isometric view of depth, location, and the important property, volume. Figure 6 illustrates the equipment in laboratory form.

Since the velocity of sound is known or easily determined for most materials, the transducers may be angled to give a wide coverage of the media and its discontinuities wherever necessary. Selection of the appropriate angle is made through the use of Snell's Law where

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

where i = angle of incidence
r = angle of refraction
V_1 = Velocity - medium 1
V_2 = Velocity - medium 2

This is necessary since the angle of propagation in most materials is appreciably different from the angle or direction of sound propagation from the transducers. The most difficult requirement of this approach is the presentation of the composite scan and the view seen by each transducer at the proper time and location on the oscilloscope screen. This, is merely an electronics problem and not overly difficult.

The success of the program is best described pictorially comparing the single and multiple transducer systems. Figure 7 shows a 5/64-inch flat bottomed hole drilled to a 3/4-inch depth in an aluminum alloy block. Using the single transducer system at 10 and 25 megacycles the hole is clearly defined as well as both front and back surfaces. In striking comparison the multiple transducer system shows additional information, V12 the sides of the hole. In figure 8, the true contribution of the system is seen. Representing a crack open to the surface is a circular saw cut 5/8-inch deep. The single transducer sees only the peak, whereas the multiple transducer system relates depth and contour of the cut. With the single transducer, the shadow of the flaw is seen on the back surface, indicative that the sound energy was reflected but not in a direction that would be detectable by the transducer.

The study proved the feasibility of the concept. Research is continuing on a second approach yielding greater detail and overcoming some of the limitations of the basic system. All of the limitations are directly related to the transducers. The multiple transducer system is complex, slow, and limited in ability to scan unusual surface configurations.

In considering the limitations of the system it must be remembered that the interpretation of discontinuity sizes is not limited by acoustic parameters but by the nature of the discontinuity that may prevent complete ultrasonic energy reflection to the transducer. Therefore, the transducer and acoustic characteristics are the factors of greatest importance. As a consequence, the entire system has been re-evaluated and re-designed from the sound beam requirements. The disadvantage of further exploitation of a multiple transducer system is the electronic complexity which would result in integrating many transducers. As the system complexity increases, the ability to scan rapidly, and also to scan contours, becomes a serious problem. A single search transducer, one manipulator and one electronic channel would be the optimum choice and this approach is currently being pursued. Figure 9 shows the new search sweep manipulator system with the transducer, data potentiometers, and the various drive mechanisms identified. This unit is designed to oscillate the transducer in a sinusoidal motion over a calculated pre-set path. This is necessary to produce a constant speed of the acoustic beam at various angles of refraction in the metal as the surface is scanned. The manipulator system is capable of positioning the transducer in such a way as to hold the point of incidence at which the sound beams enter the metal at an individual point. The unit is capable of varying the speed of the sweep and the angle through which the transducer is swept. The sweep speed is variable from 0 to 110 sweeps per minute and the angle of sweep can be varied from 0 degrees to ±18 degrees. The angular motion of the transducer is more than enough to exceed the critical angle for most materials. Another very important advantage of the system is that the transducer may be operated at distances from the metal surface ranging from 1/4 inch to 4 inches.

The sweep circuits have been designed coincident to the path of the ultrasonic energy. If the ultrasonic beam makes a ±90-degree sweep from the normal plane within the part, then the electronic beam in the presentation must show the same path. The major change has been the substitution of the multiple transducer system for one using a single transducer with a compound sweep system duplicating the actual sound beam pattern or acoustic path.

Complete development of this system will provide the capability of presenting inhomogeneities in their true perspective in relation to boundary interfaces and will establish accurate and critical material evaluations.

In contrast to the normal research and development programs for nondestructive methods, the Directorate of Materials and Processes has a series of objective projects dealing with nondestructive studies of properties and behavior of materials. These projects are profound in nature and represent tools heretofore unavailable for studying materials properties, structure and behavior.

The principles are clearly shown in a program where the netallurgical changes in metals subjected to stress cycling, are studied with ultrasonic propagation techniques involving measurement of attenuation and velocity. The data supports the theory that cycling results in a dying-out of dislocation damping effects, as well as recovery in early stages of cycling. Continued cycling, results in additional changes that are related to slip processes through the development of defects and strain regions. With these measurements, the surface of the metal samples are further studied by optical and electron microscope techniques. Examples of the changes during a material's life are shown in the following figures: Figure 10 represents a series of maximum and minimum recorded values attained during each cycle over 10^4 cycles. The material is 1100 aluminum alloy and stressed equally in tension and compression. Figure 11 shows the observation of recovery. The average values of attenuation are shown as a function of cycles, with the discontinuities representing recovery during interruption of the cycle. This material is 1100F aluminum alloy at 9000 psi and was cycled in both tension and compression.

Further research is being pursued to measure ultrasonic attenuation changes in both single and polycrystalline metals under cyclic straining and to study the correlation of these indications with the metallurgical and other mechanisms involved. Success in this endeavor will provide valuable contributions to materials technology as a means of studying both material behavior and properties.

This research has another closely related investigation which is directed toward a specific problem, that of residual stress measurement. A fact often overlooked when mentioning residual stress is, that such a system of stresses may be beneficial rather than deterimental. These stresses, that exist in a body free from external forces, have been shown to increase fatigue life when they exist as compressive surface stresses. The increasing interest in residual stresses and their importance has emphasized the need for measurement techniques, by nondestructive methods. Almost all techniques available are destructive with the exception of X-ray, which is nondestructive. However, there are many disadvantages and difficulties associated with its use, plus the fact that only surface stress can be measured.

After a very extensive literature and theoretical analysis of the feasible methods, the study of ultrasonic propagation in metals indicated the most promise.

What happens to a propagated sound beam in a material subjected to stress? Are these changes solely the result of stress? These two questions have in part been answered through extensive studies. Figure 12 shows the $(\frac{\Delta V}{V})_s$ versus stress in aluminum. This relationship of velocity and stress is not new and unique, however past efforts have not been directed toward use of this phenomena. Primary attention has been given shear wave bi-refringence or polarization under uniaxial stress. Shear wave bi-refringence was recognized early in the program as an excellent indication of stress. The magnitude of stress-induced bi-refringence varies linearly with stress level. There are still many barriers to overcome since anisotropic factors influence the results and must be known, or be small in comparison to the stress effects; nevertheless a step forward has been made.

There are several new techniques being applied in nondestructive materials analysis. One of these being explored is electrical resistivity. While electrical resistivity measurements have been common as a metallurgical tool, the particular concept which will be discussed is quite unique in approach. The basic theory involves the measurement of voltage decay produced by a created degeneration of magnetic flux within a specimen whose permeability is approximately equal to one. Present experiments utilize a non-contact eddy current principle for which equipment and accuracies are being confirmed. The transducer consists of a driver and a pick-up coil wound concentrically on a coil form in which the material to be evaluated is inserted. The outer, driver coil, is energized, and at cut off, the decay in the magnetic flux is observed by the pick-up coil as a voltage decay which is measurable. The rate of this degeneration or change of slope is measured. From these measurements resistivity can be calculated, since the decay is an exponential function in the latter portion of the degeneration. The advantages of the technique are that no direct contact is necessary and specimen shape is not important for relative measurements, that is, assuming only the changes in resistivity values in a material are desired. Absolute measurements necessitate that specimen dimensions be known. Relative measurements with an accuracy of about 2 percent are anticipated. The method offers advantages as a corollary to dynamic modulus measurements and other techniques valuable to mechanical metallurgy. Initial studies have been limited to the evaluation of the method as a measure of room temperature precipitation in 2024 aluminum alloy from the solution heat treated condition to that of T-4 or room temperature aged condition.

Another relatively recent technique involves the use of infrared. Such a method may be considered fundamentally as an extremely sensitive method of measuring heat transfer in materials. As a consequence all inhomogeneities affecting thermal transmission should be detectable. Research has been initiated for a basic workable system for defining detectability, resolution and the parameters affecting reliable use of infrared techniques. Early studies will be concentrated on gross defects. It is anticipated that eventually the system will have capabilities of measuring various metallurgical and other properties at room and elevated temperatures. One of the fortunate aspects of this undertaking is the recent wealth of background information in military, astronautical and industrial applications. Many of the limitations have been defined and are not technological barriers but merely require research skill to advance the state of the art in the direction of material analysis. The scheme of the procedure used employs the concept of scan heating and detecting transient effects. Deviating now to ceramic materials, we find that there are ample areas of concern for which nondestructive methods have not been adequate. Ceramic coatings on metal substrates, for example, is an extremely difficult problem area. Here we are dealing with a specific problem — integrity. Integrity is two-fold in a sense, considering both the coating itself and its bond to the substrate. The media involved are of inherent complexity. The worst enemy of problem solution is the multitude of factors associated with integrity which range from voids, to lack of bond, to such concealed variables as oxidation resistance. The object of defining these characteristics nondestructively has been pursued, by using ultrasonic energy, and by emphasizing continuity measurements of the ceramic-metal bond as the first issue to be settled. Three approaches have been investigated, namely: charge scanning, surface wave, and intermodulation techniques. Early studies involved understanding of these little known ultrasonic phenomena, and as experience is gained in their application to integrity problems, their resolution and sensitivity is being found to be quite remarkable.

Another aspect of ceramic and related materials which is receiving considerable attention is the analysis of brittle fracture behavior nondestructively. Through diffraction studies, radioactive tracers, capacitance, resistance and other techniques, surface and internal factors related to behavior are under scrutiny. The effects of orientation, anisotropy and other parameters are being investigated. Surface phenomena are stressed because of their importance and the desire to develop techniques capable of locating sites of crack formation prior to initiation.

In summarizing the requirements in the field of nondestructive methods development, we find that continuation and advancement of techniques through research will provide improved and new processes for a wide variety of purposes necessary to the basic understanding of materials, their behavior, and their use in providing optimum materials for precision Air Force systems.

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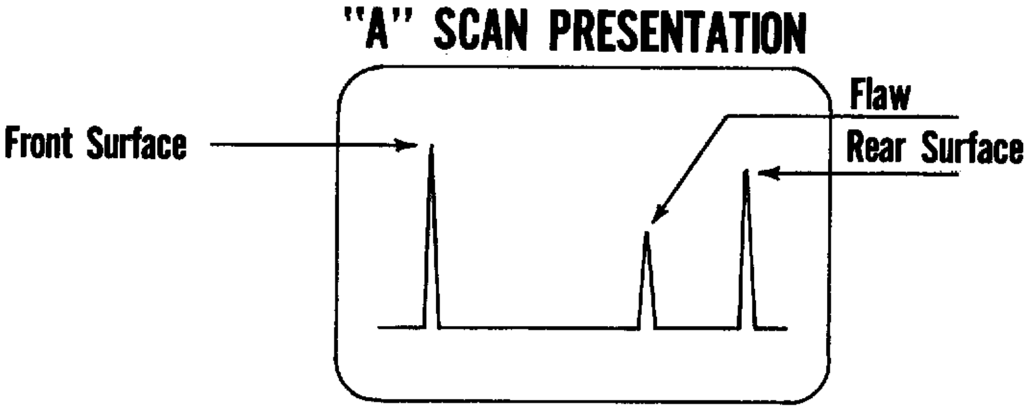


Figure 1.

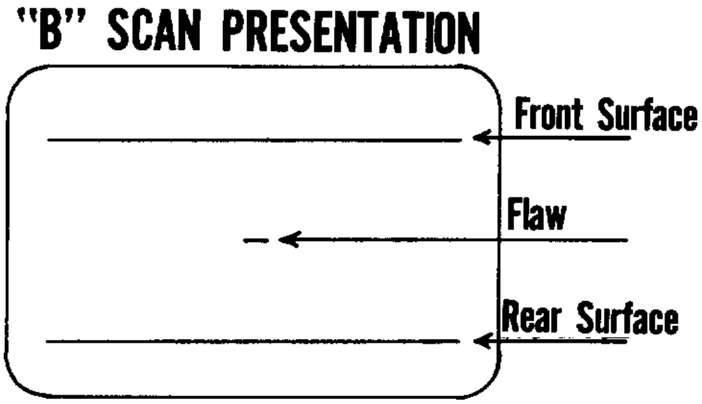


Figure 2.

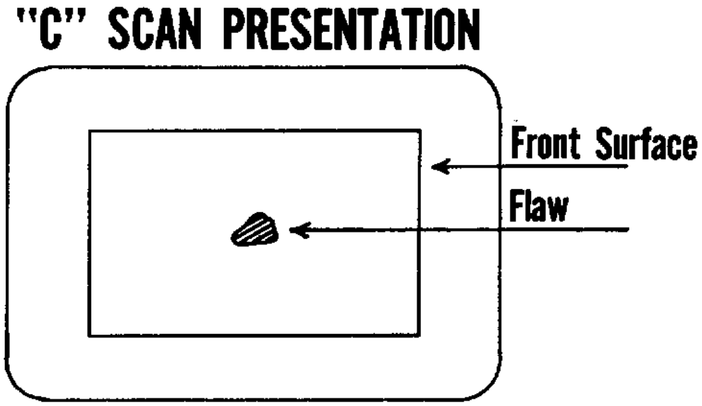
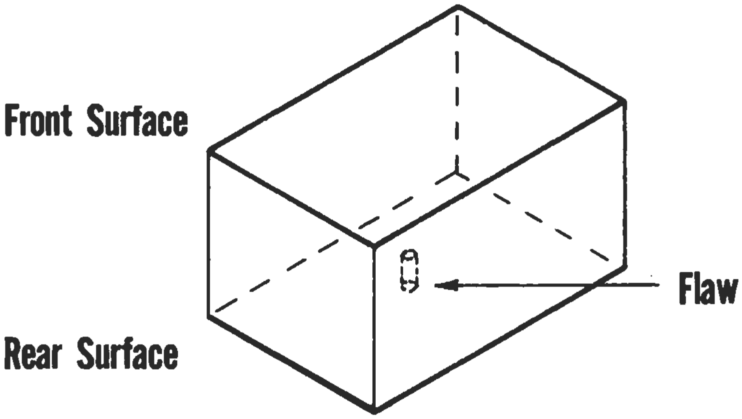
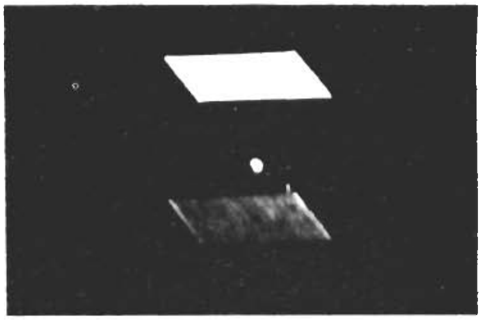


Figure 3.

STANDARD FLAT BOTTOMED HOLE





MULTIPLE TRANSDUCER PRESENTATION

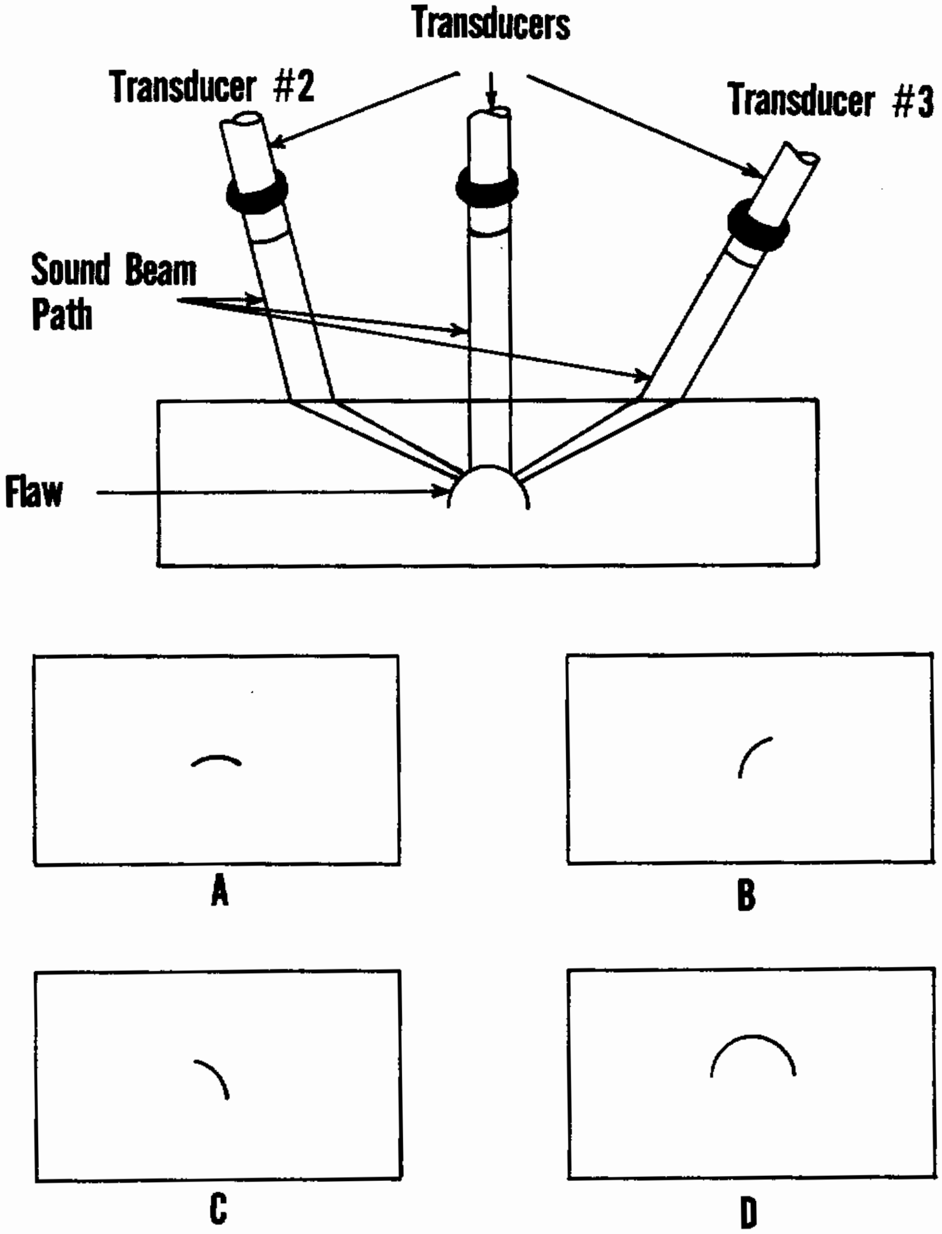
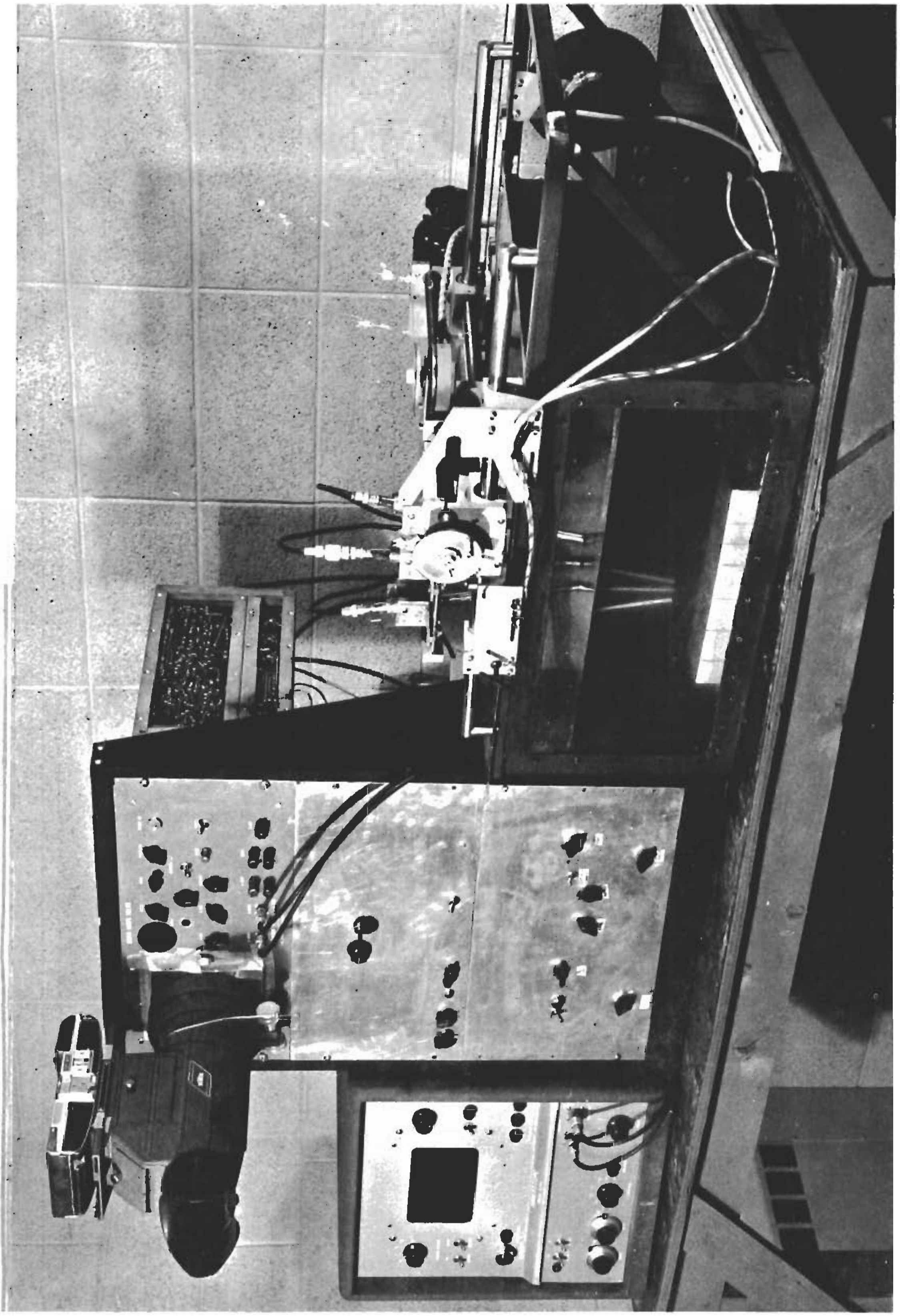


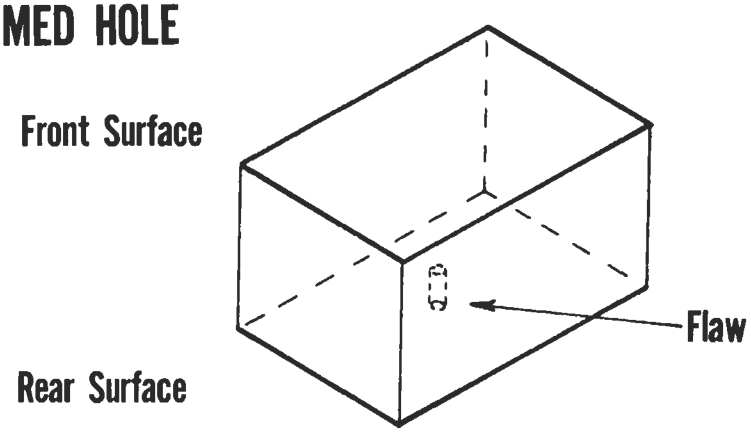
Figure 5.



PHOTOGRAPH OF LABORATORY EQUIPMENT

Figure 6.

STANDARD FLAT BOTTOMED HOLE



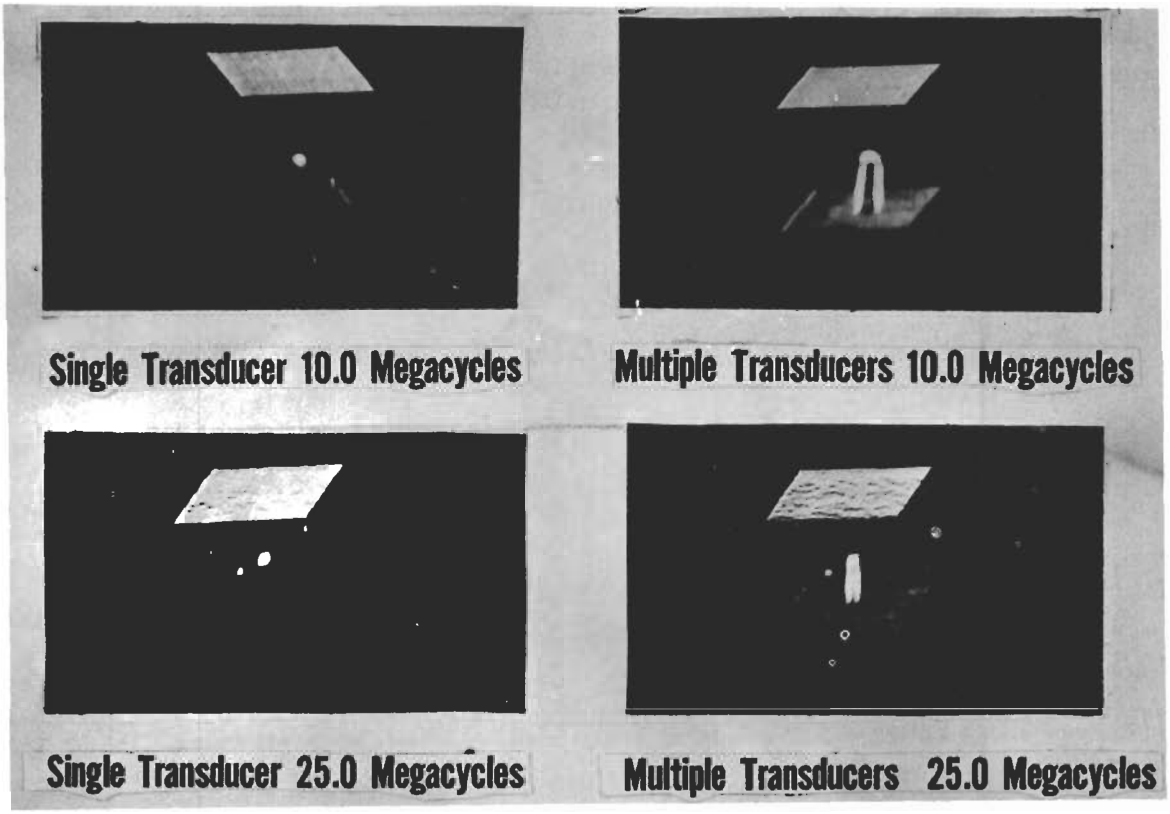


Figure 7.

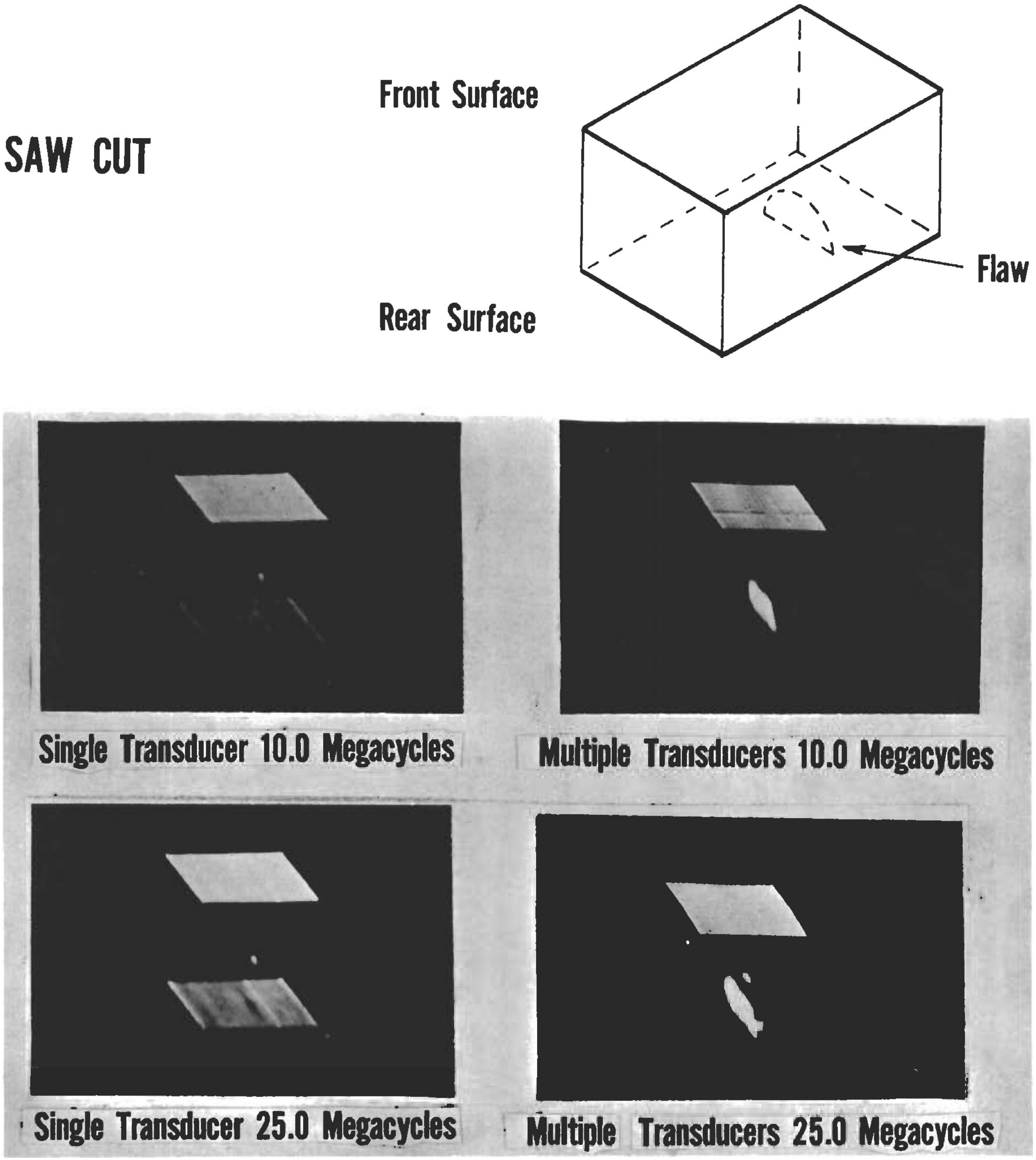

SAW CUT
Front Surface
Rear Surface
Flaw
Single Transducer 10.0 Megacycles
Multiple Transducers 10.0 Megacycles
Single Transducer 25.0 Megacycles
Multiple Transducers 25.0 Megacycles

Figure 8.

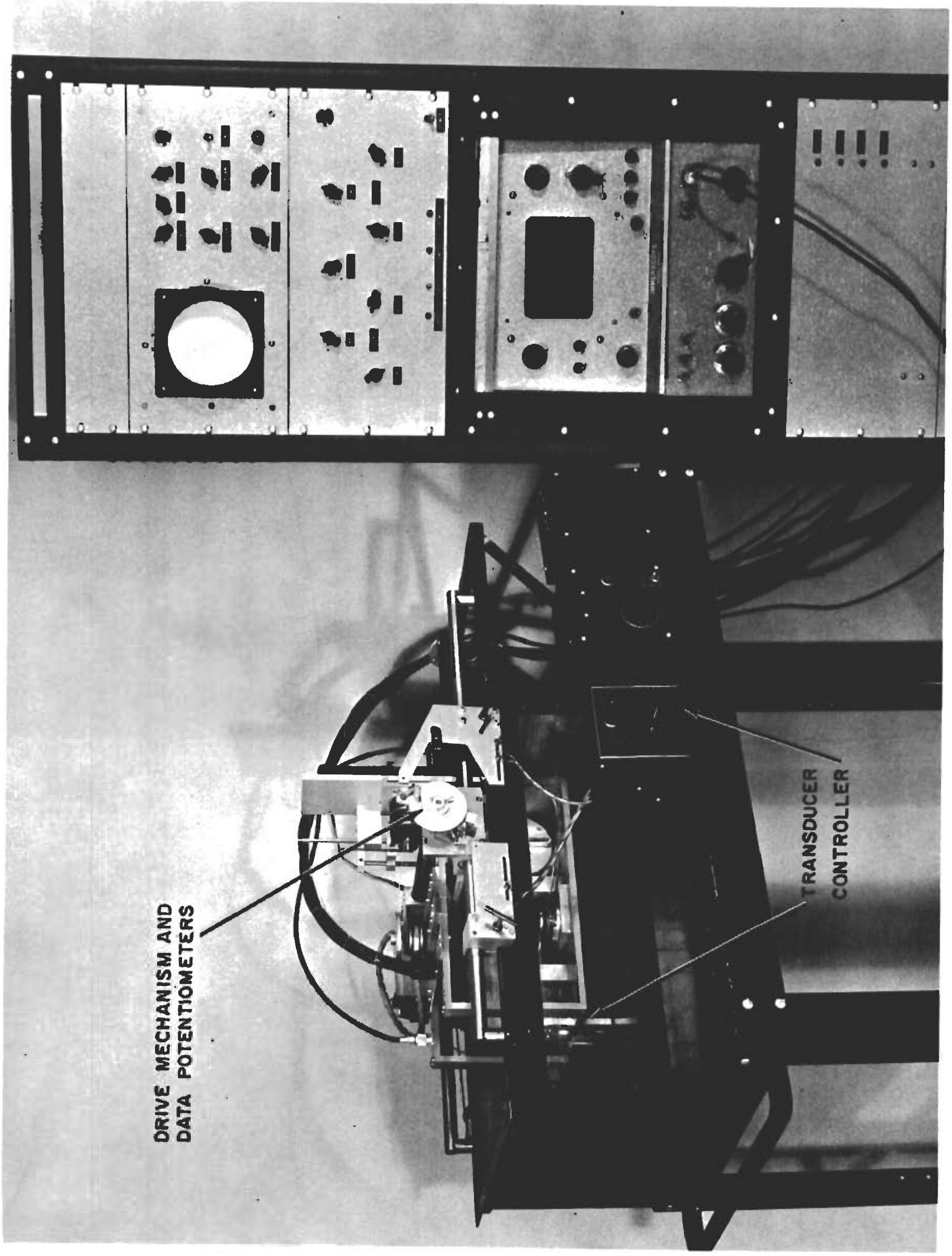

DRIVE MECHANISM AND
DATA POTENTIOMETERS
TRANSDUCER
CONTROLLER

Figure 9.

MAXIMUM & MINIMUM VALUES OF ATTENUATION ATTAINED DURING CYCLE AS A FUNCTION OF THE NUMBER OF CYCLES

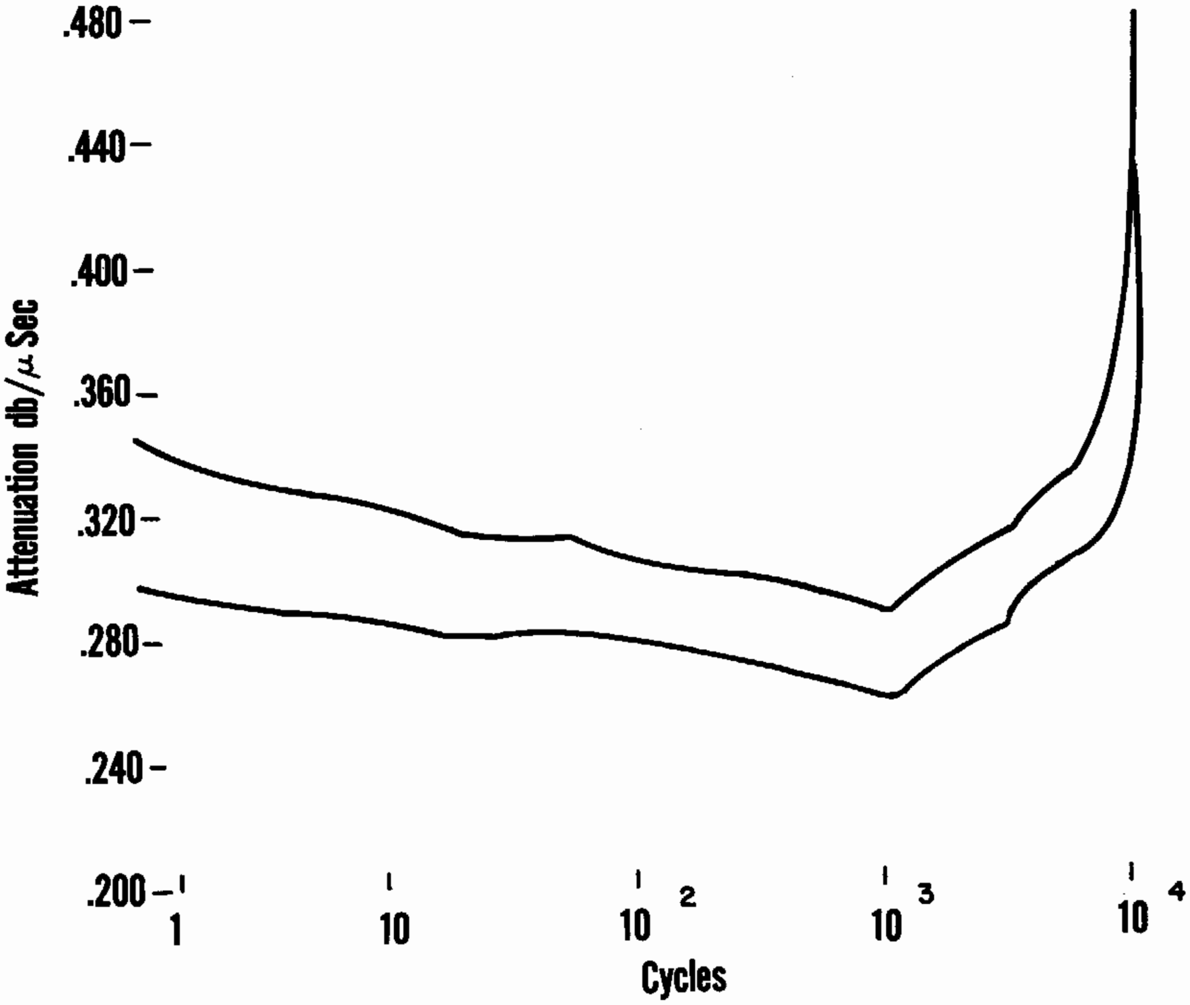


Figure 10.

RECOVERY OF ATTENUATION

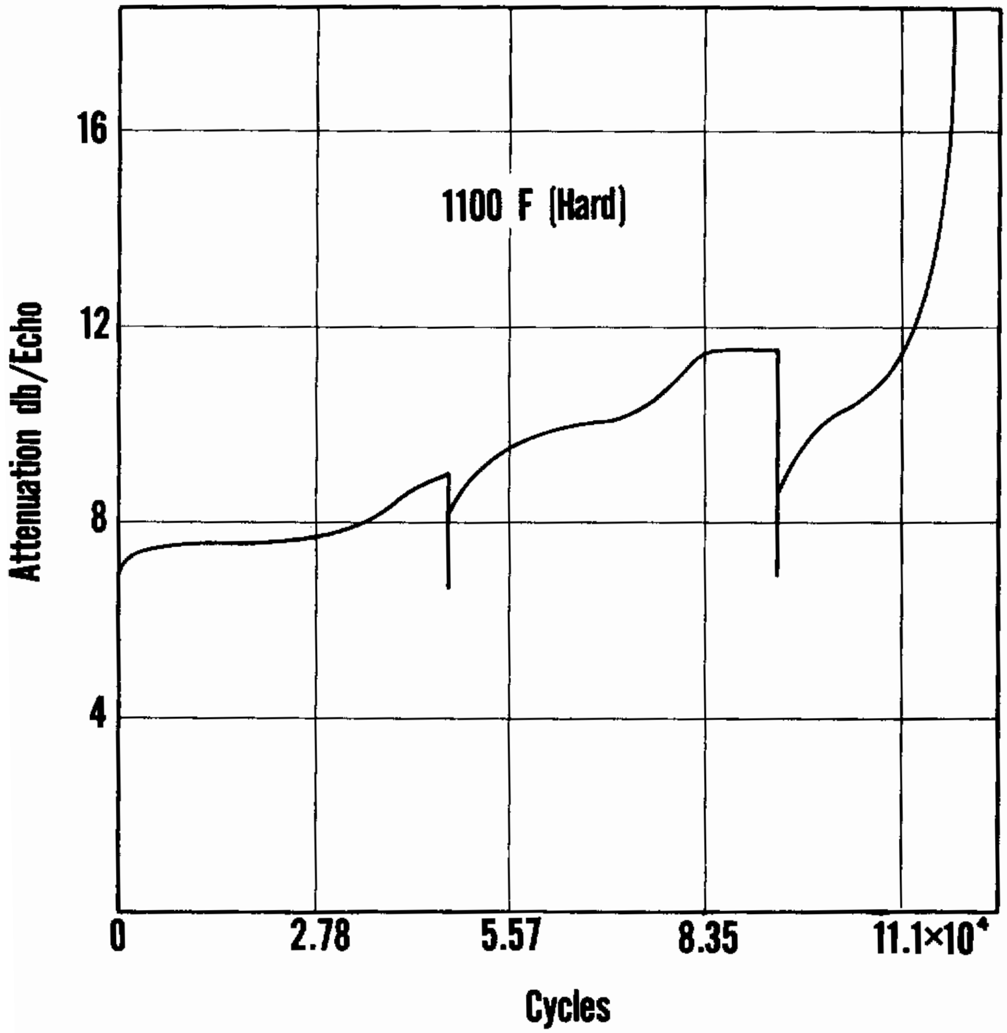


Figure 11.

$\left(\frac{\Delta V}{V}\right)$ VERSUS STRESS IN ALUMINUM AT TWO FREQUENCIES

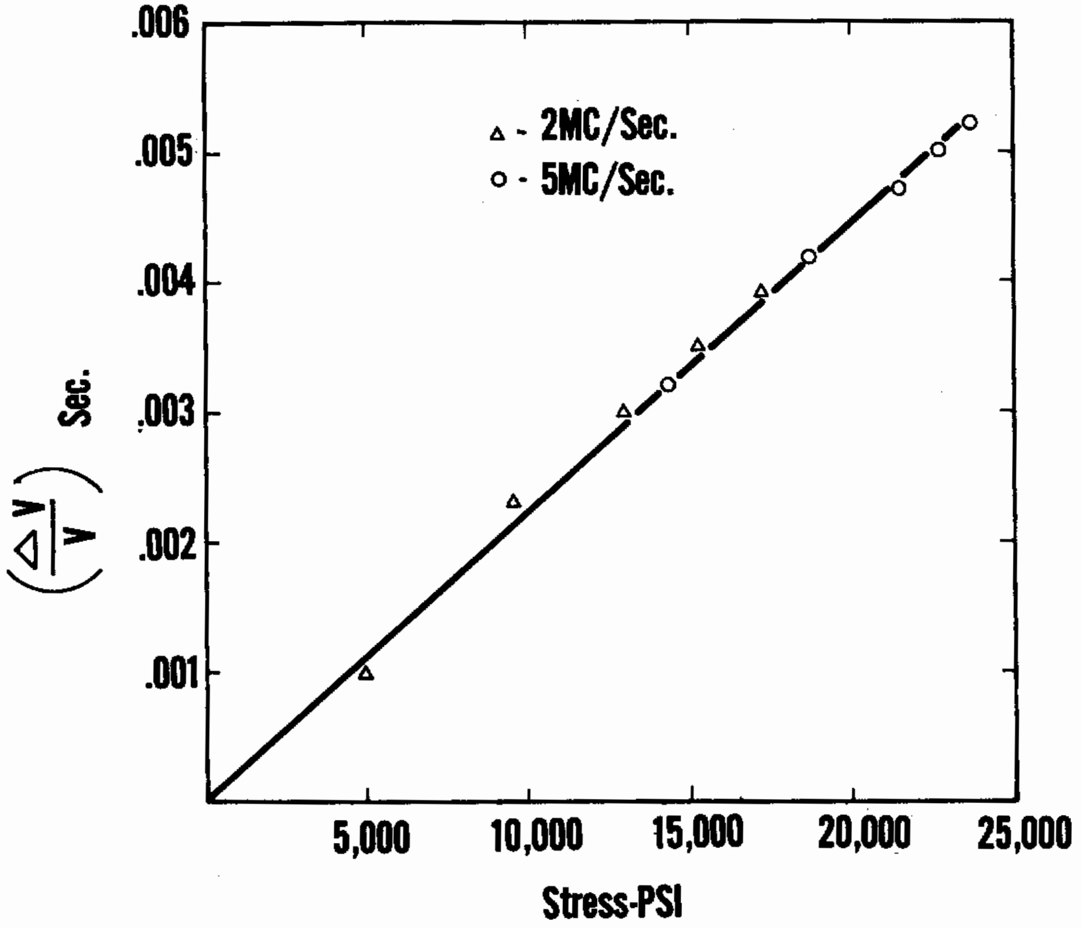


Figure 12.