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Effects of Selected Physical Agents on the Performance of Acoustically Absorptive Materials

By J. Alton Burks, T. C. Ruhe, and E. R. Spencer

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	hp	horsepower
dB/s	decibel per second	Hz	hertz
°F	degree Fahrenheit	in	inch
ft	foot	lb/ft^2	pound per square foot
ft^2	square foot	lb/ft^3	pound per cubic foot
ft^3	cubic foot	pct	percent
ft/s	foot per second	rpm	revolution per minute
gal	gallon	s	second
h	hour		

EFFECTS OF SELECTED PHYSICAL AGENTS ON THE PERFORMANCE OF ACOUSTICALLY ABSORPTIVE MATERIALS

By J. Alton Burks[1], T. C. Ruhe[2], and E. R. Spencer[1]

ABSTRACT

When acoustical materials are used in a mining environment for noise control purposes, they are subject to environmental deterioration from hydraulic fluid, moisture, and dust. These and other factors can cause physical degradation of the material, which can lessen its ability to absorb sound. In this study, the Bureau of Mines measured the sound absorption properties of 16 different acoustical materials after 4 sample treatments: (1) being kept clean and dry (as received from the supplier), as a control or reference standard, (2) immersion in water and draining, (3) immersion in 100-pct-petroleum-type hydraulic fluid and draining, and (4) exposure in a coal mine. The last three treatments were used to approximate the type of physical degradation that can be experienced in actual use. The impedance tube or standing wave method was used to measure the normal absorption coefficient. It was found that the absorption coefficient of most materials was adversely affected by the retention of either oil or water, with oil having the greater effect. The only class of materials that was affected by neither oil nor water was neoprene foam.

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INTRODUCTION

Noise levels in excess of 90 dB have been shown to be injurious to the hearing of miners exposed to such noise levels in the workplace (*1*).[3] The Federal Mine Safety and Health Act of 1977, Public Law 91-193, as amended by Public Law 95-164, mandates the control of workers' exposure to loud noise by reducing either the exposure time or the level of noise. The obvious choice is to prevent the generation of the excess noise by modifying the noise source through a change in process or equipment redesign. In most cases this approach, though preferred, is simply not feasible for a number of reasons, such as cost or lack of technology. An acceptable alternative is to somehow reduce or control the noise after it is generated but before it has reached the exposed worker. Noise control in this manner is usually achieved by the application of both sound absorption and sound barrier materials. The current study is restricted to materials classed as "sound absorptive."

The function of sound-absorbing material is to convert the sound energy into some other, inoffensive form of energy. The ability of a material to absorb sound is characterized by its absorption coefficient, which ranges from 0 (no absorption) to 1.0 (total absorption). Generally, for a material to be an effective absorber of sound, it should be soft and porous so as to offer little resistance to sound waves impinging on it. For applications in most commercial and industrial environments, the use of such material is problem free. However, in a typical mining environment these materials are frequently subjected to physical agents such as dust, water, or oils that reduce the material's effectiveness by penetrating and clogging the porous structure. Thus, the performance of acoustical materials is unpredictable for extended in-mine use.

The purpose of this Bureau of Mines study was to investigate the effect of selected physical agents on the performance of acoustically absorptive materials. A representative cross section of materials was tested under carefully controlled laboratory conditions. Preparation and treatment of the samples are described in detail, so that these tests can be replicated by others. The change in absorption coefficient was measured as a function of frequency for each of 16 different acoustical products. This study was not intended to be a comprehensive evaluation of all possible materials; rather it was conducted as a pilot study to provide some guidelines in the selection and use of acoustical materials in the harsh mining environment until more complete documentation is available for these products. This work is in support of the Bureau's mission to reduce excessive noise levels in the workplace.

DESCRIPTION OF ACOUSTICAL MATERIALS AND THEIR PERFORMANCE

DEFINITION OF ABSORPTION COEFFICIENT

In general, when sound impinges on a boundary separating two media, some of the acoustical energy will be reflected from the surface, some will be absorbed, and some will be transmitted. Let the sound intensity associated with the incident, reflected, absorbed, and transmitted sound waves be indicated by I_i, I_r, I_α, and I_t, respectively, as shown in figure 1. The fraction of the energy absorbed is called the absorption coefficient and is defined by

$$\alpha = \frac{I_i - I_r}{I_i}.$$

Careful examination of this equation shows that the absorption coefficient is actually a measure of the acoustical energy that is not reflected, and only in this sense is it a measure of the energy absorbed by a material. If 100 pct of the incident acoustic energy is transmitted through a medium or surface (such as an open window), no energy is reflected and the absorption coefficient is seen to be 1.0. However, if the same sound energy strikes an infinitely hard wall, resulting in 100-pct reflection, the absorption coefficient is 0.

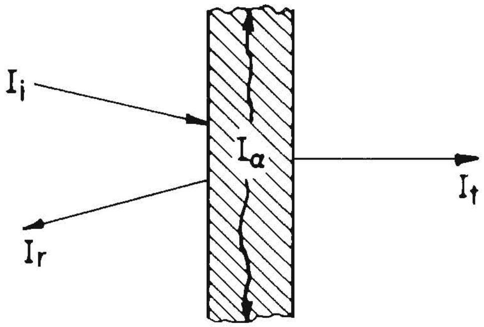

Figure 1.–Sound impinging on wall. (I_i = incident wave; I_r = reflected wave; I_α = absorbed wave; I_t = transmitted wave.)

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[3] Italic numbers in parentheses refer to items in the list of references preceding the appendixes.

ABSORPTIVE LOSS MECHANISM

Porous materials are the best known class of acoustically absorptive materials; they include glass fiber, open cell foam, mineral wool, sintered metals, and some porous ceramics. These materials are characterized by pores, which are open and allow sound energy to enter by a multitude of small holes or openings (fig. 2). The materials consist of series of tunnellike openings, which are formed by interstices in material fibers or by foamed products. If the pores and openings are too small and not opened together, the material is substantially less effective as a sound absorber.

In an effective sound absorber, the air in the center of the pores tends to move freely, expanding and contracting as compressions and rarefactions of the sound wave move through; however, the air near the boundaries of the pores (the cell walls or fibers) is still; thus, there is a shear force that results in frictional losses between this air and the freely vibrating air in the center. Because of the viscosity of air some energy is converted into heat, which is rapidly absorbed by the side walls, and isothermal expansion and contraction take place. When the sound is of low frequency, phase changes are relatively slow and there is time for heat energy to be absorbed by the boundaries from most of the vibrating air (particularly when the pores are small); thus, isothermal conditions exist for most of the air particles. When the sound is of high frequency, however, the rapid changes do not allow dissipation of the heat compression, and adiabatic conditions then exist over most of the pore space.

MEASUREMENT OF ABSORPTION COEFFICIENT

There are two standard methods for the measurement of sound absorption. The first is known as the reverberation room method and is described in American Society for Testing and Materials (ASTM) Standard C423-77, "Standard Method of Test for Sound Absorption of Acoustical Materials in Reverberation Rooms"*(2)*. This method is concerned with the performance of a material in a randomly incident, or diffuse, sound field. Such a sound field can be generated only in a special-purpose reverberation chamber. Also, the room must be sufficiently large so that the introduction of a highly absorbing specimen will not cause a net flow of energy in its direction and thus destroy the diffuse field. Because of this limitation, the specimen must be small enough that it will not interfere with the diffuseness, but it must also be large enough that data may be obtained. To avoid variations in procedures among the different laboratories, the ASTM standard requires the size of the specimen to be at least 72 ft^2, which is the usual size.

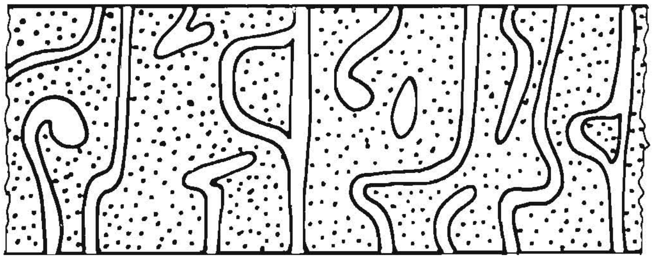

Figure 2.-Structure of porous acoustical material.

In a reverberation room, the measurement is made by introducing a source of sound into the room (usually a narrow one-third-octave band of random noise) and sustaining this source until the sound field has reached a uniform level throughout, a matter of about 1 s. The source is then quickly extinguished, and the rate at which the sound-pressure level decreases or "decays" in the room is measured. This can be done by reading the slope of a curve obtained on a high-speed graphic level recorder, or by timing with clocks the interval between two voltage levels. If an absorbent material is introduced into the reverberation room, the decay rate will be faster than it was for the empty room. The difference between the two absorption values obtained in these measurements can normally be assumed to be caused by the sample material, as the absorption of the area covered by the sample can usually be considered negligible. In equation form, the absorption coefficient is

$$\alpha_{rev} = \frac{0.9210\ V(d_2 - d_1)}{Sc},$$

where α_{rev} = acoustic absorption coefficient,

V = room volume, ft^3,

d_2 = decay rate for room with sample, dB/s,

d_1 = decay rate for empty room, dB/s,

S = area of sample material tested, ft^2,

and c = speed of sound in air, ft/s.

The second standard method of determining sound absorption is known as the impedance tube method and is restricted to sound normally incident upon a specimen. This standard method is described in detail in ASTM C384-85, "Standard Test Method for the Impedance Tube Method *(3)*." This technique has limitations because there is no way to accurately relate impedance tube data for a sample to the absorption coefficient obtained with a randomly incident sound field, which is the more common situation. However, it is a convenient laboratory method and requires only small sample sizes, e.g., sample sizes on the order of several square inches, compared with 72 ft^2 for the reverberation technique. For this reason, the impedance tube method, also known as the standing wave method, was chosen for use in this study.

The sample material is placed in front of a heavy termination at one end of a rigid walled tube, and a loudspeaker is mounted along the axis at the other end. The loudspeaker is fed with pure tone signals (at one-third-octave center frequencies), and this then radiates plane waves down the tube toward the sample; as long as the diam of the tube is small compared with the sound wavelength, transverse modes cannot be set up within the tube. The plane waves are then partially reflected by the sample and travel back along the tube toward the loudspeaker. This results in a longitudinal interference pattern consisting of standing waves set up within the tube (fig. 3). A microphone connected to an extension probe tube is moved along the axis to measure the variation in sound pressure within the standing wave tube. From measurements of the ratio of maximum to minimum sound pressure within the tube, the absorption coefficient of the sample, at normal incidence, can be calculated.

Although the principle of operation of the impedance tube is well known, it is presented here for completeness. At any point, the incident sound pressure p_i of a plane wave traveling down the tube from the loudspeaker to the specimen can be put in the form

$$p_i = A \cos \omega t,$$

where A = pressure amplitude,

ω = angular frequency, $= 2\pi f$,

f = frequency,

and t = time.

The reflected wave, at the same point in the tube, has a pressure p_r, given in terms of its amplitude B and distance $2x_i$ from the sample surface as

$$p_r = B \cos \omega \left(t - \frac{2x_i}{c} \right) .$$

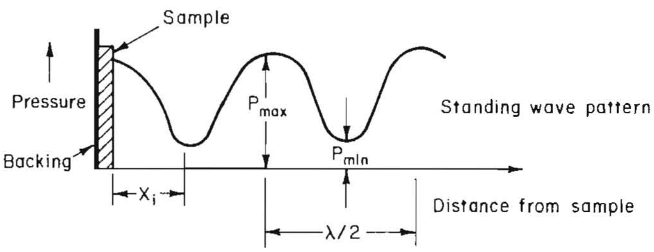

Figure 3.–Interference pattern generated in standing wave tube. (P_{max} = maximum pressure; P_{min} = minimum pressure; x_i = distance from sample; λ = wavelength.)

The total sound pressure p_T at a distance x_i from the sample is therefore

$$p_T = p_i + p_r = A \cos \omega t + B \cos \omega \left(t - \frac{2x_i}{c} \right) .$$

The maximum pressure will therefore occur when $x_i = \lambda/2$, where λ = wavelength, and will be equal to

$$P_{max} = (A + B) \cos \omega t,$$

and the minimum pressure will occur when $x_i = \lambda/4$, to give

$$P_{min} = (A - B) \cos \omega t.$$

The standing wave ratio n is defined as the ratio of maximum to minimum sound pressures within the tube so that

$$n = \frac{A + B}{A - B} .$$

Since, by definition, the reflection coefficient $r = B/A$,

$$r = \frac{n - 1}{n + 1} .$$

Using the relation $\alpha = 1 - r^2$ gives the sound absorption coefficient as

$$\alpha = \frac{4n}{(n + 1)^2} .$$

Hence, by measuring the standing wave ratio n, one can directly calculate the normal incidence absorption coefficient. It can be seen that if $n = \infty$ (i.e., $A = B$), then $\alpha = 0$; and if $n = 1$ (i.e., $B = 0$), then $\alpha = 1$, as would be expected.

It is found that the normal incidence absorption coefficient values measured in an impedance tube are generally lower than the random incidence values obtained from the reverberation room method. At low frequencies the difference is only slight, but at high frequencies the tube values are generally 50 pct lower than those measured in a room. It is important to ensure that the physical restrictions on the size of the tube are obeyed. These are that the length of the tube shall exceed $\lambda/4$ and that the diam of the tube shall not exceed 0.58λ (to ensure plane waves, and therefore no transverse waves, in the tube). Hence a 4-in-diam, 3-ft-long tube would have a useful range of 90 to 1,800 Hz. In order to make measurements over the range of 90 to 6,000 Hz, two different-sized tubes are required: a smaller one for high frequencies and a larger one for low frequencies.

MATERIAL SELECTION

Technical literature was solicited from 50 companies that supply sound absorptive materials and studied extensively. The companies were listed among the manufacturers and/or distributors of foam, glass fiber, and mineral fiber products in reference 4. It should be noted that the exposed surfaces of many acoustical materials used in harsh environments are partially or completely sealed to minimize the infiltration of oil, water, dust, and other harmful elements. The most common sealing method consists of covering the material with a thin, flexible plastic membrane. Such a covering can be applied in several ways. It can be glued to the surface of a foam or stitched to a fiberglass pad (forming a quilted blanket). In these applications, the covering is referred to as a "facing." The acoustical material can also be encased in a plastic bag.

Consultations were also held with knowledgeable Bureau staff members and U.S. Mine Safety and Health Administration (MSHA) personnel before selecting and ordering 16 noise abatement materials for testing (table 1). The following materials were recommended: fiberglass quilted blankets, fiberglass board, mineral board, fiberglass baffles, and neoprene foam. These materials generally have better flammability and temperature ratings (according to various Underwriters Laboratories (UL) and ASTM tests) than polyurethane foams, which is especially important in underground coal mining applications. The vinyl covering part of the quilted blanket materials reduces personnel exposure to irritating fibers, and rigid board (versus soft) material can be sawed and drilled for easy fabrication and installation. Removal for machine maintenance is also facilitated.

Table 1.–Noise abatement materials selected for testing

Material	Description	Trade designation	Manufacturer	Nominal density, lb/ft^3
Fiberglass quilted blanket:				
1	Yellow, gray-vinyl-faced on 1 side.	Sorba-glas 110	Industrial Noise Control.	2
2	Gray-vinyl-faced on both sides	Sorba-glas 120	do	2
Mineral board:				
3	Yellow semirigid board, unfaced.	FBX 1000	Fibrex, Inc	8
4	Brown rigid board, unfaced.	FBX 1900	do	15
Fiberglass board:				
5	Yellow rigid board, unfaced.	Type 705	Owens/Corning	6
6	Yellow rigid board, white-faced on 1 side	Type 706	do	6
Fiberglass baffle: 7	White polybag	Series 24	Industrial Noise Control.	1.6
Neoprene foam:				
8	Orange, unfaced	LS-200	Toyad Corp.	6 -8.5
9	Brown, unfaced	LF-1800	Cartex Corp.	6.5-8
Polyurethane foam:				
10	Black, foil-faced on 1 side.	Coustifoam 100 MR	Ferro Corp.	2
11	Green, foil-faced on 1 side.	Cousticomposite 25-5-50 MR.	do	11
12	Black, unfaced	Type K-10	Industrial Noise Control.	2
13	Black, plastic-faced on 1 side.	Type K-10T	do	2
14	Beige, unfaced.	Scottfelt 4-900	Scott Paper Co.	7
15	Black, embossed on 1 side.	Afonic	do	2
16	Black, rubber-faced on 1 side.	Industrial Foam 4100	Airtex Industrial	2

In addition to materials selected because of the above recommendations, materials were selected because they were listed in the majority of the technical literature from the companies selling products for industrial use. Materials in this category are fiberglass quilted blankets, fiberglass baffles, and urethane foams. The urethanes are most commonly used in unfaced, faced, and composite forms (attached to vinyl barriers). In addition to these general-purpose urethanes, three specialized types were ordered. Scottfelt polyurethane foam (material 14) has increased sound absorption properties. It is made from a standard-density foam by compression and heat, and has a higher density. Afonic polyurethane foam (material 15) has an embossed surface, which gives it a greater surface area; and Industrial Foam polyurethane foam (material 16) has a rubber coating sprayed on a surface to seal it, instead of a glued-on facing. In all three of these materials, the extra processing causes a tuning or shift of the absorption frequency spectrum from that of the original material.

MATERIAL SPECIFICATION

THICKNESS

The fiberglass baffle (material 7) has a nominal thickness, specified by the manufacturer, of 1-1/2 in. The other 15 samples are rated at 1 in. This is a standard thickness for acoustical materials; it is about the maximum that the sample disk coring tools could cut without excessive distortion or crumbling of the materials. Since the baffle has the lowest density (table 1) of all of the samples, it could easily be compressed to a thickness of less than 1 in before cutting. All nine foams and the three lowest density fibrous materials are very resilient. They could be compressed by 30 to 70 pct, and when released, they regained almost their original thickness within a minute. The 16 materials selected vary in three basic ways: chemical type, surface finish, and density.

CHEMICAL TYPE AND FLAMMABILITY RATING

The chemical composition determines the flammability rating and upper operating temperature limit of each material. This is probably the most important criterion for selection in industrial applications. Listing acoustical materials in order of decreasing temperature rating gives the following general sequence: mineral fiber, glass fiber, neoprene foam, and urethane foam. This ranking is not absolute, since the addition of enough fire retardant (chemicals) to almost any material can improve its rating. In selecting an acoustical material for a specific application, there is a tradeoff involving cost and properties. Generally a material with a higher temperature rating has a greater cost and a higher density. The materials are all rated by their respective manufacturers as having desirable flammability characteristics, according to the results of UL and ASTM tests. These specific ratings are not listed in this report because all the companies did not use the same tests to rate their materials. These specifics are detailed in each manufacturer's product literature.

The two common types of polyurethane are polyester and polyether. They are both about the same with respect to sound absorption, flammability rating, and cost. Polyester is more widely used because its higher tensile strength makes it more suitable for hanging applications. However, polyether is somewhat better in humid environments.

SURFACE FINISH

This study includes materials with the following surface finishes: unfaced, faced (both glued and stitched on), coated, and unfaced with embossing. These various surfaces have a number of different properties, advantages, and applications.

Unfaced materials cost the least and are usually placed in relatively clean and dry locations, or are covered with other materials. In this report, they represent a worst case exposure for degradation studies.

The facings selected for this study range from 0.001 to 0.005 in thick and are made of treated paper, aluminum foil, and plastic. Some were reinforced with woven threads. These types of surfaces can be cleaned to remove deposits that can impair acoustical performance. Facings are used primarily to increase the durability of a material by giving protection against surface abrasion and penetration by dirt, moisture, oil, and cleaning solvents. Facing also allows changing a material's reflectivity to increase illumination, or changing the color for safety or aesthetic appeal; e.g., a smooth sealed surface would lower the resistance to airflow in ventilation applications.

Surface coatings, although not as smooth, can perform the same functions as facings at generally lower cost. Surface coating and embossing can be used to change the acoustical properties of the materials, as mentioned previously.

DENSITY

The densities of the materials selected range from 1.6 to 15 lb/ft^3. The standard density for general-purpose noise absorbers is 2 lb/ft^3. Sample 14 is an example of a higher density material that was made by compressing a lower density material in order to tune it for better mid- and high-frequency absorption. The other higher densities listed in table 1 are inherent properties of materials chosen for other reasons.

DETAILED DESCRIPTION OF EACH MATERIAL

1. Sorba-glas 110 is a quilted blanket material with a yellow fiberglass core. This is covered on one side and the edges with a 0.005-in-thick, silver-gray-vinyl-coated glass fabric of high strength and abrasion resistance. The other side is covered with a loosely woven, white-vinyl-coated glass screen, which looks like a very coarse cheesecloth. These two facings are stitched to the central core.

2. Sorba-glas 120 is the same as Sorba-glas 110 except that both sides are covered with silver-gray vinyl fabric.

3. FBX 1000 is a semirigid, unfaced yellow mineral board, which crumbles easily when handled. It looks like fiberglass. According to the manufacturer, it is rated for use at service temperatures through 1,000° F. It is a combination of a rock steel slag fiber and a resin binder.

4. FBX 1900 is a rigid, unfaced dark gray-brown refractory mineral board. According to the manufacturer, it is rated for continuous service at temperatures up to 1,900° F. It is made from semirefractory fibers using an organic-inorganic binder system.

5. Type 705 industrial insulation is made of yellow glass fibers preformed into a rigid, unfaced board using a resin binder.

6. Type 706 insulation is made by covering type 705 insulation on one side with a white all-service jacket. This is an embossed laminate of white kraft (paper) facing with glass fiber reinforcing and a foil backing.

7. The Series 24 anechoic baffle is also known in industry as an overhead or unit absorber. It consists of a yellow fiberglass pad encased in a 0.002-in thick white polybag. The edges of the plastic bag are heat sealed. The baffle is 2 ft by 4 ft by 1-1/2 in thick, with two grommet holes for hanging along the top (long) edge. The continuous operating temperature rating is -50° to 200° F.

8. LS-200 is an unfaced orange polymeric chloroprene-neoprene-latex foam, which was originally designed for transit seating applications. It is useful as an acoustical material, but is not rated by the manufacturer as such. Neoprene (although more expensive) is preferred for underground mining applications over urethane foam, because of its better flammability rating.

9. LF-1800 is an unfaced brown polymeric chloroprene neoprene foam. The description of LS-200 neoprene foam also applies to this material.

10. Coustifoam 100 MR is a black polyether polyurethane foam with a three-layer facing on one side. This facing is made with aluminum foil on the outside, backed by Mylar polyester plastic film reinforced with fiberglass yarns.

11. Cousticomposite 25-5-50 MR is made of four layers, with nominal thicknesses as follows: 1/4-in black polyester polyurethane foam, 1/16-in green vinyl septum (1/2 lb/ft^2), 1/2-in black polyether polyurethane foam, and aluminum foil facing (backed by Mylar polyester plastic film reinforced with fiberglass yarns).

12. Type K-10 is an unfaced black polyester polyurethane foam that contains a fire retardant.

13. Type K-10T is a black polyester polyurethane foam that contains a fire retardant. It is faced on one side with black Tedlar polyvinyl fluoride plastic film.

14. Scottfelt 4-900 (firmness grade 4) is an unfaced beige polyester polyurethane fire-retardant foam. It is made by compressing and heating a standard-density foam (2 lb/ft^3) to impart a permanent compression set. This process results in a shift or tuning of the absorption spectrum to enhance the absorption of mid- and high-frequency sound.

15. Afonic is an unfaced black polyester polyurethane foam, that contains a fire retardant. It has an embossed surface on one side, which is designed to increase absorption in the low- to medium-frequency ranges.

16. Industrial Foam 4100 is a black polyester polyurethane foam, coated on one side with 748 black Foamkote Hypalon rubber, which seals the surface like a facing. This coating improves low-frequency sound absorption.

PREPARATION AND TREATMENT OF SAMPLES

Four sets of samples from the 16 candidate acoustical materials were prepared for environmental and acoustical testing. Each set was subjected to a different treatment. One set was kept clean and dry (as received) and served as a baseline control or reference standard. A second set was immersed in water for about 8 h and drained overnight (about 16 h). A third was immersed in 100-pct-petroleum-type hydraulic fluid (Mobil DTE-25) for about 8 h and drained overnight. The fourth set was placed in the Bureau's Safety Research Coal Mine (SRCM) and was left there for about a year.

The last three treatments simulated physical degradation of the type experienced in actual use. For the first three treatments, sample disks of nominal 1- and 4-in diam were first cut from the bulk sheet materials. These two sizes were dictated by the ID of the sample holders of the sound absorption measuring instrument (a Bruel & Kjaer standing wave apparatus, type 4002). Mine sample (treatment 4) disks were cut from the sheets of materials after they were exposed. For statistical analysis purposes, triplicate sound absorption measurements were made. Three different pairs of 1- and 4-in disks of each material for each of the four treatments were used. Therefore, 384 disks were required.

CUTTING

In order to cut 384 disks to two uniform sizes, special equipment was constructed. One-piece coring tools (machined from stainless steel cylinders) were made in the configuration of a hole saw, with a 2-1/2-in-long, 3/8-in-diam arbor (shaft) for mounting in a drill press chuck. The actual ID's of these two core cutters were 1-1/8 and 3-7/8 in. Instead of teeth, the cutters each had a smooth knife edge, which was initially sharpened by machining a taper around the OD. Resharpening was done by honing the outside of the edge with a small smooth-cut file. The inside depth of both cutters, which had been reduced slightly by resharpening, was about 1-7/16 in. Two 3/8-in-diam holes were drilled in each cutter, parallel to the shaft, to accommodate flat end rods for pushing out the sample disks after cutting. To minimize personnel exposure to irritating glass and mineral fibers during cutting operations, a 1/4-hp drill press was bought that was small enough to be mounted inside a laboratory exhaust hood. The drill press was operated at the slowest speed (500 rpm).

To support and restrain the soft, flexible sample materials to prevent excessive distortion on cutting, a special clamping apparatus was designed and constructed. It consisted of two 12-in-square aluminum plates that sandwiched a 10- by 14-in piece of sample. One or two layers of 1/8-in-thick cardboard were placed under the sample to prevent the cutter edge from contacting the aluminum. The bottom plate was 3/8 in thick and was bolted to the drill press table. Studs (2 in long with 1/4-20 threads) were screwed into each corner of the bottom plate. These screws, which passed through matching holes in the top 3/16-in-thick plate, served as guide pins. This top plate also had a 1-1/2- and a 4-3/4-in hole for the cutter to pass through. The studs also projected above the top plate enough to allow a wingnut to be screwed onto each one. Spring-type clamps, placed on each side of the assembly, could be used in addition to or instead of the wingnuts as required. The degree of compression required to hold each of the 16 sample materials adequately varied widely. E.g., sample 4 needed no clamping, but sample 10 had to be compressed to a thickness of less than 1/4 in. Some covered materials were cut with the facing up and others with the facing down. These factors had to be determined by trial and error.

To get 384 "good" sample disks, approximately 1,000 were cut and over half were rejected because of various defects. The foam disks were skewed if the clamping on the four sides was uneven, and tapered if the compression was excessive. Other problems on both foams and fibrous materials included having the facings separate or cutting around only part of the circumference. On some disks the material and/or the facing had ragged edges. With the fibrous board materials, the disks tended to crumble and separate into layers, especially when ejected from the cutter.

The 1/4-hp drill press used in the exhaust hood was not powerful enough to cut 4-in disks from all the materials. On fibrous board materials 4, 5, and 6, the cutter was rotated and lowered until the drill press stalled, at about 1/2-in penetration. The cutter was then removed from the chuck, and the operation was completed by rotating and pressing the cutter down by hand. A 1/2-hp drill press had to be used to cut 4-in disks from sample 14. In this case the machine would also stall unless a new, tightly stretched V-shaped drive belt and a very sharp cutter were used.

ENVIRONMENTAL DEGRADATION

Water and Oil Treatment

For water and oil treatment tests, sample disks were wrapped in single-ply cheesecloth to facilitate immersion and draining. Two sets of 16 cloth bags were assembled, with three 1-in and three 4-in weighed disks in each (fig. 4). The 1- and 4-in disks were alternated and laid flat in a single layer in the bag. The approximate overall dimensions were about 15- by 15- by 1-in thick. The disks were held in place by staples and thread. Every disk and bag was numbered. A plastic or metal number tag was attached to a brass grommet on each bag before immersion in water or oil to ensure proper identification.

A 32-gal plastic trash can was modified for use as an immersion and draining container (fig. 5). The cheesecloth bags were laid flat in the bottom and weighted to ensure total immersion for about 8 h. For draining the bags overnight (about 16 h), an aluminum band was bolted around the inside circumference of the can just below the rim to serve as a hanging rack. A 1/4-in-diam stainless steel rod was also bolted across the top center of the band. The band and rod served as supports for a removable 1/2-in-mesh galvanized wire screen. Three different positions were tried for draining the bags: lying flat on the screen, lying with the 15- by 1-in edge on the screen, and hanging by the grommet on the end of the bags. This third position gave the best results and was used for all the samples (fig. 6). While the samples were draining overnight, the can was covered with a tight-fitting lid. In the morning the bags were turned upside down and hung by the other end for about 1 h, which more evenly distributed the liquid among the six disks. Then the bags were opened, each disk was weighed, and the percent weight gain was calculated (table 2). The disks were then sealed in plastic bags until the acoustical measurements were made.

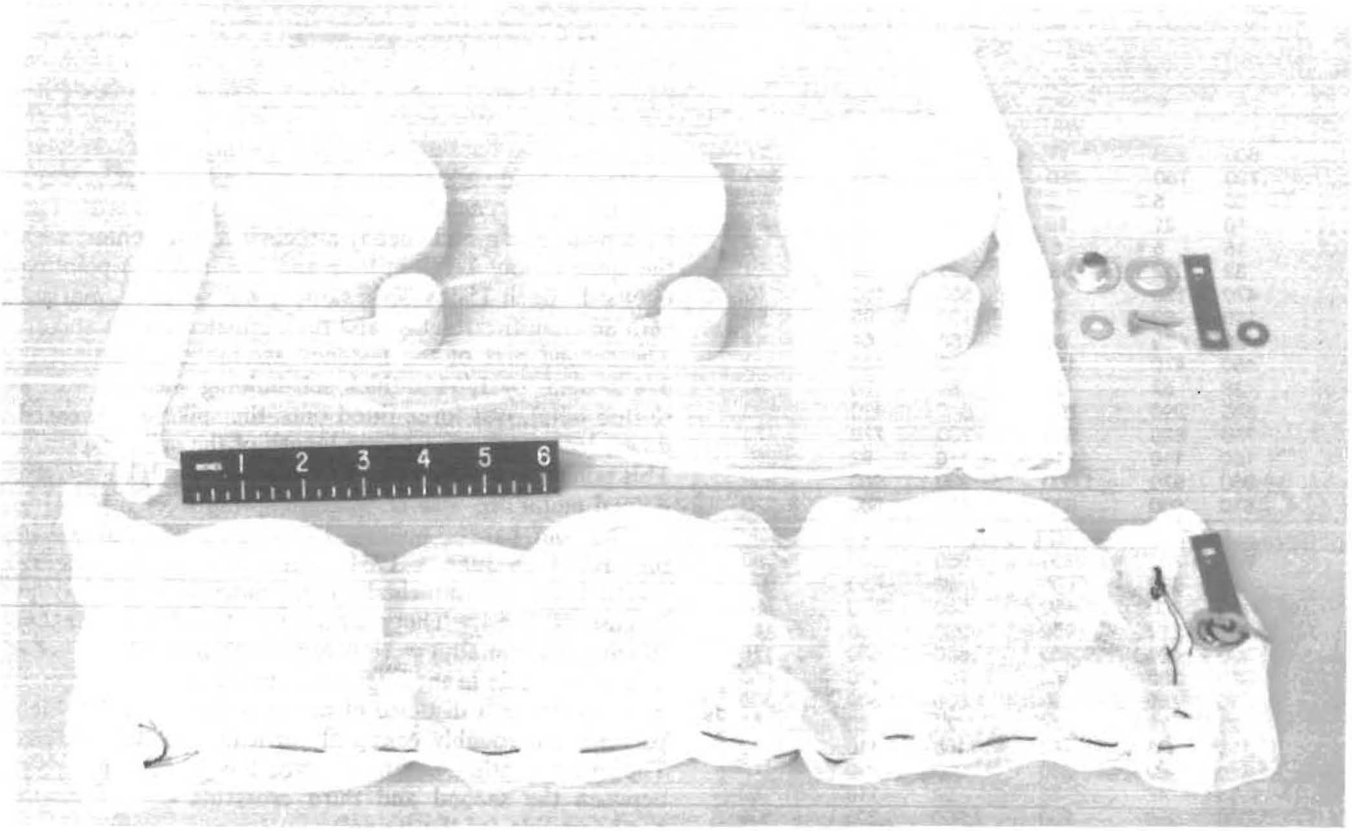

Figure 4.–Typical set of acoustical samples prepared for environmental testing.

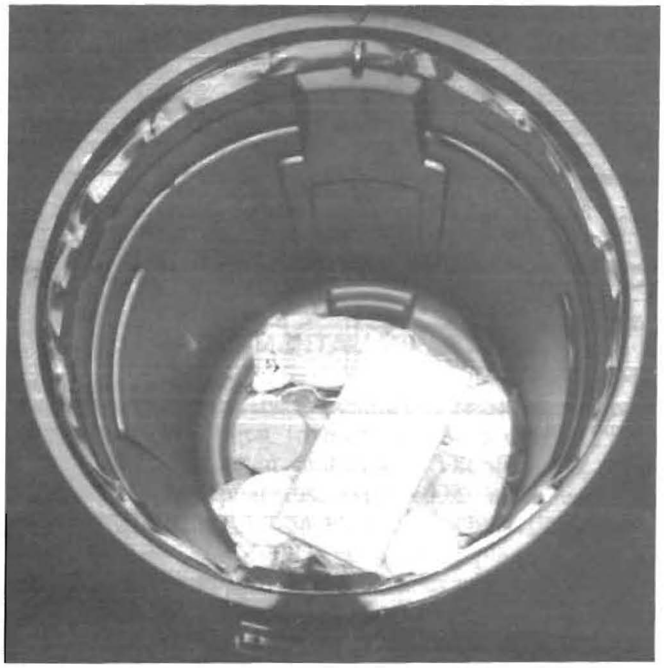

Figure 5.–Immersion apparatus for testing acoustical samples in oil or water.

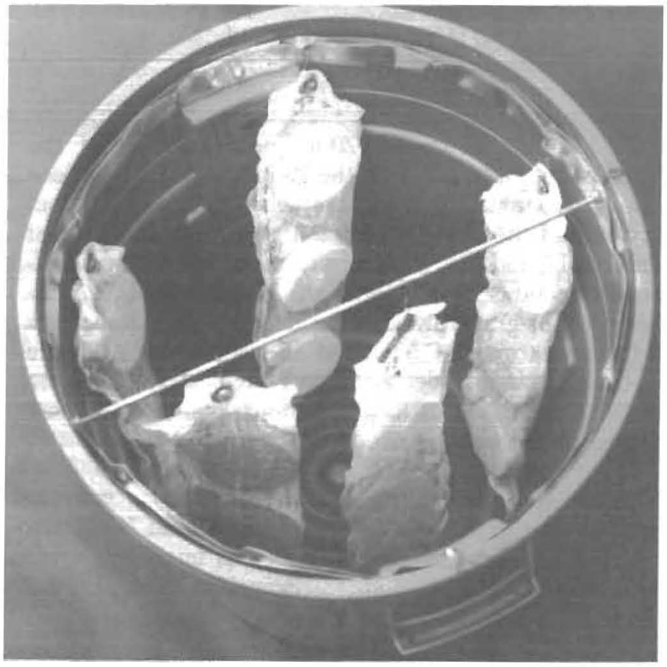

Figure 6.–Apparatus for draining oil- or water-soaked acoustical samples.

Table 2.–Percent weight gain of noise abatement materials after immersion in water and oil

Material	4-in-diam disks			1-in-diam disks		
	A	B	C	X	Y	Z
			WATER			
1	800	220	17	630	130	27
2	790	750	780	690	620	560
3	39	5.2	5	16	9.4	4.6
4	10	21	12	26	24	31
5	16	5.4	6.5	39	9.3	9.8
6	32	12	8.8	21	25	14
7	470	130	40	550	150	40
8	110	89	90	100	95	90
9	31	39	66	58	64	44
10 ...	460	470	470	420	420	430
11 ...	38	52	52	59	70	83
12 ...	590	390	700	640	470	650
13 ...	730	830	615	730	770	470
14 ...	180	110	210	170	92	260
15 ...	960	970	1,000	930	960	850
16 ...	610	650	670	450	580	520
			OIL[1]			
1	800	740	830	950	1,000	990
2	690	590	660	720	850	990
3	400	400	450	550	550	380
4	220	210	200	260	280	180
5	390	420	430	650	630	110
6	380	380	460	850	870	800
7	710	750	690	1,600	1,500	1,300
8	91	79	78	71	60	61
9	130	85	120	160	110	52
10 ...	240	500	230	210	290	240
11 ...	55	47	38	92	110	53
12 ...	1,000	980	900	1,300	1,200	630
13 ...	190	140	92	210	150	170
14 ...	550	550	500	160	630	110
15 ...	530	660	630	470	510	420
16 ...	600	550	500	490	470	410

[1] Mobil Oil Corp., DTE-25 hydraulic fluid (100-pct-petroleum type).

Coal Mine Exposure

Four wooden panels, each measuring 4 by 3 ft, were used to mount a 15- by 20-in piece of each of the 16 acoustical materials, with the 20-in and 4-ft dimensions running horizontally. Each sample was placed 2 in from the edges of the board, which left gaps between adjacent samples of 2 and 4 in, respectively, in the vertical and horizontal directions. Each panel was constructed of 1/2-in-thick exterior-grade plywood backed up with a framework of furring strips (34 by 2-1/4 in–actual size). Three lengths of 3/4-in-wide perforated steel strapping were bolted to the top (4-ft length) of each panel to facilitate hanging it on the mine rib.

Each sample was attached to the board with five stickpins, one at each corner and another at the top center position (fig. 7). This fastener assembly consisted of three parts, and the mounting was done as follows. First, a 2-in-square perforated steel base plate about 1/32 in thick, with a self-adhesive backing, was stuck to the board. To give additional holding strength, two 5/8-in-long tacks were driven through each base plate and into the board. The base plate had a nail (head) attached to the center, with the spike (about 1-1/8 in long and 1/8 in diam) pointing outward. Each 15- by 20-in sample was weighed, marked with an identification tag, and then impaled on the spikes. The second part of the fastener assembly, a nominal 1-3/4-in-diam by 1/64-in-thick self-holding washer (with a slotted hole), was force fitted onto the spike and pressed down, leaving about a 1/4-in length of the spike exposed. This point was covered with the third part, a 7/16-in-diam domed metal cap with an internal spring steel clip.

The four panels, holding 15 samples, were placed in the SRCM on June 5, 1984. Sample 16, which was received later, was attached to the panel in the mine on August 24, 1984. The panels (with the 4-ft dimension running horizontally) were wired to spads (wedge-shaped nails with a hole in the large end) driven into the 7-ft-high mine rib (over a distance of about 20 ft). The 3-ft-high panels were roughly centered vertically on the 7-ft rib. The exact location was in the No. 1 butt, return airway, between the second and third crosscuts outby, on the northeast side (of the tunnel).

In the mine, the samples were subjected to moisture, fumes, rock dust, and coal dust. The samples were removed on May 29, 1985 (after about a year) and reweighed, and the percent weight gain was calculated (table 3). Then disks were cut from the 15- by 20-in sample sheets for acoustical measurements.

Table 3.–Percent weight gain of noise abatement materials after exposure in mine for 1 year

Material[1]	*Gain*[2]	*Material*[1]	*Gain*[2]
1	0.7	9	5.5
2	.7	10 ...	3.5
3	.1	11 ...	1.7
4	.2	12 ...	1.3
5	1.1	13 ...	2.4
6	1.4	14 ...	2.0
7	.5	15 ...	6.5
8	6.7	16 ...	.6

[1] 15- by 20-in samples.

[2] Approximate.

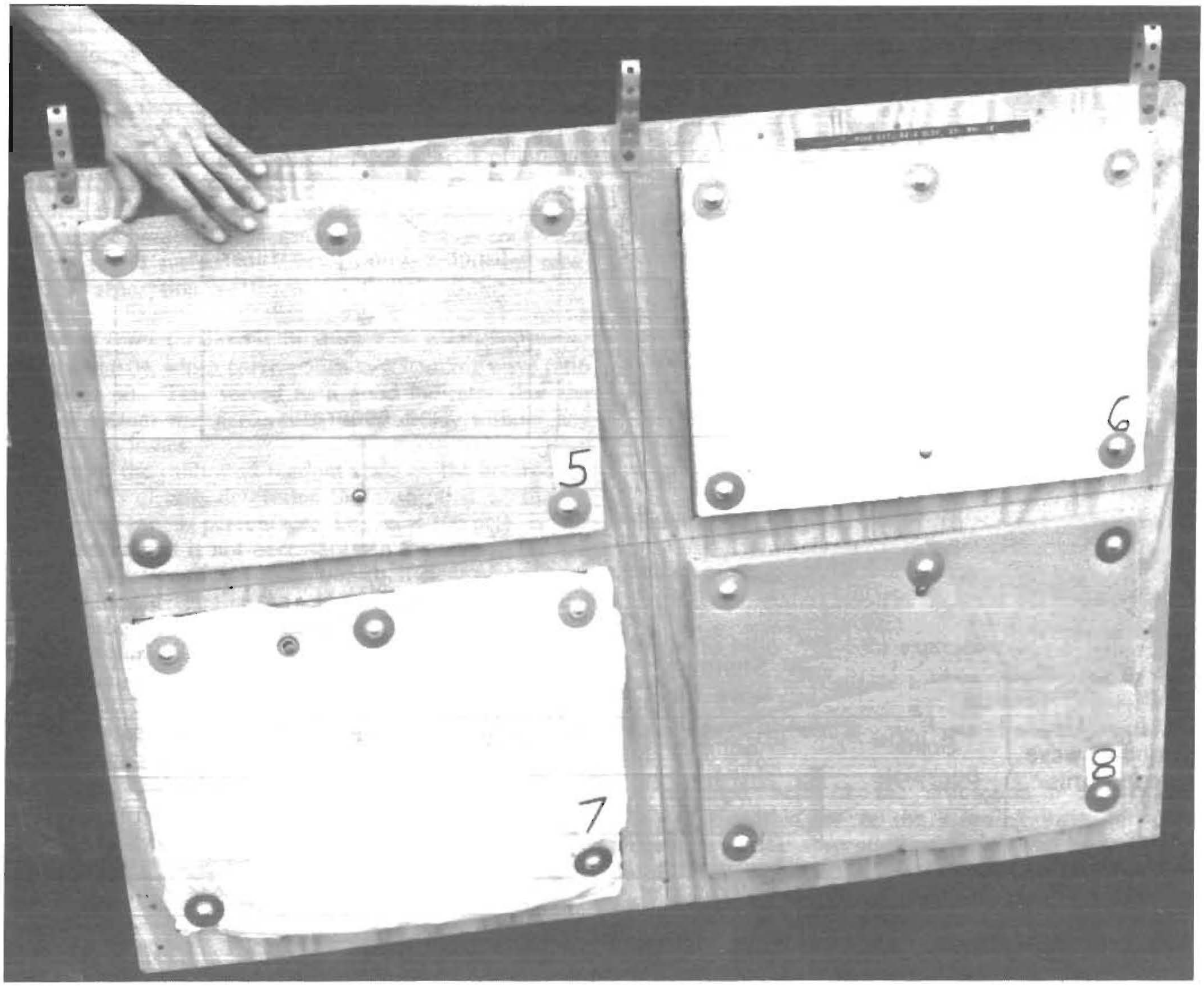

Figure 7.-Mounting of acoustical samples for in-mine testing.

MEASUREMENT OF ABSORPTION COEFFICIENT WITH THE IMPEDANCE TUBE

EXPERIMENTAL APPARATUS

As noted earlier, the impedance tube or standing wave apparatus was chosen to measure the absorption coefficient of the selected materials. The Bruel & Kjaer standing wave apparatus, type 4002, and supporting electronic instrumentation are shown schematically in figure 8. To facilitate the generation of plane waves, the apparatus is equipped with two tubes with ID's of 3.9 in and 1 in, respectively. The large tube is utilized for the frequency range from 100 to 1,600 Hz and the small tube from 800 to 6,300 Hz. The sine wave generator contained within the Bruel & Kjaer heterodyne analyzer, type 2010, is used to drive the loudspeaker at the center frequency of the one-third-octave bands from 100 to 6,300 Hz. The resulting acoustic signal is detected by the microphone probe and microphone and transmitted to the analyzer, where the sound pressure level is analyzed and displayed as a voltage or in decibels.

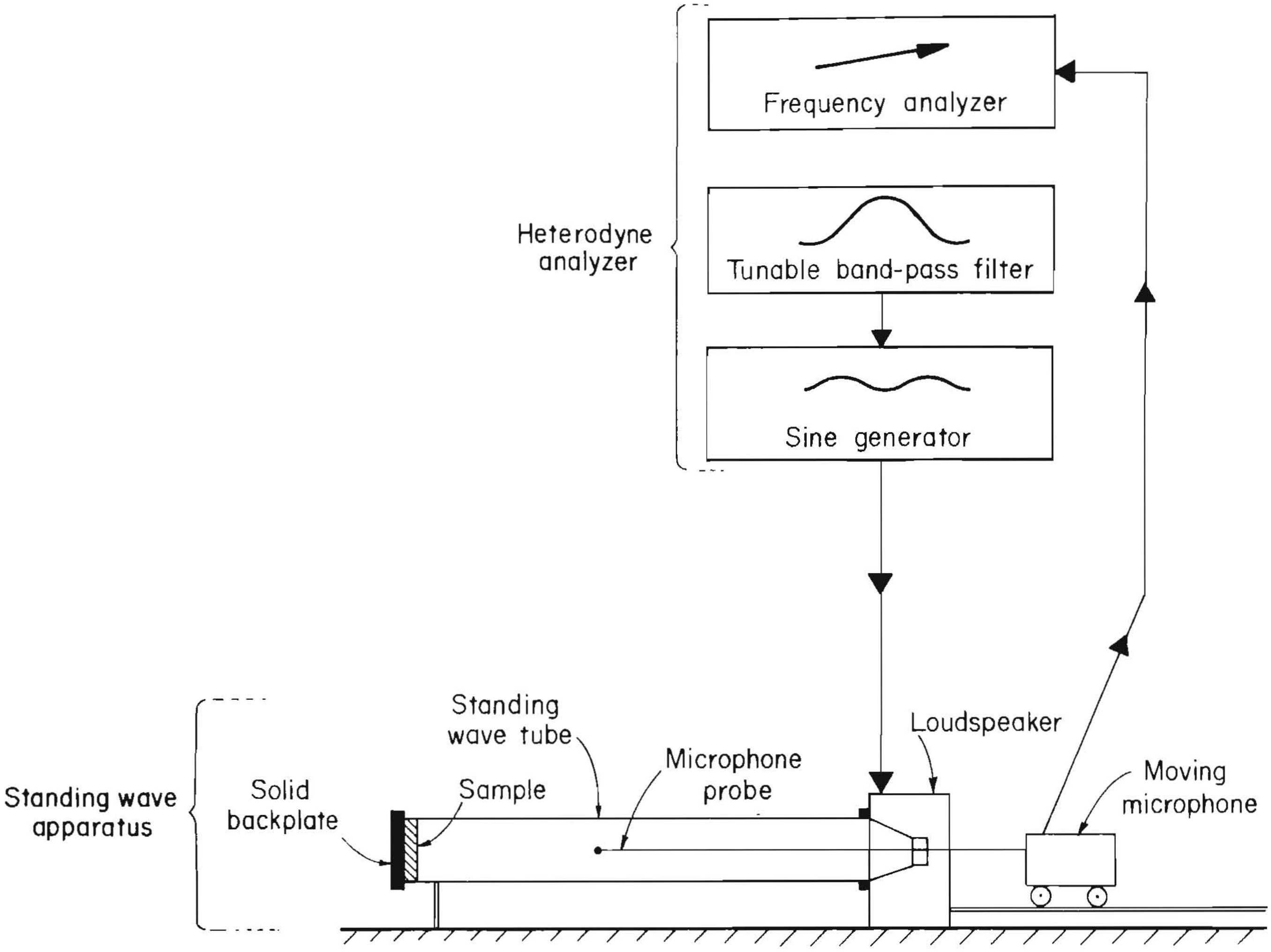

Figure 8.–Standing wave apparatus and supporting instrumentation.

EXPERIMENTAL PROCEDURES

A specimen that had been carefully prepared earlier, and stored in a plastic bag, was first placed snugly into the sample holder. The absorption coefficient was then measured by following steps as outlined in reference 5. (Words appearing in all capitals are labels on the analyzer.)

1. Set the FREQUENCY DIAL on the sine generator so that the FREQUENCY DISPLAY indicates the frequency of interest. Turn up the OUTPUT VOLTAGE until the DISTORTION lamp lights; then slightly reduce the OUTPUT VOLTAGE. A suitably high sound pressure level should then be present in the tube.

2. Move the microphone carriage up and down until a pressure maximum is detected within the tube; i.e., the probe microphone is positioned at a pressure maximum.

3. Adjust the meter deflection on the analyzer by means of the INPUT SECTION ATTENUATOR and the DIRECT INPUT "sens." (label on analyzer) to 100 pct on the scale (scale SA 0054 was used). At frequencies below 200 Hz, it may not be possible to find an isolated pressure maximum. In this case, the pressure just in front of the sample should be used as a maximum.

4. Move the microphone carriage until the minimum nearest to the sample is indicated. The reason for measuring at this point is to minimize a possible error caused by sound attenuation along the tube. The absorption coefficient can then be read directly from the scale of the

measuring amplifier. If the absorption is less than 70 pct, the gain on the amplifier can be increased by 10 dB and the absorption read from the 0- to 70-pct scale. If the absorption is less than 30 pct, then the gain should be increased a further 10 dB and the absorption read from the 0- to 30-pct scale.

5. Repeat steps 1 to 4 at other frequencies of interest and tabulate the results.

6. Remove the sample from the sample holder, reverse the sample holder, and measure the absorption coefficient of the metal surface to determine the minimum measurable absorption coefficient.

In all cases the minimum absorption coefficient never exceeded 0.04, which corresponds to a standing wave ratio of about 80. This served as a good indicator that the overall system was performing satisfactorily without any anomalous losses.

Use of the calibrated readout scale on the heterodyne analyzer to directly determine the absorption coefficient (expressed as a percentage; i.e., $\alpha \times 100$ pct) is for convenience and is not necessary. In the absence of this scale, calculation of the absorption coefficient proceeds as follows. First, determine the sound pressure level (L) using the heterodyne analyzer, or another instrument such as a sound level meter, at both a maximum and a minimum for a given frequency. Let L_{max} and L_{min} represent their values in decibels.

Recall the equation for the absorption coefficient developed previously:

$$\alpha = 1 - \left(\frac{n - 1}{n + 1}\right)^2,$$

where $n = \frac{p_{max}}{p_{min}}$.

Since $L = 20 \log \frac{p}{p_{ref}}$ dB,

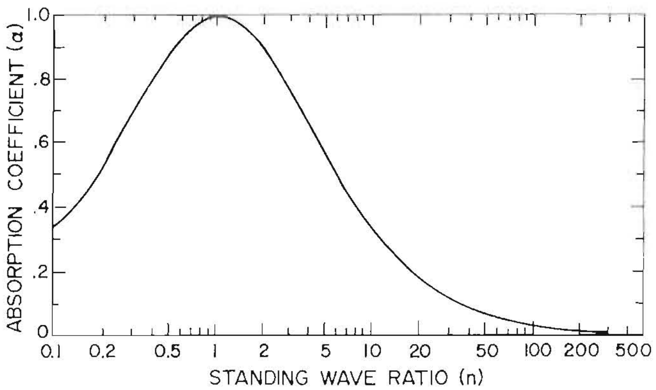

Figure 9.–Relationship between absorption coefficient and standing wave ratio.

where $P_{ref} = 20\mu$ Pa,

then $p_{max} = 10^{L_{max}/20}$

and $p_{min} = 10^{L_{min}/20}$.

From the ratio $\frac{p_{max}}{p_{min}}$, the expression

$$10^{L_{max}/20}/10^{L_{min}/20} = 10^{(L_{max} - L_{min}/20)} = 10^{\Delta L/20}$$

is obtained, with ΔL the difference in sound level. Substituting this for n, the standing wave ratio, the equation for the absorption coefficient can be written as

$$\alpha = 1 - \left(\frac{10^{\Delta L/20} - 1}{10^{\Delta L/20} + 1}\right)^2.$$

The relationship, displayed graphically in figure 9, can be used in lieu of the special scale.

RESULTS AND ANALYSIS

The absorption coefficient as a function of frequency was determined for each of the 16 types of material and each of 4 different test conditions: (1) materials kept clean and dry (baseline), (2) immersion in water, (3) immersion in a petroleum-type hydraulic fluid, and (4) 1-year exposure in a coal mine. When the front and back surfaces of the materials differed, data were obtained for both cases; seven of the materials were in this category. Thus, 23 complete sets of data were acquired as shown in table 4, with the extra tests (for samples with difference sides) denoted by the letter A or B. Since each test number was used to identify data for the 4 different environmental conditions, a total of 92 (4 × 23) tests were actually accomplished to describe the acoustic performance of the materials as a function of frequency. In each case, a mean value and standard deviation for the absorption coefficient were obtained by averaging the results of the individual measurements from the three samples. This detailed information is tabulated in appendix A. The mean, or average, values of the absorption coefficient (expressed as a percent) are presented graphically in appendix B. Each graph shows the frequency dependence of the absorption for the four different environmental test conditions and allows an easy visual comparison of the differences among test conditions. The change in absorption between the baseline and any other test condition is attributed to the effect of the physical agent involved, i.e., water, oil, or in-mine environmental agents.

Analysis of these data revealed that no measurable changes resulted when the materials were exposed to the mine environment of the SRCM. However, the laboratory tests with oil and water produced a variety of effects. In an effort to quantify the adverse effects of oil and water on the absorption coefficient (α) of the test materials, a set of criteria to describe the effects was formulated as follows:

Major.–The physical agent caused a decrease of 50 pct or more in α over most of the frequency range from 500 to 6,300 Hz.

Moderate.–The physical agent caused a decrease of 25 to 50 pct in α over most of the frequency range from 500 to 6,300 Hz, or a decrease of 50 pct or more over a limited range of frequencies.

Minor.–The physical agent caused a decrease of 25 pct or less in α over a substantial frequency range.

None.–The physical agent caused little change in α at other than a few selected frequencies.

Each set of test results was subjected to an evaluation with these criteria. A certain amount of judgment was still required in applying the criteria to the data. Table 5 reflects the results for all the materials. Also included are the average gains in weight of the samples with water and oil and the range of frequencies for which the absorption coefficient experienced a decrease.

Table 4.–Identification of tests

Material and test number	*Side tested*
Fiberglass quilted blanket:	
1A	Fiberglass side.
1B	Vinyl side.
2	Both sides the same.
Mineral board:	
3	Do.
4	Do.
Fiberglass board:	
5	Do.
6A	Plastic side.
6B	Fiberglass side.
Fiberglass baffle: 7	Both sides the same.
Neoprene foam:	
8	Do.
9	Do.
Polyurethane foam:	
10A	Foil side.
10B	Foam side.
11A	Foil side.
11B	Foam side.
12	Both sides the same.
13A	Plastic side.
13B	Foam side.
14	Both sides the same.
15A	Embossed side.
15B	Foam side.
16A	Rubber side.
16B	Foam side.

NOTE.–Test numbers correspond to material sample numbers listed in other tables. A and B denote sides of same sample where the sides were different. Each test number was used to identify data for tests under 4 environmental conditions, so each test number actually indicates 4 tests.

Table 5. - Summary of effects of water and oil treatment

Material	Water				Oil			
	Test	Av weight gain, pct	Effect on α	Frequency range, Hz	Test	Av weight gain, pct	Effect on α	Frequency range, Hz
Fiberglass quilted blanket:								
Fiberglass side	1A	304	Minor	2,000-6,300	1A	885	Major	630-6,300
Vinyl side	1B	304	Moderate	630-3,150	1B	885	do	100-6,300
Both sides the same	2	698	Major	100-5,000	2	750	do	100-6,300
Mineral board:								
Both sides the same	3	13	None	NAp	3	455	do	400-6,300
Do	4	21	do	NAp	4	222	do	315-6,300
Fiberglass board:								
Both sides the same	5	14	None	NAp	5	438	do	1,000-6,300
Plastic side	6A	19	do	NAp	6A	623	do	630-6,300
Fiberglass side	6B	19	do	NAp	6B	623	do	630-6,300
Fiberglass baffle	7	230	Minor	500-5,000	7	1,093	do	500-6,300
Neoprene foam:								
Both sides the same	8	96	None	NAp	8	73	do	NAp
Do	9	50	do	NAp	9	110	do	NAp
Polyurethane foam:								
Foil side	10A	445	Moderate	NAp	10A	285	Moderate	500-6,300
Foam side	10B	445	None	NAp	10B	285	Minor	3,150-5,000
Foil side	11A	59	Minor	315-1,000	11A	66	Major	100-6,300
Foam side	11B	59	Major	630-5,000	11B	66	do	630-5,000
Both sides the same	12	573	None	NAp	12	1,062	Minor	1,250-6,300
Plastic side	13A	691	Major	1,250-6,300	13A	159	Major	800-1,300
Foam side	13B	691	Minor	500-6,300	13B	159	Minor	100-2,000
Both sides the same	14	170	Major	400-2,000	14	400	Major	250-6,300
Embossed side	15A	945	Moderate	400-2,000	15A	537	Moderate	500-6,300
Foam side	15B	945	Major	630-6,300	15B	537	None	NAp
Rubber side	16A	580	Minor	1,600-3,150	16A	503	Moderate	1,250-6,300
Foam side	16B	580	None	NAp	16B	503	None	NAp

α Absorption coefficient.
NAp Not applicable.

Fiberglass Quilted Blanket (tests 1A-2).–These materials were affected by both the oil and water treatments, with oil having the greater impact. While the average weight gain was substantial in either case, it was especially high for oil and is probably the primary reason for the observed decrease in α.

Mineral Board (tests 3-4).–The oil treatment resulted in a major decrease in α, but little or no effect was seen for the water. Note that little water was retained in these high-density fiber materials.

Fiberglass Board (tests 5-6).–Again, the oil treatment resulted in a major decrease in α, but little or no effect was seen for the water. Note that little water was retained in these high-density fiber materials.

Fiberglass Baffle (test 7).–This material experienced over a 1,000-pct gain in weight from the oil bath and thus suffered a major reduction in α. Only a minor effect on α was caused by the 230-pct weight gain due to water.

Neoprene Foam (tests 8-9).–No change in α was seen. A partial explanation for this lies in the low weight gain, which probably is a direct result of the small opening and pore size of these foams.

Polyurethane Foam (tests 10A-16B).–The effects on these materials were varied, from none to major; no trends are evident. Perhaps this was because the materials represent four different manufacturers. It is suggested that a more detailed knowledge of the foams' chemical and physical structures is needed to fully understand the observed results. E.g., it is difficult to explain the major impact that water had in test 11B since the average gain in water weight was so low, especially when compared with the weight gain of the other polyurethane foams in this group.

In general, it was observed that the absorption coefficient is affected most at frequencies greater than 500 Hz. This frequency region is where a high degree of absorption is needed since many sources of noise in mining are characterized by a high-frequency content.

Below 500 Hz, most of the materials are already poor absorbers of sound so the addition of water or oil has little further impact. In addition, the presence of water or oil sometimes serves simply to shift the baseline absorption curve toward a lower frequency and thus shows up as causing an increase in the absorption (10B, 16A, 16B). During initial testing, a rather interesting result surfaced in materials 3, 4, and 5 when exposed to oil. All three of these materials were rigid, high-density, unfaced boards. At the lowest test frequency of 100 Hz, improvements of 400 to 700 pct were found.

This anomalous occurrence was subsequently traced to the presence of excess fluid that accumulated in the wave tube. It is speculated that the improvement in absorption at low frequencies resulted from viscous damping between the surfaces of the material and the tube.

It should also be noted that some of the tests involving oil or water show a large standard deviation (appendix A). This can probably be explained by the sensitivity of the absorption coefficient to variations in homogeneity of samples, amount of fluid retained in samples, and physical differences between samples caused by the preparation process.

SUMMARY

From this limited study of a cross section of typical sound-absorbing materials, a number of observations can be made that are immediately relevant to a user in the mining industry:

- Neoprene foam should be the absorber of choice, especially if lower frequencies are of lesser importance.
- Oil tends to have a greater effect on sound absorption than water.
- If the acoustical materials are kept protected in the mine environment, there does not appear to be any physical degradation with time that would cause a reduction in acoustical performance.
- The use of protective coating on the surface of acoustical materials is recommended even if a lower acoustical performance must be accepted. However, this requires that the exposed edges of these materials also be sealed against oil and water.
- It is evident that materials ostensibly identical in structure and appearance but produced by different manufacturers can exhibit radically different acoustical characteristics in the presence of water or oil.

It can be stated, in general, that most acoustical materials having an open structure will be affected adversely by any physical agent that is able to penetrate the material and fill the interstitial space. However, the results of this study are not extensive enough to permit an accurate prediction of the effect that the agents used in this investigation (oil and water) would have on other similar materials. The results of this pilot program suggest the need for a more comprehensive laboratory study combined with a long-term in-mine evaluation. Additional materials and physical agents should be explored. Moreover, the effect of treatments in combination should be a high research priority.

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APPENDIX A.–ABSORPTION COEFFICIENT TABLE

Frequency, Hz	Baseline Mean	Baseline sd	Water Mean	Water sd	Oil Mean	Oil sd	Mine Mean	Mine sd
Test 1A:								
100	4.8	0.3	6.3	2.0	3.0	0.0	6.0	1.0
125	4.6	.4	5.3	2.0	2.7	.6	5.3	1.2
160	3.6	.9	3.7	2.0	1.0	.0	2.7	.6
200	4.0	.2	5.0	2.0	1.7	1.2	5.3	1.2
250	7.2	.3	8.7	1.5	5.7	1.5	8.0	1.0
315	8.8	.4	13.3	2.0	12.0	3.0	10.0	2.6
400	11.7	.6	17.0	1.7	15.0	2.6	14.7	2.0
500	16.8	1.6	27.0	5.0	20.4	1.5	23.0	1.0
630	21.0	4.0	22.0	5.0	21.0	6.0	37.7	2.5
800	26.3	.9	27.5	3.3	17.9	2.8	32.4	2.9
1,000	36.0	1.2	32.3	7.6	18.9	2.0	43.2	.6
1,250	45.2	1.2	40.5	6.0	17.8	.8	55.0	.9
1,600	56.4	1.2	48.7	10.3	15.5	1.3	69.9	2.5
2,000	65.0	6.6	66.3	18.5	12.7	10.8	70.3	6.4
2,500	77.0	6.5	44.0	39.9	12.0	11.3	84.0	4.4
3,125	86.0	5.6	76.0	32.0	14.3	11.2	93.7	2.3
4,000	96.0	2.6	78.0	31.6	13.3	6.3	98.3	1.2
5,000	98.6	.9	78.0	26.7	14.0	6.2	99.0	.0
6,300	98.8	.3	80.6	17.0	16.7	7.4	98.7	.6
Test 1B:								
100	5.0	.5	6.7	2.0	3.7	.6	5.0	.0
125	5.2	.5	5.3	2.5	2.7	1.2	5.0	.0
160	4.0	.0	3.0	2.0	1.0	.0	5.3	1.2
200	5.5	.4	4.3	1.5	1.7	1.2	5.7	.6
250	9.2	.4	9.7	4.7	4.0	1.0	9.3	1.2
315	11.7	1.2	16.0	6.2	9.0	1.7	14.0	2.6
400	17.4	1.3	21.7	9.0	10.7	2.3	24.3	2.3
500	28.4	2.5	31.0	15.0	17.0	2.6	39.0	2.0
630	44.0	6.6	41.7	27.6	20.3	2.9	61.3	3.5
800	60.2	4.6	46.2	11.4	18.2	1.9	61.0	3.5
1,000	80.3	2.1	56.5	10.7	22.7	4.0	77.2	6.4
1,250	91.6	5.8	64.9	13.7	24.8	2.9	83.2	7.2
1,600	88.2	7.3	66.0	9.0	23.7	5.5	82.4	1.9
2,000	86.0	5.3	71.6	25.0	13.7	12.5	94.7	5.0
2,500	67.0	.6	56.7	21.7	10.7	9.0	89.0	14.0
3,125	61.0	4.7	50.3	14.6	11.3	10.0	79.0	16.5
4,000	43.7	4.0	43.0	6.2	13.0	9.8	62.0	19.0
5,000	37.5	.5	33.7	2.9	13.3	10.5	54.0	17.4
6,300	31.6	.8	23.0	4.0	18.0	12.3	47.0	18.0
Test 2:								
100	8.7	2.4	4.7	0.6	4.3	1.5	7.0	1.7
125	9.0	2.0	3.7	0.6	2.7	1.5	7.3	2.5
160	8.2	2.2	2.7	1.2	2.7	2.3	7.7	2.9
200	10.7	1.3	3.3	4.0	3.7	3.9	8.7	3.0
250	15.0	3.4	4.3	.6	8.3	4.2	11.0	1.7
315	21.1	6.9	7.7	1.2	12.0	3.9	16.3	4.2
400	31.7	8.0	7.0	2.0	12.0	4.2	24.7	4.7
500	44.0	5.3	12.7	2.3	15.3	3.6	39.3	4.2
630	60.0	2.6	14.0	2.6	15.0	1.7	60.0	8.9
800	68.0	3.5	14.7	2.4	12.7	6.3	55.7	2.6
1,000	80.8	.8	17.2	3.9	12.7	8.3	71.5	8.6
1,250	82.7	4.8	21.0	6.3	11.7	8.5	78.9	8.4
1,600	83.4	6.3	19.7	3.5	10.7	8.8	77.3	3.3
2,000	92.0	8.7	35.0	4.0	4.0	1.0	91.7	2.9
2,500	72.0	13.4	32.0	16.0	3.0	1.0	87.7	14.6
3,125	63.4	7.7	31.7	17.2	2.7	.6	80.3	16.8
4,000	48.0	8.9	35.3	22.5	4.7	1.2	64.0	19.0
5,000	34.0	10.0	29.3	15.5	3.0	.0	53.7	17.6
6,300	24.4	6.3	39.3	15.0	2.0	.0	44.3	15.8
Test 3:								
100	5.1	0.3	8.0	3.5	13.0	0.0	16.7	1.7
125	5.0	.0	7.0	4.4	5.0	1.1	16.3	6.4
160	5.2	2.0	6.0	4.4	4.3	1.2	16.0	6.2
200	5.0	.0	7.7	3.8	4.8	.6	17.3	4.7
250	9.7	.8	12.0	4.4	9.0	2.6	18.7	4.0
315	12.2	.8	17.7	4.6	14.3	3.8	22.7	3.2
400	18.5	.5	21.7	4.6	21.0	7.0	30.7	2.0
500	25.5	.6	30.0	4.4	28.7	10.0	39.0	2.6
630	36.5	2.4	38.0	4.5	39.3	14.0	42.3	3.2
800	42.2	.7	47.7	2.5	42.0	17.0	54.2	1.6
1,000	55.5	.8	61.6	3.2	42.0	17.0	66.7	.8
1,250	69.2	.6	76.3	1.0	46.0	10.0	76.0	1.4
1,600	81.7	2.7	87.0	1.0	45.8	13.0	83.2	.5
2,000	89.5	1.2	94.3	1.2	24.7	14.8	88.0	1.0
2,500	96.3	.6	98.7	.6	23.0	11.8	89.0	1.0
3,125	98.5	.5	99.1	.3	24.0	13.2	91.0	.0
4,000	96.8	.9	96.7	1.2	26.3	19.6	89.7	.6
5,000	95.0	.9	95.3	.6	32.3	21.6	91.0	.0
6,300	94.0	1.8	95.0	.0	26.7	18.5	93.0	.0
Test 4:								
100	9.7	1.6	8.7	1.2	13.0	.0	7.3	.6
125	10.5	1.5	9.0	1.0	5.6	1.6	8.0	1.0
160	11.5	1.5	7.7	.6	4.3	1.5	10.0	1.0
200	15.0	1.0	12.3	1.2	4.3	1.5	13.3	1.5
250	22.0	1.0	19.0	1.5	10.3	.6	20.3	1.5
315	28.7	.6	27.7	1.2	17.0	.5	27.7	.6
400	37.0	.9	38.7	2.5	24.0	1.2	37.0	1.0
500	45.0	1.0	50.7	3.5	32.0	1.7	45.7	.6
630	53.0	.6	60.0	2.0	41.6	1.2	49.3	.6
800	62.0	1.1	70.0	1.9	35.5	1.3	59.4	.8
1,000	72.0	1.0	75.9	1.0	42.0	11.0	65.0	1.2
1,250	75.0	1.0	77.0	.8	44.0	18.4	71.2	1.8
1,600	73.0	1.6	75.4	.8	23.9	42.8	71.9	2.3
2,000	78.0	.6	81.7	1.5	31.0	20.0	76.3	4.5
2,500	74.4	3.0	76.0	.6	24.0	19.3	76.3	1.5
3,125	81.4	2.2	77.0	1.2	27.3	25.7	80.0	1.7
4,000	81.4	1.6	83.7	1.5	28.0	25.0	79.0	1.7
5,000	86.0	2.1	84.7	2.5	24.7	15.0	84.0	3.0
6,300	87.5	1.3	82.7	3.2	23.3	13.7	85.0	2.1
Test 5:								
100	5.0	.1	5.5	.5	10.0	1.0	6.0	1.0
125	5.0	.1	5.0	.0	5.0	.0	6.0	1.0
160	4.3	.2	2.7	.6	6.0	1.0	5.0	1.0
200	6.5	.5	5.7	.6	4.0	.0	7.3	.6
250	10.0	.0	10.7	.6	9.5	.5	11.0	1.0
315	14.3	.4	16.7	1.6	14.0	.2	14.7	1.2
400	19.0	.6	20.1	1.0	19.0	2.0	19.7	2.0
500	27.0	1.0	28.0	1.2	26.5	.5	27.0	2.0
630	31.0	3.4	38.0	1.0	37.0	1.1	41.3	1.5
800	41.5	2.2	44.0	1.0	43.4	11.2	41.0	1.0
1,000	56.0	2.1	59.4	.5	58.3	12.2	55.2	.6
1,250	70.0	1.6	72.9	1.3	70.8	17.5	67.4	2.2
1,600	80.6	.4	84.4	.5	78.3	16.6	80.8	.3
2,000	89.0	3.5	92.0	5.0	48.7	44.4	86.3	2.3
2,500	98.0	.6	99.1	.1	44.3	43.5	97.0	1.0
3,125	99.6	.2	98.7	.9	42.7	35.0	99.0	.0
4,000	97.0	.4	96.7	1.9	33.7	29.8	97.3	.6
5,000	93.0	.0	90.7	2.5	29.3	29.0	94.0	.0
6,300	92.0	.5	93.7	1.2	32.0	31.0	92.0	.0

sd Standard deviation.

ABSORPTION COEFFICIENT TABLE–Continued

Frequency, Hz	Baseline		Water		Oil		Mine	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Test 6A:								
100	6.2	1.6	5.0	0.6	4.0	0.0	5.3	0.6
125	6.2	2.4	5.0	2.6	3.3	.6	5.3	.6
160	4.8	2.4	4.0	.0	1.7	1.2	5.3	3.2
200	6.3	1.9	6.0	.0	3.0	.0	5.3	.6
250	10.8	1.9	13.0	2.6	7.7	1.2	10.0	.0
315	14.0	1.6	17.7	.6	12.0	1.0	14.0	.0
400	18.0	1.7	21.0	2.0	17.0	1.7	19.7	.6
500	24.3	1.5	28.0	3.0	24.7	2.3	27.3	.6
630	33.0	2.0	33.0	12.0	34.0	3.6	41.9	1.5
800	40.0	.1	53.0	1.8	28.2	1.9	43.9	1.2
1,000	52.6	.9	65.4	1.4	34.9	1.0	58.9	.6
1,250	65.6	.8	76.9	.9	40.4	2.1	71.5	3.1
1,600	72.5	1.8	86.4	1.0	42.4	3.2	82.2	1.2
2,000	87.0	.4	94.7	2.5	16.0	13.9	92.7	1.2
2,500	96.0	.3	99.2	.2	17.0	15.6	98.3	1.2
3,125	99.0	.0	98.6	1.4	20.3	13.0	99.0	.0
4,000	98.0	.4	96.0	1.7	18.0	2.6	97.0	1.0
5,000	94.5	1.1	92.0	.6	21.0	8.2	93.0	1.0
6,300	92.8	1.0	91.0	1.2	19.7	12.4	92.0	1.7
Test 6B:								
100	11.3	2.0	9.0	3.6	5.7	2.1	12.7	2.0
125	11.3	2.0	8.7	4.7	5.3	3.2	12.0	2.6
160	12.0	3.5	8.0	8.9	4.0	4.4	13.3	3.0
200	12.0	4.4	8.7	9.0	5.5	3.8	12.3	4.0
250	12.0	2.6	10.0	7.6	6.7	3.0	11.7	2.9
315	15.7	4.0	13.7	9.9	13.0	2.9	15.0	3.5
400	13.3	3.8	14.0	7.2	25.0	11.9	12.7	2.0
500	15.0	4.6	16.0	7.2	23.0	7.0	15.0	1.7
630	28.7	4.9	42.0	15.7	18.0	6.0	29.0	4.8
800	44.7	5.3	50.4	6.4	17.4	1.9	55.5	7.8
1,000	34.9	2.6	64.0	8.4	14.2	3.3	45.7	2.6
1,250	35.5	5.8	47.4	2.0	12.9	1.3	53.0	12.6
1,600	49.2	3.6	51.4	9.9	10.7	.8	53.0	9.1
2,000	50.7	7.6	44.0	19.7	7.3	3.0	65.0	14.5
2,500	40.7	9.3	36.0	15.4	6.7	3.5	50.0	4.4
3,125	37.0	9.0	9.7	10.8	8.3	5.5	41.3	.6
4,000	31.0	8.8	30.7	8.1	9.0	5.6	30.3	4.0
5,000	26.3	8.6	24.0	8.7	10.0	7.2	30.7	4.5
6,300	19.7	4.5	21.7	7.6	10.3	5.0	24.0	5.3
Test 7:								
100	10.0	1.3	9.0	1.7	6.3	2.3	8.7	.6
125	10.5	1.3	10.0	4.0	7.0	2.6	8.7	.6
160	10.3	1.6	9.0	8.4	7.7	2.9	8.3	1.5
200	11.0	1.0	14.7	10.7	11.3	5.8	11.3	1.5
250	20.0	.6	24.0	13.8	20.0	8.7	20.0	2.0
315	28.5	.9	32.2	13.6	27.7	11.6	28.3	2.9
400	37.5	.5	36.7	9.8	37.0	7.2	37.3	3.8
500	51.0	.2	45.0	1.7	46.7	3.5	51.7	4.2
630	68.0	1.2	53.0	10.7	58.0	7.0	68.7	4.9
800	66.8	.7	57.0	4.5	43.4	1.8	67.0	2.3
1,000	80.0	3.0	68.5	7.4	44.8	5.5	80.0	3.0
1,250	90.0	2.3	76.5	13.1	41.0	6.5	89.7	1.0
1,600	87.3	2.0	78.4	11.3	35.7	6.3	88.3	4.3
2,000	89.0	4.6	81.0	17.0	14.3	9.0	92.3	1.5
2,500	82.8	4.4	74.0	19.5	13.0	4.6	87.7	9.0
3,125	78.0	4.6	71.0	12.7	14.3	3.2	74.0	1.7
4,000	83.0	4.4	75.7	7.6	16.3	5.5	74.0	5.6
5,000	87.0	9.8	81.0	6.8	18.0	11.1	80.7	4.9
6,300	61.7	8.3	68.0	23.0	25.7	27.0	70.7	5.5
Test 8:								
100	6.0	0.4	5.7	0.6	6.0	0.0	5.7	0.6
125	6.7	.3	6.3	.6	5.7	.6	6.0	1.0
160	7.0	.7	4.8	.8	4.3	.6	5.0	6.0
200	6.0	.2	5.0	1.0	4.7	.6	7.3	.6
250	11.0	.4	9.3	.6	8.0	.0	10.3	.6
315	13.0	.6	12.0	1.0	11.3	.6	13.0	.0
400	15.5	.9	14.0	1.0	12.3	.6	16.0	1.0
500	19.0	.7	16.7	.6	15.3	.6	19.3	3.5
630	24.8	2.6	25.0	4.0	14.6	.6	27.3	1.7
800	26.9	.3	26.0	1.0	20.9	.3	23.0	.6
1,000	33.2	.3	32.3	.4	24.5	.5	30.5	1.6
1,250	42.6	.5	41.0	.3	23.6	.3	38.0	1.9
1,600	54.0	.7	55.0	.5	46.7	1.3	49.1	1.9
2,000	66.0	1.4	76.0	6.4	58.7	1.5	58.3	.6
2,500	75.0	2.0	89.7	4.0	74.7	2.0	70.3	1.2
3,125	82.0	.6	93.7	.6	83.7	2.0	73.7	6.6
4,000	82.0	2.0	83.7	3.8	85.0	1.7	75.0	1.0
5,000	78.0	2.2	73.0	4.5	78.0	1.0	71.7	.6
6,300	77.0	2.6	76.0	6.0	79.7	1.5	68.3	.6
Test 9:								
100	5.0	.4	6.7	1.0	5.0	.0	5.7	.6
125	5.5	.2	6.6	.7	4.3	.6	6.0	.0
160	6.0	.3	6.0	1.2	3.3	1.2	3.0	.0
200	6.2	.3	7.5	1.3	5.0	1.0	5.3	.6
250	10.0	.0	10.8	.8	8.3	1.5	10.0	.0
315	13.0	.2	13.8	1.0	11.0	1.7	13.3	.6
400	15.0	.2	16.5	.9	13.3	1.5	16.3	.0
500	19.5	1.0	22.7	1.2	18.3	1.5	20.3	.6
630	25.0	1.0	2.8	1.5	19.3	1.5	28.3	1.2
800	29.5	.9	30.4	.1	29.5	1.5	28.0	.3
1,000	36.5	.2	38.9	.1	39.8	2.8	37.9	.3
1,250	47.5	.2	49.4	.1	55.0	5.5	48.2	.3
1,600	60.0	1.2	64.4	.8	75.0	7.2	60.4	.9
2,000	75.0	.0	81.0	3.0	83.3	12.0	73.3	1.2
2,500	85.0	.0	91.0	2.6	88.3	2.0	86.0	1.0
3,125	87.5	.5	91.0	1.5	83.3	14.0	86.7	.6
4,000	85.0	.3	82.0	2.6	75.3	17.8	84.0	.0
5,000	78.0	.6	73.0	2.6	73.3	9.6	77.0	.0
6,300	79.0	.6	78.7	2.0	83.3	13.6	79.0	2.6
Test 10A:								
100	13.0	.6	23.8	6.9	7.0	.0	9.7	2.9
125	14.0	.8	25.7	10.0	13.0	8.3	10.5	3.5
160	16.0	1.0	14.0	4.6	18.7	5.8	8.7	2.9
200	16.7	1.5	21.7	3.0	19.7	9.7	11.3	2.9
250	14.0	.6	10.0	2.0	25.3	13.3	25.3	11.0
315	19.6	1.3	11.7	.6	31.7	17.0	56.0	15.0
400	19.0	5.0	9.0	.0	22.3	13.0	41.7	8.5
500	30.7	14.0	14.7	3.8	23.0	9.8	41.0	5.3
630	48.7	8.6	18.0	4.0	22.0	2.0	48.0	16.6
800	65.0	3.6	41.9	6.6	26.4	6.4	57.0	3.8
1,000	63.0	5.8	38.4	6.5	42.4	4.1	55.0	3.3
1,250	62.5	.4	34.0	1.3	55.2	8.8	54.0	5.3
1,600	48.4	4.0	28.4	1.5	40.7	.6	61.7	5.5
2,000	62.7	10.0	34.0	3.5	33.7	3.2	52.3	11.2
2,500	50.7	4.2	26.0	1.7	29.7	2.9	52.7	5.0
3,125	46.7	3.0	23.0	1.7	24.7	.6	31.0	5.2
4,000	35.0	2.5	22.0	3.2	21.0	1.0	24.0	2.6
5,000	47.0	3.6	27.0	5.8	22.7	1.5	33.0	5.3
6,300	34.0	2.0	18.0	1.7	18.0	3.6	27.7	5.0

sd Standard deviation.

ABSORPTION COEFFICIENT TABLE–Continued

Frequency,	Baseline		Water		Oil		Mine	
Hz	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Test 10B:								
100	6.0	0.2	6.0	0.6	5.0	0.0	6.0	0.0
125	6.0	.2	6.0	.0	5.7	.6	5.7	.6
160	5.0	.2	5.0	.0	3.6	.6	4.0	.0
200	6.0	.4	7.0	.0	6.0	1.5	6.0	.0
250	10.0	.3	10.0	.0	8.0	1.0	10.0	.0
315	11.0	.2	13.0	1.0	11.0	1.7	13.0	1.0
400	14.0	.2	15.0	.0	14.0	1.0	14.7	.6
500	18.0	.4	20.0	.6	19.3	1.5	19.7	.6
630	24.0	.4	23.0	5.3	24.3	3.0	26.0	3.0
800	28.5	.1	30.5	1.9	34.9	.8	26.5	.3
1,000 ...	37.0	.9	40.5	.3	53.2	1.9	35.7	.3
1,250 ...	47.5	1.5	56.4	.9	73.6	2.0	45.7	.8
1,600 ...	63.0	1.1	78.4	1.3	90.7	3.3	61.5	.5
2,000 ...	79.7	2.3	91.0	1.5	92.0	1.0	73.0	1.0
2,500 ...	80.0	6.7	94.0	1.0	80.7	7.1	80.0	2.6
3,125 ...	87.0	.0	81.7	.6	69.7	10.4	87.7	.6
4,000 ...	81.5	.5	64.0	1.0	53.3	8.0	78.0	1.0
5,000 ...	76.0	.6	71.0	2.6	56.7	4.9	76.7	1.5
6,300 ...	86.0	3.0	96.0	.8	82.0	7.5	84.7	2.0
Test 11A:								
100	8.0	.3	8.0	1.4	6.0	1.7	8.7	1.5
125	9.0	.2	8.7	2.3	6.0	2.6	9.3	1.2
160	10.0	.5	9.0	4.7	5.7	4.2	9.0	.0
200	15.0	1.9	23.0	10.7	6.3	3.8	15.7	.6
250	28.8	9.4	26.0	2.6	16.3	5.1	34.7	1.5
315	34.4	10.9	23.0	6.0	28.0	10.0	42.3	9.8
400	31.7	6.0	17.0	2.0	13.3	4.2	30.0	14.0
500	35.5	2.8	15.0	.6	15.0	1.0	30.0	11.5
630	23.0	2.0	8.7	1.5	13.0	10.4	24.7	10.2
800	40.0	12.2	26.5	4.8	11.4	2.8	49.2	3.7
1,000 ...	33.8	9.4	25.9	4.3	9.7	2.8	48.2	.6
1,250 ...	29.4	6.7	28.9	3.8	10.4	1.3	38.0	3.2
1,600 ...	24.0	4.2	30.5	1.8	13.2	2.9	32.0	1.8
2,000 ...	33.0	10.8	49.0	6.0	19.3	14.5	47.3	9.5
2,500 ...	35.7	24.0	40.0	8.5	14.0	7.8	58.3	9.3
3,125 ...	62.0	6.0	36.7	4.9	17.9	9.0	65.7	6.4
4,000 ...	51.7	3.0	32.0	2.9	14.7	10.7	56.7	6.6
5,000 ...	34.0	7.5	32.0	4.0	15.3	11.8	45.7	3.0
6,300 ...	20.8	2.3	29.0	6.0	10.0	2.0	28.7	2.0
Test 11B:								
100	6.0	.8	6.3	.6	6.3	1.2	9.3	.6
125	6.0	1.2	6.3	.6	5.7	1.5	9.7	.6
160	3.7	1.6	5.0	2.0	6.0	1.0	8.7	.6
200	4.8	1.5	5.3	3.2	7.3	6.0	3.0	3.5
250	7.3	1.2	11.0	6.6	12.7	12.0	15.3	3.2
315	18.3	1.2	14.0	8.4	20.0	16.0	19.0	6.0
400	9.5	.8	22.0	10.0	14.0	8.0	29.3	11.9
500	2.5	.9	19.0	5.0	15.7	7.2	27.0	11.3
630	16.0	.5	11.0	2.0	13.0	3.0	26.0	9.6
800	40.0	1.4	13.0	1.8	13.7	.3	46.0	2.0
1,000 ...	32.9	2.4	12.5	.4	12.2	.8	17.0	4.3
1,250 ...	26.9	2.0	13.5	.5	10.8	2.1	32.7	1.3
1,600 ...	21.5	1.5	13.0	1.8	9.3	.3	35.5	2.1
2,000 ...	33.7	2.5	16.0	1.0	13.7	.6	32.0	1.5
2,500 ...	32.0	2.6	16.7	2.0	15.0	1.5	29.7	.0
3,125 ...	32.7	3.8	19.0	.0	3.0	2.0	33.0	.6
4,000 ...	36.0	4.9	29.0	3.8	25.7	2.5	39.3	1.0
5,000 ...	40.0	8.4	37.0	4.0	33.0	5.3	39.3	1.2
6,300 ...	48.0	10.4	52.0	9.0	53.0	5.2	48.7	3.8
Test 12:								
100	6.5	0.3	7.0	0.6	5.3	0.6	6.0	0.0
125	7.0	.5	7.0	.6	5.3	.6	6.0	.0
160	6.0	.4	5.0	.6	5.0	2.6	3.0	.0
200	8.0	.9	7.0	.6	5.3	.6	6.3	.6
250	12.0	1.0	12.0	1.0	9.7	.6	11.3	.6
315	17.0	1.8	17.0	.6	14.7	1.2	14.3	.6
400	21.0	1.0	20.0	.6	19.3	3.5	20.0	1.0
500	29.0	.5	28.0	1.2	28.0	5.6	28.0	1.7
630	37.0	3.5	41.7	1.2	39.7	11.6	43.0	3.6
680	51.3	1.8	51.9	3.6	48.0	3.6	49.4	.6
1,000 ...	69.6	2.8	72.0	5.5	66.5	6.6	71.7	2.8
1,250 ...	83.2	6.2	89.5	6.1	80.0	5.6	90.9	5.5
1,600 ...	96.5	1.0	90.5	1.3	76.6	3.9	96.7	3.6
2,000 ...	95.7	2.0	85.0	13.0	77.0	28.0	87.7	6.5
2,500 ...	81.0	3.5	71.0	17.2	59.7	29.0	70.3	7.0
3,125 ...	75.0	6.8	68.0	7.8	52.0	15.0	72.3	2.0
4,000 ...	80.0	2.0	84.7	4.2	53.3	5.9	83.0	3.6
5,000 ...	92.0	1.0	89.0	6.5	68.3	12.4	90.3	1.5
6,300 ...	94.4	2.6	86.7	8.1	72.0	29.0	88.7	4.3
Test 13A:								
100	7.0	.2	12.7	1.5	5.3	6.6	7.0	1.0
125	7.0	.1	14.0	.6	7.0	1.0	7.3	.6
160	7.5	.3	19.0	5.0	6.3	3.0	5.7	1.2
200	13.0	.8	25.0	2.0	18.7	8.0	10.7	1.2
250	14.7	12.0	26.0	4.7	39.3	4.2	30.0	3.0
315	23.0	3.0	3.0	6.2	51.7	6.6	59.7	5.8
400	21.7	4.0	26.0	4.7	56.7	6.8	47.3	4.2
500	34.5	4.0	32.7	4.2	59.0	13.7	67.3	5.0
630	43.0	9.3	43.0	3.6	41.0	9.5	49.0	7.8
800	50.0	1.0	40.4	9.4	47.9	4.5	58.2	5.5
1,000 ...	81.0	4.0	35.5	9.5	46.4	12.6	65.9	.3
1,250 ...	87.9	2.1	31.5	8.3	43.4	11.9	68.7	.8
1,600 ...	76.9	.1	26.2	6.2	35.0	7.8	61.5	.5
2,000 ...	59.8	1.3	30.0	10.4	32.7	17.2	61.7	1.2
2,500 ...	41.0	.0	27.0	5.6	29.7	10.0	42.9	.6
3,125 ...	54.0	1.0	34.0	8.5	24.0	6.1	51.3	3.8
4,000 ...	59.0	3.4	31.7	14.8	12.0	12.0	61.7	3.0
5,000 ...	47.0	3.5	25.0	10.5	20.7	11.2	44.0	1.0
6,300 ...	43.0	4.6	17.0	6.0	14.7	4.0	36.0	1.7
Test 13B:								
100	6.0	.3	6.5	1.3	5.0	.0	6.0	.0
125	6.3	.4	6.7	1.2	5.0	.6	6.9	.6
160	6.0	.4	4.5	1.3	2.7	.6	4.3	.6
200	7.6	.4	6.7	1.2	5.7	.6	6.9	.6
250	12.0	.2	11.0	1.0	8.3	.6	11.9	.6
315	16.0	1.0	15.0	1.7	9.3	2.3	16.0	.0
400	20.0	1.0	19.0	2.6	14.3	1.5	19.3	.6
500	27.0	3.0	27.0	6.4	19.0	2.5	27.7	2.0
630	44.7	4.7	39.0	9.0	24.0	5.2	43.7	1.2
800	51.0	.8	48.5	.9	39.5	1.8	43.3	.5
1,000 ...	62.0	3.8	71.5	15.9	50.6	3.3	61.7	.8
1,250 ...	85.9	5.3	63.4	3.4	72.0	.3	85.7	.6
1,600 ...	99.0	.5	75.8	2.2	82.2	10.2	99.0	.0
2,000 ...	94.0	1.2	76.8	17.8	92.0	4.6	94.3	2.0
2,500 ...	82.0	1.6	72.7	5.0	84.3	9.2	80.3	2.9
3,125 ...	79.0	1.6	77.0	9.5	78.0	3.6	78.3	2.5
4,000 ...	84.0	1.5	80.0	4.6	87.3	7.6	83.7	3.0
5,000 ...	97.0	1.0	84.0	8.6	92.7	1.2	98.0	1.7
6,300 ...	87.0	.5	83.0	10.6	92.3	6.5	89.0	.3

sd Standard deviation.

ABSORPTION COEFFICIENT TABLE–Continued

Frequency,	Baseline		Water		Oil		Mine	
Hz	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Test 14:								
100	5.0	0.0	7.5	0.5	4.3	1.2	5.3	0.6
125	5.0	.0	8.7	2.0	3.3	1.2	5.3	.6
160	4.0	.5	10.7	4.8	3.7	2.0	1.9	.6
200	7.0	.2	14.5	2.8	8.3	7.8	5.0	.0
250	13.0	.3	29.8	4.8	4.7	1.2	11.9	.6
315	18.0	.0	42.0	8.6	9.3	1.5	17.9	.6
400	25.0	.5	35.8	8.3	.0	2.6	24.0	.0
500	34.0	1.2	33.0	7.8	26.3	3.5	35.7	2.0
630	46.7	2.0	23.0	7.8	22.3	4.7	48.7	1.5
800	58.8	.3	29.9	6.1	26.3	13.7	60.0	1.7
1,000	73.4	.6	29.3	4.8	40.9	15.9	72.6	.3
1,250	90.5	.3	29.0	5.1	39.7	17.5	83.2	.3
1,600	95.0	.1	28.9	4.3	35.0	17.4	90.1	.3
2,000	95.0	.3	31.5	2.7	50.3	40.0	95.0	1.0
2,500	95.0	.0	28.7	9.8	44.7	35.9	93.7	1.5
3,125	90.0	.0	28.0	9.8	45.0	35.0	92.9	.6
4,000	87.5	.5	28.0	8.5	41.7	32.0	88.3	.6
5,000	87.5	.6	27.7	8.0	38.7	33.0	89.9	.6
6,300	93.5	.5	30.0	8.0	35.5	30.0	93.0	.0
Test 15A:								
100	7.0	.4	9.0	.6	7.3	.6	6.0	1.0
125	7.0	.4	9.0	.6	9.3	1.5	6.3	.6
160	7.0	.2	10.0	1.2	10.7	1.2	3.9	.6
200	9.0	.5	13.7	1.5	18.0	3.5	6.3	.6
250	16.0	3.0	23.0	.6	28.0	2.6	22.3	.6
315	24.7	5.7	31.0	.6	43.3	.6	18.0	1.0
400	38.7	10.0	35.0	3.0	45.3	4.5	24.3	2.5
500	56.0	11.3	40.7	5.0	47.3	4.9	36.7	3.8
630	65.0	6.9	38.0	4.0	36.3	3.5	55.0	3.6
800	71.5	2.3	43.0	1.5	50.5	3.5	64.5	3.8
1,000	79.0	4.7	42.5	.6	47.2	8.3	89.2	4.9
1,250	75.5	1.0	41.9	1.0	40.5	8.3	95.2	2.0
1,600	54.8	4.5	40.5	.8	39.5	8.4	77.0	2.7
2,000	53.4	2.9	52.7	4.0	43.3	3.8	64.3	10.1
2,500	51.0	1.9	57.0	5.3	52.7	16.0	59.0	4.0
3,125	57.7	1.8	67.7	7.4	60.0	1.7	66.0	4.6
4,000	60.5	1.9	70.7	11.9	69.0	7.9	80.3	2.5
5,000	63.0	.8	73.0	13.8	68.0	7.8	83.0	3.6
6,300	57.0	1.5	75.7	12.4	68.7	9.8	80.7	2.0
Test 15B:								
100	7.0	.7	8.0	.6	6.0	1.0	6.3	.6
125	7.0	.3	9.0	1.0	6.0	1.0	7.0	.0
160	7.0	.8	20.0	1.0	5.3	1.2	4.3	1.5
200	10.0	.8	14.0	.6	7.0	1.7	7.3	.6
250	14.0	2.0	23.5	1.3	12.3	2.0	13.0	1.0
315	18.3	4.0	32.0	.6	17.3	4.0	16.9	.6
400	24.5	4.3	37.0	2.6	23.0	5.3	21.3	1.5
500	37.7	7.0	41.6	7.4	32.0	7.5	31.7	.6
630	60.0	10.3	38.0	8.7	43.0	8.9	51.7	2.0
800	71.4	2.7	42.9	2.9	57.6	4.7	58.5	1.3
1,000	83.2	3.0	38.0	1.4	74.0	5.9	82.0	7.4
1,250	85.0	5.9	36.0	.6	78.2	6.5	95.9	1.4
1,600	72.3	5.0	30.4	2.7	69.8	2.0	83.4	1.8
2,000	72.0	8.2	42.0	1.5	70.3	6.0	76.0	9.2
2,500	66.8	6.0	42.0	1.0	72.0	4.6	67.7	1.5
3,125	76.0	5.3	48.0	3.6	81.3	8.0	72.7	3.2
4,000	75.0	5.0	49.0	.6	78.3	9.6	86.7	2.9
5,000	77.0	4.5	49.0	1.5	72.0	9.5	89.0	4.0
6,300	76.6	4.6	49.7	1.5	72.0	7.9	88.3	4.0
Test 16A:								
100	7.0	1.0	8.0	0.8	5.7	0.6	6.3	0.6
125	7.3	.9	8.0	1.5	6.7	.6	6.3	.6
160	6.6	1.0	7.0	2.5	4.3	1.2	5.3	.6
200	7.0	.6	8.0	3.2	11.0	5.2	6.3	.6
250	12.0	1.0	14.5	6.5	15.0	1.0	11.0	.0
315	15.0	1.5	19.0	6.8	22.0	1.0	14.3	.6
400	19.0	1.0	24.0	9.6	43.0	5.3	18.3	.6
500	25.0	2.6	33.0	20.2	72.0	5.3	26.3	1.5
630	34.0	1.0	44.0	8.5	83.7	8.7	30.0	.0
800	40.7	1.4	48.7	1.5	51.8	3.8	39.8	.8
1,000	56.8	1.6	65.0	2.8	56.5	2.5	57.2	1.0
1,250	77.2	2.3	84.7	7.1	66.2	.8	76.5	.5
1,600	93.0	.9	88.5	11.1	53.2	15.9	92.7	.6
2,000	95.0	.8	87.0	4.0	52.3	1.2	97.3	.6
2,500	82.0	1.6	61.0	4.5	31.3	1.2	90.3	1.2
3,125	69.0	1.7	50.0	2.0	29.0	1.0	69.3	2.0
4,000	54.6	1.3	66.0	3.0	45.7	7.6	57.0	.0
5,000	80.5	2.2	92.7	4.0	49.0	7.8	76.3	2.0
6,300	97.0	1.0	76.7	8.4	22.0	4.0	97.3	.6
Test 16B:								
100	6.5	.5	7.5	.0	6.0	.0	6.0	.0
125	7.0	.4	6.5	.5	6.0	.0	6.0	.0
160	6.0	1.3	5.0	1.0	3.0	.0	5.7	.6
200	6.0	.4	6.0	1.0	7.3	2.5	5.0	.0
250	10.0	.4	9.0	.0	7.3	.6	9.0	.0
315	11.0	.6	12.0	.6	10.0	.0	9.7	.6
400	13.0	.6	14.0	.6	11.7	.6	12.0	1.0
500	16.0	1.7	19.0	.6	15.0	.6	16.0	.0
630	24.0	1.7	29.7	2.0	17.7	1.5	17.0	1.2
800	24.9	2.0	33.0	.4	27.7	6.4	23.2	.3
1,000	35.3	4.1	49.5	5.5	34.2	3.8	32.9	.8
1,250	51.0	7.3	76.9	2.4	54.7	4.8	46.8	.8
1,600	71.3	5.6	91.9	2.0	80.9	5.3	67.4	1.6
2,000	81.0	.6	84.7	2.3	80.0	6.2	80.7	3.2
2,500	76.0	2.0	59.0	.6	67.0	7.5	83.7	.6
3,125	68.0	2.6	52.0	1.0	55.3	7.8	70.0	1.0
4,000	56.6	1.2	64.0	2.3	45.3	4.5	80.0	.0
5,000	77.0	3.8	95.0	1.2	75.3	6.4	70.0	2.7
6,300	98.0	2.7	75.7	6.4	88.3	7.6	97.7	1.5

sd Standard deviation.

APPENDIX B.-SOUND ABSORPTION GRAPHS

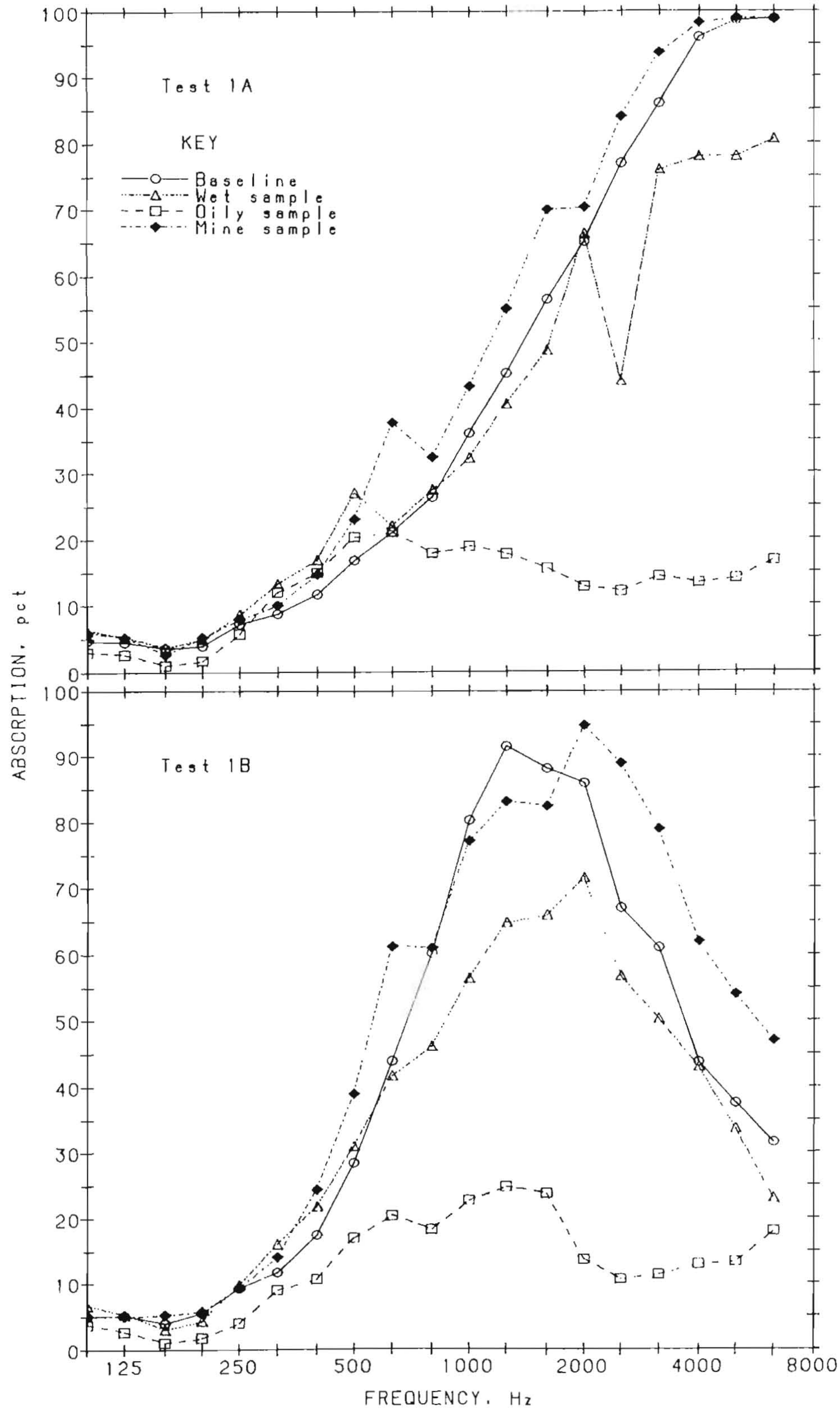

Figure B-1.-Percent sound absorption as a function of frequency.

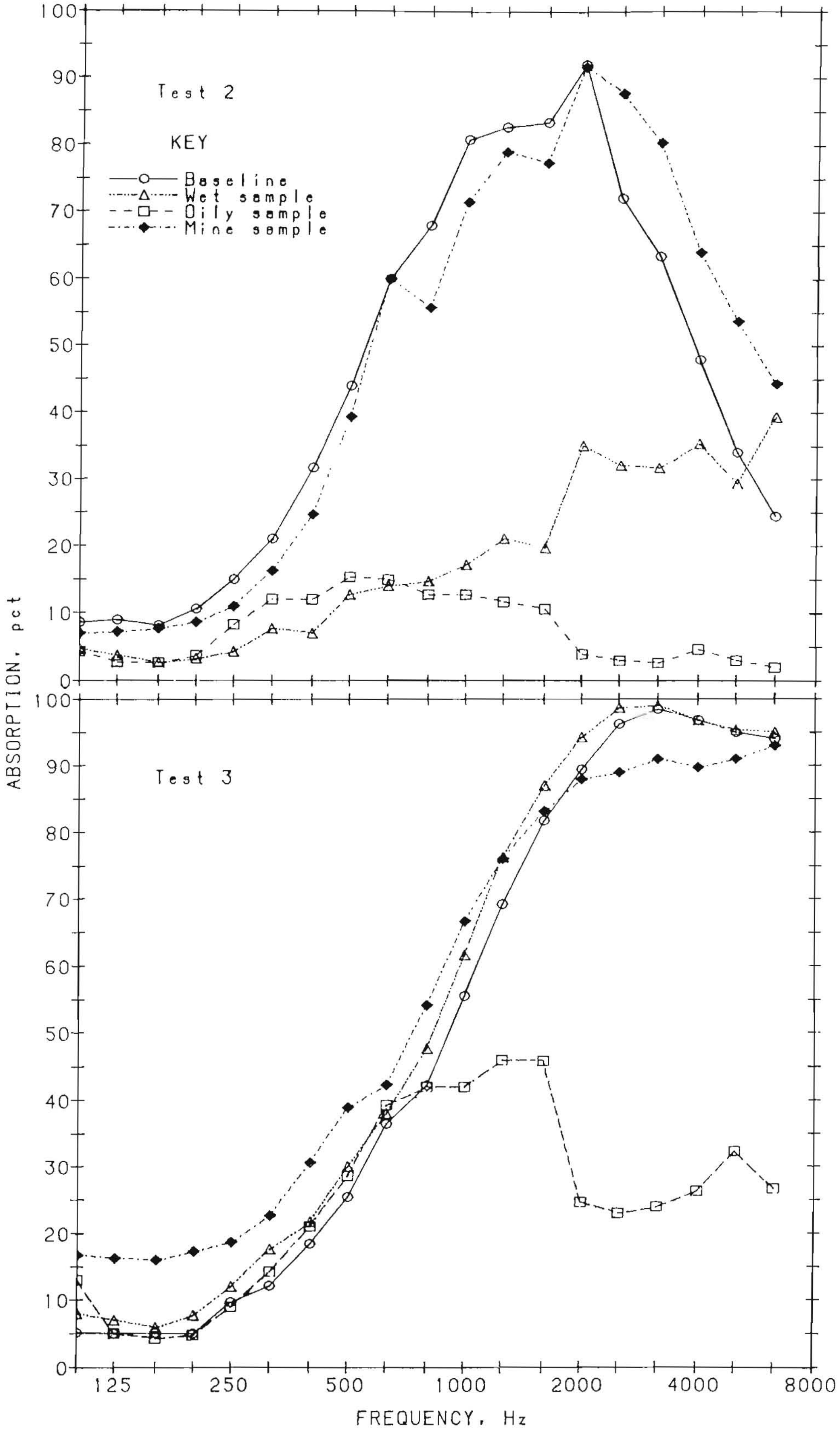

Figure B-1.–Percent sound absorption as a function of frequency–Continued.

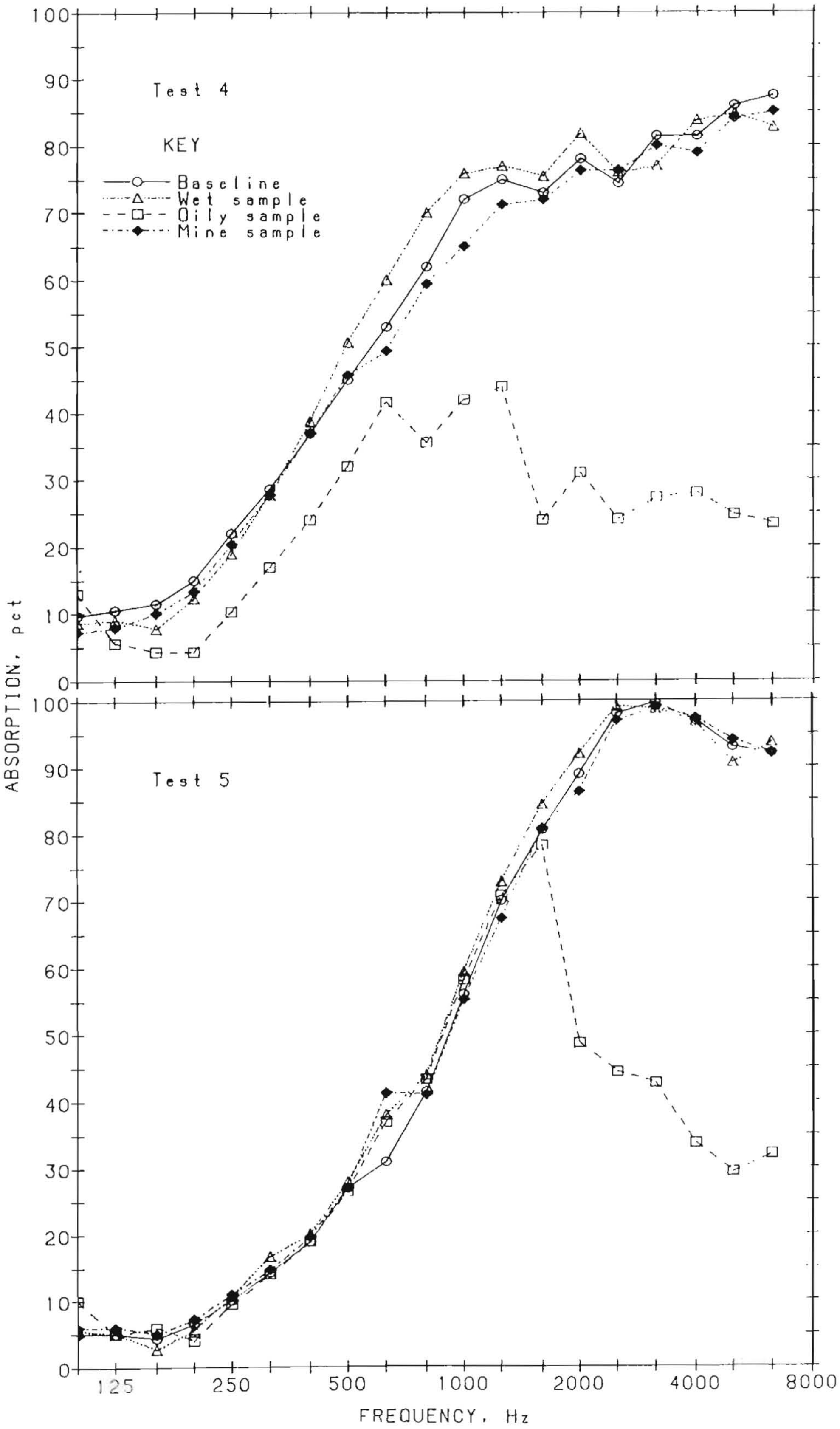

Figure B-1.–Percent sound absorption as a function of frequency –Continued.

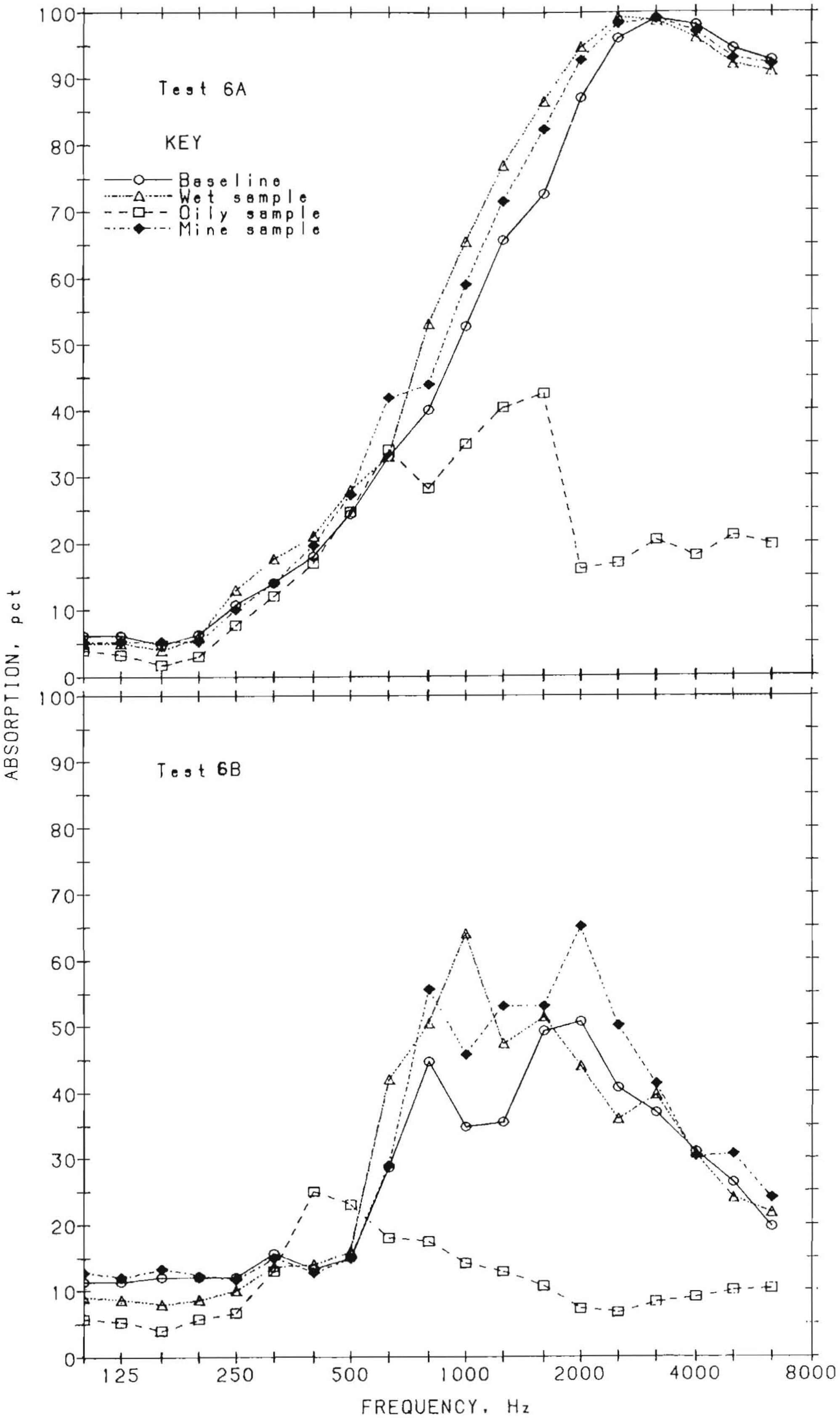

Figure B-1.–Percent sound absorption as a function of frequency –Continued.

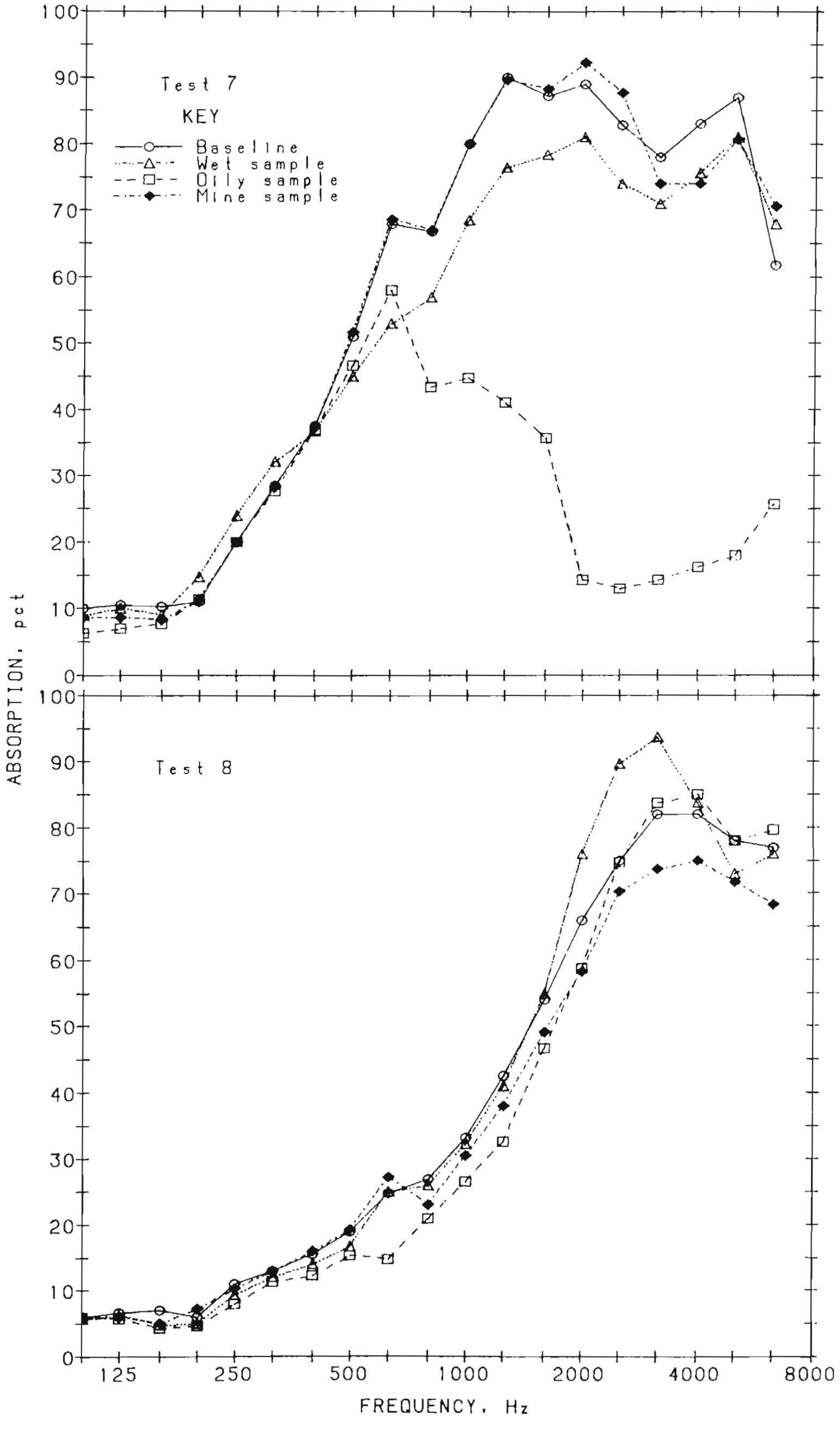

Figure B-1.–Percent sound absorption as a function of frequency –Continued.

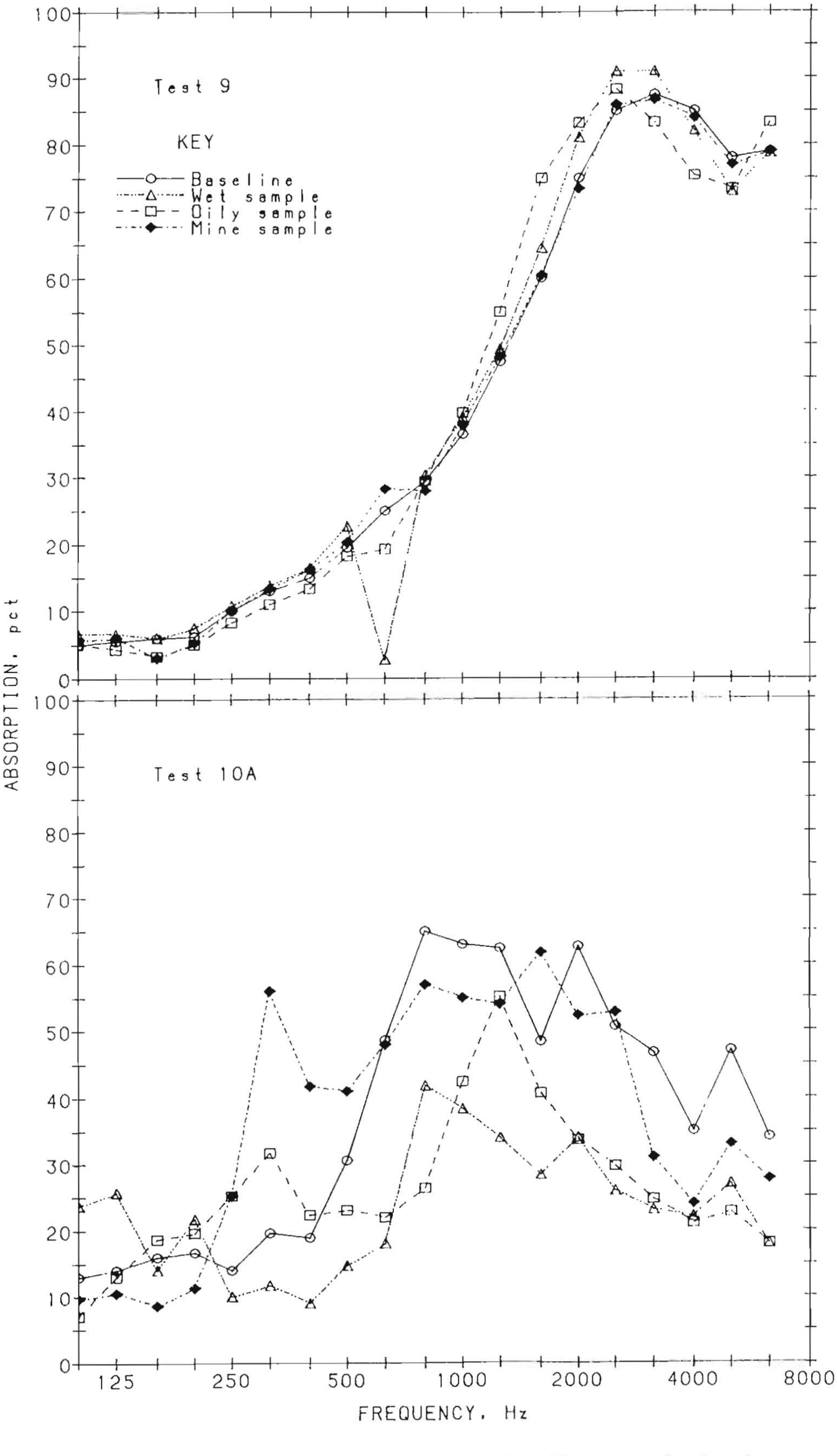

Figure B-1.–Percent sound absorption as a function of frequency–Continued.

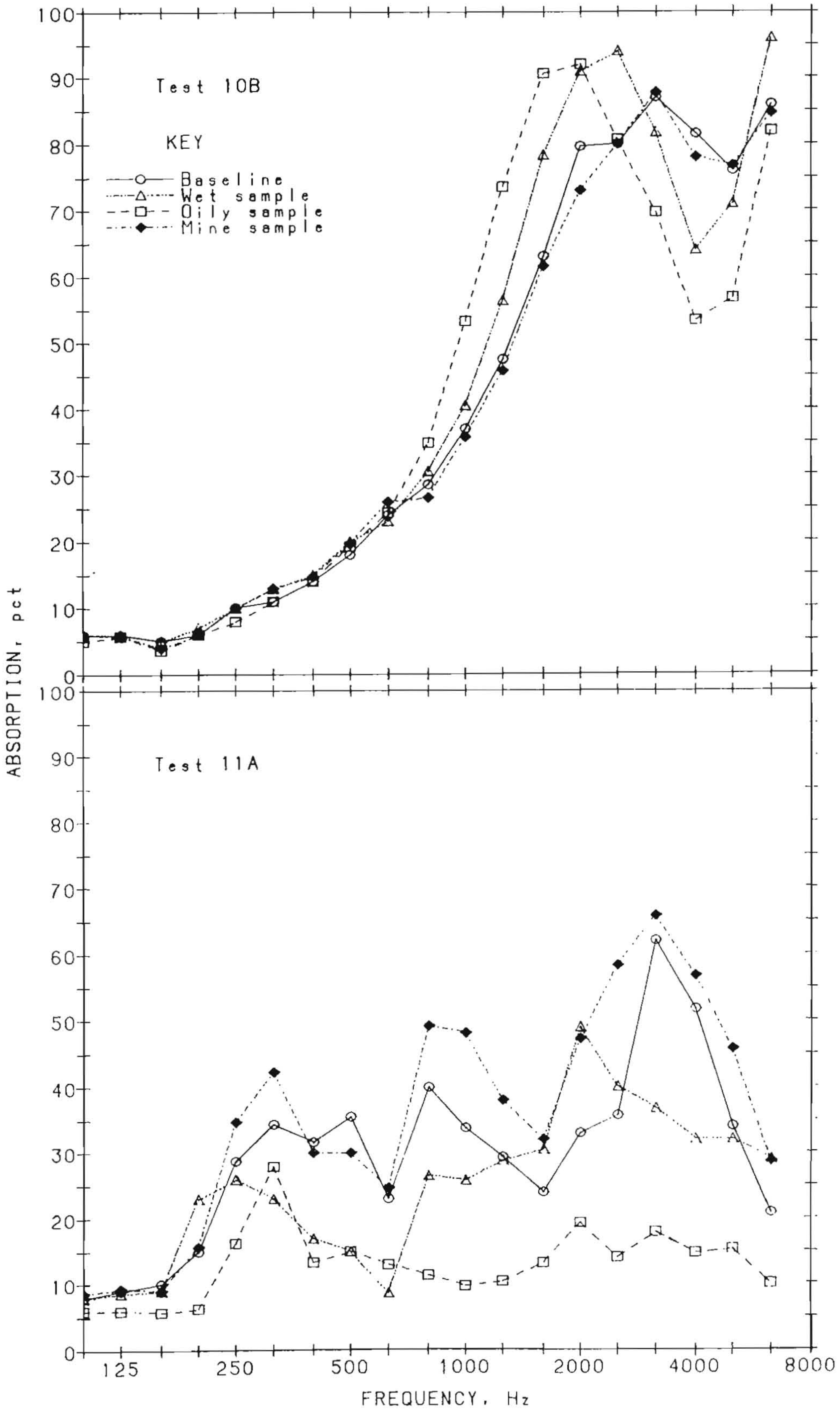

Figure B-1.-Percent sound absorption as a function of frequency -Continued.

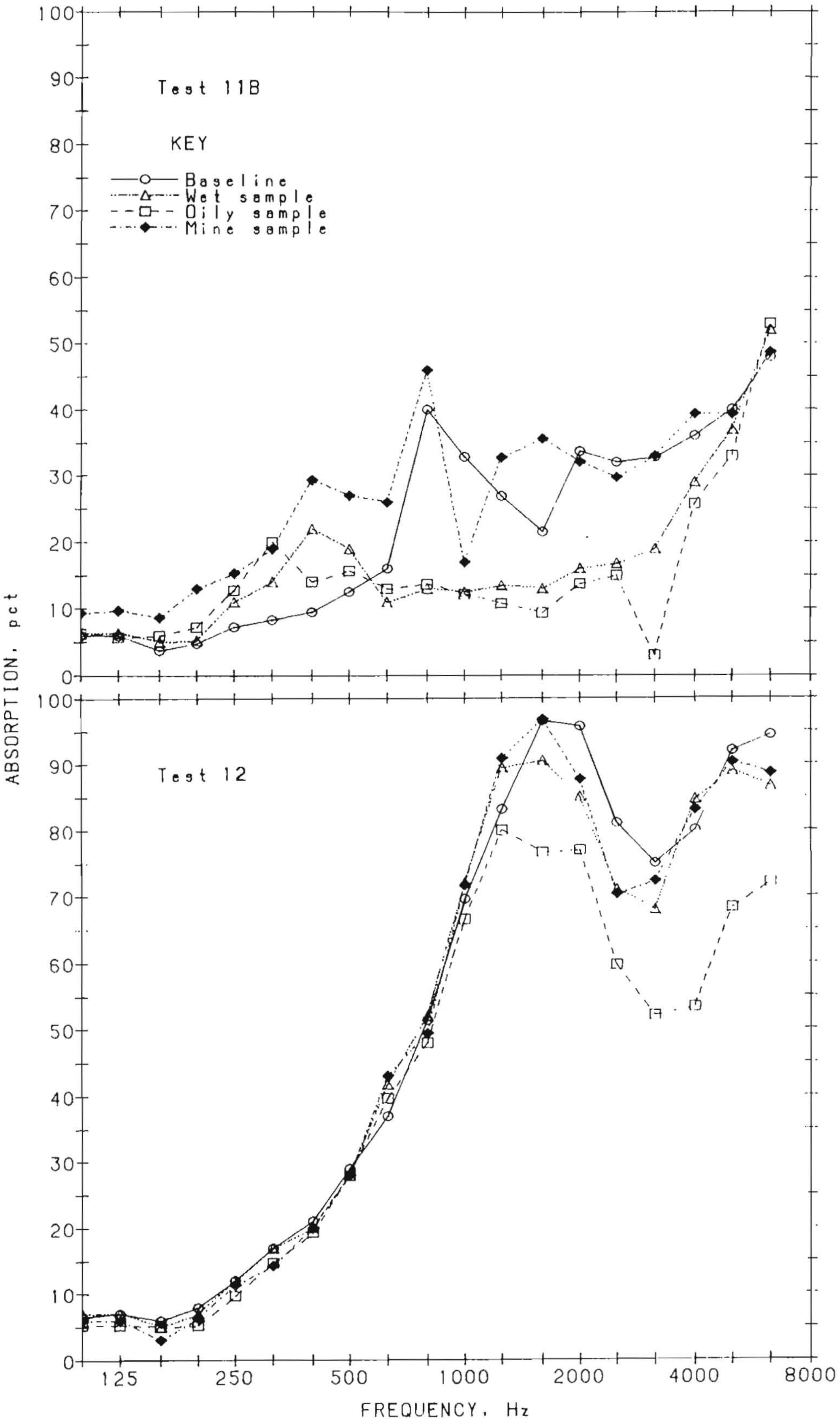

Figure B-1.-Percent sound absorption as a function of frequency -Continued.

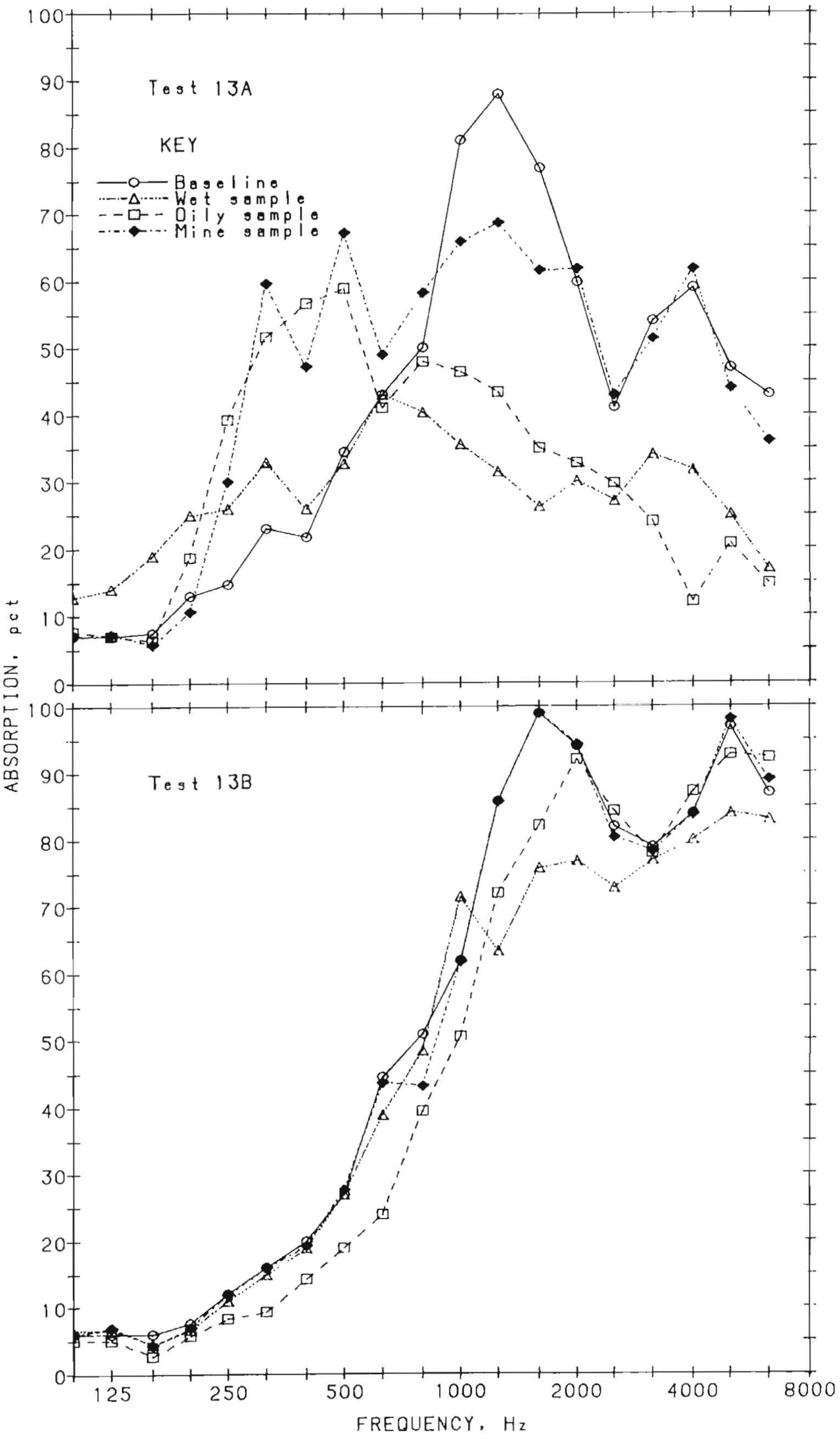

Figure B-1.-Percent sound absorption as a function of frequency -Continued.

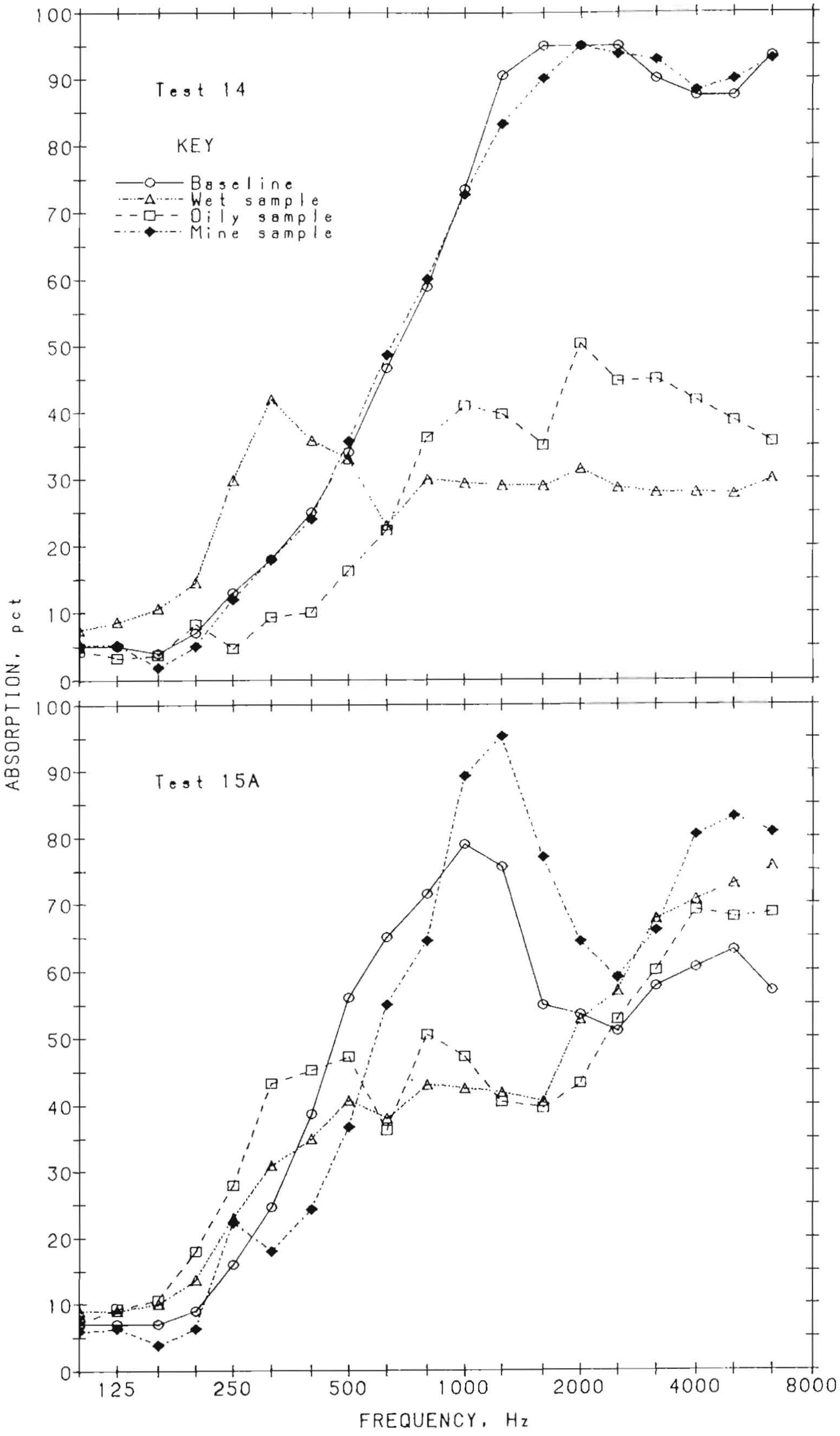

Figure B-1.–Percent sound absorption as a function of frequency –Continued.

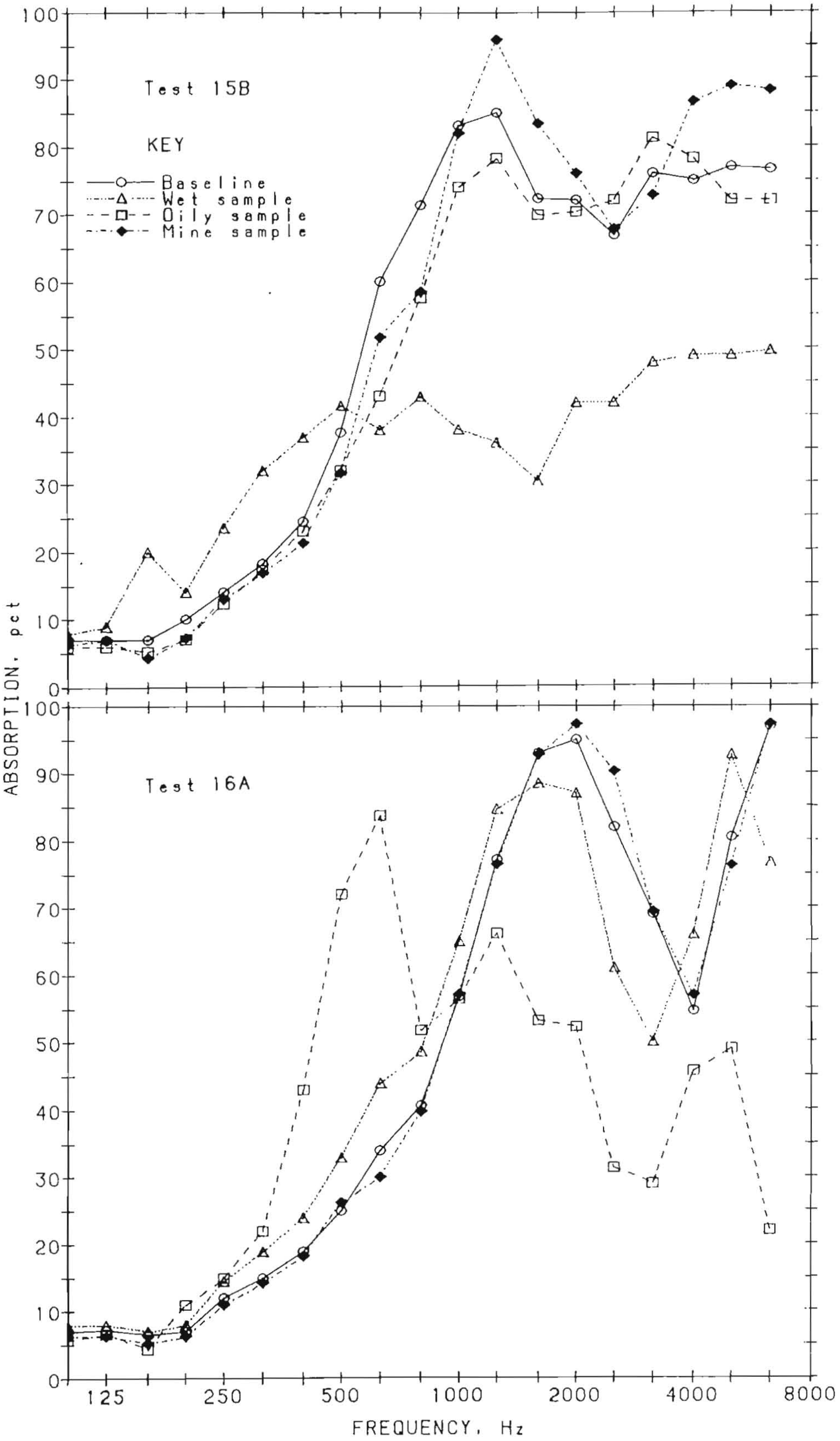

Figure B-1.–Percent sound absorption as a function of frequency –Continued.

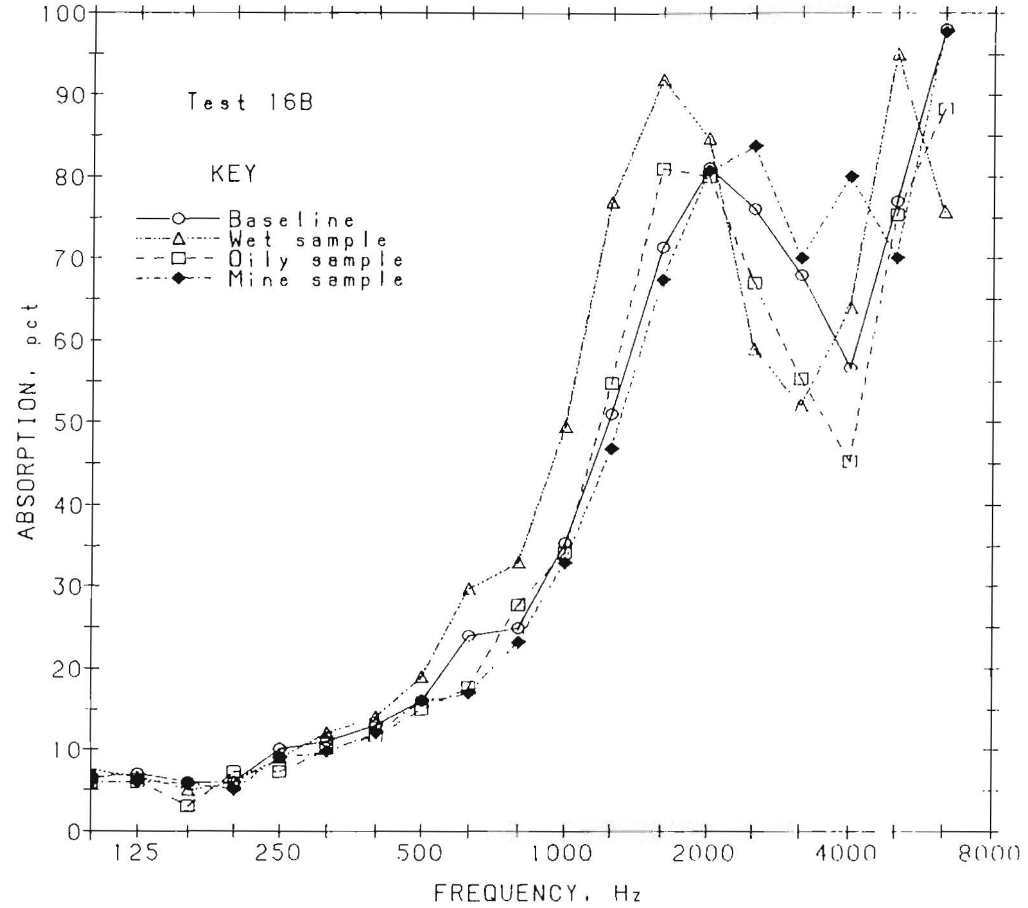

Figure B-1.–Percent sound absorption as a function of frequency–Continued.