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Airblast Instrumentation and Measurement Techniques for Surface Mine Blasting

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

AIRBLAST INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR SURFACE MINE BLASTING

by

Virgil J. Stachura,[1] David E. Siskind,[1] and Alvin J. Engler[2]

ABSTRACT

The Bureau of Mines has investigated techniques and instrumentation that measure accurately the airblast overpressures from surface mine blasting. The results include equivalencies between broadband research instrumentation and commercially available impulse precision sound level meters measuring: root-mean-square, peak, fast, slow, impulse, A and C weighting, C-weighted sound exposure level (CSEL), and "linear" (flat) response. These values were obtained from field measurements and broadband FM tape recordings of production blasts at area and contour coal mines, limestones quarries, and iron mines. Frequency response was determined for 14 commercial systems.

INTRODUCTION

The surface mining industry has seen extensive regulation of blast effects, which has caused a need for uniform instrumentation and measurement techniques. Airblast is particularly hard to regulate because it varies widely in generation, propagation, and effects on humans and structures. Abnormal levels of airblast sometimes occur far from a surface mine, and so they can involve a much larger area than is usually associated with ground-borne vibrations. The weather conditions can cause anamalous airblast propagation through focusing caused by temperature inversions and intensification from wind (7).[3] The level and character of an airblast are also strongly affected by the degree of explosive confinement afforded by the burden, stemming, and geologic conditions.

The general airblast can be characterized as an impulsive noise primarily in the infrasonic range. Most of the energy in an airblast is inaudible, because its frequency content is below the range of human hearing (20 Hz to

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

20 kHz). Airblast level can be expressed in decibels, with the following equation for sound pressure level (SPL):

$$SPL = 20 \log \frac{P}{P_o},$$ where P_o is the reference pressure 20×10^{-6} N/m^2 or 2.9×10^{-9} psi, and P is the overpressure in N/m^2 or psi.

The reference pressure has been experimentally determined to be the threshhold of hearing for young listeners, at 1,000 hz. This corresponds to 0 dB. Many people can hear levels as much as 10 to 20 decibels lower in amplitude. Initial discomfort and pain thresholds for steady-state sounds are 110 and 140 dB, respectively (23).

Some of the sources of airblast can be seen in figure 1. The white plume just left of center is the source of stemming release pulses. To the right of center, a hole has "cratered," transmitting more energy into the atmosphere than into breaking rock. These gas releases, combined with the stress wave energy transmitted from the rock and the heaving motion around the collar, contribute to the higher frequency portion of airblast. A general swelling of the shot area, including the free face, produces the "piston effect," a low-frequency component of airblast. The high-frequency component is generally above 5 to 6 Hz, while the low-frequency portion is in the 0.5-to-2-Hz region (28). The phenomenon of airblast generation has been studied extensively by Wiss (39) and by Snell and Oltmans (33).

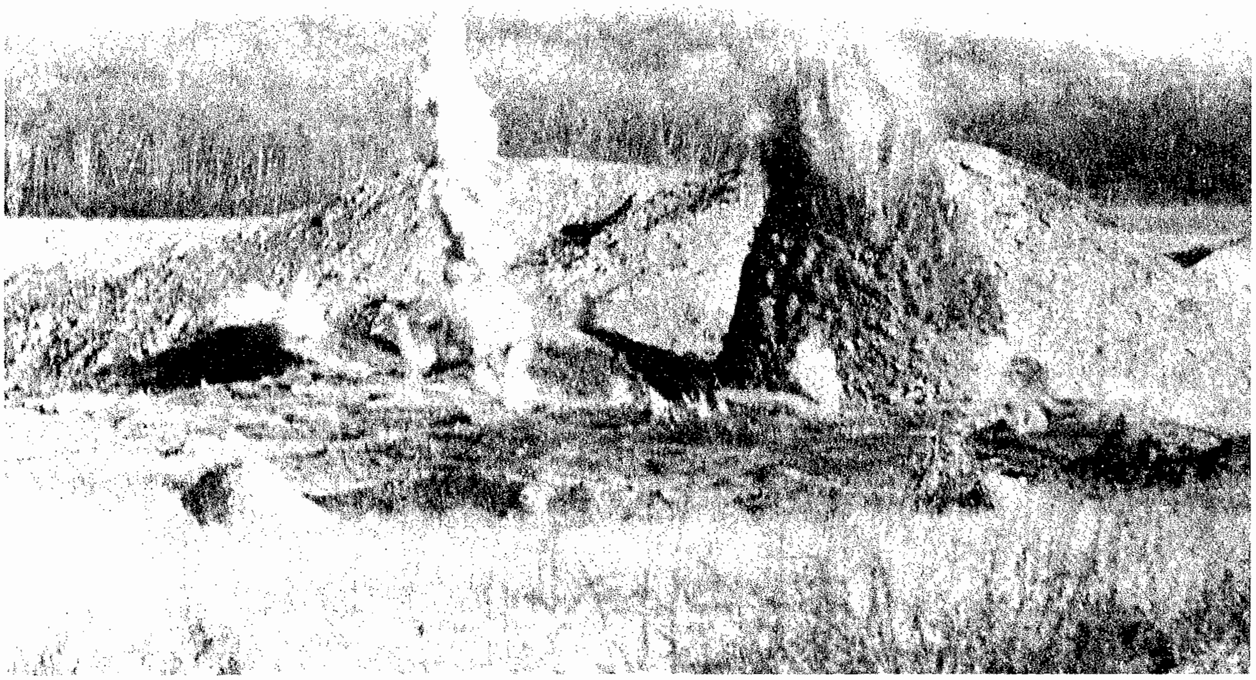

FIGURE 1. - Coal mine blast showing some airblast sources.

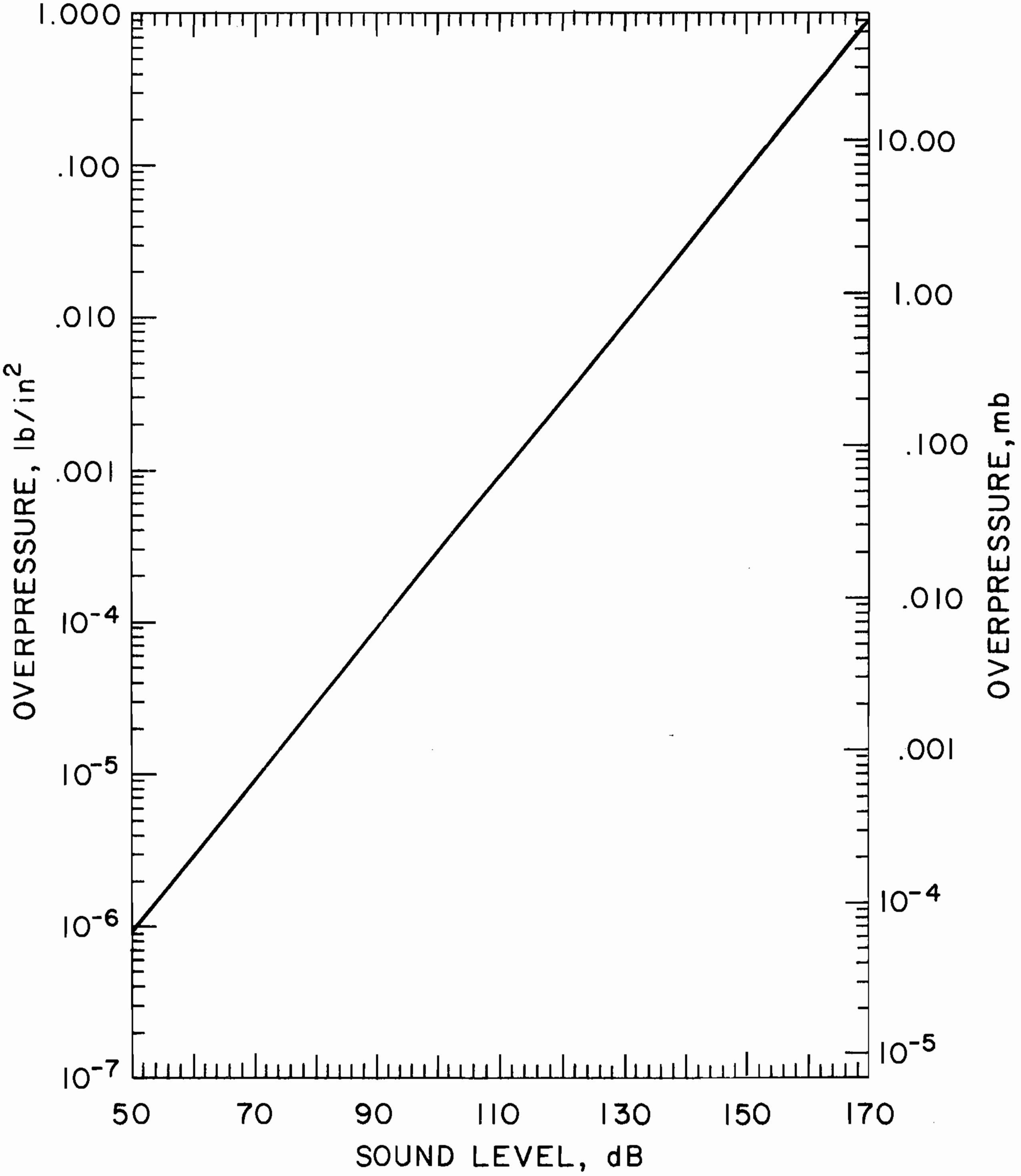

FIGURE 2. - Sound level conversion graph.

Airblast can be separated into two types, which are identified by their frequency content. Type I airblast has considerable more energy above 6 Hz than the Type II airblast. Both types are dominated by low-frequency energy (below 2 Hz), but the former has a secondary band of frequencies (over 6 Hz), which is less than 15 dB below the low-frequency energy level. The Type I airblast is more troublesome because of its energy in the resonant frequency range of structures (28). Efforts to document the environmental effects of this acoustic energy require highly specialized instrumentation, which takes into account the frequencies and amplitudes generated by the source.

In this report, sound pressure levels are expressed in decibels and overpressures in pounds per square inch (psi). Other units used in acoustics are millibars and Newtons per square meter (N/m^2), also known as Pascals (Pa). Sonic boom levels are often expressed in units of pounds per square foot (psf). A conversion chart is shown in figure 2. The two overpressure scales are slightly offset and not symmetrical.

1 psi = 0.000145 N/m^2 or Pa
1 psi = 0.006944 psf
1 psi = 0.0145 mb

ACKNOWLEDGMENTS

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PREVIOUS INVESTIGATIONS

The Bureau has studied the problems of airblast and instrumentation, starting as early as 1939 (13, 22, 37-38). Most of this work involved unconfined or poorly confined blasts that were dominated by acoustic energy in the audible range (20 Hz to 20 kHz) and that could be measured by standard commercial sound measuring systems. In 1973, Siskind and Summers (32) surveyed airblast noise from conventional quarry blasting, using instruments with a variety of frequency responses. It was evident that much low-frequency energy (less than 2 Hz) existed but that the instruments produced distortion and "ringing" from insufficient microphone low-frequency response. A sound system that could respond at 0.1-Hz low-frequency was then built for subsequent studies. Airblasts could be accurately captured to analyze structure response, damage, and annoyance potential (28-29, 35). In an interim report (32), Siskind and Summers recommended that instruments have a frequency response of 5 Hz or lower. This recognizes that houses have natural frequencies in the range that will respond to infrasonic vibrations, and that such vibrations are the most serious airblast problem in surface mining. Prior to this, many measurements, made with 20-Hz systems, could not be correlated to complaints or damage.

The main transient noise sources that cause annoyance and damage are sonic booms, surface blasts, artillery, explosive testing, nuclear blast simulation, accidental explosions, and partially confined blasts (mining, quarrying, ditching, construction, and excavation). To analyze these sources, a variety of sound descriptors have been developed or adopted from methods that characterize steady-state noise (table 1). Some are quite complex, in an attempt to be all inclusive. Others involve unproven simplifying assumptions so they can be applied to transients in general, and blasting in particular.

Kryter (18) examined sonic boom effects on structures based on peak overpressure levels, and also determined severity equivalencies between peak overpressures and "perceived noise levels" (L_{pn}, also labeled PN_{db}) from subsonic jets. L_{pn} levels are rms values calculated from the "noy" values of highest noise level in each octave (1/3 octave) band. The noy was derived from judgment tests of perceived loudness conducted in a laboratory. Noy values cannot be directly measured, so Schomer (27) described their involved calculations. A later study by Kryter (19) involved a more complex "effective perceived noise level" (L_{epn}) based on the largest L_{pn} calculated from band measurements every 0.5 sec, including a tone correction for turbine whine. Schomer (27) summarized Kryter's studies and also proposed "composite noise ratings" (CNR), a 24-hour integration with a 10-dB nighttime penalty. Schomer stated that the fear of property damage is related to complaints, both of which are different from psychological annoyance. The distinction is significant for the mining industry.

A 1978 review by Schomer (26) gathered the results of a variety of sonic boom studies, including those of Kryter. With L_{pn} the most widely analyzed descriptor, Young (40) studied annoyance effects from unconfined impulsive sources (for example, artillery) and utilized the concept of "sound exposure" levels, (L_S), which are weighted rms values integrated over the duration of the event and normalized to 1 sec. Unfortunately, labeling among studies using L_S has not been uniform. The C-weighted sound exposure level has been identified as E_C (40), L_{CE} (36), or simply CSEL, with a recently recommended standard notation of L_{SC} (34). The preferred standard symbols for A-weighted and C-weighted sound exposure levels are L_{AE} and L_{CE}, with abbreviations ASEL (or SEL alone, which implies A-weighting) and CSEL. The sound exposure analysis methods appear to offer distinct advantages over previous efforts to characterize impulsive noises. They introduce weighting, which allows selection of the frequency bands of most concern to the noise receivers (either structures or people). Unfortunately, the standard weighting bands (A, B, C, D) are not ideal for the troublesome responses. Sound exposure methods also penalize excessively long events and tolerate shorter ones (by the 1-sec normalization), recognizing that the former are more serious. This problem applies more to annoyance than structure response, since the latter has not been related to integrated airblast energy.

TABLE 1. - Sound measurement descriptors

Descriptor			Equation(s) and characteristics	Applications
Symbols	Abbreviation	Explanation		
L_p	SPL	Sound pressure level, in stated band.	$L_p = 20 \log_{10} P/P_o$ where P_o = Reference pressure $= 20 \times 10^{-6}$ N/m^2 $= 2.9 \times 10^{-9}$ psi $= 4.18 \times 10^{-7}$ psf and P = Sound pressure in an unidentified bandwidth.	Standard sound level as measured by commercial sound level meters. Converts pressures to sound levels.
L_{PN}	PNdB	Perceived noise level.	RMS values computed from the noy values of the highest noise level in each octave (or 1/3 octave) band, based on the 40-noy D-weighted scale; maximum integration is 1/2 sec (18).	Designed for aircraft and nonimpulsive sources.
L_{EPN}	EPNdB	Effective perceived noise level.	As L_{pn} except utilized a 1/2-sec time correction and pure tone penalty of up to 10 dB (for turbine whine) (19).	Do.
L_{eq}, L_T	NA	Equivalent sound level.	$L_{Aeq} = 10 \log_{10} \left[\frac{1}{T} \int_0^t 10^{L_{pA}(t)/10} dt\right]$ where L_{Aeq} = A-weighted equivalent sound level T = Time interval for average L_{pA} = A-weighted sound level during time T (any weighting can be used)	Running time average; any time duration can be used; good for long-term noise impact analysis.
L_{dn}	NA	Equivalent day-night sound level.	$L_{Adn} = 10 \log_{10} \frac{1}{86400} \left\{ \int_{t(0000)}^{t(0700)} 10^{[L_{pA}(t)+10]/10} dt + \int_{t(0700)}^{t(2200)} 10^{L_{pA}(t)/10} dt + \int_{t(2200)}^{t(2400)} 10^{[L_{pA}(t)+10]/10} dt \right\}$ where L_{Adn} = A-weighted day-night average sound level L_{pA} = A-weighted sound level within time interval (any weighting can be used) t = Time interval, sec, within hours indicated, over which intergration takes place	As above, except required at least a 24-hour integration and includes a 10-dB nighttime.
L_{CE}, L_{AE} (preferred); also L_S, L_{SC}, E_C, L_{SA}, E_A.	CSEL, SEL	C-, A-weighted sound exposure levels.	$L_{CE} = 10 \log_{10} \left[\frac{1}{t_o} \int_{t_1}^{t_2} \frac{P^2{}_c(t)}{P_o^2} dt\right]$ where L_{CE} = C-weighted SEL P_c = C-weighted sound pressure (any weighting can be used) P_o = Standard reference pressure $= 20 \times 10^{-6}$ N/m^2 t_1, t_2 = Beginning and ending times of event t_o = 1 sec Alternate form: $L_{AE} = 10 \log_{10} \frac{1}{t_o} \int_{t_1}^{t_2} 10^{L_{pA}(t)/10} dt$ where L_{pA} = A-weighted sound level during time interval t_1 to t_2 (any weighting can be used)	Measure of acoustic energy within an event; normalization to 1 sec gives a penalty to longer events (3 dB per doubling of time); it also tolerates higher SPL for durations shorter than 1 sec.
NA	PLdB	Perceived level, dB.	$PLdB = 55 + 20 \log_{10} \frac{\Delta P}{\tau}$ where ΔP = Pressure change, psi τ = Rise time, sec. corresponding to ΔP	Developed to characterize the sharpness and loudness of sonic booms.

NA Not available.

The CHABA Committee Report presents a summary of averaging and SEL measurement methods, including average sound level (L_{eq} or L_T), which runs averages over any desired time periods, and day-night average (L_{dn}), which is a 24-hour L_{eq} with a 10-dB nighttime penalty. Schomer (25) also uses L_{dn}, except that he introduces C-weighting. Both Schomer (25) and The CHABA Report (36) examine L_{CE} and L_{AE} and relate them to annoyance potential of blasts. Generally, the sources used to develop these levels--steady state (aircraft), sonic booms, and unconfined surface blasts--are quite different from mine production blasts. In particular, Schomer's (25) comparisons of artillery L_{AE}'s to blasting do not consider the vast difference between amounts of A-weighted energy present in the two sources. A more serious problem is the tendency to include transients such as blasts in long-term (that is, 24-hr) sound averages which leads to anamalous situations where the relatively coarse L_{dn} values do not accurately characterize the annoyance and damage potential of infrequent events.

Higgins and Carpenter (11) introduce the concept of perceived level (PLdB), based on the actual characteristics of the overpressure. This method uses pressure changes and corresponding rise times, and, although developed for sonic booms, could be applied to airblasts.

The Bureau (31) recently serveyed these noise descriptors and their applicability to blasting, specifically comparing L_{CE}'s, special weightings, and various linear sound levels with actual structure responses.

SOUND MEASUREMENT

Instrumentation

The measurement of frequencies below the audio range requires specialized instrumentation such as microphone carrier systems, one of which is shown in figure 3. The Bruel and Kjaer[4] (B&K) utilizes a FM carrier-demodulator system enabling it to operate down to dc response or to the lower limiting frequency of the microphone. The system shown has a 1-inch microphone with a time constant of 1.6 sec, and a frequency response that is flat from 0.1 Hz to 8kHz ± 3dB. The tolerance in the dynamic range of ± 3 dB is the relative deviation from the nominal value and is called "flat." This type of system has measured sonic booms and other acoustic transients that contain energy at very low frequencies. An auxiliary storage system must be used to capture transient overpressures. This can be a light beam oscillograph, oscilloscope with camera, storage oscilloscope, waveform recorder, FM analog magnetic tape recorder, or similar device with a frequency response that is flat (±3 dB) down to at least 0.1 Hz.

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[4] Reference to specific brand names is made for identification only and does not imply endorsement by the Bureau of Mines.

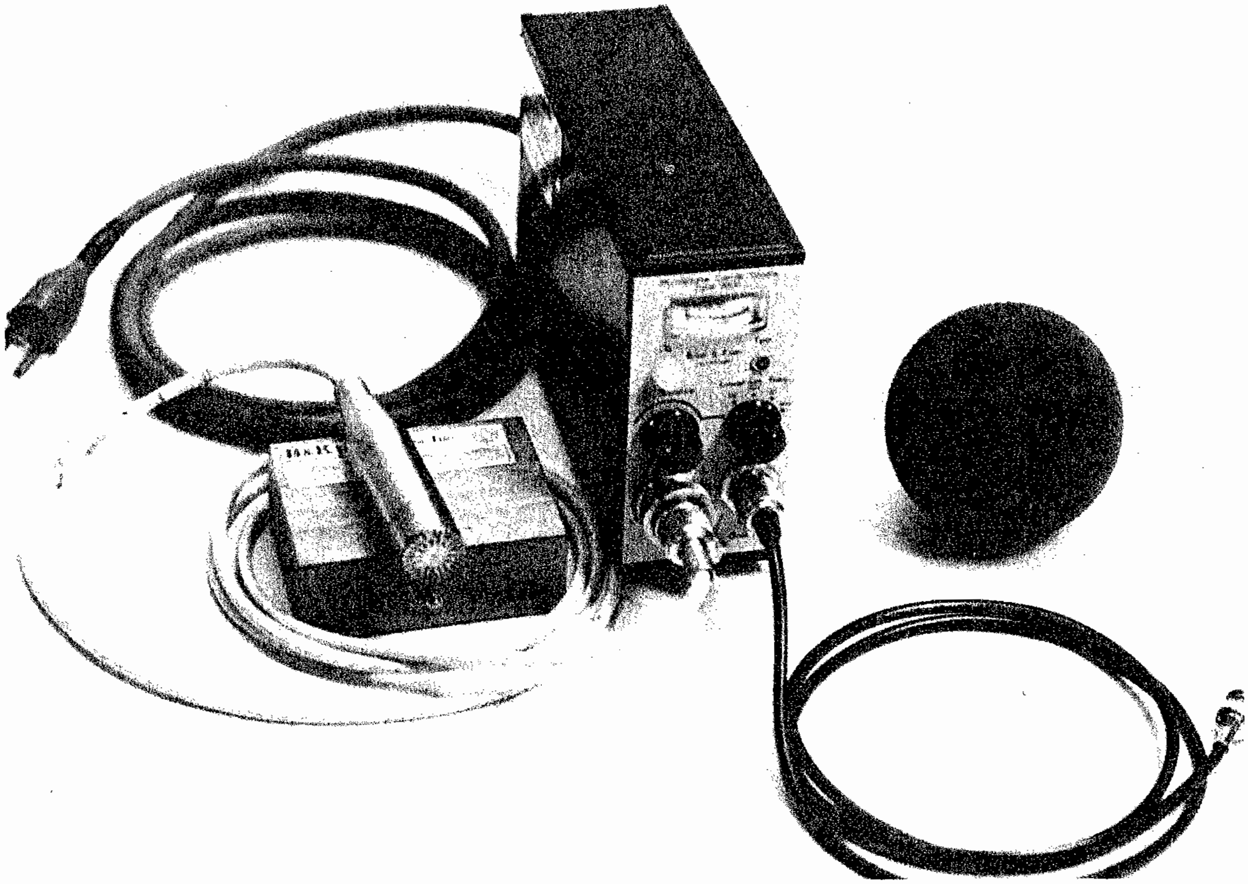

FIGURE 3. - Sonic boom microphone carrier system.

An alternate system with a differential-pressure transducer (fig. 4) has been adopted by the Bureau (29). The frequency range of this transducer is more limited at higher frequencies than the sonic boom microphone carrier system, owing to the dimensions of its air passages, but it does effectively cover the blast-generated frequency range. A precision needle valve adjusts the time constant, which controls the low-frequency response.

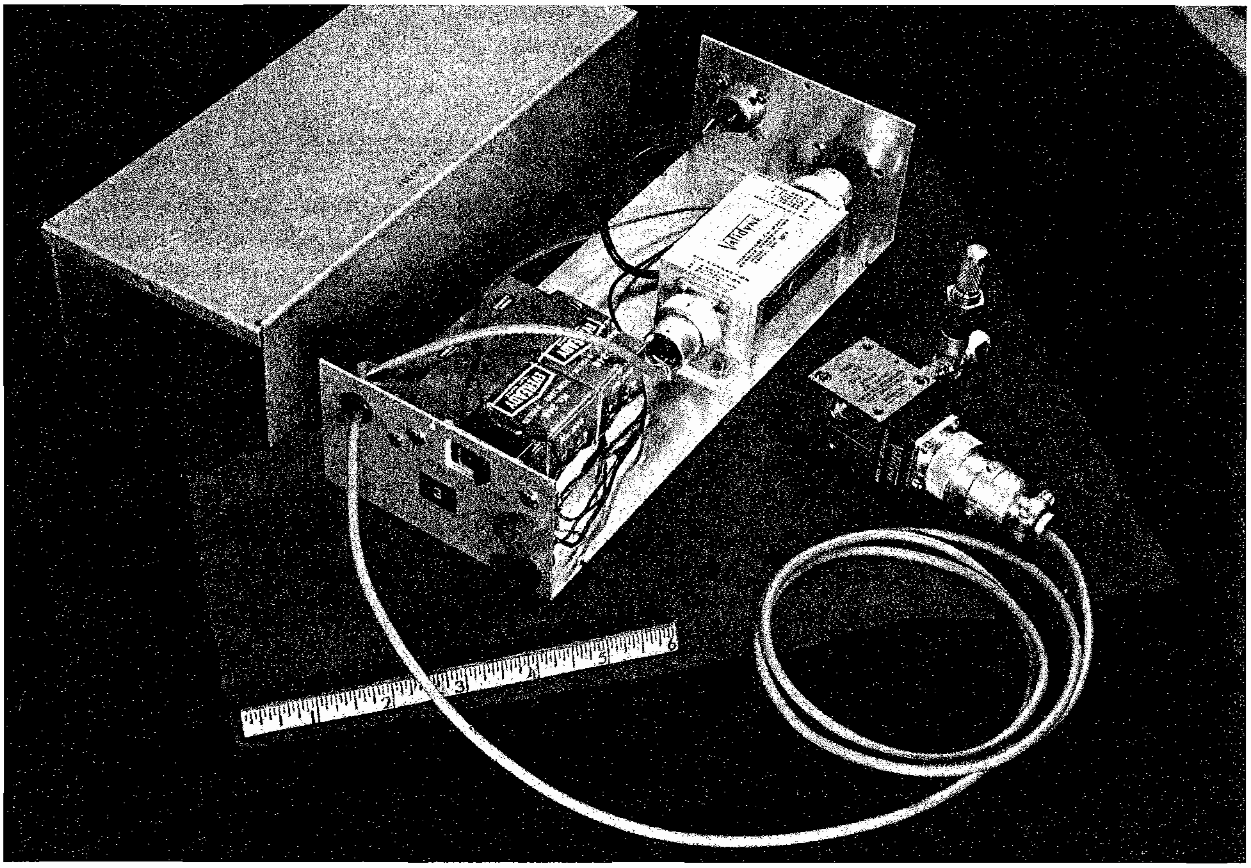

FIGURE 4. - Differential pressure transducer with a carrier demodulator.

In both carrier systems, the low-frequency limit is determined by the following equation:

$$F\ell = \frac{1}{2\pi\tau}$$

where $F\ell$ = lower limiting frequency (Hz)

and τ = time constant, (sec), for any given pressure P_0 to drop to $(1/e)\ P_0$ (see fig. 5),

with π = 3.14159...

and e = 2.71828...

This equation calculates the low-frequency limit (-3 dB) from the rate of pressure equalization between the positive and negative sides of the transducer diaphragm. A slow leakage is needed to maintain ambient atmospheric pressure in the cavity behind the diaphragm for the duration of a time constant. This pressure becomes a reference in making a differential measurement. A totally sealed cavity would give a 0-Hz (dc) lower limiting frequency, but temperature expansion and contraction of the sealed air volume and barometric pressure changes could damage the diaphragm and cause drift (29).

Determination of Frequency Response Needed

The frequency response selected for airblast measurement may meet one of several criteria. One rule-of-thumb is that gages should respond to four times the frequency of interest (24). Using this rule, previously measured airblasts (28, 31-32, 35, 39) suggest a range of 0.1 to 200 Hz. Reed defined a second criterion for the high-frequency response based on attenuation of

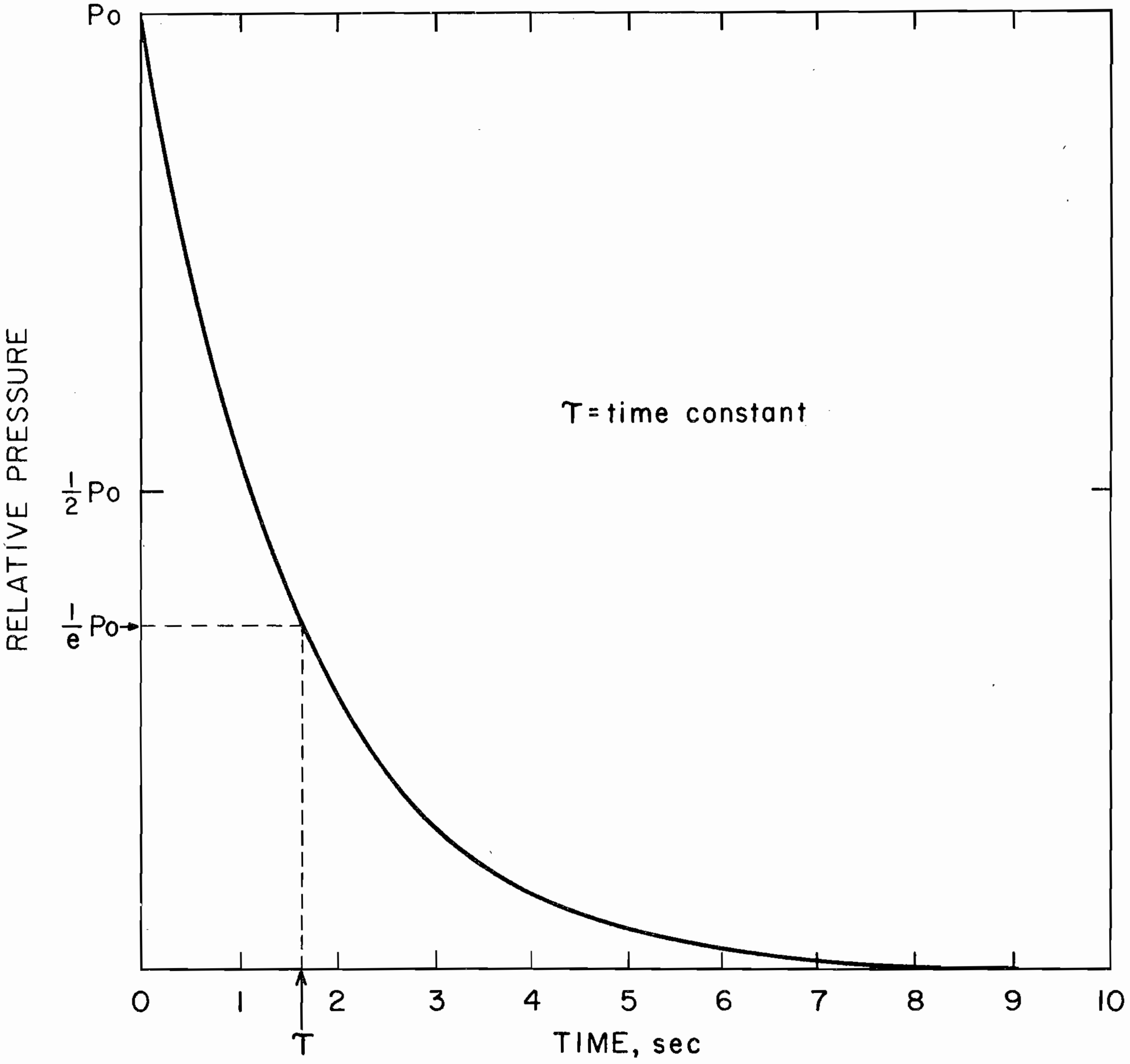

FIGURE 5. - Relationship between time constant and relative pressure.

explosion waves from unconfined high explosive and nuclear blasts. He stated that there appeared to be no need for greater response greater that 1 kHz, except at locations very close to small explosions. For environmental monitoring at levels of 114 to 144 dB at distances greater than a kilometer, 1 kHz would be adequate, if not an order of magnitude on the conservative side (24). Confined mine production blasts would not generate the high frequencies Reed observed. A third criterion is based on a theoretical study of Crocker and Sutherland, which resulted in formulas and curves for calculating upper and lower limits of frequency response (6). For ±10 pct accuracy in peak pressure and positive phase durations, a range of 0.05 Hz to 1 kHz would be required. The first criterion would be sufficient for confined mine production blasts, while unconfined surface blasts would be best measured under the second and third.

FM Tape Recorders

A typical FM tape recorder, shown in figure 6, is a portable 7-channel instrument with tape speeds from 15/16 to 60 in/sec. The frequency response is from dc (0 Hz) to a maximum determined by the tape speed selected (for example, 2.5 kHz at 7.5 in/sec. An AM tape recorder has insufficient response at low frequencies for airblast recordings. Such recorders are designed for use in the audio range (20 Hz to 20 kHz), rather than the infrasonic range where most airblast is found (21).

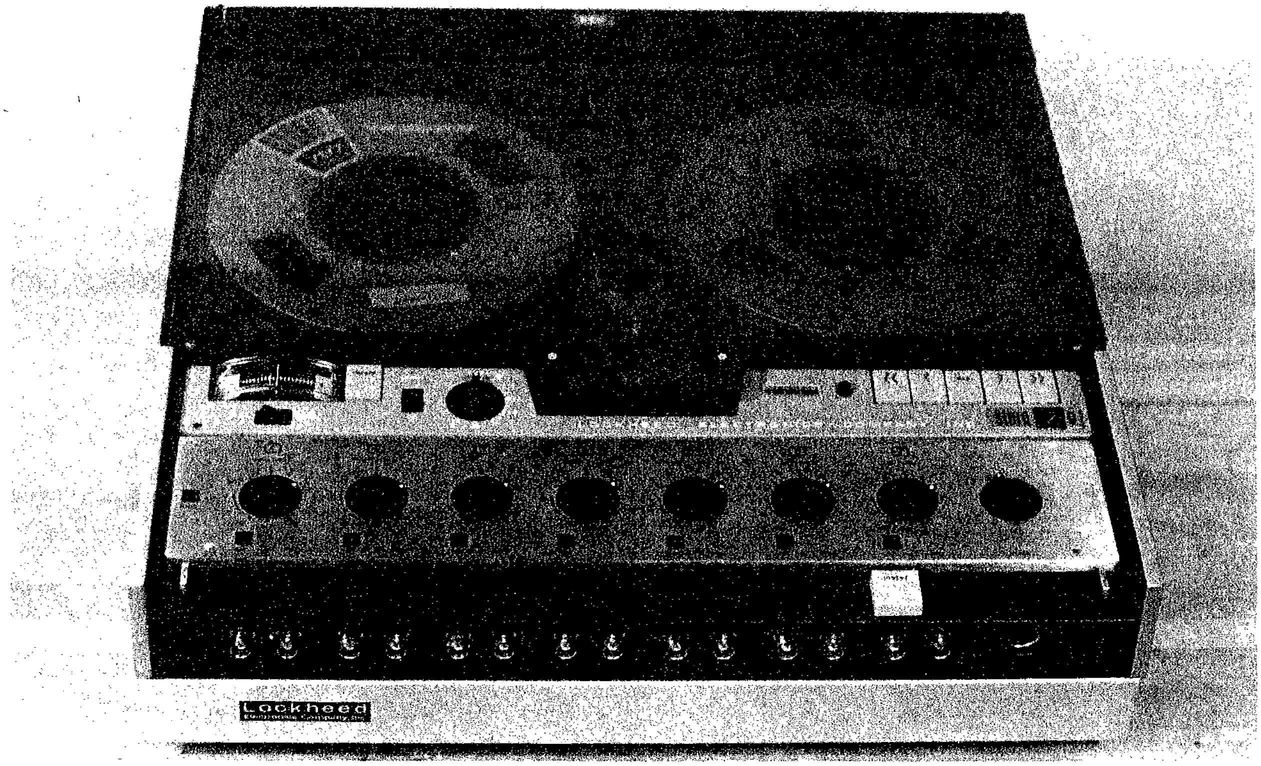

FIGURE 6. - FM tape recorder, 7 channel.

Sound Level Meters

Commercial sound level meters (SLM's) fall into four categories: Type I - Precision; Type II - General Purpose; Type III - Survey; and Type IV - Special Purpose. The tolerances for these categories are defined by the American National Standards Institute (ANSI) for A-, B-, and C-weighting (2). In figure 7 two Type I meters are shown with their respective calibrators and windscreens.

The Type I precision meter is available with an impulse response that becomes more accurate for transient noises with sharp rise times (14-15). Standard (nonimpulse) sound level meters can only resolve signals having crest factors of up to 10 dB. The type I impulse precision sound level meters contain squaring circuits that can resolve signals having 20-dB crest factors even when used with fast or slow response. Crest factor is the ratio of peak to rms and is a measure of "peakiness" of a signal.

FIGURE 7. - Precision sound level meters.

SLM's have selectable response times: slow, fast, impulse, and peak. Slow, fast, and impulse have time constants of 1,000, 125, and 35 msec, respectively (1-2). Peak response does not have a standardized time constant but should be about 10 μsec for rise times in the upper audio range. Storage of the highest peak value is an important feature (peak hold) when measuring a short, unexpected event.

Slow response is used to measure a random noise source, since its averaging effect makes reading easier. Fast response has the same effect, but to a lesser degree. Slow and fast produce rms readings only. Impulse response was designed for short-duration, single-pulse events. The 35-msec integration is based on the mean averaging time of the human ear. This setting should not be used for correlation with structure response or damage, because the response of the ear and structures are not related. The impulse setting has a 3-sec decay time constant, which can introduce errors from successive pulses such as those found in a delayed mine blast (14).

A-, B-, and C-weightings simulate human sensitivities electronically for different sound levels. A-weighting approximates the inverse of the equal loudness contour at a sound level of 40 dB (about 20 x 10^{-6} Nm^2); B- and C-weightings approximate this contour at higher sound levels. Frequency responses of these three weightings are shown in figure 8. All three weightings attenuate the lower frequencies strongly present in airblast. C-weighting, which attenuates low frequencies the least, is 3 dB down at 31.5 Hz. Flat or linear specification, found on SLM's indicates broader frequency response than C-weighting. The frequency response is controlled either by the input electronics or by the lower limiting frequency of the microphone. A typical flat and linear response is from about 5 Hz to more than 10 kHz and can vary considerably among manufacturers.

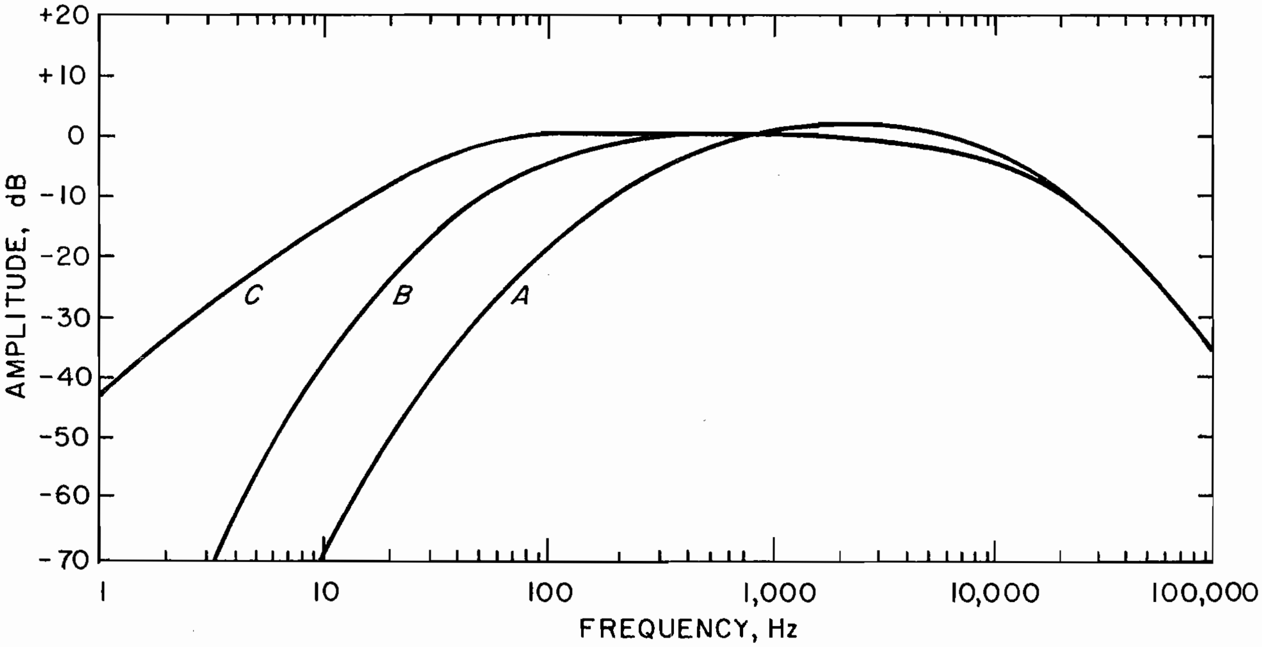

FIGURE 8. - Standard sound measurement weighting scales.

The most important features on SLM's for blast measurement are linear or flat-peak mode of operation, C-slow mode of operation for approximating sound exposure level, and peak-hold or sample-hold to retain the highest reading.

Electronic Frequency Response

The frequency response of typical SLM input circuits is shown in figure 9 (5). This is a second factor determining how the system works overall. IEC 179 is an international specification that does not define frequency response below 20 Hz, except for the upper limit, which extends to 10 Hz. The degree of frequency response rolloff must be documented when wideband recordings are played back into the input circuitry. Even if the frequency response of a microphone is extended, the whole system may not improve because the input preamplifiers have insufficient frequency response. A different microphone may change the input impedance matching so that overall response at low frequencies decreases (21). The rolloff of a condenser microphone may be altered by the introduction of a series capacitor as illustrated by the 2-Hz and 10-Hz curves in figure 9 (5). The direct curve is for an impedance matched input from a tape recorder.

Effects of Wind and Windscreens

Wind blowing across a microphone can generate turbulence, which can cause a noise measurement to be erroneously high. Figure 10 shows typical wind

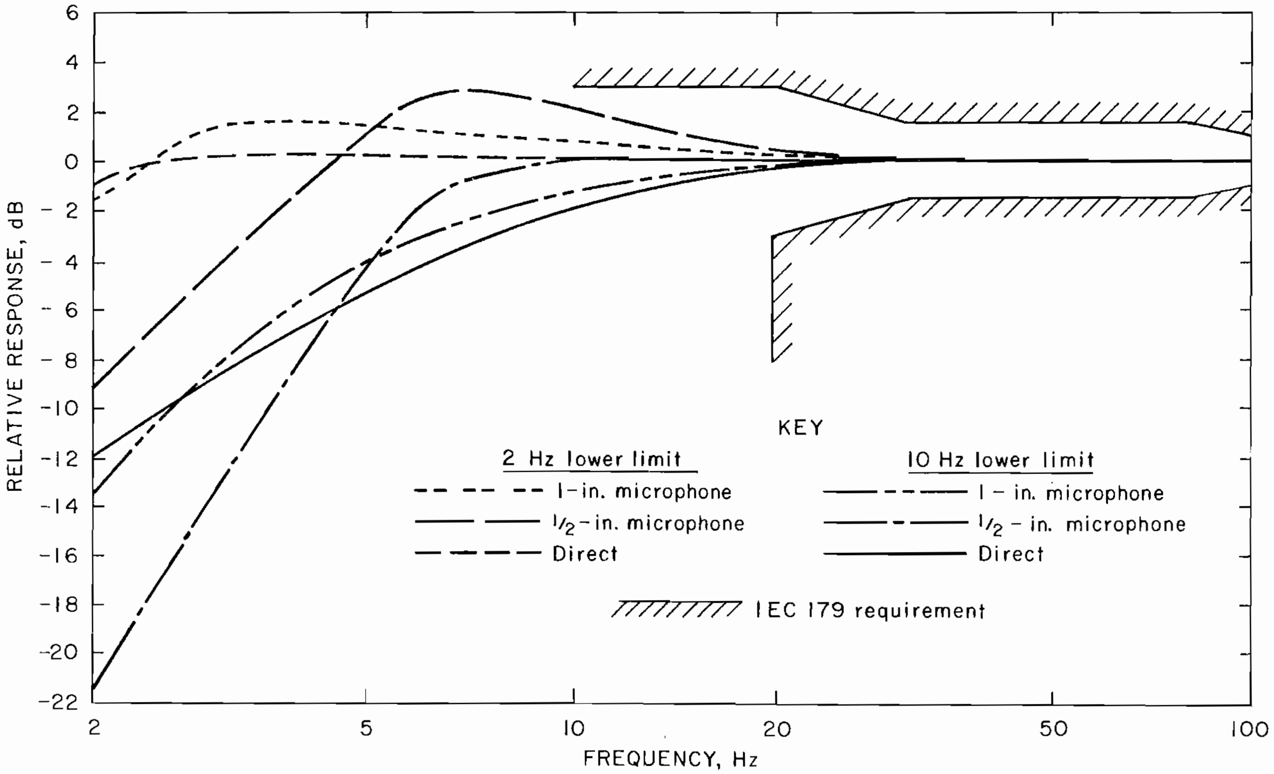

FIGURE 9. - Typical response of SLM input electronics (5).

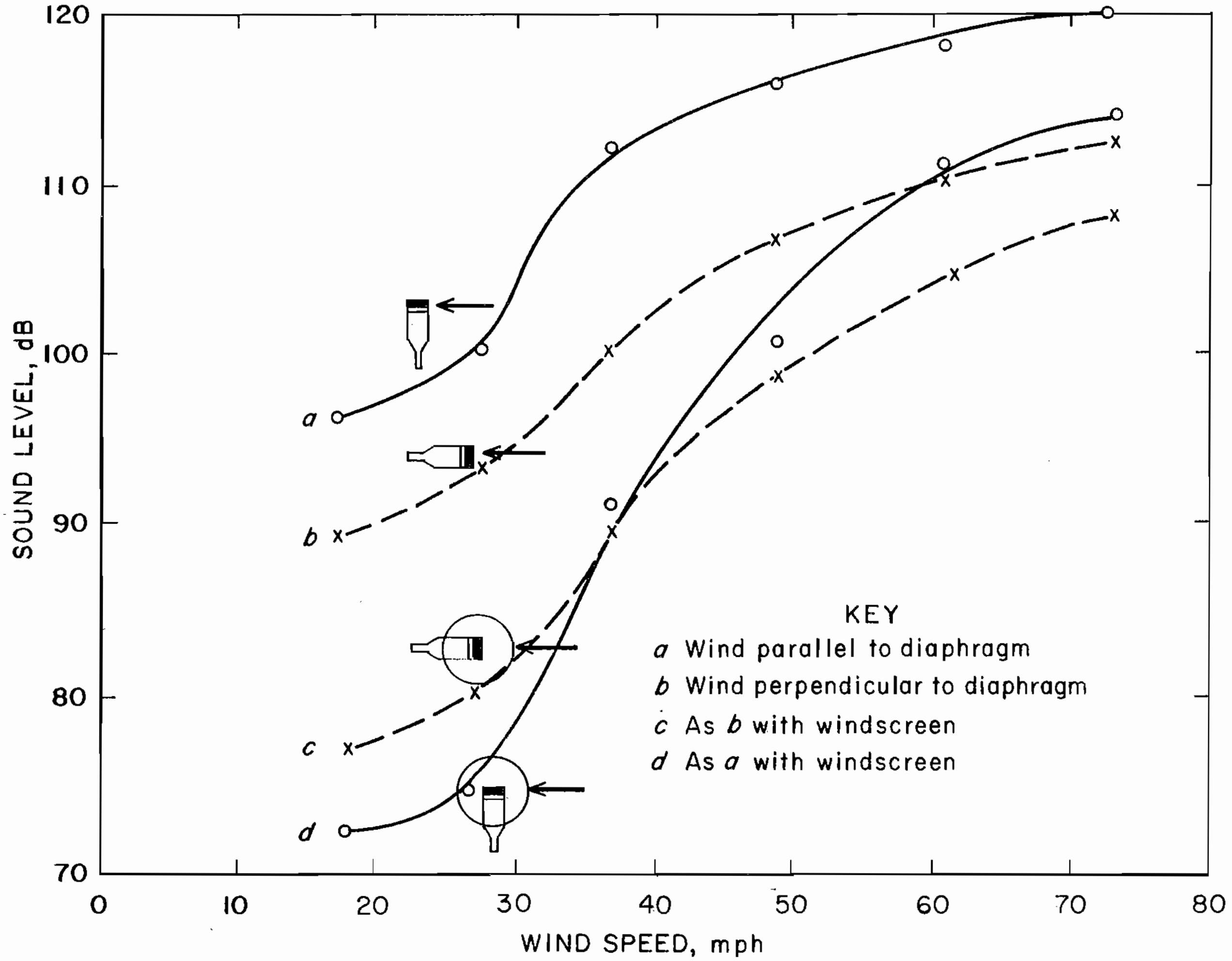

FIGURE 10. - Wind noise as function of wind speed in the range of 20 Hz to 20 kHz (3).

noise for microphones with and without windscreens (3). For example, a wind about 25 mph parallel to the diaphragm (a and d) generated about 99 dB without a windscreen and 73 dB with one. The windscreen reduced this noise by 26 dB. Figure 11 illustrates the effects of wind perpendicular to the diaphragm with and without a windscreen (23). The windscreen reduces wind noise by 17 to 28 dB in the 25 to 6,000 Hz range. The microphone should be protected from direct exposure to wind; if not possible, a windscreen should be used.

Sound Exposure Level (SEL)

The Committe for Hearing, Bioacoustics, and Biomechanics (CHABA) Working Group 69 has recommended that the U.S. Environmental Protection Agency adopt a C-weighted sound exposure level (CSEL or L_{CE}) method to regulate noise from booms, quarry blasts, or artillery fire (36). The equation for and characteristics of this level are given in table 1. One advantage of using CSEL for blast regulation is that a standard sound level meter may be used to approximate values. The meter must be set on "C-weighting" and "slow response."

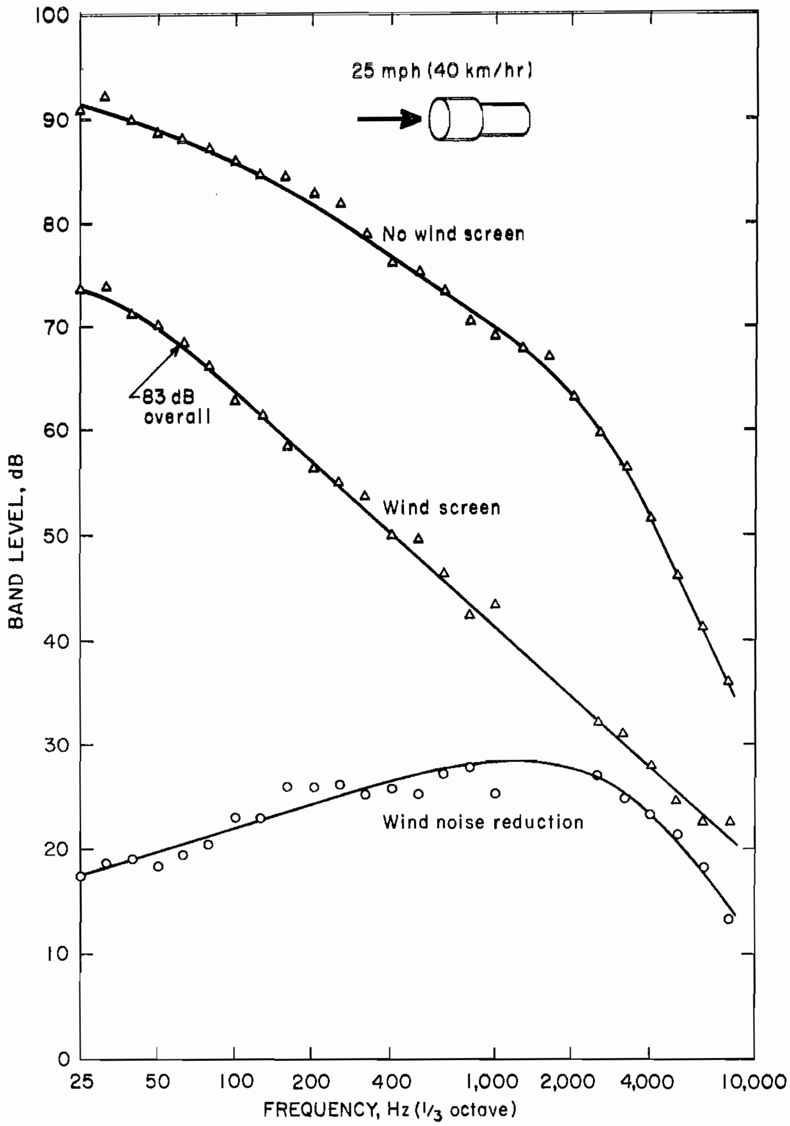

FIGURE 11. - Wind noise spectrum, flat weighting (23).

Errors for shot durations of 0.5, 1.0, and 2.0 sec will be 1, 2, and 3.5 dB, respectively (16). A Type I precision SLM may be preferred because better low-frequency response (below 20 Hz) is required (2). Unfortunately, in tests to date, use of CSEL has not appreciable improved prediction of damage over the previously recommended linear-peak measurements (17, 28, 30-31, 35).

CALIBRATION INSTRUMENTS AND METHODS

Sound level meters may be calibrated dynamically with a sound level calibrator (SLC) or a pistonphone (fig. 12). Dynamic calibration should be traceable to the National Bureau of Standards (NBS), since this assures that the proper sensitivity is being maintained. Pistonphones are slightly more accurate but are mechanically limited to lower frequencies--in the case pictured, to a single frequency of 250 Hz. The SLC illustrated has selectable frequencies of 125, 250, 500, 1,000, and 2,000 Hz.

Calibration in the frequency domain is more difficult and requires specialized equipment and techniques. Three types of pressure amplitude calibrations will be illustrated here: Change of height; a commercially available high-pressure, low-frequency calibrator; and a simply built piston-chamberphone. An additional method is described by Hunt and Schomer that locates the -3 dB point (12).

The "change of height" method can determine the -3 dB response point with the equation on page 9 and the dynamic calibration can be determined by the following equation:

FIGURE 12. - Pistonphone (left) and sound level calibrator.

$$h = P_c \frac{(T + 273)}{4.548\ P_o}$$

where h = change in altitude (m)

P_c = calibration pressure (N/m^2)

T = temperature (° C)

and P_o = atmospheric pressure (mm of Hg)

This method is only effective for microphones or transducers with good low-frequency response (long time constants), e.g. below 0.05 Hz. This method measures the change in atmospheric pressure over a measured altitude shift (for example, a change of approximately 5.2 feet would produce 120 dB re 20 x 10^{-6} N/m^2 at 0° C. and 760 mm of Hg) (29, 35). This method works best for instruments with long time constants and produces one calibration point, the -3 dB level. A commercially available high-pressure, low-frequency microphone calibrator (fig. 13) may be used over a continuous frequency range of 10^{-3} Hz to 1 kHz and can generate pressures up to 172 dB. This is a constant force rather than a constant displacement pistonphone and is driven by a miniature electromagnetic shake table. When the pressure changes are turning from adiabatic to isothermal processes, the error is minimized by this method. Changes in gas compressions can be adiabatic or isothermal depending on volume, shape of the chamber, and the rate of change (frequency). This calibrator was modified to accommodate differential pressure gages and 1-1/8-inch microphones with a minimum of internal volume changes to the pressure chamber. The frequency response curves in figures 21 to 24 were obtained with this calibrator (8, 35).

The third method of calibration is the piston-chamberphone (fig. 14). It generates a sound pressure of 0.0005 psi (125 dB peak SPL) by a gas model-airplane engine, a clear plastic chamber, and a variable-speed electric motor (29, 35). The ratio of specific heats of gas (1.30 to 1.41), which must be included when calculating the sound pressure within the chamber works out to about a 3-dB change in the pressure. A correction factor is then applied for nonadiabatic compression in the cylindrical volume for frequencies below

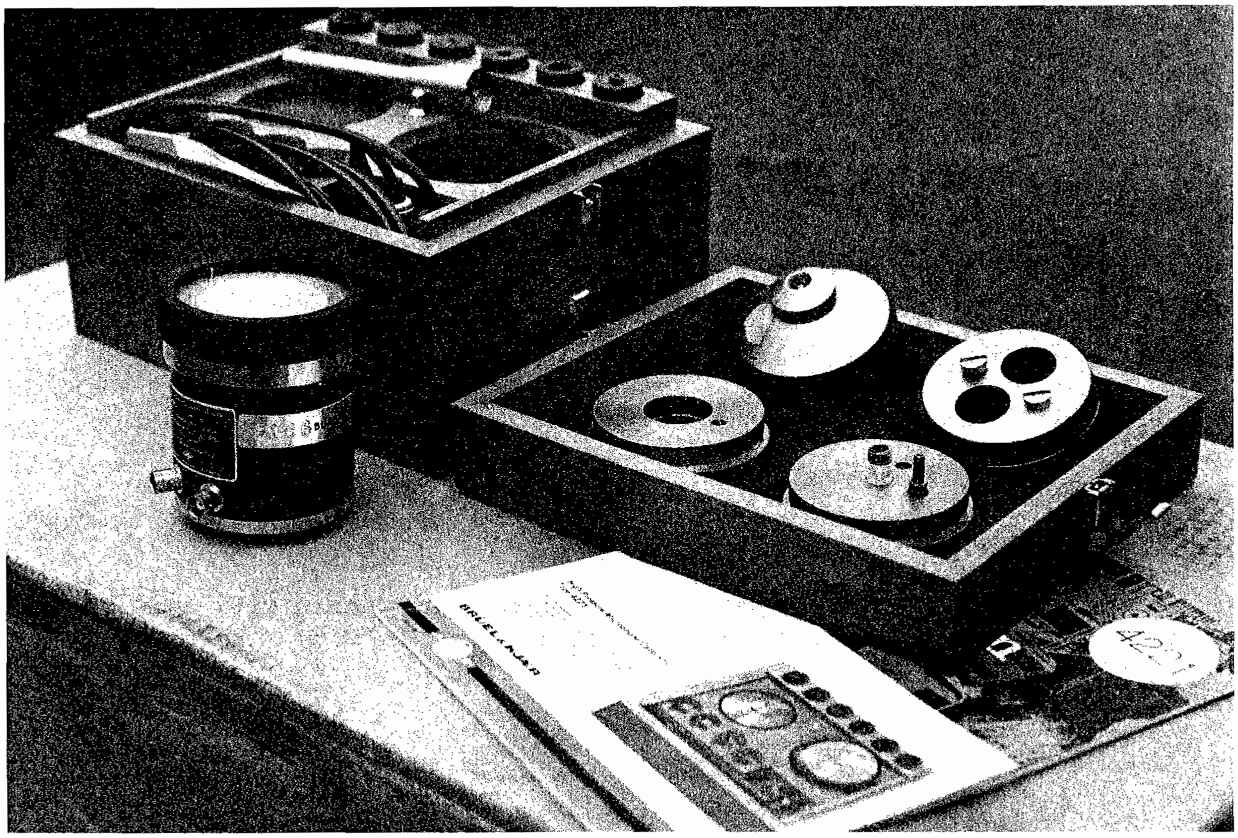

FIGURE 13. - High-pressure, low-frequency calibrator.

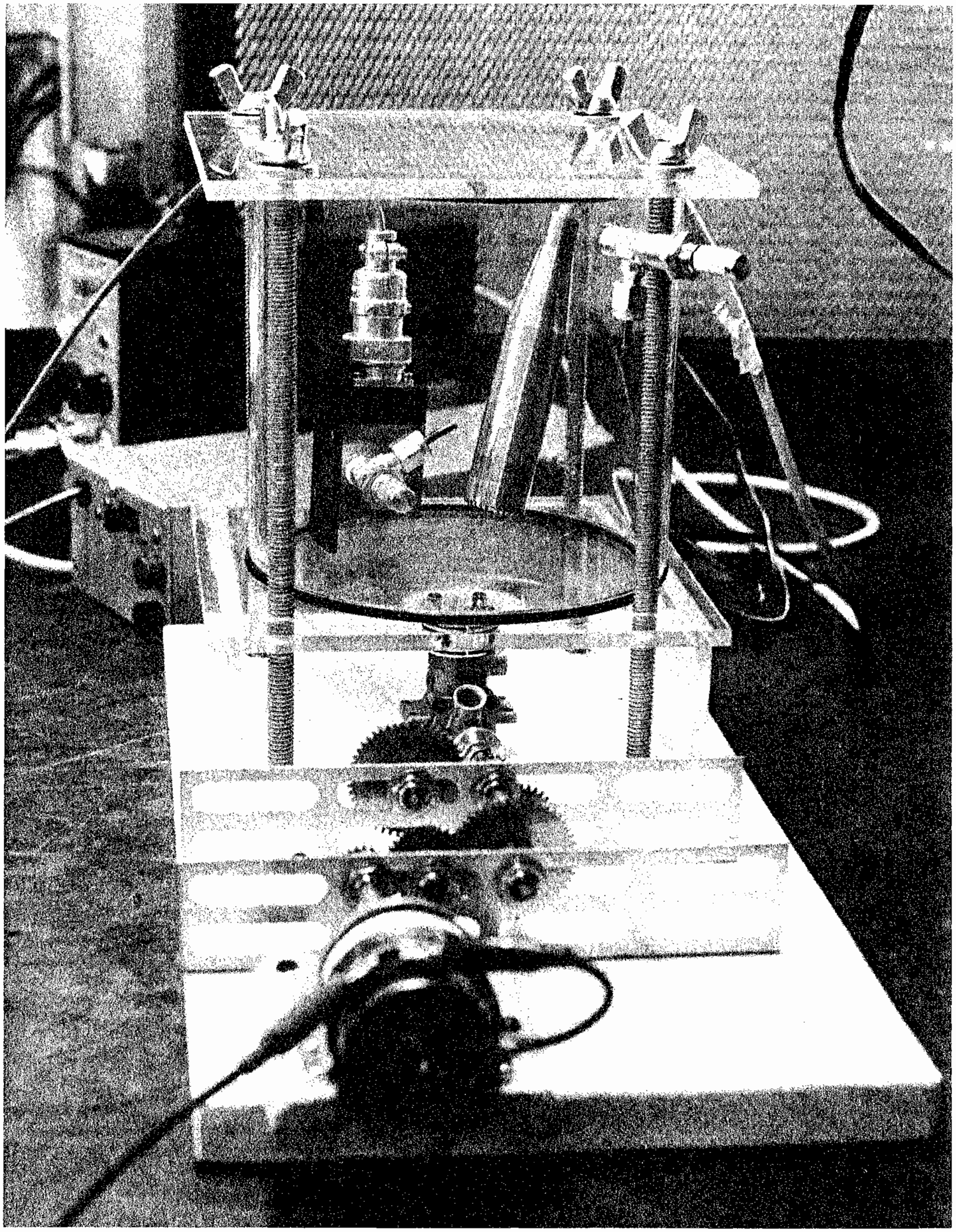

FIGURE 14. - Piston chamberphone.

3 Hz (4). On this particular system, the greatest correction was 0.59 dB at 0.1 Hz. The effective frequency range was 0.1 to 100 Hz. Sealing was a problem at low frequencies, and vibration and lubrication at the high frequencies. Some of these problems may be minimized by making the volume large compared with the surface area of the calibrator chamber (4, 21).

CALIBRATIONS AND EXPERIMENTAL RESULTS

The calibration and comparison tests in this section were used to determine the most effective instrument and measurement technique for surface mine blasting. A comparison of C-slow and CSEL normalized to 1.0 sec is presented in figure 15. Standard commercial SLM's were used to obtain the C-slow

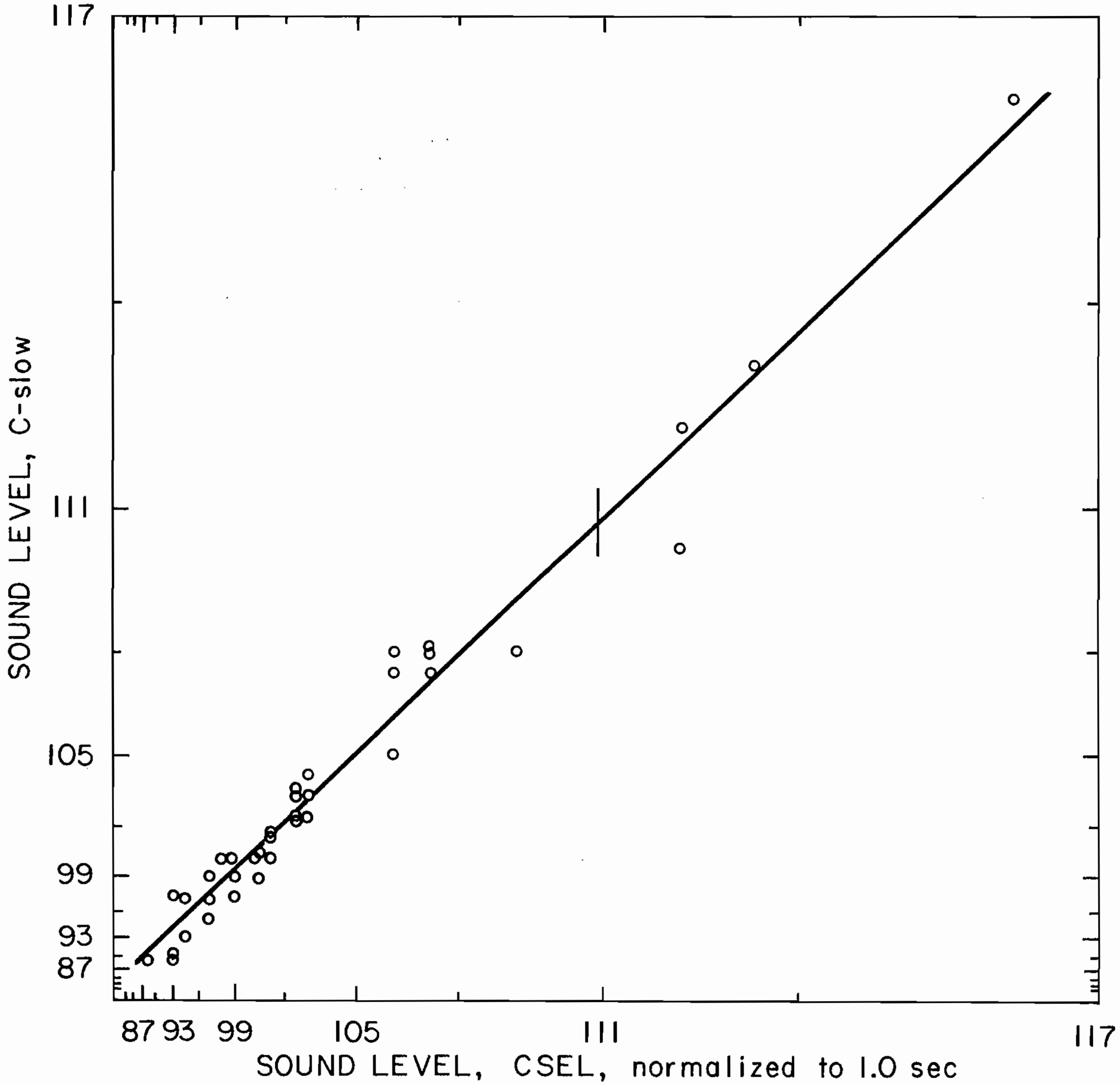

FIGURE 15. - C-Slow compared with CSEL, normalized to 1 sec.

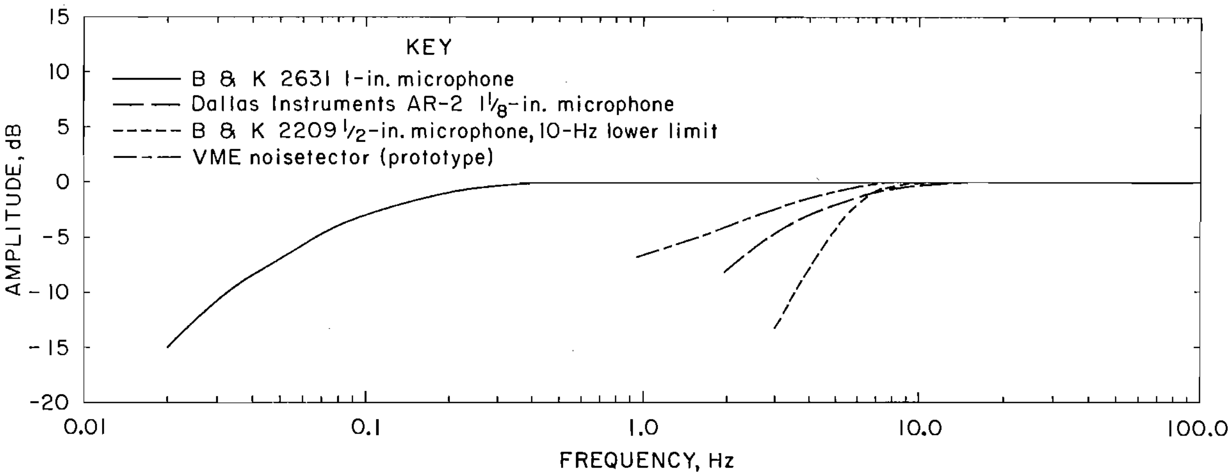

FIGURE 16. - Frequency response: B&K 2631, B&K 2209, Dallas Instruments AR-2, and VME Noisetector.

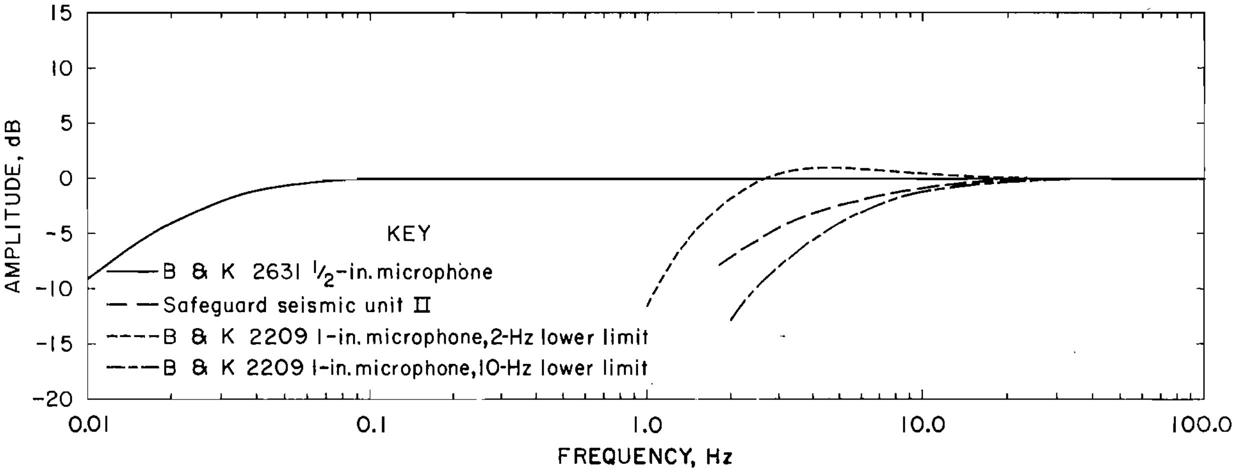

FIGURE 17. - Frequency response: B&K 2631, B&K 2209, and Safeguard Seismic Unit II.

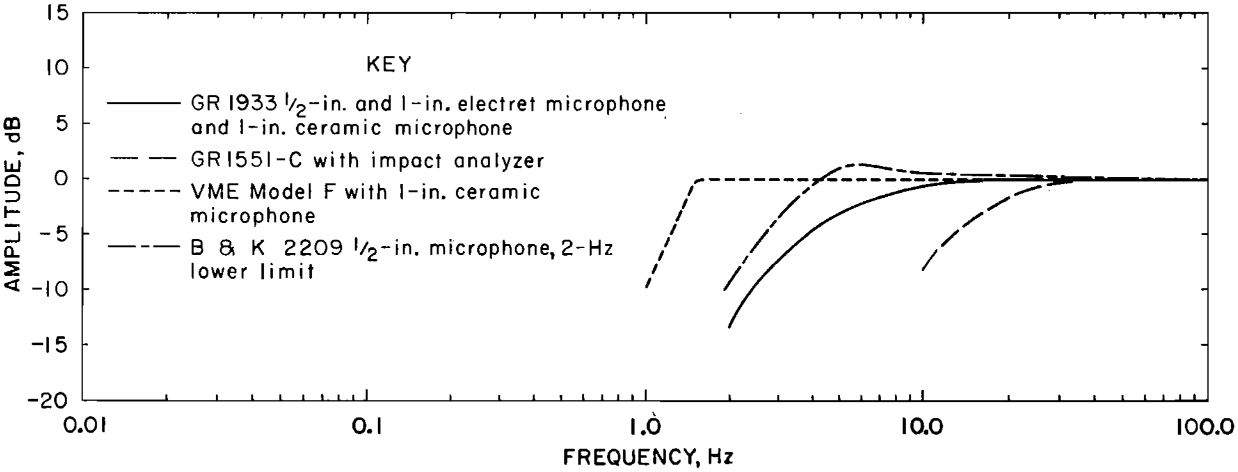

FIGURE 18. - Frequency response: GR 1933, GR 1551-C, VME Model F, and B&K 2209.

readings, and a GR-1926 rms detector was used for the CSEL values. The correlation coefficient of C-slow versus CSEL is 0.986, and standard deviation is 0.0000628 psi with a best-fit line of Y = 0.968 X + 0.0000169 psi. Individual data points are listed in table B-1. The high degree of correlation suggests that C-slow may be an approximation for shots of 1.0-sec duration or less. Longer shots require an SLM modified to integrate for longer than 1.0 sec or the correction factors given by Kamperman. His corrections for shots of 0.5, 1.0, and 2.0 sec were 1, 2, and 3.5 dB, respectively (16).

The frequency responses of all airblast instruments used or tested by the Bureau is shown in figures 16 to 19. A modified B&K 4221 high-pressure microphone calibrator was used to obtain the overall response from 100 Hz down to the frequency at which the response dropped 3 dB.

Figures 20 to 23 illustrate the effect of various frequency responses on amplitude for typical Type I and Type II airblasts. The best response is on top and the poorest is on the bottom, with the vertical scales relative in size.

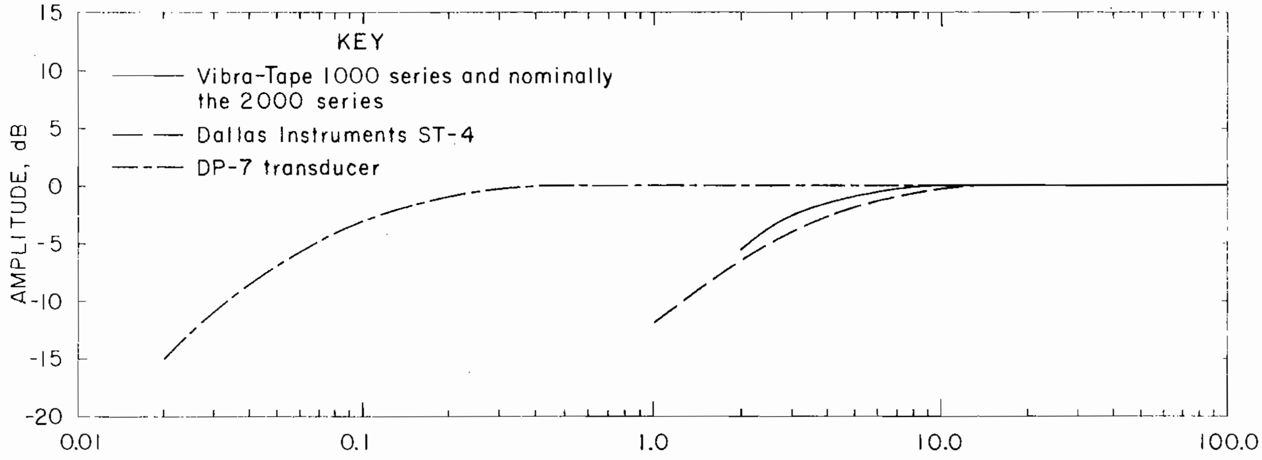

FIGURE 19. - Frequency response: Vibra-tape 1000 and 2000 series, Dallas Instruments ST-4, DP-7 transducer.

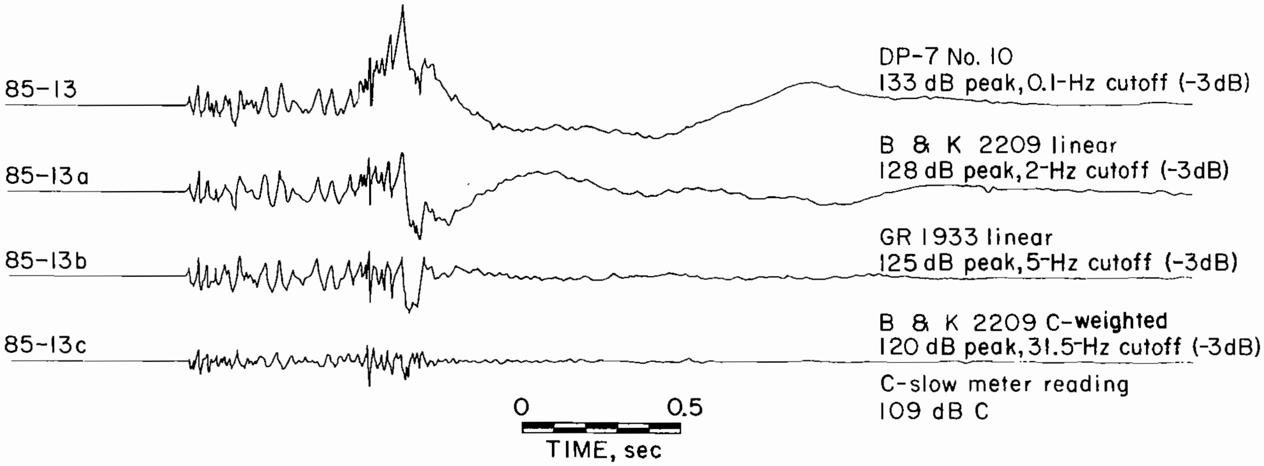

FIGURE 20. - Type I airblast measured four different ways.

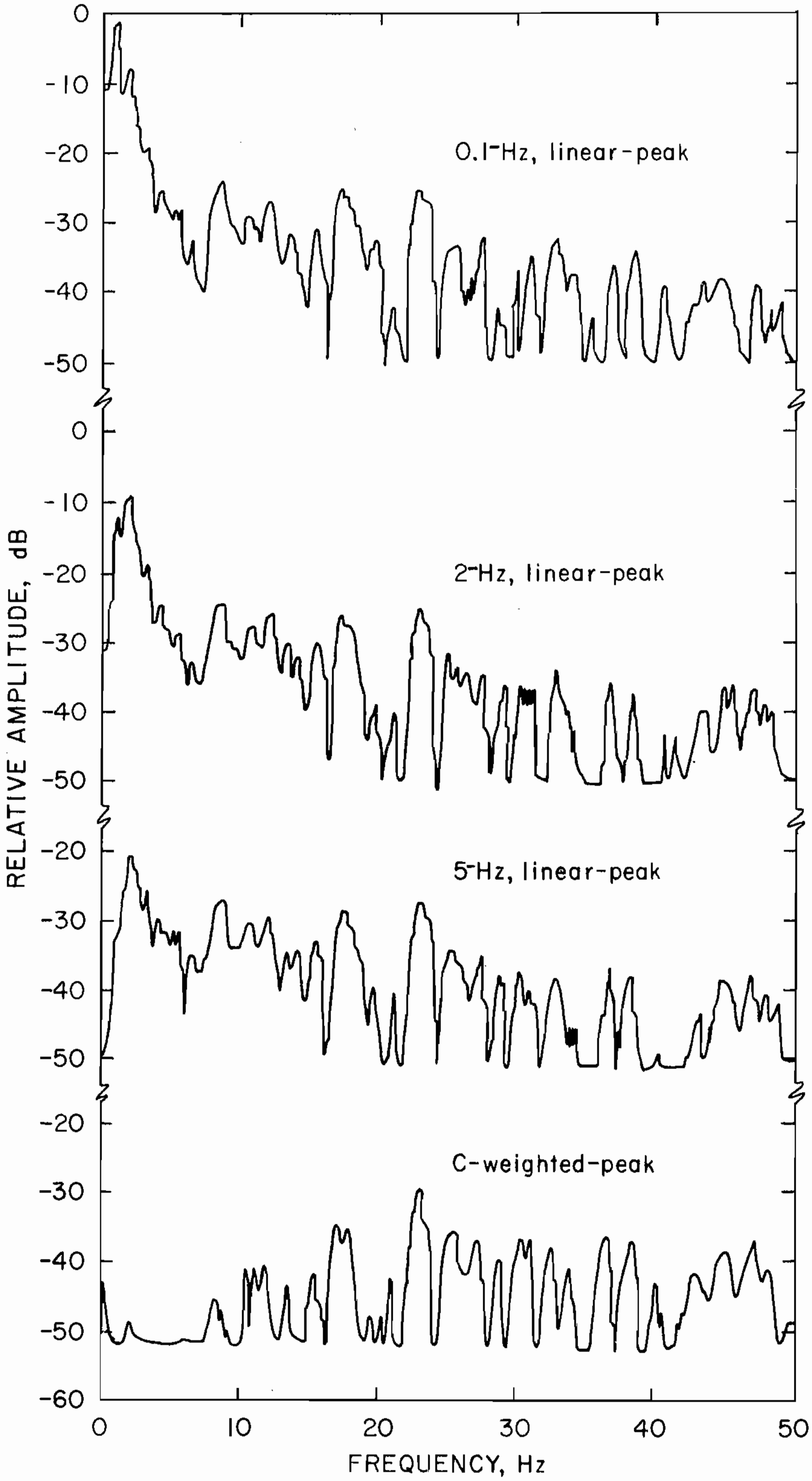

FIGURE 21. - Spectra of Type I airblast measured four different ways.

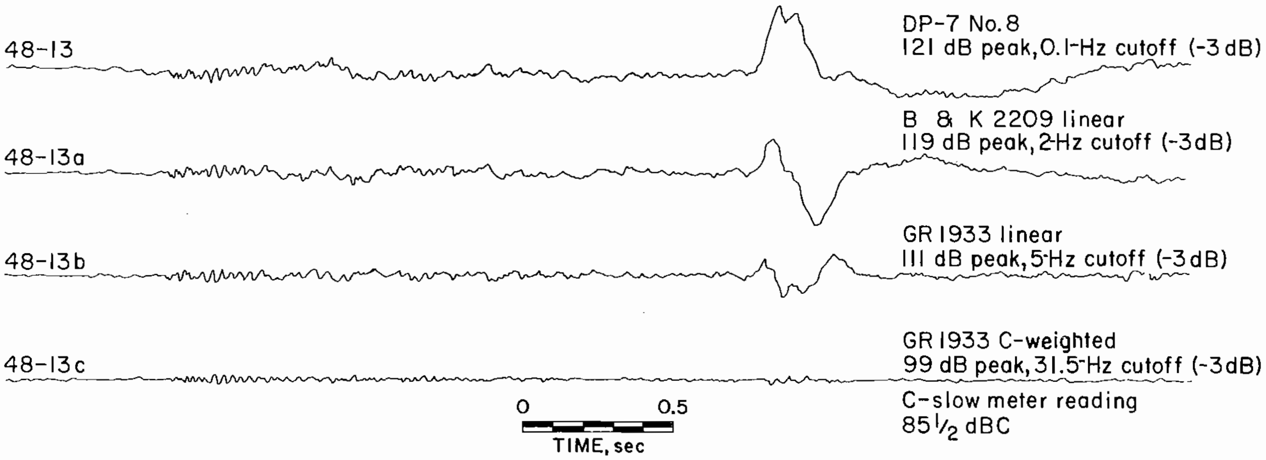

FIGURE 22. - Type II airblast measured four different ways.

A typical Type I coal mine highwall shot is shown in figure 20. The 2-Hz instrument reads 5 dB low and shows a shift in peak value to the right and below the center line because of "ringing." This ringing causes a reduction in amplitude and a phase shift due to the instrument's inability to follow the lower frequency excursions of the airblast. The 5-Hz and C-weighted instruments show further reductions in amplitude of 8 and 13 dB, respectively, with a C-slow meter reading 24 dB below the most linear instrument. The frequency spectra for figure 20 are shown in figure 21. This further illustrates the loss of amplitude at lower frequencies.

A typical Type II airblast is shown in figure 22, with its respective frequency spectrum in figure 23. The 2-Hz instrument shows a shift in peak value to below the center line and a 2-dB decrease in total amplitude. The respective reductions in amplitude for 5-Hz, C-peak, and C-slow are 10 dB, 22 dB, and 35.5 dB.

The 2-Hz instrument has its response least affected for both types of airblast, since the 1-Hz energy is so close to the -3 dB point. The response of the 5-Hz and C-weighted instruments sharply decreases (a lower reading for the same airblast) for the Type II blasts because of the absence of higher frequency energy. The 2-Hz instrument gives a more accurate measure of the total energy in an airblast than the 5-Hz or C-weighted instruments.

Shake table tests were run on the Validyne DP-7 to determine the effects of vibration at a constant peak acceleration. A comparison with the DP-7 can be made to a standard B&K 2209, with a 1-inch microphone (fig. 24). The level generated by external vibration ranges from 68 to 73 dB at a constant sinusoidal acceleration of 1 g. An additional test was made to determine the effect of air being driven into the open port of the transducer. A relatively low level of noise (58 to 63 dB) was generated at a high level of acceleration (16 g). Vibration effects were minimal.

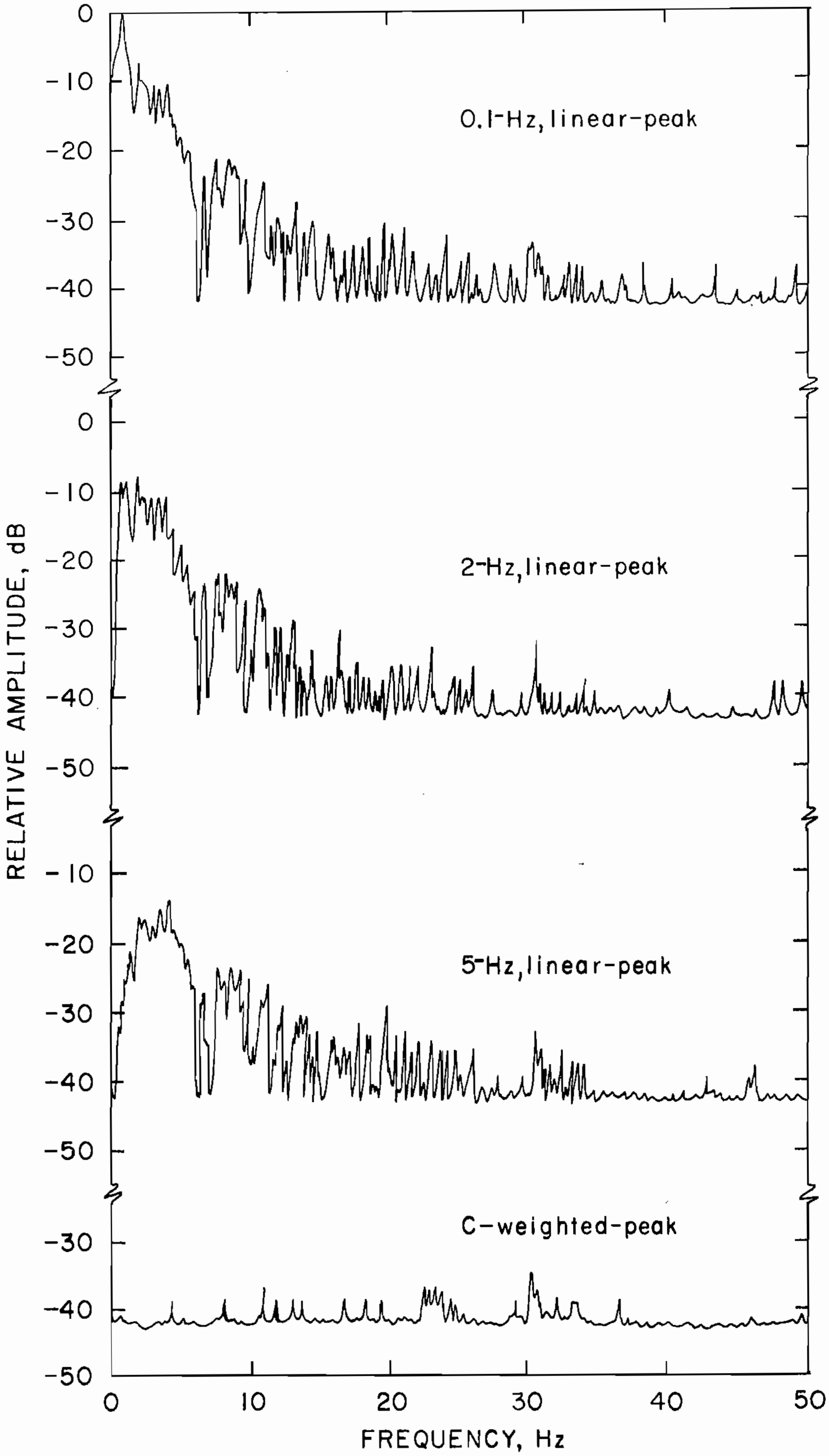

FIGURE 23. - Spectra of Type II airblast measured four different ways.

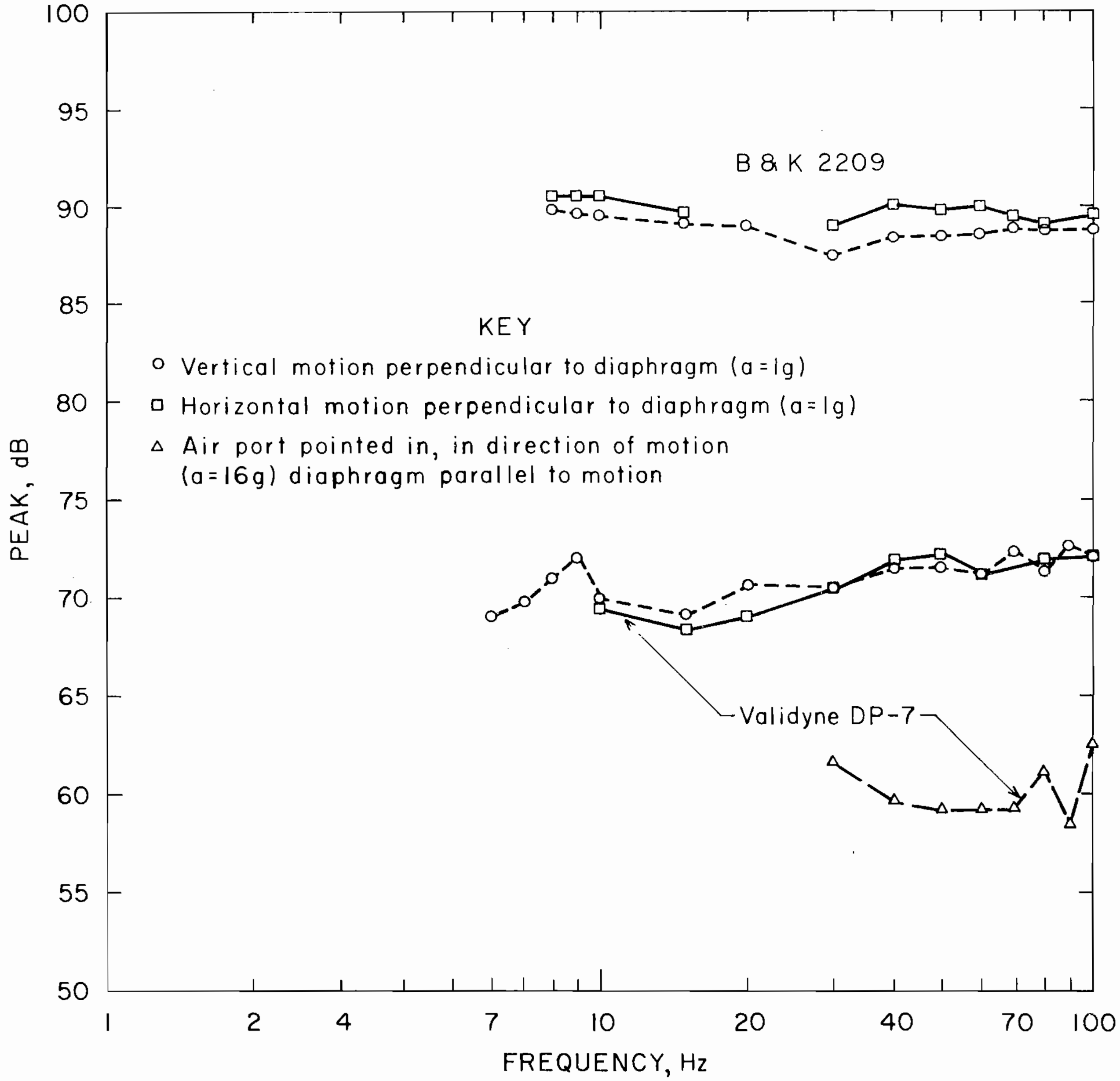

FIGURE 24. - Vibration response of DP-7 sound measurement transducer.

The change in sound level readings by type of shot and instrument or measurement technique are shown in figures 25 to 30, with their statistics in table B-2. The horizontal axis is the airblast as measured with the most linear instrument and vertical axis is the scale for the 2-Hz peak, 5-Hz peak, C-slow, and PL dB readings. For example, in figure 25, a 130-dB airblast would produce a 127-dB peak reading on a 2-Hz instrument, a 126-dB peak on a 5-Hz instrument, a 106-dB C-slow on an integrating type sound level meter, and a reading of 93 dB using perceived level (PL) techniques.

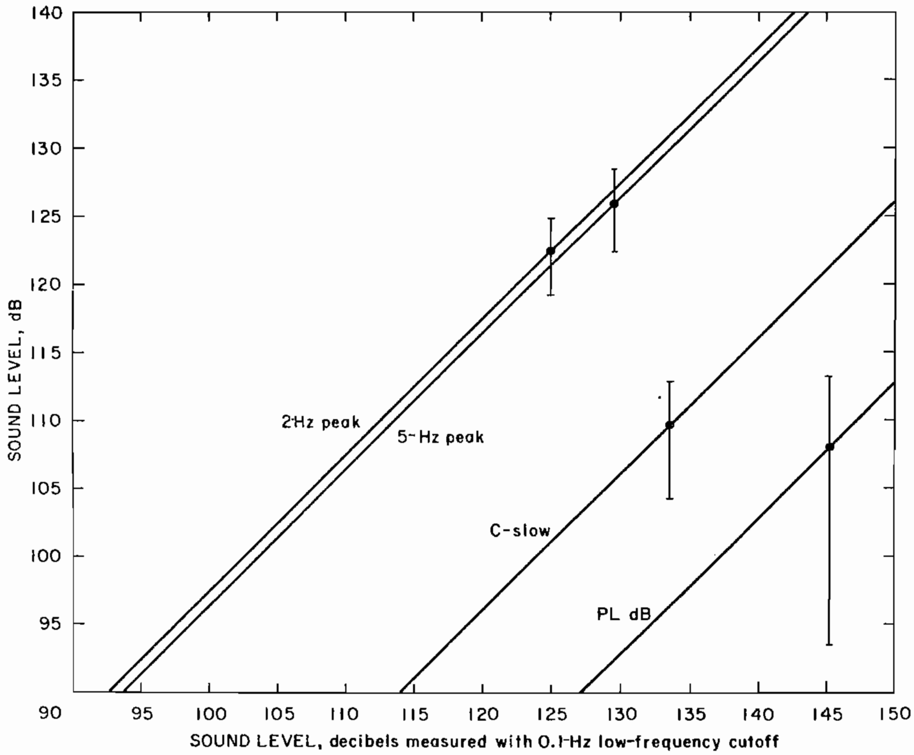

FIGURE 25. - Sound levels for coal mine highwall shots.

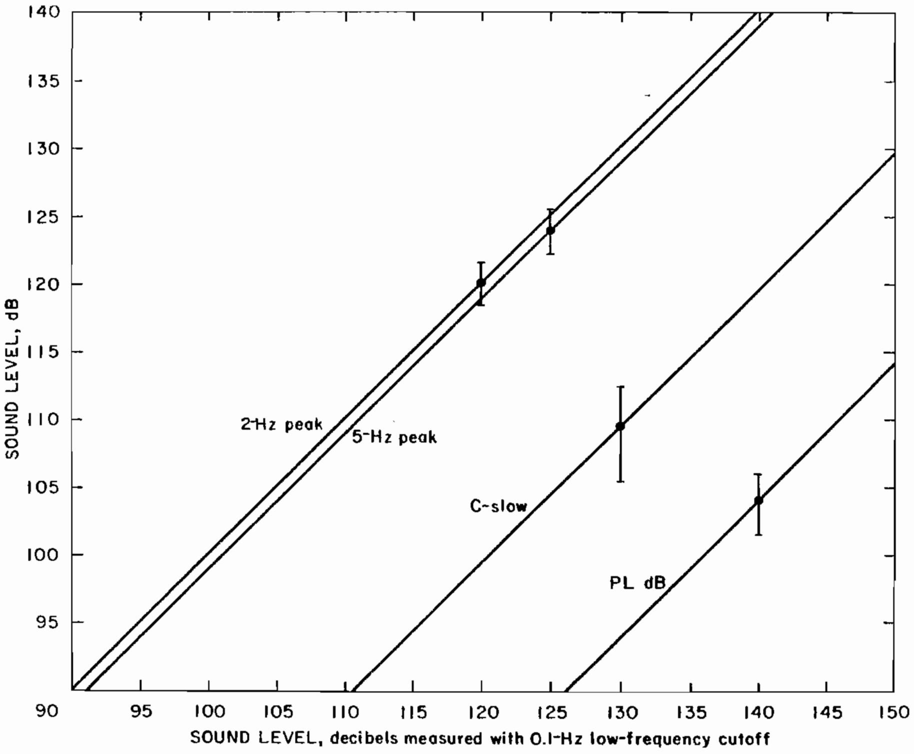

FIGURE 26. - Sound levels for coal mine parting shots.

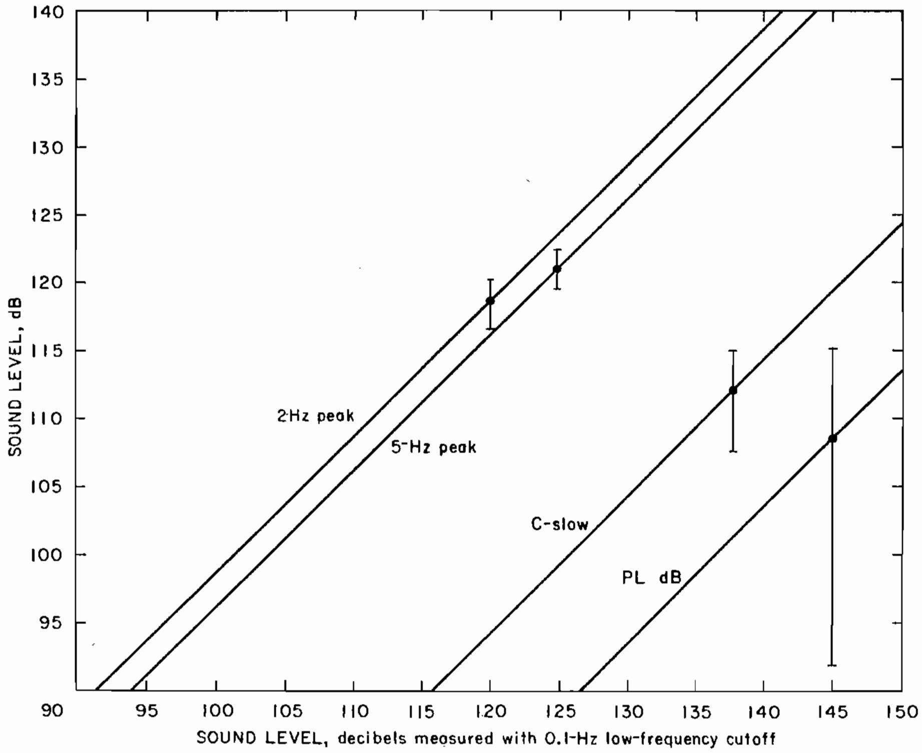

FIGURE 27. - Sound levels for coal mine assorted shots.

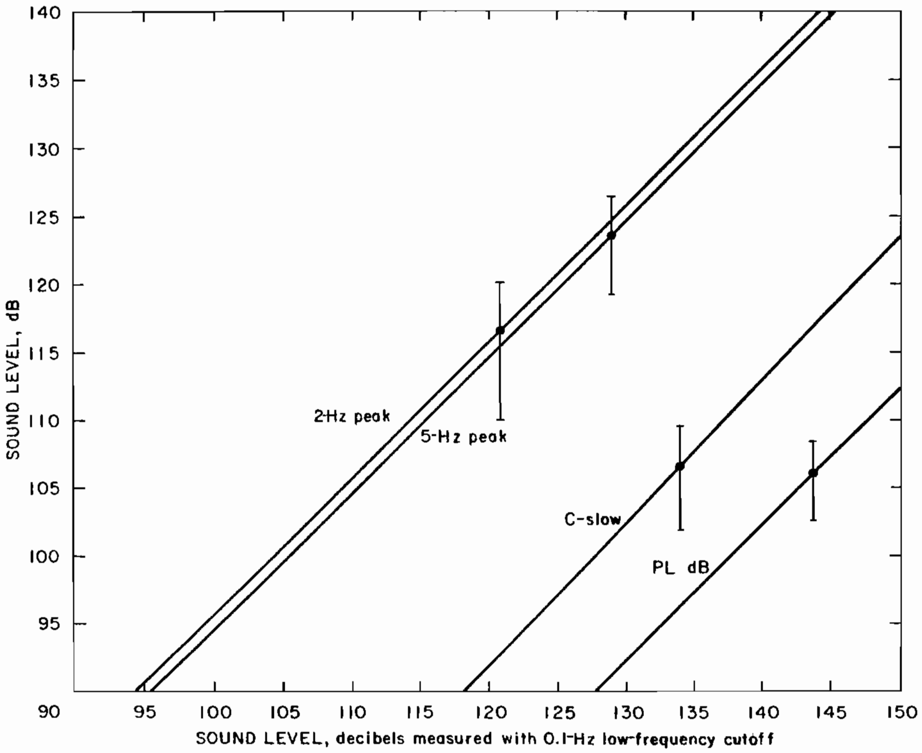

FIGURE 28. - Sound levels for quarry shots.

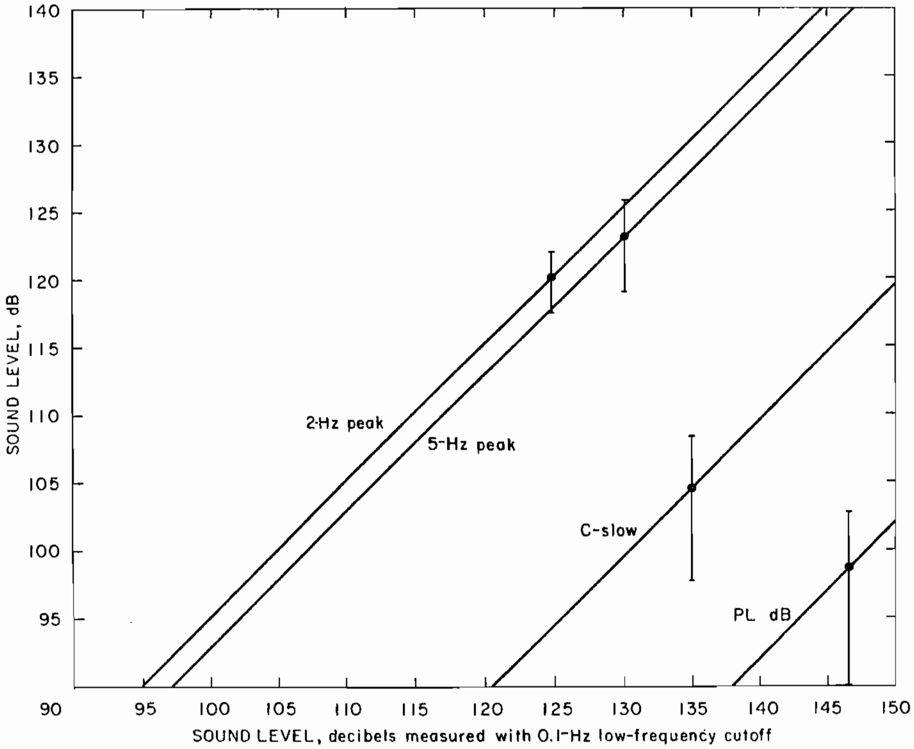

FIGURE 29. - Sound levels for metal mine shots.

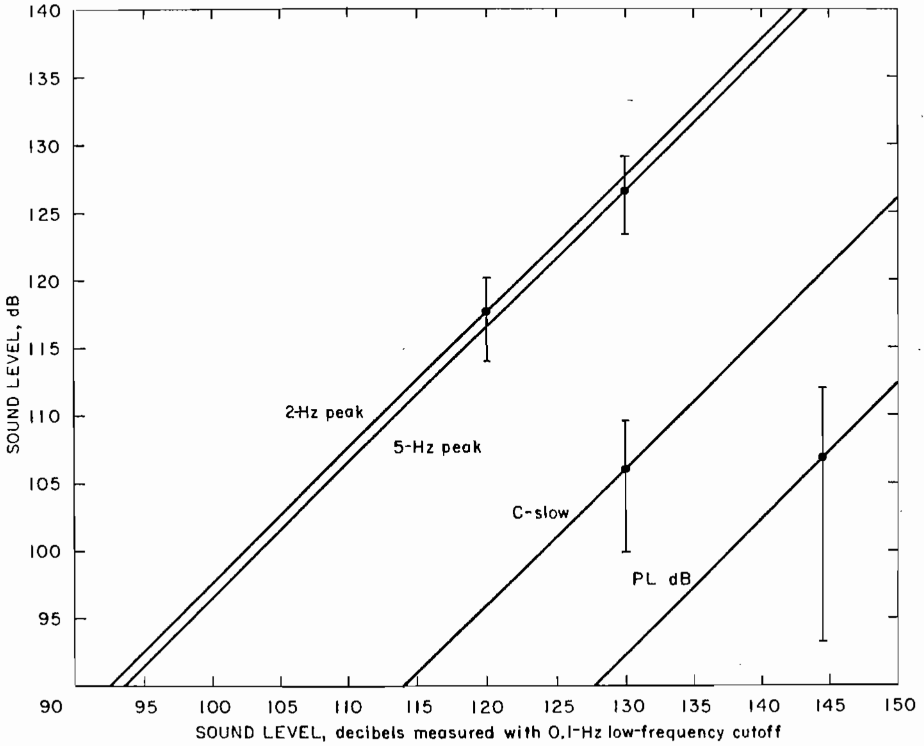

FIGURE 30. - Sound levels for all shots.

The various shots are classified by the kind of mine; the coal mine shots are broken down into three types. Highwall coal shots have a full or partial free face but are well confined, since the overburden is not extensively displaced. Parting shots are in the thin, hard material separating two coal seams and are difficult to confine well. The assorted shots included ditch and "sweetner" shots, which employed relatively shallow blast holes. "Sweetner" shots were used to break up the overburden sufficiently to level the surface for a walking dragline. All quarry blasts were in limestone. Metal mine blasts were recorded at iron mines on Minnesota's Mesabi Iron Range; these were very large and were recorded at greater distances than the coal or quarry blasts.

Parting shots are very strong Type I blasts and show consistently higher readings for 2-Hz, 5-Hz, C-slow, and PL dB methods. Metal mine shots at large distances are strongly Type II, hence the 2-Hz, 5-Hz, C-slow, and PL dB methods are consistently lower. The selection of an instrument to measure Type I blasts does not appear to be so critical as for Type II blasts, since 2-Hz and 5-Hz instruments read very nearly the same as 0.1-Hz instruments when measuring parting shots. Generally, the standard deviations are smallest for the 2-Hz and 5-Hz instruments with two exceptions: coal mine parting and quarry shots. These two exceptions are characterized by poorer confinement and the heaving of material. Coal mines and quarries are often close to residences and, therefore, reduce the chance of dispersing their high-frequency energy.

Readings obtained with different forms of instrumentation or techniques (0.1-Hz peak, 2-Hz peak, 5-Hz peak, C-slow, and PL dB) may be compared from these graphs.

CONCLUSIONS AND RECOMMENDATIONS

The type of instrument recommended is influenced by the frequencies generated by the airblast. Since 0.1-Hz equipment is expensive and difficult to maintain and use routinely, a standard sound level meter or seismograph with an airblast channel may be preferable and used effectively with the equivalence graphs presented in this report.

Any sound level meter used should be a Type I, impulse, precision instrument. This type of meter is preferred because of its higher crest factor. A peak "hold" feature is recommended when one is monitoring a short, unexpected event. A C-slow reading may be obtained with such meters that have "true" or "quasi" rms detectors with equal accuracy for blast measurements. The C-weighting should meet ANSI S1.4-1971 specifications for Type I meter.

The airblast channel on a blasting seismograph should be able to record a complete time history from which a peak measurement can be obtained. The frequencies generated can be calculated from a time history for a blast design analysis.

When obtaining monitoring equipment, documentation of the linearity of the frequency band and rolloff rates should be requested, since small variations in frequency response can change output levels considerably. The rolloff should be standardized to minimize the deviations in readings where frequencies are present below the -3 dB point. Appendix D contains a list of instruments and their rolloffs. When a sound level meter or seismograph is serviced, its low-frequency response and dynamic calibration need to be verified.

Production blasts are confined and delayed such that they generate a lower band of frequencies than do open-air, single charges. Even when a hole craters or blows out, confinement is enough to prevent the fast pressure rise times seen in open airblasts. The distances at which production blasts are monitored also reduce high frequencies through attenuation and dispersion. An upper frequency of 200 Hz is sufficient for regulatory monitoring. For airblasts generated by mine production blasting, the frequency response should meet or exceed the following specifications:

0.1-Hz peak instrumentation........	0.1-200 Hz ± 3 dB
2-Hz peak instrumentation........	2-200 Hz ± 3 dB
5-Hz peak instrumentation........	5-200 Hz ± 3 dB
C-slow..........................	ANSI S1.4-1971 (Type I meter)

The 5-Hz and 6-Hz rolloff instruments will read essentially alike, so for practical purposes they are interchangeable. For unconfined surface blasts at short distances, an upper limit of 450 Hz or higher is recommended. For example, uncovered detonating cord requires an extended high-frequency response. For research tests, the lower limit should meet or exceed 0.1 Hz. A sound level calibrator or pistonphone should be used to verify dynamic calibration before each use. This calibrator should be checked anually against a source traceable to the National Bureau of Standards.

A microphone windscreen will prevent false readings from wind gusts and protect the microphone from shock damage or adverse weather. Foreign matter could shift the frequency response by blocking the pressure equalization hole.

Microphones with a very low frequency response are more sensitive to wind than those used for voice communication. The microphones should be on a tripod or held motionless during a measurement, because variations in altitude register as air pressure changes. The microphone should be at least 3 feet aboveground and to the side of a structure to minimize reflections. The orientation of the microphone is of minor importance, since it is directional only at high frequencies (above 1,000 Hz) and essentially omnidirectional at blast-generated frequencies.

A diaphragm of 1-in diameter or greater will have a slight advantage for low-frequency response and sensitivity, but this advantage can be compensated for by electronic circuits for smaller microphones.

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APPENDIX A.--CHARACTERISTICS OF 14 TYPICAL AIRBLASTS

A set of 14 typical airblasts and their frequency spectra were assembled for illustrative purposes. A description is supplied to aid in the analysis of the characteristics of different kinds of airblasts generated at coal mines, quarries, and metal mines. Table A-1 lists the levels recorded at the field sites and processed values obtained in laboratory tests.

TABLE A-1. - Test airblasts: field and laboratory measurements

Shot	Field measurements			Laboratory measurements[1]					
	Linear peak			B&K 2209		GR 1933			
	DP-7	B&K 2209	C-slow, GR 1933	C-slow	Linear peak[1]	C-slow	10-sec time constant	Flat peak	True CSEL, GR 1925/1926
23/10	160			[2]131	159	[2]128	129	155.5	132
27/9	129	126	103	102	126	101.5	102.5	121	102
31/1	135			110	131	111	110	127	110
31/2	130			[2]107	127	107	108	124	108
31/3	132			[2]107	128	107	108	126	108
31/4	128			110	127	110	110.5	126	110
35/9	122			96	116	96	100	115	100
84/14	134	130	97	[2]107	131	108	107	126	108
101/1	121	120	>100	101	120	101	102.5	118	102.5
105/7	132	130	103	103	127	103.5	105	126	105
126/7	136		115	111.5	135	112	111.5	133	112
147/7	131	123	93	[2]93	125	95	96	117	97
C5/12	139			[2]109	138	111.5	109.5	135	112.6
163/1	155			128	154	129	127	152	129

[1] Linear peak and flat peak are equivalent.
[2] Overload light indicating on input overload.

Shot 23/10 (fig. A-1).--A very strong type I airblast that illustrates the presence of energy of up to 35 Hz at which point it is only 20 dB below the peak value. The blast has a very fast pressure rise time, with one peak predominating because of a clay seam that had been loaded through. This is a quarry blast on a 95-ft face with four holes each containing a long and short deck.

Shot 27/7 (fig. A-1).--A type II airblast that illustrates the drop-off of energy after the 1-Hz peak. The energy at 6 Hz is about 25 dB below the peak and continues to drop as the frequency increases. An interesting phenomenon is the reflection present in the latter third of the time history, at 0.95 sec after the highest peak. This represents the travel time across the quarry to an opposing face and back to the gage. This phenomenon appears more clearly in shot 105/7, shown later. This second airblast, or echo, is filtered by the physical shape of the reflecting face; it may contain higher frequencies (5 to 20 Hz) and cause a more severe structure response though lower in peak value than the first arrival.

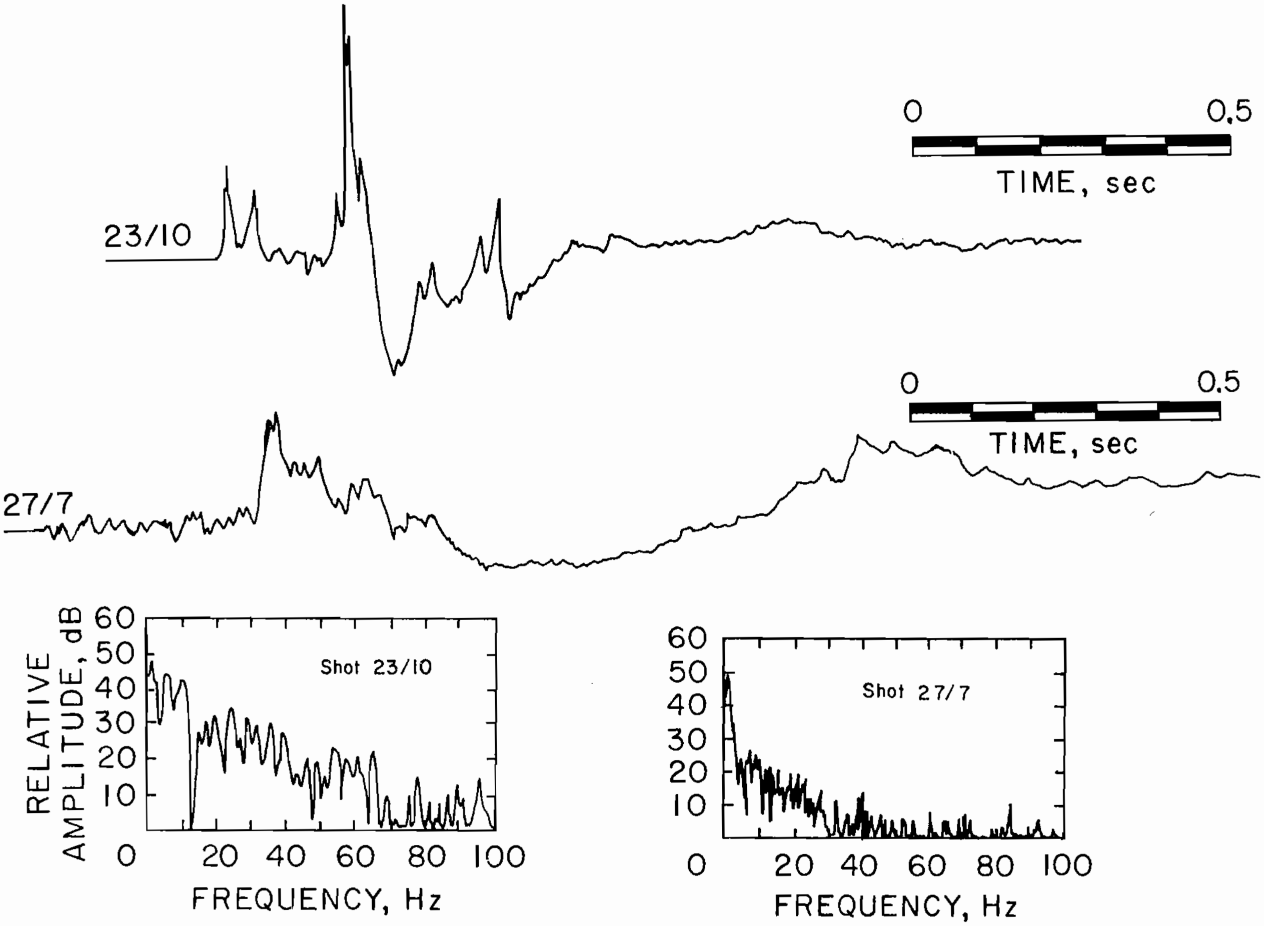

FIGURE A-1. - Quarry shots, 95-ft highwall: Type I airblast (shot 23/10) and reflected Type II airblast (shot 27/7).

<u>Shots 31/1, 31/2, 31/3, 31/4</u> (fig. A-2).--In these time histories, a quarry blast of two rows of 10 holes each was instrumented at four locations. The direction of initiation was down the free face and toward the gage location 31/1, with gage 31/3 located in the opposite direction. Gage 31/2 was behind the shot on the top of the bench, and gage 31/4 was in front on the pit bottom.

Shots 31/1 and 31/3 are similar in character except that the former appears to be a time-compressed version of the other. This happens because each successive borehole is closer to the gage station, shortening the travel time and compressing the delay intervals. This also appears in the spectra as a corresponding change in frequency content. Shot 31/1 has more energy above 20 Hz, while 31/3 continues to drop off gradually. Directing the initiation away from a structure could change the frequency content sufficiently to reduce problems.

In Shot 31/4, the individual pulses from the 10 front holes occur in 30- to 45-msec intervals. This corresponds to the energy present in the spectra

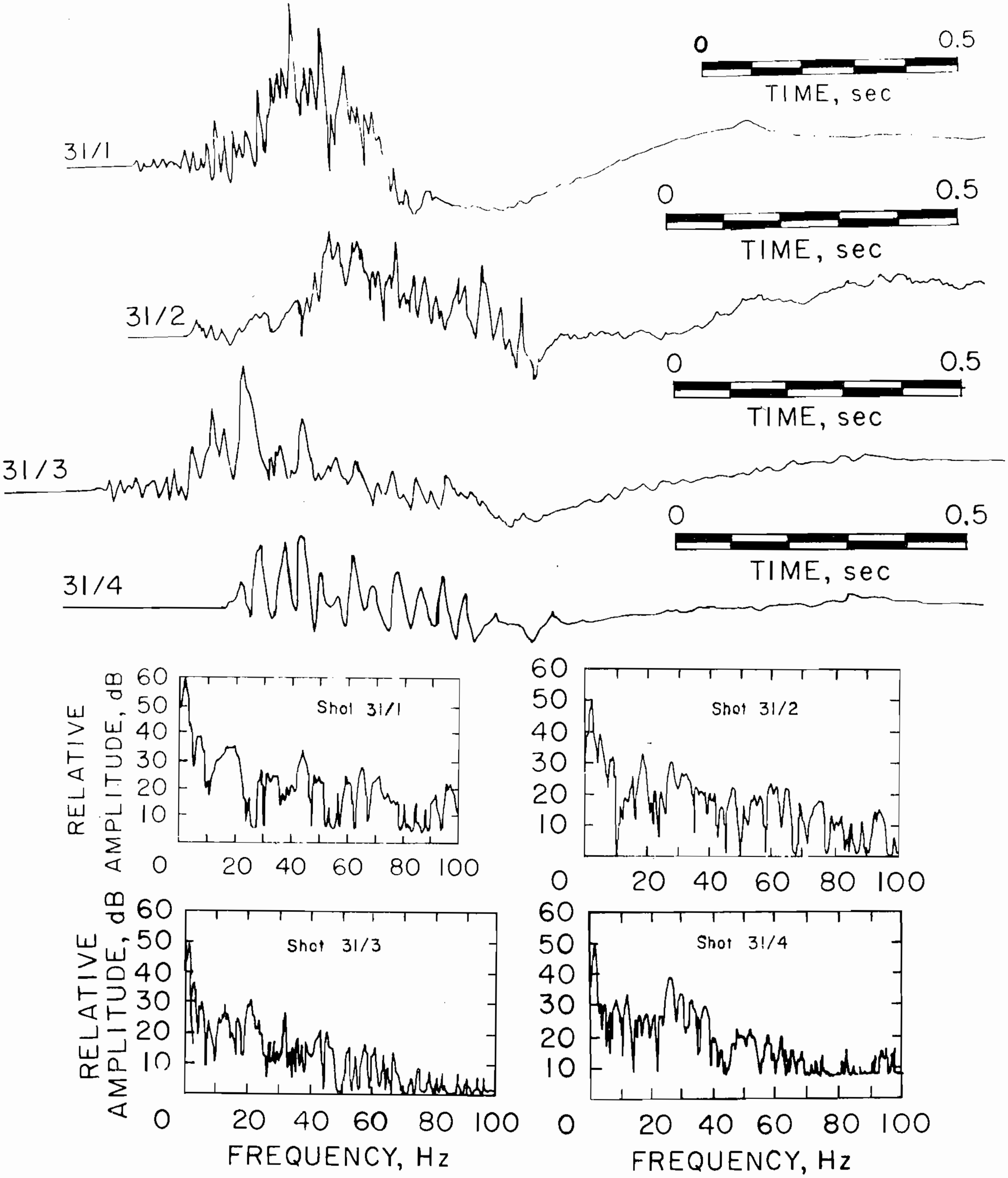

FIGURE A-2. - Quarry shots: airblast, initiation towards gage station (shot 31/1); Type II airblast (shot 31/2); airblast initiation away from gage station (shot 31/3); and Type I airblast (shot 31/4).

at 22 to 35 Hz, which is only about 12 dB down from the peak. There is more mixing of pressure pulses in shot 31/2 than in shot 31/4 because of the proximity of the second row of holes and the absence of a direct free face. More energy is directed upward rather than back toward the gage. The energy in the 22- to 35-Hz range for shot 31/2 is 20 dB or more below the peak value, in contrast to that in shot 31/4.

Shot 35/9 (fig. A-3).--This is a very long iron mine blast of 507,000 pounds of explosives, with a total of 147 delays in 148 holes. The distance to the gage station was about 3,400 ft, and the shot duration was about 3.1 sec.The spectra shows a 22-Hz peak that is only 20 dB below the low-frequency peak.

Shot 84/14 (fig. A-3).--This is a highwall coal mining shot with large blast holes (15.5 in) monitored at about 750 ft. The first arrival is the vertical motion of the ground near the microphone, since ground vibration travels faster than airblast. The airblast arrived about 650 msec later and showed the much sharper gas and stemming release pulses. Even though the time

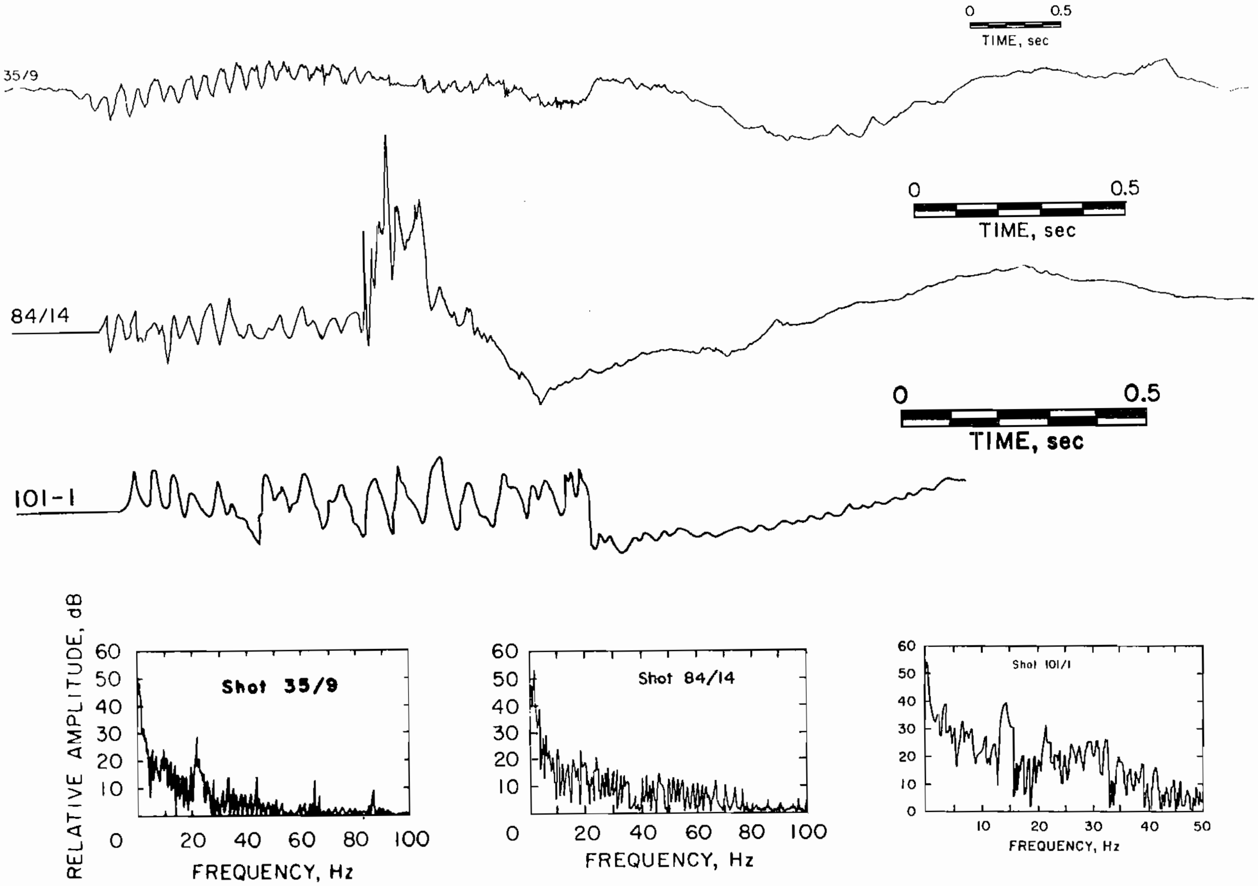

FIGURE A-3. - Metal mine shot, very long duration airblast (shot 35/9); coal mine shot, Type II airblast, large holes (shot 84/14); and coal mine shot, long-duration airblast, six decks (shot 101/1).

history shows many sharp spikes, the frequency spectra indicate a continual drop in energy to about 5 Hz, owing to the randomness of the gas and stemming release pulses that prevented a buildup of energy at any particular frequency.

Shot 101/1 (fig. A-3).--In this shot the top decks were probably 60 msec apart, which generated a large amount of energy at 17 Hz, about 13 dB below the peak value. The relatively uniform series of pulses caused the energy to build at this frequency and shook the house at this site strongly.

Shot 105/7 (fig. A-4).--A reflection is obvious about 730 msec after the first airblast arrival in this quarry shot. This "echo"contains energy in the 18-to 22-Hz region and shows up strongly in the spectra about 12 dB below the peak. The house at this location responded more to the second airblast because of its frequency content.

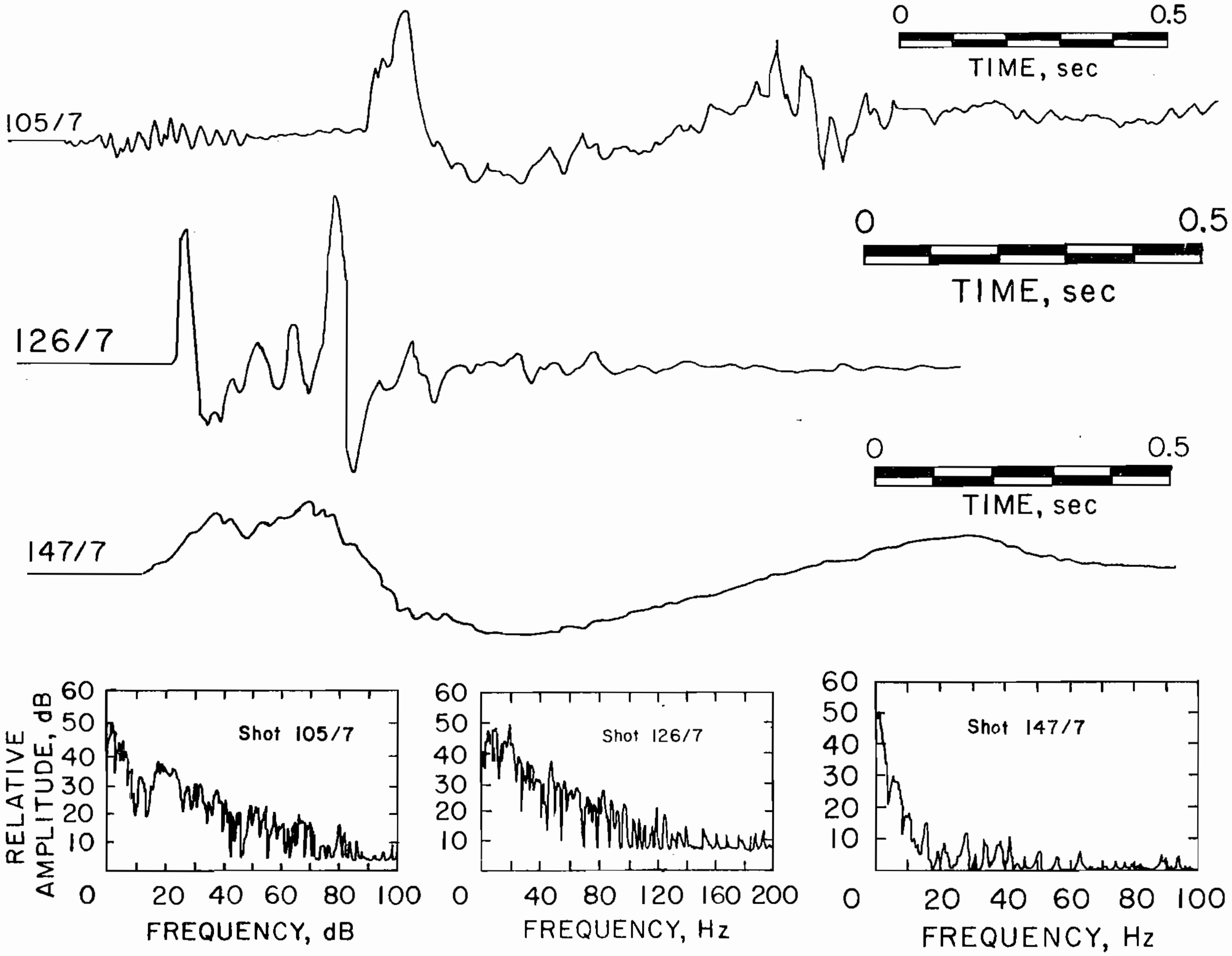

FIGURE A-4. - Quarry shot, Type II airblast initial arrival, Type I airblast when reflected (shot 105/7); coal mine shot, parting, Type I airblast (shot 126/7); and metal mine shot, Type II airblast (shot 147/7).

Shot 126/7 (fig. A-4).--This is a coal mine "parting" shot in a thin (6-ft) layer of limestone. The peak in the spectra is at 20 Hz. A lack of confinement caused the generation of considerable energy in the 20-to 50-Hz range. The home responded vigorously.

Shot 147/7 (fig. A-4).--At greater distances most high-frequency energy is despersed, as shown in this iron mine blast, recorded at a distance of 7,000 ft. The structure at this location responded weakly.

Shot C5/12 (fig. A-5).--This is a coal mine highwall blast in which a hole blew out. The single sharp pulse has much energy at 10 Hz and above, as shown in the frequency spectra. The 10 Hz point is only 10 dB below the highest point.

Shot 163/1 (fig. A-5).--A partial misfire with uncovered detonating cord is illustrated on this large iron mine shot monitoring at about 700 ft. A lot of high-frequency energy was generated by the detonating cord. The gage, located in the near field, caused the source to appear to move rather than to act as a single point.

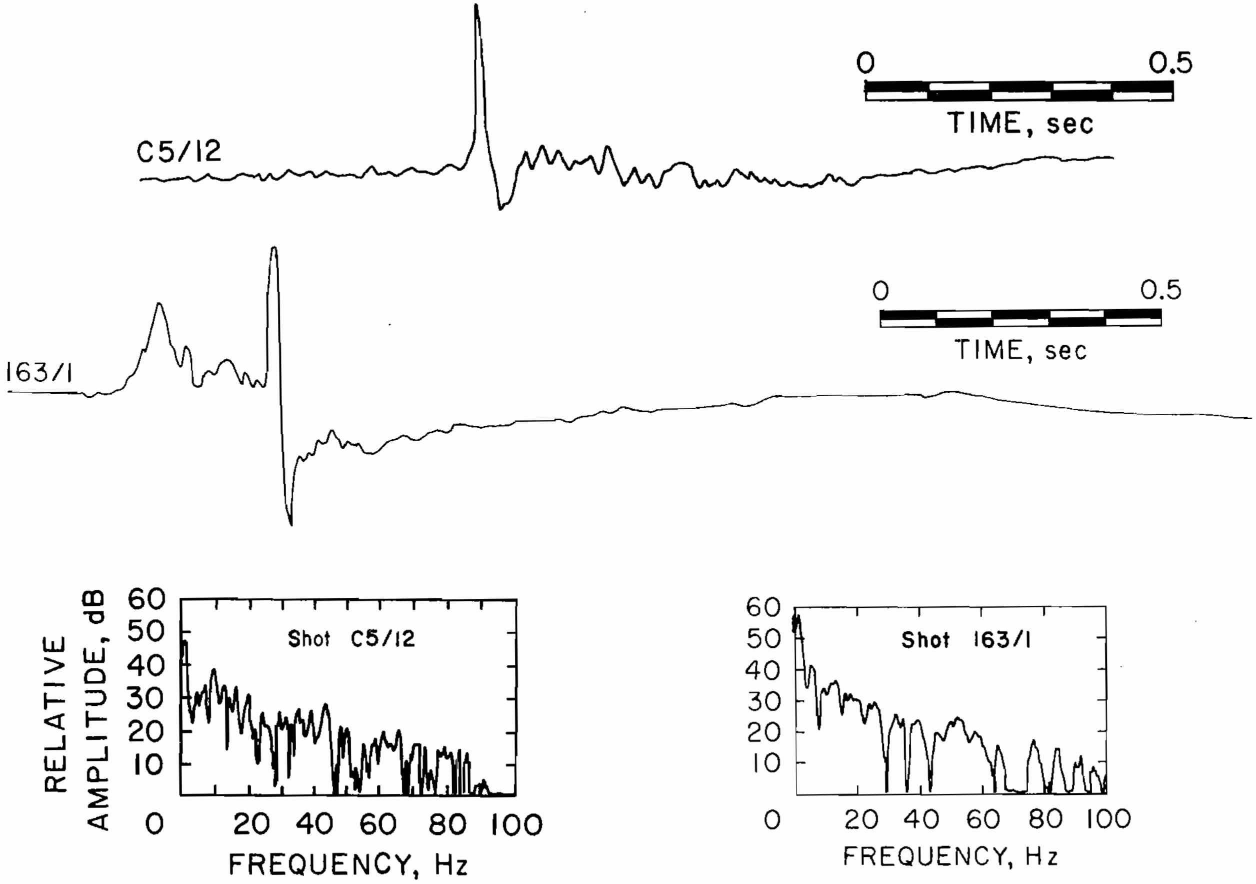

FIGURE A-5. - Coal mine shot, airblast from a blowout (shot C5/12), and metal mine shot, airblast from a partial misfire, exposed detonating cord (shot 163/1).

APPENDIX B.--DATA FOR MEASUREMENT TECHNIQUE COMPARISONS

TABLE B-1. - C-slow to CSEL comparison data

Shot	C-slow		CSEL	
	X, dB	X, psi	Y, dB	Y, psi
C-5	112.0	0.001155	112.0	0.001155
C-4	109.0	.000817	108.0	.000728
C-10	106.0	.000579	108.0	.000728
35L	97.0	.000205	97.0	.000205
36N	88.0	.000073	88.0	.000073
148KK	97.0	.000205	95.0	.000163
1460	93.0	.000130	87.0	.000065
150	93.0	.000130	91.0	.000103
45T	94.0	.000145	93.0	.000130
62	99.0	.000258	99.0	.000258
64	100.0	.000290	100.0	.000290
67	100.0	.000290	99.0	.000258
70	97.0	.000205	99.0	.000258
71	99.0	.000258	100.0	.000290
78	101.0	.000325	101.0	.000325
79	106.0	.000579	105.0	.000516
80	103.0	.000410	104.0	.000460
81	102.0	.000365	103.0	.000410
84	116.0	.001830	116.0	.001830
85	106.0	.000579	107.0	.000649
86	107.0	.000649	107.0	.000649
90	102.0	.000365	102.0	.000365
92	102.0	.000365	103.0	.000410
94	103.0	.000410	103.0	.000410
95	101.0	.000325	100.0	.000290
99	94.0	.000145	97.0	.000205
100	99.0	.000258	97.0	.000205
101	103.0	.000410	102.0	.000365
103REFL[1]	98.0	.000230	99.5	.000274
103W	107.0	.000649	108.0	.000728
105WDTR[2]	101.0	.000325	101.0	.000325
126	113.0	.001295	113.0	.001295
128	102.0	.000265	102.0	.000365
130	107.0	.000649	108.0	.000728
141	100.0	.000290	100.0	.000290
154	93.0	.000130	97.0	.000205
161	112.0	.001155	110.0	.000917

[1] Reflected airblast or echo.

[2] Direct airblast or first airblast arrival.

TABLE B-2. - Comparison of measurement techniques to 0.1-Hz linear peak airblasts

Measurement technique	Correlation coefficient	Standard deviation	Equation
Coal mine shots:			
High wall shots:			
2 Hz peak	0.953	31.9% +2.4dB, -3.3dB	Y=0.740X
5 Hz peak	.951	32.0% +2.5dB, -3.5dB	Y= .662X
C-slow	.911	45.6% +3.3dB, -5.3dB	Y= .064X
PLdB	.785	81.2% +5.2dB,-14.5dB	Y= .014X
Parting shots:			
2 Hz peak	.986	17.5% +1.4dB, -1.7dB	Y=1.014X
5 Hz peak	.985	18.0% +1.4dB, -1.7dB	Y= .885X
C-slow	.940	37.3% +2.8dB, -4.1dB	Y= .095X
PLdB	.978	24.7% +1.9dB, -2.5dB	Y= .016X
Assorted shots:			
2 Hz peak	.981	20.5% +1.6dB, -2.0dB	Y= .856X
5 Hz peak	.991	15.5% +1.3dB, -1.5dB	Y= .637X
C-slow	.936	39.9% +2.9dB, -4.4dB	Y= .052X
PLdB	.698	114.7% +6.6dB,-16.7dB	Y= .015X
Quarry shots:			
2 Hz peak	.893	52.2% +3.6dB, -6.4dB	Y= .601X
5 Hz peak	.937	38.3% +2.8dB, -4.3dB	Y= .535X
C-slow	.931	41.1% +3.0dB, -4.6dB	Y= .044X
PLdB	.959	32.4% +2.4dB, -3.4dB	Y= .013X
Metal mine shots:			
2 Hz peak	.972	25.9% +2.0dB, -2.6dB	Y= .571X
5 Hz peak	.949	36.2% +2.7dB, -3.9dB	Y= .438X
C-slow	.887	54.4% +3.8dB, -6.8dB	Y= .030X
PLdB	.872	62.8% +4.2dB, -8.6dB	Y= .004X
All shots:			
2 Hz peak	.947	34.2% +2.6dB, -3.6dB	Y= .750X
5 Hz peak	.946	34.5% +2.6dB, -3.7dB	Y= .666X
C-slow	.890	51.3% +3.6dB, -6.2dB	Y= .063X
PLdB	.783	80.6% +5.1dB,-14.2dB	Y= .013X

APPENDIX C.--EQUIPMENT USED IN TESTS

TABLE C-1. - Precision sound level meters tested by the Bureau of Mines

	Bruel and Kjaer 2209 impulse precision	General Radio 1933
Microphone type	1- and 1/2-in. condenser	1- and 1/2-in. electret-condenser.
Frequency response, ±3 dB, Hz:		
1-in. microphones	2-30k, selectable to 6-20k	5-15
1/2-in. microphones	3-1/2-40k, selectable to 5-1/2-40k	5-24
Maximum dynamic range, dB:		
1-in. microphones	140	130
1/2-in. microphones	140	140
Weightings:		
1-in. microphones	A, B, C, D, Linear	A, B, C, Flat.
1/2-in. microphones	A, B, C, D, Linear	A, B, C, Flat.
Dimensions, cm (in.):		
Length	33 (14.8)	22.9 (9)
Width	12 (4.75)	15.8 (6.19)
Height	9 (3.5)	7.6 (3)
Notes	"Hold" feature on peak, battery check.	Battery check, available with nicad batteries and charger.

[1] Output method for all: Meter reading or analog waveform; all with fast, slow, impulse, and peak response time.

TABLE C-2. - Seismographs with airblast channels tested by the Bureau of Mines

	Dallas Instruments, Inc.[1]	Phillip R. Berger and Associates, Bradfordwoods, Pa.	VME-Nitro Consult, Inc., Evanston, Ill.	Vibra-Tech Engineers, Inc., Hazelton, Pa.
Model	St-4 (Vi-Sel Monitors, Inc., Dallas, Tex.; EverLert Vibra-Tape (Vibra-Tech); White Seismo Sentinel (White Engineering Inc., Joplin, Mo.).	Safeguard Seismic Unit II.	Model F sound velocity recorder.	Vibra-tape 1,000 and 2000 series.
Microphone type	1-1/8-in. ceramic	1-in. ceramic	1-in. ceramic	1-1/8-in. ceramic.
Output method	Records FM analog on magetic tape; separate play back system for recorded digital level and analog waveform; analysis available from distributors.	Light beams on direct-write photographic paper.	Light beams on direct-write photographic paper.	Records FM analog on magnetic tape; analysis of playback available from Vibra-Tech.
Frequency response, Hz ±3 dB nominal.	5-200 on analog waveform, 5-500 on digital.	3-1/2-200	2-2,000	5-5,000 on 1000 series, 4-1,000 on 2000 series.
Maximum dynamic range. dB	137 on tape, 140 on digital readout.	128-148 on paper tape, switchable.	140	137 on 1000 series, 137 or 147, switchable on 2000 series.
Power source	Rechargeable 12-volt battery.	Rechargeable 12-volt battery.	Rechargeable 12-volt battery.	3- to 6-volt lantern battery (1000 series). 2- to 6-volt lantern battery (2000 series).
Weight kg (lb)	13.6 (30)	12.3 (27)	18.1 (40)	11.6 (26), 1000 series, 12.3 (27), 2000 series.
Dimensions, cm (in.):				
Length	52.1 (20.5)	45.8 (18)	49.2 (19.4)	38.1 (15), 1000 43.2 (17), 2000.
Width	25.4 (10)	35.6 (14)	24.8 (9.8)	33.0 (13) 34.9 (7.3).
Height	17.8 (7)	15.3 (6)	22.9 (9)	19.0 (7.5) 18.4 (7.3).
Notes	Operates up to 1 month unattended; in a standby mode, records 4-channel event when vabration exceeds a preset threshold.	Self-contained unit in aluminum finished briefcase.	Self-contained unit in carry case.	Other dynamic ranges optional; electromagnetically shielded case.

[1] Multiple distributers, see model.

TABLE C-3. - Long-term monitors tested by the Bureau of Mines[1]

	VME-Nitro consult, Inc., Sound-tector, model 1800	Dallas Instruments, model AR-2
Microphone type.........	1-in. ceramic..............	1-1/8-in. ceramic.
Frequency response, Hz.. ±3 dB nominal.	2-2,000	5-8,000
Maximum dymanic dB.. range.	140 plus 8 over range capability.	Up to 150 optional.
Weightings.............	A, C, Flat.................	A, B, C, Flat.
Response time...........	Fast rms and impulse peak.	Slow rms and peak impulse.
Power source............	110 or 220 volts ac; 12 volts dc.	3- to 6-volt lantern battery or 12-volt car battery.
Weight.........kg (lb)..	10 (22)	10.4 (23)
Dimensions, cm (in.):		
Length................	34.3 (13.5)	36.8 (14.5)
Width.................	27.9 (11)	25.4 (10)
Height................	26.7 (10.5)	17.8 (7)
Notes...................	Operates for 30 days continuously on ac power, 15 days on batteries; type S-1 tolerance; A- and C-weighting conform to type I ANSI specifications below 2,000 Hz.	Can operate for 1 month continuously; type II tolerance.

[1] Common features: Output is a bar graph on pressure-sensitive paper, dot printed.

TABLE C-4. - Wide-band, research-type instrumentation tested by the Bureau of Mines[1]

	Bruel and Kjaer, model 2631	Validyne Engineering Corp., model DP-7/CD-16
Transducer type..........	1-in. and 1/2-in. condenser microphones.	Variable reluctance differential pressure transducer.
Frequency response, Hz.. ±3 nominal.	0.1-8,000 (for 1-in.), 0.02-16,000 (for 1/2-in.). 0.02-16,000 (for 1/2-in.).	0.1->380.[1]
Maximum dynamic dB.. range.	162	177.
Power source.............	100-240 volts ac...........	22-35 volts dc.
Weight..........kg (lb)..	2 (4.3)	1.5 (3.3).
Control unit dimensions, cm (in.):		
Length.................	20.0 (7.9)	25.4 (10).
Width..................	6.1 (2.4)	10.2 (4).
Height.................	13.3 (5.2)	6.4 (2.5).
Notes....................	"Sonic boom"microphone carier system.	Adapted from gas line pressure systems.

[1] Adjustable, requires addition of needle valve for acoustic use.

APPENDIX D--LOW-FREQUENCY ROLLOFF OF TESTED EQUIPMENT

The following table D-1 lists the approximate low-frequency rolloff of typical airblast measurement instruments. Since airblast frequencies often fall in the region of the rolloff for 2-Hz and 6-Hz instruments, a measurement difference between instruments can occur. The rolloff is listed in dB/decade and dB/octave and can be used to estimate possible reading errors between instruments. It is hoped that manufacturers will adopt a standard low-frequency rolloff in the interest of consistency.

TABLE D-1. - Low-frequency rolloff of tested equipment

Instrument	dB/decade	dB/octave	-3dB frequency, Hz
6-Hz instruments:			
B&K 2209 1 in (10 Hz lower limit)...	33	10	6
B&K 2209 0.5 in (10 Hz lower limit).	45	13.5	5.5
B&K 2209 direct (10 Hz lower limit).	18	5.5	7
B&K 2209 0.5 in (2 Hz lower limit)..	26.7	8	3.5
Berger seismograph.................	30	9	4.5
ST-4...............................	21	6.3	4
Vibra-Tape 1000....................	22.5	6.8	5
GR 1933 0.5 in electret............	35	9.5	5
GR 1933 1 in electret..............	22	6.5	5
GR 1933 2 in ceramic...............	39.5	12	5
AR-2 acoustic monitor..............	23	7	4
2-Hz instruments:			
B&K 2209 1 in (2 Hz lower limit)....	42.5	12.5	1.8
VME "F" seismograph................	55	16.5	1.7
0.1-Hz instruments:			
B&K 2631 1 in......................	24.5	7.5	.1
B&K 2631 0.5 in....................	21.3	6.5	.02
Validyne DP-7......................	30	9	.09

APPENDIX E.--MICROPHONE TYPES SUITABLE FOR AIRBLAST MEASUREMENT

There are three basic types of microphone construction; air condenser (condenser), electret-condenser (electret), and ceramic (piezo-electric).

Air-condenser microphones are built so the diaphragm is one plate of a capacitor. The motion of the diaphragm varies the capacitance at a rate proportional to the change in air pressure. A potential (polarization voltage) across the capacitor maintains a constant charge in this system and produces a voltage inversely proportional to the change in capacitance for the duration of a time constant (20-21).

The electret-condenser microphone is similar to the air-condenser except for the method of maintaining a constant charge. An electret material is constructed with a permanent charge and is used along with an air gap as part of the dielectric to form a capacitor. No polarization voltage is necessary. The capacitance is measured across this dielectric between the backplate and a conductive diaphragm (20-21).

Ceramic microphones have a connecting rod between diaphragm and piezoelectric material. A voltage is generated across this material when it is deformed by a pressure change (20-21).

"Random" incidence microphones are for use in a diffuse field; that is, one made up of many reflected waves from all directions that combine to form a uniform energy-density level. This feature makes such microphones suitable for indoor use or in other areas with many reflections. At frequencies below 1 kHz, its response is the same as a grazing or perpendicular incidence microphones. "Grazing" and "perpendicular" incidence refer to the preferred angle at which the pressure wave strikes the diaphragm, 90 degrees and 0 degrees, respectively. The angle is the orientation needed to obtain the best response. Microphones may also be said to have "free field" response, which means all sound of interest arrives from one direction with no reflections such as those found in an enclosed space. Grazing incidence response is also called pressure response. Any of these three microphones (condenser, electret, and ceramic) is appropriate since their directional sensitivity is indistinguishable at airblast frequencies (3, 20, 23).

APPENDIX F.--RMS PROCESSING SYSTEM

The rms detector used to determine weighted-energy levels was the GR 1926, shown in figure F-1. For both airblast and ground vibration signals, equipment was assembled to record and process them quickly and efficiently (fig. F-2). The original blast time histories were recorded on FM tape.

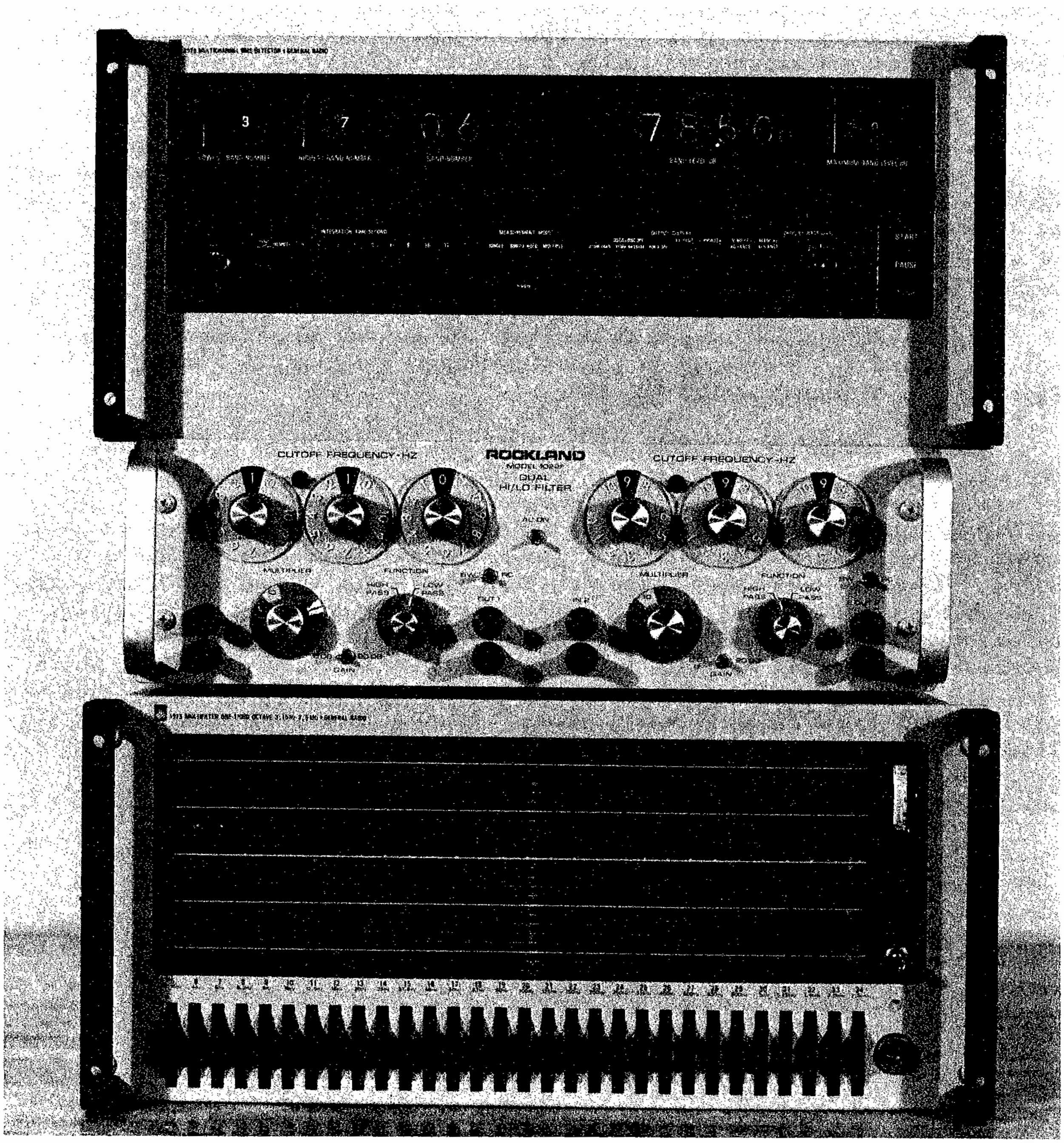

FIGURE F-1. - RMS detection system.

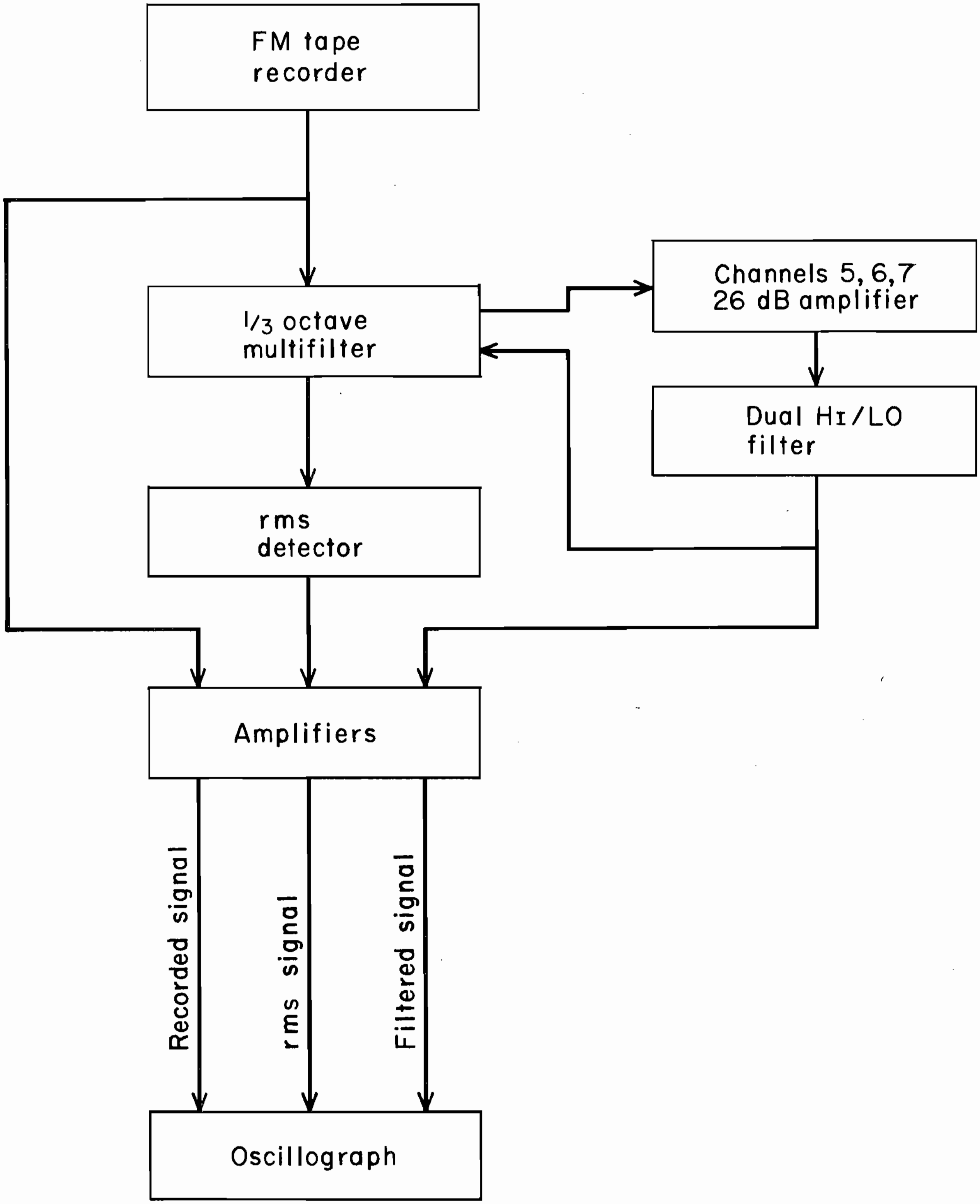

FIGURE F-2. - RMS detection system block diagram.

From the tape recorder, they were first fed into a General Radio Type 1925 Multifilter, which is a spectrum shaper and equalizer and which has ten 1/3-octave-band, six-pole, active Butterworth filters. These filters range in center frequency from 3.15 Hz to 2.5 kHz. There is a set of calibrated 1-dB/step attenuators, one for each of the 30 channels can be output separately or summed, and internal filters are also available to obtain A-, B-, and C-weighting for airblast noise analysis (9).

For the required application, two modifications were made to the filter. A special low-frequency band was added with a center frequency of 1.6 Hz. This modification lowered the upper limit of the frequency range to 1.25 kHz. Then, the filter that was in channels 5, 6, and 7 was replaced by a 26-dB gain amplifier (fig. F-3). Cables were run from this printed circuit board card to the housing to allow the introduction of an external filter. This filter could then be adjusted to a frequency range not available on the Multifilter itself, or to bypass the 1/3-octave filtering characteristics of the Multifilter. This externally filtered signal could then be accessed by using the channels available on the dummy card. An externally filtered version of the input signal could then be introduced without providing a separate interface to the rest of the system. The 26-dB gain was necessary because that gain is present in the other 1/3-octave-band filters.

The external filter was Rockland 1022F Dual Hi/Lo filter consisting of two identical, independent filters mounted in the same case, with separate input and output terminals. This can be set to act as either a high-or a low-pass filter, with either RC or 4th-order (24-dB/octave) Butterworth characteristics. The cutoff frequency was digitally selected by a dial on the front of the instrument, and the dynamic range was 0.1 Hz to 111 kHz. The filter was used in a band pass configuration accomplished by setting the input in the high-pass mode and cascading it with the second in the low-pass mode, and then selecting the frequency range of interest; the 4th-order Butterworth characteristics were used on both. The bandpass-conditioned signal from the Rockland was fed into the Multifilter, and the signal was available on its channels 5-7.

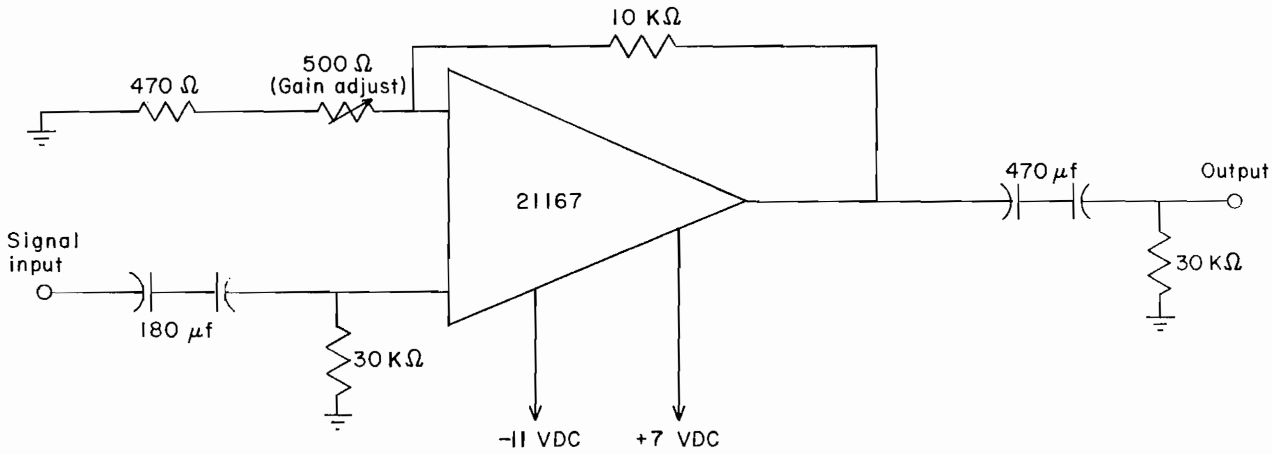

FIGURE F-3. - Amplifier modification for Multifilter.

Once this range has been determined, a reference signal is needed. In all cases, a calibration signal was recorded on the FM tape, just before or after the data were recorded. This was done to take into account electronic variances owing to temperature, humidity, etc. This calibration was then fed into the detector, and the input level was adjusted with the GR 1925 Multi-filter input signal attenuator until the rms value of the calibration signal equaled the maximum band level setting, as shown by a Nixie-tube digital display of the band level energies. The airblast was then run through the system and the output recorded on the oscillograph. Figure F-4 shows a processed airblast. The top trace is of the rms levels of each integration period. The data are displayed in the manner of the expanded view shown in figure F-5. The output scale is linear over the 60 dB range; therefore, the rms level of the signal can be measured by dividing the height of the signal output by the full-scale output and taking this ratio times 60 dB. The final level is

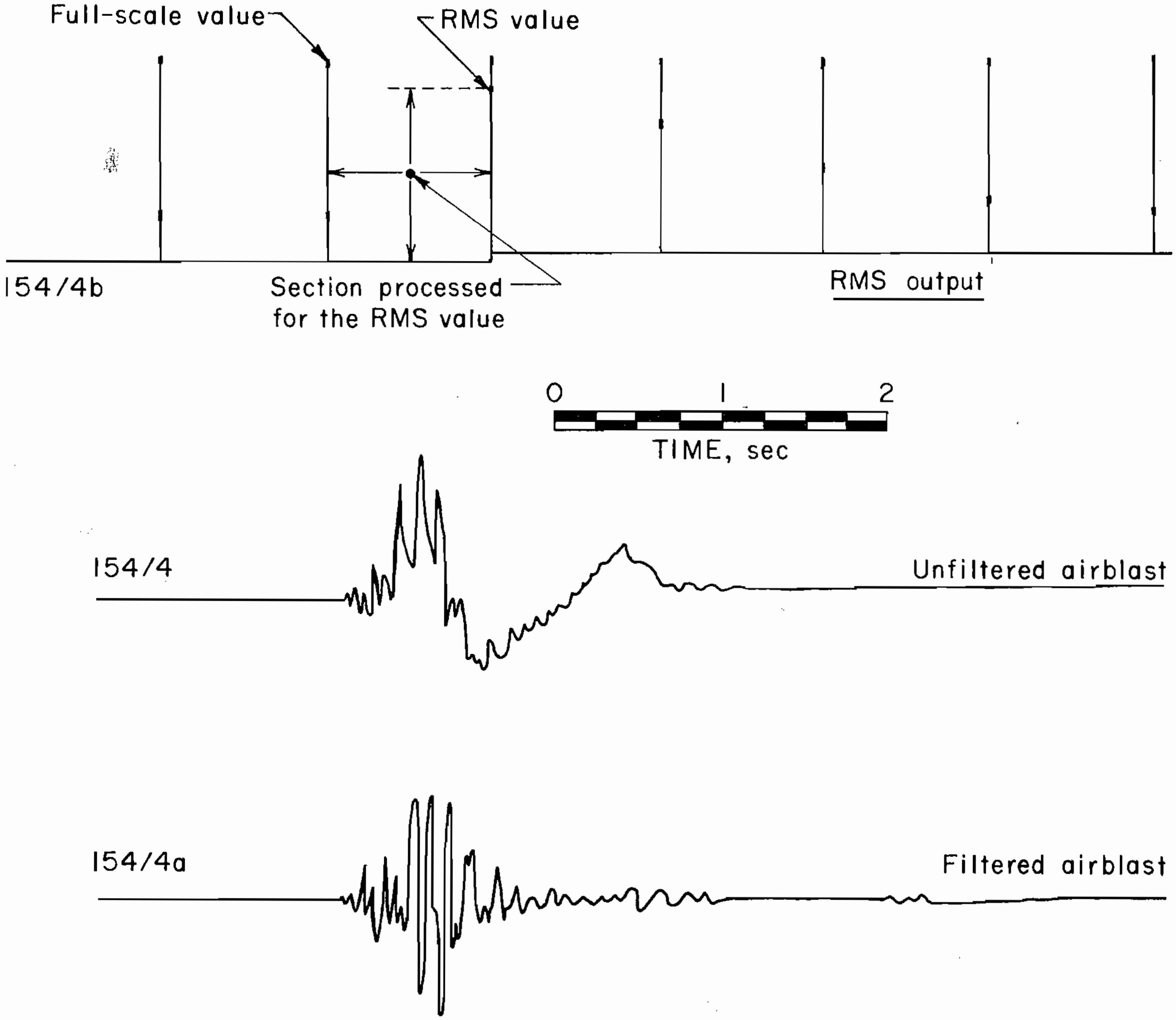

FIGURE F-4. - Typical RMS output from an airblast.

The GR 1926 rms detector was then directly interfaced to the GR 1925 Multifilter. The detector measured the rms value of each band of the Multifilter selected. Any range of bands can be scanned, and the rms value of each computed (10).

The GR 1926 rms detector has a 70-dB dynamic input range and a 60-dB dynamic output range. The input signals from the multifilter are sampled with integration times of 1/8, 1/4, 1/2, 1, 2, 4, 8, 16, or 32 sec, depending on the nature of the signal being processed. The number of samples and sampling rate depend on the integration time chosen, as shown in table F-1. For most frequencies the sampling rate was below the Nyquist rate. Since reconstruction of the input signal was not required, this is of no consequence. The measurements of the rms energy of each band can be made accurately at a low sampling rate.

TABLE F-1. - Integration-time parameters for GR 1926 rms detector

Integration time, sec	Number of samples	Average sampling rate, samples/sec	Average sample spacing, msec	80-pct confidence limits for independent samples (noise input, ±dB)
1/8	128	1,024	0.781	0.5
1/4	256	1,024	.813	.34
1/2	512	1,024	.877	.24
1	1,024	1,024	1.00	.17
2	1,024	512	2.01	.17
4	1,024	256	4.02	.17
8	1,024	128	8.04	.17
16	1,024	64	16.08	.17
32	1,024	32	32.2	.17

The GR 1926 rms detector has both analog and digital outputs, and can be interfaced to a PDP 11 computer, storage oscilloscope, printer, or X-Y plotter. The output was fed into a Bell & Howell 5-135 oscillograph.

To find the best correlation between rms energy levels of structure response and excitation, a sample was chosen that was considered representative of the many channels of recorded data. Samples of airblast, ground vibrations, corner, and midspan structure responses were chosen and run through the rms detector system with integration times of 1/8, 1/4, 1, 2, and 4 sec.

To process an airblast signal through the detector, it is necessary to determine its peak level in decibels and then adjust the maximum band level control. This control sets the limits for 60-dB dynamic output range. For example, a maximum band level setting at 130 dB will measure the part of the signal between 70 and 130 dB. In other words, the level specifies the high end of the 60-dB dynamic output range.

found by adding the floor level; that is, the maximum band level minus 60 dB, which could be done for each integration period. For our purposes, however, only the peak energy level was of interest; it alone was measured.

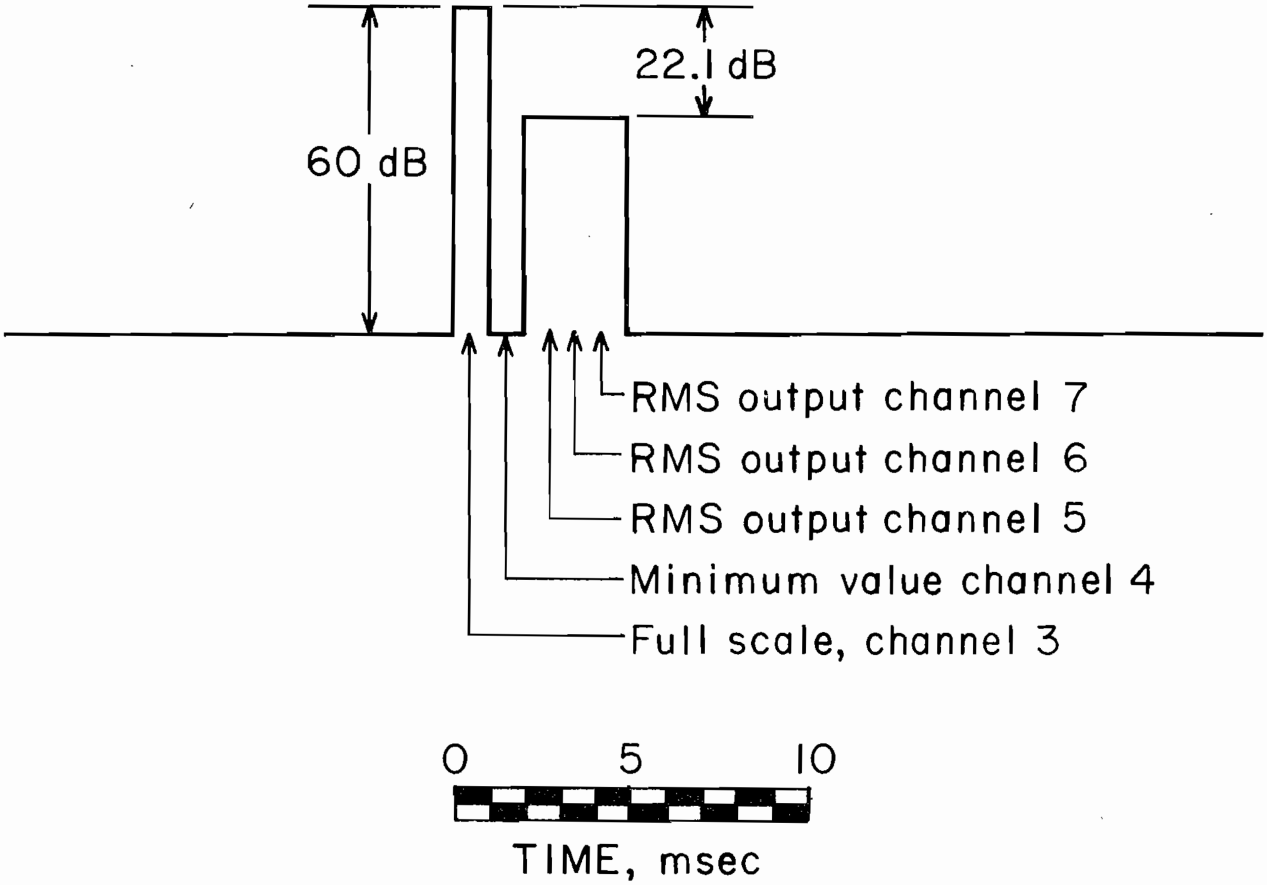

FIGURE F-5. - Expanded output of rms detector.