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Report of Investigations 8485

Structure Response and Damage Produced by Airblast From Surface Mining

By David E. Siskind, Virgil J. Stachura, Mark S. Stagg, and John W. Kopp

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ERRATA

Page 13 (table 1): Insert under Notes for both Bruel and Kjaer 2209 and GenRad 1933 "Recording device is optional."

Page 51 (figure 38): Caption should include "(Numbers in parentheses correspond to regression lines in table 9.)"

Page 52 (figure 39): Caption should refer to "table 9" instead of "table 5."

Page 55, Title for fourth paragraph should read "Criteria."

Page 61 (figure 40): Caption should read "Numbers in parentheses correspond to references."

Page 76, Line 8 from bottom should read "...function of depth as given..."

Page 76, APP equation should have "D_{cg}" as part of exponent.

Page 76, following the APP equation, it should read "for small-scale blasts in limestone, where D_{cg} is the distance..."

Page 76, last sentence should read "Wiss quantified the confinement effect from full-scale coal mine blasts:"

Page 77, equation at top of page should be $APP + SRP = K_2 e^{-1.0 \, B_s}$.

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STRUCTURE RESPONSE AND DAMAGE PRODUCED BY AIRBLAST FROM SURFACE MINING

by

David E. Siskind,[1] Virgil J. Stachura,[1] Mark S. Stagg,[2] and John W. Kopp[3]

ABSTRACT

The Bureau of Mines studied airblast from surface mining to assess its damage and annoyance potential, and to determine safe levels and appropriate measurement techniques. Research results obtained from direct measurements of airblast-produced structure responses, damage, and analysis of instrument characteristics were combined with studies of sonic booms and human response to transient overpressures. Safe levels of airblast were found to be 134 dBL (0.1 Hz), 133 dBL (2 Hz), 129 dBL (6 Hz), and 105 dB C-slow. These four airblast levels and measurement methods are equivalent in terms of structure response, and any one could be used as a safe-level criterion. Of the four methods, only the 0.1-Hz high-pass linear method accurately measures the total airblast energy present; however, the other three were found to adequately quantify the structure response and also represent techniques that are readily available to industry. Where a single airblast measuring system must be used, the 2-Hz linear peak response is the best overall compromise. The human response and annoyance problem from airblast is probably caused primarily by wall rattling and the resulting secondary noises. Although these will not entirely be precluded by the recommended levels, they are low enough to preclude damage to residential structures and any possible human injury over the long term.

INTRODUCTION

Airblast, like ground vibrations, is an undesirable side effect of the use of explosives to fragment rock for mining, quarrying, and excavation. Blasts at large surface mines and quarries can produce noticeable airblasts at large distances, particularly when weather conditions are favorable for propagation. Because of these variations in propagation, and the strong relationship between blast confinement and airblast character and levels, prediction and control are often more difficult for airblast than for such other adverse blast effects as ground vibrations, dust, and fumes.

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FIGURE 1. - Occupied residences near an operating surface mine.

This report summarizes research by the Bureau of Mines on airblast effects on residential structures. Discussed is research by the Bureau and other institutions on ground vibration response and damage, human response, sonic booms, airblast generation and propagation, and instrumentation as they apply directly to the airblast-tolerance problem. Reports are being prepared on blast-vibration generation and propagation, ground vibration damage, and instrumentation methodology, and while work is continuing on many other aspects of the blasting problem including blast design and human annoyance.

Research in areas related to airblast was also analyzed-specifically, sonic booms and human response to transient overpressures. Most of this work is in general agreement with the Bureau's results; however, it was mainly supportive data because of characteristic differences in the sources and their resulting effects.

An understanding of how residential structures respond to airblast and the airblast characteristics most closely related to this response will enable blasts to be designed to minimize these adverse effects. The mining industry needs not only appropriate design levels for blast effects, but also practical techniques to attain these levels. At the same time, environmental agencies responsible for blasting control and noise abatement must be provided with reasonable, appropriate, and technologically established and supportable criteria on which to base their regulations. Finally, neighbors around mines and other blasting operations require protection of their health and property (fig. 1).

ACKNOWLEDGMENTS

The authors wish to acknowledge the very generous assistance of regulatory agencies, engineering consultants, powder companies, homeowners, and mine and quarry operators. Paul D. Schomer of the Corps of Engineers and George W. Kamperman Associates made helpful suggestions in the area of measurement techniques. Special thanks are due to the Illinois Environmental Protection Agency for demonstrating the immediate need for this airblast research. Much of the fieldwork and data reduction was done by student employees Alvin J. Engler, Steven J. Sampson, David M. Purdham, Patrick G. Corser, Stephen Lepp, and Michael P. Sethna, who put in long hours. Philip D. Murray, whose thesis material was referenced in the structure-character analysis, also provided additional support.

AIRBLAST CHARACTERISTICS

Causes of Airblast

Airblast is an impulsive sound generated by an explosive blast and resulting rock fragmentation and movement. Four causes of airblast overpressures are generally recognized: (1) direct rock displacement at the face or mounding at the blasthole collar, (2) vibrating ground, (3) gas escaping from the detonating explosive through the fractured rock, and (4) gas escaping from the blown-out stemming. Wiss labels these four contributions to the total airblast (1) air pressure pulse (APP), (2) rock pressure pulse (RPP), (3) gas release pulse (GRP), and (4) stemming release pulse (SRP) (83)[4]. Their characteristics have been described in various other studies (53, 58, 83). The GRP is also termed the gas vent pulse (58).

The air pressure pulse (APP) will dominate in a properly designed blast, and will only be absent for cases of total confinement (that is, underground blasts). Each blasthole acts as an APP source. Close-in or front-of-face airblast measurements with wide-band systems usually detect a series of APP pulses corresponding in time to the interval between the top decks or front-row holes. At large distances or behind the face, dispersion and refraction mask the individual pulses and the blast timing becomes less evident. The time histories then lose their APP spikes and associated high frequencies.

The rock pressure pulse (RPP) is theoretically generated by the vertical components of the ground vibration summed over all the area, which acts as a large vibrating piston. A simple relationship was found by Wiss (53, 83) between RPP and the vertical ground vibration V_v:

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

$$RPP = 0.0015\ V_v,$$

with RPP in pounds per square inch (lb/in^2) and V_v in inches per second (in/sec). Normally, RPP has the least amplitude of the airblast components; however, it is typically of higher frequency (identical to the V_v which spawns it), and enables us to predict the minimum airblast level expected (for example, 1.0 in/sec V_v will generate 0.0015 lb/in^2, or 114 dB-peak). It arrives at the receiver simultaneously with the ground vibration and prior to APP.

The gas release pulse (GRP) and stemming release pulse (SRP) are the most undesirable and theoretically controllable parts of the airblast, since they involve the blast design variables of stemming, spacing, burden, and detonation velocity. SRP and/or GRP result from a blowout and appear as a spike or series of spikes superimposed on the APP. Because they have rise times of only a few milliseconds, they are rich in unwanted high-frequency airblast energy. Snell (58) reports that simply the use of an AN-FO explosive contributes to the irregular occurrence of SRP because of its slow detonation. Other conditions that may contribute to this effect are small-diameter holes (lower detonation velocities), wet holes, long columns, and high propagation velocities of the rock. Consequently, SRP would be more of a potential problem for quarries than coal strip mines. Figure 2 shows a coal mine production blast soon after

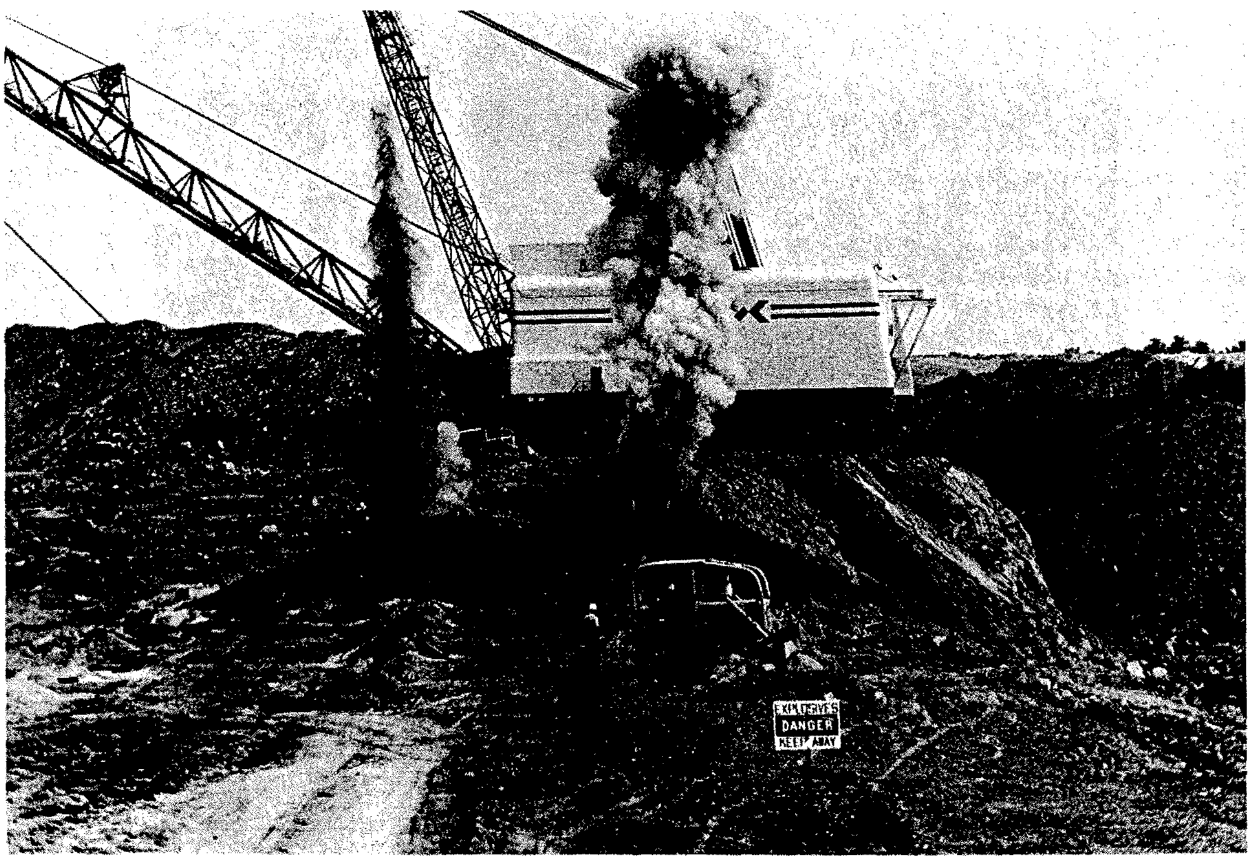

FIGURE 2. - A production blast in a surface coal mine.

initiation. The mounding which produces APP energy and the stemming plume are both visible, signifying that less than total confinement was obtained.

Surface detonating cord is a potential source of high-frequency airblast, and at small to moderate distances may be the dominant source. It is easily controlled by increasing the ground cover, and its effects diminish with distance.

Airblast Types Observed In Mining

Airblasts from surface mines have been classified according to their frequency character (53). Figure 3 shows the time history and spectra of a type 1 airblast which has prominent APP pulses resulting from almost line-of-sight propagation conditions, and exhibits a 15-Hz spectral peak corresponding to the 60-msec separation betwen hole detonations. This 15-Hz peak in the spectra is not the largest, but it is the most important in terms of its noticeability and effects on structures. The magnitude of the APP peaks is a fundamental result of the rock fragmentation process, and cannot be appreciably reduced. However, the delay interval and the resulting airblast frequency are part of the blast design and can be controlled. A type 2 airblast is shown in figure 4, with the APP pulses spread out into a single, very-low-frequency overpressure. This type of airblast typically occurs at large distances and behind the rock face. For quarries, APP pulses are produced by rock movement directly away from, and in front of, the face. The relatively high frequency airblast energy represented by the APP spikes cannot readily diffract behind and around obstacles, including the face itself. Consequently, type 1 airblasts are typically encountered in front of the face, and type 2, behind. An exception to this noted by Stachura (61) involved a high face across the pit from the blast. The face served as a simultaneous reflector and high-pass filter and returned the APP pulses as a ghost type 1 airblast. For coal mine highwall shots in area strip mines, where little or no rock displacement occurs, the heaving of the bench at the collar of each hole generates some APP, which should not be as horizontally directional as it is in contour mines or quarries. For all blasts, the air is a dispersive and selectively absorptive medium for sound transmission. The high frequencies are attentuated at a higher rate, and all airblasts become similar to type 2 at large distances.

The time history and spectra of a coal mine highwall shot producing a blowout and significant SRP appear in figure 5. This sharp pulse caused a large structural response and a high level of sound. Theoretically, blasts can be designed to prevent the generation of SRP and GRP; however, the natural variability of the blasted material (mainly, its nonhomogeneity and anisotropic character) makes it impossible to control SRP at all times.

Small blasts such as those used in construction and coal-mine-parting shots are particularly troublesome, not only for the high levels of airblast they can produce, but also because they are of high frequency (as much as 5-25 Hz compared with the usual 0.5-1.5 Hz). Obtaining sufficient confinement is the usual problem with these shots.

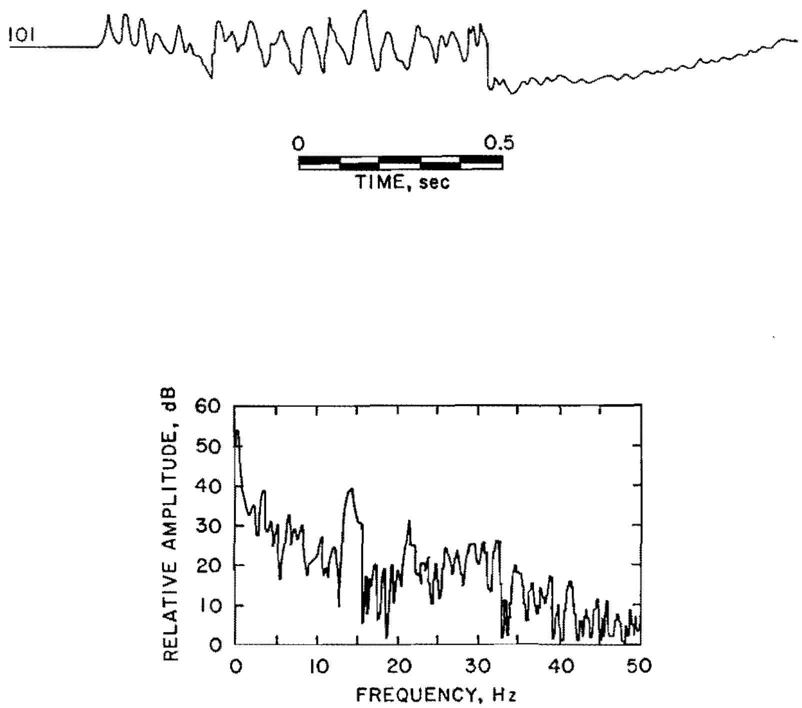

FIGURE 3. - Airblast time history and spectrum of a type 1 airblast (shot 101).

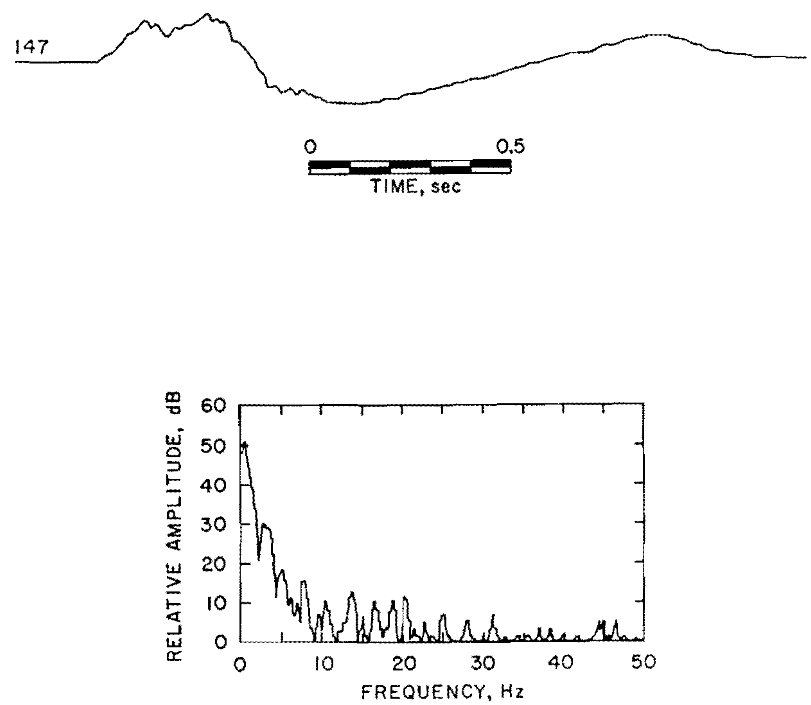

FIGURE 4. - Airblast time history and spectrum of a type 2 airblast (shot 147).

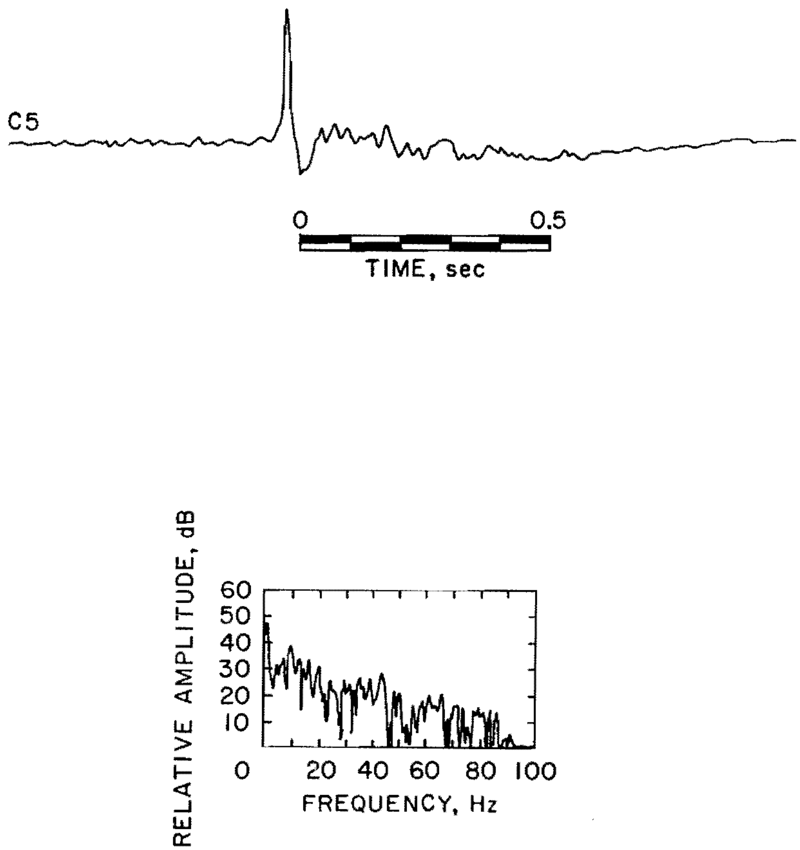

FIGURE 5. - Airblast time history and spectrum of a blowout (shot C5).

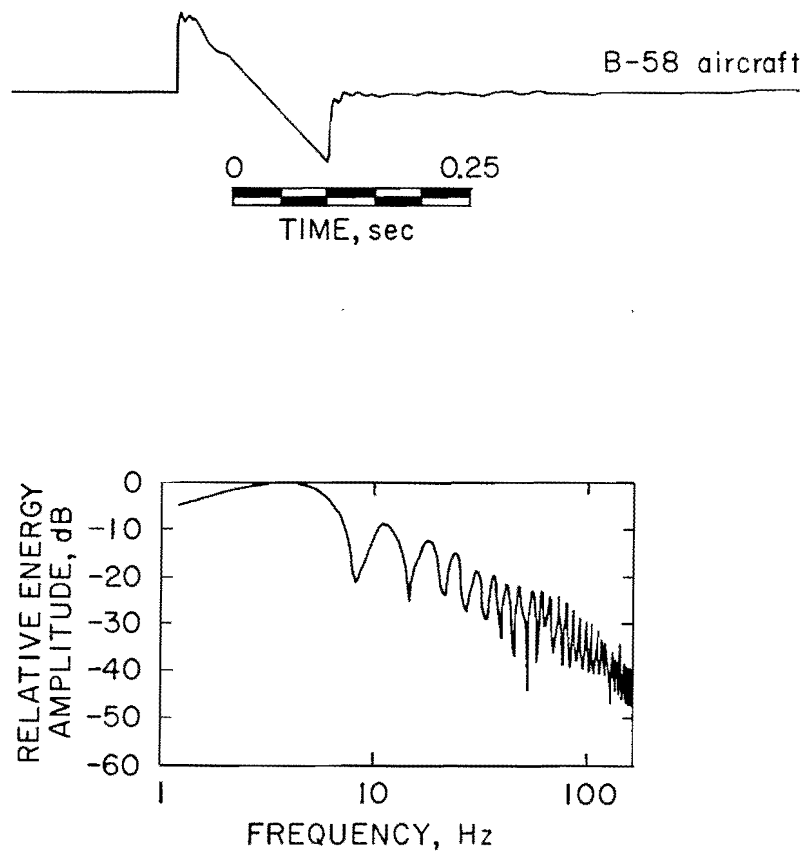

FIGURE 6. - Airblast time history and spectrum of a sonic boom.

Unconfined Blasts

Even more serious than poorly confined blasts is the problem of totally unconfined blasts exemplified by artillery, open-air detonations, uncovered surface detonating cord, and explosive testing. These produce high-frequency airblast and the highest levels per amount of explosive. Studies of the effects of unconfined airblast cannot readily be applied to the mining airblast problem, except possibly to provide a worst case or, when unconfined blasts are observed at large distances, to simulate confined blasts (58). These studies are discussed in the "Human Tolerance" section.

Sonic Booms

A typical sonic boom time history (N-wave) and spectra are shown in figure 6 (86). Considerable work has been done on the damage from and response of structures and humans to sonic booms. With caution, these results can be applied to the blasting problem.

The period of a sonic boom depends on the aircraft size and ranges from 75 msec for an F-104 to 206 msec for an XB-70. The spectrum is smoother than an airblast and like it contains much low-frequency energy. Sonic booms do not have isolated frequency spikes as do SRP and APP, and probably should not be directly equated in effect to type 1 or blowout-dominated airblasts. Most sonic boom spectra drop off at 12 dB per octave in pressure from the spectral peak, which can be roughly determined by inverting the N-wave duration and typically ranges between 4 and 11 Hz.

MEASUREMENT AND INSTRUMENTATION

Airblast is a transient time-varying overpressure, which can be expressed in any units of pressure. Various types of studies have specified pounds per square foot, pounds per square inch, millibars, and Newtons per square meter, and various expressions of relative sound levels, in decibels (dB). An equivalence and conversion chart for overpressure units is shown in figure 7.

Sound Pressure Levels

Shown in figure 7 is a line representing the sound pressure level (L_p) defined by the standardized relationship:

$$L_p = 20 \log_{10} \frac{P}{P_0},$$

where P_0 is the reference pressure of 20×10^{-6} N/m^2 or 2.9×10^{-9} lb/in^2 (5, 38, 61). Airblast time histories (figs. 3-6) plot pressure versus time with amplitudes proportional to changes around the zero line (ambient pressure). The measurement of sound is a complex subject involving factors of weighting (filtering), short-term integrations (fast or slow), long-term averaging (L_{dn}), root mean square (RMS), impulse and peak values, and a multitude of special descriptors (5, 38, 48, 53, 60, 70). Stachura (61) describes these measurement factors as they pertain to airblast.

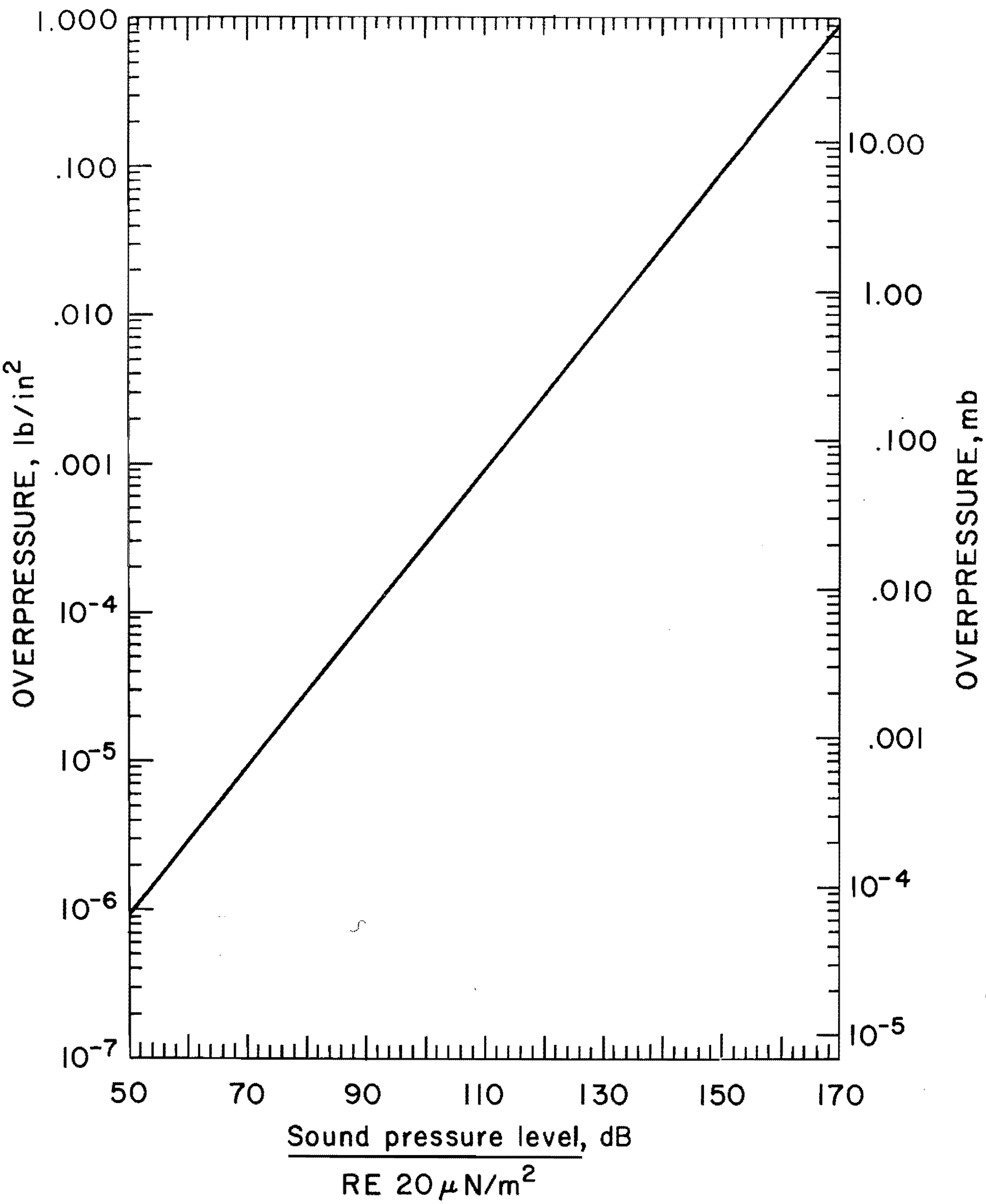

FIGURE 7. - Airblast level conversion and equivalence.

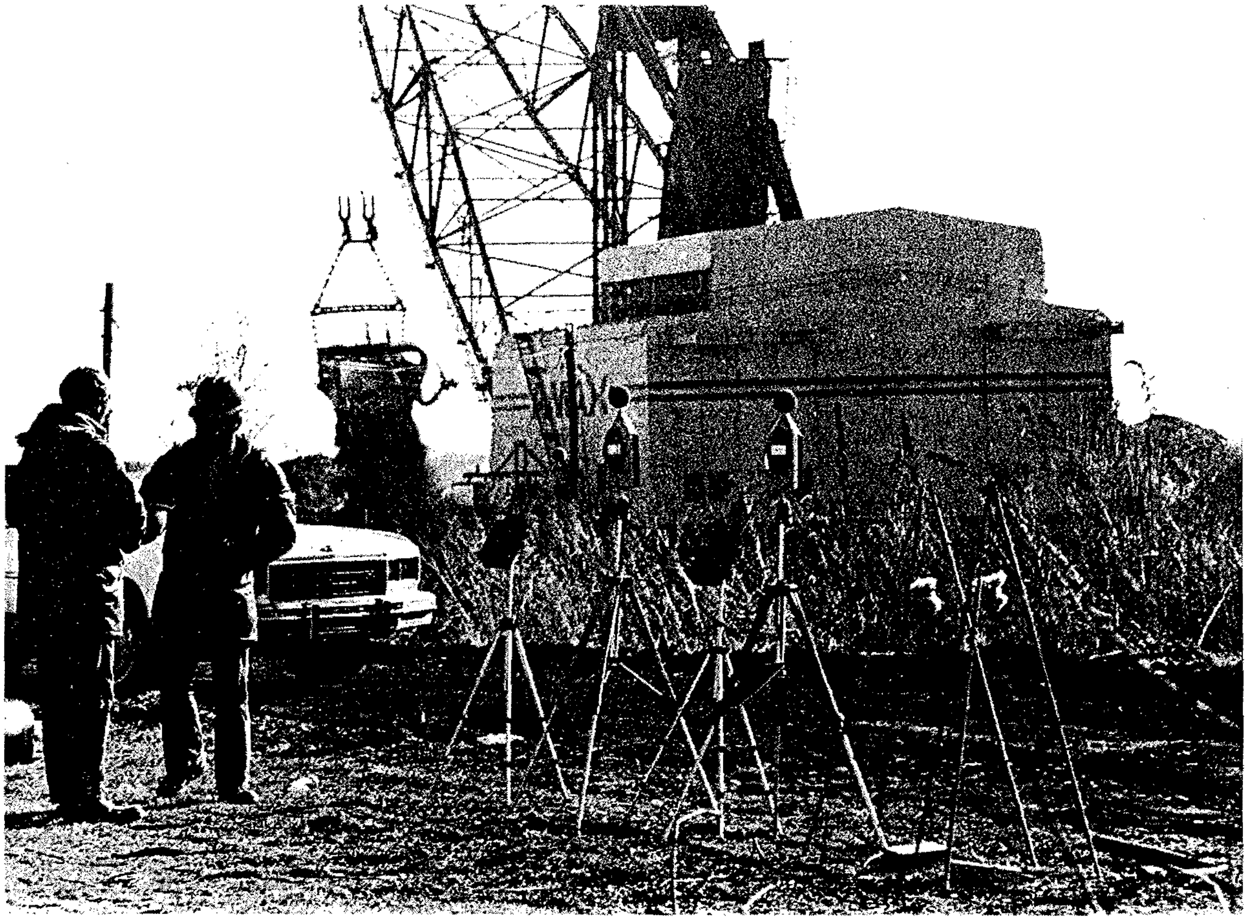

FIGURE 8. - Instrumentation for measuring airblasts.

Survey Instrumentation

The measurement and recording systems used for the Bureau of Mines airblast studies have been described in interim reports (54, 55). Low-frequency pressure transducers of 0.1- to 380-Hz response were used in 7- and 14 channel FM recording systems (figs. 8-9). From these "ultralinear" airblast time histories, other "linear" measurements were generated by appropriate filtering. The 0.1-Hz low-frequency response was required for research purposes to measure accurately the 1-Hz energy often present in the airblasts (8, 53, 56). The high-frequency response of the measuring system could be a problem for some sources (detonating cord, SRP), although in practice, only a 200-Hz response is required (23). The 0.1-Hz airblast time histories were processed by playback through various analysis systems (including the filtering networks of standard sound-level meters,) and then correlated with measured structure responses. Supplementing these values were direct measurements using a 0.1-8,000-Hz sonic boom measuring system (B&K 2631)[5] and sound level meters giving

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

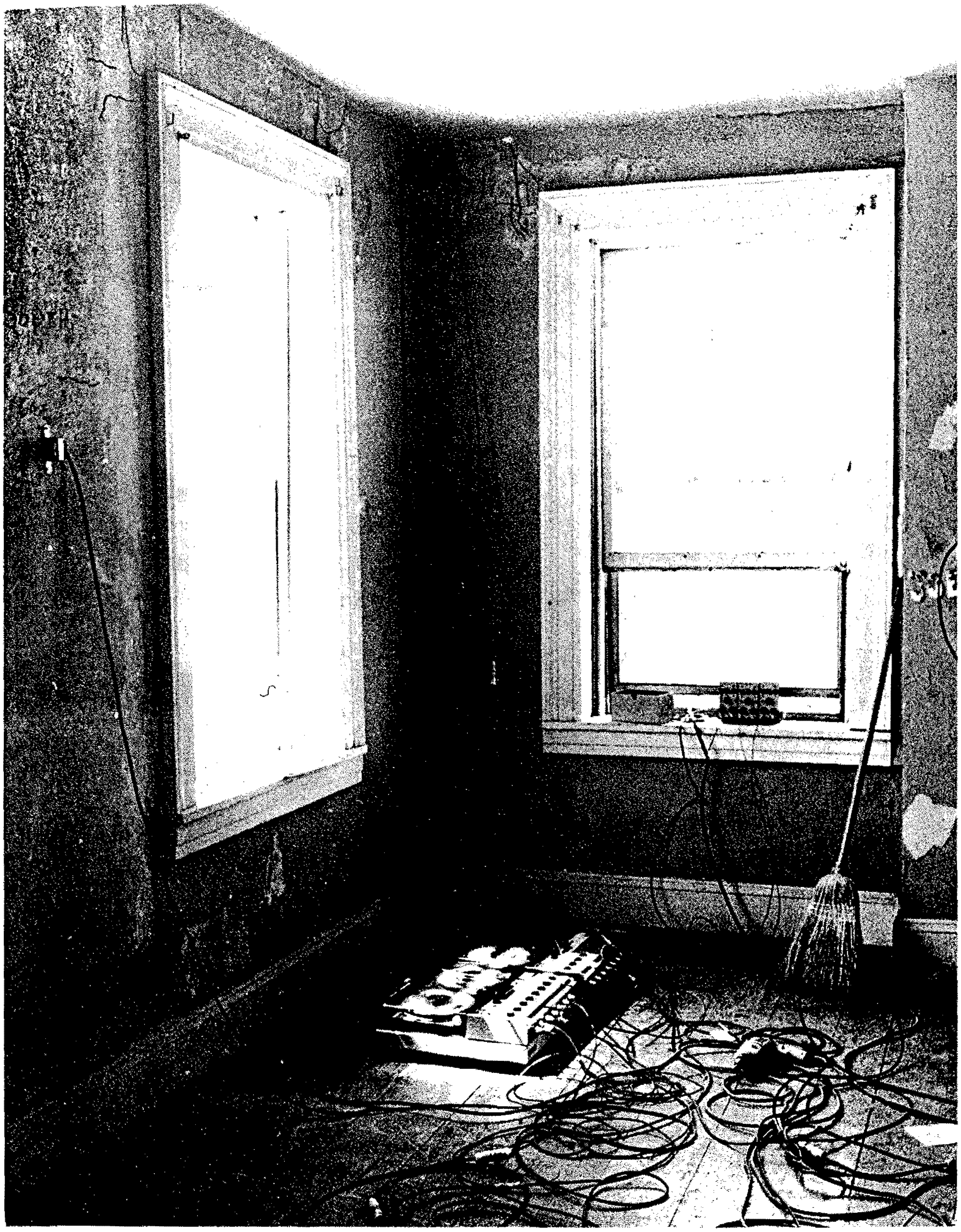

FIGURE 9. - Measurement and recording system for structure response.

2-Hz, 5-Hz, 6-Hz linear, and C-weighted-slow values. The analyses are further described in the section on processing airblast time histories, and also in Stachura's report (61).

Structure responses and ground motions were measured by direct-reading velocity gages of 2.5- and 4.75-Hz natural frequencies (Vibra-Metrics 120 and 124) with flat frequency responses of 3-500 Hz and 5-2,000 Hz (-3 dB), respectively (62).

The airblast measuring instruments and their application (table 1) are discussed in other reports (5, 38, 54, 61). It is often convenient to measure airblast with blasting seismographs, most of which have an airblast channel as well as three components of ground vibration. They typically give permanent film or paper records, but often limit the choices of weighting, integrating times, and frequency ranges. Stagg (62) and Stachura (61) describe these systems, many of which have been frequency-calibrated by the Bureau of Mines. Two of the devices in table 1 are not complete systems, but transducers which require some type of recorder (B&K 2631 and Validyne DP-7). Two are impulse-precision sound level meters with multi-function capability (B&K 2209 and GenRad 1933). Permanent records can be obtained by using a suitable recorder on their outputs; however, the sound level meters give only numerical readings. The B&K 2209 has a "hold" capability which greatly facilitates the reading of transients. The acoustic monitor (Dallas AR-2) is designed for long-term unattended recording. The ultralinear system is the only one which accurately measures the true waveform, and should be used wherever later processing is required.

TABLE 1. - Airblast-measurement systems

Name	Quantities measured	Output	Time history capability	Permanent record capability	Frequency response (± 3dB), linear or flat setting	Weight, lb	Notes
Brüel and Kjaer 2209.	A-, B-, C-weighted RMS; flat, peak, and impulse; fast and slow response	Direct sound-level-readings and voltage.	No............	No............	With 4145 (1-in) microphone, it is 2 Hz-18 kHz or 6 Hz-18 kHz selectable; with 4165 (½-in) microphone, it is 3.5 Hz-20 kHz or 5.5 Hz-20 kHz selectable.	6	Sound-level meter, hold capability on meter, battery operation.
GenRad 1933.	A-, B-, C-weighted RMS; flat, peak, and impulse; fast and slow response; octave band levels (10).	.....do......	No............	No............	With 1961-9601 (1-in) microphone, 5 Hz-12 kHz; with 1962-9601 (½-in) microphone, 5 Hz-19 kHz.	5.5	Sound-level meter, does not hold peak readings, battery, operation.
Brüel and Kjaer 2631.	Overpressures.	Voltage proportional to pressure.	Yes, when used with ancillary recorder.	Yes, when used with ancillary recorder.	With 4146 (1-in) microphone; 0.1 Hz-8 kHz.	4.3	Sonic boom system. Recording device is required (oscilloscope, oscillograph, tape recorder).
Validyne DP-7 pressure gage with CD-16 carrier demodulator.	Overpressures.	.....do.....	.....do.......	.....do.......	Selectable low frequency to 380 Hz.	3.3	Do.
Dallas Instruments AR-2 acoustic monitor. slow response.	A-, B-, C-weighted RMS: flat and peak; slow response	Bar graph, not printed.	No............	Yes...........	5 Hz-8 kHz.	23	30-day recording monitor. Runs 5-7 days on internal battery, 1-2 months on 12-volt automotive battery.

TEST STRUCTURES

A total of 56 different structures were studied for airblast and ground vibration response and damage (table 2). All were houses, except No. 54, which was a mobile home. In addition, structures 13, 15, 16, and 50 were somewhat larger than single-family residences. Some structures (19 and 20) were studied for a variety of blasts, highwalls, parting, and surface. The response of structures 1-6 were described in an earlier study (55). Of the 56 structures, only 17 had significant and identifiable levels of airblast response (figs. 10-24). In many cases, the blasting did not result in high airblast levels and/or high-frequency airblasts. Measurements were generally made near the blasts since ground vibration were also being sought. Time separation between the ground vibration and the airblast was not always sufficient to identify the latter response. The coal-mine-parting and quarry shots usually produced good airblast data, as did the coal highwall shots with long delay intervals.

TABLE 2. - Test structures and their measured dynamic properties

Structure	Number of stories	Dimensions, feet: Plan dimensions, NS x EW	Dimensions, feet: Overall height	Construction: Superstructure	Construction: Exterior covering	Construction: Interior covering	Construction: Foundation	Total structure: Natural frequency, Hz: N-S	Total structure: Natural frequency, Hz: E-W	Total structure: Damping, pct: N-S	Total structure: Damping, pct: E-W	Midwall: Natural frequency, Hz	Midwall: Damping, pct	Shot numbers (table 3)	Air-blast response
1	1	22 x 30	14	Wood frame.......	Wood siding.	Gypsum wallboard.	Full basement.					16		13,14,17, 18	X
2	1	30 x 70	14	Masonry and wood.	Stone...	..do....	..do......							15	
3	1-1/2	35 x 35	16	Wood frame.......	Brick and wood.	..do....	..do......					13		16	
4	2	30 x 40	22	.....do..........	Wood siding.	..do....	Full basement.	8.2		2.0		19,22		17,18	X
5	2	40 x 40	22	.....do..........	Brick and wood siding.	..do....	Partial basement.					19		19	
6	1	40 x 40	14	.....do..........	Wood siding.	..do....	Full basement.	9.6				32		19	
7	1	48 x 25	15	.....do..........	Asbestos siding.	..do....	..do......							33	
8	1	15 x 10	12	.....do..........	Wood siding.	..do....	Concrete slab.							33	
9	1	61 x 29	14	.....do..........	..do......	..do....	Full basement.							34	
10	2	44 x 29	22	.....do..........	Asphalt sheathing.	Plaster.	..do......							35	
11	2	26 x 32	30	.....do..........	Masonite siding.	Gypsum wallboard.	..do......					36		35	
12	1-1/2	27 x 36	20	.....do..........	Cedar shakes.	..do....	..do......					25		35	X
13	1	34 x 100	16	.....do..........	Brick and stucco.	..do....	Slab and crawlspace							35	
14	1-1/2	35 x 35	23	.....do..........	Wood siding.	..do....	Full basement.	10.4		6.5		14		36,38	X
15	1	125 x 25	12	Steel frame......	Steel.....	..do....	Concrete slab.	5.6		2.8		17		36,38	
16	1	80 x 80	17		Brick and stucco.	..do....	Full basement.					8.3		36	
17	1-1/2	19 x 40	20	Wood frame.......	Wood shingles.	..do....	..do......	10	8.6	4.5	6.7	18		37,146	
18	1	44 x 28	13	.....do..........	Wood siding.	..do....	Pillars in dirt.	8.8	8.0	2.3	4.3	11.4		37,146	
19	2	33 x 35	24	.....do..........	Wood siding.	Plaster and lathe.	Partial basement.	4.1	3.9	3.9	7.0	13,17	4.5, 5.1	39-48, 59-96	X
20	1-1/2	39 x 29	21	.....do..........	..do......	Gypsum wallboard.	Full basement.	8.3	7.6	3.0	3.6	20	3.1	42-58	X
21	1	48 x 28	15	.....do..........	..do......	..do....	..do......	8.0	6.4	2.9	3.3	13.4, 14.5	2.9, 2.3	97-102 110,111, 113,114, 117, 135,136	X
22	2	27 x 76	26	.....do..........	Brick and masonite.	Gypsum and paneling.	Crawlspace	7.5	6.5	2.1	1.8	12.3, 13.1	2.0, 3.0	103,104	X
23	1	62 x 26	14	.....do..........	Asbestos shingles.	Gypsum wallboard.	..do......	7.4	7.3	2.8	4.9	18.5		103-105	X
24	1	24 x 55	15	.....do..........	Brick.....	..do....	Crawlspace	10.6	5.9	1.7	3.3			106	
25	1-1/2	41 x 24	22	.....do..........	Wood siding.	..do....	Full basement.	8.1	10.1	3.3	3.2	13.7, 16.3	1.8, 3.6	106	
26	1	40 x 31	15	.....do..........	Aluminum siding.	..do....	Crawlspace							107	
27	1	51 x 30	15	.....do..........	Wood siding.	Plaster and lathe.	Partial basement.	7.2	6.3	6.2	6.3	17,24		C.1-C.11	X
28	1	42 x 28	14	.....do..........	Wood and aluminum.	Gypsum wallboard.	Crawlspace	7.0	10.1	1.7	1.3			108,122	
29	2	26 x 35	22	.....do..........	Wood	..do....	..do......	6.6	7.9	2.2	1.9	17.7, 13.0	1.1, 2.2	109,120, 121	
30	1	34 x 48	16	.....do..........	Stone.....	..do....	Full basement.							112	
31	1	35 x 44	13	.....do..........	Wood siding.	..do....	Crawlspace	8.1	5.9	2.9	2.2	12.2, 16.6	1.5, 1.2	115,116, 118	
32	1-1/2	58 x 26	22	.....do..........	Brick and masonite.	Paneling and wallboard.	Concrete slab.							119	
33	1-1/2	69 x 27	24	.....do..........	Stone.....	Gypsum wallboard.	Full basement	7.5	7.9	1.6	3.0	16.0, 19.7	1.5, 2.1	124,125, 132-134, 137-139	
34	1	33 x 33	18	.....do..........	Asphalt sheathing.	Plaster.	Crawlspace	7.1	6.4		3.4			126,127, 130,131	X
35	1	32 x 37	18	.....do..........	..do.......	Gypsum wallboard.	..do......	7.1	6.1	1.4	4.0			128,129, 140	X

TABLE 2. - Test structures and their measured dynamic properties--Continued

Structure	Number of stories	Dimensions, feet: Plan dimensions, NS x EW	Dimensions, feet: Overall height	Construction: Superstructure	Construction: Exterior covering	Construction: Interior covering	Construction: Foundation	Total structure: Natural frequency, Hz: N-S	Total structure: Natural frequency, Hz: E-W	Total structure: Damping, pct: N-S	Total structure: Damping, pct: E-W	Midwall: Natural frequency, Hz	Midwall: Damping, pct	Shot numbers (table 3)	Air-blast response
36	1	28 x 40	14	.....do..........	Asphalt shingle.	..do......	..do......	6.3	7.1	3.0		14,17		141-145	X
37	1-1/2	32 x 26	20	.....do..........	Wood siding.	Plaster and lathe.	Full basement.	8.6	10.0	2.0	1.9	18.5,20		146,150	X
38	2	28 x 32	20	Masonry and wood.	Brick and aluminum	Wood paneling.	Concrete slab.	4.6	5.5	3.8	3.0			147,148	X
39	1	34 x 29	15	Wood frame.......	Masonite siding.	Paneling and wall-board.	Full basement.	5.0	4.8	7.3		14		147	
40	1-1/2	28 x 31	18	.....do..........	Stucco...	Plaster and lathe.	Partial basement.	5.5	7.5	2.6	2.4	13.6		148	
41	2	40 x 28	22	.....do..........	Wood siding.	Gypsum and plaster.	Full basement.	9.9	8.1	2.5	2.3	16.6		149	
42	1-1/2	44 x 30	20	.....do..........	..do.....	Paneling.	..do......	5.4	6.7	4.7	3.7	11.9, 13.9		151-153	
43	1-1/2	28 x 46	23	.....do..........	..do.....	..do......	..do......	8	5.1			18,18		154	X
44	1	--	15	.....do..........	..do.....	--	..do......					11,11		156-156	
45	2	55 x 44	32	Solid brick......	Brick....	Plaster on brick	..do......	6.3	7		8.1			157-159	
46	1-1/2	38 x 40	21	Concrete block...	Concrete block.	Plaster....	..do......					11,11			
47	1	87 x 38	15	Wood frame.......	Brick....	Gypsum wall-board.	..do......					12.5, 13.3		160	
48	1-1/2	36 x 24	22	.....do..........	Wood siding.	..do.......	..do......		8.3			16.7, 16.7		161	X
49	1-1/2	41 x 35	27	.....do..........	..do.....	Gypsum wall-board and plaster.	..do......	5.4	5	10	4.2	18.2, 18.2		162,164-166,172	
50	1	46 x 180	14	.....do..........	Aluminum siding.	Gypsum wall-board.	Concrete slab.							163	
51	2	50 x 43	28	Solid rock.......	Brick....	Plaster on brick and lathe.	Full basement.	8.3						167-171, 173-182	
52	1	37 x 24	16	Wood frame.......	--	Wood paneling.	..do......							183	
53	1	24 x 35	15	.....do..........	Wood siding.	--	Crawlspace							184	
54	1	12 x 60	15	Metal walls......	Metal....	Paneling...	None......							186,187, 189-192	
55	1-1/2	40 x 31	23	Wood frame.......	Wood siding.	--	Full basement.							193	
56	1-1/2	34 x 57	20	.....do..........	Wood siding.	--	..do......							194,196	

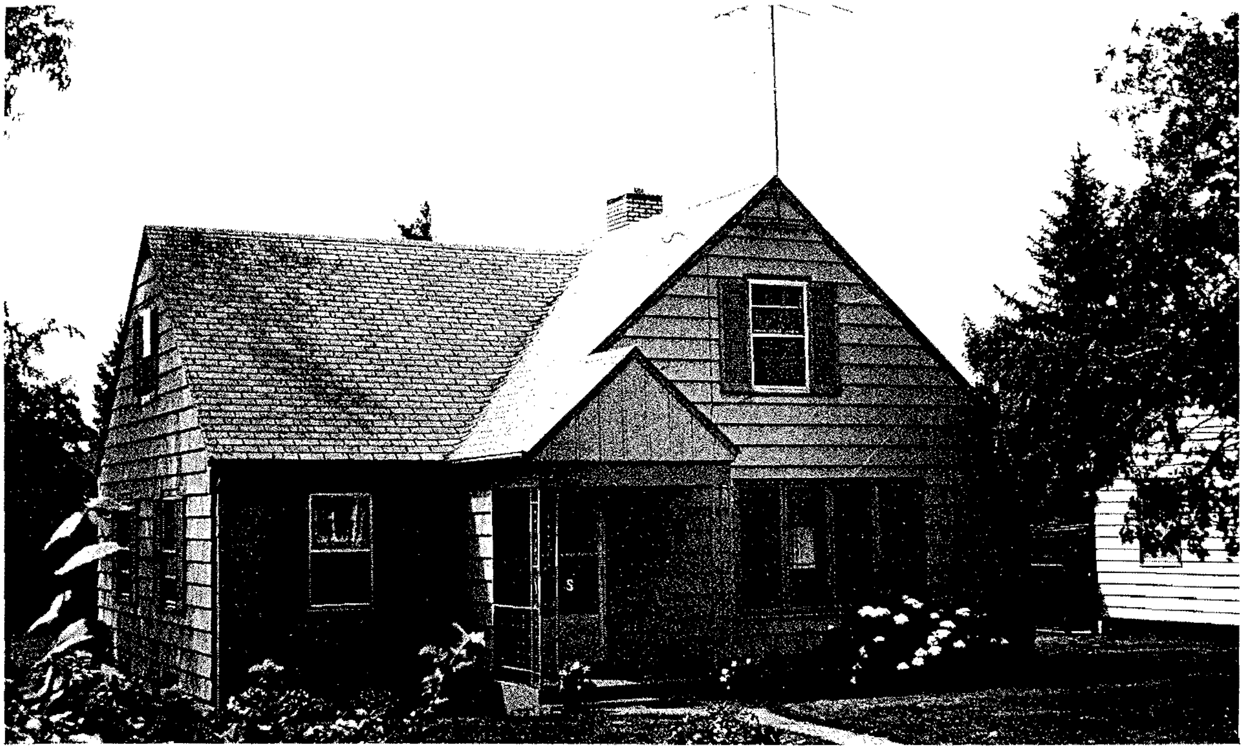

FIGURE 10. - Test structure 12, metal mine.

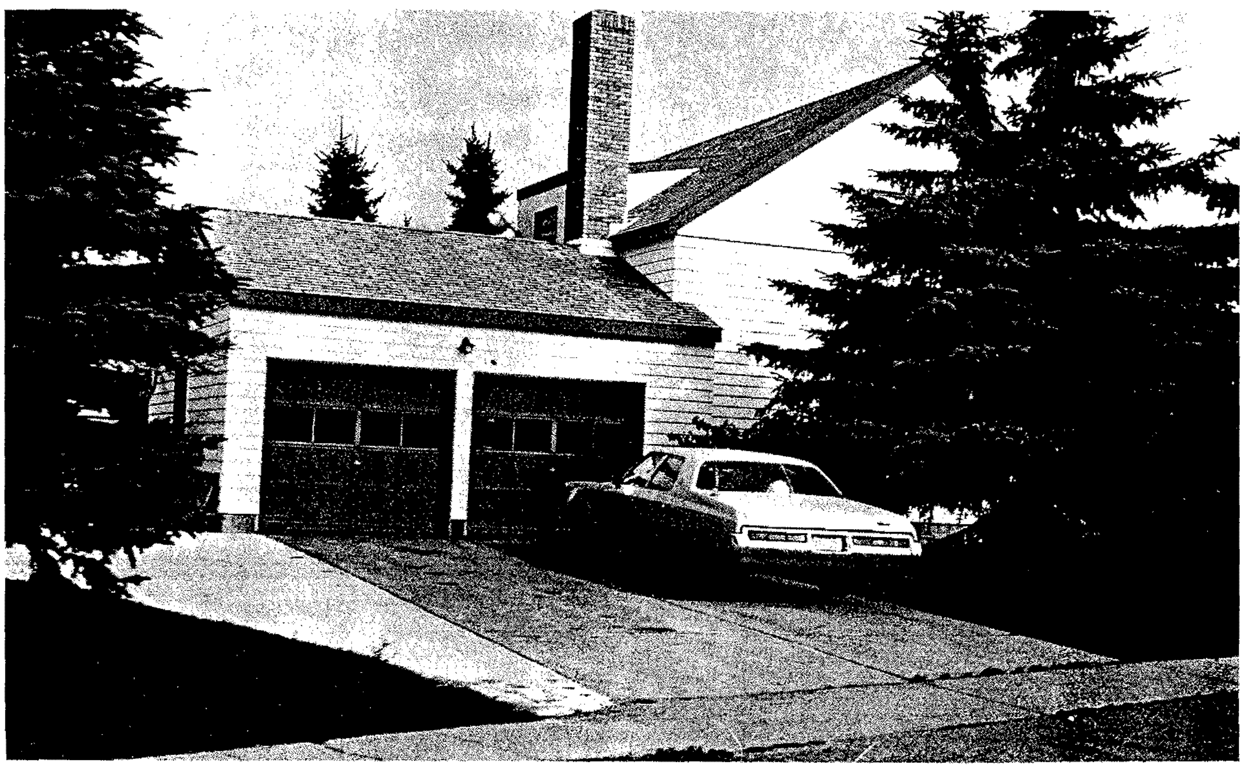

FIGURE 11. - Test structure 14, metal mine.

FIGURE 12. - Test structure 19, coal mine.

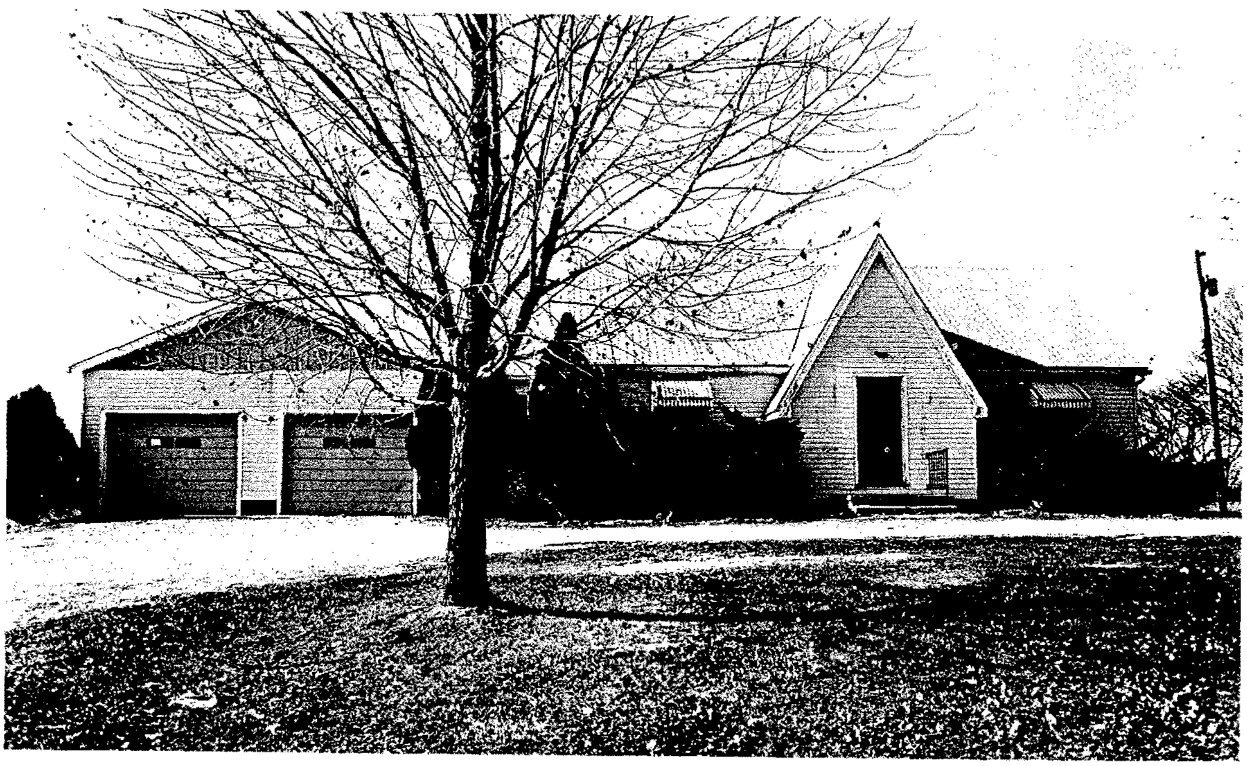

FIGURE 13. - Test structure 20, coal mine.

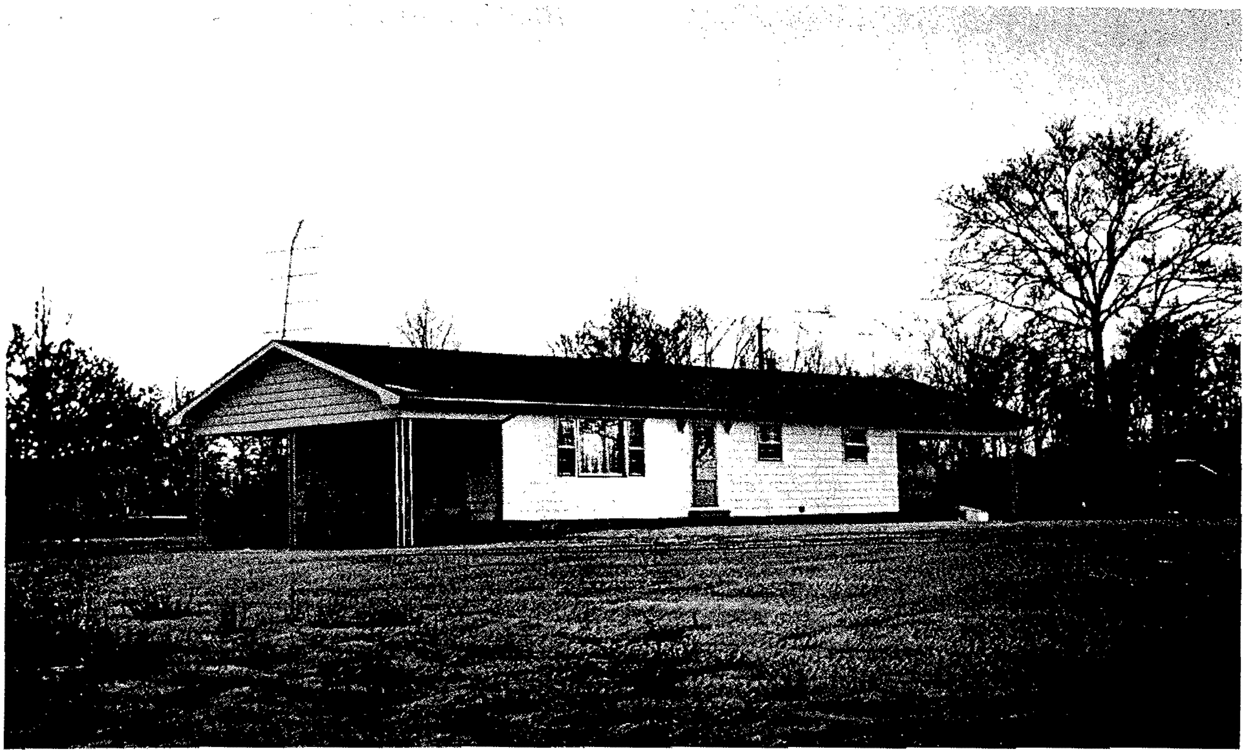

FIGURE 14. - Test structure 21, coal mine.

FIGURE 15. - Test structure 22, stone quarry.

FIGURE 16. - Test structure 23, stone quarry.

FIGURE 17. - Test structure 27, coal mine.

FIGURE 18. - Test structure 34, coal mine.

FIGURE 19. - Test structure 35, coal mine.

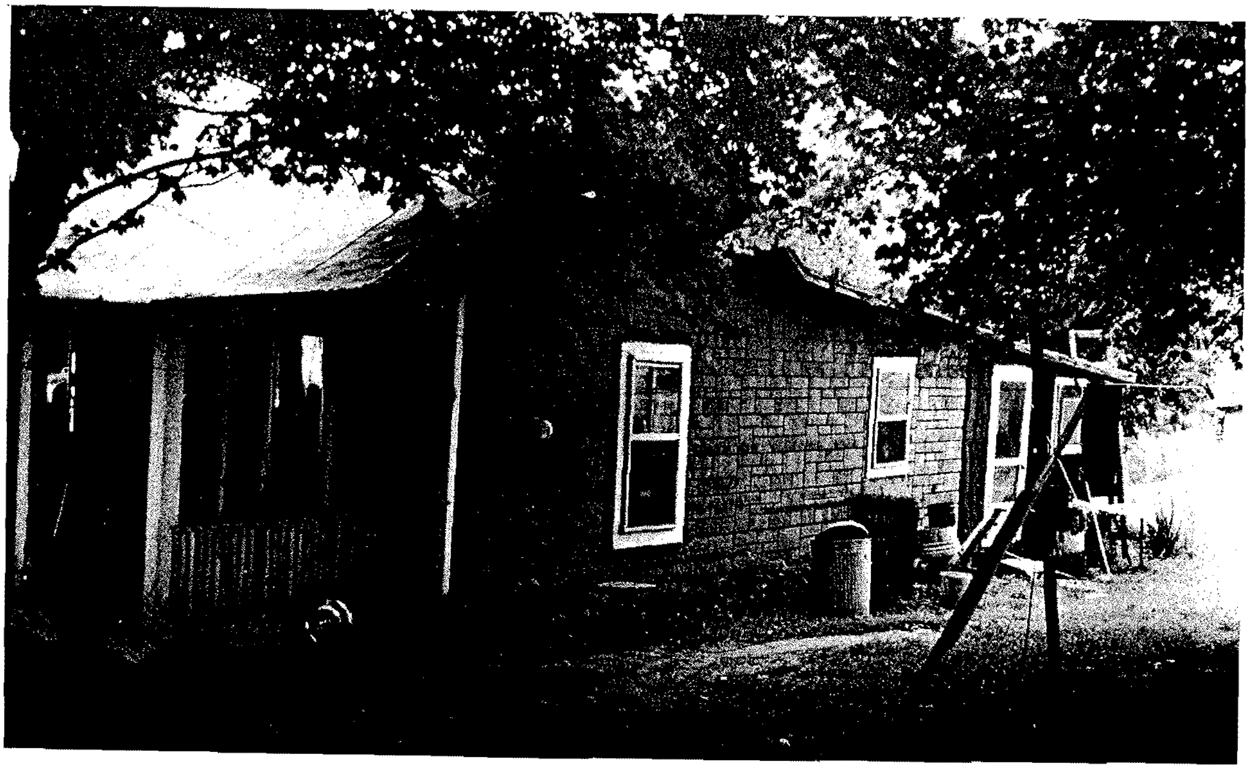

FIGURE 20. - Test structure 36, coal mine.

FIGURE 21. - Test structure 37, metal mine.

FIGURE 22. - Test structure 38, metal mine.

FIGURE 23. - Test structure 43, coal mine.

FIGURE 24. - Test structure 48, coal mine.

Instrumenting For Response

Outside ground vibration, airblast, and corner and midwall responses of the structure were measured for each shot. The ground vibration was measured by three orthogonal 2.5-Hz velocity gages buried about 12 inches into the soil next to the foundation (62). Outside airblast was measured with at least one DP-7 gage, and two sound level meters (one reading C-slow). The structures were instrumented for horizontal motions by a pair of gages mounted low on the first-floor vertical walls in the corner closest to the blast and one or more mid-walls. Typically, the vertical motion was measured in the same corner. Additional channels were usually available and used for various additional corner-motion measurements at mid-heights, near the ceiling, or on the next floor; additional floor-motion measurements such as mid-floor verticals; basement wall horizontal measurements; opposite-corner responses (for rotational motions); and inside noise.

Corner measurements assessed the racking motions (distortion) of the structure. Essentially all blast damage occurs where stresses and deformations are produced within the planes of the wall as shear stresses. Consequently,

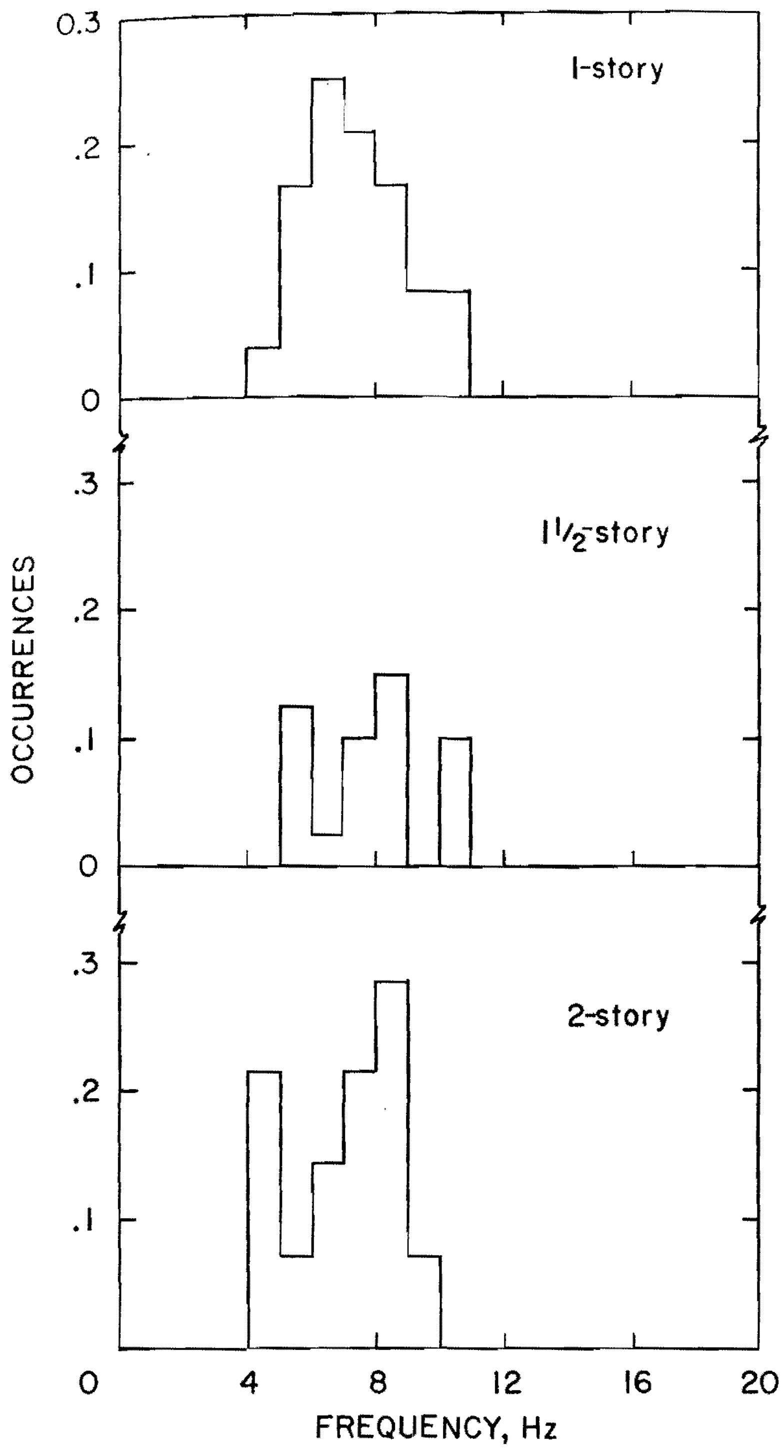

FIGURE 25. - Natural frequencies of residential structures.

the vibration measurements made in the corners were assumed to indicate damage potential, because they measured whole-structure response. Other types of response caused different but consequential results. Midwall motions (perpendicular to the wall surface) are primarily responsible for window sashes rattling, picture frames tilting, dishes jiggling, and knick-knacks falling. Midwall accelerations in excess of 0.4 g (12.8 ft/sec^2) are occasionally generated and could cause items to fall off shelves. These midwall motions are not necessarily dangerous to the structure since walls can vibrate in this mode without producing high levels of stress. Midwall motions are mostly annoying. Floor motions present a problem similar to midwalls. Like them, they also produce secondary noises and can lift hanging objects off nails and cause them to drop to the floor. Structures are designed to resist normal vertical load, so vertical corner motions of less than 1 g should not warrant serious concern.

Natural Frequencies and Damping

Natural frequency and damping are the most important structure-response characteristics. The natural frequencies of the structures as measured from blast-produced corner motions are summarized in figure 25, with individual values listed in table 2. Structures continue to vibrate after the sources (ground vibration and airblast) decay, and natural frequencies and damping can be measured from the time histories. The vibrations of structures, especially midwalls, are approximately sinusoidal; therefore, the natural frequencies are calculated by inverting their periods (in seconds). The damping values are given by

$$B = \frac{100}{2\pi m} \mathrm{Ln} \; (A_n / A_{n+m}),$$

where B is the percentage of critical damping, A is the peak amplitude at the n^{th} cycle, and m is any number of cycles later. Murray (28) discussed the general problem of structure frequencies and damping and also computed many of the values in table 2. He noticed that damping values were level-dependent, indicating that friction was nonlinear.

Little difference in natural frequencies was observed between 1-, 1-1/2-, and 2-story houses. Medearis (27) measured frequencies and damping values for 61 houses and found similar results, except for some higher frequencies for the 1- and 1-1/2-story homes. He found frequency ranges of 8-18 Hz (1 story), 7-14 Hz (1-1/2 stories), and 4-11 Hz (2 stories). Two potential problems exist in Medearis' data. He utilized bumping and door slamming for his vibration sources, and these might excite only parts of the structure (unlike blasting). Bureau measurements of bumping vibrations also gave higher and more scattered values than the blast-produced responses. In addition, midwall frequencies are higher than the vibration frequencies of the structure as a whole (fig. 26), and could contribute to the corner vibration measurements, as was the case with the corner mid-height horizontal measurements. Damping is summarized in figure 27.

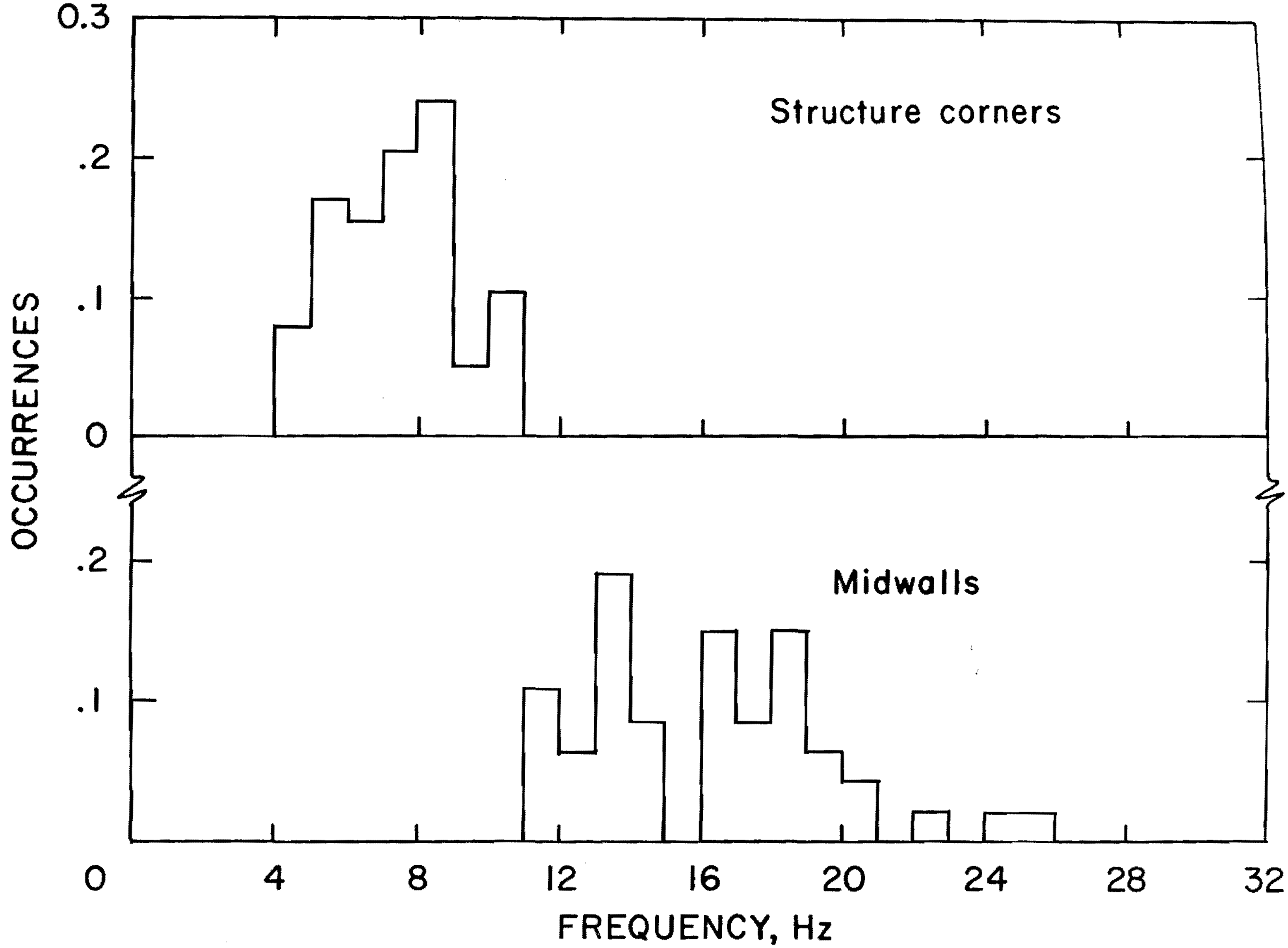

FIGURE 26. - Summary of natural frequencies of residential structures.

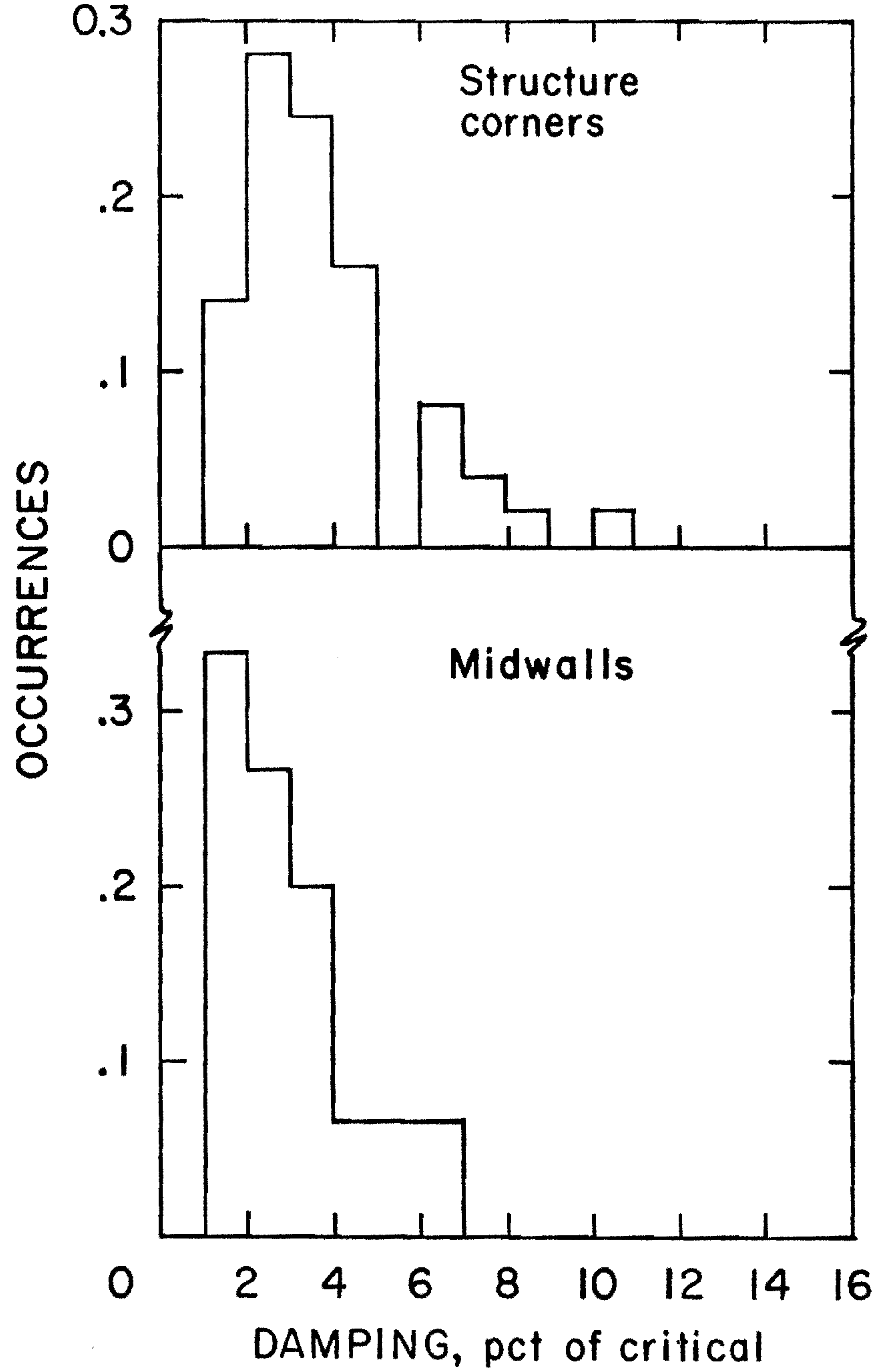

FIGURE 27. - Damping values of residential structures, corners and midwalls.

PRODUCTION BLASTING

Table 3 lists 196 production blasts. The first 12 shots were used for airblast instrumentation calibration, and are not included. A wide range of charge sizes, distances, and blast types produced airblasts of various peak values, durations, and frequency character. Quarries typically had a high free face, with strong directional effects. Quarries in urban areas used multiple decks, and hole diameters seldom exceeded 6 inches. Shots 21 to 30 were in an isolated quarry with high airblast levels at the close-in measuring locations, but no house vibration measurements were made.

Coal mine highwall blasts varied from well-confined blasts producing no throw whatsoever, to quarry-type blasts with three free faces (top, front, and one side). Where ground vibration appeared to be more serious than airblast, emphasis was put on sufficient relief. Parting shots involve blasting a thin, often hard, rock layer, and can produce high levels of airblast. The difficulty in obtaining sufficient confinement has resulted in some parting blasts being almost as loud as with unconfined explosive.

The metal mines produced a wide range of airblast concerns, depending on the proximity of residences. One operation (shots 36 and 38) had no structures nearby that were not company owned, and consequently loaded to the collar in order to fragment hard rock near the surface.

The operators recognized the airblast problem created by exposed surface detonating cord; none of the coal or stone quarry shots had uncovered cord. A few shots were designed with long delays which greatly influenced the airblast frequency character (for example, shot 101 (fig. 3)).

An extensive study was made by Wiss (83) of the blast design factors of noise and vibration. These are summarized in appendix B of this report, and reference 56.

PROCESSING OF AIRBLAST TIME HISTORIES

Descriptors for Sound

A variety of descriptors characterize levels of sound; however, no consensus exists on the appropriate measurement methodologies for impulsive noise sources. The nonuniformity of symbols among studies also complicates the problem, so the Environmental Protection Agency (EPA) has recently recommended standard terminology (59).

Stachura (61) defines and discusses various sound descriptors for impulsive noises. The applicability of these descriptors to blast-produced noise is discussed in this report in the section on tolerable airblast levels.

Perceived Noise Level (L_{pn}), also labeled PNdB, was analyzed by Kryter (19) for aircraft and nonimpulsive sources. Kryter (20) later examined a modified L_{pn}, which included a time and tone correction, calling it "Effective Perceived Noise Level" (L_{epn}), which he labeled EPNdB. Both L_{pn} and L_{epn} have been correlated with peak sonic boom levels by subjective assessment of test subjects (19-20, 48, 50).

TABLE 3. - Production blasts and airblast measurements

Blast design								Sound levels, dB						Structure response from airblast				
Shot No.	Facility	Shot type	Total charge weight, lb	Lb/delay	Distance, ft	Scaled distance Ft/lb$^{1/2}$	Scaled distance Ft/lb$^{1/3}$	Peak linear 0.1-Hz high pass	Peak linear 2-Hz high pass	Peak linear 5-Hz high pass	C-slow	Perceived level, PLdB	Rock pressure pulse (RPP)	Peak corner motion, in/sec	Peak midwall motion, in/sec	Structures monitored	Orientation of gage to blast free-face	Airblast type
13[1]	Quarry	High-wall.	2,033	280	400	24	61	130			105	88	111		0.70	1		1
14	..do..	..do..	4,353	218	900	61	149	125	116		<110	79	102			1		1,2
15	..do..	..do..	1,995	303	900	52	134	111	114		<90		102			2	90°	2
16	..do..	..do..	2,850	187	1,200	88	210	125				84				3		1,2
17	..do..	..do..	5,047	200	1,400	99	239	131	126	124		97			.41	1	270°	1,2
17	..do..	..do..	5,047	200	1,800	129	308	130				87	101		.28	4	270°	1,2
18	..do..	..do..	2,367	305	400	23	59	128		125			107			1		1,2
18	..do..	..do..	2,367	305	800	46	119	115					105			4		1,2
19	..do..	..do..	2,450	160	1,100	86	204	124		119		89	106			5	270°	1
19	..do..	..do..	2,450	160	1,500	119	276	116								6	270°	
21	..do..	..do..	4,240	1,470	240	6.3	21	143				103						
21	..do..	..do..	4,240	1,470	620	16.2	54	144									270°	
21	..do..	..do..	4,240	1,470	260	6.8	23	154									270°	
21	..do..	..do..	4,240	1,470	475	12.4	42		134									
21	..do..	..do..	4,240	1,470	75	2.0	6.6	140									90°	
22	..do..	..do..	3,560	790	425	15.1	46		133		116						0°	
22	..do..	..do..	3,560	790	260	9.3	28	149									270°	
22	..do..	..do..	3,560	790	610	22	66	144									270°	
22	..do..	..do..	3,560	790	290	10.3	32	139									180°	
22	..do..	..do..	3,560	790	82	3.0	8.9	140				110					90°	
23	..do..	..do..	5,540	985	210	6.7	21	143									270°	
23	..do..	..do..	5,540	985	400	12.7	40	160									180°	
23	..do..	..do..	5,540	985	705	22.4	71	153										
23	..do..	..do..	5,540	985	230	7.3	23	156	142		115	137					0°	
23	..do..	..do..	5,540	985	110	3.5	11.1	143										
24	..do..	..do..	3,500	580	750	31	75	123	120								0°	
24	..do..	..do..	3,500	580	550	23	66	139									270°	
24	..do..	..do..	3,500	580	190	7.9	23	126									180°	
24	..do..	..do..	3,500	580	250	10.4	30	130									270°	
25	..do..	..do..	4,600	790	440	15.7	48	127									0°	
25	..do..	..do..	4,600	790	550	20	60	138				104					270°	
25	..do..	..do..	4,600	790	410	14.6	45	124									90°	
25	..do..	..do..	4,600	790	550	20	60	125	117									
26	..do..	..do..	3,620	790	238	10.1	26	133									0°	
26	..do..	..do..	3,620	790	365	13.0	40	136									270°	
26	..do..	..do..	3,620	790	590	21	64	142									270°	
26	..do..	..do..	3,620	790	105	3.8	11.4	137									180°	
26	..do..	..do..	3,620	790	142	5.1	15.5	131	115	115							90°	
27	..do..	..do..	3,500	755	480	17.5	53	134									0°	
27	..do..	..do..	3,500	755	530	19.3	58	140									270°	
27	..do..	..do..	3,500	755	209	7.6	23	137									180°	
27	..do..	..do..	3,500	755	238	8.7	26	130	126	123	103						90°	
28	..do..	..do..	2,900	402	215	10.7	29	138									0°	
28	..do..	..do..	2,900	402	650	32	88	140									270°	
28	..do..	..do..	2,900	402	300	15.0	41	135									180°	
28	..do..	..do..	2,900	402	280	14.0	38	126									90°	
28	..do..	..do..	2,900	402	395	19.7	54	134		127	106						180°	
29	..do..	..do..	3,960	860	115	3.9	12.1	142									0°	
29	..do..	..do..	3,960	860	440	15.0	46	147									270°	
29	..do..	..do..	3,960	860	179	6.1	18.8	141									180°	
29	..do..	..do..	3,960	860	139	4.7	14.6	136									90°	
29	..do..	..do..	3,960	860	440	15.0	46	133		120	103						180°	
30	..do..	..do..	3,520	402	498	25	67	130	127	125								
31	..do..	..do..	4,470	115	150	14.0	31	135									0°	
31	..do..	..do..	4,470	115	645	60	133	128									270°	
31	..do..	..do..	4,470	115	130	12.1	27	132									180°	
31	..do..	..do..	4,470	115	470	44	97	123	116									
31	..do..	..do..	4,470	115	400	37	82	130									90°	
32	..do..	..do..	4,320	110	312	30	65	143										
32	..do..	..do..	4,320	110	390	37	82	142										
32	..do..	..do..	4,320	110	120	11.4	25	153										
32	..do..	..do..	4,320	110	300	29	63	144									90°	
33	..do..	..do..	8,762	700	3,300	125	372	117								7,8		
34	..do..	..do..	1,985	68	1,200	146	294	112								9		
35	Metal.	High-wall.	507,060	4,200	1,160	18	72	129					119			10	180°	
35	..do..	..do..	507,060	4,200	1,600	24.7	99				109							
35	..do..	..do..	507,060	4,200	3,440	53	213	122	116	115	97	77	100			11,12,13		
36	..do..	..do..	592,150	21,000	18,800	130	681	129	121	116	88	74			.081	14,15		2
36	..do..	..do..	592,150	21,000	7,000	48	254	132			105					16		
37	..do..	..do..	184,240	2,184	4,000	86	308	122			96		104			18		
37	..do..	Test..	2	2	4,000	2,828	3,176	117			96					17		
38	..do..	High-wall.	212,990	15,530	41,700	335	1,671	123			86		100			14		
38	..do..	..do..	212,990	15,530	42,700	343	1,712	122								15		
39	Coal..	High-wall.	20,300	2,300	3,084	64	234	122					97			19		
40	..do..	Parting.	648	72	6,506	767	1,564	114		113	93					19		
41	..do..	High-wall.	21,800	2,600	2,979	58	217	125					99			19		
43	..do..	..do..	20,700	2,600	2,872	56	210	124	121		93		101			19		
43	..do..	..do..	20,700	2,600	2,241	44	163	123	117		98		107			20		
44	..do..	..do..	20,600	2,300	2,757	57	209	123	119		90		100			19		
44	..do..	..do..	20,600	2,300	2,287	48	173	121			94		108			20		
45	..do..	..do..	20,700	2,300	2,651	55	201	121	115		90		98			19		

See footnotes at end of table.

TABLE 3. - Production blasts and airblast measurements--Continued

Shot No.	Facility	Shot type	Blast design: Total charge weight, lb	Lb/delay	Distance, ft	Scaled distance: $Ft/lb^{1/2}$	$Ft/lb^{1/3}$	Sound levels, dB: Peak linear 0.1-Hz high pass	Peak linear 2-Hz high pass	Peak linear 5-Hz high pass	C-slow	Perceived level, PLdB	Rock pressure pulse (RPP)	Structure response from airblast: Peak corner motion, in/sec	Peak midwall motion, in/sec	Structures monitored	Orientation of gage to blast free-face	Airblast type
45	..do..	..do..	20,700	2,300	2,347	49	178	120	114	113	93	75			0.020	20		2
46	..do..	Ditch.	3,600	600	2,231	91	265	111	113				87			19		
46	..do..	..do..	3,600	600	1,753	72	208				88					20		
47	..do..	Highwall.	21,600	2,600	2,535	50	184	123	120		87		98			19		
47	..do..	..do..	21,600	2,600	2,413	47	176		115		90					20		
48	..do..	..do..	20,600	2,300	2,430	51	184	120	117		89		99			19		
48	..do..	..do..	20,600	2,300	2,480	52	188		113		92					20		
49	..do..	..do..	19,800	2,200	2,548	54	196	117	109		87		105			20		
50	..do..	..do..	19,700	2,200	2,617	56	201	119	114		91		105			20		
51	..do..	..do..	19,300	2,200	2,687	57	207	113	110		84		103			20		
52	..do..	Parting.	384	24	3,347	683	1,162		106		87					20		
53	..do..	..do..	264	24	3,042	621	1,055	108	106		88					20		
54	Coal..	Parting.	360	36	2,547	425	772	>113	108	112	93					20		
55	..do..	Highwall.	18,400	2,100	2,764	60	216	118	112		85		103			20		
56	..do..	..do..	17,700	2,000	2,843	64	226	116	111		84		103			20		
57	..do..	..do..	6,000	2,000	2,912	65	231	114	110		89		98			20		
58	..do..	Parting.	480	30	2,434	444	782				97					20		
59	..do..	..do..	294	30	4,314	788	1,389		117		98					19		
60	..do..	Highwall.	21,400	2,000	1,696	38	135	125					111			19		
61	..do..	..do..	24,700	2,100	1,608	35	125		127		104					19		
62	..do..	Sweetner.	1,500	150	1,696	138	318	127	127	124	99	74		.13	.40	19		1
63	..do..	Parting.	384	24	4,127	842	1,431	112	115	112	96					19		
64	..do..	Highwall.	24,600	2,100	1,501	33	117	128	122	120	100	87	111		.53	19		1,2
65	..do..	..do..	15,700	2,200	1,428	30	110	126	124		97		111			19		
66	..do..	..do..	15,800	1,900	1,339	31	108	128	126		102		115			19		
67	..do..	..do..	13,540	1,900	1,248	29	101	129	126	123	103	73	107		.70	19		1,2
68	..do..	Parting.	300	30	3,904	713	1,256	107	108	106	83					19		
69	..do..	Highwall.	11,040	2,000	1,160	26	92	121	117		96		110			19		
70	..do..	Sweetner.	2,100	300	1,485	86	222	129	126	124	101	87		.06	.56	19		2
71	..do..	Hilltop.	9,020	410	1,359	67	183	131	129	125	103	87	97	.11	.28	19		1,2
72	..do..	Ditch.	3,060	510	2,096	93	263	113	111				88			19		
73	..do..	Highwall.	19,600	2,000	1,093	24	87	132	128		105					19		
74	..do..	..do..	17,100	2,000	1,011	23	80	129	125				114			19		
75	..do..	Ditch.						118	114		89		92			19		
76	..do..	..do..	3,360	280	1,549	93	238	126	123				<90			19		
77	..do..	..do..	1,200	220	1,519	102	251	117	115		90					19		
78	..do..	Highwall.	22,200	2,100	928	20	72	129	124	120	103	95	114		1.10	19		1
79	..do..	..do..	24,900	2,200	853	18.2	66	132	129	126	107	91	120		1.18	19		1,2
80	..do..	..do..	25,100	2,300	801	16.7	61	132	127	124	108	93	109		1.50	19		1,2
81	..do..	Sweetner.	3,240	360	699	37	99	126	126	123	106	99	98		.70	19		1,2
82	..do..	Hilltop.	27,000	1,000	699	22	70		133				112			19		
83	..do..	Ditch.	2,040	340	1,487	81	213	122	120		99					19		
84	..do..	Highwall.	25,600	2,200	754	16.1	58	134	130	126	116	108	>110		1.40	19		2
85	..do..	..do..	25,400	2,200	732	15.6	56	133	128	125	109	97	120	.22	1.04	19		2
86	..do..	..do..	25,900	2,200	716	15.3	55	135	132	130	107	92	119	.24	2.50	19		2
87	..do..	Ditch.	1,320	220	1,459	98	241	120	120		95		88			19		
88	..do..	Parting.	360	36	2,593	433	786	125			108					19		
89	..do..	..do..	360	36	2,229	372	675	114			94					19		
90	..do..	Highwall.	25,500	2,200	720	15.4	55	129	124	120	104	86	121		.49	19		2
91	..do..	..do..	31,500	2,200	738	15.7	57	132	128		105		119			19		
92	..do..	Ditch.						131	129	128	104	93	93	.12	.58	19		1
93	..do..	Parting.	114	12	2,167	626	947	110	109	111	94					19		
94	..do..	Highwall.	30,700	2,200	800	17.1	62	133	130	127	104	88	108		.30	19		2
95	..do..	..do..	26,600	2,200	840	17.9	65	128	123	120	101	83	114		.59	19		2
96	..do..	..do..	20,500	2,000	906	19.3	72	132			102		115			19		
97	..do..	..do..	9,000	450	2,500	118	326	119	115		91					21		
98	..do..	..do..	14,400	450	2,700	127	352	120	121		95					21		
99	..do..	Parting.	20,880	773	1,400	50	153	128	125	123	96	88	99		.72	21		2
100	..do..	..do..	18,000	200	750	53	128	118	114	112	97		112			21		
101	..do..	..do..	17,500	350	1,800	96	255	121	120	118	102	83	98	.10	.91	21		1
102	..do..	..do..	27,040	208	700	48	118	119	120		100		117			21		
103	Quarry	Highwall.	4,956	632	1,558	62	182	122		121	94	84	103	.070	.28	22	0°	

See footnotes at end of table.

TABLE 3. - Production blasts and airblast measurements--Continued

Shot No.	Facility	Shot type	Blast design: Total charge weight, lb	Lb/delay	Distance, ft	Scaled distance: $Ft/lb^{1/2}$	Scaled distance: $Ft/lb^{1/3}$	Sound levels, dB: Peak linear 0.1-Hz high pass	Peak linear 2-Hz high pass	Peak linear 5-Hz high pass	C-slow	Perceived level, PLdB	Rock pressure pulse (RPP)	Structure response from airblast: Peak corner motion, in/sec	Peak midwall motion, in/sec	Structures monitored	Orientation of gage to blast free-face	Airblast type
103R[4]	..do..	..do..	4,956	632	1,558	62	182	124	120	121	98	88	103	0.089	0.65	22	270°	
103	..do..	..do..	4,956	632	701	28	82	133	132	130	106	99	110	.25	.60	23		
103R[3]	..do..	..do..	4,956	632	701	28	82	131			108	92	110	.16	.87	23	270°	
104	..do..	..do..	5,752	632	1,481	59	173	121			<90					22	270°	
104	..do..	..do..	5,752	632	646	26	76	133								23	270°	
105	..do..	..do..	4,350	615	550	22	64	132	130	126	101	89	113	.34	.46	23	0°	
105R[2]	..do..	..do..	4,350	615	550	22	64	126			103	87	113	.10	.40		270°	
106	..do..	..do..	17,604	852	4,208	144	443	133	124		<100					24	270°	
106	..do..	..do..	17,605	852	2,304	79	243	121	113		<90		102			25	90°	
107	Coal..	High-wall.						127	123		100		105			26	90°	
108	..do..	..do..						122					112			28	90°	
109	..do..	..do..		300	1,811	105	271	105			<80					29	90°	
110	..do..	Part-ing.	21,600	240	800	52	129	118	115	116	98		114			21		
111	..do..	..do..	112,200	320	1,000	56	146	120	122	121	98		106			21		
112	..do..	High-wall.		300	1,409	81	210	111	111		<90		103			30	90°	
113	..do..	Part-ing.	112,200	320	1,100	61	161	120	120	117	96		112			21		
114	..do..	..do..	23,680	370	1,300	68	181	119	113	114	94		105			21		
115	..do..			21	1,801	393	653	124								31	90°	
116	..do..	High-wall.	12,000	300	652	38	97	114	117		94		105			31	90°	
117	..do..	Part-ing.	14,400	360	3,000	158	422	120	112	114	92					21	90°	
119	Quarry	High-wall.	16,608	782	4,301	154	467	124	123		<90					32	270°	
120	Coal..	..do..	15,120	120	1,443	132	293		115		92					29	90°	
122	..do..			15	1,698	439	689	122	111		<90		97			28	90°	
124	..do..	Part-ing.	1,340	20	2,000	447	737	130			111			.09	1.77	33	90°	
125	..do..	High-wall.	10,200	200	2,000	141	342	114	113	112	95					33		
126	..do..	Part-ing.	1,200	20	1,750	391	645	136	135	133	115	103		.14	1.71	34		
127	..do..	High-wall.	12,000	400	..do.	88	238	108	106							34		
128	..do..	Part-ing.	1,500	20	3,250	727	1,197	127	127	125	102	89	98	.13	1.80	35		
129	..do..	High-wall.	15,000	350	3,100	166	440	113					94			35		
130	..do..	Part-ing.	890	20	1,750	391	645	127	128	127	107	91		.040	1.09	34		
131	..do..	High-wall.	10,800	400	1,750	88	238	111	108							34		
132	..do..	Part-ing.	1,300	30	1,200	219	386	130	130	131	113					33		
133	..do..	High-wall.	24,000	400	1,200	60	163	98								33		
134	..do..	High-wall.	2,300	400	2,000	60	163	113	113	111	92		106			33		
135	..do..				2,000			127					113			21		
136	..do..	Part-ing.	29,700	900	500	16.7	52	126	128	125	108					21		
137	..do..	Part-ing.	2,300	20	2,000	447	737	122		122	97					33		
138	..do..	..do..	2,300	20	2,000	447	737	119		119	98		106			33		
139	..do..	High-wall.	19,200	400	2,000	100	271	116	116				97			33		
140	..do..	Part-ing.	1,000	20	3,500	783	1,289	116	116	113						35		
141	..do..	..do..	1,000	20	2,400	537	884	124	125	123	101	86		.025	.86	36		
142	..do..	..do..	1,000	20	2,400	537	884	121		119	95					36		
143	..do..	High-wall.	40,000	400	2,400	120	326	111					94			36		
144	..do..	Part-ing.	2,400	10	2,400	759	1,114	118	115	113	92					36		
145	..do..	High-wall.	40,000	400	2,400	120	326	109	106		82		91			36		
146	Iron mine.	High-wall.	573,610	4,580	5,800	86	350	117	112	108	87	62	104		.15	17,18		2
146	..do..	..do..	573,610	4,580	6,400	95	387	116	111		85		104			37		
147	..do..	..do..	524,030	8,800	6,900	74	336	131	123		93		102			38,39		
148	..do..	..do..	593,720	8,230	6,730	74	332	131	127	124	95	81	94	.12	.47	38,40		1
149	..do..	..do..	58,000	2,500	11,050	221	814	117	112		86					41		

See footnotes at end of table.

TABLE 3. - Production blasts and airblast measurements--Continued

	Blast design							Sound levels, dB						Structure response from airblast				
Shot No.	Facility	Shot type	Total charge weight, lb	Lb/delay	Distance, ft	Scaled distance Ft/lb$^{1/2}$	Scaled distance Ft/lb$^{1/3}$	Peak linear 0.1-Hz high pass	Peak linear 2-Hz high pass	Peak linear 5-Hz high pass	C-slow	Perceived level, PLdB	Rock pressure pulse (RPP)	Peak corner motion, in/sec	Peak midwall motion, in/sec	Structures monitored	Orientation of gage to blast free-face	Airblast type
150	..do..	..do..	184,500	3,260	5,820	102	393	127	123	120	94	84	92	0.082	0.246	37		2
152	Coal..	..do..	3,585	255	2,110	132	333	111			88					42		
153	..do..	..do..	3,783	152	2,110	171	395	117	105		90		106			42		
154	..do..	..do..	3,000	125	575	51	115	125	121	118	97	82	107		.85	43		
155	..do..	..do..	5,400	120	475	43	95	122	121				102			44		
156	..do..	..do..	3,600	80	365	41	85	126	122				109			44		
157	..do..	..do..	4,500	75	1,100	127	261	115		112	94					45		
157	..do..	..do..	4,500	75	450	52	107	124			96					46		
158	..do..	..do..	2,460	41	1,150	180	334	112		108			91			45		
158	..do..	..do..	2,460	41	360	56	104	123	122		98		110			46		
159	..do..	..do..	920	23	1,200	250	422	104		106	86		88			45		
159	..do..	..do..	920	23	250	52	88	125	123		102		108			46		
160	..do..	..do..	5,460	78	450	51	105	119		116	98		94			47		
161	..do..	..do..	3,280	41	215	34	63	130	130	128	112	94			1.25	48		
162	..do..	..do..	13,040	602	1,500	61	177	119	112		<90		102			49		
163	Iron mine.	..do..	210,600	8,530	600	6.5	29	155	154	152	129		129	1.19	3.78	50		
164	Coal..	..do..	3,510	351	835	45	119	121	119		97	85	98		.40	49		
165	..do..	..do..	4,914	351	815	44	116	115			<90					49		
166	..do..	..do..						117			91		101			49		
167	..do..	..do..	1,750	35	301	51	92	119	119		97		107			51		
168	..do..	..do..	4,300	86	250	27	57	128			108		112			51		
169	..do..	..do..	4,300	86	178	19.2	40	129		127	108		112			51		
170	..do..	..do..	4,300	86	150	16.2	34	129		127	>110		115			51		
171	..do..	..do..	1,775	71	150	17.8	36	129		127	105		115			51		
172	..do..	..do..						120			<90		103			49		
173	..do..	..do..	2,150	86	249	27	56	122	125		101		107			51		
174	..do..	..do..	4,300	86	192	21	44				106		112			51		
175	..do..	..do..	5,150	212	144	9.9	24	135	134	135	112		124			51		
176	..do..	..do..	3,550	71	58	6.9	14.0	133		132	114		121			51		
177	..do..	..do..	3,240	36	58	9.7	17.6	127		126	110					51		
178	..do..	..do..	1,320	33	260	45	81	121	119		<100					51		
179	..do..	..do..	2,145	33	180	31	56	128	124	125	.103					51		
180	..do..	..do..	1,620	18	17	4.0	6.5	137	133	135	112					51		
181	..do..	..do..	1,980	22	87	18.5	31	136	125	128	104					51		
182	..do..	..do..	1,620	18	14	3.3	5.3	132	129	131	110					51		
183	..do..	Contour.	2,375	125	2,300	206	460	106								52		
184	..do..	..do..	18,500	200	2,600	184	445	121	116		<90					53		
185	..do..	..do..	545	5	600	268	351	110	110	109	91							
186	..do..	..do..	350	35	750	127	230	105			<90		87			54		
187	..do..	..do..	350	35	750	127	230	108	108		86		81			54		
188	..do..	..do..	9,450	175	1,500	113	268	117	117		94							
189	..do..	..do..	360	40	750	119	220	121	121		94		89			54		
190	..do..	..do..	720	40	750	119	220	105			86		87			54		
191	..do..	..do..	400	40	750	119	220	118	116		93		89			54		
192	..do..	..do..	960	40	750	119	220	106			84		84			54		
193	..do..	..do..	9,780	60	280	36	71	125			101					55		
194	..do..	..do..	320	40	1,100	174	322	111	108		87					56		
195	..do..	..do..	424	40	1,100	174	322	106	105		85					56		
196	..do..	..do..	680	40	1,100	174	322	113	111		90					56		
[3]C-1	..do..	Highwall.	6,000	500	851	38	107	117								27	90°	
C-2	..do..	..do..	7,200	600	796	33	94	123								27	90°	
C-3	..do..	..do..	7,800	650	743	29	86	125								27	90°	
C-4	..do..	..do..	7,200	1,200	695	20	65	131	127	128	108	100			.53	27	90°	1
C-5	..do..	..do..	7,800	1,300	652	18.1	60	139	138	135	112	103	109	.58	2.30	27	90°	Blowout
C-6	..do..	..do..	7,800	650	615	24	71	121					111			27	90°	
C-7	..do..	..do..	7,800	650	585	23	68	127								27	90°	
C-9	..do..	..do..	6,600	550	552	22	67	127								27	90°	
C-10	..do..	..do..	5,400	450	555	26	72	132	132	129	108	96	113	.20	.64	27	90°	1
C-11	..do..	..do..	3,600	300	564	33	84	126								27	90°	

[1]The first 12 shots were for instrumentation-calibration only.
[2]R = Airblast which had been reflected from the highwall accross the pit.
[3]Additional shots, not to be confused with the calibration shots previously mentioned.

Young (85) examined human tolerance to impulsive sources designed to simulate artillery firing. He used sound exposure levels (L_{SC}, L_{SA}, L_{D2}, for C, A, and D_2 weightings, respectively). C-weighted sound exposure levels, also labeled variously L_{CE} and CSEL, have been suggested as appropriate discriptors for assessing structure response from airblast (17, 46, 53, 60). Although it is recognized that the C-weighting cuts off the low frequencies above the house response frequencies, it is the closest of the standardized sound weightings to the desired frequency range.

One advantage of L_{SC} methods for regulating blast noise is that they are normalized to 1 second, which penalizes excessively long events (3 dB per doubling of duration), and allows higher levels for short duration events. Direct measurement of L_{SC} is complex. Kamperman (17) states that standard sound level meters on slow response can be used to measure L_{SC} and L_{SA} for events up to 1-second duration, within 2 dB accuracy.

Schomer (46) and von Gierke (70) have used day-night average sound levels, L_{dn}, to characterize the annoyance potential of impulsive sources involving long-term averages. This requires a minimum of 24-hour integration and both C-weighting (46, 70) and A-weighting (46). This technique may be applicable to quasi-static sources (a pile driver), but is probably not meaningful for infrequent blasting.

Higgins and Carpenter (14) analyzed Perceived Levels (PLdB) which are calculated from factors of sonic boom sharpness, such as rise time and peak values. The authors also give PLdB values for various levels of acceptability.

Airblast Processing For Structure Response

Airblast time histories were recorded with a system having ±3 dB linearity of at least 0.1 to 380 Hz as described in the section on survey instrumentation. Early tests with a 0.1- to 8,000-Hz sonic boom system (B&K 2631) verified that little significant airblast energy was present above 100 Hz at the distance of concern. Time histories from shot No. 86, with three components of ground vibrations, three corner motions, two midwalls, and the outside airblast appear in figure 28. The structure responded to both ground vibration and the airblast. As was typical, most corner responses were of lesser particle velocity amplitude than the incoming ground vibration. This was also true for measurements made in lower, upper, and second floor corners. The mid-height corner measurement appears to be a combination of corner and midwall responses. Midwalls experienced roughly equal amounts of ground vibration and airblast produced vibration response for this particular shot. Isolating the airblast effects requires good time separation between the two kinds of vibration, as well as an airblast of sufficiently high-level and high-frequency energy (for example, 10 Hz as in shot 86).

Many of the linear airblasts, including all which produced measureable structure responses, were further processed in order to determine the most

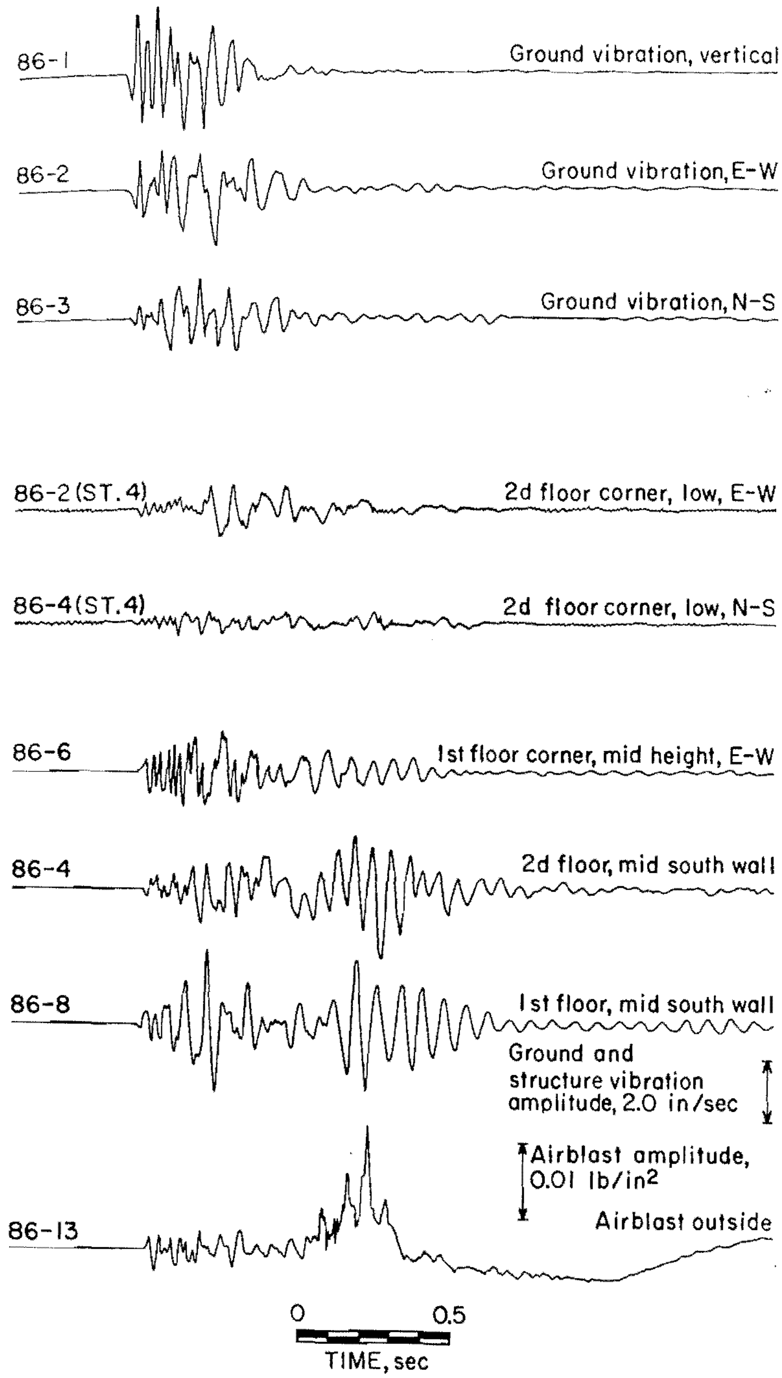

FIGURE 28. - Ground vibration, structure vibration, and airblast time histories from a coal mine highwall shot (shot 86).

appropriate structure-response descriptors (table 3). Playback of linear records through the two commercial sound-level meters gave "linear" sound levels with 2-, 5-, and 6-Hz low-frequency cutoffs. These laboratory-derived values agreed well with direct field sound level measurements made with the same meters (typically ±1 dB). Much of the airblast energy is below the low-frequency cutoffs of the linear range, and phase distortion as well as filtering will occur. However, the RMS value quantifies the energy in the airblast and is independent of phase distortion. Therefore, sound exposure levels (RMS values) with both special filtering and C-weighting were determined. A 0.1-Hz linear airblast time history with 500 msec of RPP and a combination type 1 and 2 APP character is shown in figure 29. The 5-Hz highpass (low frequency, 3 dB cut-off) removes the dominant low frequency (≈1 Hz), also distorting the waveform. C-weighting further filters the airblast's low frequencies, and the 1-sec averaging of the C-weighted sound would be dominated by the RPP in this case.

Sound exposure levels were determined by an RMS detecting and filtering system described by Stachura (61) and defined by:

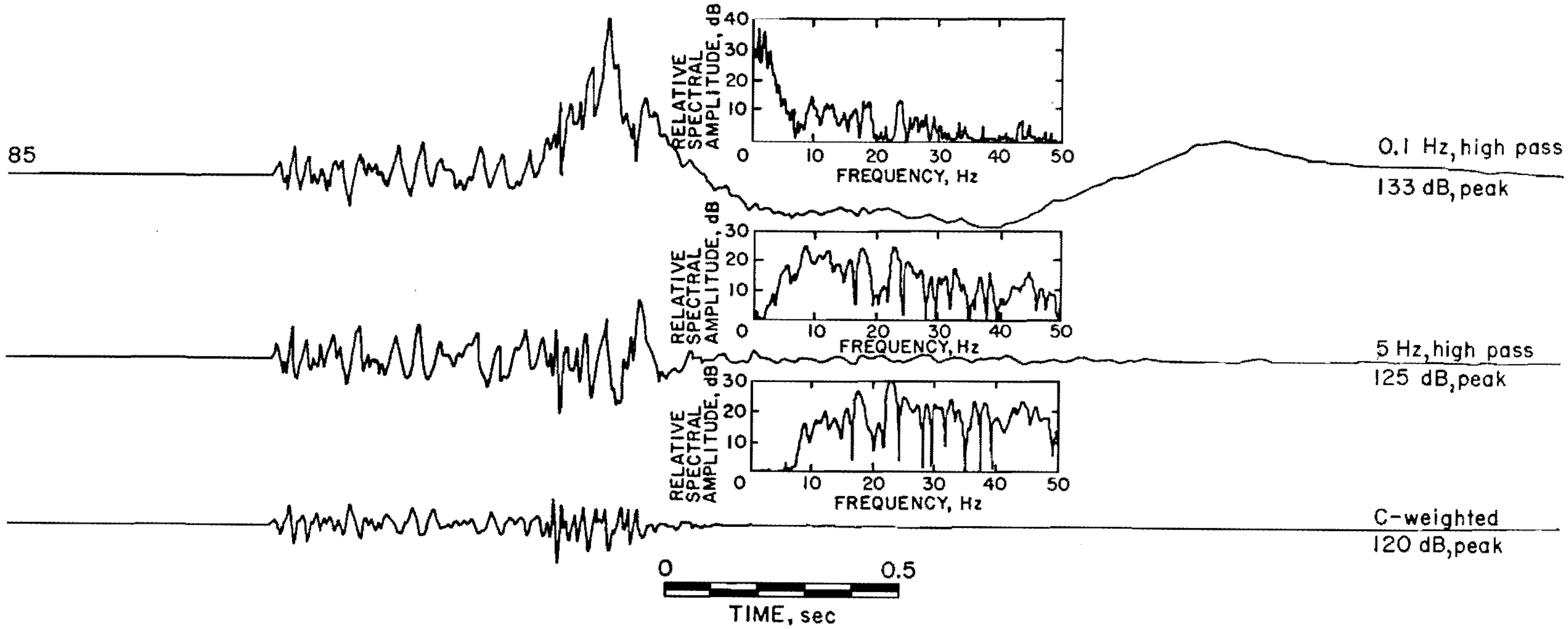

FIGURE 29. - Filtering of a complex airblast from a highwall production blast (shot 85).

$$L_s = 10 \log_{10}\left[\frac{1}{t_0}\int \frac{p_w^2}{p_0^2}\ dt\right],$$

where t_0 = 1 second, p_w = weighted sound pressure, and $p_0 = 20 \times 10^{-6}$ N/m^2. Analysis was made of the standard C-weighting sound levels as well as 3.5-10 Hz, 10-24 Hz, and 4-40 Hz band pass, with integration times of 1/8, 1/4, 1/2, and 4 seconds. These values plus peak 0.1-, 2, 5, and 6-Hz linear sound levels were correlated with peak corner and midwall motions, and also with the structures velocity exposure levels (VEL) determined with the various filtering and integration times used for SEL (see "Structure Response"). SEL values are given in table A-1.

Percieved levels (PLdB) were also calculated and included in table 3 for those airblasts with observable structure response, using the Higgins and Carpenter (14) formula:

$$\text{PLdB} = 55 + 20 \log_{10} \frac{\Delta p}{\tau},$$

where Δp = pressure change, in pounds per square foot, and τ = rise time, in seconds, corresponding to Δp.

PROPAGATION AND GENERATION OF AIRBLASTS

Much research has been done on airblast generation (72, 75-78) confinement and depth of burial effects (36, 40, 42, 73-74), airblast propagation (24, 34, 36, 39, 42-44, 58, 77, 81), and weather influences on airblast levels and character (2, 11, 18, 36, 37, 39, 50). Much of this work applies only indirectly to airblast from mining, since the experiments were designed to study other situations. A comprehensive study was recently completed by Wiss which examined many of the blast design and environmental factors influencing the generation and propagation of surface mine-produced airblast and ground vibration (83). Bureau of Mines and other research on airblast generation and propagation are described in Appendix B, Blast Design and Airblast Generation; Appendix C, Weather Effects on Propagation; and Appendix D, Terrain Effects on Propagation.

STRUCTURE RESPONSE FROM AIRBLAST

The response of structures, primarily residential, is the most critical indicator of troublesome or potential damaging airblast. There is little direct evidence that infrequent short-duration impulsive noises contribute directly to annoyance. All studies at occupied houses have found that damage and fear of damage are of primary concern. Some sonic boom tolerance tests indicate that booms may have a relatively different effect than airblasts on humans inside and outside structures, and that for sonic booms, an annoyance criterion may be more appropriate than a damage criterion. Relevant to the airblast problem are the whole-building response (corner measurements indicating racking effects on the frame) and midwall responses (best correlated with secondary effects; such as window sashes rattling, dishes and knick-knacks falling, etc.).

Measured structural response from mine and quarry airblasts are shown in figures 30 through 37. They are separated into corner and midwall responses

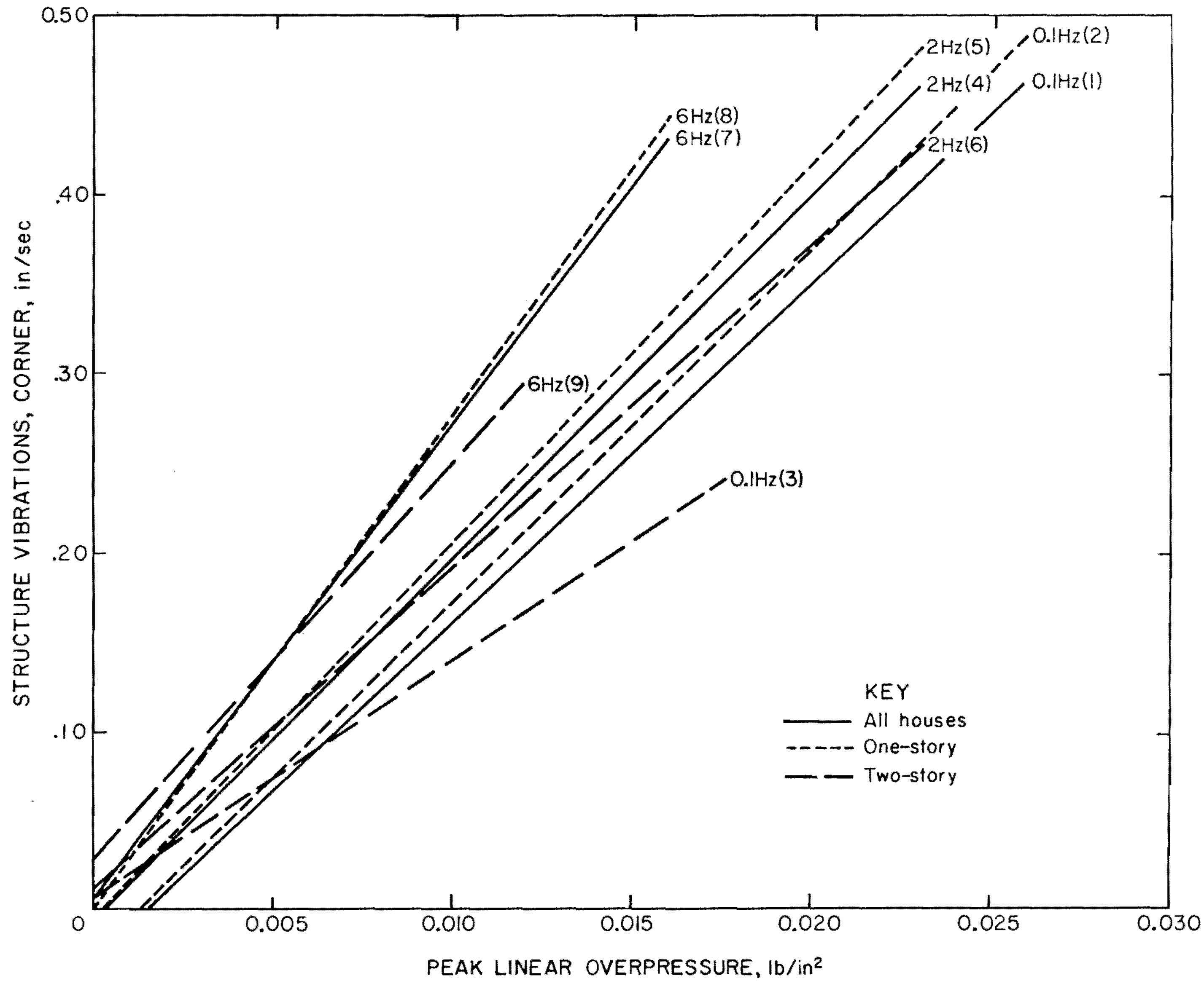

FIGURE 30. - Structure responses (corners) from peak linear overpressures, regressions. (Numbers in parentheses correspond to regression lines in table 4.)

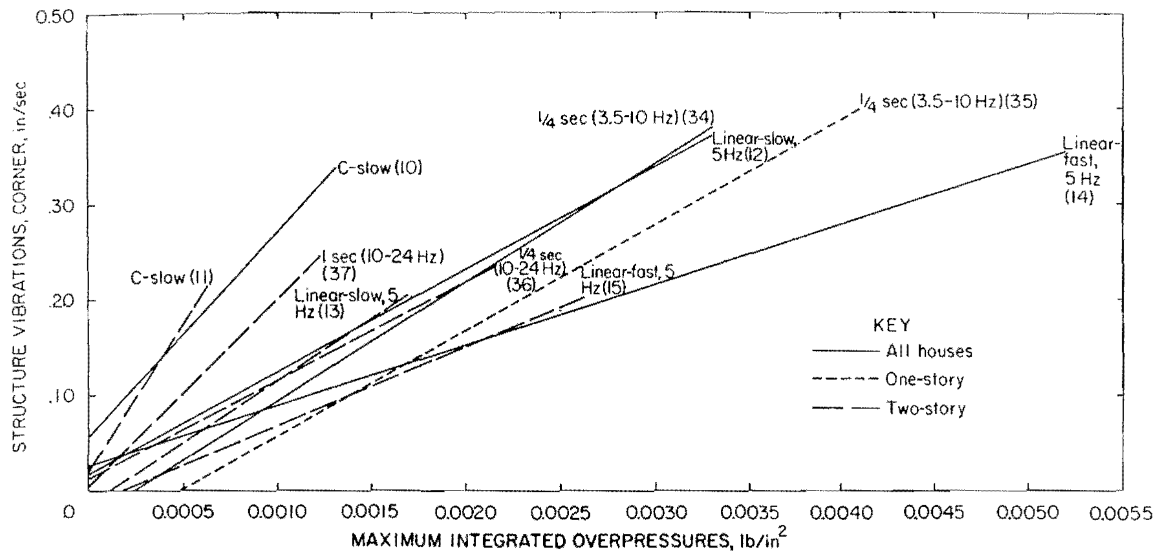

FIGURE 31. - Structure responses (corners) from maximum integrated overpressures, regressions. (Numbers in parentheses correspond to regression lines in table 4.)

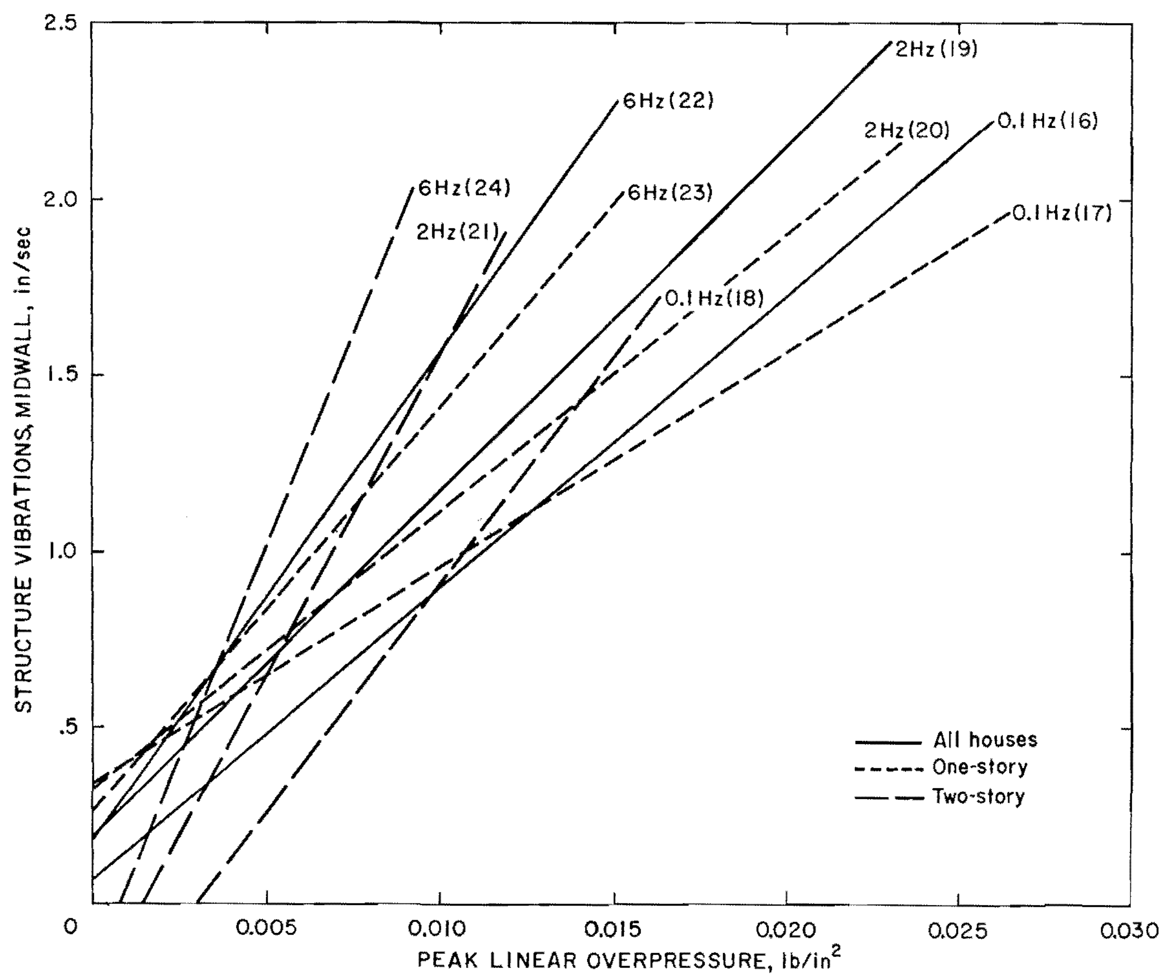

FIGURE 32. - Midwall responses from peak linear overpressures, regressions. (Numbers in parentheses correspond to regression lines in table 5.)

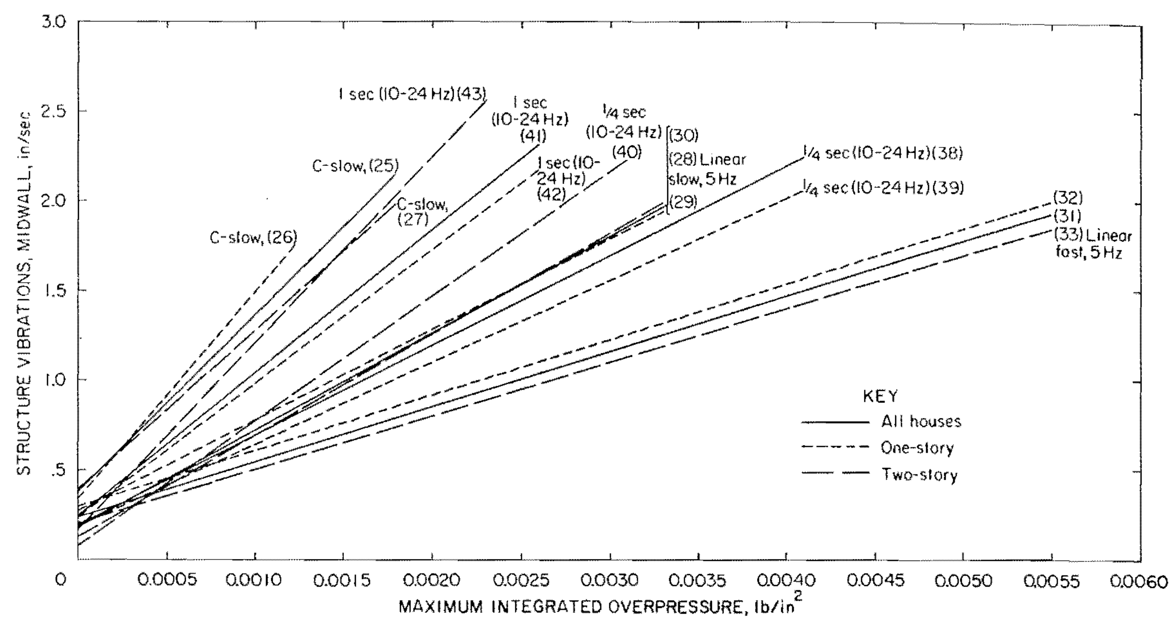

FIGURE 33. - Midwall responses from maximum integrated overpressures, regressions. (Numbers in parentheses correspond to regression lines in table 5.)

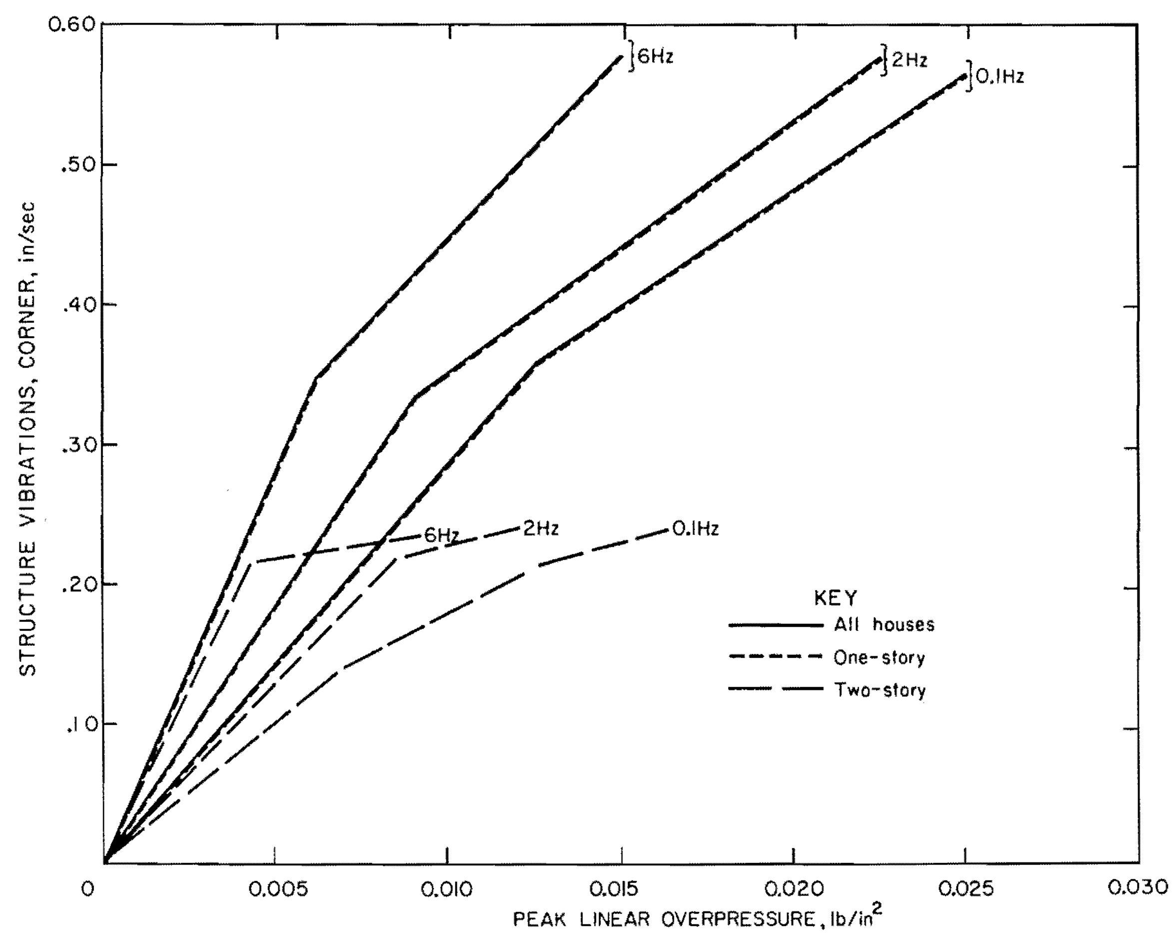

FIGURE 34. - Structure responses from peak overpressures, envelopes of maximum value.

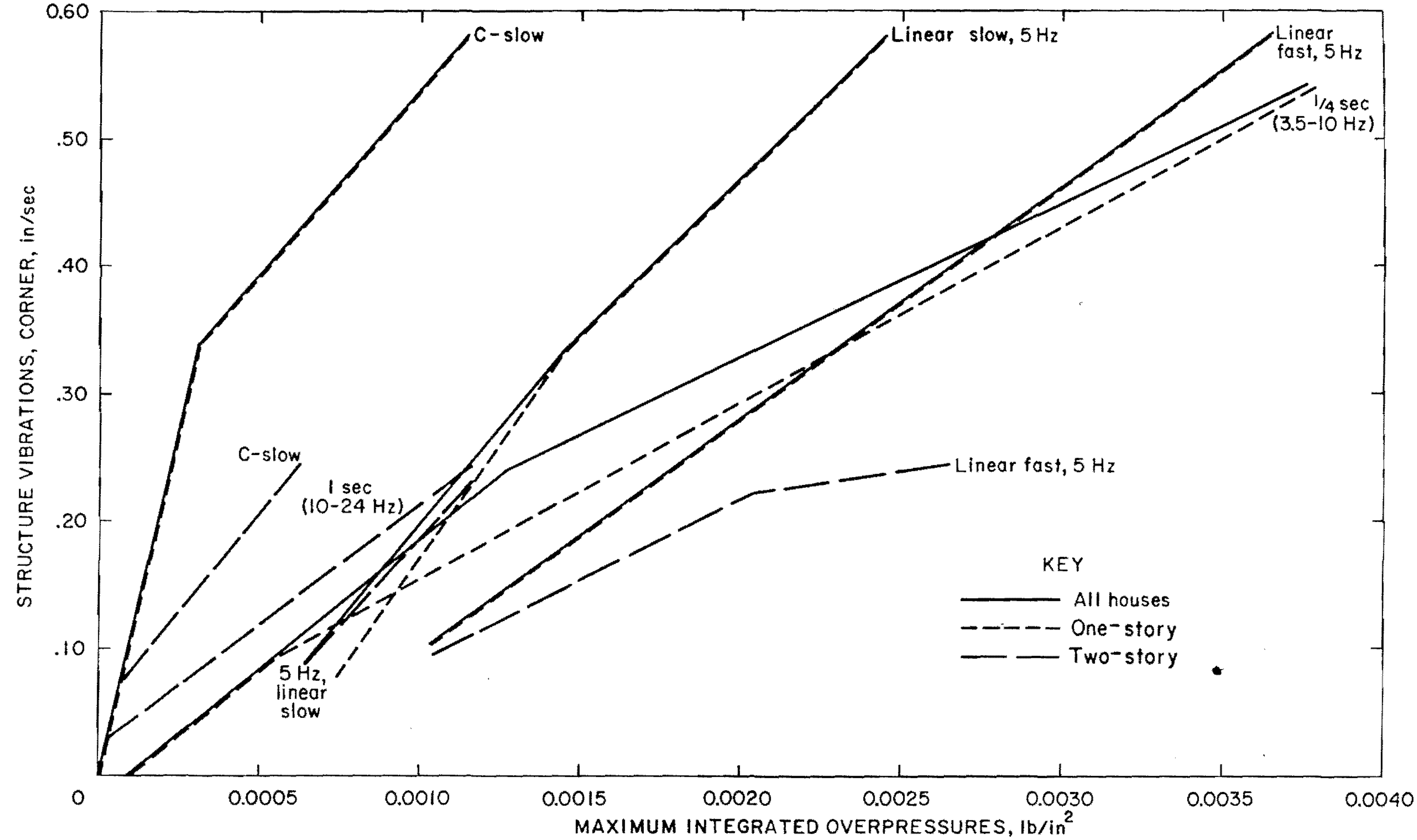

FIGURE 35. - Structure responses from maximum integrated overpressures, envelopes of maximum values.

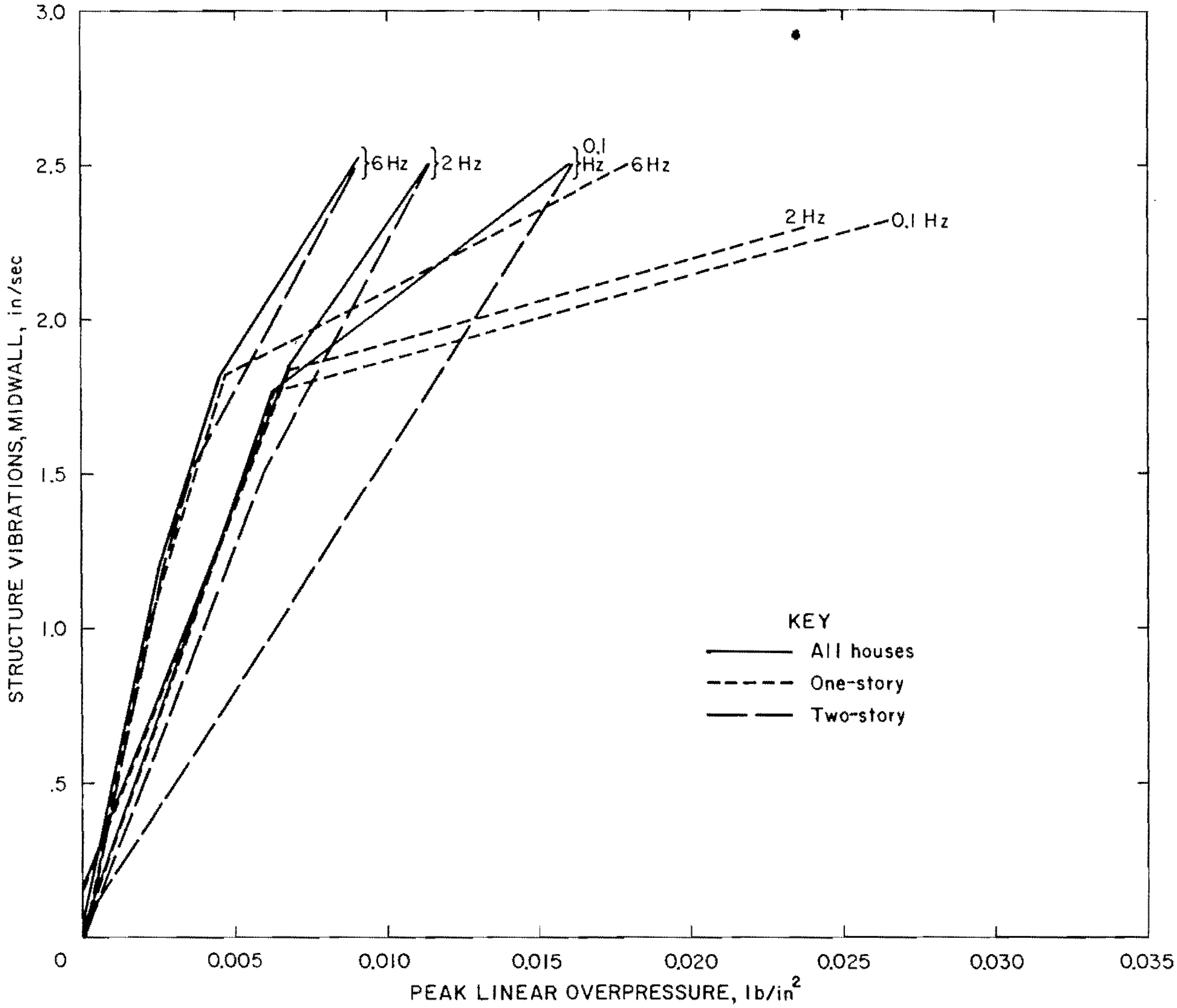

FIGURE 36. - Midwall responses from peak overpressures, envelopes of maximum values.

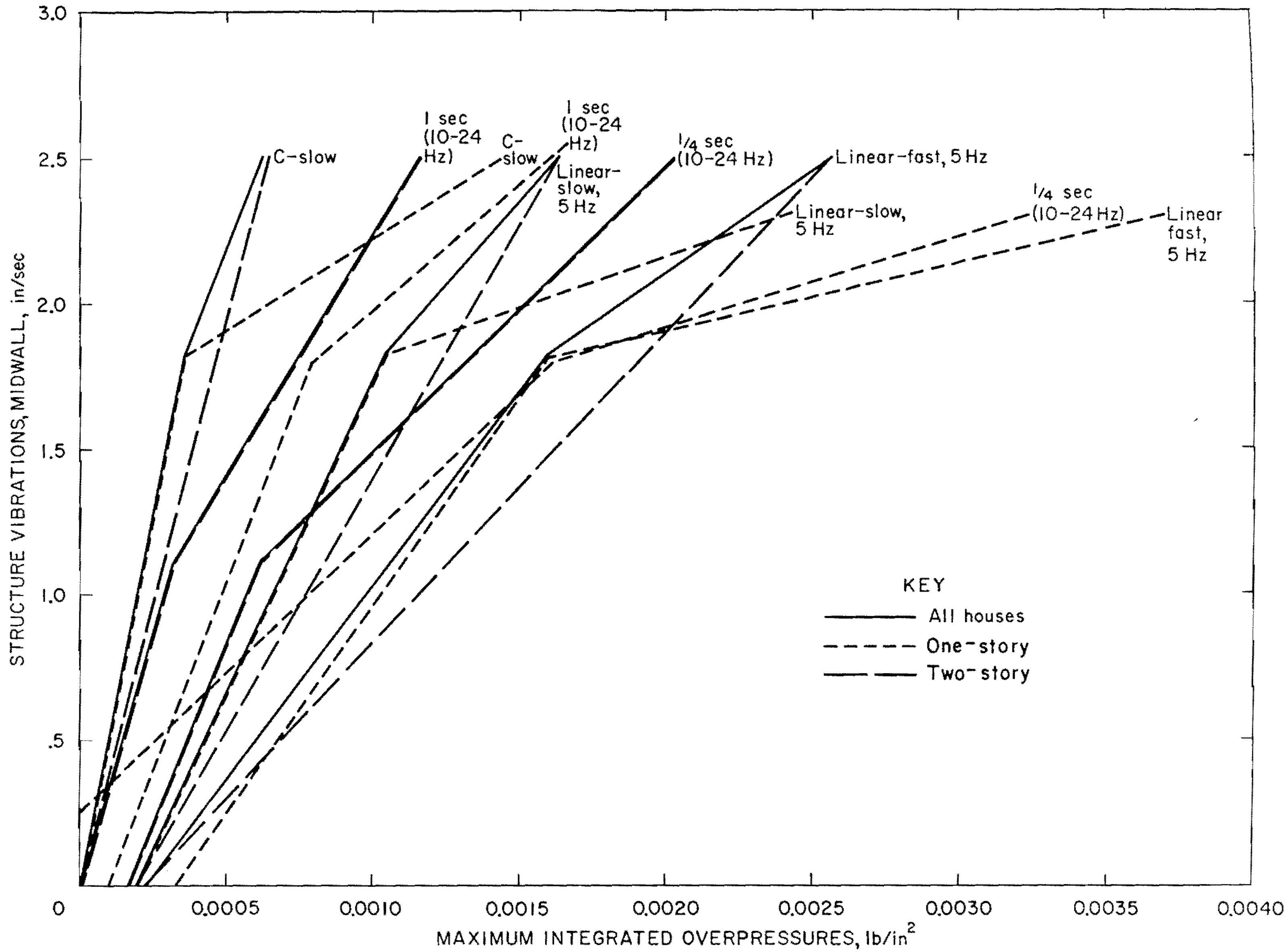

FIGURE 37. - Midwall responses from maximum integrated overpressures, envelopes of maximum values.

of one-story, two-story, and all homes, and the best of the 27 sound descriptors studied. (The airblast values used in the response plots are given in table 3.) A total of 222 correlations were made between measured responses and the various airblast descriptors. Those with the highest correlation coefficients and lowest standard errors (standard deviations) were plotted in figures 30 through 33; the equations and statistics for the plots are in tables 4 (corner or structural) and 5 (midwall). The remaining correlations are given in appendix tables E-1 (peak structural responses), E-2 (integrated structural responses), E-3 (peak midwall responses), and E-4 (integrated midwall responses). No standard error bars are shown on the response curves to avoid confusion; however, the values are given in tables 4-5, and E-1 through E-4. Comparisons were required between the various descriptors, some of which involved operations on the dependent variable. Therefore, a normalized standard error was calculated by dividing the standard error by the mean of the dependent variable. Comparisons between the descriptors of peak structure motions (tables 4-5, E-1 and E-3) and the integrated structure motions (tables E-2 and E-4), and also between the various integrated methods, require examination of the normalized standard errors. However, the statistics for peak structure motions can be compared using either the normalized or conventional standard error values.

TABLE 4. - Equations and statistics for peak corner structure vibration (SV) responses from airblasts - best results

		Equation[1]	Correlation coefficient	Standard error	Normalized standard error	Regression line
		ALL HOMES				
Peak SV (corner) versus	Peak AB (0.1 Hz)....	SV=-0.0274 + 18.8 AB	0.824	0.0760	0.458	1
	Peak AB (2 Hz)......	SV=- .0044 + 20.9 AB	.795	.0820	.482	4
	Peak AB (6 Hz)......	SV= .0073 + 26.6 AB	.676	.100	.586	7
	Maximum C-slow AB...	SV= .0584 +213 AB	.537	.114	.671	10
	Maximum linear-slow AB (5 Hz).	SV= .0166 +107 AB	.535	.112	.699	12
	Maximum linear-fast AB (5 Hz).	SV= .0271 + 62.9 AB	.502	.115	.612	14
	Maximum 1/4-sec integrated AB (3.5-10 Hz).	SV=- .0247 + 98.4 AB	.750	.0838	.513	34
	Maximum 1-sec integrated AB (3.5-10 Hz).	SV= .0353 +118 AB	.502	.110	.680	--
		ONE-STORY HOMES				
Peak SV (corner) versus	Peak AB (0.1 Hz)....	SV=-0.0265 + 19.9 AB	0.821	0.100	0.491	2
	Peak AB (2 Hz)......	SV=- .0058 + 21.2 AB	.784	.109	.535	5
	Peak AB (6 Hz)......	SV=- .00040+ 27.6 AB	.642	.135	.660	8
	Maximum C-slow AB...	SV= .0769 +188 AB	.433	.158	.774	--
	Maximum linear-slow AB (5 Hz).	SV= .0553 + 98.4 AB	.454	.157	.817	--
	Maximum linear-fast AB (5 Hz).	SV= .0550 + 54.8 AB	.405	.161	.838	--
	Maximum 1/4-sec integrated AB (3.5-10 Hz).	SV=- .0519 +109.5 AB	.785	.0989	.518	35
	Maximum 1-sec integrated AB (3.5-10 Hz).	SV= .0269 +129 AB	.515	.137	.720	--
		TWO-STORY HOMES				
Peak SV (corner) versus	Peak AB (0.1 Hz)....	SV= 0.0062 + 13.4 AB	0.855	0.0360	0.267	3
	Peak AB (5 Hz)......	SV= .0121 + 18.1 AB	.771	.0450	.332	6
	Peak AB (6 Hz)......	SV= .0274 + 22.3 AB	.736	.0480	.353	9
	Maximum C-slow AB...	SV= .0215 +304 AB	.917	.0280	.209	11
	Maximum linear-slow AB (5 Hz).	SV= .0135 +131 AB	.693	.0460	.371	13
	Maximum linear-fast AB (5 Hz).	SV=- .0127 + 81.8 AB	.738	.0430	.348	15
	Maximum 1/4-sec integrated AB (10-24 Hz).	SV= .0133 +103 AB	.843	.0360	.277	36
	Maximum 1-sec integrated AB (10-24 Hz).	SV= .00490+196 AB	.956	.0202	.152	37

[1]SV = Structure vibration , in/sec.
[2]AB = Airblast overpressure, lb/in.

TABLE 5. - Equations and statistics for peak midwall structure vibration (SV) responses from airblasts - best results

	Equation	Correlation coefficient	Standard error	Normalized standard error	Regression line
ALL HOMES					
Peak SV (midwall) versus Peak AB (0.1 Hz)....	SV= 0.0662+ 83.0 AB	0.669	0.439	0.538	16
Peak AB (2 Hz)......	SV= .193 + 97.8 AB	.700	.422	.509	19
Peak AB (6 Hz)......	SV= .177 + 139 AB	.713	.415	.500	22
Maximum C-slow AB...	SV= .368 + 987 AB	.618	.465	.560	25
Maximum linear-slow AB (5 Hz).	SV= .180 + 540 AB	.613	.465	.579	28
Maximum linear-fast AB (5 Hz).	SV= .234 + 309 AB	.569	.473	.589	31
Maximum 1/4-sec integrated AB (10-24 Hz).	SV= .186 + 501 AB	.728	.392	.490	38
Maximum 1-sec integrated AB (10-24 Hz).	SV= .224 + 802 AB	.686	.416	.519	41
ONE-STORY HOMES					
Peak SV (midwall) versus Peak AB (0.1 Hz)....	SV= 0.342 + 61.3 AB	0.623	0.481	0.510	17
Peak AB (2 Hz)......	SV= .327 + 78.3 AB	.733	.418	.433	20
Peak AB (6 Hz)......	SV= .262 + 115 AB	.722	.425	.451	23
Maximum C-slow AB...	SV= .650 +1090 AB	.660	.462	.489	26
Maximum linear-slow AB (5 Hz).	SV= .270 + 503 AB	.626	.476	.512	29
Maximum linear-fast AB (5 Hz).	SV= .298 + 308 AB	.619	.479	.515	32
Maximum 1/4-sec integrated AB (10-24 Hz).	SV= .187 + 455 AB	.757	.384	.424	39
Maximum 1-sec integrated AB (10-24 Hz).	SV= .237 + 743 AB	.716	.412	.453	42
TWO-STORY HOMES					
Peak SV (midwall) versus Peak AB (0.1 Hz)....	SV=-0.381 + 129 AB	0.779	0.369	0.497	18
Peak AB (2 Hz)......	SV=- .256 + 181 AB	.764	.384	.517	21
Peak AB (6 Hz)......	SV=- .139 + 234 AB	.782	.370	.500	24
Maximum C-slow AB...	SV= .384 + 889 AB	.570	.489	.660	27
Maximum linear-slow AB (5 Hz).	SV= .129 + 560 AB	.581	.467	.647	30
Maximum linear-fast AB (5 Hz).	SV= .211 + 597 AB	.557	.476	.660	33
Maximum 1/4-sec integrated AB (10-24 Hz).	SV= .0617+ 693 AB	.738	.388	.528	40
Maximum 1-sec integrated AB (10-24 Hz).	SV= .168 + 1037 AB	.675	.424	.577	43

Both peak and integrated structure motions were compared to the various airblast descriptors, also expressed as peak and various integrations. The integrated values are variously filtered "velocity exposure levels" (VEL) analogous to sound exposure levels (SEL) for sound. They are an indication of energy represented by the structure vibration, as opposed to the simple quantities of peak velocity, acceleration, and displacement. A prior assumption was not made that peak particle velocity would most appropriately indicate damage and annoyance potential. Consequently, it was considered appropriate to analyze VEL of the structures. However, the computed VEL levels did not correlate well with the SEL or various peak linear overpressures. Additionally, all studies of structure damage and response had quantified the structure responses in terms of peak motions and/or strains. No VEL damage data exists. The VEL response equations and statistics are presented in tables E-2 for structures, and E-4 for midwalls, but do not presently appear useful.

Measured Corner Responses

The corner responses from linear-peak airblasts are shown in figure 30. The 0.1-Hz (high-pass, or low-frequency -3-dB point) peak-linear measurement required a pressure transduce or a sonic boom system (such as the B&K 2631). The 2-Hz values were obtained with a standard type 1 commercial sound level meter (B&K 2209) set to peak-linear-hold, and the 6-Hz measurements were obtained with standard sound level meters (such as B&K 2209 and GenRad 1933) or other systems as described by Stachura (61). A complete analysis was also made of the 5-Hz peak-linear measurement, but it was essentially identical to the 6-Hz; therefore, the responses given for 6 Hz are assumed to apply to 5 Hz as well.

Responses from integrated methods of sound measurement (sound exposure levels) are shown in figure 31. The linear-slow, linear-fast, and C-weighted-slow were measured with type 1 meters, and the 1-second integrations approximated by the "slow" setting.

Special filter ranges were studied, in the hope of finding an ideal sound descriptor for structure response. Three frequency ranges were examined--4 to 40 Hz for overall response, 3.5 to 10 Hz for corner response, and 10 to 24 Hz for midwall response. Because of phase distortion, the filtered peak values did not appear meaningful; therefore, sound exposure values were measured from the airblast recordings, using the three filter ranges plus C-weighted, with integration times of 1/8, 1/4, 1, 2, and 4 seconds. Stachura (61) describes the system used for this analysis. Standard sound level meters can measure SEL values for C-weighting and also with external filters for special frequency ranges. The slow and fast responses approximate 1-second and 1/8-second integrations, respectively. Other integration times cannot be measured without a complex processing system or a modified sound level meter (61).

The statistics for the various sound measurement methods for the different sets of structures are in table 4. Depending on the criterion of superiority, different descriptors appear better. In addition to the maximum correlation coefficient and the minimum standard error, a better prediction is suggested by a small intercept in the equation, since theory predicts that this term

TABLE 6. - Ranking of best airblast descriptors for structure response

Homes	Ranking	Correlation coefficient		Standard error		Zero intercept	
PEAK STRUCTURE VIBRATION (CORNERS)							
All......	1..........	Peak, 0.1 Hz.........	0.824	Peak, 0.1 Hz........	0.076	Peak, 2 Hz...........	0.0044
	2..........	Peak, 2 Hz...........	.795	Peak, 2 Hz..........	.082	Peak, 6 Hz...........	.0073
	3..........	1/4-sec, 3.5-10 Hz...	.750	1/4-sec, 3.5-10 Hz..	.084	Linear-slow, 5 Hz....	.0166
	4..........	Peak, 6 Hz...........	.676	Peak, 6 Hz..........	.100	1/4-sec, 3.5-10 Hz...	.0246
1-Story..	1..........	Peak, 0.1 Hz.........	.821	1/4-sec, 3.5-10 Hz..	.099	Peak, 6 Hz...........	.00040
	2..........	1/4-sec, 3.5-10 Hz...	.785	Peak, 0.1 Hz........	.100	Peak, 2 Hz...........	.0058
	3..........	Peak, 2 Hz...........	.784	Peak, 2 Hz..........	.109	Peak, 0.1 Hz.........	.0265
	4..........	Peak, 6 Hz...........	.642	Peak, 6 Hz..........	.135	1-sec, 3.5-10 Hz.....	.0269
2-Story..	1..........	1-sec, 10-24 Hz......	.956	1-sec, 10-24 Hz.....	.0202	1-sec, 10-24 Hz......	.0049
	2..........	C-Slow...............	.917	C-Slow..............	.028	Peak, 0.1 Hz.........	.0062
	3..........	Peak, 0.1 Hz.........	.855	Peak, 0.1 Hz........	.036	Peak, 2 Hz...........	.0121
	4..........	1/4-sec, 10-24 Hz....	.843	1/4-sec, 10-24 Hz...	.036	Linear-fast, 5 Hz....	.0127
PEAK MIDWALL VIBRATIONS							
All......	1..........	1/4-sec, 10-24 Hz....	0.728	1/4-sec, 10-24 Hz...	0.392	Peak, 0.1 Hz.........	0.0662
	2..........	Peak, 6 Hz...........	.713	Peak, 6 Hz..........	.415	Peak, 6 Hz...........	.177
	3..........	Peak, 2 Hz...........	.700	1-sec, 10-24 Hz.....	.416	Linear-slow, 5 Hz....	.180
	4..........	1-sec, 10-24 Hz......	.686	Peak, 2 Hz..........	.422	1/4-sec, 10-24 Hz....	.186
1-Story..	1..........	1/4-sec, 10-24 Hz....	.757	1/4-sec, 10-24 Hz...	.384	1/4-sec, 10-24 Hz....	.187
	2..........	Peak, 2 Hz...........	.733	1-sec, 10-24 Hz.....	.412	1-sec, 10-24 Hz......	.237
	3..........	Peak, 6 Hz...........	.722	Peak, 2 Hz..........	.418	Peak, 6 Hz...........	.262
	4..........	1-sec, 10-24 Hz......	.716	Peak, 6 Hz..........	.425	Linear-slow, 5 Hz....	.270
2-Story..	1..........	Peak, 6 Hz...........	.782	Peak, 0.1 Hz........	.369	1/4-sec, 10-24 Hz....	.062
	2..........	Peak, 0.1 Hz.........	.779	Peak, 6 Hz..........	.370	Linear-slow, 5 Hz....	.129
	3..........	Peak, 2 Hz...........	.764	Peak, 2 Hz..........	.384	Peak, 6 Hz...........	.139
	4..........	1/4-sec, 10-24 Hz....	.738	1/4-sec, 10-24 Hz...	.388	Linear-fast, 5 Hz....	.211

Measured Midwall Responses

Figures 32 and 33 show midwall responses from various peak and integrated airblasts, respectively, analogous to the corner responses of figures 30 and 31. Statistics and equations are given in table 5 and , like those for the corner responses, indicate that neither unanimity nor major differences exist among the methods. The methods are ranked in table 6. As expected, the 10 to 24 Hz SEL correlated well with midwall motions; however, the 2 Hz and 6 Hz peak methods were consistently good. For the two-story homes, 0.1 Hz peaks was also excellent. Because of scatter in all the measurements, small differences among values of the correlation coefficients and standard errors have no meaning, so the ranking of one method over the next is not always significant.

The low-frequency response systems (0.1 and 2 Hz) are generally best for assessing likely corner responses, and the higher one (6 Hz) and SEL values (integrated sound levels) correlate better with midwall responses. This suggests that the damage potential of airblasts should be measured with the low-frequency sound systems, which have a flat response down to at least 2 Hz. The annoyance potential is strongly influenced by midwall responses and should be measured with special integrated sound levels or with systems having a flat response down to 6 Hz. The statistical differences between many of the descriptors are small (table 6), which would allow the use of one or more of several linear and integrated measurement methods for airblasts. The most practical existing measurement methods are linear-peak with 2- and 6-Hz (or 5-Hz) low-frequency response and C-slow (type 1 precision impulse).

Envelopes of Maximum Airblast Responses

The most severe cases of residential-type structure response are shown in figures 34 through 37 as the envelopes of maximum response values. Predictions could also be made by taking some number of standard deviations from the response plots (figs. 30-33), although the scatter (indicated by the correlation coefficients) introduces much uncertainty about some of the descriptors.

Comparison of Responses From All Sources

The racking and midwall responses from airblasts and other impulsive noise sources are summarized in tables 7 and 8. All responses, including those in the previous investigations (Appendix F), have been converted to vibration levels in the structures per pound per square inch (lb/in^2) overpressure. It is not possible to assess the reliability of many of the responses since some are based on very few individual measurements, and all involve various instrumentation and measurement techniques. Some descriptors were calculated on the assumption of simple harmonic motion (usually good for midwall motions and fair for racking motions) and measured frequencies, where available. Where frequencies were not given by the authors, the racking and midwall frequencies were assumed to 8 and 16 Hz, respectively. Sonic boom and large blast studies typically use wide-band instrumentation; therefore, the Bureau of Mines response data in tables 7 and 8 are from the 0.1 Hz low-frequency cut-off plots of figures 30 and 32.

TABLE 7. - Racking response of structures from various impulsive noise sources

Author	Displacement, in/psi	Velocity, in/sec/psi	Strain, μin/in/psi	Source of noise
				Production blasts:
This research......		17.8		All homes.
Do...............		18.8		1-story homes.
Do...............		13.8		2-story homes.
				Sonic booms:
Kryter (19)........	0.461	[1]23.0		B-58.
Wiggins (80).......	.050-0.096	[1]2.59- 4.90	488-1,125	B-58 and F-104.
Newberry (33)......	.107	[1]5.38		FD-2, roof response.
Clarkson (7).......	<.486	[1]<24.4		Shear response at 2d floor.
Blume (3)..........	.245- .326	[1]12.3 -16.4		B-58 and F-104, roofline.

[1] Calculated.

TABLE 8. - Midwall response from various impulsive noise sources

Author	Displacement, in/psi	Acceleration, g/psi	Velocity, in/sec/psi	Stress, lb/in²/psi	Strain μin/in/psi	Source of noise
This research.	[1]0.852	[1]22.3	85.6			Production blasts: All homes.
Do..........	[1].744	[1]19.4	74.8			1-story homes.
Do..........	[1]1.04	[1]27.3	105			2-story homes.
Kamperman (18)	[1].165		16.6			Floor motion.
Kryter (19)...	1.01		[1]101			Sonic booms: B-58 Ceiling.
Do..........	1.53		[1]154			B-58, midwall.
Wiggins (80)..	.302-0.634		[1]30.2-63.4			B-58 and F-104 midwall.
Do..........	5.7-18.7		[1]197-646		864-3,312	8x10-ft window.
Newberry (33).	1.15		[1]116			FD-2, walls.
Leigh (22)....	2.13	40.2	[1]124-223			XB-70, walls.
Do..........					446-677	Gypsum panels.
Mayes (25)....				4,752-7,200		Sonic boom.
Do..........				2,016-2,347		Single charge blast.
Clarkson (7)..	<1.04	7.2-28.8	<[1]104			Sonic booms: XB-70, B-58, F-104. Exterior walls.
Do..........	<.45		<[1]45			Interior walls.
Do..........	<.875		<[1]87.5			Window, 5 x 10 ft x 0.25 in.
Blume (3).....	.87	41.0	[1]117			B-58 and F-104 walls.
Do..........					4,320	Window.

[1] Calculated.

The racking responses (table 7) produced by sonic booms and blasting appear comparable on the basis of the Kryter (19), Blume (3), and Clarkson (7) studies. The Wiggins (80) and Newberry (33) values are comparable to each other and to about one-third of the others. (Newberry measured roof response, as opposed to corners or walls.)

Midwall responses also show reasonably good agreement between production blasts and sonic booms, despite the widely varying frequency character in sources, geometric factors of orientation, wall surface area, etc.

Kamperman's (18) floor response is about one-fifth of the vertical wall response, as expected. The Wiggins (80) midwall response is somewhat low, but within the scatter of the blast responses. Window responses are either much greater according to Wiggins (80), or comparable as found by Clarkson and Mayes (7). In summary, the sonic boom produced responses (peak particle velocities) range from the same as production blasting to about three times higher; the average was greater by a factor of 1.8.

STRUCTURE RESPONSE FROM GROUND VIBRATION

Structure and midwall responses from production mine blasting (figs. 38-39) can be compared with analysis of the airblast responses. In all cases,

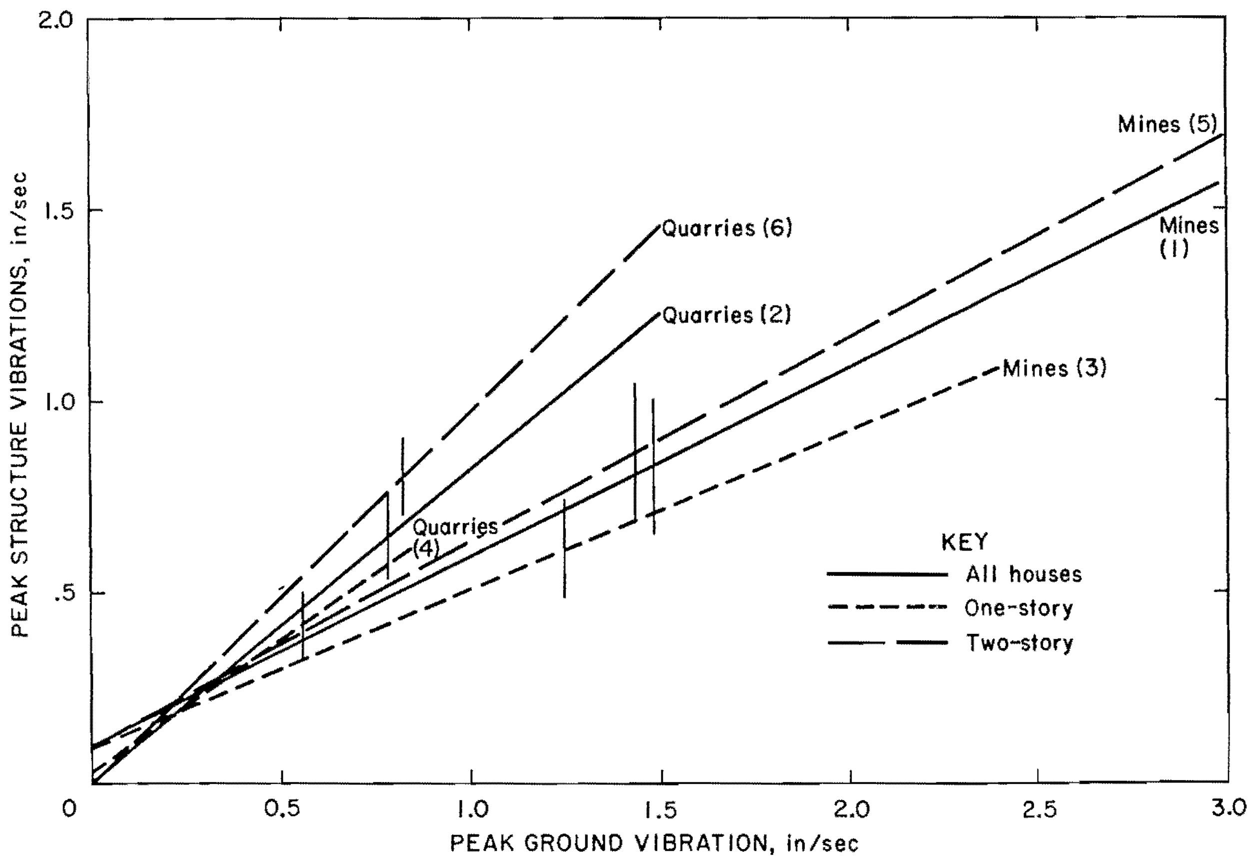

FIGURE 38. - Structure responses (horizontal corner motions) from peak ground vibrations.

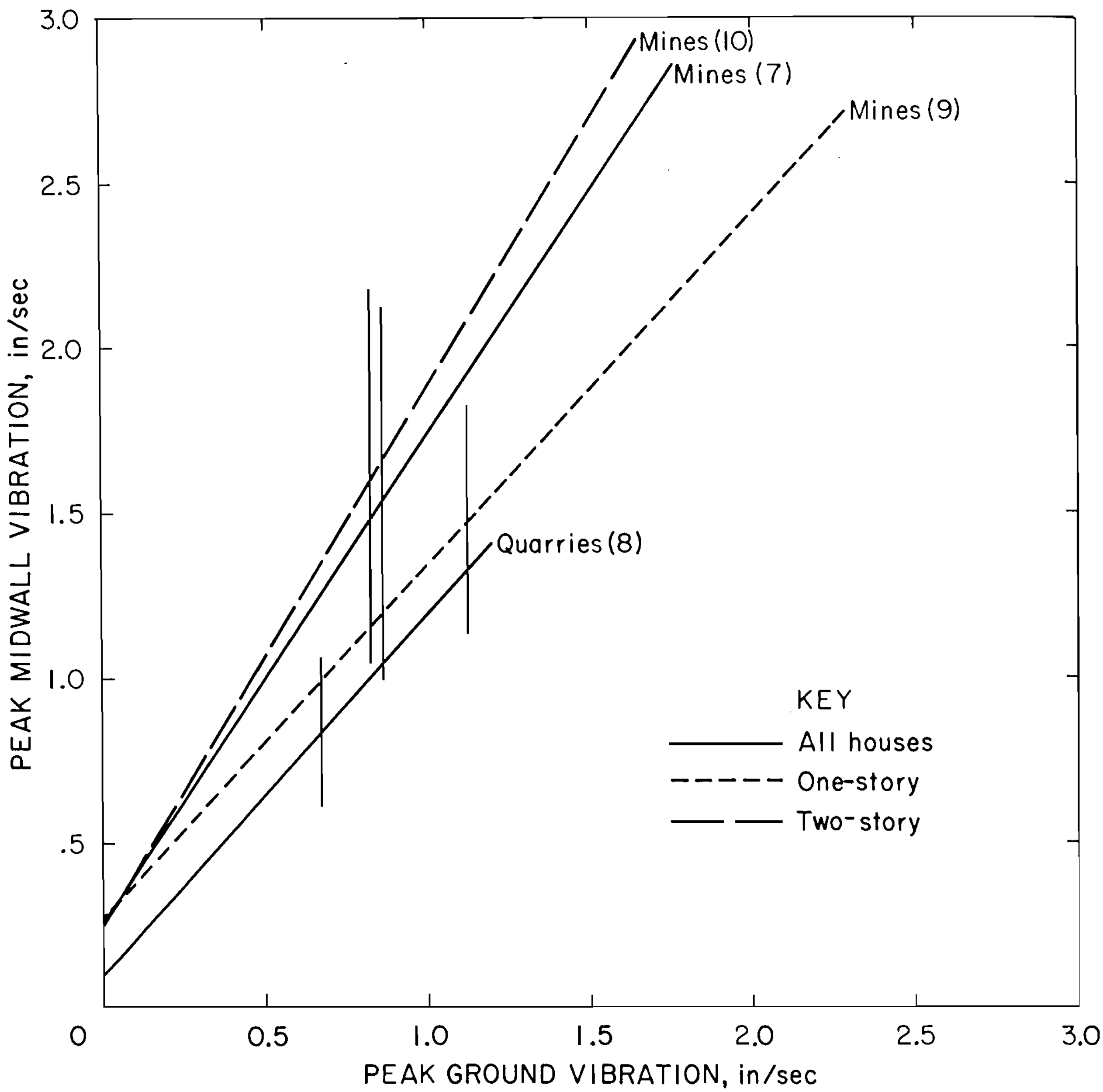

FIGURE 39. - Midwall responses from peak ground vibrations. (Numbers in parentheses correspond to regression lines in table 5.)

the largest corner and midwall responses from any given blast were plotted against the largest of three ground vibration components, to give the worst cases. The horizontal components did not necessarily correspond to the true radial (or longitudinal) and transverse, the velocity gages were oriented parallel to the structure walls.

Most interesting is that the racking response (corner or structure vibration) as shown in figure 38 is significantly lower than the input ground vibration velocity, when measured either on the first or second floor. The difference between the data from quarries and surface coal and metal mines was significant. For both kinds of mine blasts, responses were greater for two-story than one-story structures, probably resulting from significant low-frequency energy in the ground vibrations. Midheight corner measurements could not be used to evaluate the structural motions because of contamination by the higher amplitude midwall vibrations.

The midwall responses from the blast vibrations have an amplification effect as indicated by the slopes exceeding 45° (figure 32). They also show more scatter than the corner motion plot. In contrast to the corner vibrations, both types of mines produced greater structure vibration levels than the quarries. Summarized in table 9 are the equations and statistics for ground vibration-structure response plots in figures 38 and 39.

TABLE 9. - Equations and statistics for peak structure vibration (SV) responses from ground vibration

Sites	Homes	Equation	Correlation coefficient	Standard error	Normalized standard error	Regression line
PEAK STRUCTURE VIBRATION (CORNER) VERSUS PEAK GROUND VIBRATION						
Mines.....	All homes.	SV=0.101 + 0.491 GV	0.887	0.177	0.394	1
Quarries..	..do......	SV= .011 + .838 GV	.934	.112	.378	2
All sites.	..do......	SV= .101 + .497 GV	.886	.175	.405	
Mines.....	1-story...	SV= .097 + .410 GV	.925	.123	.300	3
Quarries..	..do......	SV= .035 + .686 GV	.956	.088	.324	4
All sites.	..do......	SV= .101 + .415 GV	.920	.125	.310	
Mines.....	1-1/2- and 2-story.	SV= .100 + .532 GV	.893	.183	.396	5
Quarries..	..do......	SV= .008 + .965 GV	.950	.106	.383	6
All sites.	..do......	SV= .098 + .539 GV	.892	.182	.407	
PEAK STRUCTURE VIBRATION (MIDWALL) VERSUS PEAK GROUND VIBRATION						
Mines.....	All homes.	SV=0.261 + 1.47 GV	0.863	0.574	0.427	7
Quarries..	..do......	SV= .097 + 1.09 GV	.832	.229	.453	8
All sites.	..do......	SV= .202 + 1.50 GV	.866	.550	.449	
Mines.....	1-story...	SV= .267 + 1.07 GV	.910	.345	.324	9
Quarries..	..do......	SV= .112 + 1.17 GV	.861	.245	.422	
All sites.	..do......	SV= .222 + 1.10 GV	.910	.324	.340	
Mines.....	1-1/2- and 2 story.	SV= .246 + 1.62 GV	.881	.570	.401	10
Quarries..	..do......	SV= .107 + .937 GV	.787	.208	.505	
All sites.	..do......	SV= .193 + 1.64 GV	.882	.559	.423	

A complete analysis of the Bureau's ground vibration response and damage study is available in a separate report (56).

It is necessary to note that all the responses discussed in this paper are applicable to residential-type structures with frame superstructures. The airblast or ground vibration response values may not apply to multi-story steel frame structures or large structures with masonry load-supporting walls. The natural frequencies of vibration of a large-span structure such as warehouse would be considerably lower than the 4 to 24-Hz range for residences and their midwalls. The larger structures will not only be more responsive to the low frequency airblast, but the responses will not correlate with the various sound discriptors in the same way as do the small residential structures.

TOLERABLE LEVELS OF AIRBLAST

Several research areas have developed data that apply to the problem of safe and tolerable levels of impulsive noise. These studies have used a variety of sound descriptors that are not readily comparable, and results have been based on different criteria of acceptability. Much work has been done on glass breakage, because glass is the element in a typical home most sensitive to airblast damage. Human and structural tolerance to sonic booms was extensively studied in the event of increased supersonic air traffic. The Army has long been interested in tolerable exposure to short-term impulse noise as from artillary firing. Environmental agencies, concerned with protecting the quality of life and property, are also aware of economic and social costs in the regulation of such adverse environmental effects as blast noise. The considerable work done on structural vibration and damage from ground vibration applies to the airblast problem, as the findings can be related through structure responses.

Comparisons Between Airblast and Ground Vibration Responses

Ground Vibration Damage

The Bureau has recently completed an extensive study of the response and damage from blast-produced ground vibrations (56). Ten data sets were analyzed, including three described in earlier damage analyses done by the Bureau (9, 34), an additional Canadian study (35), Dvorak's analysis of brick structures (10), and new residential damage data from surface coal mines obtained by the Bureau of Mines (56). The previously recommended 2-in/sec safe blasting criterion still appears applicable to those blasting situations which produce only high-frequency ground vibrations at the receiving structures >40 Hz. Such situations include small-scale blasting (excavation and construction) and homes sitting directly on rock at small distances (< 300 ft). A 5-pct minor damage probability level for these high-frequency blasts as measured by both Langefors (21) and recent Bureau work is approximately 2 to 3 in/sec, and no damage has been observed below 2 in/sec (56).

Significant problems exist for blasting where the ground vibration frequencies are close to the structure response frequencies (4 to 25 Hz). This is well demonstrated by the differences in the scatter for the two types of damage data analyzed in the earlier Bureau of Mines summaries (fig. 3.7 of reference 34). Both the minor and major damage threshold have a small amount of scatter for the high-frequency vibrations, indicating that the use of particle velocity in this frequency range is a good damage descriptor. In a response-spectrum analysis, this is the velocity-bound range of particle velocity frequencies. However, at lower frequencies (2.5 to 40 Hz), the particle velocity alone results in significant scatter (large standard deviations), and the statistically determined probability of damage at 2 in/sec for such data alone can exceed 10 pct. This problem results from both the structural resonances and large particle displacements occurring at these low frequencies. The British have noted the need for a displacement-bound criterion at low frequencies, and use 0.008 and 0.016 inches peak displacement as caution and maximum levels, respectively, for safe blasting (56). Assuming simple harmonic motions, these convert to 0.5 in/sec and 1.0 in/sec peak particle velocities at 10 Hz.

Direct measurement of blast damage and reanalysis of the nine previous studies have demonstrated that a stricter safe vibration level is required for low-frequency situations. In addition, the concept of a threshold for the most superficial types of damage needs to be reintroduced in the light of the latest data. Nonstructural cracks on interior walls are the most sensitive indicators of blast damage, and have a threshold level (with a 95-pct confidence of nondamage) of 0.75 in/sec. Inclusion of the Bureau's shaker tests (66) and the Dvorak blast data (10) lowers this to approximately 0.5 in/sec, although the shaker tests are somewhat suspect since they produce only localized vibrations and last longer than blasts. This lower criterion is applicable to sensitive residential structures (plaster interior walls), superficial damage (hairline plaster cracks), and low-frequency ground vibrations (structure on soft ground or thick overburden, and/or at long distances). Wallboard (gypsum Drywall) is more damage resistant than plaster by a factor of approximately two, and as previously discussed the high-frequency damage threshold is considerably higher (2 to 3 in/sec).

Data was collected from many shots for some structures; in one example, there were 12 nondamaging blasts exceeding 1 to 2 in/sec. However, this study did not fully address the long-term fatigue problem or the characteristics of masonry response. Consequently, the conservative 0.5-in/sec criterion is justified for long-term blasting under the conditions described. Modern construction (Drywall) should be afforded the same degree of protection at peak particle velocity of approximately 1.0 in/sec. Further work on long-term blasting and fatigue is continuing.

Airblast Criterian From Response Analysis of Structures

Airblast criteria have been developed from these ground vibration criteria and from comparisons between the airblast responses (figs. 30-33) and ground vibration responses (figs. 38-39), with equivalent damage risks. One method involves comparing the mean values of the airblast and ground vibration plots. Airblast levels equivalent to the 0.5-in/sec peak particle velocity in terms of whole-structure response are 135 dB (0.1 Hz), 134 dB (2 Hz), 132 dB (6 Hz), and 112 dB C-slow (table 10).

TABLE 10. - Airblast sound levels for control of structure response based on ground vibration response and damage levels

Type of blasting	Structures	Equivalent vibration, in/sec	Sound levels, lb/in² (dB) 0.1 Hz	2 Hz	6 Hz	C-slow	Assumptions
Mine......	All.....	0.50	0.0195 (137)	0.0171 (135)	0.0126 (133)	0.00133 (113)	Utilized mean values of both airblast response and ground vibration response.
	1-story.		.0164 (135)	.0144 (134)	.0109 (132)		
	2-story.		.0272 (139)	.0198 (137)	.0154 (135)	.00115 (112)	
Quarry....	All.....		.0237 (138)	.0210 (137)	.0156 (135)	.0017 (115)	
	1-story.		.0206 (137)	.0183 (136)	.0138 (134)		
	2-story.		>.018 (>136)	.026 (139)	.024 (138)	.0012 (112)	
Mine......	All.....		.0093 (130)	.0073 (128)	.0045 (124)	.00037 (102)	Based on 5-percent probability of strong response to airblast and weak response to ground vibration. This is the least favorable airblast case. All other predictions give higher airblast levels.
	1-story.		.0080 (129)	.0063 (127)	.0039 (123)		
	2-story.		.0153 (135)	.0107 (131)	.0080 (129)	.00065 (107)	
Quarry....	All.....		.0161 (135)	.0136 (133)	.0094 (130)	.00088 (110)	
	1-story.		.0131 (133)	.0110 (132)	.0076 (128)		
	2-story.		>.017 (>135)	.0207 (137)	>.012 (>132)	.00130 (113)	
Mine......	All.....	1.0	.0225 (138)	.0193 (137)	.0139 (134)	.00144 (114)	
	1-story.		.0186 (136)	.0160 (135)	.0116 (132)		
	2-story.		>.017 (>135)	>.020 (137)	>.012 (>132)	>.0015 (>114)	
Quarry....	All.....		>.025 (>139)	>.020 (137)	>.015 (>134)	>.0015 (>114)	
	1-story.		>.025 (>139)	>.020 (137)	>.015 (>134)	>.0015 (>114)	
	2-story.		>.017 (>135)	>.020 (137)	>.015 (>134)	>.0015 (>114)	
Mine......	All.....	0.75	.0193 (136)	.0166 (135)	.0109 (132)	.00077 (109)	Based on maximum airblast values (envelope of measured data) and mean ground vibration responses.
	1-story.		.0151 (134)	.0127 (133)	.0082 (129)	.00053 (105)	
	2-story.		>.020 (>137)	>.020 (>137)	>.020 (>137)	>.0007 (>108)	
Quarry....	All.....		~.029 (140)	~.029 (140)	~.029 (140)	>.0012 (>112)	
	1-story.		.0241 (138)	.0211 (137)	.014 (134)	.00105 (111)	
	2-story.		>.020 (>137)	>.020 (>137)	>.020 (>137)	>.0007 (>108)	

A more statistically rigorous analysis can be made by taking 0.76 standard deviation for each of the two responses using the most unfavorable case (with a probability of occurrence of only 5.0 pct), and projecting the resulting airblast levels. Statistically, this is equivalent to the simultaneous occurrence of a strong airblast response and a small ground vibration response. This resulting 5-pct occurrence probability could be combined with the 5-pct damage probability level (0.50 in/sec for blasting) for a very conservative set of airblast criteria with an overall probability of 0.25 pct. The resulting average airblast levels for mines (all mines) are 130 dB (0.1 Hz), 128 dB (2 Hz), 124 dB (6 Hz), and 102 dB C-slow for all structures. The same analysis, using the more appropriate ground vibration criterion of 1.0 in/sec for modern construction, gives mining airblast levels of 138 dB (0.1 Hz), 137 dB (2 Hz), 134 dB (6 Hz), and 114 dB C-slow (table 10). Again, it is necessary to note that these represent the levels with a small chance of the most superficial type of damage, and also correspond to the assumption of a ground vibration response in the most risky situations of low-frequency vibrations and structural foundations on soft ground.

A third method of determining safe airblast levels is to not assume any distribution of airblast responses, but use the envelopes of maximum values (figs. 34-35) and the mean values of the ground vibration responses. This strategy yields airblast levels of 134 dB (0.1 Hz), 133 dB (2 Hz), 129 dB (6 Hz), and 105 dB C-slow for the worst response case (one-story structures) and corresponds to a ground vibration of 0.75 in/sec (table 10). The same analysis, when used to obtain equivalence to 1.0 in/sec, gives airblast levels which are 3 dB higher for each measurement method.

It is necessary to note that the analysis performed for the levels in table 10 does not apply to individual shots. For each type of response, from both airblast and ground vibration, the mean values represent what is expected from the shots that were favorable for response (dominant and distinctly measureable). It is characteristic of the analyses that cases of small or nonexistent responses do not show up in table 3 or on the response graphs. Consequently, the response comparison techniques actually include a factor of safety for any individual shot, because strong confinement, which typically can increase ground vibration, will also lead to lesser airblast. For example, a coal mine parting shot produces high levels of airblast and small amounts of ground vibration.

The three analysis techniques for assessing airblast impact are summarized in table 10, based on measured corner (structure) responses to both airblast and ground vibration. Any other combination of airblast descriptors, levels, responses, and ground vibration responses can be made by direct comparison between figures 30 to 37 and figures 38 and 39. With the exception of the conservative case of the combination of 5-pct chance-of-occurrence and the 0.5-in/sec peak particle velocity, the three cases result in quite similar airblast levels for the four measurement methods. From the lowest (safest) of the three cases, overall safe airblast criteria based on structural response and potential damage become 134 dB (0.1 Hz), 133 dB (2 Hz), 129 dB (6 Hz), and 105 dB C-slow. These levels correspond to essentially zero (< 1 pct chance probability of damage, (even superficial) in a typical residential structure.

As with the responses, no assumption should be made that these values are safe for larger structures or those with totally different response characteristics.

Airblast Criteria From Midwall Responses

Similar comparisons were made between airblast- and ground-vibration-produced midwall responses. Table 11 shows the predicted airblast levels derived from the mean values of the two sets of responses. Most evident is that they are lower than the corresponding values from the corner responses, showing that airblasts are relatively efficient generators of midwall motion. Consequently, the regulation of airblast based on an equivalence to ground vibration effects on midwalls would result in lower tolerance levels for airblast. As noted, the problem with midwall motions is that they produce annoyance from the secondary effects of rattling of objects and the motion and occasional fall of wall-mounted items. These results demonstrate that airblast is probably responsible for much of these secondary effects through its midwall responses.

A more direct evaluation of airblast-produced midwall motion could be made by determining the midwall motions required to produce rattling and the other secondary effects. Accelerations that cause something to rattle, move, and tilt, vary from 0.1 to 1.0 g, depending on the shape, center of gravity, and natural frequencies of the vibrating items. A wall acceleration of 0.5 g is sufficient to shake most items, and this roughly corresponds to the maximum safe airblast levels based on whole-structure responses. Table 11 lists airblast levels corresponding to 0.2- and 0.5-g wall motions computed at the typical wall natural frequency of 16 Hz, and derived from the midwall response plots in figures 32 and 33. These values are consistent with the observation that complaints about rattling occur at airblast levels exceeding about 120 dB (6 Hz), roughly corresponding to wall acceleration of 0.1 to 0.2 g. It is evident that the safe airblast levels as determined from structure response and damage are still high enough to produce secondary vibration effects. Similar rattling can be produced by truck traffic, airplanes, and normal household activities. The general problem of annoyance is discussed under the section on "Human Tolerance to Airblast."

TABLE 11. - Airblast sound levels for midwall response based on ground vibration levels and midwall accelerations

Type of blasting	Structure	Equivalent ground vibration, in/sec	Sound levels, lb/in² (dB) 0.1 Hz	2 Hz	6 Hz	C-slow	Assumptions
Mine......	All.....	0.5	0.0102 (131)	0.0073 (128)	0.0053 (125)	0.00133 (105)	Utilized mean values of both airblast response and ground vibration response.
	1-story.		.0076 (128)	.0061 (127)	.0048 (124)		
	2-story.		.0012 (132)	.0073 (128)	.0052 (125)	.00115 (108)	
Quarry....	All.....		.0069 (128)	.0046 (124)	.0033 (121)	.00027 (99)	
	1-story.						
	2-story.						
Mine......	All.....	1.0	.021 (137)	.0157 (135)	.0112 (132)	.00138 (114)	
	1-story.		.0162 (135)	.0127 (133)	.0093 (130)	.00097 (110)	
	2-story.		>.0165 (>135)	.0117 (132)	.0086 (129)	.00153 (114)	
Quarry....	All.....		.0134 (133)	.0101 (131)	.0072 (128)	.00082 (109)	
	1-story.						
	2-story.						
All.......	All.....		.0086 (129)	.0060 (126)	.0043 (123)	.00043 (103)	0.2 g wall acceleration; 0.772 in/sec at 16 Hz.
	1-story.		.0071 (128)	.0057 (126)	.0045 (124)	.00043 (103)	
	2-story.		.0090 (130)	.0057 (126)	.0040 (123)	.00037 (102)	
All.......	All.....		.0225 (138)	.0178 (136)	.0127 (133)	.00158 (115)	0.5 g wall acceleration; 1.93 in/sec at 16 Hz.
	1-story.		.026 (139)	.0204 (137)	.0146 (134)	.00174 (116)	
	2-story.		>.017 (>135)	.012 (133)	.0089 (130)	>.00125 (>113)	

Airblast Damage Summary

Many studies have been made of glass and structural damage from impulsive noises including airblasts (Appendix G) and sonic booms (Appendix H). Despite the widely varied source characteristics, assumptions of damage probabilities, and experimental design, and also the differing interpretations among the studies, there is a consensus that damage becomes improbable below approximately 0.030 lb/in^2 (140 dB). The various safe airblast and sonic boom damage criteria are summarized in table 12, based on no greater damage risk than one chance in a thousand. The apparently greater damage risk from sonic boom is probably an artifact of the analyses, with large populations sampled with few preboom damage inspections.

TABLE 12. - Summary of maximum safe overpressures from all sources

Author	Overpressure source	Maximum safe Lb/in^2	Overpressure dB	Sensitive element
Windes (82).....	Single unconfined charges.	0.100	151	Glass, poorly mounted.
Perkins (36)....	.....do........	.100	151	Do.
Poulter (39)....	.....do........	.032	141	Do.
Reed (43).......	Large surface blasts.	.017	136	<64-ft^2 window 1 chance in 10^3.
Reed (42).......	General........	.029	140	Glass.
ANSI (1)........	Single unconfined charges.	.057	146	Do.
von Gierke (70).	Confined blasts	.047	144	<1 chance in 10^5 1,000 people impacted, glass.
Redpath (41)....	Blasts.........	.060	141	<1 chance in 10^4 3.5 ft window.
Sutherland (63).	Steady-state sources, fatigue.	>.041	>143	Wood frame and concrete walls.
Taylor (64).....	Small line charges.	<.029	<140	35,000 panes in 30 greenhouses 0.7% damaged.
Do.............	General........	.014	134	Threshold.
Sutherland (63).	Sonic booms....	.045	144	Plaster.
Do.............	.....do........	.053	145	Glass.
Wiggins (80)....	.....do........	.015	134	Paint fleck fell.
Do.............	.....do........	.035	142	Plaster, new.
Do.............	.....do........	.056	146	Glass,
Kryter (19).....	.....do........	.035	142	39-ft^2 window.
Clarkson (7)....	.....do........	.076	148	Plaster.
Leigh (22)......	.....do........	>.069	>148	Plaster.
Blume (3).......	.....do........	.026	139	Glass.
This research...	Production blasting.	.014	134	Based on response and ground vibration.

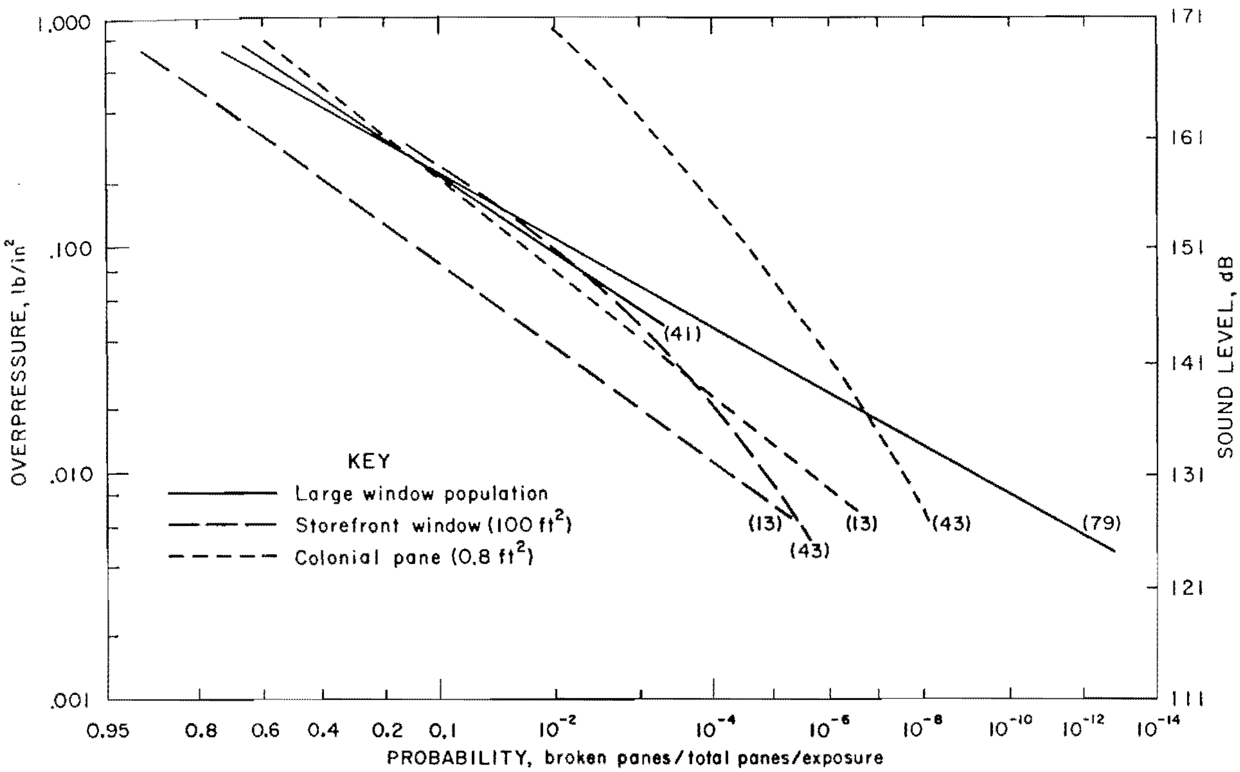

FIGURE 40. - Glass breakage probability from sonic booms and airblasts. (Numbers in parentheses correspond to regression lines in table 5.)

The glass-breakage probabilities versus airblast overpressures, as computed from several models and based on observed failures for large populations, are given in figure 40. Damage probabilities are again very small below 0.030 lb/in^2 (140 dB).

Human Tolerance to Airblasts and Impulsive Sounds

Health Risks

Hirsch assessed the injury and hearing damage risk from impulsive noise (15). He concluded that the thresholds of ear drum rupture and inner ear damage were 2 to 4 lb/in^2 and 5 lb/in^2 (178-184 dB and 185 dB), respectively. The U.S. Army has been concerned with hearing conservation amid impulsive noise sources such as gunfire, and has published noise limits (67). The Army's safe impulsive noise criteria are based on peak overpressure and the two time parameters of positive phase duration (A), and total time during which the signal is within 20 dB of the peak values (B). No ear protection is required for peak levels below 140 dB, regardless of the number of events per day or the A and B durations.

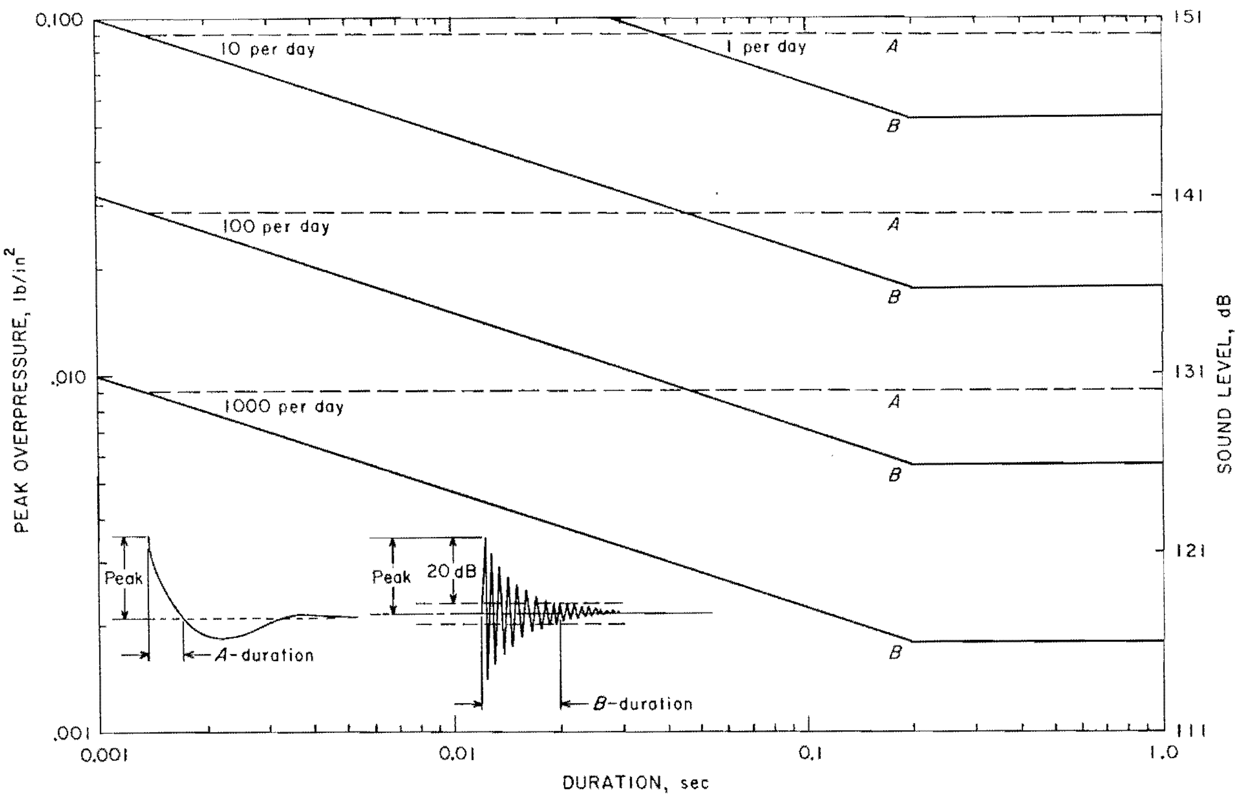

FIGURE 41. - Human tolerance to impulsive noise.

An evaluation of environmental noise and public health was made by the U.S. Environmental Protection Agency (68). Discussed were both the 1968 CHABA[6] damage risk criterion for impulsive noise, which was the basis of the Army specifications, and also a modified criterion for additional protection. The modified criterion is based on a maximum of 5 dB NIPTS (noise-induced permanent threshold shift)[7] at 4,000 Hz in 10 pct of the people after 20 years. The original criterion specified a maximum of 20 dB NIPTS at 3,000 Hz in 5 pct of the people affected, which allows higher noise levels by 12 dB.

Figure 41 shows the modified CHABA impulsive noise tolerance for humans, based on the A- and B-durations and the number of events per day. The criterion in figure 41 can be applied to mine production blasting even though it was designed for noise sources with rather different characteristics. The typical type 1 airblast appears as a series of spikes with A durations of 0.050 sec or less. Since there are no significant negative phases or oscillations for this type of airblast, the B durations are not meaningful. A large coal mine could have as many as four shots per day over the long run, each producing 10 to 15 type 1 spikes. This rather extreme case involving 40 to 60 "events" per

[6] Committee on Hearing, Bioacoustics, and Biomechanics, Washington, D.C.
[7] Threshold shifts represent hearing losses, or changes in minimum levels at which sounds can be heard. A certain amount of threshold shift occurs naturally with age.

day would result in a maximum allowable peak level of 142 dB, using the graph in figure 41. A large taconite mine could possibly produce type 1 airblasts with 100 spikes; however, these mines produce blast only a few times a month. Quarries are similar to metal mines in that they blast infrequently (usually not more than two or three times per week), and use blasts with up to 10 to 20 front-row holes (20 type 1 spikes, maximum). Consequently, the quarries could produce 5 to 10 "events" per day of 50-msec A duration, at a maximum peak level of 150 dB. More prevalent is the production of type 2 airblasts, which have very long B durations caused by their infrasonic (low-frequency) wave train. The resulting one event per blast (four per day maximum), gives an allowable peak level of 139 dB.

The recommended maximum 134 dB (0.1 Hz) peak airblast for minimum damage risk to structures and window glass is also low enough to meet the most strict CHABA criteria for human health. Furthermore, 134 dB (0.1 Hz) is a maximum level rather than a design level, which gives an additional factor of safety in actual practice. The modified CHABA criterion for human tolerance allows a maximum of 400 type 1 events per day or 16 type 2 shots per day, both at 134 dB (0.1 Hz). For type 1, the "events" would be the front-row holes on separate delays (or spikes countable on the airblast time histories), multiplied by the number of shots per day.

Airblast from confined, surface-mine blasts consists mostly of acoustic energy below 20 Hz, where human hearing becomes less acute. This infrasonic sound can still be perceived as harmonics generated by distortion of the middle and inner ear. Johnson (16) has evaluated the human tolerance for this kind of sound, noting also that its presence is not at all rare. A 6-inch change of height associated with jogging produces a 90-dB "sound" with a frequency of 2 to 3 Hz; a 3-inch change of depth while swimming produces 140 dB. Any activity or condition which produces a change in the pressure field acts as an infrasonic sound source: examples include elevator rides, aircraft flights, open windows in autos, wind, and barometric pressure changes. Laboratory studies of humans have indicated that infrasonic sound could be heard at least down to 1 Hz, with a rolloff of approximately 13 dB per octave below 20 Hz (16, 71). No threshold shifts have been found for subjects at levels of 150 dB (1 to 8 Hz) and 130 to 139 dB (1.5 Hz) for 5-minute exposures.

An analysis was made of impulsive infrasound from sonic booms by von Geirke and Nixon (71) who found no adverse effects from levels up to $1.34 \times 10^3 N/m^2$ (157 dB) from 1,800 booms at White Sands, N. Mex., and up to $6.9 \times 10^3 N/m^2$ (171 dB) at Tonopah, Nev.

Annoyance

Little research has been done on the problem of subjective reactions to blast noise, although annoyance surveys have been made for sonic booms and other impulsive sources and applied to blasting with various degrees or justification. A major problem is to define just what is objectionable about the noise, and separate those factors from other psychological and physiological reactions. In contrast to many noises, mine blasts are infrequent, typically one a week to a few a day. They generate impulsive noises with much energy outside the usual hearing frequency range, are of short duration (typically 300 msec), and affect relatively few people over a long period of time. Other types of blasting (such as construction and excavation) may be louder and more frequent, but are generally accepted as being temporary nuisances. The usual reasons for objecting to noise, such as speech, radio, and TV interference, do not generally apply to airblasts. Similarly, the discomfort descriptors of "unpleasant", "uncomfortable", and "fatiguing" also don't apply. Since blasting is usually restricted to daylight hours, sleep interference is only a potential problem for the fraction of the population who sleep during the daytime. Most objections to blasting are based on damage to houses and fear of damage to homes. Fright from fear of property damage is the primary reaction of citizens near blasting sites. "Startle" and "Fright" are the only discomfort descriptors clearly applicable to blasting.

The variable nature of airblast propagation creates special problems. Occasional weather conditions can cause anomalous noise levels at locations that do not usually receive strong enough airblast to rattle buildings. Since the airblast is predominantly infrasonic and sometimes totally so beyond a few miles, ground vibrations are usually blamed for shaking the house. The degree to which the noise is considered essential and unavoidable strongly influences public reaction. Where jobs and economy are tied to local mines, tolerances are considerably higher. For mining or quarrying, the general population is sufficiently removed from the end product that they fail to understand the necessity for blasting or problems inherent to the industry. Complicating the noise-response problem are the other problems associated with have a mine in one's neighborhood, such as truck and rail traffic, noise, dust, fumes, and possible unsightliness.

Studies made on annoyance from impulsive noises are discussed in Appendix I. The overall consensus was a composite of five impulse noise studies. The maximum safe levels, as given in this report and derived from structural response and damage considerations, would be acceptable to 95 pct of the population for relatively infrequent events (1-2 per day) (table 13). With variations between sources (sonic booms and unconfined, partially, and full confined blasts), and the number of events actually produced per day, the intolerable percentage at the maximum airblast levels will range from 0 to 10 pct.

TABLE 13. - Summary of airblast levels considered 95 pct acceptable

Author	Overpressure source	Maximum Levels		Basis
		Lb/in²	dB	
von Gierke (70).	General	-	57 $dBL_{C\,dn}$	5 pct annoyed. Equivalent to 1 sec duration 107 dBC Event
Higgins (14)....	Coal highwall.	0.0205	137 dBL	5pct annoyed. Equivalent to PLdB level as per Table I-1. All dBL values are with 0.1 Hz high pass system.
	Coal parting..	.0115	132 dBL	
	Quarry........	.0183	136 dBL	
	Overall.......	.0145	134 dBL	
Kryter (19-20)..	General.......	.015-0.0216	135-137 dBL	Just acceptable. Equivalent to 0.0105 lb/in² (131 dBl) sonic boom
Borsky (4)......		.0145	134 dBL	5 pct more than moderately annoyed (fig. I-1).
Schomer (47)....		-	108 dBC-slow	

In summarizing the airblast annoyance problem, it is evident that the results of other related studies are only roughly applicable and that additional research is needed. Specifically, the annoyance factors from airblast and resulting rattling effects should be quantified and a survey for blasting similar to Borsky's (4) should be made. The attitudes of both the blaster and the neighbors are quite significant. As Borsky found for sonic booms, the belief that the source is necessary and unavoidable, the blaster's public relations role, and possible economic connections may have greater effect on airblast tolerance than specific levels, number per day, etc. It is theoretically possible to obtain total protection of neighbors by regulating the allowable levels to those lower than can be detected outside the mine's property line. Not only is this impractical, it is also unreasonable since other noise sources are not restricted in this manner. However, it is possible to minimize any real impact by careful control of blasting and a responsive public relations program.

CONCLUSIONS

Safe airblast levels have been determined from an analysis of structure response and damage including applicable studies of ground vibrations, sonic booms, mining, quarrying and construction blasts, surface and accidental explosions, and laboratory studies of fatigue and damage. Based on a minimal probability of the most superficial type of damage in residential-type structures, any of the following represent safe maximum airblast levels:

0.1-Hz high-pass system	134 dB
2-Hz high-pass system	133 dB
5- or 6-Hz high-pass system	129 dB
C-slow (events not exceeding 2-sec duration)	105 dB

These criteria could be lowered at locations with many large plate glass windows. The single best airblast descriptor is the 2 Hz, although many of the existing instruments were designed to be linear down to only 5 Hz.

Levels exceeding 120 dB will produce some annoyance from rattling and fright, with as much as 5 to 10 pct of homes exhibiting such disturbances at the maximum level of 134 dBL (0.1-Hz high-pass). Public reaction depends strongly on the blaster's public relations and the general attitudes of the neighbors to the economic and social requirement for the blasting. Tolerance increases where jobs are involved. Trade-offs between the costs and benefits of more restrictive criteria may have to be made.

In the absence of monitoring, the following minimum cube-root-scaled distances should be maintained:

Coal highwall	180 $ft/lb^{1/3}$
Coal parting	500 $ft/lb^{1/3}$
Quarries and mines	250 $ft/lb^{1/3}$
Construction and excavation	500 $ft/lb^{1/3}$
Unconfined blasting	800 $ft/lb^{1/3}$

Because these are necessarily restrictive, it would be an advantage to monitor enough blasts to determine typical site values, particularly for the highly variable parting shots.

Airblast character and level are dominated by factors of charge weight, distance, delay intervals, face orientation, explosive confinement, and weather. The following conditions require additional caution because of anomalously high levels (HL) or high frequencies (HF) that are in the range of structure response (5 to 25 Hz):

Large charge weight delay	HL
Effective delay too short (reinforcement)	HL
Effective delay too long (> 25 msec)	HF
Face toward receiver	HL, HF
Insufficient confinement	HL, HF
Wind toward receiver	HL
Severe temperature inversions	HL

The type 1 airblast is most serious in terms of potential damage and response, because of its resulting high frequency. Where its presence is unavoidable, effective delays should be chosen outside the range of 25 to 250 msec. The conditions which favor production of type 1 airblast often result in higher levels too. Where possible, a change in the face orientation may be helpful.

All blasting conditions that have low confinement require special precautions. Surface blasts, thin partings, exposed detonating cord, explosives testing, and construction blasting are all potentially serious. The worst case can be determined from the "unconfined" line in the propagation summary (fig. B-5).

Wind direction and speed are most critical weather influences on airblast propagation; inversions are secondary. Strong winds blowing from the sound source toward the receiver can increase the sound level by over 20 dB from the normal cube-root-scaled propagation.

It is necessary to emphasize that the safe levels specified in this report for both airblast and ground vibration levels are based on the worst cases of damage and response, and are therefore conservative levels for typical modern homes and the average blast effects. Previously, safe maximum levels of 140 dBL-peak and 2.0 in/sec provided sufficient protection in most cases, although they were high enough for significant annoyance. The new recommended levels in this report should provide 95 to 99 pct nondamage probability and 90 to 95 pct annoyance acceptability.

Airblast is an undesirable side effect of blasting rock for mining, quarrying, construction, and excavation. Since blasting is the most economic and presently the only practical way to fragment rock, it is the responsibility of the mining industry and others to design their blasting programs for minimum environmental impact. At the same time, those affected are part of a social, technological, and economic system that depends on mining and quarrying for a myriad of products, some far removed from raw material sites. This assessment of airblast levels and effects was made to provide guidelines for the industry which uses explosives, the regulatory agencies which are charged with control of environmental degradation, and the general population which must always bear the ultimate cost.

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APPENDIX A.--SOUND AND VELOCITY EXPOSURE LEVELS FOR AIRBLAST RESPONSE

Shot	Site	Peak air-blast, dB (0.1-Hz high-pass)	Sound exposure levels (L_s, L_{sc}), dB: 4-40 Hz, Integration, sec				3.5-10 Hz, Integration, sec				10-24 Hz, Integration, sec				C-weighting, Integration, sec		Peak particle velocity, in/sec		Velocity exposure level (L_v), in/sec: Midwalls, Integration, sec				Corners, Integration, sec			
			1/8	1/4	1	2	1/8	1/4	1	2	1/8	1/4	1	2	1	4	Mid-wall	Corner	1/8	1/4	1	2	1/8	1/4	1	2
35	12	122	110	109	108	107	107	106	103	101	107	106	105	103	97	94	0.19		0.10	0.11	0.07	0.07				
36	14	129	115	110	98	98	112	112	107	104	101	101	95	93	88	86	.081		.068	.068	.042	.030				
45	20	120	118	118	113	109	103	102	99	97	103	102	96	94	94	92	.20		.13	.13	.12	.07				
62	19	127	116	116	109	107	115	115	108	106	112	112	107	105	99	93	.40	0.13	.26	.15	.08		0.06	0.04	0.03	0.02
64	19	128	112	109	105	103	112	111	106	104	105	103	98	96	99	94	.53		.24	.21	.17	.09				
67	19	129	116	114	109	106	117	116	110	109	108	106	101	99	99	94	.70		.49	.37	.23					
70	19	129	115	115	108	107	117	114	110	107	113	111	104	103	97	92	.56	.06	.24	.21	.13	.11	.028	.024	.014	.014
71	19	131	117	116	111	110	119	117	112	110	111	111	105	103	99	94	.28	.11	.14	.12	.08		.06	.06	.04	.04
78	19	129	113	112	107	105	113	113	106	103	110	107	101	100	100	95	1.10		.47	.42	.24					
79	19	132	118	118	113	109	116	116	111	109	117	115	108	106	104	100	1.18		.54	.46	.23	.18				
80	19	132	112	111	106	106	113	111	106	104	114	113	106	104	103	97	1.50		.82	.54	.47	.36				
81	19	126	113	113	106	104	114	113	107	105	112	109	104	101	102	96	.70		.50	.40	.25	.19				
84	19	134	124	123	118	116	122	121	118	117	122	119	115	114	116	110	1.40		.70	.61	.35					
85	19	133	118	116	111	107	117	117	109	106	114	114	111	106	106	101	1.04	.22	.60	.52			.16	.14	.09	
86	19	135	120	118	113	110	114	113	108	105	120	117	112	110	107	102	2.50	.24	1.67	1.27	.96	.63	.105	.098	.060	.053
90	19	129	114	113	109	107	111	109	105	103	114	111	108	106	99	96	.49		.18	.19	.17					
92	19	131	120	115	111	109	118	117	113	109	115	114	108	104	102	96	.58	.12	.34	.27	.19	.14	.07	.06	.05	.04
94	19	133	121	118	112	109											.30									
95	19	128	113	109	108	106	104	103	99	97	104	104	100	98	97	95	.59		.33	.31	.20		.09	.06		
99	21	128	117	116	109	108	116	116	110	107	110	110	105	102	94	90	.72		.32	.30	.17					
101	21	121	112	112	109	108	110	106	104	102	111	111	108	106	102	97	.91	.10	.53	.50	.40	.30	.07	.06	.05	.03
103	22	122	107	106	101	99	107	106	102	99	103	102	98	94	94		.28	.07	.14	.12	.09		.03	.03	.02	
103R	22	124	113	112	106	104	111	110	105	103	110	107	103	100	98	95	.65	.09	.25	.25	.13	.12	.04	.04	.03	.02
103	23	133	122	120	115	113	121	121	115	111	116	116	110	107	106	101	.60	.25	.32	.21			.13	.10	.08	
103R	23	131	122	120	115	115	117	116	111	109	117	117	111	110	108	101	.87	.16	.40	.34	.21	.21	.08	.08	.06	
105	23	132	120	120	112	111	119	119	113	111	113	112	106	103	101	95	.46	.34	.23	.20	.15		.15		.08	.06
105R	23	126	116	114	110		113	113	107	105	114	112	107	104	103	98	.40	.10	.20	.18	.14	.10	.05	.05	.03	
126	34	136	129	125	121	118	124	121	118	115	126	123	119	117	113	107	1.71	.14	1.16	1.00	.66	.50	.09	.08	.04	.03
128	35	127	121	118	111	109	116	115	108	106	116	115	109	106	102	96	1.80	.13	1.22	.80	.46	.40	.08	.05	.04	.03
130	34	127	122	119	113	111	113	111	107	104	119	117	111	110	107	101	1.09	.04	.45	.42	.25	.19	.020	.019	.009	.006
141	36	124	117	114	109	106	110	110	106	103	115	112	107	103	100	94	.86	.025	.55	.42	.20	.15	.015	.012	.009	.007
146	37	117	102	101	98	96	107	106	102	101	101	101	99	99	88	87	.15		.11	.09	.07	.05				
148	38	131	121	117	113	112	121	119	116	113	110	109	103	102	97	93	.47	.12	.20	.17	.12	.10	.043	.040	.026	.023
150	37	127	115	111	109	107	117	112	109	108	115	106	101	99	93	87	.246	.082	.213	.185	.116	.088	.077	.067	.038	.033
154	43	125	114	113	109	106	112	109	107	104	108	107	104	102	93	88	.85		.53	.40						
161	48	131	121	119	117	115	115	114	111	109	117	115	112	109	112	107	1.25		.78	.58						

APPENDIX B.--BLAST DESIGN AND AIRBLAST GENERATION

Vortman has made several studies of the generation of explosive-produced airblast, mainly for nonmining situations. He examined close-in airblast (77) and propagation both along the line and perpendicular to a row of charges fired with no delays between charges (75, 78). He found airblast reinforcement when measured perpendicular to the array (overpressures were multiplied by the number of holes), and partial addition of overpressures for the in-line case (75). Snell (58) reviewed Vortman's work on spacing and orientation. He concluded that reinforcement, or simultaneous arrival of airblasts from different holes would not occur for delay periods (T) given by:

$$T_{sec} = 0.53 \cdot \frac{S}{V_s},$$

where S is the spacing (ft) and V_s is the sonic velocity in air (ft/sec).

This relationship represents supersonic detonation down the face as successive holes fire before the arrival of airblast from adjacent holes. This case, and that of near-sonic velocity (with the spacing divided by the effective delay, equaling the velocity of sound), lead to airblast reinforcement in specific directions. For mining, a highly subsonic succession of detonations is recommended:

$$Tsec \geq 2\frac{S}{V_s}$$

Good blast design also calls for 1-3 msec per foot of burden between rows of holes, to allow sufficient relief. Even greater time separation is sometimes used for deep multiple-row blasts, although there is increased risk of hole cut-offs.

As discussed previously, the degree of blast confinement strongly influences both airblast levels and frequency character. Vortman (73) discusses the airblast components produced by the venting (GRP) and ground shock (APP) for alluvium, clay, sand, and basalt, and also by confinement of very large blasts (40,000 lb) (74). Reed (42) also studied confinement in his analysis of cratering and excavation and noted that airblast amplitudes are 5 to 35 pct of free air levels. Other investigators have examined confinement and airblast generation for various depths of burial (36, 40). Wiss (83) intensively investigated airblast from mining production blasts with various degrees of confinement. He determined relationships for burden and stemming, both important confinement factors. The APP pulse, which dominates airblasts that have no stemming release or gas venting, is a function of burden as given by:

$$APP = K_1 \, e^{-0.13} \, D_{cg}$$

where D_{cg} is distance (in feet) to the charge weight center of gravity and K is a constant. The stemming length has a far greater effect on resulting airblast levels, with a confined SRP being approximately one-tenth of the APP, and unconfined SRP, about two and one-half times the APP (83). Wiss quantified the confinement effect:

$$SRP = K_2 e^{-1.0\ B_s},$$

where B_s is the scaled depth of burial ($ft/lb^{1/3}$).[1] The B_s values can be computed from--

$$B_s = D_{cg}/W^{1/3}$$

for stemming lengths shorter than explosive charge lengths, and--

$$B_s = \frac{3}{2}\frac{S^{2/3}}{W^{1/3}}$$

for stemming lengths longer than explosive charge lengths, where S is the stemming length (in feet) and W is the charge weight (in pounds). Wiss's study quantified the reduction of airblast by burial as follows:

2.3 $ft/lb^{1/3}$ scale depth of burial.........	20 dB reduction (1/10)
4.6 $ft/lb^{1/3}$ scale depth of burial.........	40 dB reduction (1/100)
6.8 $ft/lb^{1/3}$ scale depth of burial.........	60 dB reduction (1/1000)

for 9-12 inch horizontal and vertical holes of up to 120 ft in length. An analysis (36) for spherically shaped charges found that lesser depths were required for similar reductions:

0.75 $ft/lb^{1/3}$ scale depth of burial..........	20 dB reduction
1.50 $ft/lb^{1/3}$ scale depth of burial..........	40 dB reduction

Although these reductions may vary considerably at sites with differing geologies, they demonstrate how confinement dominates airblast levels.

Airblast levels as measured with four different low-frequency cut-offs (high-pass frequencies) for two types of coal-mine production blasts are shown in figure B-1. Most obvious is the higher levels resulting from the parting blasts, which are frequently underconfined. These airblasts are 10 to 15 dB higher in level than the highwall shots, although still approximately 10 dB lower than the free air levels (unconfined). They are also typically of high frequency and resemble type 1 airblast. These data have a moderate amount of scatter, as they represent few measurements from each of many sites, with varying weather conditions, geology, and blast designs. The primary purpose of this study was to analyze response and damage. These propagation data (83) used an array of gages with many measurements at a few sites, resulting in less scatter.

Airblasts from coal mine highwall airblasts are shown in figure B-2. Lines one through six are different sites or blast designs of the Wiss study (83). Line seven is a compilation of values from this study, where all shots are decked. The Bureau's results show slightly more scatter than Wiss; however, decking evidently produces higher airblast levels for a given charge

[1]Note that the units of scaled depth of burial are the same as cube-root-scaled distance.

RI 8485 (1980)

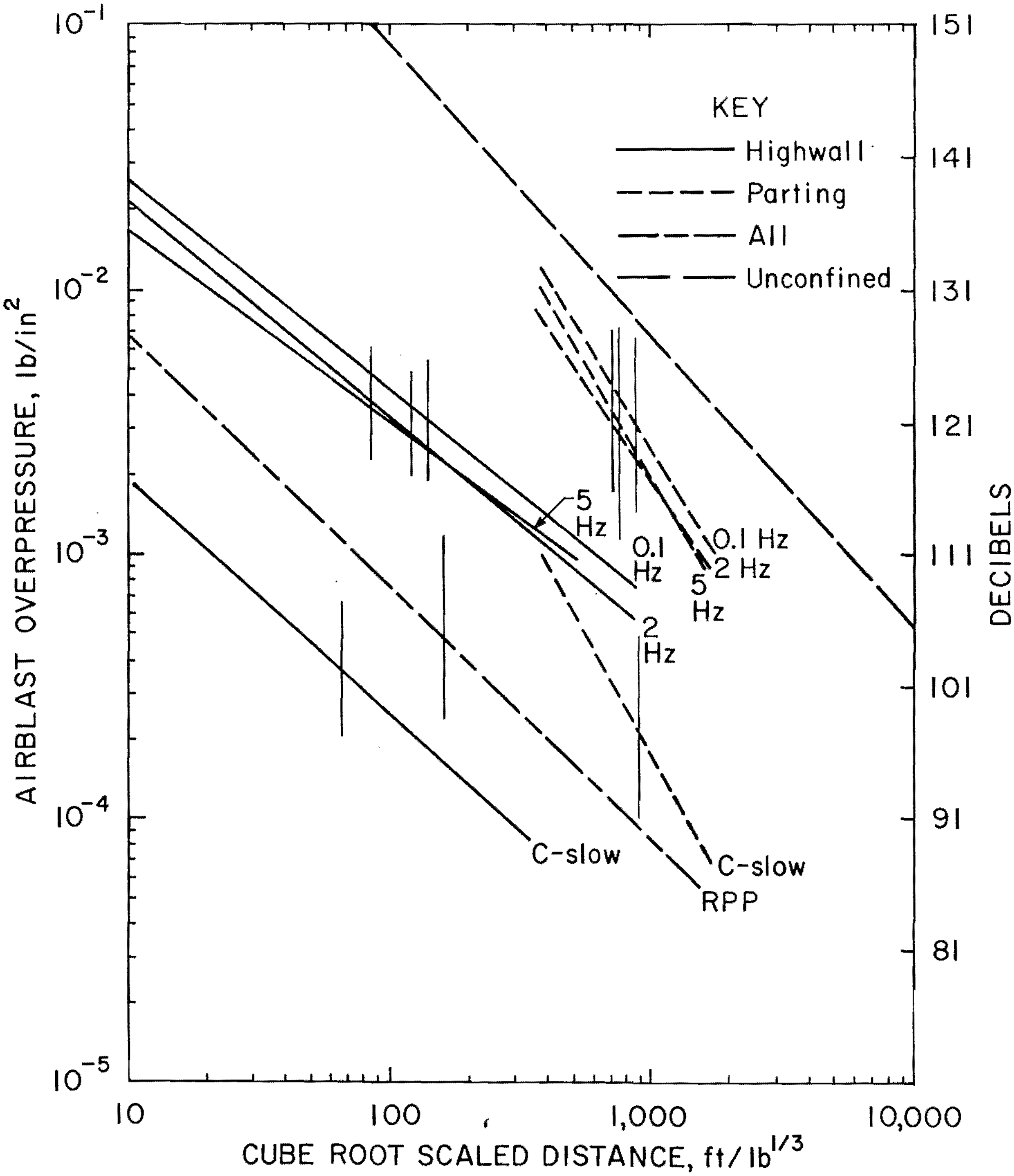

FIGURE B-1. - Airblast propagation from surface coal mine production blasts.

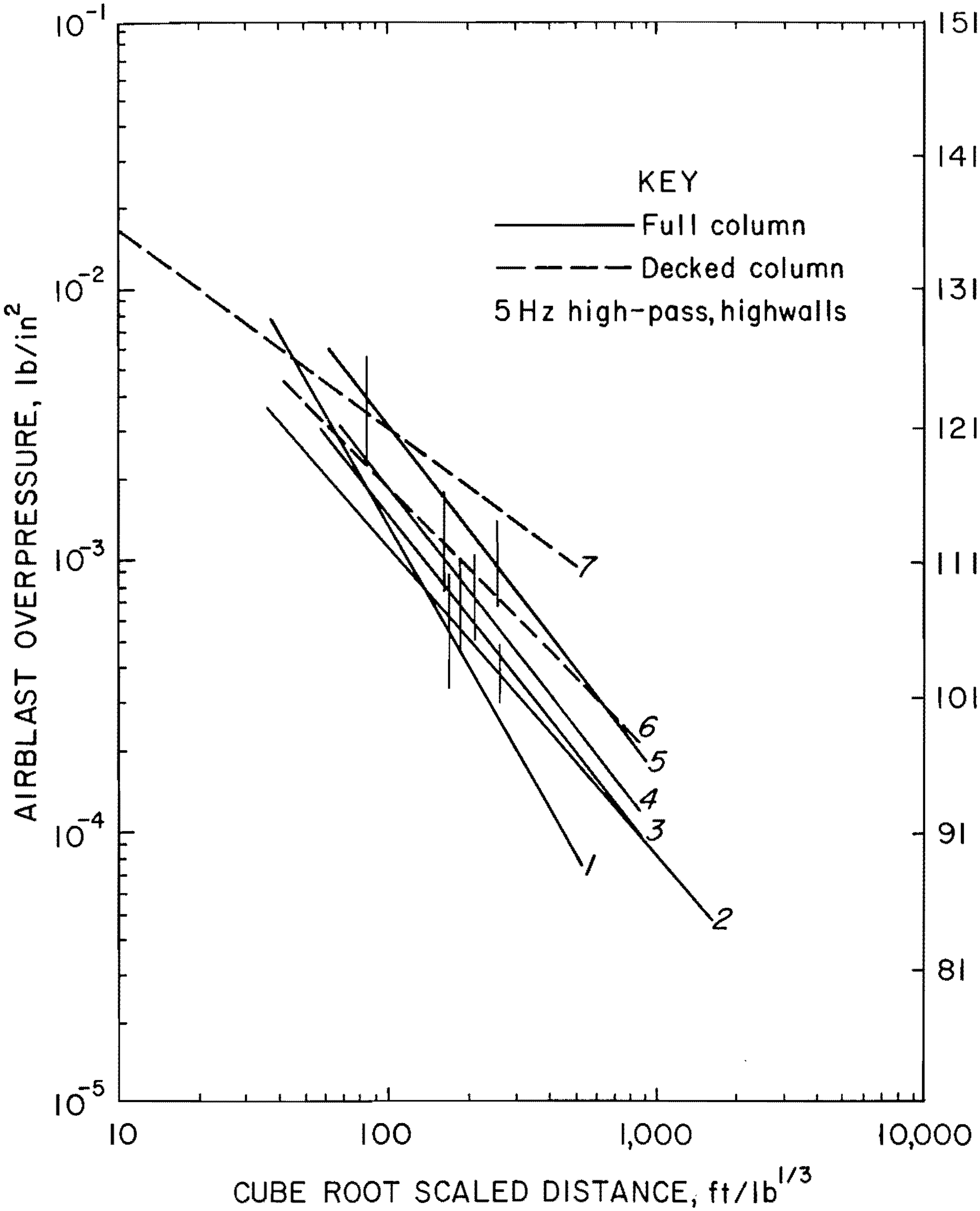

FIGURE B-2. - Airblasts from individual surface coal mines, highwalls with 5-Hz high-pass.

weight per delay, particularly at large distances. This is likely a confinement problem, with the generation of some GRP from the rock fracturing being produced by the earlier detonations within the blastholes. Examination of type 1 airblast records shows only one APP per hole, regardless of the number of decks. Undoubtly, the upper deck has a dominating influence on the airblast. The airblast levels from decked and undecked blasts are essentially the same at small distances.

BuMines Bulletin 656 (34) describes investigations of airblasts from quarry production shots and derives a design relationship of 2.6 ft of stemming per inch of blasthole diameter. This was developed for small-diameter holes (about 3 inches), but is presently considered unnecessarily restrictive, particularly for large holes. In some cases, the 2.6-ft/in value would require a hole full to the collar with only stemming.

Airblasts from a variety of sources are shown in figure B-3 (0.1-Hz high-pass for BuMines, and 2-Hz for VME data). The quarry and metal mine data have much scatter; however, on the average they represent greater airblast levels than coal mine highwall shots, and less than parting shots for moderate scaled distances (less than 600 $ft/lb^{1/3}$). The VME study (24) found lower average levels, but also demonstrated that greater confinement and the lack of a requirement to displace the rock gave lower airblast levels in most coal highwall blasting.

Several investigators have noticed the different airblast levels and character in various directions from the free face. Both Kamperman (18) and Taylor (64) observed a 5- to 10-dB difference between levels at the front and back of the pit face. Figure B-4 shows airblast propagation curves for four directions, relative to both the free face and the direction of the blast initiation down the face. The horzontal hole values are from Wiss (83). Most mines are concerned with vertical holes and, as stated earlier, the front direction is potentially more serious because of both the higher levels and the tendency to produce high-frequency, type 1 airblasts. In all directions, constructive interference can occur, and this involves solving the geometric problems of the blast patterns and delay intervals (83). The directional airblast data for the Bureau measurements are from table 3, with 0° being the direction of blast initiation down the face, 180° opposite, 270° in front of the free face, and 90° behind.

Detonating cord poses a special problem, but one which is easily solved. Cord on the ground surface can be treated as any other unconfined explosive on a per weight basis. Wiss (83) and Viksne (69) describe airblasts from various amount and types of detonating cord, with and without cover. Wiss (83) found that 3 inches of sand reduces 50 grain cord by 20 dB (factor of 10), and 12 inches gives almost total confinement. Wiss measurements were made within 1,000 ft. At large distances, detonation cord becomes a less of a problem due to attenuation of high frequencies.

The Bureau's airblast measurements from all sources with linear frequency response down to 5 Hz or lower are summarized in figure B-5. The upper and lower limit predictions are shown by the free-air (unconfined) and RPP lines, respectively. The difference between total confinement and free-air blasts

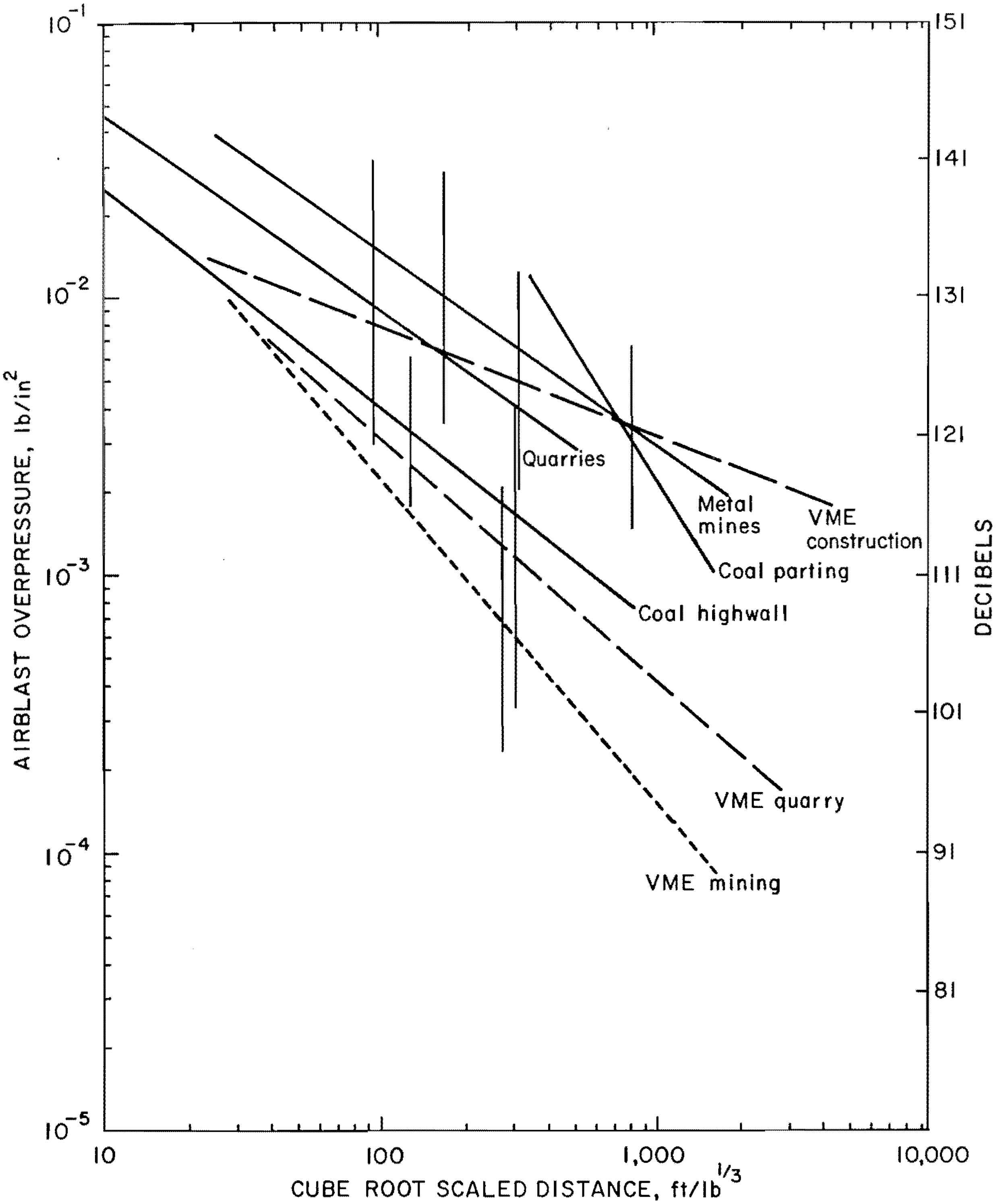

FIGURE B-3. - Airblasts from various types of mining, 0.1-Hz high-pass.

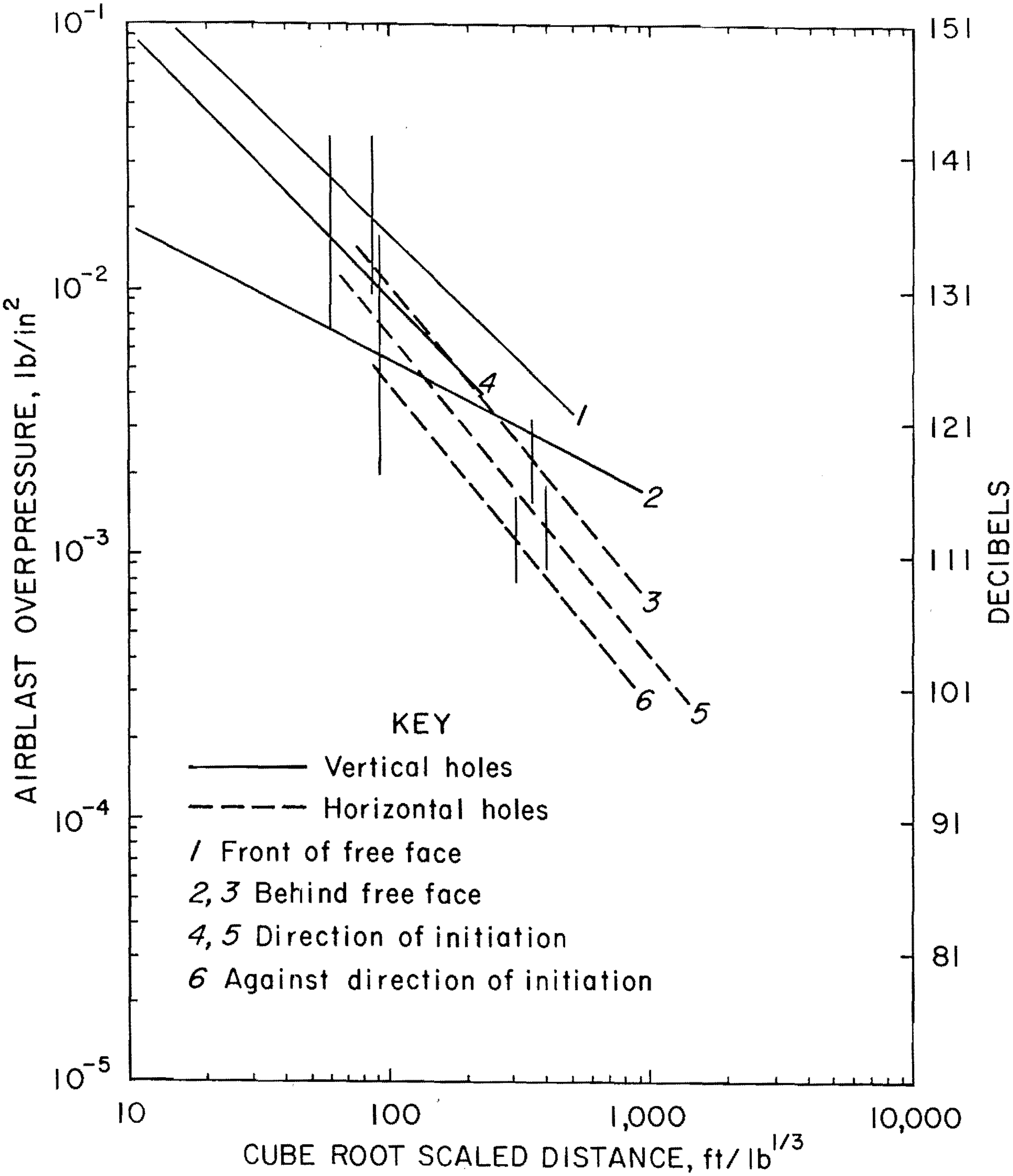

FIGURE B-4. - Airblast propagation from various face orientations.

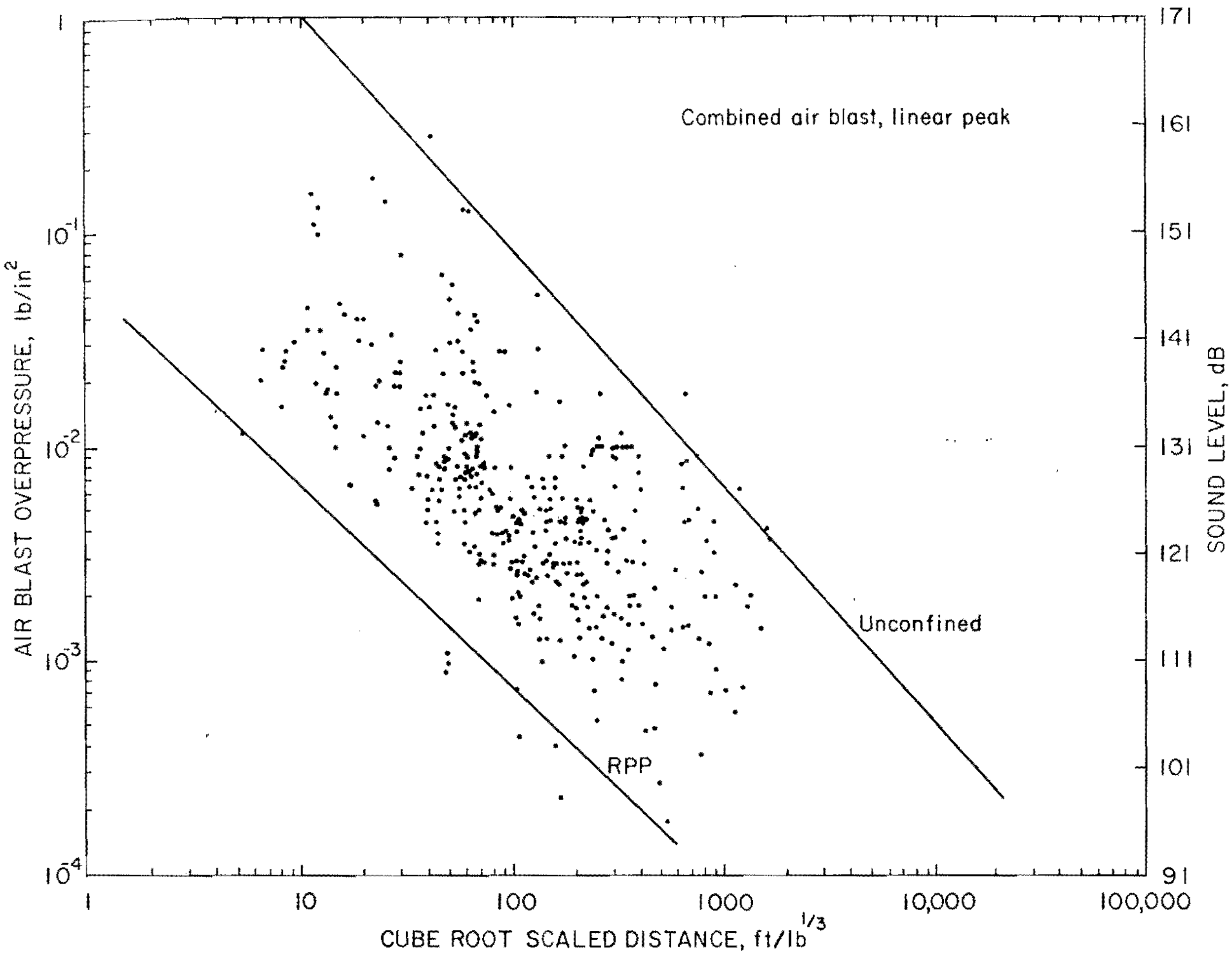

FIGURE B-5. - Combined airblast measurements, all sites.

is a remarkably constant 41 ± 5 dB. Most of the high values (> 145 dB) in this figure were obtained closer than the nearest house.

Table B-1 lists the airblast propagation equations and statistics. The effects of blast design on airblast generation are still not fully understood, and research is continuing on reinforcement between holes, delay intervals, and decking.

TABLE B-1. - Equations and statistics for airblast propagation

	Equation	Correlation coefficient	Standard error, pct	Transformed standard error, pct	Number of measurements
Coal highwall..0.1 Hz..	AB= 0.162 $(D/W^{1/3})^{-0.794}$	0.739	88.2	5.5	115
2 Hz..	AB= .146 $(D/W^{1/3})^{-.823}$	.774	75.0	4.9	83
5 Hz..	AB= .087 $(D/W^{1/3})^{-.725}$	.839	61.2	4.1	41
C-slow..	AB= .015 $(D/W^{1/3})^{-.885}$	.792	83.2	5.7	89
Coal parting...0.1 Hz..	AB=169 $(D/W^{1/3})^{-1.623}$	.587	120	6.8	19
2 Hz..	AB= 49.6 $(D/W^{1/3})^{-1.477}$	.500	159	8.3	16
5 Hz..	AB=194 $(D/W^{1/3})^{-1.666}$	.657	105	6.2	16
C-slow..	AB= 41.6 $(D/W^{1/3})^{-1.785}$	.603	122	6.9	22
Metal mine,					
highwall......0.1 Hz..	AB= .401 $(D/W^{1/3})^{-.713}$	.679	138	7.5	14
Quarry.........0.1 Hz..	AB= .246 $(D/W^{1/3})^{-.711}$	.580	165	8.4	73
Quarry[1]........0.1 Hz..	AB= .979 $(D/W^{1/3})^{-1.120}$	.757	120	6.9	10
Quarry[2]........0.1 Hz..	AB= .056 $(D/W^{1/3})^{-.515}$	.571	145	7.8	28
Quarry[3]........0.1 Hz..	AB= .028 $(D/W^{1/3})^{-.098}$	.050	193	9.3	11
Quarry[4]........0.1 Hz..	AB= 1.317 $(D/W^{1/3})^{-.966}$	.793	103	6.1	22

AB Airblast, lb/in^2.
D Distance, ft.
W Charge weight, lbs.
[1]Direction of initiation.
[2]Behind face.
[3]Opposite initiation.
[4]Front of face.

APPENDIX C.--WEATHER EFFECTS ON PROPAGATION

Reed has made several studies of long range airblast propagation from large surface blasts (1, 42, 44) and developed the IBM-M prediction scheme for free airblasts (43). Reed's airblast propagation is in the form--

$$\Delta P = K\, W^{0.4} D^{-1.2},$$

with ΔP being the airblast overpressure, W the charge weight, and D the distance (units arbitrary). This equation is identical to the following cube-root-scaled propagations used by the Bureau and others:

$$\Delta P = K\, (D/W^{1/3})^{-1.2}.$$

Nichols, Johnson, and Duval (34) include a summary of airblast propagation for stone quarry blasts, but do not plot an overall regression because of scatter between sites and tests. Vortman studies close-in propagation from row charges and found overpressures proportional to $R^{-1.1}$ (-6.6 dB per doubling of distance) (76). Schomer discusses airblast propagation and specifies -6.6 dB per doubling (50). Kamperman (18) studied propagation from quarry blasts and found a falloff of -20 dB per decade (also -6 dB doubling).

Oltmans (57) determined a decay of airblast level with distance proportional to $R^{-1.2}$ (-7.2 dB per doubling). Lucole (24) compiled airblast and ground vibration measurements gathered during 1 year by his firm, and plotted sound propagations for mining, quarrying, and construction (cube root scaled for airblast). As with many of the preceding studies and also the current Bureau of Mines research, meteorological factors were not specifically analyzed although they contribute to the scatter among measurements.

Sound propagation, particularly at large distances, depends on wind and temperature, both of which can bend the wavefronts and create anamolous sound levels. It is likely that the occasional complaints occurring at large distances are the result of weather-produced focusing of airblast. Studies have been made on weather effects on airblast; however, a practical prediction scheme has not been developed. Some mines use small pilot shots to assess propagation before the production blast. This is simple, but there may not be a good correlation between the pilot and production shots. The higher frequencies of the pilot shots do not propagate or undergo refraction the same way as the lower frequency energy from the full-scale blasts. Poulter (39) examined propagation as a function of temperature, humidity, and wind. He found that barometric pressure has no effect and humidity only a minor one. The factors of wind and temperature are critical to sound propagation. The wind changes the angle of the wavefront, and concentrates it near the ground when propagating downwind and up from the ground when propagating upwind. In the absence of inversions to refract it back down again, the upwind sound level will be far less than the downwind.

Schomer (50), Grant (11) and Kamperman (18) discuss wind effects on propagation, and Kamperman's analysis of close-in quarry measurements gave 10 to 15 dB greater sound level downwind than with cross or no wind conditions.

Wiss (83) analyzed wind effects from coal mine shots out to about 3 miles. He found that it changed the nominal -7.7 dB doubling to:

$$-(7.7 - 0.16\ V_{mph}\cos\theta\ \mathrm{dB}),$$

where θ is the angle between the wind vector and direction vector of concern, and V is the wind speed in miles per hour. For example, a 15 mph wind blowing directly from the blast toward the area of concern (0°) would give -(7.7 - 2.4) dB per doubling, or -5.3 dB per doubling, and in the upwind direction (180°) would give -(7.7 + 2.4) or -10.1 dB per doubling. Wiss also gives corrections to the airblast propagation exponents for quantifying the wind effects. The magnitude of the slope correction was $\pm 0.0265\ U_v$, where U_v is the vector wind velocity $U\cos\theta$, in miles per hour. As an example, the coal parting 5-Hz propagation equation from table B-1 was given as follows:

$$AB = 194\ (D/W^{1/3})^{-1.666}.$$

In a 20-mph wind blowing directly from the blast toward the point of concern, the exponent which describes the airblast overpressure decay will be reduced by an amount 0.530, determined from (0.0265 x 20 cos 0°), and the propagation equation becomes

$$AB = 194\ (D/W^{1/3})^{-1.136}.$$

Berning (2) also discusses wind and other unfavorable conditions for airblast propagation including a case of abnormal upwind propagation (skipping).

Air temperatures normally decrease with increasing altitude, with the reverse of this called a "temperature inversion," or warm air layer. The index of refraction of air changes with temperature, so that the normal condition of cooler air at higher altitudes refracts sound away from the ground. Conversely, temperature inversions refract sound downward, leading to higher than normal sound pressure levels at points of focus. Much work had been done on theoretical calculations of airblast focusing from temperature inversions (36-37, 39). Perkins (36) predicted that a single inversion could cause airblast to be 3 to 6 times more intense. Poulter (36) concluded that within a distance of two times the height of the inversion, no intensification would occur. Taylor (64) stated that up to a 10-dB increase can occur from inversion-produced refraction. Schomer (50) discussed both low-altitude inversions and jet stream focusing, for propagation distances of 2 to 40 miles and 30 to 300 miles, respectively. The short range case is applicable to mine blasts; a 3-times intensification was the maximum measured and the average was 1.8 times (5.1 dB).

APPENDIX D.--TERRAIN EFFECTS ON PROPAGATION

Terrain is another possibly critical factor for airblast propagation. The effect of the bench and blast face on levels and character was treated in the section on airblast characteristics. Wilton (81) discusses experiments of "air bursts" over valleys and the resulting 50-pct increase of intensity compared to flat terrain. He and Wiggins (80) both state that a 300-pct increase is possible. Topographic effects may be responsible for high airblast levels reported in the valleys of the Appalachian Mountain during strip mining.

APPENDIX E.--ADDITIONAL EQUATIONS AND STATISTICS

TABLE E-1. - Peak structure responses from airblasts

		Equation	Correlation coefficient	Standard error	Normalized standard error
ALL HOMES					
Peak SV (corner) versus	Peak AB (5 Hz)....................	SV=-0.0065 + 26.6	AB 0.725	0.092	0.556
	1/8-sec integrated AB (4-40 Hz)....	SV= .0675 + 31.4	AB .419	.112	.711
	1/4-sec integrated AB (4-40 Hz)....	SV= .0059 + 68.4	AB .626	.0963	.612
	1-sec integrated AB (4-40 Hz)......	SV= .0424 + 95.0	AB .491	.107	.686
	2-sec integrated AB (4-40 Hz)......	SV= .0482 +118	AB .437	.113	.705
	1/8-sec integrated AB (3.5-10 Hz)..	SV= .0021 + 71.3	AB .675	.0936	.579
	2-sec integrated AB (3.5-10 Hz)....	SV= .0198 +181	AB .541	.107	.661
	1/8-sec integrated AB (10-24 Hz)...	SV= .0864 + 38.2	AB .364	.118	.731
	1/4-sec integrated AB (10-24 Hz)...	SV= .0515 + 69.5	AB .498	.110	.680
	1-sec integrated AB (10-24 Hz).....	SV= .0746 + 98.4	AB .416	.115	.711
	2-sec integrated AB (10-24 Hz).....	SV= .0939 +100	AB .335	.119	.737
	1-sec C-weighted AB...............	SV= .0538 +223	AB .557	.102	.654
	4-sec C-weighted AB...............	SV= .0464 +454	AB .551	.104	.643
	Perceived level AB................	SV= .08 +692	AB .583	.105	.636
ONE-STORY HOMES					
Peak SV (corner) versus	Peak AB (5 Hz)....................	SV=-0.0106 + 27.2	AB 0.700	0.126	0.613
	1/8-sec integrated AB (4-40 Hz)....	SV= .0875 + 26.5	AB .313	.145	.772
	1/4-sec integrated AB (4-40 Hz)....	SV=- .0213 + 74.6	AB .593	.123	.612
	1-sec integrated AB (4-40 Hz)......	SV= .0528 + 87.3	AB .403	.139	.692
	2-sec integrated AB (4-40 Hz)......	SV= .0593 +109	AB .343	.150	.705
	1/8-sec integrated AB (3.5-10 Hz)..	SV=- .0161 + 79.2	AB .723	.110	.577
	2-sec integrated AB (3.5-10 Hz)....	SV= .0018 +206	AB .577	.131	.681
	1/8-sec integrated AB (10-24 Hz)...	SV= .121 + 27.6	AB .246	.155	.813
	1/4-sec integrated AB (10-24 Hz)...	SV= .0690 + 60.9	AB .388	.147	.769
	1-sec integrated AB (10-24 Hz).....	SV= .112 + 68.8	AB .266	.154	.807
	2-sec integrated AB (10-24 Hz).....	SV= .137 + 58.6	AB .182	.157	.824
	1-sec C-weighted AB...............	SV= .0660 +200	AB .449	.136	.677
	4-sec C-weighted AB...............	SV= .0561 +421	AB .458	.135	.672
	Perceived level AB................	SV= .11 +622	AB .521	.133	.692
TWO-STORY HOMES					
Peak SV (corner) versus	Peak AB (5 Hz)....................	SV= 0.0103 + 23.1	AB 0.707	0.049	0.365
	1/8-sec integrated AB (4-40 Hz)....	SV= .00570+ 62.2	AB .708	.0453	.364
	1/4-sec integrated AB (4-40 Hz)....	SV=- .0123 + 89.1	AB .726	.0441	.354
	1-sec integrated AB (4-40 Hz)......	SV=- .0202 +170	AB .762	.0415	.333
	2-sec integrated AB (4-40 Hz)......	SV= .0242 +151	AB .500	.0560	.450
	1/8-sec integrated AB (3.5-10 Hz)..	SV= .103 + 12.3	AB .118	.068	.511
	1/4-sec integrated AB (3.5-10 Hz)..	SV= .055 + 47.5	AB .395	.0630	.473
	1-sec integrated AB (3.5-10 Hz)....	SV= .110 + 18.0	AB .0817	.0683	.513
	2-sec integrated AB (3.5-10 Hz)....	SV= .125 + 0.156	AB .0005	.0686	.515
	1/8-sec integrated AB (10-24 Hz)...	SV= .0335 + 66.0	AB .707	.0485	.365
	2-sec integrated AB (10-24 Hz).....	SV= .0119 +254	AB .877	.0329	.247
	1-sec C-weighted AB...............	SV= .0196 +335	AB .964	.0171	.137
	4-sec C-weighted AB...............	SV= .022 +585	AB .941	.022	.177
	Perceived level AB................	SV= .06 +809	AB .680	.047	.403

TABLE E-2. - Integrated structure responses from airblasts

	Equation	Correlation coefficient	Standard error	standard error
ALL HOMES				
1/8-sec SV (corner) versus 1/8-sec AB (4-40 Hz)....	SV= 0.0375 + 17.1 AB	0.408	0.0628	0.736
1/4-sec SV (corner) versus 1/4-sec AB (4-40 Hz)....	SV= .0068 + 30.5 AB	.583	.0492	.689
1-sec SV (corner) versus 1-sec AB (4-40 Hz)........	SV= .0090 + 36.4 AB	.474	.0431	.811
2-sec SV (corner) versus 2-sec AB (4-40 Hz)........	SV= .0031 + 38.8 AB	.431	.0367	.909
1/8-sec SV (corner) versus 1/8-sec AB (3.5-10 Hz)..	SV= .0076 + 37.0 AB	.645	.0539	.616
1/4-sec SV (corner) versus 1/4-sec AB (3.5-10 Hz)..	SV= .0026 + 42.4 AB	.682	.0455	.622
1-sec SV (corner) versus 1-sec AB (3.5-10 Hz)......	SV= .0093 + 42.3 AB	.453	.0449	.822
2-sec SV (corner) versus 2-sec AB (3.5-10 Hz)......	SV= .0040 + 55.6 AB	.530	.0357	.857
1/8-sec SV (corner) versus 1/8-sec AB (10-24 Hz)...	SV= .0454 + 27.3 AB	.384	.0652	.745
1/4-sec SV (corner) versus 1/4-sec AB (10-24 Hz)...	SV= .0166 + 36.7 AB	.553	.0519	.708
1-sec SV (corner) versus 1-sec AB (10-24 Hz).......	SV= .0195 + 40.0 AB	.425	.0456	.836
2-sec SV (corner) versus 2-sec AB (10-24 Hz).......	SV= .0226 + 27.1 AB	.299	.0403	.964
1-sec SV (corner) versus 1-sec C-weighted..........	SV= .0103 + 92.0 AB	.580	.0399	.751
2-sec SV (corner) versus 4-sec C-weighted..........	SV= .0079 +134 AB	.550	.0340	.842
ONE-STORY HOMES				
1/8-sec SV (corner) versus 1/8-sec AB (4-40 Hz)....	SV= 0.0364 + 16.8 AB	0.352	0.081	0.839
1/4-sec SV (corner) versus 1/4-sec AB (4-40 Hz)....	SV=- .0250 + 38.8 AB	.630	.061	.762
1-sec SV (corner) versus 1-sec AB (4-40 Hz)........	SV= .00935+ 35.5 AB	.407	.056	.903
2-sec SV (corner) versus 2-sec AB (4-40 Hz)........	SV= .00520+ 36.8 AB	.364	.050	1.06
1/8-sec SV (corner) versus 1/8-sec AB (3.5-10 Hz)..	SV=- .0160 + 44.9 AB	.724	.0625	.618
1/4-sec SV (corner) versus 1/4-sec AB (3.5-10 Hz)..	SV=- .0273 + 51.3 AB	.746	.0549	.651
1-sec SV (corner) versus 1-sec AB (3.5-10 Hz)......	SV= .0091 + 44.0 AB	.434	.0582	.895
2-sec SV (corner) versus 2-sec AB (3.5-10 Hz)......	SV=- .0047 + 57.6 AB	.518	.0488	.963
1/8-sec SV (corner) versus 1/8-sec AB (10-24 Hz)...	SV= .0498 + 21.0 AB	.331	.0855	.845
1/4-sec SV (corner) versus 1/4-sec AB (10-24 Hz)...	SV=- .0039 + 43.7 AB	.555	.0685	.812
1-sec SV (corner) versus 1-sec AB (10-24 Hz).......	SV= .028 + 33.5 AB	.320	.0612	.940
2-sec SV (corner) versus 2-sec AB (10-24 Hz).......	SV= .0298 + 21.6 AB	.217	.0556	1.101
1-sec SV (corner) versus 1-sec C-weighted..........	SV= .00792+ 83.4 AB	.517	.053	.853
2-sec SV (corner) versus 2-sec C-weighted..........	SV= .00407+144 AB	.519	.046	.971
TWO-STORY HOMES				
1/8-sec SV (corner) versus 1/8-sec AB (4-40 Hz)....	SV= 0.0170 + 29.8 AB	0.563	0.034	0.472
1/4-sec SV (corner) versus 1/4-sec AB (4-40 Hz)....	SV= .0191 + 29.3 AB	.457	.031	.501
1-sec SV (corner) versus 1-sec AB (4-40 Hz)........	SV=- .00553+ 55.1 AB	.686	.017	.411
2-sec SV (corner) versus 2-sec AB (4-40 Hz)........	SV=- .0183 + 68.7 AB	.825	.0079	.251
1/8-sec SV (corner) versus 1/8-sec AB (3.5-10 Hz)..	SV= .0575 + 9.00 AB	.161	.0416	.544
1/4-sec SV (corner) versus 1/4-sec AB (3.5-10 Hz)..	SV= .0308 + 22.9 AB	.398	.0338	.464
1-sec SV (corner) versus 1-sec AB (3.5-10 Hz)......	SV= .0249 + 20.3 AB	.256	.0239	.234
2-sec SV (corner) versus 2-sec AB (3.5-10 Hz)......	SV= .0154 + 24.4 AB	.306	.0416	.426
1/8-sec SV (corner) versus 1/8-sec AB (10-24 Hz)...	SV= .0417 + 23.6 AB	.422	.0382	.500
1/4-sec SV (corner) versus 1/4-sec AB (10-24 Hz)...	SV= .0239 + 37.3 AB	.573	.0302	.460
1-sec SV (corner) versus 1-sec AB (10-24 Hz).......	SV= .0049 + 59.5 AB	.807	.0146	.293
2-sec SV (corner) versus 2-sec AB (10-24 Hz).......	SV= .0311 + 39.4 AB	.614	.0121	.353
1-sec SV (corner) versus 1-sec C-weighted..........	SV= .00865+104 AB	.833	.0128	.310
2-sec SV (corner) versus 2-sec C-weighted..........	SV= .0148 + 99.8 AB	.678	.010	.318

TABLE E-3. - Peak midwall responses from airblasts

		Equation	Correlation coefficient	Standard error	Normalized standard error
ALL HOMES					
Peak SV (midwall) versus	Peak AB (5 Hz).....................	SV= 0.181+126 AB	0.672	0.437	0.536
	1/8-sec integrated AB (4-40 Hz)....	SV= .286+217 AB	.560	.466	.590
	1/4-sec integrated AB (4-40 Hz)....	SV= .214+307 AB	.583	.457	.579
	1-sec integrated AB (4-40 Hz)......	SV= .241+519 AB	.562	.466	.590
	2-sec integrated AB (4-40 Hz)......	SV= .257+658 AB	.529	.481	.601
	1/8-sec integrated AB (3.5-10 Hz)..	SV= .364+238 AB	.447	.511	.638
	1/4-sec integrated AB (3.5-10 Hz)..	SV= .370+272 AB	.416	.519	.649
	1-sec integrated AB (3.5-10 Hz)....	SV= .423+415 AB	.376	.529	.661
	2-sec integrated AB (3.5-10 Hz)....	SV= .405+578 AB	.392	.525	.656
	1/8-sec integrated AB (10-24 Hz)...	SV= .241+369 AB	.709	.403	.504
	2-sec integrated AB (10-24 Hz).....	SV= .268+992 AB	.668	.425	.532
	1-sec C-weighted AB................	SV= .379+944 AB	.620	.442	.534
	4-sec C-weighted AB................	SV= .355+1862 AB	.607	.448	.558
	Perceived level AB.................	SV= .54 +2000 AB	.495	.494	.629
ONE-STORY HOMES					
Peak SV (midwall) versus	Peak AB (5 Hz).....................	SV= 0.277+104 AB	.706	.435	.461
	1/8-sec integrated AB (4-40 Hz)....	SV= .238+211 AB	.623	.445	.507
	1/4-sec integrated AB (4-40 Hz)....	SV= .113+317 AB	.626	.449	.510
	1-sec integrated AB (4-40 Hz)......	SV= .178+511 AB	.579	.465	.528
	2-sec integrated AB (4-40 Hz)......	SV= .194+660 AB	.539	.484	.532
	1/8-sec integrated AB (3.5-10 Hz)..	SV= .363+249 AB	.577	.480	.529
	1/4-sec integrated AB (3.5-10 Hz)..	SV= .420+259 AB	.482	.515	.568
	1-sec integrated AB (3.5-10 Hz)....	SV= .448+423 AB	.426	.532	.586
	2-sec integrated AB (3.5-10 Hz)....	SV= .356+700 AB	.500	.509	.561
	1/8-sec integrated AB (10-24 Hz)...	SV= .305+317 AB	.711	.413	.455
	2-sec integrated AB (10-24 Hz).....	SV= .299+889 AB	.678	.433	.477
	1-sec C-weighted AB................	SV= .352+997 AB	.649	.434	.493
	4-sec C-weighted AB................	SV= .351+1880 AB	.610	.452	.513
	Perceived level AB.................	SV= .51 +2768 AB	.600	.453	.529
TWO-STORY HOMES					
Peak SV (midwall) versus	Peak AB (5 Hz).....................	SV=-0.190+223 AB	0.711	0.414	0.558
	1/8-sec integrated AB (4-40 Hz)....	SV= .147+329 AB	.525	.477	.666
	1/4-sec integrated AB (4-40 Hz)....	SV= .147+400 AB	.564	.463	.647
	1-sec integrated AB (4-40 Hz)......	SV= .142+719 AB	.571	.460	.643
	2-sec integrated AB (4-40 Hz)......	SV= .180+858 AB	.514	.480	.671
	1/8-sec integrated AB (3.5-10 Hz)..	SV= .420+191 AB	.248	.556	.759
	1/4-sec integrated AB (3.5-10 Hz)..	SV= .339+279 AB	.306	.546	.745
	1-sec integrated AB (3.5-10 Hz)....	SV= .435+367 AB	.280	.551	.750
	2-sec integrated AB (3.5-10 Hz)....	SV= .474+405 AB	.257	.555	.756
	1/8-sec integrated AB (10-24 Hz)...	SV= .115+493 AB	.727	.394	.538
	2-sec integrated AB (10-24 Hz).....	SV= .186+1261 AB	.667	.428	.584
	1-sec C-weighted AB................	SV= .395+898 AB	.575	.458	.640
	4-sec C-weighted AB................	SV= .357+1844 AB	.589	.457	.639
	Perceived level AB.................	SV= .53 +1561 AB	.427	.518	.737

TABLE E-4. - Integrated midwall responses from airblasts

	Equation	Correlation coefficient	Standard error	Normalized standard error
ALL HOMES				
1/8-sec SV (midwall) versus 1/8-sec AB (4-40 Hz)......	SV= 0.175 +120 AB	0.504	0.303	0.666
1/4-sec SV (midwall) versus 1/4-sec AB (4-40 Hz)......	SV= .113 +141 AB	.561	.224	.596
1-sec SV (midwall) versus 1-sec AB (4-40 Hz)..........	SV= .0832+160 AB	.514	.165	.643
2-sec SV (midwall) versus 2-sec AB (4-40 Hz)..........	SV= .0675+174 AB	.538	.131	.999
1/8-sec SV (midwall) versus 1/8-sec AB (3.5-10 Hz)....	SV= .246 +117 AB	.355	.333	.724
1/4-sec SV (midwall) versus 1/4-sec AB (3.5-10 Hz)....	SV= .196 +161 AB	.374	.255	.666
1-sec SV (midwall) versus 1-sec AB (3.5-10 Hz)........	SV= .148 +112 AB	.305	.187	.729
2-sec SV (midwall) versus 2-sec AB (3.5-10 Hz)........	SV= .104 +155 AB	.364	.147	.706
1/8-sec SV (midwall) versus 1/8-sec AB (10-24 Hz).....	SV= .144 +209 AB	.651	.270	.600
1/4-sec SV (midwall) versus 1/4-sec AB (10-24 Hz).....	SV= .0976+230 AB	.702	.196	.513
1-sec SV (midwall) versus 1-sec AB (10-24 Hz).........	SV= .0885+239 AB	.620	.154	.618
2-sec SV (midwall) versus 2-sec AB (10-24 Hz).........	SV= .0642+258 AB	.697	.113	.544
1-sec SV (midwall) versus 1-sec C-weighted............	SV= .126 +297 AB	.560	.159	.647
2-sec SV (midwall) versus 4-sec C-weighted............	SV= .0382+753 AB	.711	.108	.520
ONE-STORY HOMES				
1/8-sec SV (midwall) versus 1/8-sec AB (4-40 Hz)......	SV= 0.116 +124 AB	0.597	0.287	0.689
1/4-sec SV (midwall) versus 1/4-sec AB (4-40 Hz)......	SV= .0335+157 AB	.640	.218	.523
1-sec SV (midwall) versus 1-sec AB (4-40 Hz)..........	SV= .0151+187 AB	.725	.124	.460
2-sec SV (midwall) versus 2-sec AB (4-40 Hz)..........	SV= .0348+178 AB	.633	.115	.488
1/8-sec SV (midwall) versus 1/8-sec AB (3.5-10 Hz)....	SV= .238 +124 AB	.472	.326	.631
1/4-sec SV (midwall) versus 1/4-sec AB (3.5-10 Hz)....	SV= .213 +113 AB	.435	.264	.612
1-sec SV (midwall) versus 1-sec AB (3.5-10 Hz)........	SV= .111 +154 AB	.534	.158	.562
2-sec SV (midwall) versus 2-sec AB (3.5-10 Hz)........	SV= .0898+177 AB	.581	.126	.535
1/8-sec SV (midwall) versus 1/8-sec AB (10-24 Hz).....	SV= .156 +186 AB	.684	.269	.523
1/4-sec SV (midwall) versus 1/4-sec AB (10-24 Hz).....	SV= .0625+228 AB	.780	.183	.427
2-sec SV (midwall) versus 2-sec AB (10-24 Hz).........	SV= .0575+227 AB	.782	.0963	.410
2-sec SV (midwall) versus 4-sec AB C-weighted.........	SV= .0452+640 AB	.759	.096	.407
TWO-STORY HOMES				
1/8-sec SV (midwall) versus 1/8-sec AB (4-40 Hz)......	SV= 0.111 +179 AB	0.456	0.313	0.744
1/4-sec SV (midwall) versus 1/4-sec AB (4-40 Hz)......	SV= .105 +168 AB	.503	.228	.662
1-sec SV (midwall) versus 1-sec AB (4-40 Hz)..........	SV= .0894+179 AB	.395	.188	.818
2-sec SV (midwall) versus 2-sec AB (4-40 Hz)..........	SV=- .0565+443 AB	.600	.131	.707
1/8-sec SV (midwall) versus 1/8-sec AB (3.5-10 Hz)....	SV= .282 + 89.6 AB	.185	.354	.820
1/4-sec SV (midwall) versus 1/4-sec AB (3.5-10 Hz)....	SV= .191 +131 AB	.264	.261	.747
1-sec SV (midwall) versus 1-sec AB (3.5-10 Hz)........	SV= .191 + 50.7 AB	.109	.209	.883
2-sec SV (midwall) versus 2-sec AB (3.5-10 Hz)........	SV= .217 - 58.6 AB	-.0573	.171	.885
1/8-sec SV (midwall) versus 1/8-sec AB (10-24 Hz).....	SV= .0863+275 AB	.645	.275	.632
1/4-sec SV (midwall) versus 1/4-sec AB (10-24 Hz).....	SV= .0725+288 AB	.651	.206	.583
1-sec SV (midwall) versus 1-sec AB (10-24 Hz).........	SV= .0869+283 AB	.493	.183	.774
1-sec SV (midwall) versus 1-sec C-weighted............	SV= .149 +234 AB	.417	.186	.809

APPENDIX F.--STRUCTURE RESPONSES FROM OTHER IMPULSIVE NOISE SOURCES

Some research has been done on response from transient air overpressures, primarily to assess sonic booms. Kamperman (18) investigated the transfer functions of airblasts from quarries into annoying floor motions. He used only standard deviation to rank the descriptors and did not measure 2-Hz, 5-Hz, and 6-Hz peak airblasts. As with the midwall response results from this study, Kamperman found that the best correlations were with various SEL values and that the difference among many of the techniques were not significant. Some of his results (tables 3.4-4) are comparable to the Bureau's midwall responses (for example, the C-slow, peak, and 4- to 200-Hz SEL airblasts versus peak floor vibrations). However, his values are 3 to 6 times lower indicating that airblasts are a poorer source of energy for floor excitation than for vertical walls.

Kryter (19) cites a White Sands study with worst-case displacements of 0.035 inches for the ceiling, 0.053 inches for the midwall, and 0.016 inches for racking from a 5-lb/ft^2 (0.0347-lb/in^2 or 142 dB) sonic boom;[1] assuming a midwall frequency of 16 Hz and a racking frequency of 8 Hz, these become 3.52, 5.33, and 0.80 in/sec particle velocities, respectively. These are higher than the extrapolation of the mean of the Bureau's blast responses (from figs. 30 and 32) by about 30 pct, but within the ranges measured.

Kryter also discusses the difference in spectra among sonic booms from different size planes and the greater damage risk from larger planes. The larger aircraft have increased low-frequency energy (2-6 Hz) so the energy spectra for the boom should better match that of the structure. As with blasting, increased response with high frequency has been observed and dominates the response plots ("high" this time refers to 4-16 Hz, as compared to type 2 airblast frequencies of 0.5-1.5 Hz).

Sutherland (63) described acoustic response tests on 8x10-foot wall panels, presumably from steady-state sources and found maximum responses at resonance frequencies of

5.57 g/psi for uninsulated wood-frame wall,

2.79 g/psi for insulated wood-frame wall,

and 0.10 g/psi for 8-inch concrete block wall.

Resonant frequencies were not given, but assuming 16 Hz for the wood-frame wall, 25 Hz for the block wall, and an airblast level of 0.01 psi (131 dB), the three responses become 0.21, 0.107, and 0.0024 in/sec, respectively. Unlike the wood-frame walls, the concrete block wall responded greater at other

[1]All sonic boom and long-range airblast measurements were made with wideband systems (at least 0.1-Hz low-frequency cut-off) unless specified otherwise. These overpressure values are based on a wide-enough bandwidth to measure all the acoustic energy present. For convenience, sound levels re 20 x 10^{-6} N/m^2 have been calculated for these overpressures.

than its resonant frequency, increasing to 1.0 g/psi (0.024 in/sec/psi) at 30 times that of its natural frequency. These values are lower than the Bureau's measured response by 5 to 10 times, either because of the steady-state sources or the modeling problems with wall sections.

Wiggins (80) extensively describes the response of structures to sonic booms and includes the analysis of the complicated response-spectrum technique and also the more practical use of peak response (e.g., peak particle velocity) and peak airblast overpressure. Wiggins computed racking responses from the effective load (front minus back pressure) for comparisons with measured responses and measured mean response data from both low- and high-frequency sonic booms (3-10 Hz). He noted 3.38 to 7.81 micro inch per inch per pound per square foot (μin/in/psf) strain in a vertical stud, racking displacements of 3.5 to 6.7 x 10^{-4} in/psf. Window strains ranged up to 23 μ in/in/psf and peak displacements up to 0.13 in/psf depending on window size and aircraft path. Wiggins discussed how various motion or sound descriptors can be used depending on the relative frequencies of the source and the object affected. For airblast analysis, this is complicated by the frequency variability among the different airblast types. It may be possible, although impractically complex, to develop a descriptor that simulates peak overpressures for $T_{AB} > T_S$ and impulse for $T_{AB} < T_S$ (where T is the period). Wiggins recommended peak pressure alone, since no better descriptor was then known.

Conversion of the Wiggins peak displacement data to peak particle velocities using 8 Hz for the racking and 16 Hz for the midwalls, gives 0.018 to 0.034 in/sec/psf and 0.21 to 0.44 in/sec/psf, respectively. Structure responses from airblasts (figs. 30 and 32), are significantly higher at 0.09 to 0.11 in/sec/psf and 0.39 to 0.71 in/sec/psf.

Newberry (33) measured sonic boom effects on house walls and roofs of 2.3 to 4.8 lb/ft^2. His displacement responses ranged from 0.00074 to 0.0080 in/psf, roughly corresponding to the highest of Wiggin's responses for racking and midwalls, respectively. Conversion to particle velocities gives maximum wall responses of up to 0.80 in/sec/psf which is within the range of the Bureau's findings for midwalls (fig. 32). His roof response was about one-third of the Bureau's whole house racking motion.

Leigh (22) describes sonic boom response measurements in a wood-frame house with a measured peak displacement of 0.034 inch at 16.7 Hz, and acceleration of 0.64 g at 20 Hz from a sonic boom of 2.29 lb/ft^2 (135 dB). These do not covert to the same particle velocity, suggesting that Leigh's midwall motions are not sinusoidal (unlike the Bureau's wall motion data). From displacement and acceleration, the responses compute to 1.55 and 0.86 in/sec/psf, respectively, somewhat higher than Newberry. Leigh also tested gypsum panels for sonic-boom-induced strain, and measured 31 to 47 μ in/in for a 10 lb/ft^2, and 0.069 lb/in^2, sonic boom N-wave of 100-msec duration.

Mayes (25) described sonic boom and blast-induced stresses in a wall stud and found values of 33 to 50 lb/in^2/psf for sonic booms and 14 to 16.3 lb/in^2/psf for single charge blasts.

Clarkson and Mayes (7) describe building responses from sonic booms including wall accelerations, displacements, and stresses. The stress results were previously reported by Mayes (25), and the shear displacements and the wall accelerations corresponding to a 2-lb/ft^2 sonic boom (0.0139 lb/in^2, 134 dB) were 0.0030 to 0.0065 inch and 0.1 to 0.4 g, respectively. Midwall displacements were different for the inside and outside walls; the maximum envelopes were 0.0063 inch and 0.0144 inch for the 2-lb/ft^2 sonic boom. Unlike most other results, the inside wall responses measurement did not increase linearly with increasing overpressure.

Blume (3) studied the responses of structure to sonic booms, providing much of the data for the comprehensive sonic boom summarizes (7, 19, 25, 63, 80). Roof line racking displacements of 0.0042 to 0.0050 inch were measured for overpressures of approximately 2.0 lb/ft^2, and maximum midwall displacements and accelerations were 0.023-0.034 inch and 0.46-0.74 g. (Mean values were typically lower by a factor or about one-half.)

The Langley Research Center studied Concorde-noise-induced building vibrations (29-31). Because the responses were from steady-state noise sources, and were processed as 1/2-sec integrated values, they are not comparable with the data from sonic boom and airblast response studies.

Seaman (51) describes a theoretical analysis of window breakage recognizing that the process is nonlinear and that a small chance for damage exists even at low airblast levels for large enough populations.

A summary of all structure responses from the various impulsive noise sources is given in tables 7 and 8 in the main text of this report.

APPENDIX G.--OTHER AIRBLAST DAMAGE RESEARCH

Early research by the Bureau of Mines (82) and Ballistics Research Laboratory (36) determined that the breakage of window glass in structures should occur at lower levels than other damage. Windes (82) evaluated glass breakage from small open-air shots consisting of one to two sticks of 1- by 8-inch dynamite at distances of 3 to 30 feet. Damage occurred at overpressures of 0.88 to 1.10 lb/in^2 (170 to 172 dB); none was observed at 0.62 to 0.72 lb/in^2 (167 to 168 dB). These levels apply to properly mounted glass; however, glass under strain could fail at overpressures as low as 0.10 lb/in^2 (151 dB). Perkins and Jackson (36) conducted extensive tests on glass panes mounted in frames with similar results. They defined damage threshold for properly mounted glass of 0.75 lb/in^2 (168 dB), and for poorly mounted glass under stress of 0.10 lb/in^2 (151 dB). They also noted that rattling of window sashes occurred at 0.03 to 0.05 lb/in^2 (141 to 145 dB). It has been recognized that these levels are too high for continuous use in urban areas and where there are large number of people or objects affected. They do not provide realistic guidelines for either blast design or environmental regulation (57). The likely reasons for their high damage thresholds are the small high-frequency shots and small panes studied.

Poulter (39) evaluated glass breakage and plaster damage produced by airblast from totally unconfined explosives. He found that glass damage could occur at cube-root-scaled distances as high as 260 ft/lb$^{1/3}$, and plaster cracking as high as 63 ft/lb$^{1/3}$. This agrees with the conclusions of other studies (36, 82) that plate glass is more damage-sensitive than plaster. Using the "unconfined" line in figure B-5, these minimum-scale distances correspond to approximately 0.0320 lb/in^2 (141 dB) and 0.290 lb/in^2 (160dB), respectively. Poulter's scaled-distance values are based on weather conditions which favor maximum damage.

Several studies of airblast propagation by Reed have been indirectly concerned with the problem of glass damage (1, 42–43, 45). Primarily interested in airblast at large distances (tens of miles) from large-scale surface blasts, Reed has also studied other related problems such as the accidental Medina blast in San Antonio, Tex., 1968, which resulted in claims for 3,644 windows (43, 45). Reed predicted the existence of strong focusing east of the blast produced by westward winds at a 6,000-ft altitude and correlated this with the many damage claims for the large population impacted (45). He noted that damage costs become very small below 3 mb (0.0435 lb/in^2, 144 dB), although they still exceed the laboratory tests conducted by Pittsburgh Plate Glass Co. by a factor of 10. Overall claims for window damage correspond to \$7.00 per 1,000 people for an overpressure of 1.12 mb (0.0162 lb/in^2, 135 dB), and can be computed for other pressures by the following relationship:

$$C = 4.75 \times 10^{-3} (\Delta p)^{2.78},$$

where C is the cost in dollars (1973) and Δp is the overpressure in millibars (1 mb = 0.0145 lb/in^2). From the Medina blast, Reed developed two equations for probabalities of single pane damage and number of panes broken based on a large population sample (43):

$$P = 3.71 \times 10^{-6} A^{1.22} (\Delta p)^{2.78},$$

where P is the breakage probability for a single pane, A is the pane area, in square feet, and Δp is the peak overpressure, in millibars. Reed also derived a predictor for the number of broken panes:

$$Q = 1.3 \times 10^{-4} N (\Delta p)^{2.78},$$

where Q is the number of panes broken, and N is the population impacted. Both equations give very small estimates of damage at typical airblast levels of 120 to 130 dB. At 130 dB, for a large window (64 ft^2), and significant population (100), the two values become $P = 1.67 \times 10^{-4}$ and $Q = 3.67 \times 10^{-3}$, still a small damage risk.

Reed also examined the log-normal damage model by combining the high and low level data for a new window damage equation:

$$\Delta p \text{ (50\%)} = 75 \times (2.5)^{\pm 1}$$

where Δp (50%) is the overpressure, in millibars, corresponding to the 50-pct probability of damage (43). This gives a wide range of values, 30 to 187 mb (0.44 to 2.71 lb/in^2, 164 to 179 dB). However, this equation is not useful for the mining airblast problem since it is necessary to consider the probabilities at the extremes of the predictions (e.g., low levels). Reed's glass breakage probability and also a sonic boom risk analysis by Wiggins (79) are given in figure 40 (main text). Two other papers by Reed specified 2 mb (0.029 lb/in^2, 140 dB) as a general glass damage threshold for single point explosions in air (1).

Taylor described an analyses by Warren on glass breakage in 30 greenhouses from small line charges (64). For an airblast level of 4.2 lb/ft^2 (0.0292 lb/in^2, 140 dB), breakage was 0.7 pct, or 239 out of 35,000. This is approximately ten times what would be predicted by Reed's equation (43); however, the state of stress and other conditions in the greenhouse are not discussed.

An extensive review by Sutherland (63) described fatigue in wood-frame and concrete residential walls from steady-state sound. Damage was found for the following cases: 143 dB sound pressure level for 80 min (walls); 145 dB sound pressure level for 20 min (roof); and 153 dB sound pressure level for 10 min (8-inch concrete wall). No damage was observed in the concrete wall from a 139 dB level held for 170 minutes. Fatigue stress for the concrete at 5×10^6 cycles was 55 pct of the ultimate stress.

An analysis of airblast damage data for glass was included in general analysis of environmental impact of noise and vibration by von Gierke (70). He lists safe charge weights for a variety of conditions, corresponding to less than a 50-pct probability of the breakage of even a single pane. For clustered populations ($N \geq 4$) and surface explosions, the safe quantity of explosive is--

$$W < 328 R^3/N,$$

where N is the population impacted, R is the distance, in kilometers, and W the charge weight per delay, in kilograms. For a uniform population distribution, this reduces to $W < 40\ R^3$, where R is the distance to the nearest residence. Proper confinement allows an increase in explosive weights by a factor of about 80 times, assuming that the scale depth of burial exceeds 1.4 $m/kg^{1/3}$, a condition usually met in typical mine blasts (scale depths of burial can be computed by Wiss' formulas given in the section on blast design). The safe charge weights than become $W < 26{,}430\ R^3/N$ for a clustered population, and $W < 3{,}200\ R^3$ for a uniform distribution. These are probably stricter than necessary for many mining situations, (such as well confined blasts such as for highwalls). Von Gierke also gives a variation of Reed's broken glass estimation equation:

$$Q = 1.56 \times 10^{-16}\ N\ (PK)^{2.78},$$

where Q is the number of panes broken, N is the population impacted and PK is the peak-to-peak amplitude of the pressure variation in Pascals (N/m^2). Von Gierke assumes that PK is 2.7 times the peak free air pressure owing to both reflection at the ground and the use of peak-to-peak pressures. However, blasting at close ranges usually does not generate significant negative phases (figs. 3-5 and 28-29 in the main text), and ground reflection effects are already included in the measured overpressures. Therefore, the equation as given is a reasonable predictor for glass damage from airblast. A worst case from figure 3 corresponds to PK equalling two times the peak overpressure, giving a Q of 2.67×10^{-9} for N equalling 100 and peak overpressure of 200 N/m^2 (149 dB).

Redpath (41) combined several studies including Reed's on the Medina blast (43) and another accidental surface blast to derive a glass breakage predictor which he feels is more representative (and restrictive) in the overpressure range of 0.1 lb/in^2 to 1.0 lb/in^2 (151 to 171 dB). At an overpressure of about 0.060 lb/in^2 (146 dB), he predicts a breakage probability of 0.0012 (0.12 pct) which is close to Reed's estimate of 8.9×10^{-4} for a window pane area of 3.5 ft^2. Extrapolating beyond the limits of Redpath's data gives a glass damage probability of 0.00010 (0.010 pct) at 0.036 lb/in^2 (141 dB).

Implicit in the analyses of the damage probabilities are several statistical assumptions. The airblast events are considered independent; that is, the damage risk not influenced by past airblast history. This contrasts to the hypothesis that a window which was not broken by a given airblast would be less likely to be broken by another airblast at the same level. The damage risk is also assumed to be directly proportional to the number of exposures so that risk from all airblasts is the sum of all the individual risks. As an example, a 10^{-5} damage probability from one blast becomes 10^{-2} for 1,000 similar blasts.

APPENDIX H.--SONIC BOOM DAMAGE

Sutherland (63) summarized theoretical and experimental studies of sonic boom damage. He notes that a sonic boom overpressure of 2.5 lb/ft^2 (0.0174 lb/in^2, 136 dB) would preclude damage, based on the theoretical damage calculations of stresses in the structure. The results of experimental sonic boom tolerance tests at White Sands were--

Cracks in plaster on wood lath............	6.5-10 lb/ft^2 (0.045-0.069 lb/in^2, 144-148 dB)
Nail popping--1/2-inch gypsum board........	10.3 lb/ft^2 (0.0715 lb/in^2, 148 dB)
Paint flaking on old gypsum board..........	4.0 lb/ft^2 (0.0625 lb/in^2, 147 dB)
Falling bric-a-brac and rattling dishes....	6-11 lb/ft^2 (0.0417-0.0764 lb/in^2, 143-148 dB).

The estimated peak stress in the wood frame at an overpressure of 6.5 lb/ft^2 (0.045 lb/in^2, 144 dB) is 180 lb/in^2, which corresponds to a strain of 150 x 10^{-6} μ in/in. Assuming the same amount of strain in the cement or mortar in plaster or gypsum board gives peak stresses of 290 to 810 lb/in^2 (depending on the board's formulation). These are close to the failure stresses observed in static tests.

Sutherland (63) also reviews window and other damage from sonic booms. In a study of 24 windows 3 ft x 3 ft x 1/8 in, no failures were observed below 20 lb/ft^2 (0.139 lb/in^2, 154 dB). However, precracked windows failed at levels as low as 7.6 lb/ft^2 (0.053 lb/in^2, 145 dB). A sonic boom criterion for no damage is given by--

$$p_o \left(\frac{a}{h}\right)^2 \geq 0.8 \times 10^6 \ lb/ft^2,$$

where p_o is sonic boom overpressure, in pounds per square foot, a is the side of an approximately square window, and h is the window thickness (same units as a). With a/h generally less than 330, the safe maximum overpressure is 7.3 lb/ft^2 (0.051 lb/in^2, 145 dB). Sutherland noted that for large population samples and sonic boom overpressures of 1.7 lb/ft^2 (0.0118 lb/in^2, 132 dB), it was typical to receive one claim per 300,000 homes. These involved mostly bric-a-brac with about 10 pct of the claims for plaster damage.

Wiggins analyzed the sonic boom tests in Oklahoma City and White Sands in detail, listing all the "damage events" and associated boom levels which occurred at White Sands (80). The lowest value for any event was 2.1 lb/ft^2 (0.0146 lb/in^2, 134 dB) which caused the fall of a fleck of loose paint. A plaster crack from structure racking was observed at approximately 4.2 lb/ft^2 (0.029 lb/in^2, 140 dB); however, plaster cracks typically required 7 to 14 lb/ft^2 (0.049 to 0.097 $lb.in^2$, 145 to 151 dB). A hairline settlement crack was extended about 2 inches after 20 booms of 5.2 lb/ft^2 (0.0361 lb/in^2, 142 dB); however, further extension was also caused by a person jumping on the floor near the wall. Wiggins lists cases of glass damage, which typically had thresholds of 8 to 16 lb/ft^2 (0.056 to 0.11 lb/in^2, 146 to 152 dB) and notes that a significant amount of breakage occurred at 38 lb/ft^2 (0.264 lb/in^2, 159 dB). Much of the glass damage was attributed to impact of the severely rattling window sashes, rather than direct pressure against the panes. Consequently, the mechanism of glass failure may be different for windows in loose frames and glass mounted to be immovable. The panes which failed at White Sands were two 8- x 10-foot store front windows (at 38 lb/ft^2). Wiggins evaluates the Oklahoma City data by recommending a 5-lb/ft^2 (0.035 lb/in^2, 142-dB) safe level for new plaster and 10 lb/ft^2 (0.069 lb/in^2, 148 dB) for cured plaster.

Clark (6) describes a sonic boom impact study in the St. Louis area which involved widespread pretest publicity and mechanisms for complaints. Out of 76 flights over the metropolitan area of 3 million people, a total of 84 complaints were received, all for damage or falling objects. Investigators judged 27 of these complaints to have likely validity (40 pct plaster, 30 pct glass, 10 pct both). Sonic boom overpressures were not measured, but estimated to be up to 3 lb/ft^2 (0.021 lb/in^2, 137 dB).

Kryter (19) calculated maximum "safe overpressures" for large panes subjected to booms from four different aircraft, based on Wiggins' (80) maximum failure rate of one crack per 100,000 (table H-1). A low damage threshold is evident for the largest windows, consistent with the matching of their 3-Hz natural frequency with long N-wave duration for the large aircraft (the 0.250- to 0.350-sec period is approximately equivalent to 3 Hz). Table H-1 shows that a relatively low sonic boom overpressure level will meet a 10^{-5} damage probability for a 100- x 200-inch window. However, this window is larger than the majority of windows residences, as is the next smaller size. Additionally, the 1/4-inch thickness appears substandard for the two largest window sizes, where 5/16 inch is normal for an 80-ft^2 pane and 3/8 or 1/2 inch is standard for a 139-ft^2 pane (51). Increasing the thickness of the 80-ft^2 and 139-ft^2 windows increases their safe levels by 2 and 5 dB, respectively.

TABLE H-1. - Maximum safe[1] sonic boom overpressures for large glass panes of 1/4-inch thickness (19)

Window size, in	Area, ft^2	Natural frequency, Hz	N-wave duration, sec	Typical aircraft	Maximum safe overpressure Lb/ft^2	Maximum safe overpressure Lb/in^2	Maximum safe overpressure dB
100 x 200	139	3.0	0.250-0.350	SST, B-70.......	0.35	0.0024	119
			.170	B-58..........	.59	.0041	123
			.100	F-106.........	1.4	.0097	131
76 x 152	80.2	5.0	.250-.350	SST, B-70.......	1.57	.0109	132
			.170	B-58..........	1.57	.0109	132
			.100	F-106.........	2.6	.0181	136
53 x 106	39	10.0	.250-.350	SST, B-70.......	5	.035	142
			.170	B-58..........	5	.035	142
			.100	F-106.........	5	.035	142

[1]Safe as defined as less than one chance in 10^5 per pane per boom.

The safe values from table H-1, corrected for thickness are plotted in figure H-1. These are based on the probability of one minor crack in 100,000 window-exposures. The frequency notably affects the safe level, demonstrating

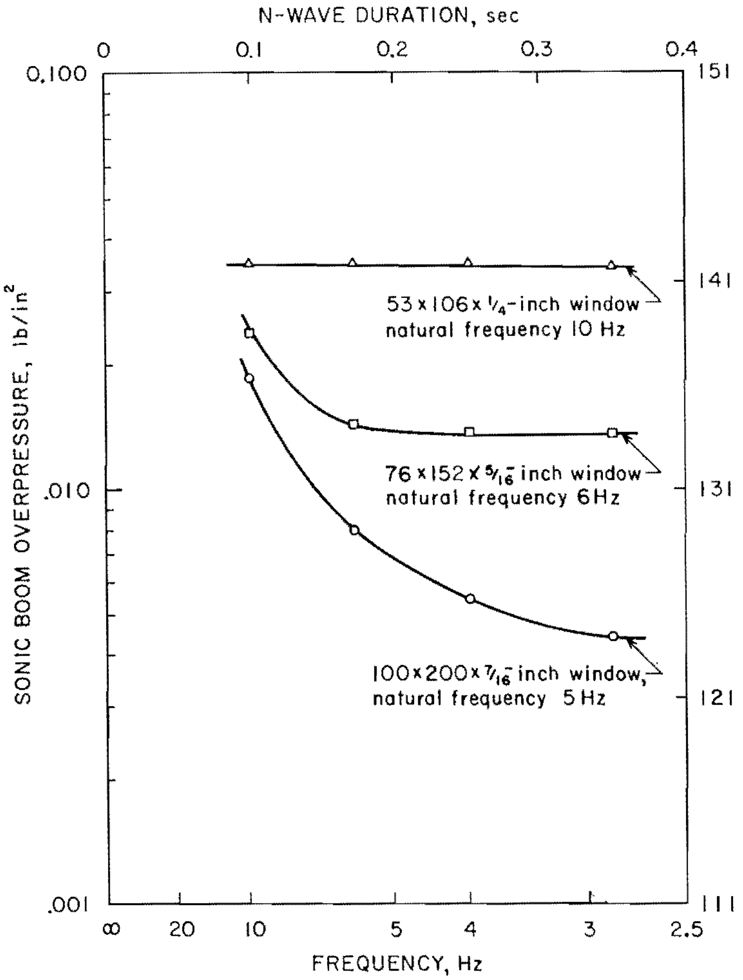

FIGURE H-1. - Maximum safe sonic boom overpressures based on a 10^{-5} glass breakage probability.

that failure probability decreases for sonic booms of frequency higher than that of the window resonance. For airblasts, the type 1 airblast theoretically should present a lower damage probability than the low-frequency type 2. Figure H-1 shows that it is prudent to apply a safety factor of 9 dB per doubling of window area for large panes. Consequently, the maximum recommend (0.1 Hz) airblast overpressure of 134 dB should then be reduced by 9 dB per doubling of window size above 80 ft^2, to maintain the same 10^{-5} damage probability. Where a higher damage probability is acceptable, this correction is not necessary. Reed's damage equation (43) gives 7.3 dB per doubling of area, which is in good agreement.

Leigh examined the failure and fatigue of plaster panels subjected to sonic-boom-type loading (22). He subjected 13 panels to 1,000 N-waves of 10-lb/ft^2 (0.0694-lb/in^2, 148-dB) overpressure, having a duration of 100 msec. Generated strains were 31 to 47 μin/in; the single failure was attributed to too much clamping pressure around the edges. Noting that the static failure strain for plaster panels (wallboard) is approximately 460 μin/in and resulting stress 300 lb/in^2, Leigh predicted that panels will fail at 10^4 sonic booms that produce 260 μin/in.

Taylor's analysis of the general airblast problem included relevant sonic boom data (64). The St. Louis sonic boom study, involving many millions of boom-person exposures (BPE), concluded that superficial damage such as glass cracks began at levels of 2.0 to 3.0 lb/ft^2 (0.0139 to 0.0208 lb/in^2, 134 to 138 dB), and a similar study at Oklahoma City found no damage at 6 lb/ft^2. (Smaller aircraft produce less damaging higher frequency sonic booms.) Taylor noted that 2 lb/ft^2 overall is a minimum damage threshold for general sonic boom exposure.

A summary review of the effects of sonic booms and similar impulsive noises on structures was also made by the National Bureau of Standards for the U.S. Environmental Protection Agency (32). They noted that 2,000 flights in Virginia, Missouri (St. Louis study), Oklahoma (Oklahoma City study), and California (Edwards Air Force Base) produced no significant damage at overpressures up to 6 lb/ft^2 (0.042 lb/in^2, 142 dB). Similarly, no significant damage was found in New Mexico (White Sands study) for 1,200 flights at up to 3.3 lb/ft^2 (0.023 lb/in^2, 139 dB). In unmonitored tests, it was normal to receive 12 to 25 claims per million BPE for glass, plaster, or bric-a-brac at levels of 1.8 lb/ft^2 (0.0125 lb/in^2, 133 dB).

Another review of sonic boom damage was made by Clarkson and Mayes (7). They summarized the damage claims from the St. Louis study (390 x 10^6 BPE), Oklahoma City (462 x 10^6 BPE), and Chicago (305 x 10^6 BPE). The boom overpressures were nominally 1.8 lb/ft^2 (0.0125 lb/in^2, 133 dB), except for Oklahoma City at 1.2 lb/ft^2 (0.0083 lb/in^2, 129 dB); payment for damage claims were \$151, \$192, and \$377 per million BPE, respectively, for the three areas. For normal blasting impact, claims of this magnitude would be essentially insignificant. Clarkson and Mayes describe an analysis of cumulative crack growth damage in plaster on wood lath in a two-story structure over a period of several weeks. Booms were kept at 5 lb/ft^2 (0.0347 lb/in^2, 142 dB) for 20 days, and then increased in increments of 2 lb/ft^2 until damage occurred. The change of slope at 11 lb/ft^2 (0.0764 lb/in^2, 148 dB) corresponded to the onset of damage.

Blume's study of sonic boom responses of two residences at Edwards Air Force Base found no damage from the approximately 2.2 lb/ft^2 (0.0153 lb/in^2, 134 dB) sonic booms (3). However, three cases of damage occurred within the community, out of 110,000 panes, with an estimated minimum overpressure of 3.75 lb/ft^2 (0.026 lb/in^2, 139 dB).

APPENDIX I.--ANNOYANCE FROM IMPULSIVE NOISE

Most studies of annoyance from impulsive noise have been done for predictions of sonic boom and artillery impact.

The CHABA noise guidelines include annoyance from impulsive sources based on C-weighted day-night average (L_{cdn}) (70). They generalize that the yearly C-weighted average should be kept below 55 dB for minimum complaints (for any type or duration of noise). Based mainly on Borsky's sonic boom survey (4), which involved a test program of eight events per day for 6 months, the CHABA team derived three specific annoyance relationships for impulsive noises. Two of these are survey curves from the Oklahoma City study representing impulses with differences between peak and L_{sc} (C-weighted sound-exposure level) of 26 and 20 dB. The 26 dB line in the CHABA report most closely represents blasting, and shows 2.5, 5, and 13 pct annoyed at 57, 58, and 60 dBL_{cdn}, respectively. The third CHABA annoyance criteria is a generalized annoyance relationship based on 19 surveys and shows approximately 5, 8, and 15 pct annoyed at 57, 60, and 65 dBL_{cdn}, respectively. The CHABA report also discusses the use of C-weighted sound exposure measurements, which are used to derive L_{cdn}, but does not recommend maximum L_{sc} levels. No mining-type blasts were used in these analyses.

Using the L_{cdn} curves from the CHABA report (70) or from Stachura's study (61), an airblast which has a constant 105 dBC level for 1 sec would give an L_{cdn} level of 55.6 dB. Consequently, the upper limit of the safe airblast level derived from analysis of response and damage is equal to the annoyance criterion of 56 dB (approximately 5 pct annoyed), where some complaints could be expected. This assumes that the CHABA guidelines do apply to blasting as evaluated by C-weighted sound-exposure levels. Shot 101 which was used as the type 1 example, was an almost constant 102 dBC-slow for 0.95 sec, or an L_{dn} level of 52.4 dB. No attempt was made to compute L_{cdn} for the many blasts in table 3 (in the main text of this report) since almost all have time-varying C-weighted levels. Presumably, L_{cdn} levels could be obtained from all the recordings for comparisons with other sound descriptors and measured responses. The Department of Housing and Urban Development (HUD) is using L_{cdn} contours to evaluate the suitability of land for development, based on the CHABA criteria. The proposed 65 dB L_{cdn} would allow nine events per day of 105 dBC-slow.

The Environmental Protection Agency (EPA) recommends an L_{dn} of 55 dB outdoors in residential areas to protect the public health and welfare and prevent annoyance based on the CHABA guidelines (68). No special provisions are specified with regard to impulse noise and annoyance.

Attempts to produce a single descriptor for all annoying noise are laudable; however, they tend to smooth over significant differences in characteristics and fail to represent the annoyance potential of infrequent, impulsive noises. The L_{cdn} technique averages the C-weighted airblast over periods of 1 day to 1 year, equating it to a lower level, steady-state source. However, it does not allow for the different annoyance factors that exist for the impulsive sources, which seldom exceed 1 second, and steady-state noises, which are typically perceived as interfering with everyday activities. Most airblast concern is with house rattling, startling, and fear of damage.

The L_{Cdn} measurement methodology has been developed to characterize the overall environmental impact of impulsive noise, and not specifically to regulate the sources of impulse noise. Being responsive to weighted levels, frequency of events, and the time of day, this is probably the best method available for assessing the general state of noise at a site. For a small number of events per unit time and those for which C-weighting is not consistently applicable, this descriptor becomes less reliable as opposed to Army base artillery practice and sonic booms near military airfields. Blasting represents a case where L_{Cdn} may be too coarse a descriptor. Airblast control requires a measure of a peak level or sound exposure level, which averages only over the duration of the event. This study has shown that C-weighted or special-filtered sound exposure levels are sometimes the best impulsive sound descriptors for structural response, although it is not necessary to use them exclusively.

Sonic booms were the subject of many studies in anticipation of the widespread use of supersonic transports. These impulsive noises are similar to blasting but have different spectra and shorter durations. They are of higher frequency than type 2 airblast and are in just the right range for strong structural response (3 to 10 Hz). The frequency spread of energy is typically wider than blasting, which makes excitation of residential structure more likely. Sonic boom impact is reduced because of their characteristic short duration and small amount of energy for their peak level. They are not much more than a single N-wave cycle, and so are potentially less annoying than the airblasts. Peak responses from sonic booms were discussed previously, and in many cases exceeded the levels of responses measured from production blasts (See table 7 and 8.)

Higgins and Carpenter examined perceived levels (PLdB) to evaluate sonic boom impact compared to aircraft flyovers (14). Table I-1 shows equivalences between the PLdB and the 0.1-Hz linear airblast using Higgins' PLdB equation (previously discussed under the section on Processing of Airblast Time Histories). The acceptability clearly varies for the different types of production shots and the 134-dB (0.1-Hz) maximum level is generally equivalent to the 93- to 97-pct acceptability range, or a PLdB of 100. All PLdB values in table I-1 were computed from production-blast time histories and were made by comparing least-square fits of PLdB levels from production blasts (table 3), broken down by the type of blast. Stachura (61) gives the equations and statistics for these comparisons.

TABLE I-1. - Annoyance versus perceived level and equivalent 0.1-Hz peak airblast

PLdB	Equivalent peak linear (0.1 Hz) airblast, dB				Acceptability, pct	
	Coal highwall	Coal parting	Quarry	All	Mean	Range
111	148	143	147	145	50	36-78
108	145	140	144	142	80	54-87
100	137	132	136	134	95	93-97
95	132	127	131	129	99	

Kryter compared reactions of people to both aircraft flyovers and sonic boom overpressures (19-20). The perceived noise levels (PNdB) (not the same as Higgins' perceived levels) were determined for equivalent severity to the peak sonic boom overpressures. At Edwards Air Force Base, where the population has long been subjected to sonic booms, a 1.69-lb/ft^2 (132-dB) boom was judged equivalent to 109 PNdB indoors and 105 PNdB outdoors, and rated between "just acceptable" and "unacceptable" by 27 to 33 pct of subjects interviewed. At nearby towns, the same sonic boom levels were rated noiser by 9 dB indoors and 3 to 6 dB outdoors, with 40 pct of the people rating them unacceptable. Since the great majority of sonic boom objections are based on house rattling and other inside noises, a direct comparison can be made between airblasts and sonic booms from the midwall responses in table 8 (main text of this report) and the observation by Kryter that a peak midwall displacement of 0.016 in is considered "just acceptable" (20). Table 8 shows that most studies of sonic booms, including Kryter's, found peak midwall responses were comparable to or greater than those resulting from blasting. Using Kryter's 1.53-in/psi sonic boom data and the Bureau's 0.74 to 1.04 in/psi for blasting, the "just acceptable" sonic boom is 0.0105 lb/in^2 (131 dB) and airblast is 0.015 to 0.0216 lb/in^2 (135 to 137 dB). Other measured sonic boom responses from table 8 (main text) would give similar values; however, the Wiggins (80) study would lead to lower airblasts for equivalent responses by at least 6 dB. Assuming that the C-slow wall responses would be the same for blasts and sonic booms, the 0.016 in displacement corresponds to a maximum of 112 dB C-slow.

Aside from the Higgins and Carpenter and the Kryter analyses, the only human response data applicable to blasting is the Borsky survey of human annoyance from sonic booms in Oklahoma City in 1964 (4). An average of eight booms per day for 6 months was generated at nominal levels of 1 to 2 lb/ft^2 (128 to 134 dB). Actual mean levels for the three series of tests were 1.13, 1.23, and 1.60 lb/ft^2 (table I-2). However, over 5 pct of all booms in the last two series over the closest two zones exceeded 2.2 lb/ft^2 (134 dB). Tests were preceded with extensive publicity to make the population aware that it was being subjected to a test involving SST flights. Borsky's survey involved three interviews at each of 3,000 households plus almost 400 control interviews and 441 partial studies (fewer than three interviews per household), for a total of 10,293 interviews. The survey determined annoyance, interference, complaints, acceptability, attitude, and damage claims.

TABLE I-2. - Overpressures from sonic boom annoyance survey by Borsky (4)

Zones, miles from central track	Sonic boom overpressures, lb/ft^2 (dB)								
	Mean			5 percent exceeded			Maximum		
	Series 1	Series 2	Series 3	Series 1	Series 2	Series 3	Series 1	Series 2	Series 3
0-8	1.1 (128)	1.2 (129)	1.6 (132)	1.7 (132)	2.2 (134)	2.6 (136)	2.7 (136)	3.2 (138)	3.8 (139)
8-12	.8 (126)	1.1 (128)	1.4 (130)	1.6 (132)	2.2 (134)	2.4 (135)	2.5 (135)	3.2 (138)	3.4 (138)
12-16	.7 (125)	.9 (126)	1.0 (128)	1.2 (129)	1.7 (132)	2.1 (134)	1.8 (133)	2.7 (136)	3.0 (137)

The metropolitan area was divided into three zones 0-8, 8-12, and 12-16 miles from center line. Variations between the overpressures from zone to zone were small compared with variations between series (table I-2). The most commonly reported reactions were to house rattles (86 to 89 pct) and from startling (15.2 to 21.3 pct). A significant number of people reported sleep or rest interference (6.9 to 10.9 pct) and radio, TV, or conversation interference (3.6 to 6.8 pct) (table I-3). Most sleep and rest complaints probably resulted from the first daily booms at 7 a.m. As the levels increased, more people reported that they felt like complaining, although fewer actually did (probably from resignation). Essentially all objections to the sonic booms were indoor-related interference. Table I-3 was based on Borsky's urban data (his table 11), because this more closely applies to the blasting environment.

Highly significant was the attitude of the people surveyed on acceptability. Among those who considered the SST and its boom necessary (favorable population), the acceptability to eight booms per day (series 1) was twenty times greater than among those who considered both unnecessary; however, this ratio decreased to seven times at higher levels (table I-3). This same effect occurs for mining communities and underscores the importance of good public relations and a visible and conscientious attempt to minimize blast effects. In general, a belief that the sonic booms were necessary and unavoidable decreased the number of people indicating "more than a little annoyed" from 74 pct to 29 pct.

TABLE I-3. - Reactions from sonic boom annoyance survey by Borsky (4), by series

Series	Interference, percent				Very annoyed, percent				Complained, percent		Acceptability, 8 boom/day, percent		
	House rattles	Startled	Rest or sleep	Radio, TV	House rattles	Startled	Rest or sleep	Radio, TV	Felt like	Did	General	Favorable population	Unfavorable population
1	86.3	15.2	6.9	3.6	11.8	7.1	4.0	2.0	11	2.7	4.8	0.8	16
2	85.8	17.0	8.3	5.1	18.7	9.0	5.3	2.5	13.9	2.3	13.5	3.8	35
3	89	21.3	10.9	6.8	25.8	11.7	7.5	3.9	14.2	2.0	18.4	5.3	40

Borsky also analyzed his data by zones of sonic booms as compared to other environmental intrusions (table I-4), from his table 102. The case of 1 to 2 events per day most closely represents mining or quarrying. Approximately 4 pct would object to one or two daily sonic booms averaging 125 to 132 dB (5 pct of booms exceeding 129 to 136 dB) and having maximum overpressures of 133 to 139 dB (tables I-2 and I-4). At about 12 miles from the aircraft's flight path, sonic booms became less than significant in terms of a neighborhood's pattern of life. This indicates that 125 to 128 dB would be acceptable as a mean value, and 133 to 137 dB as a maximum for sonic booms, based on a survey of the third zone (12-16 miles).

The sonic boom levels versus the percent "more than moderately annoyed," from both the Borsky (4) and Kryter (20) studies are shown in figure I-1. For linear-peak sonic boom overpressures, there is no significant difference between aircraft types. Kryter's data indicates an increasing rate of annoyance beginning at 133 dB, and both studies inticated that 5 pct would be annoyed at a mean sonic boom level of 124.5 dB. The maximum sonic boom levels, and those not exceeded 95 pct of the time in the Borsky study are also plotted, with tolerable sonic booms of 134 and 130 dB, respectively (5 pct annoyed). Schomer derives C-weighted sound exposure levels (L_{SC}) of the Borsky sonic booms (47) and found mean, 95 percentile, and maximum boom levels for 5 pct annoyed of 98.5, 105 and 108 dB C-slow.

TABLE I-4. - Reactions from sonic boom annoyance survey by Borsky (4), by zones

Zone, miles	Could not accept sonic booms, percent		General dislikes about neighborhood	
	10-12 per day	1-2 per day	Objecting to sonic boom, percent	Ranking of sonic boom
0-8	14.8	3.4	18.5	1st
8-12	17.0	4.3	16.8	2d
12-16	7.7	1.8	7.3	8th

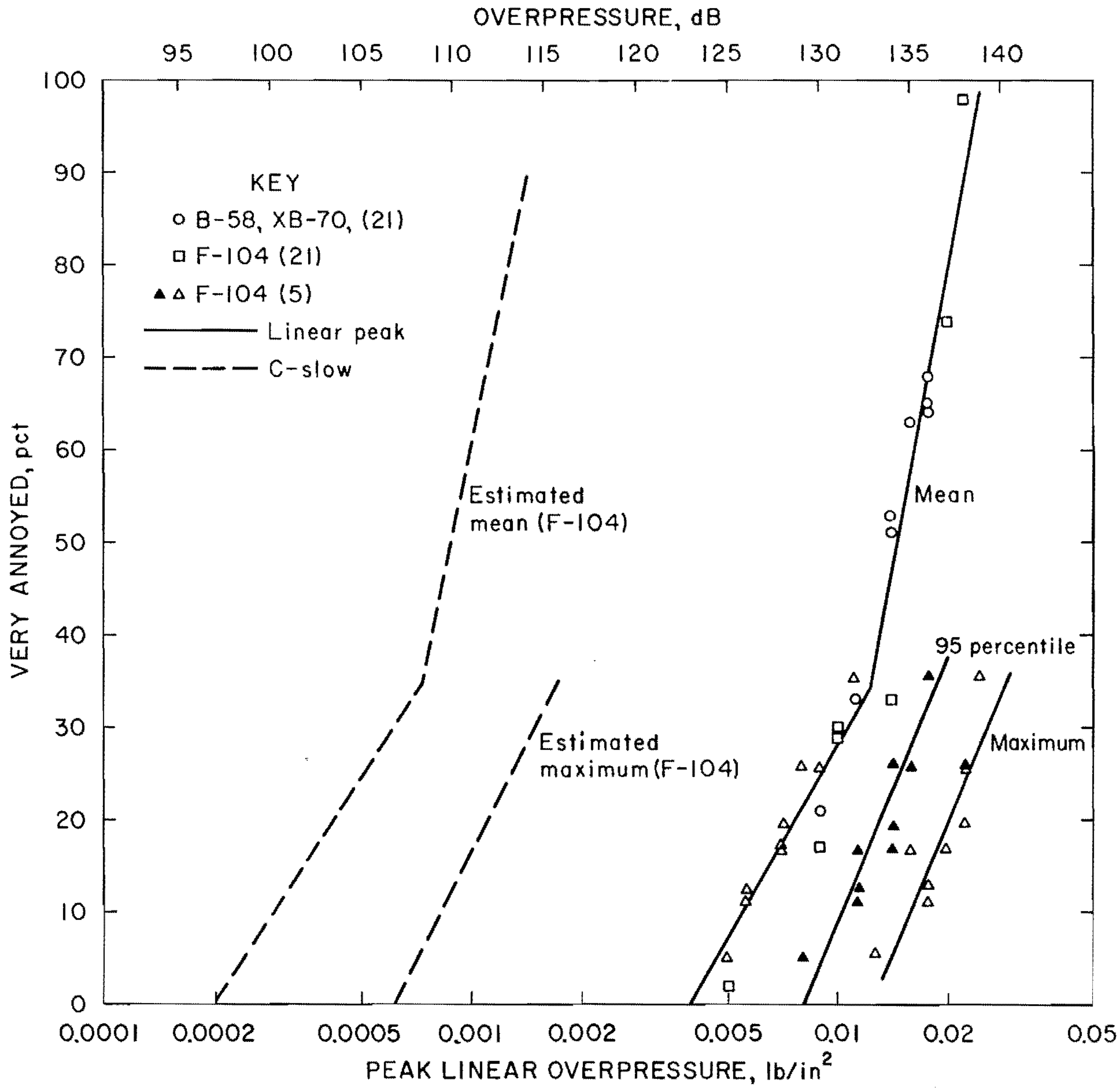

FIGURE I-1. - Population very annoyed by sonic boom-produced house rattles.

Application of the sonic boom data to blasting requires comparison of their relative midwall responses. As discussed previously, the midwall motions (plate response) can produce considerable motion of loose objects, and resulting secondary noise. Blume's (3) sonic boom response values from table 8 (in the main text) are similar to airblasts, although the booms are worse in terms of peak motions. The sonic booms produced approximately the same or slightly greater peak midwall motion, depending on which motion descriptor is used. For equivalent wall displacements, velocities, and accelerations, the airblast can be 0, 2.8, and 5.3 dB greater than the sonic booms, respectively. Since it is not known which motion descriptors best assess rattling potential, or the possibility of racking-produced rattling, it is reasonable to make a rough equivalence between blasting and sonic booms when both are measured as the linear peak levels. The C-slow (approximating C-weighted sound exposure level) does not correlate as well with midwall motions (table 5); however, within a wide band of uncertainty (± 6 dB), the C-slow annoyance values for sonic boom could be used to estimate such values for blasting.

Young examined the human tolerance to simulated artillery blasts on 30 subjects in a small room (85). Comparisons were made between the impulse, consisting of a cam-operated piston on the room wall, and a variety of steady-state noise sources including aircraft landings and takeoffs. At sound pressure levels in the range of 100 to 120 dB, the simulated artillery was judged equal in annoyance to

(1) Aircraft operations of 8 dB less (linear peak);
(2) Aircraft operations of 10 dB more (L_{SA}); and
(3) Aircraft operation (L_{SC}).

The test impulses were predominantly 75 to 100 Hz which may be appropriate for artillery but are far too high for confined blasting. The artillery was about as annoying as aircraft for L_{SC} but less so when measured using peak linear methods. Therefore, the steady-state sources must have more low-frequency energy than the simulated artillery. Since confined blasting has relatively more infra-sonic energy than some steady-state sources, the artillery appears more potentially annoying to people than mining airblast for the descriptors above. Without knowing the human reaction to both, or at least quantifying their spectral differences, the impact of blasting cannot be directly compared to other sources.

Schomer has made several evaluations of impulsive noise to assess the environmental impact of artillery and demolition airblasts around Army bases (46, 50). The Army's concern is both to minimize adverse environmental effects on its neighbors and define land use criteria for development around bases. Schomer's approach to the impact surveying and assignment of noise-contour building criteria are applicable to blasting; however, his quantitive analyses may not be applicable since the sources and resulting responses have not been shown to represent effects from confined production blasts.

In an analysis of the Young study, Schomer corrected the L_{SA} for the losses in transmission through building walls (46). An analysis for outdoor comparison was made by shifting the artillery noise 5 to 10 dB downward (for an equivalent reaction), and showing that the A-weighted sound exposure (L_{SA}) greatly underestimates the annoyance. Schomer found that L_{SC} was better than L_{SA}; however, for blasting, the L_{SC} will also underestimate the annoyance potential, as the predominant frequencies of production mining airblasts are far below those of Young's simulation. Schomer does not examine the annoyance characteristics which result from secondary effects of the wall vibrations. It is significant that outdoor and indoor tolerances to the levels of impulsive noise are different because of transmission loss; however, Borsky (4) showed that the annoyances stem from indoor-related interferences. Consequently, it is through analyses of structure responses (wall motions) that annoyance comparisons between different sources should be made. A summary of airblast annoyance is given in table 13, based mainly on the Borsky study (4).

Schomer summarizes sonic boom and Reed's airblast analyses to predict community response to blast noise (49). Although Schomer had no quantitive data on mining-type airblasts or its response effects, some of his observations are relevant. In reviewing sonic boom studies, Schomer noted that fear of property damage correlated with complaints, and that spectral differences strongly influence a signal's annoyance value. Consequently, sonic boom data should not directly applied to the blasting situation unless relative responses are determined.

Schomer describes the use of Effective Perceived Noise Levels (EPNL) and Composite Noise Ratings (CNR), which are rather too complex for the mining industry and regulatory agencies, and have not been shown to be superior to a simple peak or event-duration time average for evaluating impulsive noise impact. For nonimpulsive sources, a day time EPNL of 92 to 110 dB is the rough threshold of complaints, corresponding to peak levels (at close distances of about 2,000 ft) of 116 to 130 dB. Schomer does not currently recommend using EPNL methods, but rather the L_{dn} methodology discussed previously.

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STRUCTURE RESPONSE AND DAMAGE PRODUCED BY AIRBLAST FROM SURFACE MINING

by

David E. Siskind, Virgil J. Stachura,
Mark S. Stagg, and John W. Kopp

ERRATA

Page 13 (table 1): Insert under Notes for both Bruel and Kjaer 2209 and GenRad 1933 "Recording device is optional."

Page 51 (figure 38): Caption should include "(Numbers in parentheses correspond to regression lines in table 9.)"

Page 52 (figure 39): Caption should refer to "table 9" instead of "table 5."

Page 55, Title for fourth paragraph should read "Criteria."

Page 61 (figure 40): Caption should read "Numbers in parentheses correspond to references."

Page 76, Line 8 from bottom should read "...function of depth as given..."

Page 76, APP equation should have "D_{cg}" as part of exponent.

Page 76, following the APP equation, it should read "for small-scale blasts in limestone, where D_{cg} is the distance..."

Page 76, last sentence should read "Wiss quantified the confinement effect from full-scale coal mine blasts:"

Page 77, equation at top of page should be $APP + SRP = K_2 e^{-1.0} B_s$.