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Ground Vibrations and Airblasts Monitored in Swedesburg, Pennsylvania, from Blasting at the McCoy Quarry

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UNIT OF MEASURE ABBREVIATIONS

dB	decibel
ft	feet
$ft/lb^{1/2}$	feet per square root of pounds of explosive
$ft/lb^{1/3}$	feet per cube root of pounds of explosive
Hz	hertz, number of cycles per second
in	inch
in/s	inches per second
$\mu\varepsilon$	microstrain
Pa	pascal (Newtons per square meter)
lb	pound
lb/in^2	pound per square inch
mi	mile
s	seconds

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ABSTRACT

The Bureau of Mines, in cooperation with the Department of Environmental Resources (DER), Commonwealth of Pennsylvania, monitored homes in Swedesburg, PA, for ground vibrations and airblast overpressures produced from blasting at the nearby McCoy Quarry. Five privately owned homes were instrumented in total, with four continually monitored from May through December, 1992, and from March through December, 1993. During the study, 106 blasts were detonated at the McCoy Quarry resulting in 206 recorded events at the homes. In addition, the McCoy Quarry furnished blast design information and peak seismograph readings at compliance stations for all of their 544 blasts from January, 1989, through December, 1993.

Peak ground vibration and airblast amplitudes (collectively, "blast vibration" amplitudes) from McCoy compliance monitoring before and during the study were compared to determine if vibration levels monitored in Swedesburg would be representative of previous blasting. Blast vibration measurements were also correlated against envelopes and average values determined from previously published data to see if vibration levels are typical of other sites in terms of generated amplitudes and frequencies. Full-waveform ground vibration and airblast time histories were recorded at the Swedesburg homes during the study and selected examples are displayed and analyzed. The effects of blast design on the resulting peak ground vibrations and airblast amplitudes monitored in Swedesburg were also examined.

Peak ground vibration amplitudes in Swedesburg ranged from below 0.02 in/s (the lowest triggering level for the seismographs used) to a maximum of 0.11 in/s. Frequencies associated with the peak particle velocity phase of the highest recorded ground vibration amplitudes varied from about 10 to 100 Hz. The highest peak airblast was measured at 119 dB (5-Hz highpass system). The maximum ground vibration and airblast amplitudes recorded in Swedesburg are far below damage-threshold levels established by previous research and therefore have effectively zero probability of causing even hair-size cracks in interior walls, breaking windows (with respect to airblast) or creating other types of structurally-related damage.

INTRODUCTION

The Bureau of Mines has studied blast vibrations (collectively meaning both ground vibrations and airblasts) impacting homes in the southeastern Pennsylvania town of Swedesburg. A map of Pennsylvania indicating the location of Swedesburg relative to other cities in the state is shown in figure 1. The ground vibrations and airblast overpressures were generated from blasting at the nearby McCoy Quarry, owned and operated by Glasgow Incorporated, of Glenside, PA.

Figure 1. Map of Pennsylvania showing location of Swedesburg relative to other cities in the state.

For over 20 years, citizens in Swedesburg have had serious concerns that the blast vibrations are damaging their homes. A previous study sponsored by the Commonwealth of Pennsylvania and Glasgow, Inc., [Fang, 1976] concluded that the McCoy blasting could not be causing damage to homes in the area. Still, homeowners continued to believe that blast vibrations are responsible for cracks and other structural problems that were being observed.

Realizing that the situation in Swedesburg required additional investigation, the Department of Environmental Resources (DER), Commonwealth of Pennsylvania, organized a new plan to study the blast vibrations in conjunction with the peoples' perception of them. A team from Villanova University, under the direction of Dr. Stanley Jacobs, undertook the community response issue while the Bureau of Mines was asked to monitor and analyze the ground vibrations and airblast. The DER intends to use both of these studies to determine if a measurable relationship exists between the blast vibrations and the people's perception of them.

The Bureau's specific role in this investigation was to determine if the ground vibrations and airblasts produced by blasting at the McCoy Quarry are typical of those created by blasting at other quarries, to ascertain if blast vibrations produced during the study were representative of previous blasting, and to assess the possible effects that the blast vibrations may have on homes in Swedesburg.

In cooperation with the DER, Bureau researchers installed seismographs at four homes in Swedesburg to record ground vibrations and airblasts that were impacting the homes. The seismographs were in continuous, self-triggering operation for an 18-month period from May to December, 1992, and then from March to December, 1993. A total of 106 production blasts were detonated at the McCoy Quarry during the study resulting in 206 sets of ground vibration and airblast recordings at the Swedesburg homes.

Glasgow, Inc., supplied peak ground vibration and airblast measurements from their monitoring program for all of the blasts at McCoy from January, 1989, through December, 1993; a five-year period where a total of 544 shots were detonated. These measurements were made at compliance stations located adjacent to quarry property, but outside of the Swedesburg town-limits or on the edge of town between the homes and the quarry. The compliance information provided a "benchmark" for comparison to vibrations measurements at other quarries and to the new measurements made in Swedesburg

A comprehensive "Background" section has been included to explain important aspects of blast vibrations monitoring and analysis. It is hoped that this will aid the reader who may not be completely familiar with the material of this report and also to serve as a general reference.

Financial support for this project came from a special fund established by the DER, comprised of non-tax dollars collected from mining and quarrying companies in Pennsylvania as fees and penalties. The DER also provided and maintained the monitoring equipment that was installed at homes in Swedesburg and served as liaison between all the parties involved.

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The authors gratefully acknowledge the assistance it received from many people without whose help this study would not have been possible: The Department of Environmental Resources, Commonwealth of Pennsylvania, in particular, Mike Getto and Roger Hornberger; Glasgow, Inc. represented by Jack Rath and Bob Ruth; the Swedesburg residents for allowing us into their homes and the opportunity to collect the vibrations data fundamental for this study; and to Mr. Ed Dybicz for supplying us with very useful historical and media information.

BACKGROUND

The long-term interest in the environmental effects of blasting occurs because the mining, quarrying, and construction industries consume 4 billion lbs (4×10^9 lbs) of commercial explosives per year in the U.S. and expose large numbers of neighbors to the resulting vibrations and noise. Although these relatively well-confined blasts are intended to fragment and move rock, they do produce some ground vibrations and airblast as wasted energy.

Ground vibrations and airblasts from mining, quarrying and construction have been subjects of many studies dating back to at least 1942. Three Bureau of Mines reports contain detailed summaries of vibration generation and impacts to low-rise, residential-type structures. Bulletin 656 summarized quarry blasting and contained criteria for safe levels of both vibrations and airblast to avoid damage to homes

[Nicholls et al., 1971]. A pair of Bureau reports followed which included the Bulletin 656 data, additional measurements by the Bureau and others, and larger coal mine stripping blasts. These two summaries, RI 8485 [Siskind et al., 1980a] and RI 8507 [Siskind et al., 1980b], also included more restrictive and complex safe level criteria for both airblast and ground vibration, respectively, having frequency as well as amplitude considerations.

Ground Vibrations

Generation and Blast Design

The amplitude and frequency content of blast-produced ground vibrations are primarily related to the blast design; particularly, the type and amount of explosive and initiation sequencing used. Of lesser importance are the blasthole size and the layout dimensions of burden, spacing, subdrilling, and how well the explosive fills the blasthole (i.e., coupling). The most important of these parameters, by far, is the maximum amount of explosive detonating within a time interval of at least 8 ms. This is usually called "lbs per delay" or "charge weight per delay" with "delay" defined to be greater than 8 ms. RI 8507 [Siskind et al., 1980b] describes the effects of these design parameters including studies done to identify their relative importance.

Propagation and Geology

Ground vibrations from blasting are acoustic waves that propagate through the earth. They are also termed "seismic" waves because their propagation characteristics are similar to the vibrations produced from earthquakes. Ground vibrations from blasting have much lower peak amplitudes and higher dominant frequencies than earthquake vibrations but the propagation velocity, amplitude and frequency of both are related to the elastic properties of the rock, soil and other materials through which they travel.

Propagation effects and geology change the amplitude and frequency character of ground vibrations as they travel from the blast region to measurement locations. The most important influence is dissipation, or "geometric spreading", where the finite amount of vibration energy fills an increasingly larger volume of earth as it travels outward in all directions away from the blast. The consequence is generally an exponential decrease in vibration amplitude with increasing distance from the source.

Other propagation effects are absorption, dispersion (where different frequency components travel at different propagation velocities), and the formation of surface waves. Generally, the strongest influence on blast vibration amplitude is simple distance and the charge weight per delay. Ground vibration frequencies are influenced by distance and the geology through which the waves travel.

At close distances, typically within a few hundred to about one-thousand feet from the blast, ground vibrations are dominated by relatively high frequencies created from the time-delayed detonations of the individual blastholes. Current initiator and explosives technology allows limited control of ground vibration amplitudes and dominant frequencies close to the blast.

At distances beyond a few hundred feet, "surface waves" tend to dominate the vibration wave-train. Surface waves are particular types of seismic waves that do not contain the high frequencies of close-in ground vibrations, being most influenced by geologic structure and composition. At large distances from the blast, typically beyond about 1000 ft, changes in shot design have increasingly less effect on ground vibration frequencies and peak amplitudes because of the influence of surface waves.

The physical properties of the ground at the measurement site will affect the frequency and amplitude characteristics of the ground vibration received there. Blast vibration energy passing through material such as thick soil layers, fill material, glacial or stream-bed deposits generate surface waves with lower frequencies (of about 4-8 Hz) and higher amplitudes compared to vibrations propagating through solid rock (with comparable distances and charge weights). In southwestern Indiana dominant ground vibration frequencies as low as 4 Hz were found in areas dominated by glacial deposits [Siskind et al., 1989; 1993].

Measurement

Ground vibrations from blasting are typically measured with motion-sensing transducers attached to either digital or analog recorders. "Blasting seismographs" are self-contained devices most often used for ground vibrations (and airblast) monitoring although some research applications may require the use of different types of equipment.

A seismic wave passing through the point will cause temporary ground motion in three dimensions. Ground vibration measurements are made relative to a point, or "particle", in the ground. Particle motion oscillations are measured about a zero amplitude reference line and thus have plus and minus values. The location of motion sensing transducer would define the position of this point, initially stationary and "at rest". Unless the measurement point is near the blast, in the fragmentation or back-break zones, the particle will return to its initial rest position.

Seismographs and similar types of instrumentation measure ground movement in three mutually orthogonal (i.e., perpendicular) directions, or "components of motion" with two directional axis in the horizontal plane and one in the vertical. The horizontal components are traditionally labeled as "longitudinal"or "radial" (aligned in the direction of the blast) and "transverse" (aligned perpendicular to the direction of the blast). The longitudinal and transverse directions are alternatively identified as "H1" and "H2", respectively.

Particle motions can be measured as displacement, velocity or acceleration, although current practice favors velocity for blast-produced ground vibrations. Unless otherwise specified, "peak particle velocity", or "peak ground vibration", is defined as the highest particle velocity of all three components of motion without respect to sign.

Frequency of the ground vibration is a measure of how quickly a point in the ground oscillates, or cycles, about its resting position in response to the ground vibration disturbance. Frequency content can be calculated in a variety of ways including Fourier techniques and period inversion. The fast Fourier transform (FFT) [Brigham et al., 1974] can be used to compute the frequency distribution of the vibration time history as a continuous spectrum but does not directly preserve amplitude information contained in the time signal. The FFT is useful for signal processing (e.g., filtering) and other types of "frequency-domain" analysis because the time signal can be reconstructed by reversing the FFT process.

Period inversion is a mathematically less rigorous method for frequency determination than the FFT, but maintains the intrinsic relationship between frequency and time-history amplitude. Frequency is computed as the inverse of the period, or time needed for one cycle of oscillation: $f = 1/T$, where f is frequency, in Hertz, and T is the period, in seconds.

Analysis based on peak particle velocity and the associated frequency is commonly used in blasting regulation because they correlate with observations of cosmetic structural cracking and more severe forms of damage [Nichols et al., 1971, Siskind et al., 1980b]. Figure 2 shows the pertinent features of a ground vibration time history and the associated frequency domain amplitude spectra.

Figure 2. Ground vibration time history (left) and Fourier amplitude spectra. Notation on the time history (seismogram) points out waveform duration, peak amplitude (peak particle velocity) and period of the peak amplitude portion of the waveform [after Siskind et al., 1980b].

Propagation Analysis

Determination of the propagation characteristics of ground vibrations (and airblast) at a site can be useful for controlling amplitudes in situations where levels could exceed compliance limits. Site characterization begins by measuring peak particle velocities at various distances from the blast. A "propagation plot" is the graph of peak ground motion amplitude versus absolute or scaled distance. Peak amplitudes are usually expressed as particle velocities with simple scaled distance defined as the distance (ft) between the blast and the monitoring station divided by the maximum explosive charge weight (lbs) per 8 ms delay period. Square root scaled distance, commonly used in the analysis of peak particle velocity ground vibration propagation, incorporates the square root of the maximum charge weight. (Similarly, cube root scaled distance is used to study peak airblast propagation and incorporates the cube root of the maximum charge weight.)

Ideally, propagation measurements should be made using an array of widely-spaced seismographs positioned in a line between the blast and the monitoring location. This approach is best for accurate site characterization and is a necessary procedure when studying the effects of blast design on controlling ground vibrations. If setting up linear arrays are not practical, monitoring at fixed locations over a period of time can be adequate if enough variation in scaled distance is achieved. If too few measurements are made than the reliability of the data is in question. If the range of distances are too small, the particle velocity data will become grouped, or "clustered", and can only be used for predictive purposes within that limited range.

In critical situations, such as a marginal compliance to a legal limit, measurement at the point in question is preferable to predictions based on propagation plots. In practice, propagation plots are very useful for comparisons between sites and blasting techniques provided they are not being excessively extrapolated and that not too many design variables are being changed at once.

Table 1 has examples of square root scaled propagation equations for peak particle velocities. Also given are unscaled equations for 240 and 500 lbs of explosive (derived from the first equation in table 1) that can be used to estimate vibration amplitudes using only distance for a "typical" quarry having blasts of those sizes. Propagation equations in table 1 are plotted in figures 3 (unscaled) and 4 (scaled).

Figure 3. Propagation plot regressions of vibration amplitudes versus distance for two sizes of quarry blasts, in lbs per delay, derived from Nicholls et al. [1971].

Figure 4. Propagation plot regressions representing peak vibration amplitudes as functions of scale distances for two types of blasts, adopted from Siskind et al. [1980b].

Table 1. - Propagation Equations for Blast Vibrations

Type of blasting	Equation	Reference source
Quarry, typical production blasts	$V = 182 (D/W^{1/2})^{-1.82}$	Bulletin 656 [Nicholls et al., 1971]
Coal mine summary, production blasts	$V = 119 (D/W^{1/2})^{-1.52}$	RI 8507 [Siskind et al., 1980b]
Single charge	$V = 84 (D/W^{1/2})^{-1.41}$	RI 9078 [Siskind et al., 1987]
Quarry blasts of 240 lbs	$V = 26{,}672 D^{-1.82}$	Calculated from the Bull. 656 equation, above.
Quarry blasts of 500 lbs	$V = 52{,}016 D^{-1.82}$	Calculated from the Bull. 656 equation, above.

V = in/s, peak particle velocity for all three components of motion
D = ft, distance from the blast to measurement location
W = lbs, maximum charge weight per 8 ms delay
$D/W^{1/2}$ = square root scaled distance

Ground Vibration Effects on Structures

House Response

The measured response of residential structures is a critical indicator of troublesome or potentially damaging ground vibrations. Essentially, cracking from blast vibrations occurs when excessive stresses and strains are produced within the planes of the walls or between walls at the corners. Corner response is assumed to be a better indicator of cracking potential than midwall motion because blast-induced crack patterns are indicative of the whole-structure and shearing forces that are created from corner motions. Midwall motions (perpendicular to the wall surface) are primarily responsible for window panes rattling, picture frames tilting, dishes jiggling, and knick-knacks falling.

Other types of response cause different but still consequential results. Structures are designed to resist static vertical load; however, differential vertical motions within a structure can produce high strains in floors and ceilings. Vertical floor motions are also of concern for potential human response.

Aboveground structures tend to amplify horizontal ground motion with the amount of response dependent on the natural frequency of the structure and frequency of excitation. The highest response is expected from excitation at the structure's natural frequency, which for one- and two-story homes is within the natural frequency band of 4 to 12 Hz [Siskind et al., 1980b]. Figure 5 shows structure corner-response measurements at several different structures from a variety of studies. The highest amplification factors of 2 to 4-1/2 times correspond to excitation frequencies within the 4 to 12 Hz range.

Figure 5. Corner responses of one to three story structures from mine blasting showing frequency dependence of amplification, from Crum and Siskind [1993].

Cosmetic Cracking in Homes

The most comprehensive study of blasting vibration impacts on homes is the already mentioned Bureau RI 8507 [Siskind et al., 1980b]. Supplementing this was a follow-up study of repeated long-term vibration effects on a single structure's construction, components, and materials, by Stagg et al. [1984] published as RI 8896. These two studies summarized all the available and appropriate observations of blast-produced cracking from low-level ground vibrations done up to that time. Their scopes of study were low-rise residential structures, small to moderate-size blasts (up to about 4,000 lb per delay), and moderate distances of a few hundred feet to a few miles.

A major finding reported in RI 8507 [Siskind et al., 1980b] was the importance of vibration frequency to both structural response and damage potential. Figure 6 shows the Bureau's recommendations for safe ground vibration levels to avoid cracking in homes superimposed on actual crack damage observations. It includes the dynamic vibration response of low-rise residential structures (e.g., homes) of two or fewer stories and guidelines for the prevention of cosmetic threshold "hairline" cracking or worse. The "safe-envelope" is based on structural response and actual observations of cracking damage in residences from nine previous investigations plus the Bureau studies described in RI 8507; a total of 718 blasts, many of which produced relatively high-level ground vibration amplitudes (for simplicity, non-damage observations were not shown on the graph).

Figure 6. Ground vibration damage summary adopted from RI 8507 [Siskind et al., 1980b]. Dashed line defines the Bureau of Mines recommended safe level limits using a combination of velocity (horizontal lines) and displacement (angled lines) criteria.

The follow-up Bureau of Mines fatigue study described in RI 8896 [Stagg et al., 1984] exposed a newly built home to a year of environmental forces (e.g., settling, daily and seasonal temperature cycles, humidity variations, etc.), then 587 production blasts followed by one week of mechanically produced shaker vibrations. The latter test comprised nearly 360,000 vibrational cycles roughly equivalent to 50 years of blasting. The results of these tests in conjunction with the findings from RI 8507 [Siskind et al., 1980b] would conclude that 0.5 to 1.0 in/s would represent ground vibration levels at which crack rates began to rise in response to blasting-type activity.

Cracking of Concrete

Massive concrete is understandably very resistant to vibration-induced cracking. Oriard and Coulson [1980] specified some historical guidelines for new (green) concrete that has not yet fully cured, estimating a safe level of 2 to 4 in/s after 7 to 10 days (The American Concrete Institute recommends similar criteria for peak vibrations of 2 to 7 in/s). In actual tests, they found that over 100 in/s vibration was required to crack 8-day-old concrete and that "old" concrete could withstand 375 in/s. Oriard and Coulson [1980] also listed Tennessee Valley Authority (TVA) criteria for mass concrete, which specify a safe level of 12 in/s for concrete over 10 days old at distances beyond 250 ft from the blast. Closer distance allows higher vibrations, up to 20 in/s within 50 ft, presumably because of higher frequencies which would lessen the probability for damage. The higher vibration levels are not of concern outside the immediate vicinity of a blast (within a few feet or tens-of-feet).

A more recent study by Oriard [1992] described tensile failure in concrete with a threshold failure of about 700$\mu\varepsilon$ and skin spall at about 1200$\mu\varepsilon$. Corresponding peak particle velocities for these strains are about 110 and 200 in/s, respectively. Frequencies were not specified but are assumed to be high because of the short shot-to-receiver distances described in the report.

The Bureau also collected a small amount of data on cracks in basement-wall concrete blocks in its previous studies of vibration impacts on homes [Siskind et al., 1980b]. Three observations of cracks in these walls occurred from ground vibrations with amplitudes of 6 to 11 in/s, and dominant frequencies of about 12 Hz.

A recent study was completed by the Bureau examining the possibility of foundation and concrete damage in a community five miles from a large surface coal mine [Crum et al., 1992; Siskind et al., 1993]. Despite the low vibration amplitudes of 0.02-0.06 in/s, homeowners were concerned that observed cracks may have been a consequence of the blasting. The most seriously damaged homes were located on an upland area of loess (wind deposited silt-sized particles) which is highly susceptible to water-caused erosion. These soils contained moderately expansive clays which can shrink or swell depending on moisture content and are therefore sensitive to rainfall amounts. The existing cracks were determined to be most likely from water intrusion along the foundation, resulting soil forces, erosion, and slope creep. All of these can create far stronger forces on house foundations than the blast vibrations that were being experienced. A more distant but similar upland area not exposed to blast vibrations was also examined in a recently published follow-up study and found to have similar types and amounts of damage [Office of Surface Mining, Reclamation and Enforcement, 1994].

Ambient Vibrations

Although only suspected at the time of publication of RI 8507, a vibration level criterion of 0.5 in/s was found to have special significance because it approximates typical ambient, or regular, conditions in houses. Human activity such as walking and closing doors produced internal strains equivalent to ground vibrations of about 0.5 in/s. An even higher equivalent particle velocity of about 1.2 in/s corresponded to weather influences such as wind gusts, temperature and humidity cycles, [Stagg et al., 1984]. Since houses are regularly immersed in such an environment, it is not surprising that no blast-produced cracking was observed in tests with vibrations below 0.5 in/s. As a result, Bureau researchers concluded that vibration levels below 0.5 in/s were likely insignificant, except for two possible cases: those involving particularly sensitive devices, such as scientific instruments, and those involving vibrations with frequencies below those studied for blasting (below 4 Hz). Examples of the latter are earthquakes or other teleseismic events such as nuclear tests which produce ground motions at large distances comparable to those within a few tens-of-feet of a blast.

In addition to the Bureau's studies, other work has compared ambient forces to blasting including one study by H. Y. Fang [1976] in Swedesburg, PA. Fang directly measured strains in 9 homes. He reported that structure responses from non-blasting unknowns, environmental forces, and human activity including trains and traffic exceeded those from the blasts at the nearby McCoy quarry, then limited to 200 lbs/delay. "Quasi-Static" changes (or slowly changing forces), such as temperature and humidity cycles, over periods of 1-7 days produced changes in crack widths in these structures from 0.28 to 5.0 m. By contrast, dynamic changes from the blasting were typically 0.0025 to .0102 m (the highest being 0.04 m), making observed blasting effects relatively insignificant.

Two recent papers by United Kingdom (U.K.) authors also examined blasting impacts on structures and comparisons between blasting and ambient forces [White et al., 1993a,b]. Their results were entirely in agreement with the previous studies in terms of vibration levels corresponding to damage and responses to non-blasting forces. In particular, they found temperature cycles and human activity within the structure to have strong influences on crack widths, with blasting vibrations having little or no effect at the distances measured.

The U.K. researchers found crack extensions during non-blast periods which were attributed to periods of low outside temperature, while the lowest positive blast damage observation appeared to be from a vector sum amplitude (worst case magnitude) of 24.1 m/s (0.95 in/s). They concluded that the amount of cracking was four times as high from "all causes" than from just ground vibrations, even with peak vector sum particle velocities reaching 60 m/s (2.4 in/s). The U.K. studies support the Bureau's re-evaluation of its safe-level criteria [Siskind, 1991] and the conclusion that at 0.5 to 2.0 in/s, they do provide protection of low-rise structures from cracking related to blast vibrations, even under worst-case conditions.

Human Response to Vibrations

Whole Body Vibrations

Vibration effects on persons are also covered in the comprehensive RI 8507 [Siskind et al., 1980b]. Three possible effects are of potential concern, in order of increasing amplitudes of motion: (1) perceptibility and startle (comfort), (2) proficiency boundary or activity interference, and (3) health and safety.

The American National Standard Institute (ANSI) addresses whole-body vibration concerns for the general population [ANSI S3.18-1979]. The ANSI guidelines are basically for steady-state rather than transient blast-like vibrations and address issues of health, task proficiency, and comfort (table 2).

Table 2. Whole-body vibration (inches per second) tolerated by humans for 1-minute durations (after ANSI S3.18-1979)

Frequency, Hz	Comfort	Proficiency	Health limits
4	1.40	4.40	8.80
8	0.70	2.20	4.40
20	0.70	2.20	4.40

Persons in Buildings

ANSI recognized that people perceiving vibrations impacting buildings have different concerns than do persons performing a task or concerned with comfort and health within a vibration environment other than buildings (e.g., operating a vehicle). ANSI developed a separate standard for this case, which implicitly includes the factors of attitudes, fears of damage, and feelings of intrusiveness into a private situation (such as one's home) [ANSI S3.29-1983]. Here, people are not responding directly to the vibration, but to the structure's response to the vibration, including all the secondary effects such as window rattling, superstructure groans and creaks, and movement of loose items on shelves and pictures on walls. Table 3 lists values of peak particle velocity for transient vibrations of less than 1-s duration for ANSI's worst case combined vertical and horizontal motion.

Table 3. Peak vibration amplitudes* (inches per second) tolerated by humans in buildings (after ANSI S3.29-1983)

Number of events per day	1	12	26
Critical structure (e.g., hospital)	0.0050	0.0027	0.0019
Residence, night	.008	.0038	.0026
Residence, day	.50	.25	.17
Office or workshop	.71	.35	.24

*Combined curve for frequencies of 8 to 80 Hz.

RI 8507 researchers noted that the chief concern of homeowners is fear that their homes are being damaged by the vibrations. Any vibration-produced structure rattling, including the already mentioned secondary effects, can fuel that fear. Where people are assured that damage is not going to occur, they will tolerate up to 0.5 in/s (table 3), at least during the day when ambient vibrations are also high. However, when their fears are not allayed, any perceptible rattling is a potential problem. Complaints would then be expected from some persons whenever the impacting vibration (outside-measured vibration) exceeds perceptibility, about 0.01 in/s. As will be discussed, airblasts can also produce structural vibrations and rattling and similar fears of possible damage.

The lowest values in table 3 are less than the experimentally determined threshold of perceptibility. For these sensitive cases, any amount of noticed vibration could be judged unacceptable and it would be difficult to clearly distinguish blasting from other vibration sources, such as automobile traffic.

Airblasts

Generation and Propagation

In addition to ground vibrations discussed above, blasting produces airborne energy called airblast overpressure or impulsive sound. As with ground vibrations, airblast dissipates with distance and loses energy amplitude or "loudness" as distance increases from the blast to the monitoring location. Also, as with ground vibrations, explosive charge weight per delay and distances are important prediction parameters for airblasts.

The additional factor of the degree of confinement of the blast is far more important for airblast than it is for ground vibration. "Confinement" describes how well the blast is contained within the rock being blasted. ("Relief" can be used as a measure of confinement and is based on the shot geometry and delay timing used. See the "Blast Design" section for more on relief.) A "poorly confined" blast may result in excessive airblast noise but also may reduce ground vibration amplitudes in relation to a "well confined" blast. Whereas confinement may affect ground vibration amplitudes by a factor of less than 2-times, airblast changes may be on the order of 10- to 100-times or more.

Unlike ground vibrations, the airblast amplitudes are influenced by weather conditions, particularly wind and temperature inversions. For these reasons, airblast overpressures for a given charge and distance can vary more than ground vibrations by as much as two orders of magnitude (a factor of 100).

In a parallel effort to its mine-blasting ground vibration studies, the Bureau also studied airblasts and airblast-produced structural responses which are summarized in RI 8485 [Siskind et al., 1980a]. Peak airblast amplitudes are given in units of pressure (lb/in^2, mb, or Pa) or in relative units of decibels (dB). The decibel scale is logarithmic with values representing pressure changes above or below a standardized reference pressure [Stachura et al., 1991]. A change of 20 dB represents an order of magnitude (10-times) difference in relative units of pressure. Peak airblast measurements are also used to correlate with window breakage, structural cracking and other types of damage.

Degree of Confinement

Generally, mining blasts have sufficient confinement to ensure that most of the explosive energy goes into breaking rock. Airblast is then primarily the result of rock motion through the piston effect of the forward or upward moving rock face. This is called the "air-pressure pulse". When confinement is insufficient or deliberately designed to be low, explosive energy can vent directly into the atmosphere, producing excessive airblast (overpressure amplitudes) and also a sharper, higher frequency sound. Mining examples of the latter situation are some parting blasts (in thin and hard rock layers), conventional bench blasts with seams of weakness or other easy paths for an explosive breakthrough, cast blasting, and secondary blasting such as breaking a boulder.

Although RI 8485 [Siskind et al., 1980a] contains propagation curves for a variety of blast designs these are only approximately applicable to any particular mine or quarry because of the importance and variability of confinement on airblast generation.

Propagation Curves

Figure 7 summarizes mining airblasts for three cases: (1) total confinement (deep burial), (2) mining highwall bench blasts, and (3) slightly confined coal mine parting blasts. Traditional cube root scaled distance is used to account for variations in charge sizes. Propagation equations for these curves are in table 4.

Figure 7. Propagation plot regressions of airblast from surface mining [Siskind et al., 1980a].

Table 4. Propagation equations for airblasts from mining-type blasts in figure 8 (from RI 8485, Siskind et al., 1980a)

Type of blasting	Equation*	Correlation coefficient	Standard error, pct
Parting	$AB = 169\ (D/W^{1/3})^{-1.623}$	0.587	120
Coal highwall	$AB = 0.162\ (D/W^{1/3})^{-0.794}$	0.739	88
Total confinement	$AB = 0.061\ (D/W^{1/3})^{-0.956}$	NA	130

NA = Not applicable
*AB = airblast, lb/in^2
D = distance from blast, ft
W = maximum charge weight per delay, lb

Figure 8 summarizes all the mining airblasts and includes a minimum line representing total confinement and a maximum line for unconfined surface blasts derived from a Ballistic Research Laboratories study [Perkins and Johnson, 1964]. (This figure is adapted from RI 8485 figure B-5, which had an incorrectly plotted unconfined line). Most significant is the wide range of measured values resulting from variation in confinement and undocumented weather influences. For instance, a 1,000-lb blast at 3,000 ft could produce from 0.00026 to 0.060 lb/in^2 overpressure (99 to 146 dB). This is an enormous range of uncertainty for predicting airblast levels for a mining blast with only the knowledge of charge size and distance. When blast designs are known or fixed, however, predictions are considerably improved, as indicated by the reasonable standard deviation shown in figure 7.

Figure 8. Combined mining and quarrying airblasts from all sites, adapted from RI 8485 [Siskind et al., 1980a].

Weather Influences

Both RI 8485, [Siskind et al., 1980a], and ANSI S2.20-1983 on explosions in air discuss the effects of weather conditions on the propagation of airblasts. Two atmospheric conditions are significant: Temperature inversions and wind (direction and strength). Both of these conditions can increase airblast levels above what would be expected in their absence at a given scaled distance. They do not produce additional airblast energy, but only affect its distribution.

In temperature inversions, warm air overlies cooler air. This is the reverse of the normal situation of steadily falling temperature with altitude up to about 35,000 ft. Under normal conditions, airblast ray paths are bent away from the earth's surface by the process of acoustic refraction (analogous to optical refraction of light). When an inversion exists, by contrast, these rays are bent downward in the inversion layer and can produce one or more focus points at large distances from the blast. A focus location will be an area of abnormally high airblast, with a relatively silent zone between it and the source.

A review of cases in RI 8485 describes predicted inversion-produced sound intensifications of up to 3 times and averaging 1.8 times (5.1 dB). The ANSI standard also reports some tests of atmospheric focusing and compares measured values with a linear probability distribution in its figure 20. Tests showed a 1-pct chance of a two-times amplification above the standard curves.

Temperature inversions are common in the mornings and evening as the ground surface and air heat and cool at different rates. One reason surface mines tend to blast near the middle of the day is to avoid these types of inversions. The DuPont Blasters' Handbook [E.I. DuPont, 1977] has examples of inversion effects on airblast waves.

Wind is the second significant weather influence on airblast propagation. Examples of wind effects are 10- to 15-dB increases of sound level downwind compared with levels in cross- or no-wind conditions for close-in quarry blasts, and a change of the propagation decay exponent proportional to wind velocity [Siskind et al., 1980a].

Airblast Effects on Structures

Structural Response

As with ground vibrations, airblasts can produce structure rattling and, in extreme cases, cracking and other damage. The Bureau summary airblast report, RI 8485, includes plots of residential structure response to airblasts for a variety of measurement methods. Figures 9 and 10 show measured racking (corner) and midwall responses of structures to a variety of mining blasts for wide-band monitored airblasts, detected by a system with flat response from 2 Hz to at least 500 Hz.

Figure 9. Corner, or structural racking, responses of homes from airblasts. The solid line is prediction from RI 8485 data [Siskind et al., 1980a]. An overpressure of 0.025 lb/in^2 is equivalent to 139 dB (the horizontal axis indicates airblast overpressure, lb/in^2).

Figure 10. Midwall responses of homes from airblasts. The solid line is prediction from RI 8485 data [Siskind et al., 1980a]. An overpressure of 0.025 lb/in^2 is equivalent to 139 dB.

Racking or whole-structure response is measured by corner-mounted transducers. Because cracking of structure walls generally results from strains in the plane of the wall, this type of response is directly related to significant damage potential. For mining blasts, worst case equivalencies based on structure responses between airblast overpressures and crack-producing ground-vibration responses are that 0.0145 lb/in^2 (134 dB, 0.1-Hz system) equals about 0.50 in/s [Siskind et al., 1980a,b].

Midwall responses to airblasts are about six times higher than racking responses for a given overpressure. As discussed in detail in RI 8485 [Siskind et al., 1980a], midwall responses do not produce in-plane stains and are not presumed to be significant in the cracking potential of structure walls, with the possible exception of window breakage. (Cracking of window glass has been found to be the first indication of airblast damage, as discussed later in this report.) Midwall responses are responsible for much of the secondary rattling noise and other observed effects such as movement of pictures, clocks, etc. Although not significant to structural risk, these situations result in much of the perceptible noise and the homeowners' concern that something serious and dangerous could be happening to their homes.

Much research has been done on sonic-boom-produced structure response. The RI 8485 authors compared six sonic-boom studies with investigations of mining airblast effects and concluded that responses were roughly comparable for equivalent overpressures.

Significant to airblast response is a relationship for wind-induced responses given in the Anniston study of munitions disposal blasts by the U.S. Army [Ursenback, 1957]:

$$P = 5.04 \times 10^{-3} V^2$$

where P is pressure in pounds per square foot and V is wind speed in miles per hour. As an example, a wind of 20 miles per hour produces a pressure of 2.02 lb/ft^2 (0.0140 lb/in^2, 133.7 dB). Although such a wind is comparable in amplitude to a strong airblast, its effects are not as noticeable. This is because of the relatively slow rate of pressure changes caused by wind and the correspondingly minor or nonexistent rattling, compared with the relatively rapid pressure changes produced from airblast waves.

Cosmetic Cracking and Glass Breakage

Bureau RI 8485 [Siskind et al., 1980a] contains a summary of 18 older studies plus new analyses of airblast damage risks. A few observations of very minor damage (e.g., fall of loose plaster flakes) were found at 134 dB, and the Bureau authors chose this level as their worst case safe-level airblast criterion (also considering response data and equivalent ground-vibration effects). Most of the 21 studies in table 12 of RI 8485 concluded that an impulsive event sound level of 140 dB represents a reasonable threshold for glass and plaster damage. Figure 11 summarizes glass breakage probabilities for a variety of window sizes.

Figure 11. Glass breakage probability from sonic booms and airblasts. Numbers in parentheses are references in Bureau of Mines RI 8485 [Siskind et al., 1980a].

Structural Cracking

Damage risk to structures, other than cosmetic plaster cracks and glass breakage, has not been of interest to airblast and sonic-boom researchers because of the extremely high overpressures required and the nonexistence of such overpressures under typical blasting situations. Napadenski and Longinow [1985] gives structural failure probabilities of 10 pct for the following cases:

Framed construction 1 to 3 stories	1.5-2.0 lb/in^2 (174-177 dB)
Low rise masonry	1.7 lb/in^2 (175 dB)
Multistory steel construction	3.5 lb/in^2 (182 dB)

ANSI S2.20-1983 gives a structural damage criterion of about 0.25 lb/in^2 (159 dB) based on "zero replacement cost." The standard also states that "claims for damages from airblast such as cracked concrete foundations or broken pipes are invalid."

Human Response

The responses of people inside homes to airblast are very much like their responses to ground vibration. Again, the primary concern is the apprehension that damage could be occurring, which is fueled by structural response as noticed by the people in their homes. Complaints from citizens about blasting almost always involve persons experiencing the "vibration" while in their homes rather than outside. Consequently, they are actually responding to structural motions that create rattling and groaning noises. In reality, people do not usually feel the direct ground vibration and sometimes do not even hear the direct airblast, which actually arrives about 1 s after the initial ground vibration for every 1,000 ft of source-to-receiver distance. For this reason, researchers measure all three quantities (vibration, airblast, and structure responses)on time-correlated multi-channel systems. In this way, they can tell if and how much the structure responds to both the ground vibration and airblast. Figure 12 shows such a set of records from RI 8507 [Siskind et al., 1908b], with a structure responding to both vibrations and airblast.

Figure 12. Ground vibrations, structures vibrations, and airblast from a coal mine highwall blast [Siskind et al., 1980b].

As an example, a distant blast may produce noticeable airblast response even though the airblast amplitude could be relatively low. This airblast will be of very low frequency, with little energy above 5 Hz, because the atmosphere selectively attenuates the higher frequencies. Persons inside a house may not hear or notice the direct sound. However, if house has a natural vibration frequency near 5 Hz it will respond to the airblast and produce higher frequency secondary noise (rattling). The occupants, not hearing the direct sound, attribute the rattling (and even possible floor vibration) to ground vibrations. They do not realize that the low-level ground vibration arrived unnoticed several seconds earlier.

Regulation of Blasting

Ground Vibration

Regulatory application of the figure 6 vibration damage threshold curve has been mixed mainly because of the absence of a simple method of determining compliance with the curve. The only existing Federal blast vibration regulations are those of the Office of Surface Mining (OSM) for surface coal mining and they allow these alternatives: 1) A close variant of the figure 6 curve; 2) criteria based on scaled distance; and 3) a distance-dependent set of amplitude values, the lowest of which is 0.75 in/s for houses beyond 5,000 ft [Department of the Interior, 1983].

The RI 8507 authors recognized the implementation problem with the figure 6 curve and therefore included an alternative which involved only two frequency ranges. For the most damage-risk cases of old houses with plaster and lath, these recommendations specify a maximum velocity of 0.5 in/s for vibrations which are below 40 Hz and 2.0 in/s for those above as per table 13 in RI 8507 [Siskind et al., 1980b].

Many states and even local government bodies have passed or proposed regulations on blast vibration levels permitted at a neighbor's structure. Many of these specify a 2.0 in/s maximum with no regard to frequency, based on older Bureau 1950-1960 research and other related early studies [Nicholls et al., 1971]. In response to the 1980 RI 8507 safe level criteria, some of these regulatory bodies are revising their older rules. For example, the State of New Jersey has recently proposed adapting the figure 6 curve (dashed line), and Wisconsin has passed into law both this curve and the simpler but more restrictive guidelines proposed in table 13 of RI 8507

[Wisconsin Dept. of Industry, Labor, and Human Relations, 1987]. In contrast to these two states, most other regulatory bodies, including OSM, generally use a simple but workable distance-dependent peak particle velocity criteria: 1.25 in/s for 0 to 300 ft; 1.0 in/s for 301 to 5000 ft; and 0.75 in/s for distances greater than 5000 ft, while recognizing that a more rigorous treatment may be needed in special cases, such as that outlined in RI 8507.

Airblast

Airblast regulations have fewer variations but are as inconsistent as those controlling ground vibrations. The federal rules for airblast from surface coal mining (OSM) exactly follow the recommendations of U.S. Bureau of Mines RI 8485 [Siskind et al., 1980a]. Four limits are recommended, which range from 105 to 134 dB, depending on how the airblast is measured and analyzed. For non-coal blasting, there is little consistency or uniformity in airblast regulation. The already-mentioned Wisconsin rules of 1987 which control vibration and airblast also adopted the RI 8485 criteria for general blasting situations. Most states have no specified airblast limits.

HISTORY OF THE McCOY - SWEDESBURG RELATIONSHIP

The McCoy quarry has been operating for nearly 150 years. Earliest records of quarrying in the Swedesburg area date back to 1843 when Nathan Rambo operated a limestone quarry on property owned by his family since the early 1700's. The quarry continued to prosper as his sons took over the operation, and a wharf was built along the Schuylkill River to transport the limestone. A commander of one of the ore boats, Robert McCoy, began to buy Rambo quarries and kilns in 1879 to further develop the business. By 1896, McCoy had consolidated his holdings to form the McCoy Lime Quarries. Although ownership of the quarry properties has changed several times over the last 70 years, Robert McCoy established the name that is still used to identify the pits.

McCoy sold his operation in 1917 to Charles Warner who continued to produce limestone from the original quarries. Warner bought the adjacent operation from the Merion Lime and Stone Company in 1929 to expand the McCoy quarries. In 1951, the Bethlehem Mines Company reportedly paid Warner one million dollars for 160 acres of the McCoy Quarry. The most recent turnover in ownership occurred in 1972, when Glasgow bought the McCoy Quarry from the Bethlehem Mines Company.

Citizen's Concerns

Interactions between residents of Swedesburg and the quarry operators have increased in frequency as the quarry and the community have expanded over the past several decades. Earliest accounts of the residents' concern related to quarry operations occurred in 1951 when the Bethlehem Mines Company proposed reopening the McCoy quarry. Residents objected to this proposal, citing blasting problems as their main concern. The land was zoned heavy industrial and was therefore allowed to open, but the Upper Merion Board of Supervisors warned that they would intervene if there were any threats of danger to the residents. The Board rejected fear of problems, noting that current technology allows control of blasting.

In 1963, residents again objected to the Bethlehem Mine Company's application for a zoning variance that would allow expansion of the quarry and facilities. Residents protested the blasting, dust, and heavy truck traffic produced by the quarry.

On May 3, 1973, shortly after Glasgow Quarry, Inc., took over operations of the McCoy Quarry, the company submitted an application for a permit to operate the quarry until the deposit is exhausted. On September 19, 1973, the DER denied the application "on the ground that the blasting procedures proposed by Glasgow 'do not adequately safeguard the health, safety and welfare of the citizens of the Commonwealth" [Environmental Hearing Board, 1973]. The decision to deny the permit application was based, in part, on complaints the DER received from citizens living adjacent to the quarry, and in part from discussions with Glasgow regarding the blasting procedures. The permit denial was appealed to the Environmental Hearing Board (EHB) by Glasgow nine days later.

Many discussions ensued between Glasgow and the DER in the four months between the permit request and denial including a fact-gathering project involving outside expertise. The DER had requested a modification to the blasting procedures described in the permit application that would minimize complaints by the residents. In both the original permit denial and Glasgow's appeal to the Environmental Hearing Board, the State specified that measurement of the effects of blasting should consider both ground vibrations and community response. Glasgow modified former blasting procedures, including recording seismic data for each shot, reducing the maximum pounds per delay by fifty percent and reducing the maximum blast hole diameter. According to Glasgow, these measures reduced peak particle velocities from blasting in the Swedesburg area. Other accommodations were also made in efforts by Glasgow to minimize impacts of blasting on the homeowners.

Related Technical Studies

Geological investigations of the McCoy Quarry were conducted in 1973 by the Bureau of Topographic and Geologic Survey at the request of the Director of the Bureau of Surface Mine Reclamation (discussed previously). The purpose of the study was "to determine whether any unique geologic conditions at or adjacent to the quarry existed and could be related in some way to the many complaints of damage to homes."

The DER had hired a consultant to study structural effects of blasting on the nearby homes, and concluded that structural damage observed in several homes was caused by the vibrations from quarry blasting. This consultant, Dr. Robert Koerner, Prof. of Civil Engineering, Drexel University visited the site twice prior to permit denial and once during the following period and prior to the EHB decision. He based his assessment of blasting impacts in the community on observations and memory of amounts and degrees of cracking in homes in Swedesburg. However, he did not document his initial observations, relate damage to specific events, obtain a control group of structures, or make any serious studies of alternative damage causes.

Following a review of facts and opinions, the Environmental Hearing Board upheld the permit denial but reversed the cease and desist order on August 28, 1974. This allowed Glasgow to continue to operate and "experiment with techniques for reducing community impact of its quarry blasting" [EHB, 1974].

Since that ruling, H.Y. Fang of Lehigh University finished his 1976 study of blasting, cultural and human activity-induced responses in homes and other structures in Swedesburg and vicinity. His findings contrasted strongly with Koerner's assessment of blasting impacts to homes in Swedesburg, with relatively strong influences from non-blasting sources.

During these deliberations and studies, the U.S. Bureau of Mines was asked about its recommendations for safe vibration levels and an assessment of the Glasgow case in a meeting with the DER and the Governor's Environmental Strike Force in Harrisburg, March 19, 1974. The Bureau could advise little beyond what was published in Bulletin 656 [Nicholls, et. al., 1971]. There was some concern that the Bulletin's criteria, dating back to an earlier study [Duvall, et al., 1962], were not sufficiently protective in all cases. The follow-up RI 8507 [Siskind, et al. 1980], which corrected this, was still six years in the future.

Another effort to examine the blasting impact issue in Pennsylvania developed from a proposal from KMA, Inc., and a subsequent project sponsored by the National Crushed Stone Association (NCSA). On November 19, 1973, Kenneth Medearis of KMA proposed an examination of an alternative way to examine structure response and damage data. This resulted in funding by NCSA and a final report with recommendations [Medearis, 1976]. The Bureau of Mines, Institute of Makers of Explosives (IME) and others had concerns about the applicability of the KMA techniques and particularly the lack of new crack damage data. The KMA recommendations included reasonable peak particle velocity limits which were more restrictive than those in Bulletin 656 and not much more lenient than those which would later be derived in the analyses for RI 8507.

In December, 1980, the Bureau of Mines published RI 8507 [Siskind, et al.] which is believed to provide positive protection for structures near mines and quarries. A big part of the incentive for the Bureau's research leading to RI 8507 were the concerns about blasting in Pennsylvania and the inadequacy of the existing regulations as recognized by the DER.

DESCRIPTION OF THE STUDY AREA

Geology and Geography

The McCoy Quarry is located in Upper Merion Township, Montgomery County, Pennsylvania, northwest of Philadelphia. The quarry is directly west of the Schuylkill River, and south of the Pennsylvania Turnpike and residential Swedesburg. The residences that are being monitored in this study are west of the Schuylkill River, but north of the Turnpike (see figure 14).

The general geology of the study site and surrounding area are described by O'Neill and Schuster. A geologic map is shown in figure 13 which depicts the surface formations and also includes a cross-section showing the relationship of the McCoy Quarry and Swedesburg to surrounding stratigraphic units [1973].

Figure 13. Generalized surface geology and geologic cross section in the vicinity of the McCoy Quarry and Swedesburg, PA.

The geology of the area consists of Cambrian metamorphic and sedimentary formations that are cut by several major faults. The strike of the faults is slightly northeast-southwest, with a nearly vertical dip. In the Swedesburg area, the two units of greatest interest are the Antietam and Harpers Formation, and the Ledger Formation. The Antietam and Harpers Formations consist of Cambrian quartzite, schist, and phyllite. These are very resistant, tough metamorphosed sandstones and shales that are located north of the Quarry, and form the bedrock on which the residences are situated. Where highly fractured, the Antietam and Harpers Formations may be weathered to great depths. Remnant sedimentary bedding planes dip about 40 degrees to the south.

The quarry is located in the Ledger Formation, a younger Cambrian dolomite. The light gray dolomite is dense and crystalline, with indistinct bedding in the massive lower portion. Bedding becomes more obvious in the blue and gray upper part of the formation, striking north 85 degrees west and dipping 45-55 degrees to the south. The Ledger Formation contains extensive joints and fractures. The general strike of the fracture planes is north-south; one set of fracture planes dips 70-80 degrees to the east, and another set dips 70-80 degrees to the west.

Overburden at the quarry averages 8-10 feet. The overburden is deeper in scattered clay-filled pockets and over zones of high fracturing. In some places the joints and fractures have been enlarged by solution and subsequently filled with clay material. O'Neill and Schuster [1973] reported that there is no indication of an interconnected, conduit-cave system.

The Pensauken and Bridgeton Formations are located inside the quarry boundary and extends into the town of Swedesburg. They are isolated thin deposits of Quaternary gravel and clays; consisting mainly of deeply weathered and sandy gravels. Very few are more than 10-feet in thickness and may consist of mere films of surface water-worn gravel. In Upper Merion Township, the exact boundaries of the formations are in doubt because of the thin nature of the unconsolidated deposits. The Pensauken formation is so thin in most spots that foundation conditions are dependent on the underlying limestone or dolomite formations [Upper Merion Township Planning Commission, 1966].

Groundwater levels in the Antietam and Harpers Formations underlying Swedesburg should be unaffected by quarrying at McCoy. In fractured and soluble rocks, extensive pumping of groundwater will generally form a cone of depression that is elongated along the strike of the beds and along major fracture zones. At the McCoy Quarry, the elongation would be in a general NW-SE direction; however, only minor amounts of water (several hundred gallons per minute) have been pumped from the quarry. The quarry operations, therefore, have little effect on the prevailing groundwater conditions in the area, including the development of sinkholes.

Sinkholes have been documented at several sites to the west and southwest of the McCoy Quarry, but none have been found in the Swedesburg area. Although a few prominent sinkholes occur in the Ledger Formation, sinkholes are more common in the still younger Cambrian Elbrook Formation. The Elbrook Formation is a well-bedded limestone with interbeds of dolomite. Sinkholes and other solution features, such as caverns and pinnacles, are formed in carbonate rocks by the dissolution of the carbonates as water flows through open joints and along bedding planes. The residences that are currently being monitored are located north of the Pennsylvania Turnpike in the metamorphic Antietam and Harpers Formation, and are not influenced by solution processes.

Large earthquakes that have occurred within eastern North America had relatively minor impact in Pennsylvania and Montgomery County, in particular, where Swedesburg is located [Scharnberger, 1989]. Magnitudes from earthquakes with epicenters near New Madrid, Missouri (in the year 1811) , the St. Lawrence River region (1663, 1925, 1929 and 1944), and Charleston, South Carolina (1886) ranged between 5 and 7. Although these earthquakes resulted in local damage near the epicenter, only the St Lawrence earthquake of 1929 was reported to have caused damage in Pennsylvania (at Sayre, Bradford County). Historical data on earthquakes from other east coast areas suggest seismic intensities from IV or V (based on perception) that may have been felt in Philadelphia in 1755. No recent records of significant magnitudes have been made. The Lancaster seismic zone in Lancaster and Lebanon Counties, roughly 60 mi west of Montgomery County, is the most recently active earthquake area in the state. Richter magnitudes in this zone are generally low to moderate, ranging from 2.6-4.6. On January 16, 1994, a 4.6 magnitude earthquake was centered near Reading, Pennsylvania, about 50 mi northwest of Philadelphia; the event was felt up to 250 mi away. Only local damage was reported near the epicenter, described as minor damage to some water and gas lines and a buckled roadway. There were no reports of injuries or fatalities.

McCoy Quarry Operations

The McCoy Quarry is extends over 1/4 of a square mile and produces sized aggregate rock primarily for the construction industry. As mentioned in the previous section, the quarried rock is the dolomitic limestone of the Ledger Formation. Drilling and blasting is done on seven different depth levels: the deepest is near the center of the quarry with progressively shallower levels of excavation towards the perimeter. The seventh level is the deepest, with the top of this bench being 170 feet below the top of the first level bench. The blasted rock is removed from the pit with loaders and trucks and transported to a primary crusher and sieving complex on the west side of the quarry. The sorted rock is piled here according to size for sale and delivery to various customers. Blasting from 1989 through 1993 is summarized in Table 5. During these five years, over one million tons of rock were blasted in 544 individual blasts.

Table 5. Annual Blasting at the McCoy Quarry, 1989-1993

Year	Number of Blasts
1989..........	195
1990...........	156
1991...........	64
1992...........	59
1993...........	70
Total	544

Residences in Swedesburg Township

As described previously, Swedesburg is situated on a small hill of quartzitic rock that rises about 190 feet above the north boundary of the McCoy Quarry. Some homes are located on the south side of the hill overlooking the quarry but most of the town is built on the opposite side facing away from the McCoy complex.

Typical homes in the study area have wood-frame superstructures and are between two and two-and-one-half stories tall. There are many duplex-style homes in Swedesburg as well as single-family dwellings. All of the homes studied by the Bureau had full basement foundations built with masonry block or mortared stone. Most of the homes appear to have been built between 1910 and 1950 and seemed to be in generally good condition. Some houses have been remodeled and the original plaster-lath interior walls replaced with drywall. Exterior materials are usually brick veneer, stucco, false-brick asphalt sheeting or imitation wood shakes.

MONITORING

The Bureau of Mines and DER installed seismographs in four homes in Swedesburg during the week of April 20, 1992. The first blasts were not recorded at any of the homes until May, 1992. The locations of the homes are indicated on the map shown in figure 14, with the individual monitoring sites identified by the first letter of the homeowner's last name.

Figure 14. Plan map of the McCoy Quarry showing the relative locations of Swedesburg, monitored homes in the town, McCoy compliance stations, and the blasts detonated from May, 1992 to December, 1993.

Seismographs were originally installed in houses "K", "M", "G" and "P". The seismographs were removed for scheduled recalibration during December 1992 after the quarry had stopped blasting operations for the year. The seismographs were reinstalled in the homes in early March, 1993 except for house "G" where the seismograph was permanently removed at the homeowner's request. House "V", one block east of house "G", was selected for replacement and instrumented for the 1993 monitoring period. No blasts were detonated in January, 1993 but four blasts were missed in late February. The locations of the McCoy compliance stations are also indicated in figure 14.

Seismograph Description

Ground vibrations and airblast were recorded with Everlert II seismographs owned and supplied by the DER. As do all modern blasting seismographs, the Everlert II has four recording channels for airblast and three components of ground vibration. The three ground vibration sensors are aligned orthogonally in mutually perpendicular directions, contained in a weather- and dirt-resistant housing often referred to as the "geophone". When aligned properly, motion is recorded in one vertical and two horizontal directions. Airblast overpressures are recorded with a microphone.

The units are "self-triggering" and continuously monitoring when activated, but do not record an event unless a specified triggering level is exceeded. A 500 ms data buffer ensures that information arriving before the triggering amplitude is captured. Blast vibrations are recorded digitally onto solid state memory and automatically transferred to a 3.5-inch floppy disc for removal to a PC-type computer for further analysis. The date and time are included with each recording for later correlation to the actual shot time from the blasting report.

Frequency response and dynamic range for the Everlert II are typical for modern blasting seismographs and were adequate for the principal objectives of this study. The instruments were specified as having a frequency range for ground vibration from 2 to 200 Hz and 5 to 200 Hz for air overpressure. According to industry standards, the seismographs must have an accuracy of ±3 dB, or about ±30 pct, within this frequency range. The dynamic ranges of the instrument are 0.01 - 10.0 in/s for ground vibration and 100 - 160 dB for air overpressures. Resolution for ground vibrations is 1/100 in/s and for airblast approximately 5×10^{-5} psi.

The 4-channel seismographs used by the McCoy Quarry for their compliance monitoring were older models than the Everlert II, but had similar technical specifications.

General Description of Geophone Installation

The seismographs were placed in the basements of the houses to protect them from the weather and possible vandalism. All of the ground vibration transducers were also installed inside the homes at or near the side of the home facing the quarry. The geophones were installed as level as possible (within a few degrees of horizontal), well within tolerance limits. All were aligned so that the "longitudinal" direction was orientated due south, in the general direction of the quarry. Melted adhesive, or "hot glue", was used to attach the geophones to basement walls or floors.

Installation of Airblast Microphones

The airblast microphones were placed outside the homes. A windscreen was attached to each microphone and the entire package then sealed inside a light-weight plastic bag to protect from moisture. The microphone package was then attached under a first-floor porch or soffit overhang to further protect from wind and moisture, on the side of the house closest to the quarry (usually the south-facing side).

Monitored Homes

Five homes were jointly monitored for ground vibrations and airblast by the Bureau of Mines and the DER. A formal damage investigation was not proposed under this study, but general observations about the condition of the homes are given.

House "M"

House "M", shown in figure 15, is owned by a citizen noted for his opposition to the quarry blasting. This home was also studied by Fang [1976] in a previous vibrations study. The DER officials thought that this would be an important house to study and the homeowner agreed, giving his full cooperation.

Figure 15. House "M" monitored in Swedesburg.

The house is a two-story duplex (i.e., two-family) structure with plaster-covered walls and ceilings, and has a full basement foundation of concrete block construction. This home is located near the top of the hill in Swedesburg at an elevation of about 150 ft, approximately 60 feet higher than the nearest edge of the quarry, and in line-of-sight of the McCoy Quarry.

Numerous cracks ranging in size from very small (less than 0.1 m wide) to a few tenths of an inch wide are visible in the plaster-covered interior walls and ceilings. The basement wall also had many visible cracks. This type of cracking is common in such older homes and is usually associated with foundation settling and environmental stresses such as seasonal temperature changes and humidity variations. The homeowner believes, however, that many of the larger cracks were indeed created by blast vibrations.

The ground vibration transducer at house "M" was located at ground level near the corner of the south-facing wall. It was attached to a masonry basement window sill that was flat and level. Siskind and Stagg [1985] have shown that ground vibrations recorded on a basement wall at ground level are similar to those that would be recorded from a geophone buried outside the home in the same general location. The airblast microphone was placed underneath the porch soffit and aligned in the direction of the quarry.

House "G"

House "G" was selected because of its relatively close proximity to the quarry and would supposedly receive the highest ground vibration and airblast levels. The home is also a two-story duplex-style structure with a full concrete block and mortar constructed basement foundation. (No photographs are available showing this home, but it is very similar to house "V" described below.) The house appeared to be in good condition with small existing cracks in the basement walls, a condition common in homes of its age.

The geophone at house "G" was attached to the basement floor next the wall about 1.5 ft below ground level because the wall itself did not allow for good coupling. The airblast microphone was attached under the porch roof and pointed in the general direction of the quarry.

As mentioned before, house "G" was one of the original homes monitored, but upon the homeowner's request was not instrumented in 1993.

House "K"

Located on the north side of the hill, facing away from the quarry, house "K", shown in figure 16, was monitored to give an indication of what levels of vibration were received at structures not in "direct line" with the quarry blasting.

Figure 16. House "K" monitored in Swedesburg.

This house is a two-story duplex-style home in very good condition. Basement walls were covered so no general observations could be made of existing conditions.

Unlike the other homes, the geophone transducer was not attached to the basement wall but was buried in fill material beneath the back porch at grade-level. The porch faced south, in the direction of the quarry. The airblast microphone was secured to the porch awning.

House "P"

House "P" was the only single-family style home monitored in this study. Pictured in figure 17, it is a two-story, wood-frame home with full block-basement. It was selected because of its location away from the other monitored homes and would be relatively close to blasting at the east side of the quarry.

Figure 17. House "P" monitored in Swedesburg.

The homeowner told researchers that he was continually annoyed by the blasting vibrations. He noted a long, vertical crack in the homes false-brick stucco exterior that he felt was the result of blast vibrations. Generally, the house appeared to be in very good condition with common-looking minor cracks in the basement walls that were about 1/10-in wide.

The geophone was attached to a sturdy aluminum 90-degree angle bracket glued to the south-facing basement wall at ground level. This method has been used by Bureau researchers before with excellent results. It provides a protected placement for the geophone inside a house while still maintaining the necessary positioning. The airblast microphone was placed beneath the first-floor soffit at the southwest corner of the home facing the quarry.

House "V"

As mentioned previously, house "V", shown in figure 18, was not one of the original homes monitored but was selected as a replacement site for house "G", located only a few blocks west. Monitoring began here with the reinstallation of the seismographs in Swedesburg in March, 1993, after recalibration by the distributor. This home is very similar to house "G" as were most of the homes in the immediate neighborhood: A two-story duplex-style wood-frame home with full concrete block basement.

Figure 18. House "V" monitored in Swedesburg.

Personnel from the DER installed the seismograph in this home and Bureau researchers only had a brief glimpse of the interior of the home when assisting during a visit to change data diskettes. The home, though, appeared to be in good condition and the homeowner did not address any specific cracks or other damage concerns.

The geophone was installed inside the basement at ground level with an angle bracket as described above for house "P". The airblast microphone was positioned on the south side of the porch.

Closest Structure Compliance Monitoring

Glasgow, Inc., is required to monitor ground vibrations and airblast at the closest occupied structure for every shot to assure that the quarry's blasting is in compliance with vibrations limits. The McCoy compliance stations are noted on the site map, figure 14. Two sewage treatment plants are located adjacent to the quarry's property, and the closest one to the blast is monitored. A second location along the southern edge of Swedesburg is also monitored for each blast; the closest of three positions is to the blast is used.

Glasgow, Inc., supplied the Bureau with the peak ground vibration and airblast measurements from their compliance monitoring for the five-year period from January, 1989, to December, 1993. Other pertinent information was supplied including the date and time of the blast, location of the compliance station, scaled distance, and maximum charge weight.

Structure Response Monitoring

Above-ground monitoring of superstructure response motions was originally considered as secondary to the primary objective of the project, which was to characterize the blast vibrations impacting Swedesburg. A limited number of seismographs were initially available for long term monitoring and researchers felt they would best be used to monitor ground vibrations and airblast: Above-ground superstructure response monitoring would require a seismograph that could otherwise be used to monitor ground vibrations and airblast.

Eventually two additional seismographs became available. Researchers determined that sufficient vibrations data was being collected and decided to use the extra instruments for structure response monitoring. The seismographs were installed in house "M" and house "P" from May to June, 1993. An Everlert II seismograph was at house "M" and a Geosonics SU2000 seismograph, with features similar to the Everlert II, was operating at house "P". The geophones were attached to the second-story floor: in the southeast corner of house "M" and the southwest corner of house "P", aligned in the same manner as the respective ground vibration transducer.

ANALYSIS AND FINDINGS

This chapter describes the analysis and findings of the DER-Bureau study. The first section will discuss the blast design and patterns used at the McCoy Quarry with subsequent sections addressing the ground vibrations and airblast measurements, respectively.

Blast Pattern and Design

During the 18-month DER-Bureau monitoring program in Swedesburg, 106 blasts were detonated at the McCoy Quarry on 4 different bench levels. The locations of the blasts are shown in figure 14. Bench level numbers correspond to distances from an arbitrary datum to the top of the bench: Level 2 at 0 ft (datum level); level 4 at 65 ft; level 5 at 120 ft; and level 6 at 170 ft. Face orientation and direction of initiation varied for different levels and also occasionally within a certain level. Bench level location, bench face orientation and direction of blast initiation for these shots are summarized in Table 6 with the individual blast information given in Tables B-1 and B-2 in the Appendix section.

Table 6. Distribution of Shot Design Parameters

Bench Level	Number of Blasts
2	9
4	29
5	34
6	34

Face Orientation	Number of Blasts
NW	0
SE	31
NE	60
SW	15

Direction of Initiation	Number of Blasts
NW-SE	11
SE-NW	77
NE-SW	12
SW-NE	6

(Note: NW = northwest; NW - SE = northwest to southeast, etc. Some blasts with SE orientation were center-initiated resulting in a SE-NW direction of initiation-see footnote for Tables B-1 and B-2.)

The blasts were more or less evenly distributed between levels 4, 5 and 6, with level 2 having the fewest. No blasts were detonated with a face orientation toward the northwest, in the direction of Swedesburg. Sixty of the 106 blasts had face orientations toward the northeast and seventy-seven had a direction of initiation toward the town of Swedesburg (SE-NW).

Maximum explosive charge weights for the individual shots varied from 5.25 to 462 lbs per delay, with most being in the 200- to 300-lb range. The choice of charge weight used by the quarry is based on production needs and requirements for active vibrations control. Decking (i.e., separating charges in a hole both physically and with delay time) was often used to reduce peak ground vibrations. A typical delay pattern utilized for two decks is illustrated in figure 19.

Figure 19. Schematic representation of the typical type of blast design used at the McCoy Quarry throughout the DER-Bureau study.

The blast pattern and detonation delays remained generally constant throughout the monitoring period. Surface delays included 42 ms between holes in a row and 25 ms between rows. Down hole delays in a decked design separated individual charges in each hole by 25 ms. Each blast usually consisted of two rows of holes. Similar surface delays were utilized for holes loaded with a single column of explosives. Most of the drill patterns were rectangular in shape with over 80 percent of the patterns having burdens of 17- to 20-ft with 12- to 14-ft spacings, resulting in an effective burden of 10 to 11 feet.

Based on the shot design parameters used at the McCoy Quarry, the average relief was about 4 ms per foot of burden. An average relief of 3 to 5 ms per foot of burden is typically recommended for good fragmentation, minimization of flyrock, and control of peak airblast and ground vibration amplitudes [Atlas Powder Company, 1987].

When blasts were decked, the bottom deck fired first. Adjacent holes had decks detonating 17 ms apart (bottom deck of one versus the top deck of the adjacent hole) equating to a time interval of approximately 1 ms per foot of spacing. This has been shown to be the critical delay interval which can produce higher air overpressures from the reinforcement, or superposition, of airblast wavefronts [Kopp and Siskind, 1986]. However, Siskind et al. [1980a] concluded that only one air pressure pulse per hole contributes to the airblast signal regardless of how many decks were used, and that the upper deck is the dominating influence on airblast amplitudes. Top-deck to top-deck detonation of adjacent holes in a row for a decked blast was 42 ms, giving at least 3 ms per foot of spacing and therefore an adequate time interval for avoiding the superposition of airblast wavefronts.

Analysis of Ground Vibrations

McCoy Compliance Monitoring

Glasgow, Inc., supplied the Bureau with peak ground vibrations and airblast measurements for all of their shots for the five year period from January, 1989, through December, 1993. This information and other blast design parameters are given in the tables of Appendix C. The McCoy compliance stations were closer to the quarry than any of the homes in the town (see figure 14).

A small percentage of the blasts was not recorded due to mechanical problems with the seismographs or because vibration amplitudes were too low to trigger the instrument. A record of the trigger levels is not available, but the Bureau was informed by Glasgow, Inc., that ground vibration trigger levels were set at 0.05 in/s.

The five years of McCoy compliance measurements were separated into "contemporary" and "historical" groups shown in figure 20. The "contemporary" measurements (figure 20-A) are from blasts between May, 1992, and December, 1993, coinciding with the DER-Bureau monitoring in Swedesburg. The "historical" group (figure 20-B) is comprised of peak particle velocities measured from shots detonated between January, 1989, and April, 1992, before the DER-Bureau monitoring project began. Figures 20-A and 20 -B are shown with the same scale as are many other related sets of graphs in this report. The reader can directly compare the data graphs constructed with the same scale by overlaying them on a light table or other illuminated surface.

Figure 20. Peak ground vibrations from McCoy compliance stations. A: "Contemporary" data collected from May, 1992, to December, 1993, during the DER-Bureau study; B: "Historical" data from January, 1989 to April, 1992, before the DER-Bureau study began.

The analysis of peak particle velocity, which considers only the largest absolute ground vibrations amplitude for all three components of ground motion, is consistent with the approach used in RI 8507 [Siskind et al., 1980b]. The RI 8507 authors found that peak particle velocities correlated well with visual observations of structural cracking and were also easily measured with modern instrumentation.

The solid lines in figure 20 are the "mean regression lines" calculated from a least-squares formula [Speigel, 1961] after log transformation of the particle velocity and scaled distance data. As discussed previously, this line represents the mean, or average, particle velocity at a particular scaled distance. The dashed lines above and below the mean line represent plus and minus two standard deviations from the mean, computed as two-times the "standard deviation of y on x" [Speigel, 1961]. In a normal distribution, the plus-minus two standard deviation envelope encompasses at least 95 pct of the measurements and gives an indication to the amount of scatter inherent in the data set; the wider the envelope, the greater the scatter. Equations for the regression and deviation lines are given in the figure in exponential form: $PPV = Intercept \times SRSD^{slope}$, with the intercept being the PPV value at SRSD = 1 $ft/lb^{1/2}$.

The propagation data in figure 20 exemplifies the strong dependence of peak particle velocity amplitude on scaled distance. Even though a trend can be identified related to a decrease in particle velocity with increasing scaled distance, the relationship is not perfect and inconsistencies exist with individual measurements exhibiting a inverse particle velocity - scaled distance relationship. Variations of this type are most always found in propagation plots.

Parameters derived from statistical analysis, such as slope and intercept values, should only be considered as approximate because of the inaccuracies associated with blast vibrations monitoring. Instrumentation accuracy for typical blasting seismographs like the machines used at the McCoy compliance stations and Swedesburg homes can vary by as much as ±3 dB (±30 pct), a standard commonly employed by seismograph manufactures, and by -3 dB (-30 pct) near the upper and lower limits of the seismograph's frequency range. (Frequency response characteristics of seismographs can vary between machines even between those of the same make and model.) Also, the ground vibrations measurements have a maximum resolution of 1/100 in/s and lower amplitude measurements will have a greater possible error than higher amplitude readings. For example, the possible error associated with instrument resolution for amplitudes of 1.0 in/s would be only ±0.5 pct, but at 0.1 in/s it would be ±5 pct, and at 0.05 in/s the possible error would double to ±10 pct, and so on. (Similar considerations apply to airblast monitoring with the instrument resolution for air overpressures being about 5×10^{-5} psi.) Since the historical McCoy compliance measurements contains much more lower amplitude measurements than the contemporary compliance data, the slope and intercept values derived from the historical data are influenced more by instrumentation effects than are the values associated with the contemporary compliance measurements.

With this in mind, the two data sets were compared. It was found that the slope of mean regression line fit to the historical compliance data was only about 4 pct steeper than the slope computed from the contemporary compliance measurements and the intercept of the contemporary data was about 13 pct higher than intercept for the historical ground vibrations. The average difference between the mean values of the two data sets within the range of overlapping scaled distances (from about 35 to 160 ft/lb$^{1/2}$) is approximately 0.05 in/s, a value near the amplitude resolution limits of the seismographs. Therefore, the average peak ground vibration amplitudes during the DER-Bureau study may have been slightly higher than the monitoring period before the study, but the measurement differences could be caused by instrumentation effects and therefore may not be significant. More extensive statistical analysis may yield subtle differences between the two sets of peak vibrations measurements, but their significance would be questionable because such small discrepancies may be the result of the errors normally associated with ground vibrations monitoring.

The cautions discussed about the application of statistical analysis to low amplitude blast vibration recordings apply throughout this report and additional concerns will be addressed where appropriate.

Comparison of Historical McCoy Monitoring to Bulletin 656 Data

Peak ground vibration particle velocities from the Bulletin 656 [Nichols et al., 1971] measurements at eleven limestone quarries displayed in figure 21, and the individual particle velocities and related scaled distances listed in table D of the Appendix.

Figure 21. Collective peak ground vibration amplitudes from Bureau of Mines Bulletin 656 [Nichols et al., 1971] for limestone quarries. Equations for the mean and standard deviation lines are shown on the figure.

The Bulletin 656 data is presented as an example of peak particle velocity propagation representative of typical quarry blasting. These ground vibration measurements were collected using experimental procedures designed to compile highly accurate propagation data. The monitoring equipment used in the Bulletin 656 research had considerably higher resolution and dynamic range than the blasting seismographs used for the McCoy compliance monitoring.

Figure 22 compares the mean and standard deviations computed from the combined McCoy historical and contemporary compliance data (i.e., combining the data in figures 20-A and 20-B) and the Bulletin 656 peak particle velocity information for limestone quarries (figure 21). The equations for the lines representing the combined McCoy compliance data are given in the figure 22 caption. The vertical bars in the figure indicate the width of the plus- and minus-2 standard deviation envelope that would parallel the respective mean.

Figure 22. Comparison of representative mean regression lines and plus-minus two standard deviation bars for the Bulletin 656 data (figure 21) and the combined McCoy Quarry contemporary and historical compliance measurements (figures 20-A and 20-B). The equation for the mean regression line for the composite McCoy compliance data is: $PPV = 14.45 \times SRSD^{-1.101}$ with $\pm 2\sigma = PPV \times 10^{\pm 0.527}$.

The scaled distances associated the Bulletin 656 data span a broad range with particle velocities being measured down to a scaled distance of about 2 $ft/lb^{1/2}$. A more accurate slope and intercept value can be derived from this data compared to the McCoy compliance measurements in part because less extrapolation of the data to the y-intercept is assumed. For this reasons, the authors have a greater confidence in the predictive value the regression line derived from the Bulletin 656 data than for the McCoy compliance measurements.

Given these considerations, it is not surprising that the two regression lines have different slopes, intercepts and standard deviations. At the upper bound of overlapping scaled distances, 22 $ft/lb^{1/2}$, the Bulletin 656 mean is 0.27 in/s higher and at the lower bound of 344 ft/lb$^{1/2}$the McCoy compliance mean is 0.008 in/s greater. Where the largest amplitude differences exist, the McCoy measurements are lower.

Within the overlapping range of scaled distances, the average difference between the McCoy compliance data and Bulletin 656 mean regression lines is about 0.04 in/s. Again, this value is close to the instrument resolution of the seismographs used to collect the McCoy compliance data and therefore may not be significant. The amplitude differences are not very large considering the range normally produced by quarry blasting which can be greater than two orders-of-magnitude, exemplified by the Bulletin 656 data shown in figure 21.

As can be seen by direct comparison of figures 20 through 22, there is a great deal of common overlap between the individual Bulletin 656 and McCoy compliance measurements. Over 80 pct of the McCoy compliance measurements fall within the ±2 standard deviation envelope derived from the Bulletin 656 data (which encompasses 95 pct of the Bulletin 656 peak particle velocity measurements) and less than 2 pct of the McCoy peak measurements above the Bulletin 656 plus-2 standard deviation envelope.

Although it cannot be unambiguously proven, there is strong subjective and statistical evidence that peak ground vibration propagation from blasting at the McCoy Quarry is similar to or possibly lower than blasting at other quarries as characterized by the cumulative Bulletin 656 data.

Monitoring During the DER-Bureau of Mines Study, 5/92 - 12/93

Analysis of Selected Vibration Waveforms

Sample vibration recordings are given in figures 23 through 27. Ground vibration traces are shown for each of the homes monitored. Structure response measurements are also given for houses "M" and "P", the only homes monitored for response.

The ground vibrations shown for house "G", "K" and "V" were among the highest amplitude blasts, chosen because they gave the best signal to noise ratio for visual clarity. They were also selected for display because the vibration shapes (i.e., visually apparent frequencies) were typical of the majority of the recordings made at that location. The ground vibrations displayed for houses "M" and "P" are also typical, but were selected because a corresponding structure response recording was also obtained.

Waveform Digitization and Fast Fourier Transform (FFT) Analysis

As discussed previously, all of the ground vibrations and the structure response from house were recorded with the Everlert II instruments except the structure response from house "P" which was monitored with an SSU 2000 seismograph. The seismograms from the Everlert instruments shown were each scanned and digitized using an photo-copied enlargement of the waveform printout. The SSU 2000 recording was supplied by the DER in digital form and used as such. The waveform processing software package "Igor" [WaveMetrics, 1989] was used to perform the Fast Fourier Transforms (FFTs) and to create the figures for this section from the digitized data.

The Fourier amplitude spectrum for each waveform is shown next to the respective vibration time-history. Spectral amplitudes are plotted on a linear vertical scale as a percentage of the maximum amplitude but can also be displayed on a log or decibel vertical scale (see figure 2). The spectral amplitudes computed from an FFT are relative only to the source wave and cannot be directly compared to amplitudes of spectra derived from other waveforms.

Several of the spectra shown in figures 23 through 27 show significant low frequency components below about 5 Hz which resulted from the inability to successfully zero-mean and detrend vibration waveform and do not represent actual vibration energy. If minus 5 Hz energy did exist, it would be visible in the time history as a long period signal lasting 0.2 s or longer, superimposed with the higher frequency, shorter period vibration.

Selected Vibrations at Individual Homes

House "M"

Figure 23 shows the ground vibration (top) and structure response (bottom) recorded at house "M" on May 19, 1993. The original seismogram had extraneous electronic "noise" on the N-S channel that was superimposed on the vibration making the signal difficult to interpret. The frequency of the noise was higher than the frequency band of the ground motion and was filtered without apparent significant loss of peak amplitude information. The electronic noise recorded with the vibration or the filtering process may have altered the shape of actual waveform, as evidenced by the smooth lobes in the early part of the N-S (i.e. north - south) directional component. A sharper inflection (i.e., higher frequency peak or trough) would be expected as seen in the other two channels, which appear normal.

Figure 23. Ground vibration (top) and structure response (bottom) at house "M" for the blast on May 19, 1993. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

Noise was evident on the N-S directional channel for almost all of the blasts recorded at house "M", which unfortunately went unnoticed until after monitoring was complete. The peak velocities measured from noisy N-S components of several blast recordings were similar to the other two channels of the respective seismogram and consistent with the range of peak ground vibration amplitudes measured in Swedesburg. Although the electronic noise can influence the accuracy of measuring vibration amplitudes, the effects do not appear to be severe enough to alter the results of this investigation.

Maximum vibration amplitudes in figure 23 for house "M" are 0.03 to 0.06 in/s, with dominant frequencies about 12 and 18 Hz, which could be considered low frequencies for quarry blasting but are not unusual. As mentioned before, because the transducer was mounted on the foundation, high frequencies contained in the ground vibration may have been attenuated by the structure because the foundation does not respond to those high frequencies. Another reason for the particular frequency characteristics may be related to the surface geology. Referring to figure 13, the Pensauken and Bridgeton Formations may be underlying homes in Swedesburg. The weathered gravels and clays composing these formations are characteristic of a low seismic-velocity material. These can produce lower frequency ground vibrations than would be found in more consolidated rock such as the Antietam and Harpers Formation underlying Swedesburg. Not enough is known about the extent and thickness of the Pensauken and Bridgeton Formations in the area - factors that would contribute to the types of ground vibration frequencies produced - to draw any definite conclusions.

Structural amplification factors at House "M" for the May 1993 blast were about 0.6-times in the north-south direction, 1.3-times in the vertical direction and 1.0 in the east-west direction. These ratios are not a "true" structure response amplification factor since ground vibration and structure response are not time-correlated (see appendix A). Non-time correlated amplification factors would represent a minimum-value amplification and would be less than or equal to the "true" amplification. "True" structural amplification factors as high as 2- to 4-times have been commonly observed due to ground vibration frequencies from 4 to 10 Hz coinciding with the natural frequency range of structures as discussed previously (see figure 5).

Five pairs of structure response and ground vibration recordings were made at house "M". All showed similar structure response characteristics to ground vibrations that had similar amplitude but slightly different frequency content.

House "P"

Figure 24 depicts the ground-level vibration and structure response at house "P" for the blast on July 23, 1993. The ground-level vibration is higher frequency and higher amplitude than the example given above for house "M". The vertical component of above-ground structure motion shows similar amplitude and frequency characteristics of the ground vibration; typical response for measurement in the vertical direction.

The N-S component of structural motion has a frequency response limited to about 9 Hz with a non-time-correlated 2.4-times amplification of the ground vibration. The E-W component for structure response contains a broader range of significant frequencies but motion is still dominated by the 10 Hz component. Ground vibration and structure response amplitudes in the E-W direction are about the same. Interpretation of the structure response seismogram would suggest that the house has a natural frequency of about 9 or 10 Hz.

The FFT analysis of the ground vibration yields a dominant frequency in the N-S direction of about 7 Hz whereas period inversion analysis of the time history would indicate a dominant frequency of 32 Hz. The house appears to be responding to the low frequency components of the vibration and ignoring the higher frequencies even though high frequencies appear to dominate the ground vibration time history. This phenomenon has been observed elsewhere and is a general consequence of response to excitation at the structure's natural frequency.

Figure 24. Ground vibration (top) and structure response (bottom) at house "P" for the blast on July 23, 1993. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

The peak ground vibration amplitude of 0.07 in/s (E-W component). However, structure response to natural frequency excitation, even at this low amplitude, can be quite noticeable to persons inside the home. Structural response motions can cause rattling of loose brick-a-brack and create "creaking" noises that can be annoying or disturbing, even though there is zero statistical probability for causing any form of vibrations induced cracking from ground vibrations below 0.5 in/s have [Siskind et al., 1980 b].

Ground Vibration at Houses "G", "K" and "V"

Houses "G", "K" and "V" were monitored only for ground vibrations and airblast and not structure response. Representative ground vibrations and corresponding amplitude spectra are shown for these homes in figures 25, 26 and 27, respectively.

Figure 25. Ground vibration at house "G" for the shot on October 2, 1992. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

Figure 26. Ground vibration at house "K" for the shot on August 7, 1993. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

Figure 27. Ground vibration at house "V" for the shot on September 23, 1993. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

All of the displayed ground-level blast vibrations have relatively low peak amplitude levels. The frequency content of the individual waveforms have many similarities but also a few distinct differences. Houses "G", "K" and "V" have frequency distributions similar to house "P". Vibrations recorded at house "M" were the most different because they contained a more limited range of frequencies. The N-S horizontal component for house "K" reveals a relatively high dominant frequency of 57 Hz, compared to the other recordings and was typical of measurements made at house "K".

Peak Amplitude Propagation

Peak particle velocities recorded at the homes in Swedesburg and at the McCoy compliance stations are shown in figures 28 and 29 for May -December, 1992, and January - December, 1993, respectively. The data was separated into two periods to avoid too much data cluttering a single plot. Figures 28 and 29 are presented on the same scale and can be overlain to study the combined particle velocity information. Measurements in Swedesburg are displayed with the McCoy compliance data for the same monitoring period. The mean regression line and plus-minus two standard deviation envelope calculated from the McCoy historical compliance data (see figure 20-B) are included in the graphs for comparison.

Figure 28. Peak particle velocity versus scaled distance from May to December 1992. A: McCoy Quarry compliance monitoring and DER-Bureau monitoring at the homes in Swedesburg ; B: Individual Swedesburg homes; and C: Expanded-scale view of B. The solid and dashed lines are the mean regression line and ±2 standard deviation envelope, respectively, from the McCoy historical (figure 20-B).

Figure 29. Peak particle velocity versus scaled distance from March to December, 1993. A: McCoy Quarry compliance and DER-Bureau monitoring at the homes in Swedesburg ; B: Individual Swedesburg homes; and C: Expanded-scale view of B. The solid and dashed lines are the mean regression line and ±2 standard deviation envelope, respectively, from the historical McCoy compliance data (figure 20-B).

In an attempt to apply statistical methods to the blast vibrations data collected at the Swedesburg homes, slopes, intercept values, averages and standard deviations were computed for various combinations of the Swedesburg data that included monitoring location, bench position, blast initiation and wind effects (for airblast). Researchers soon became aware of problems with this approach because the standard deviations were large compared to the range of scaled distances and particle velocity amplitudes so that apparent systematic trends could not be justifiably distinguished from natural variation or instrumentation effects. Concerns also arose about the validity of applying statistical analysis because of problems related to the quality of the data such as the limited and inconsistent number of measurements at the houses and the resolution errors associated with monitoring low amplitude blast vibrations.

The highest peak ground vibration amplitude recorded in Swedesburg was 0.11 in/s at house "V" and the average peak particle velocity level for all measurements at the homes being closer to 0.05 or 0.04 in/s. Peak particle velocities associated with the Swedesburg homes tend to decrease more rapidly with respect to increasing scaled distance than do the McCoy contemporary data or the mean established for the historical McCoy compliance data (shown in figures 28-A and 29-A as "+" symbols and solid lines in figures 28 and 29, respectively). All the Swedesburg measurements fall within the plus-minus two standard deviation envelope of the historical McCoy compliance data with the majority of values below the historical McCoy compliance mean. Although there is some variation, peak particle velocities at the homes in Swedesburg are generally consistent to values expected from historical data at corresponding scaled distances. Where the largest differences do exist, the Swedesburg measurements are of lower amplitude.

Comparing the 1992 and 1993 data (figure 28 and 29, respectively), peak ground vibration amplitudes at house "G" are considerably lower than those at house "V", even though they were in close proximity to each other. The seismic transducer for house "G" was attached to the basement floor about two feet below ground level, which is a likely contributor to the lower amplitude readings.

Peak Ground Vibrations and Cracking Thresholds

Figure 30 shows the highest peak particle velocity amplitudes recorded at the homes in Swedesburg with the corresponding frequency. Frequencies were computed as the inverse of the time period needed for one complete the cycle of the peak particle velocity portion of the waveform: frequency, Hz = 1/period, s. The particle velocities and frequencies are plotted with the RI 8507 Appendix B safe-level criteria for ground vibrations [Siskind et al., 1980b]. Vibration levels below these lines have effectively zero probability of creating or extending cosmetic threshold-level cracks in homes which includes masonry, dry wall and plaster-covered lathe. To the authors' knowledge, blast-related damage to structures has never been documented at ground vibration levels below 0.5 in/s despite several painstaking studies by Bureau of Mines and other investigators to find such low-level damage. The probability of creating or extending cosmetic-type interior cracks in worse-case structures is only 20 pct for ground vibration amplitudes of 1.0 in/s [Siskind et al, 1980b, figure 59]. More extensive damage, such as falling plaster and visually noticeable cracking a few millimeters wide or more, does not have significant probability of occurring until peak particle velocities exceed about 1.0 in/s.

Figure 30. Worse-case Peak particle velocity versus frequency for ground vibrations recorded at Swedesburg homes from plotted against the RI 8507 [Siskind et al., 1980b] Appendix B threshold criteria for prevention of cracking in homes.

The horizontal dashed line in figure 30 represents the maximum, or worse-case, peak particle velocity envelope for ground vibrations recorded in Swedesburg during the DER-Bureau study. Ground vibration amplitudes recorded in Swedesburg ranged from about 0.02 in/s (the lowest triggering amplitude available for the seismographs used) to a maximum 0.11 in/s. These are, respectively, about 25- to 4.5-times lower than the Bureau's threshold guidelines. They are also at least 4.5-times below 0.5 in/s threshold. At such low amplitudes, ground vibration frequencies are insignificant in assessing cracking potential. Study of sub-threshold amplitudes also adds a safety factor to the analysis and allows conclusions related to damage probability to be made with more certainty. As an example, even with an abnormally high experimental error of 50 pct, peak amplitudes of the types measured in Swedesburg would still be more than 3.3-times below the minimum threshold cracking levels.

As mentioned previously, ground vibrations from many blast were not recorded in Swedesburg because of technical difficulty with the seismographs resulting from electronic interference. It is unlikely that any ground vibration amplitudes in Swedesburg were significantly higher than those actually recorded for the following reasons: There is no evidence from the McCoy compliance monitoring of anomalous high ground vibration amplitudes produced from any blast; all of the 1992 - 1993 vibrations measurements are generally consistent with respect to local historical norms; and there were no significant changes in regular blasting procedures. In order to have higher peak ground vibration amplitudes in Swedesburg that approach threshold crack-inducing levels, drastic changes would have to be made to the blast design used at McCoy. Using the propagation equations derived from the McCoy compliance data (see figure 20), charge weights per delay at the quarry would have to be increased by 15-times to raise the average ground vibration amplitudes impacting Swedesburg to near-threshold levels for interior cosmetic cracking, an amplitude increase of 4.5-times relative to the maximum 0.11 in/s measured in the town, assuming similar shot-to-home distances. There is no evidence in the blasting reports studied by the Bureau, from January, 1989, to the present, indicating that such increased charge weights were ever employed at the McCoy Quarry. It is also unlikely that any unforeseeable mishaps in loading a shot or in detonation sequencing could cause crack-producing ground vibration amplitudes to occur in Swedesburg.

Studies of blast-related damage are limited in the sense that every house being impacted by blast vibrations has not been extensively studied, but this is neither practical nor necessary in order to draw reasonable conclusions from the information at hand. Based on all the available research on structural damage due to ground vibrations from blasting, and all the ground vibration measurements reported in this study, there is no practical reason to suspect that the homes in Swedesburg have been damaged by the ground vibrations caused by blasting at the McCoy Quarry. This also includes indirect damage to structures by possible shifting of soils or other foundations material due to the blast vibrations (see Siskind et al., 1993 for a discussion on soil-house interaction).

Although a detailed structural investigation was not performed on houses in Swedesburg, existing cracks were noticeable in some of the homes, especially in the interior of house "M" and exterior of house "P". Bureau researchers have experience with a similar situation in southwestern Indiana where relatively low level ground vibrations were impacting homes and producing complaints of damage [Siskind et al., 1993]. Based on this experience, a more plausible explanation of the cracking would be related to ordinary natural causes such as settling, temperature and humidity cycles, soil effects and down-slope creep. Most of these non-blasting effects can produce strains in a home exceeding those from blast vibrations of 1.0 in/s or more.

Ground Vibration Frequency and Response Potential

Because ground vibration amplitudes are so low, ground vibration frequencies are not important when considering cracking potential, but can be important from a human response perspective. Increased structure response and human sensitivity to ground vibrations frequencies at or near the 4 to 12 Hz natural frequency range for homes [Siskind et al., 1980b] are likely to be most noticeable to persons inside a home compared to frequencies far outside this range. The highest amplitude ground vibrations recorded in Swedesburg had dominant frequencies from about 12 to 100 Hz (see figure 30) but lower frequency components were detected on many of the ground vibration recordings studied, some of which are shown in figures 23 through 27. Therefore, some of the blasts will be more noticeable than others and the "perceptibility" of the blast vibrations could vary from shot to shot.

Analysis of Airblast

McCoy Compliance Monitoring

Peak airblast overpressure measurements were also supplied by Glasgow from monitoring at the McCoy compliance stations and are shown in figure 31. The measurements are subdivided into "contemporary" and "historical" periods in similar fashion to the previous ground vibrations analysis. The solid lines in the figure represent the corrected bounds from RI 8485 [Siskind et al., 1980a] and are included for reference. The airblast bounds do not constitute an all-encompassing envelope but denote average maximum and minimum values. Peak airblast amplitudes are expected to fall between the representative minimum line for totally confined blasts and the maximum airblast line pertaining to unconfined surface blasts. The dashed line is the average of the maximum and minimum bounds for overlapping scaled distances (refer to figure 7). Solid, or blotchy, portions of the graph indicate the occurrence of several coincident data points.

Figure 31. Peak airblast amplitudes from McCoy compliance stations. A: "Contemporary" data collected from May, 1992, to December, 1993, during the DER-Bureau study ; B: "Historical" data from January, 1989, to April, 1992, before the DER-Bureau study began.

A correction factor applied to the McCoy airblast compliance data may be necessary for direct comparison to the airblast bounds which were derived from measurements using a recording system with a broader dynamic range than the blasting seismographs used in this study. To compensate for differences in instrumentation, 6 dB would be added to the McCoy compliance airblasts with frequencies below 6 Hz.

Peak airblast levels from the McCoy historical and contemporary compliance data correspond to low or moderate level airblasts. Most of the peak airblast measurements are below the average line even if a plus-6 dB correction were applied to all the data. The majority of the peak measurements would compare to well-confined blasts. The average peak airblast amplitude, regardless of scaled distance, is 115 dB for each set of data suggesting that "typical" levels were comparable before and during the DER-Bureau study. Two "maverick" points exist at 136 and 145 dB in the historical data (figure 31-B) suggesting a "blowout" or other underconfined condition, but still have peak amplitudes within expected limits. Although some of the airblasts may have been noticeable at the more distant homes in Swedesburg, none would have had the potential to break windows or cause cracking in the homes.

As seen in figure 31, airblast amplitudes are highly variable over relatively small scaled distance intervals. Statistical analysis applied to airblast propagation data has questionable value if amplitudes have a strong vertical distribution as is the case with the McCoy compliance data. Airblast generation is strongly dependent on confinement, and propagation analysis based on amplitude versus distance is less predictable than that for ground vibrations because air overpressures are sensitive to atmospheric variables that can rapidly change in unforeseeable ways.

Monitoring During the DER-Bureau Study

Airblast Time Histories at Monitored Homes in Swedesburg

Airblast time histories recorded at houses "G", "K", "M" and "P" are shown in figure 32. The Everlert II seismograph airblast channel has a frequency range for airblast of 5 to 200 Hz [Vibra-Tech, undated], a "5-Hz highpass" system. The airblasts shown are among the highest amplitude overpressures recorded during the study. They were digitized from paper records and were chosen for display because their signals showed the most detail. Airblast time histories were supplied by the DER for only the earliest recorded blasts during the DER-Bureau study. Peak amplitude information was supplied for all of the recorded blasts and because of the low amplitudes Bureau researchers felt that this information was sufficient. No airblast time history was supplied for house "V" since monitoring began there after the initial months of the study.

Figure 32. Airblast overpressure time histories from DER-Bureau monitoring in Swedesburg (5-Hz highpass recording system).

The peak amplitude levels for the airblasts are well below crack-producing thresholds. As discussed in the "Background" section, widespread window-pane breakage at residences would be the first indication of airblast-related damage. Window breakage will not occur below 129 dB (5- to 6-Hz highpass systems, Siskind et al., 1980b) for even large panes, but is possible although unlikely between 133 and 139 dB. As an example, the largest peak amplitude shown in figure 32 is 115 dB at house "G". On the logarithmic dB scale, 115 dB is almost 5-times lower than the 129 dB minimum threshold level for window pane breakage.

The airblast time histories shown are all relatively low frequency which is indicative of blasting greater than about 1000 feet from the monitoring site. The airblast recording at House "M" is unusually high compared to measurements at the other houses which had lower scaled distances. This "inverse" relationship appears regularly with airblasts and will be discussed further in the next section.

Peak Airblast Overpressures

Peak airblast overpressure measurements made during the DER-Bureau monitoring period are shown in figure 33 for May to December, 1992, and figure 34 for the year 1993, separated into the two time periods to avoid graphs that are overly cluttered with data but use the same axis scales. The airblast measurements may require a maximum correction factor of plus-6 dB for direct comparison to the limit bounds and average line because of the different microphone characteristics discussed in the preceding section.

Figure 33. Peak airblast overpressure measurements for May - December, 1992. A: McCoy Quarry compliance and DER-Bureau monitoring in Swedesburg; B: Measurements at the individual Swedesburg homes; C: Expanded-scale view of the Swedesburg data shown in B. The solid and dashed lines are the maximum and minimum airblast bounds and their average, respectively, as described in figure 31.

Figure 34. Peak airblast overpressure measurements for March - December, 1993. A: McCoy Quarry compliance monitoring and DER-Bureau monitoring in Swedesburg; B: Measurements at the individual Swedesburg homes; C: Expanded-scale view of the Swedesburg data shown in B. The solid and dashed lines are the maximum and minimum airblast bounds and their average, respectively, as shown in figure 31.

The airblast levels measured at the Swedesburg homes are either similar to or well below the levels of the McCoy compliance measurements at comparable scaled distances. Peak amplitudes from the Swedesburg monitoring have an almost vertical distribution over a span of 25 dB (about 1.2 orders-of-magnitude) within a narrow scaled distance interval of about 200 to 400 ft/lb$^{1/3}$. The vertical distribution is not an uncommon for airblast data and shows how difficult it can be to predict airblast propagation due to typical variations despite the narrow range of scaled distances. The airblast amplitudes below the totally confined boundary are unusually low when compared to the RI 8485 "totally confined" envelope.

House "M" appears to have consistently received higher amplitude airblasts compared to readings at other homes for similar scaled distances. Many peak readings at house "M" are comparable to those at houses "G" and "V", which were at significantly closer absolute and scaled distances. House "M", though, has the highest elevation of the houses monitored. Airblast becomes more focused at points of higher elevation creating an enhanced amplitude effect. Even though house "M" is further from the blasting, its elevation would likely enhance airblast amplitudes compared to homes "G" and "V" which were closer to the quarry.

The location of a house may also have another role the perception of airblast. House "M" is situated much farther away from the Pennsylvania Turnpike than houses "G" and "V", and therefore would not experience the masking effect of constant traffic noise from the highway. With the ambient noise level being lower, comparable airblast levels could be more noticeable at house "M" and incite more complaints related to the blasting.

Other unusual peak airblast measurements in Swedesburg to house "K". This home was on the northwest side of the hill facing away from the quarry. The hill, creating a topographic high between the house and the quarry, would ordinarily block airblast waves reaching homes on the northwest side, but house "K" is receiving airblast levels comparable to homes on the side of the hill facing the quarry. Winds blowing across the quarry in the direction of the house could bend airblast waves over the hill to reach homes on the north side (Leet, 1946), but winds at the quarry were primarily from a westerly direction (as will be discussed in the following section) which should create relatively lower airblast levels at house "K".

Frequency components of the airblasts may have wavelengths near to or greater that the size of the hill and therefore it would not be a significant obstruction. For example, a 5 Hz airblast wave traveling though air would have a wavelength of 220 ft, more than twice the height of the hill above the rim of the quarry (assuming a velocity of sound in air of 1100 ft/s). Lower frequency airblast would have longer wavelengths. Airblasts recorded in Swedesburg, such as those shown in figure 32, contain a significant amount of low frequency energy below 5 Hz and therefore may not be obstructed by the hill.

Peak airblast measurements at the Swedesburg homes are at least 4.5-times below threshold levels for breaking glass and have zero statistical probability for causing any form of structural cracking. Since there have been no reports of widespread glass breakage, it may be assumed that the airblasts not recorded by the seismographs were also incapable of causing damage.

The airblasts in Swedesburg, though, do have the potential to be noticeable to people inside homes at the time of the blast. The frequencies of the airblasts received in Swedesburg are predominantly infrasonic and are not well perceived by humans, but they can still produce structural response and related secondary rattling that are of higher frequency and can easily be heard. Human perception thresholds for response to structural rattling are not well known; but as an example, an airblast of 120 dB (about 0.005 lb/in^2) can cause a structural corner response of 0.1 in/s which could induce noticeable secondary rattling. An airblast of 110 dB (about 0.001 in/s) would produce a corner motion of about half, or 0.05 in/s [Siskind et al., 1980a]. As with ground vibrations, discussed earlier, airblast at certain homes may be more noticeable due to an assortment of parameters that are difficult to define, such as the looseness of windows in their tracks, floor support of cabinets, loose items on shelves, etc.

Effects of Wind Direction and Speed

Siskind et al. [1980a] identified wind direction and speed as the most influential environmental factors on the distribution of peak airblast amplitudes. Wind directions and speeds for the blasts monitored in Swedesburg were measured by quarry personnel on the bench or from local weather reports and are not presumed to be highly accurate. Wind speeds were obtained by the Bureau from the blasting logs supplied by Glasgow, Inc.

Wind direction for the vast majority of the blasts were from a westerly direction and therefore not enough variation exists to correlate with observed changes in peak airblast levels.

The peak airblast readings in Swedesburg were grouped according to wind speeds of less than or equal to 5 mph, or greater than 5 mph, and plotted in figures 35 and 36 for the 1992 and 1993 monitoring periods, respectively. The 5 mph cutoff was chosen because wind speeds were usually reported at velocities below 5 mph, at 5 mph and at 10 mph. The 5 mph cutoff seemed reasonable for separating "lower" velocity winds from "higher" wind speeds.

Figure 35. Peak airblast amplitude at Swedesburg homes versus wind speed on the bench at the time of the blast for May - December, 1992.

Figure 36. Peak airblast amplitude at Swedesburg homes versus wind speed on the bench at the time of the blast for March - December, 1993.

Airblast amplitudes measured in Swedesburg do not appear to be greatly effected by wind speed. Since winds were predominantly from a westerly direction away from the town and towards the mine, it would be expected that lower rather than higher wind speeds would correlate better with higher airblast amplitudes, but peak amplitude distributions appear similar regardless of wind speed. Three exceptions of comparatively high peak airblast levels noted for houses "K" (2 at 116 dB) and "V" (119 dB) are associated wind speeds above 5 mph. Since winds were from a westerly direction during these measurements, the amplitudes are more likely related to the blast design parameters discussed below but could be a result of natural variation or other unidentifiable causes.

Blast Design Influence on Peak Ground Vibration and Airblast in Swedesburg

Throughout the DER-Bureau study, many blast design factors changed significantly. Changes in explosive charge weight and shot-to-receiver distances has been accounted for by using scaled distance. Face orientation of the bench, direction of blast initiation and bench level location are the other blast design changes commonly made at the McCoy Quarry. Detonation delay periods, drill diameter and spacing to burden ratios, though, remained generally constant throughout the DER-Bureau study.

To properly examine blast design effects on the propagation of ground vibrations and airblast, special monitoring procedures are needed. This includes monitoring blast vibrations with several widely-spaced seismographs oriented in a line (i.e., a linear array) and properly spaced to measure propagation at distances away from the blast. Drilling, loading and detonation should be closely monitored and changes to the blast design need to be made systematically. Resources were not available to accomplish this within the scope of the project, but limited analysis of blast design effects on ground vibrations was attempted using the information collected during the DER-Bureau study. Concerns about using statistical methods to analyze the Swedesburg data were expressed previously.

Bench-Face Orientation

Figures 37 and 38 show peak particle velocities and airblast amplitudes recorded in Swedesburg, respectively, grouped according to face orientation of the shot, which is defined as the direction that the highwall side of the bench was facing. No benches were directly facing northwest, in the direction of Swedesburg.

Kopp and Siskind [1986] identified higher ground vibration levels in the direction opposite the face orientation. A southeast face orientation would have greater likelihood of producing higher peak ground vibration amplitudes, but no systematic variation in peak amplitude ground vibration propagation due to changes in face orientation are apparent from the data represented in figure 37.

Figure 37. Peak particle velocity versus scaled distance from monitoring in Swedesburg grouped according to face orientation of the blast (all data).

Figure 38. Peak airblast versus scaled distance from monitoring in Swedesburg grouped according to face orientation of the blast (all data).

It may appear that benches face orientation to the northeast created the worst airblast conditions at house "V" (and also house "G" because of the close proximity to one another), but closer inspection reveals that the levels are not much higher than for initiation from the other two directions. Face orientation to the southwest, however, created repeatedly higher peak airblast amplitudes at houses "P" and "K".

Airblast is dominated by the air pressure pulse which is created by the direct displacement of rock at the bench face [Siskind et al., 1980a]. Although no blasts were oriented to the northwest, towards Swedesburg, the highest amplitude airblasts would be expected if a bench was aligned in this direction.

Direction of Blast Initiation

Kopp and Siskind [1986] also reported that the direction of blast initiation can have a profound effect on blast vibrations with higher amplitudes found from monitoring in front of the detonation path. Figure 39 shows peak particle velocities measured in Swedesburg grouped in relation to the direction of blast initiation. The majority of the blasts were initiated towards Swedesburg from the southeast to northwest (SE to NW in figure 39-C). Except for house "V", peak particle velocities were generally higher at most of the homes for initiation from the southeast. Peak amplitudes around 0.1 in/s were recorded at house "V" for each direction of initiation except for initiation from northwest to southeast, the least used design.

Figure 39. Peak particle velocity versus square root scaled distance from monitoring at the individual Swedesburg homes grouped according to direction of blast initiation (all data).

Peak airblast amplitudes at the homes in Swedesburg grouped in relation to initiation direction are shown in figure 40. Blast initiation towards Swedesburg, from southeast to northwest correlated with generally higher peak levels at all the homes.

Figure 40. Peak airblast amplitudes versus cube root scaled distance from monitoring at the individual Swedesburg homes grouped according to direction of blast initiation (all data).

Bench Level Location

A distinctive feature of the McCoy Quarry is their multi-level operation which was described in the "Blast Design" section. The effect of blasting at different depths could have an influence on ground vibration amplitudes because of the potentially different travel paths that the seismic energy could follow.

To examine the influence of multi-level blasting, ground vibration and airblast information were analyzed according to the bench level where blasting occurred. Bench levels, described in the "Blast Design" section, indicate the vertical distance below a reference datum to the top of the bench that was being blasted. The majority of the shots at a certain bench level had similar designs but some specific shot parameters did vary, especially face orientation and direction of blast initiation, which were discussed previously.

Effects on Ground Vibrations

Figure 41 shows the peak particle velocity propagation data according to bench level. Blasting on levels 2 and 4 produced noticeably lower peak vibration amplitudes for scaled distances below 100 ft/lb$^{1/2}$ except for house "P" which received slightly higher peak amplitudes from blasting on level 4 compared to levels 5 and 6. No readings were obtained at house "P" or "G" from level 2 blasting (it cannot be confirmed whether or not the seismographs were operating at these homes during level 2 blasts).

Figure 41. Peak particle velocity versus scaled distance at individual Swedesburg homes grouped according to bench level where the blast occurred.

Effects on Airblast

Figure 42 displays airblast measurements in Swedesburg in relation to the bench level where the blasting occurred. Bench level location does not appear to have a discernable influence on the distribution of peak airblast amplitudes. No consistent patterns or trends in the data are observed that would suggest that blasting at a certain bench level systematically influenced airblast amplitude although the highest levels at house "K", 116 dB, were produced from blasting on level 6. (These measurements were also associated with higher wind speeds shown previously in figure 36.)

Figure 42. Peak airblast amplitude versus scaled distance at homes in Swedesburg grouped according to bench level where the blast occurred.

SUMMARY AND CONCLUSIONS

The Bureau of Mines, in cooperation with the Department of Environmental Resources (DER), Commonwealth of Pennsylvania, has monitored homes in Swedesburg, PA, for ground vibrations and airblast overpressures produced from blasting at the nearby McCoy Quarry. Five privately owned homes were instrumented in total, with four continually monitored from May through December, 1992, and from March through December, 1993. During the study, 106 blasts were detonated at the McCoy Quarry resulting in 206 events recorded at the homes. In addition, the McCoy Quarry furnished blast design information and seismograph readings for all of their 544 blasts from January, 1989, through December, 1993.

The Bureau's role in this investigation was to determine if the ground vibrations and airblasts produced by blasting at the McCoy Quarry are typical of those created by blasting at other quarries, to ascertain if blast vibrations produced during the study were representative of previous blasting, and to assess the possible effects that the blast vibrations may have on homes in Swedesburg.

Statistical methods were applied throughout this report in analyzing the blast vibrations data but the authors also relied on analysis by inspection to supplement statistical analysis and as the primary analytical method when statistics could not offer reliable or unambiguous results. Statistical results could be biased by errors induced by instrumentation effects, especially at the low amplitudes where the majority of the measurements were made.

The blast pattern and detonation delays used at the McCoy Quarry remained generally constant and represented practices that should minimize ground vibrations, airblast and flyrock. The blast design parameters that changed the most during the study were the orientation of the blast, direction of initiation, bench level and maximum explosive charge weight per 8 ms delay period. The effects of changes in charge weight and shot-to-receiver distances on peak amplitudes were taken into account throughout this study with the use of scaled distance.

An average difference of 0.05 in/s was found between the mean scaled-distance distribution of peak ground vibration amplitudes at McCoy compliance stations during the DER-Bureau study compared to compliance monitoring during the 41 months prior. Specific concerns about the reliability of this analysis were discussed in the report. Airblast propagation from McCoy compliance monitoring during the study period was very similar with respect to previous monitoring. The differences that did exist are not considered significant with respect to propagation and cracking probability, but higher amplitudes could increase community perception of the blasting. Peak ground vibration and airblast propagation measured at the McCoy Quarry and the monitored homes in Swedesburg are typical compared to propagation at other mines and quarries that were studied in previous Bureau of Mines research.

The maximum ground vibration amplitude recorded in Swedesburg was 0.11 in/s. This is less than one-fourth of the 0.5 in/s threshold established in RI 8507 [Siskind et al., 1980b] for the producing ultra-thin "hairline" cosmetic cracks in interior plaster-covered walls. Cosmetic cracking, the most superficial form of ground vibrations-related damage, has never been documented at particle velocities below 0.5 in/s. The highest airblast overpressure was measured at 119 dB (5-Hz highpass system), which is about one-third of the 129 dB threshold level for window pane breakage and plaster cracking, the most superficial types of airblast-induced damage [Siskind et al., 1980b]. These cracking thresholds for ground vibrations and airblast are conservative, therefore widespread cracking would not be expected nor considered feasible until much higher peak amplitude levels occur. Even though the blast vibration amplitudes are relatively low, they do have the ability to generate secondary house rattling noises that could be noticeable to persons inside a house and thereby produce apprehension about damage.

Frequencies associated with peak ground vibrations measured in Swedesburg varied over a broad range from 12 to 100 Hz, typical of quarry blasting. Peak ground vibration amplitudes are low enough so that frequencies will not have an influence on increased cracking potential. Because the amplitude of structure response is related to excitation frequency, the perception of the blast by a person inside a home may vary depending on the frequency content of the ground vibration relative to the natural frequency of the house.

Changes in face orientation, direction of blast initiation and bench level location were examined for their influence on peak ground vibration and airblast amplitudes. Direction of blast initiation towards Swedesburg corresponded to higher levels at most of the monitored homes. Blasting on levels 2 and 4 produced noticeably lower peak ground vibration amplitudes for scaled distances below 100 ft/lb$^{1/2}$. Bench face orientation to the southwest created repeatedly higher peak airblast amplitudes at houses "P" and "K".

It is the authors' hope that this report will help alleviate the concerns that Swedesburg homeowners may have about the blast vibrations. Years of cumulative scientific research would conclude that cracking or worse types of structural damage could not be caused by the ground vibrations and airblasts that were studied during this investigation. Relying on the information obtained, noticeable shaking will continue in the future, but it is unlikely that the blast vibrations could ever become strong enough to induce cracking.

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APPENDIX A: COMPUTING AMPLIFICATION FACTOR

The potential for ground vibrations to induce cracking in homes is related to the amplitude of the ground vibration, the amplification of the ground vibration induced by the structure and the differences in position of parts of the structure at any time during excitation (i.e., differential motions). The amount of structural motion is frequency dependent, which is reflected in RI 8507 criteria for safe ground vibration levels to avoid damage to structures [Siskind et al., 1980b]. For one- and two-story homes amplification factors can vary from about 0.1-times to 4- or 5-times [Crum et al., 1993; Siskind et al., 1980b]. Larger amplification occurs when ground vibration frequencies coincide with the natural frequency of the structure. Natural frequency range for typical 1- and 2-story homes is typically between 4 and 12 Hz .

Amplification factors are a measure of the amount structural response to ground vibrations or airblast excitation. They are traditionally calculated from blast vibration (either ground vibration or airblast) and structure response time histories that are directionally coordinated and synchronized in time (i.e., time correlated). "True" amplification factors are computed as the ratio of the maximum absolute-value structure response amplitude (i.e., regardless of plus or minus sign) to the amplitude of the blast vibration cycle inducing that motion in the structure. Usually, structure response lags the excitation in time depending on the excitation frequency. Computation of amplification factor sometimes requires subjectivity and a trained eye to choose the proper excitation and response cycles.

When the vibration signals are not time-correlated, an approximation to the true amplification factor can be obtained by using the ratio of peak structure response amplitude to the peak ground vibration amplitude measured in the same direction of motion. This value will be less-than or equal-to the "true" amplification factor computed with time-correlated waveforms, as described above. Visual analysis of the waveforms should allow an experienced observer to determine if the approximated amplification factor is likely to be similar to "true" value.

Often, secondary amplifications are considered if significant response is occurring (traditionally 50 to 75 pct of peak) due to ground vibrations of a much different frequency. This method was used in the RI 8507 study, examining peaks with different frequencies that were within 50 pct of the peak structure response amplitude.

Table B-1: Directional Blast Design Parameters for May - December, 1992

Shot Number	Bench Level	Face Orientation†	Direction of Initiation¥	Shot Number	Bench Level	Face Orientation†	Direction of Initiation¥
24	6	SE	SW - NE	42	4	SW	SE - NW
25	5	NE	SE - NW	43	4	SE	SE - NW*
26	4	SW	SE - NW	44	4	SE	NE - SW
27	6	SW	SE - NW	45	6	NE	SE - NW
28	4	SW	SE - NW	46	4	SE	SE - NW*
29	6	SE	SW - NE	47	2	SE	SW - NE
30	6	SW	SE - NW	48	6	NE	SE - NW
31	5	NE	NW - SE	49	4	SE	SE - NW*
32	5	NE	NW - SE	50	6	NE	SE - NW
33	4	SW	SE - NW	51	2	SE	NE - SW
34	6	SE	SW - NE	52	4	SE	SE - NW*
35	4	SW	SE - NW	53	6	NE	SE - NW
36	2	SE	NE - SW	54	4	SW	SE - NW
37	4	SW	SE - NW	55	4	NE	SE - NW
38	4	SE	SE - NW*	56	6	NE	SE - NW
39	6	SE	SW - NE	57	2	NE	SE - NW
40	4	NE	SE - NW	58	4	NE	SE - NW
41	6	NE	SE - NW	59	6	NE	SE - NW

† Direction bench highwall is facing: NE=northeast, ect.

¥ Direction of blast progression: SW-NE=southwest to northeast, etc.

* The blast record indicated initiation from the center of blast pattern.
Therefore the direction of initiation is considered to be from the front of the pattern to th back or as in all instances where this occurs, SE - NW.

Table B-2: Directional Blast Design Parameters for January - December, 1993

Shot Number	Bench Level	Face Orientation†	Direction of Initiation¥	Shot Number	Bench Level	Face Orinetation†	Direction of Initiation¥
1	6	NE	SE - NW	36	5	NE	SE - NW
2	4	NE	SE - NW	37	4	SE	NE - SW
3	2	NE	SE - NW	38	5	SE	NE - SW
4	5	NE	NW - SE	39	5	NE	NW - SE
5	6	SW	SE - NW	40	2	SE	NE - SW
6	4	NE	SE - NW	41	2	NE	SE - NW
7	5	NE	SE - NW	42	6	NE	SE - NW
8	6	SW	SE - NW	43	5	NE	NW - SE
9	6	NE	SE - NW	44	4	NE	SE - NW
10	4	NE	SE - NW	45	5	SE	NE - SW
11	5	NE	NW - SE	46	6	NE	SE - NW
12	6	SW	SE - NW	47	5	SE	NE - SW
13	2	NE	SE - NW	48	5	SE	NE - SW
14	6	NE	SE - NW	49	6	NE	SE - NW
15	4	NE	SE - NW	50	5	SE	NE - SW
16	6	SW	SE - NW	51	5	NE	SE - NW
17	4	NE	SE - NW	52	5	NE	SE - NW
18	6	SW	SE - NW	53	5	SE	SE - NW*
19	6	NE	SE - NW	54	6	NE	SE - NW
20	6	SW	NW - SE	55	5	NE	NW - SE
21	5	NE	SE - NW	56	5	SE	SE - NW*
22	4	NE	SE - NW	57	5	NE	SE - NW
23	6	SE	SE - NW*	58	5	NE	SE - NW
24	6	SE	SE - NW*	59	4	NE	SE - NW
25	4	NE	SE - NW	60	6	NE	SE - NW
26	2	NE	SE - NW	61	5	NE	SE - NW
27	6	SE	SE - NW*	62	4	SE	SE - NW*
28	6	NE	SE - NW	63	5	NE	NW - SE
29	4	SE	NE - SW	64	6	NE	SE - NW
30	4	NE	SE - NW	65	5	SE	SW - NE
31	5	SE	SE - NW*	66	5	NE	SE - NW
32	5	SE	NE - SW	67	5	NE	SE - NW
33	5	NE	SE - NW	68	5	NE	NW - SE
34	5	SE	SE - NW*	69	5	NE	SE - NW
35	5	NE	NW - SE	70	6	NE	SE - NW

† Direction bench highwall is facing: NE=northeast, ect.

¥ Direction of blast progression: SW-NE=southwest to northeast, etc.

* The blast record indicated initiation from the center of blast pattern. Therefore the direction of initiation is considered to be from the front of the pattern to the back or as in all instances where this occurs, SE - NW.

Table C-1. 1989 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #**	SRSD*, ft/lb^1/2†	Peak Particle Velocity, in/s			CRSD*, ft/lb^1/3†	Airblast, dB
						H1	Vertical	H2		
1	1.04	142	1299	NA‡	109	0.06	0.04	0.05	249	126
2	1.04	247	676	NA	43	0.28	0.35	0.28	108	116
3	1.04	257	882	NA	55	0.42	0.33	0.26	139	119
5	1.10	247	597	NA	38	0.19	0.19	0.12	95	132
6	1.10	232	868	NA	57	0.31	0.53	0.42	141	120
7	1.11	207	1194	NA	83	0.08	0.06	0.05	202	109
8	1.13	232	899	NA	59	0.18	0.34	0.18	146	128
9	1.13	207	1194	NA	83	0.15	0.09	0.16	202	118
10	1.17	332	1093	NA	60	0.08	0.07	0.08	158	120
11	1.19	192	901	NA	65	0.41	0.26	0.24	156	125
12	1.19	222	1192	NA	80	0.13	0.12	0.17	197	116
13	1.20	242	1105	NA	71	0.10	0.11	0.10	177	121
14	1.23	114	822	NA	77	0.14	0.12	0.15	170	114
15	1.26	242	1198	NA	77	0.18	0.11	0.18	192	113
16	1.27	222	849	NA	57	0.35	0.15	0.29	140	122
17	1.30	402	1444	NA	72	0.31	0.35	0.34	196	127
18	1.30	247	1132	NA	72	0.06	0.07	0.07	180	115
19	2.01	197	842	NA	60	0.09	0.06	0.08	145	110
20	2.01	222	1207	NA	81	0.14	0.10	0.16	199	114
21	2.03	172	1128	NA	86	0.11	0.09	0.10	203	115
22	2.07	227	1251	NA	83	0.12	0.10	0.11	205	113
23	2.08	322	1453	NA	81	0.05	0.03	0.04	212	115
24	2.10	227	1251	NA	83	0.11	0.10	0.14	205	113
25	2.13	297	1293	NA	75	0.09	0.11	0.09	194	131
26	2.15	442	1493	NA	71	0.07	0.04	0.05	196	119
27	2.17	247	943	NA	60	0.38	0.19	0.37	150	115
28	2.21	342	1442	NA	78	0.07	0.05	0.06	206	126
29	2.23	212	757	NA	52	0.21	0.26	0.14	127	114
30	2.27	347	1397	NA	75	0.05	0.04	0.06	199	115
31	3.01	254	1562	NA	98	0.04	0.03	0.04	247	118
32	3.07	243	1294	NA	83	0.04	0.03	0.04	207	119
33	3.10	403	1104	NA	55	0.05	0.05	0.04	149	118
34	3.10	372	1138	NA	59	0.09	0.09	0.10	158	113
35	3.13	223	1792	NA	120	0.06	0.02	0.04	296	110
36	3.15	272	1303	NA	79	0.08	0.04	0.06	201	110
37	3.14	292	1401	NA	82	0.07	0.05	0.04	211	113
38	3.17	362	1104	NA	58	0.11	0.06	0.09	155	115
39	3.17	432	1206	NA	58	0.12	0.09	0.11	159	112
40	3.22	441	1449	NA	69	0.05	0.02	0.04	190	108
41	3.24	458	1434	NA	67	0.07	0.04	0.03	186	116
42	3.27	484	1100	NA	50	0.07	0.03	0.07	140	115
44	3.28	422	1048	NA	51	0.10	0.05	0.11	140	111
45	3.30	457	1390	NA	65	0.05	0.02	0.03	180	112
46	3.30	144	792	NA	66	0.20	0.18	0.21	151	110
47	4.03	322	1095	NA	61	0.07	0.04	0.07	160	114
48	4.04	472	1499	NA	69	0.08	0.04	0.07	193	109
49	4.04	442	1051	NA	50	0.07	0.06	0.07	138	115
50	4.06	392	1485	NA	75	0.07	0.03	0.04	203	117
51	4.06	106	844	NA	82	0.13	0.07	0.06	178	125
52	4.10	342	1258	NA	68	0.09	0.03	0.08	180	115
53	4.11	457	1496	NA	70	0.05	0.05	0.04	194	111
55	4.18	458	1391	NA	65	0.04	0.04	0.03	180	112
57	4.21	247	597	NA	38	0.33	0.24	0.23	95	115
58	4.24	433	1498	NA	72	0.04	0.02	0.04	198	113

Table C-1. 1989 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s			CRSD, ft/lb^1/3	Airblast, dB
						H1	Vertical	H2		
59	4.25	262	599	NA	37	0.40	0.36	0.28	94	128
61	5.02	242	700	NA	45	0.31	0.30	0.17	112	115
62	5.04	422	1397	NA	68	0.07	0.04	0.05	186	111
63	5.04	252	1492	NA	94	0.04	0.05	0.05	236	107
64	5.08	392	1069	NA	54	0.09	0.01	0.05	146	110
66	5.09	413	1321	NA	65	0.07	0.05	0.09	177	110
67	5.10	283	673	NA	40	0.13	0.06	0.07	102	126
68	5.11	412	1319	NA	65	0.06	0.04	0.06	177	113
69	5.15	393	793	NA	40	0.17	0.14	0.13	108	112
70	5.15	177	346	NA	26	0.50	0.36	0.20	62	121
71	5.19	472	1608	NA	74	0.09	0.02	0.04	206	117
72	5.18	202	497	NA	35	0.36	0.30	0.18	85	110
73	5.18	703	1087	NA	41	0.11	0.07	0.06	122	112
74	5.19	283	673	NA	40	0.34	0.40	0.29	102	128
75	5.24	182	324	NA	24	0.40	0.64	0.36	57	118
76	5.26	283	606	NA	36	0.33	0.21	0.17	92	131
77	5.30	392	1129	NA	57	0.12	0.06	0.15	154	122
78	5.30	163	294	NA	23	0.32	0.40	0.33	54	116
79	5.31	492	1198	NA	54	0.03	0.02	0.03	152	112
80	6.01	382	1310	NA	67	0.12	0.06	0.05	180	113
81	6.05	462	1096	NA	51	0.05	0.02	0.06	142	116
82	6.06	492	1087	NA	49	0.05	0.05	0.04	138	114
83	6.09	452	1106	NA	52	0.08	0.03	0.06	144	111
84	6.09	183	298	NA	22	0.79	0.41	0.64	52	116
85	6.13	403	1285	NA	64	0.06	0.03	0.07	174	122
86	6.13	372	791	NA	41	0.08	0.07	0.09	110	119
87	6.13	182	297	NA	22	0.15	0.12	0.16	52	112
88	6.15	592	998	NA	41	0.07	0.05	0.06	119	119
89	6.15	442	1093	NA	52	0.00	0.03	0.02	144	108
91	6.19	182	351	NA	26	0.73	0.66	0.55	62	118
92	6.19	482	1098	NA	50	0.07	0.03	0.05	140	113
93	6.21	182	351	NA	26	0.33	0.52	0.31	62	120
94	6.22	453	1256	NA	59	0.14	0.04	0.10	164	121
95	6.26	192	319	NA	23	0.00	0.51	0.45	55	117
96	6.28	392	1703	NA	86	0.08	0.03	0.09	233	123
97	6.28	463	1291	NA	60	0.05	0.03	0.04	167	121
98	6.30	202	341	NA	24	0.35	0.52	0.29	58	120
99	7.03	462	1118	NA	52	0.01	0.01	0.01	145	129
100	7.06	432	1289	NA	62	0.08	0.04	0.03	170	121
101	7.06	202	398	NA	28	0.21	0.43	0.24	68	121
102	7.11	472	1304	NA	60	0.12	0.08	0.13	167	124
103	7.11	462	1698	NA	79	0.03	0.02	0.03	220	119
104	7.13	402	1704	NA	85	0.10	0.05	0.14	231	122
106	7.14	282	705	NA	42	0.25	0.29	0.17	108	131
107	7.14	577	1441	NA	60	0.19	0.08	0.12	173	127
108	7.17	333	1697	NA	93	0.05	0.04	0.03	245	117
109	7.19	482	1142	NA	52	0.17	0.08	0.09	146	126
110	7.19	352	994	NA	53	0.07	0.05	0.11	141	115
113	7.25	372	1196	NA	62	0.06	0.04	0.03	166	115
114	7.25	252	587	NA	37	0.35	0.34	0.25	93	126
115	7.26	512	1086	NA	48	0.09	0.09	0.10	136	123
116	7.28	252	492	NA	31	0.27	0.20	0.21	78	118
117	7.31	408	909	NA	45	0.06	0.06	0.13	123	119
118	8.01	348	1138	NA	61	0.12	0.07	0.06	162	115
119	8.03	482	1120	NA	51	0.04	0.04	0.06	143	114

Table C-1. 1989 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s H1	Vertical	H2	CRSD, ft/lb^1/3	Airblast, dB
120	8.04	262	647	NA	40	0.09	0.11	0.10	101	130
121	8.08	253	557	NA	35	0.26	0.33	0.22	88	119
123	8.11	592	998	NA	41	0.07	0.07	0.08	119	117
124	8.15	573	1197	NA	50	0.05	0.02	0.04	144	110
125	8.16	242	451	NA	29	0.69	0.29	0.29	72	120
126	8.18	282	504	NA	30	0.41	0.41	0.20	77	133
127	8.21	202	455	NA	32	0.23	0.39	0.26	78	115
128	8.23	242	451	NA	29	0.26	0.30	0.22	72	115
129	8.23	552	987	NA	42	0.04	0.03	0.04	120	115
130	8.25	562	1185	NA	50	0.07	0.05	0.09	144	111
131	8.29	202	455	NA	32	0.21	0.19	0.24	78	119
132	8.30	493	1110	NA	50	0.12	0.03	0.04	141	113
133	9.01	182	499	NA	37	0.29	0.19	0.24	88	117
134	9.07	183	501	NA	37	0.31	0.41	0.23	88	113
135	9.08	482	1098	NA	50	0.07	0.11	0.05	140	111
136	9.08	312	1095	NA	62	0.16	0.08	0.17	161	127
137	9.12	142	453	NA	38	0.23	0.36	0.31	87	115
138	9.14	503	1099	NA	49	0.09	0.08	0.14	138	125
139	9.14	144	804	NA	67	0.10	0.08	0.09	153	116
140	9.15	247	566	NA	36	0.25	0.36	0.26	90	130
141	9.18	392	990	NA	50	0.10	0.08	0.09	135	115
142	9.21	428	1200	NA	58	0.11	0.12	0.22	159	118
143	9.22	242	1400	NA	90	0.09	0.03	0.05	225	113
144	9.22	353	1372	NA	73	0.03	0.03	0.04	194	105
145	9.26	272	1056	NA	64	0.29	0.13	0.13	163	128
147	9.28	162	445	NA	35	0.36	0.54	0.46	82	115
148	9.28	172	472	NA	36	0.97	1.06	0.77	85	123
149	10.03	142	441	NA	37	0.24	0.33	0.20	85	115
150	10.04	452	957	NA	45	0.08	0.09	0.14	125	112
151	10.04	142	441	NA	37	0.20	0.23	0.12	85	122
152	10.04	214	790	NA	54	0.07	0.10	0.08	132	118
153	10.04	252	651	NA	41	0.40	0.55	0.29	103	133
154	10.09	282	1041	NA	62	0.26	0.23	0.13	159	138
155	10.09	142	441	NA	37	0.09	0.13	0.09	85	114
156	10.10	462	946	NA	44	0.14	0.13	0.21	122	118
157	10.12	413	1097	NA	54	0.07	0.12	0.08	147	112
157	10.12	413	1402	NA	69	0.10	0.09	0.16	188	110
158	10.12	284	1095	NA	65	0.07	0.07	0.08	167	112
158	10.12	284	1500	NA	89	0.03	0.02	0.03	228	110
159	10.17	247	550	NA	35	0.17	0.15	0.27	88	124
160	10.19	212	699	NA	48	0.24	0.27	0.24	117	128
160	10.19	212	2155	NA	148	0.02	0.02	0.03	361	123
161	10.19	393	1090	NA	55	0.07	0.09	0.08	149	116
161	10.19	393	1507	NA	76	0.08	0.06	0.07	206	113
162	10.20	402	1143	NA	57	0.11	0.05	0.14	155	113
163	10.24	122	398	NA	36	0.28	0.33	0.31	80	118
163	10.24	122	3004	NA	272	0.01	0.02	0.01	606	110
164	10.24	402	1243	NA	62	0.12	0.07	0.10	168	106
164	10.24	402	1804	NA	90	0.09	0.07	0.07	245	113
165	10.25	247	802	NA	51	0.26	0.21	0.16	128	113
165	10.25	247	2295	NA	146	0.04	0.02	0.02	366	103
166	10.27	143	694	NA	58	0.20	0.20	0.16	133	118
166	10.27	143	2093	NA	175	0.03	0.02	0.03	400	109
167	10.31	252	1397	NA	88	0.03	0.03	0.02	221	113
168	10.31	353	1109	NA	59	0.08	0.06	0.09	157	118
169	11.01	443	989	NA	47	0.07	0.08	0.09	130	114

Table C-1. 1989 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s			CRSD, ft/lb^1/3	Airblast, dB
						H1	Vertical	H2		
170	11.02	247	550	NA	35	0.29	0.42	0.31	88	126
171	11.08	282	840	NA	50	0.40	0.34	0.22	128	113
172	11.08	127	1195	NA	106	0.03	0.02	0.02	238	108
173	11.08	127	1296	NA	115	0.02	0.02	0.03	258	106
174	11.10	142	643	NA	54	0.19	0.19	0.23	123	111
175	11.14	393	1090	NA	55	0.04	0.05	0.07	149	122
176	11.14	42	499	NA	77	0.09	0.05	0.06	144	125
177	11.15	247	550	NA	35	0.48	0.36	0.31	88	126
177	11.15	247	1242	NA	79	0.04	0.02	0.04	198	114
178	11.15	403	1204	NA	60	0.14	0.08	0.00	163	110
179	11.17	22	2580	NA	550	0.08	0.10	0.10	921	111
180	11.17	122	398	NA	36	0.25	0.45	0.28	80	117
181	11.22	142	548	NA	46	0.08	0.03	0.05	105	106
182	11.27	333	1095	NA	60	0.08	0.05	0.08	158	121
183	11.28	247	644	NA	41	0.63	0.35	0.46	103	134
183	11.28	247	1996	NA	127	0.06	0.06	0.13	318	114
184	12.01	247	597	NA	38	0.50	0.21	0.28	95	113
185	12.04	122	398	NA	36	0.24	0.26	0.21	80	117
185	12.04	122	2297	NA	208	0.03	0.03	0.03	463	107
186	12.05	362	1104	NA	58	0.09	0.07	0.09	155	122
187	12.07	428	1572	NA	76	0.11	0.09	0.09	209	122
188	12.08	342	795	NA	43	0.33	0.19	0.13	114	114
189	12.08	50	983	NA	139	0.12	0.12	0.12	267	113
190	12.12	122	398	NA	36	0.60	0.50	0.41	80	120
190	12.12	122	2297	NA	208	0.02	0.01	0.01	463	114
191	12.13	247	597	NA	38	0.56	0.49	0.42	95	135
191	12.13	247	1996	NA	127	0.04	0.02	0.06	318	115
192	12.15	142	751	NA	63	0.14	0.18	0.13	144	112
193	12.18	432	1102	NA	53	0.11	0.07	0.13	146	123
194	12.26	312	1042	NA	59	0.15	0.11	0.07	154	121
194	12.26	312	1042	NA	59	0.03	0.02	0.03	154	118
195	12.28	252	1048	NA	66	0.04	0.05	0.04	166	118
195	12.28	252	1238	NA	78	0.14	0.10	0.10	196	112

* SRSD = Square Root Scaled Distance and CRSD = Cube Root Scaled Distance.

** Inst. Loc. is the instrument location number as shown in the text.

†The carat symbol "^" denotes superscript. i.e. ^1/2 = "to the 1/2 power" or square root.

‡ NA = This information was not available.

Table C-2. 1990 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #**	SRSD*, ft/lb^1/2†	Peak Particle Velocity, in/s			CRSD*, ft/lb^1/3†	Airblast, dB
						H1	Vertical	H2		
1	1.02	362	1123	1	59	0.05	0.05	0.06	158	123
1	1.02	362	1142	4	60	0.11	0.08	0.10	160	120
2	1.04	52	1096	5	152	0.10	0.08	0.14	294	NA‡
3	1.08	452	1148	1	54	0.13	0.06	0.06	150	126
3	1.08	452	1382	4	65	0.10	0.07	0.09	180	127
4	1.10	247	550	3	35	0.29	0.49	0.42	88	134
5	1.10	202	1194	1	84	0.05	0.02	0.03	203	115
5	1.10	202	1748	3	123	0.10	0.12	0.09	298	113
6	1.12	142	2002	1	168	0.04	0.03	0.04	384	105
7	1.16	178	1001	3	75	0.10	0.14	0.09	178	111
7	1.16	178	2001	1	150	0.04	0.02	0.05	356	104
8	1.16	242	1042	1	67	0.05	0.04	0.04	167	116
8	1.16	242	1307	5	84	0.27	0.28	0.15	210	117
9	1.18	177	1104	3	83	0.20	0.14	0.12	197	117
9	1.18	177	1996	1	150	0.05	0.04	0.03	355	107
10	1.22	177	971	3	73	0.22	0.17	0.16	173	111
10	1.22	177	1996	1	150	0.08	0.04	0.07	355	109
11	1.24	243	1044	1	67	0.10	0.07	0.06	167	117
11	1.24	243	1278	5	82	0.26	0.36	0.17	205	NA
12	1.24	212	2068	1	142	0.03	0.03	0.07	347	102
13	1.26	314	1045	3	59	0.27	0.22	0.24	154	119
13	1.26	314	1949	1	110	0.10	0.05	0.06	287	103
14	1.30	412	1096	3	54	0.11	0.06	0.11	147	121
14	1.30	412	1198	1	59	0.28	0.07	0.19	161	116
15	1.30	242	1042	1	67	0.05	0.07	0.05	167	118
15	1.30	242	1245	5	80	0.20	0.27	0.17	200	117
17	2.01	354	1091	3	58	0.43	0.20	0.28	154	116
17	2.01	354	1900	1	101	0.05	0.03	0.09	269	107
18	2.02	247	1949	1	124	0.04	0.03	0.05	311	113
18	2.02	247	550	3	35	0.59	0.56	0.39	88	132
19	2.06	321	896	3	50	0.23	0.22	0.26	131	121
19	2.06	321	1899	1	106	0.00	0.09	0.05	277	109
20	2.06	242	1042	1	67	0.10	0.11	0.09	167	114
20	2.06	242	1245	5	80	0.38	0.31	0.25	200	115
21	2.08	354	790	3	42	0.33	0.30	0.35	112	116
21	2.08	354	1881	1	100	0.05	0.02	0.06	266	110
22	2.13	177	692	3	52	0.34	0.35	0.28	123	113
22	2.13	177	1889	1	142	0.09	0.04	0.06	336	110
23	2.14	247	692	3	44	0.39	0.29	0.26	110	111
23	2.14	247	1996	1	127	0.03	0.02	0.05	318	110
24	2.14	122	398	3	36	0.59	0.26	0.54	80	117
24	2.14	122	2297	1	208	0.02	0.02	0.03	463	111
25	2.16	321	950	3	53	0.42	0.21	0.33	139	121
25	2.16	321	1863	1	104	0.05	0.03	0.06	272	106
26	2.19	293	1061	5	62	0.15	0.16	0.19	160	114
26	2.19	293	1147	4	67	0.06	0.06	0.08	173	119
27	2.21	177	599	3	45	0.35	0.25	0.30	107	113
27	2.21	177	2089	1	157	0.02	0.02	0.03	372	109
28	2.21	4.8	500	3	228	0.01	0.01	0.01	296	102
29	2.22	412	1096	2	54	0.10	0.07	0.12	147	121
29	2.22	412	1401	3	69	0.11	0.05	0.09	188	114
30	2.27	177	639	3	48	0.22	0.15	0.16	114	115
30	2.27	177	2115	1	159	0.05	0.06	0.06	377	114
31	2.28	352	994	5	53	0.26	0.28	0.16	141	117

Table C-2. 1990 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s			CRSD, ft/lb^1/3	Airblast, dB
						H1	Vertical	H2		
31	2.28	352	1201	4	64	0.09	0.06	0.08	170	112
32	3.01	177	652	3	49	0.13	0.15	0.18	116	115
32	3.01	177	2102	1	158	0.03	0.01	0.01	374	104
33	3.01	177	652	3	49	0.22	0.17	0.16	116	109
33	3.01	177	2102	1	158	0.03	0.02	0.02	374	105
34	3.05	412	1116	2	55	0.18	0.22	0.20	150	124
34	3.05	412	1449	3	71	0.11	0.07	0.08	195	116
35	3.06	177	700	3	53	0.15	0.20	0.19	125	115
35	3.06	177	2129	1	160	0.03	0.02	0.04	379	103
36	3.07	342	1091	5	59	0.21	0.32	0.24	156	118
36	3.07	342	1147	4	62	0.09	0.05	0.12	164	113
37	3.12	214	951	3	65	0.18	0.13	0.19	159	111
38	3.14	178	694	3	52	0.33	0.33	0.39	123	116
39	3.06	212	699	3	48	0.13	0.11	0.12	117	108
40	3.19	247	597	3	38	0.39	0.28	0.30	95	125
40	3.19	247	1965	1	125	0.06	0.03	0.03	313	111
41	3.19	177	492	3	37	0.29	0.29	0.31	88	120
41	3.19	177	2195	1	165	0.04	0.02	0.04	391	112
42	3.20	242	653	5	42	0.20	0.29	0.18	105	104
42	3.20	242	996	4	64	0.08	0.06	0.06	160	111
43	3.21	402	1003	1	50	0.07	0.05	0.14	136	118
44	3.23	242	591	5	38	0.37	0.35	0.16	95	115
44	3.23	242	980	4	63	0.08	0.06	0.06	157	114
45	3.27	413	1097	2	54	0.12	0.11	0.16	147	124
45	3.27	413	1199	3	59	0.10	0.05	0.08	161	119
46	3.28	242	591	5	38	0.27	0.31	0.19	95	101
46	3.28	242	949	4	61	0.14	0.14	0.15	152	119
47	3.28	286	4312	3	255	0.07	0.05	0.07	655	112
48	3.28	122	420	3	38	0.66	0.44	0.36	85	118
48	3.28	122	2308	1	209	0.03	0.02	0.03	465	114
49	3.30	212	641	3	44	0.30	0.34	0.17	107	111
49	3.30	212	2140	1	147	0.02	0.01	0.02	359	106
50	4.02	242	700	5	45	0.24	0.17	0.11	112	114
50	4.02	242	902	4	58	0.22	0.09	0.12	145	115
51	4.04	247	817	3	52	0.37	0.49	0.36	130	111
51	4.04	247	1917	1	122	0.05	0.03	0.06	306	110
52	4.04	213	1000	3	69	0.18	0.25	0.22	167	114
52	4.04	213	2058	1	141	0.03	0.04	0.04	345	110
53	4.04	212	946	3	65	0.09	0.19	0.09	159	116
53	4.04	212	2242	1	154	0.02	0.01	0.03	376	104
54	4.06	242	933	4	60	0.06	0.04	0.05	150	116
55	4.09	247	2100	1	134	0.06	0.03	0.08	335	116
55	4.09	247	943	3	60	0.32	0.26	0.26	150	109
56	4.09	242	560	5	36	0.22	0.25	0.15	90	124
56	4.09	242	856	4	55	0.13	0.11	0.10	137	112
57	4.12	247	613	3	39	0.56	0.00	0.00	98	132
57	4.12	247	1902	1	121	0.08	0.06	0.07	303	116
58	4.13	242	1136	5	73	0.12	0.00	0.00	182	113
58	4.13	242	887	4	57	0.07	0.09	0.07	142	110
59	4.16	247	896	3	57	0.62	0.00	0.00	143	119
59	4.16	247	2043	1	130	0.05	0.03	0.03	326	111
60	4.18	242	887	4	57	0.14	0.09	0.10	142	110
60	4.18	242	793	5	51	0.19	0.00	0.11	127	116
61	4.18	122	398	3	36	0.56	0.43	0.42	80	119
61	4.18	122	2308	1	209	0.06	0.03	0.04	465	111

Table C-2. 1990 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s			CRSD, ft/lb^1/3	Airblast, dB
						H1	Vertical	H2		
62	4.20	262	842	5	52	0.18	0.13	0.07	132	117
62	4.20	262	939	4	58	0.08	0.04	0.05	147	113
63	4.20	472	956	5	44	0.14	0.10	0.16	123	111
65	4.25	248	2016	1	128	0.05	0.02	0.04	321	110
65	4.25	248	1008	3	64	0.23	0.15	0.24	160	118
66	4.27	433	916	5	44	0.12	0.09	0.11	121	115
66	4.27	433	1020	1	49	0.06	0.07	0.06	135	114
67	4.27	462	860	5	40	0.21	0.11	0.13	111	117
67	4.27	462	924	1	43	0.08	0.08	0.14	120	111
68	5.01	248	803	3	51	0.15	0.28	0.13	128	115
68	5.01	248	2299	1	146	0.07	0.07	0.07	366	110
69	5.01	122	398	3	36	0.19	0.20	0.18	80	115
69	5.01	122	2794	1	253	0.07	0.05	0.08	563	112
70	5.03	247	629	3	40	0.68	0.59	0.53	100	121
71	5.07	412	893	5	44	0.37	0.21	0.40	120	115
71	5.07	412	995	1	49	0.15	0.07	0.14	134	120
72	5.10	377	913	1	47	0.08	0.01	0.03	126	117
72	5.10	377	913	5	47	0.09	0.12	0.00	126	121
73	5.14	247	849	3	54	0.34	0.58	0.22	135	123
74	5.16	177	492	3	37	0.78	0.44	0.52	88	130
74	5.16	248	598	1	38	0.09	0.06	0.06	95	119
75	5.17	247	990	3	63	0.11	0.13	0.09	158	121
75	5.17	247	1996	1	127	0.04	0.04	0.04	318	112
76	5.21	432	852	5	41	0.21	0.10	0.15	113	113
76	5.21	432	1018	4	49	0.10	0.06	0.07	135	115
77	5.22	123	399	3	36	0.20	0.23	0.18	80	118
77	5.22	123	2307	1	208	0.06	0.08	0.06	464	99
78	5.24	247	990	3	63	0.14	0.10	0.09	158	120
78	5.24	247	1949	1	124	0.05	0.08	0.05	311	110
79	5.30	412	995	4	49	0.16	0.04	0.07	134	121
79	5.30	412	1482	5	73	0.22	0.19	0.15	199	119
80	5.31	262	599	3	37	0.37	0.36	0.32	94	122
80	5.31	262	1926	1	119	0.05	0.07	0.07	301	116
81	6.04	122	353	3	32	0.05	0.01	0.02	71	125
81	6.04	122	2297	1	208	0.05	0.05	0.05	463	124
82	6.05	254	1195	5	75	0.10	0.07	0.09	189	108
82	6.05	254	1402	4	88	0.00	0.00	0.00	221	0
83	6.06	182	499	3	37	0.34	0.41	0.22	88	125
83	6.06	182	2091	2	155	0.07	0.08	0.09	369	111
84	6.08	252	1048	5	66	0.00	0.00	0.00	166	0
85	6.11	262	874	3	54	0.00	0.00	0.00	137	0
85	6.11	262	2218	1	137	0.06	0.06	0.05	347	109
86	6.14	247	1949	1	124	0.04	0.05	0.06	311	117
87	6.15	202	867	3	61	0.13	0.12	0.17	148	113
87	6.15	202	2246	1	158	0.04	0.04	0.05	383	116
88	6.15	352	976	2	52	0.10	0.05	0.06	138	118
88	6.15	352	0	3	0	0.05	0.05	0.06	0	125
89	6.18	262	1343	1	83	0.09	0.03	0.06	210	111
89	6.18	262	1392	3	86	0.11	0.06	0.11	218	117
90	6.19	362	980	5	52	0.22	0.19	0.11	137	115
90	6.19	362	1237	1	65	0.08	0.05	0.06	174	117
91	6.21	262	599	3	37	0.67	0.60	0.34	94	124
91	6.21	262	1845	2	114	0.10	0.07	0.07	288	111
92	6.22	120	5488	1	501	0.03	0.03	0.03	1113	116
93	6.25	248	1050	3	67	0.14	0.12	0.11	167	125

Table C-2. 1990 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s			CRSD, ft/lb^1/3	Airblast, dB
						H1	Vertical	H2		
93	6.25	248	2000	4	127	0.08	0.06	0.07	318	103
94	6.27	252	1048	4	66	0.11	0.10	0.15	166	115
95	6.29	247	1100	3	70	0.17	0.12	0.09	175	126
95	6.29	247	1886	4	120	0.04	0.05	0.05	301	109
96	7.02	352	938	2	50	0.11	0.06	0.09	133	119
96	7.02	352	1989	3	106	0.05	0.05	0.06	282	117
97	7.05	282	1008	3	60	0.15	0.22	0.09	154	115
97	7.05	282	2200	4	131	0.03	0.05	0.05	335	114
98	7.06	122	353	3	32	0.25	0.33	0.16	71	122
98	7.06	122	2297	1	208	0.05	0.04	0.04	463	113
99	7.10	282	1008	3	60	0.18	0.19	0.11	154	122
99	7.10	282	2217	4	132	0.05	0.05	0.04	338	120
100	7.12	245	845	3	54	0.14	0.09	0.05	135	115
101	7.13	247	1069	3	68	0.29	0.22	0.10	170	131
101	7.13	247	2059	4	131	0.05	0.06	0.06	328	118
102	7.16	412	1096	2	54	0.13	0.08	0.11	147	124
102	7.16	412	1401	3	69	0.10	0.09	0.07	188	122
103	7.18	175	847	1	64	0.08	0.07	0.06	151	111
104	7.19	282	957	1	57	0.28	0.22	0.16	146	123
104	7.19	282	1898	4	113	0.06	0.08	0.06	289	115
105	7.20	242	840	5	54	0.20	0.20	0.15	135	115
105	7.20	242	1011	4	65	0.12	0.10	0.13	162	118
106	7.25	142	858	3	72	0.14	0.07	0.07	164	118
106	7.25	142	1144	4	96	0.02	0.03	0.02	219	104
107	7.26	407	1170	2	58	0.08	0.06	0.09	158	122
107	7.26	407	1453	3	72	0.08	0.07	0.07	196	116
108	7.26	282	957	3	57	0.23	0.18	0.13	146	118
108	7.26	282	1881	1	112	0.06	0.06	0.06	287	118
109	7.30	147	897	3	74	0.09	0.03	0.06	170	118
110	7.31	182	499	2	37	0.27	0.44	0.18	88	120
110	7.31	182	2091	3	155	0.06	0.04	0.04	369	109
111	8.01	282	840	3	50	0.38	0.35	0.34	128	118
111	8.01	282	1898	1	113	0.07	0.07	0.06	289	112
112	8.03	166	902	3	70	0.05	0.07	0.05	164	116
113	8.08	247	1022	4	65	0.09	0.13	0.12	163	113
114	8.13	177	918	3	69	0.12	0.12	0.09	163	119
114	8.13	177	2195	4	165	0.06	0.07	0.08	391	115
115	8.13	162	840	3	66	0.14	0.10	0.12	154	109
116	8.15	282	823	3	49	0.34	0.49	0.29	125	118
116	8.15	282	1898	1	113	0.10	0.08	0.10	289	111
117	8.16	163	894	3	70	0.07	0.09	0.06	164	115
119	8.17	242	793	5	51	0.18	0.31	0.22	127	NA
119	8.17	242	1042	4	67	0.09	0.10	0.15	167	114
120	8.22	354	997	3	53	0.15	0.19	0.18	141	NA
120	8.22	354	2201	4	117	0.02	0.03	0.02	311	114
121	8.24	247	707	5	45	0.20	0.33	0.14	113	114
121	8.24	247	1037	4	66	0.10	0.12	0.09	165	119
122	8.30	282	957	3	57	0.58	0.34	0.34	146	121
122	8.30	282	1898	1	113	0.07	0.07	0.07	289	117
123	9.05	242	700	5	45	0.30	0.17	0.20	112	104
123	9.05	242	996	4	64	0.05	0.08	0.05	160	114
124	9.10	212	990	3	68	0.20	0.14	0.20	166	120
125	9.13	242	980	2	63	0.12	0.05	0.09	157	111
125	9.13	242	1618	3	104	0.02	0.02	0.02	260	112
126	9.13	107	548	3	53	0.08	0.12	0.08	115	109

Table C-2. 1990 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s			CRSD, ft/lb^1/3	Airblast, dB
						H1	Vertical	H2		
127	9.17	107	548	3	53	0.11	0.19	0.12	115	111
128	9.19	252	2238	4	141	0.06	0.08	0.07	354	117
129	9.19	252	794	4	50	0.44	0.40	0.29	126	114
129	9.19	252	2159	3	136	0.06	0.08	0.07	342	120
130	9.24	252	952	2	60	0.07	0.06	0.07	151	113
131	9.26	242	980	3	63	0.21	0.22	0.15	157	111
131	9.26	242	1073	4	69	0.11	0.15	0.15	172	114
132	10.03	247	770	3	49	0.23	0.20	0.19	123	116
132	10.03	247	723	4	46	0.04	0.06	0.04	115	123
133	10.04	252	952	2	60	0.07	0.03	0.05	151	113
133	10.04	252	1587	3	100	0.14	0.13	0.14	251	114
134	10.08	252	746	3	47	0.07	0.03	0.03	118	101
134	10.08	252	1937	1	122	0.09	0.08	0.09	307	112
135	10.09	242	902	5	58	0.19	0.19	0.14	145	112
135	10.09	242	1105	4	71	0.10	0.15	0.16	177	117
136	10.16	252	587	3	37	0.43	0.34	0.28	93	129
136	10.16	252	1953	1	123	0.14	0.13	0.13	309	116
137	10.22	252	1000	2	63	0.12	0.07	0.09	158	118
138	10.29	242	591	5	38	0.16	0.20	0.19	95	109
138	10.29	242	1089	4	70	0.14	0.11	0.14	175	111
139	10.31	252	740	3	47	0.40	0.12	0.29	117	120
139	10.31	252	1953	1	123	0.12	0.11	0.12	309	116
141	11.07	122	398	3	36	0.30	0.37	0.20	80	119
141	11.07	122	2253	2	204	0.06	0.06	0.05	454	109
142	11.07	242	544	5	35	0.16	0.19	0.31	87	116
142	11.07	242	1089	4	70	0.16	0.15	0.15	175	119
143	11.12	242	996	2	64	0.08	0.04	0.05	160	114
143	11.12	242	1540	1	99	0.11	0.11	0.11	247	114
144	11.13	222	521	5	35	0.36	0.25	0.22	86	111
144	11.13	222	1192	4	80	0.14	0.15	0.14	197	119
145	11.20	282	974	3	58	0.24	0.20	0.17	149	125
145	11.20	282	1847	1	110	0.09	0.09	0.10	282	115
146	11.26	182	580	3	43	0.73	0.49	0.66	102	121
146	11.26	182	2199	1	163	0.15	0.14	0.14	388	120
147	11.28	212	801	5	55	0.33	0.16	0.15	134	112
147	11.28	212	1107	4	76	0.10	0.14	0.10	186	112
148	11.30	122	453	3	41	0.52	0.62	0.35	91	116
149	12.04	242	638	5	41	0.24	0.39	0.23	102	115
149	12.04	242	996	4	64	0.08	0.10	0.12	160	112
151	12.07	402	1103	2	55	0.10	0.07	0.10	149	127
151	12.07	402	1303	1	65	0.11	0.12	0.10	177	127
152	12.07	107	879	3	85	0.06	0.07	0.06	185	112
153	12.12	242	964	4	62	0.08	0.04	0.05	155	112
153	12.12	242	793	5	51	0.18	0.19	0.16	127	120
154	12.12	74	800	3	93	0.11	0.08	0.12	191	111
155	12.14	102	353	3	35	0.20	0.32	0.24	76	117
155	12.14	102	2252	1	223	0.04	0.05	0.03	482	106
156	12.19	247	723	3	46	0.25	0.21	0.15	115	126
156	12.19	247	2200	4	140	0.06	0.06	0.07	351	117

* SRSD = Square Root Scaled Distance and CRSD = Cube Root Scaled Distance.

** Inst. Loc. is the instrument location number as shown in the text.

†The carat symbol "^" denotes superscript. i.e. ^1/2 = "to the 1/2 power" or square root.

‡ NA = The information is not available

Table C-3. 1991 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #**	SRSD*, ft/lb^1/2†	Peak Particle Velocity, in/s			CRSD*, ft/lb^1/3†	Airblast, dB
						H1	Vertical	H2		
1	3.14	277	1215	3	73	0.25	0.14	0.14	186	122
2	3.20	75	650	3	75	0.06	0.07	0.07	154	114
3	3.26	247	566	3	36	0.64	0.48	0.37	90	119
3	3.26	247	1839	2	117	0.07	0.13	0.09	293	108
4	3.27	292	1247	3	73	0.17	0.13	0.08	188	118
4	3.27	292	1743	4	102	0.05	0.06	0.05	263	104
5	4.02	382	1368	1	70	0.09	0.03	0.09	189	114
5	4.02	382	1388	3	71	0.08	0.11	0.12	191	120
6	4.03	292	1247	3	73	0.10	0.12	0.09	188	127
6	4.03	292	1726	1	101	0.08	0.13	0.11	260	112
7	4.05	352	1144	2	61	0.10	0.05	0.08	162	113
7	4.05	352	1445	3	77	0.06	0.06	0.05	205	116
8	4.09	222	1147	3	77	0.12	0.10	0.09	189	120
8	4.09	222	1773	1	119	0.04	0.06	0.05	293	108
9	4.12	372	1234	5	64	0.09	0.05	0.11	172	115
9	4.12	372	1331	1	69	0.11	0.08	0.13	185	111
10	4.15	177	1051	3	79	0.08	0.07	0.06	187	112
10	4.15	177	1902	1	143	0.03	0.04	0.03	339	109
11	4.17	282	1142	3	68	0.19	0.17	0.11	174	121
11	4.17	282	1763	1	105	0.08	0.09	0.11	269	114
12	4.19	422	1438	3	70	0.15	0.12	0.16	192	114
13	4.25	292	1299	3	76	0.11	0.71	0.11	196	119
13	4.25	292	1350	1	79	0.10	0.07	0.10	203	113
14	4.29	282	1142	3	68	0.17	0.14	0.10	174	126
14	4.29	282	1713	1	102	0.05	0.05	0.09	261	111
15	5.01	422	1253	1	61	0.15	0.06	0.08	167	110
15	5.01	522	1599	3	70	0.14	0.07	0.12	199	117
16	5.03	102	374	3	37	0.45	0.38	0.31	80	118
16	5.03	102	242	2	24	0.05	0.05	0.03	52	105
17	5.11	282	1142	3	68	0.19	0.24	0.17	174	128
17	5.11	282	1679	1	100	0.06	0.06	0.07	256	111
18	5.14	42	1270	3	196	0.02	0.03	0.03	365	104
19	5.15	292	1128	3	66	0.16	0.13	0.09	170	118
19	5.15	292	1999	1	117	0.05	0.05	0.07	301	112
20	5.06	10	503	2	159	0.02	0.02	0.02	233	106
21	5.11	462	1247	1	58	0.10	0.08	0.12	161	114
21	5.11	462	1483	3	69	0.13	0.05	0.10	192	120
22	5.22	292	1094	3	64	0.12	0.17	0.10	165	118
22	5.22	292	2033	1	119	0.03	0.03	0.04	307	112
23	5.31	282	1092	3	65	0.18	0.17	0.17	166	119
23	5.31	282	2049	1	122	0.03	0.03	0.03	312	115
24	6.03	283	1245	3	74	0.19	0.18	0.13	190	125
24	6.03	283	1716	1	102	0.08	0.03	0.06	261	111
25	6.04	82	344	3	38	0.36	0.50	0.23	79	117
25	6.04	82	2028	2	224	0.04	0.04	0.04	467	108
26	6.05	74	637	1	74	0.06	0.04	0.07	152	107
26	6.05	262	1441	3	89	0.15	0.11	0.09	225	118
27	6.06	283	1060	3	63	0.13	0.13	0.14	161	119
27	6.06	283	2002	1	119	0.04	0.04	0.04	305	112
28	6.07	72	1095	2	129	0.05	0.04	0.04	263	105
30	7.17	282	1050	3	63	0.13	0.20	0.14	160	115
31	7.18	282	1259	3	75	0.14	0.20	0.14	192	124
32	7.31	202	1029	3	72	0.11	0.10	0.10	175	117
33	8.07	282	1041	3	62	0.13	0.21	0.09	159	117

Table C-3. 1991 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s			CRSD, ft/lb^1/3	Airblast, dB
						H1	Vertical	H2		
34	8.14	282	1293	3	77	0.15	0.13	0.09	197	124
35	8.19	177	492	3	37	0.59	0.50	0.21	88	123
37	8.27	177	1996	2	150	0.04	0.03	0.03	355	109
38	8.29	282	1142	3	68	0.17	0.24	0.10	174	121
38	8.29	282	1948	4	116	0.08	0.09	0.07	297	112
39	9.04	282	1713	4	102	0.09	0.12	0.09	261	106
40	9.06	77	351	3	40	0.37	0.19	0.22	83	118
41	9.06	25	1900	3	380	0.03	0.04	0.04	650	109
42	9.12	40	696	4	110	0.07	0.08	0.07	203	110
43	9.13	45	718	4	107	0.08	0.10	0.08	202	114
44	9.17	55	719	4	97	0.12	0.20	0.08	189	110
45	9.19	24	750	4	153	0.08	0.08	0.08	260	108
46	9.20	252	1222	1	77	0.12	0.12	0.11	194	114
48	9.27	262	1198	3	74	0.15	0.17	0.23	187	118
49	10.03	262	1311	3	81	0.14	0.17	0.13	205	122
50	10.07	252	1206	1	76	0.08	0.06	0.05	191	112
50	10.07	252	1492	3	94	0.11	0.12	0.10	236	113
51	10.09	77	342	3	39	0.42	0.46	0.38	80	118
53	10.16	282	1696	4	101	0.06	0.04	0.04	259	110
53	10.16	282	1394	3	83	0.19	0.24	0.15	213	124
54	10.17	242	669	3	43	0.10	0.22	0.13	107	119
54	10.17	242	1229	1	79	0.08	0.05	0.06	197	99
55	10.24	344	1002	2	54	0.08	0.04	0.05	143	119
55	10.24	344	1651	3	89	0.02	0.02	0.02	236	112
56	10.28	262	1424	3	88	0.15	0.24	0.14	223	125
57	10.29	364	1698	3	89	0.02	0.02	0.02	238	114
57	10.29	364	992	2	52	0.06	0.03	0.04	139	97
58	10.30	6.5	1002	2	393	0.02	0.03	0.02	537	122
59	10.31	344	964	2	52	0.10	0.06	0.07	138	116
59	10.31	344	1688	3	91	0.04	0.04	0.05	241	117
60	10.31	242	1493	3	96	0.10	0.06	0.08	240	119
60	10.31	242	1042	5	67	0.19	0.24	0.24	167	112
61	11.07	6	1100	1	449	0.04	0.05	0.03	605	108
63	12.10	247	1242	5	79	0.10	0.09	0.12	198	115
63	12.10	247	1289	3	82	0.16	0.11	0.11	205	118
64	12.11	252	1000	5	63	0.27	0.16	0.16	158	114
64	12.11	252	1492	3	94	0.11	0.12	0.11	236	118

* SRSD = Square Root Scaled Distance and CRSD = Cube Root Scaled Distance.

** Inst. Loc. is the instrument location number as shown in the text.

†The carat symbol "^" denotes superscript. i.e. ^1/2 = "to the 1/2 power" or square root.

Table C-4. 1992 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #**	SRSD*, ft/lb^1/2†	Peak Particle Velocity, in/s			CRSD*, ft/lb^1/3†	Airblast, dB
						H1	Vertical	H2		
1	1.10	247	1100	5	70	0.08	0.07	0.09	175	115
1	1.10	247	1352	3	86	0.18	0.13	0.18	215	122
2	1.13	252	1000	5	63	0.04	0.22	0.17	158	113
2	1.13	252	1508	3	95	0.10	0.12	0.12	239	113
3	1.15	307	1034	2	59	0.13	0.10	0.10	153	116
3	1.15	307	1419	3	81	0.05	0.02	0.02	210	119
4	1.22	77	298	3	34	0.23	0.55	0.29	70	115
4	1.22	77	474	2	54	0.07	0.07	0.07	111	109
5	1.30	187	2092	2	153	0.09	0.06	0.09	366	111
5	1.30	187	465	3	34	0.46	0.56	0.23	81	126
6	2.03	26	999	2	196	0.09	0.08	0.10	337	108
7	2.11	484	1738	3	79	0.08	0.07	0.07	221	118
7	2.11	484	968	2	44	0.14	0.10	0.14	123	118
8	2.26	247	1100	5	70	0.11	0.20	0.13	175	111
8	2.26	247	1446	3	92	0.26	0.22	0.24	230	122
9	3.04	252	1619	3	102	0.10	0.10	0.07	256	117
11	3.10	328	960	2	53	0.14	0.08	0.14	139	115
11	3.10	328	1702	3	94	0.07	0.05	0.05	247	112
12	3.11	262	1505	3	93	0.21	0.26	0.19	235	121
12	3.11	262	1084	5	67	0.20	0.17	0.18	169	113
13	3.17	242	902	5	58	0.15	0.27	0.24	145	111
13	3.17	242	1696	3	109	0.13	0.13	0.11	272	115
14	3.24	262	1068	5	66	0.19	0.33	0.22	167	113
14	3.24	262	1570	3	97	0.13	0.20	0.14	245	123
15	3.26	242	840	5	54	0.11	0.05	0.02	135	99
15	3.26	242	1696	3	109	0.13	0.13	0.14	272	125
16	3.30	77	369	3	42	0.45	0.42	0.25	87	120
17	3.31	262	1052	5	65	0.25	0.32	0.15	164	112
17	3.31	262	1570	3	97	0.01	0.01	0.02	245	121
18	4.07	262	1052	5	65	0.19	0.22	0.10	164	111
19	4.08	252	825	5	52	0.17	0.29	0.16	131	112
19	4.08	252	1222	4	77	0.09	0.09	0.06	194	109
20	4.09	242	996	5	64	0.23	0.21	0.14	160	112
21	4.14	322	951	2	53	0.14	0.07	0.11	139	122
22	4.15	252	1222	4	77	0.08	0.11	0.09	194	112
22	4.15	252	794	5	50	0.27	0.28	0.27	126	111
23	4.28	242	1649	3	106	0.14	0.15	0.11	265	121
23	4.28	242	996	5	64	0.21	0.24	0.15	160	113
24	5.13	262	955	5	59	0.21	0.26	0.13	149	113
24	5.13	262	1586	3	98	0.17	0.19	0.23	248	118
25	5.19	262	647	3	40	0.47	0.29	0.28	101	124
26	6.05	242	1229	4	79	0.10	0.11	0.09	197	104
27	6.10	262	939	5	58	0.13	0.17	0.10	147	111
27	6.10	262	1683	3	104	0.12	0.11	0.10	263	118
28	3.12	242	747	5	48	0.10	0.11	0.10	120	111
28	6.12	242	1213	4	78	0.19	0.21	0.20	195	115
29	6.16	262	906	5	56	0.19	0.27	0.10	142	112
29	6.16	262	1586	3	98	0.19	0.18	0.14	248	117
30	6.23	262	890	5	55	0.11	0.13	0.10	139	113
30	6.23	262	1748	3	108	0.14	0.13	0.16	273	120
31	7.07	82	353	3	39	0.37	0.45	0.40	81	118
32	7.30	177	532	3	40	0.30	0.37	0.40	95	125
32	7.30	177	2049	2	154	0.03	0.04	0.05	365	111
33	8.05	242	684	5	44	0.03	0.37	0.28	110	120

Table C-4. 1992 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s			CRSD, ft/lb^1/3	Airblast, dB
						H1	Vertical	H2		
33	8.05	242	1913	3	123	0.08	0.11	0.08	307	118
34	8.12	282	873	5	52	0.18	0.34	0.39	133	112
34	8.12	282	1612	3	96	0.01	0.23	0.17	246	122
35	8.13	222	641	5	43	0.18	0.20	0.25	106	115
35	8.13	222	1222	4	82	0.07	0.10	0.09	202	113
36	8.18	164	1114	2	87	0.04	0.05	0.05	204	110
37	8.25	222	611	5	41	0.17	0.21	0.15	101	109
37	8.24	222	1252	4	84	0.11	0.10	0.13	207	111
38	8.25	222	700	5	47	0.17	0.12	0.20	116	118
38	8.25	222	1177	3	79	0.08	0.05	0.09	194	122
39	9.14	282	856	5	51	0.27	0.22	0.23	131	113
40	9.15	222	1296	4	87	0.08	0.08	0.08	214	110
40	9.15	222	641	5	43	0.14	0.18	0.18	106	113
41	9.15	262	939	5	58	0.19	0.11	0.12	147	115
41	9.22	262	1538	3	95	0.15	0.13	0.14	240	116
42	9.22	222	611	5	41	0.14	0.18	0.17	101	111
42	9.23	222	1326	4	89	0.08	0.08	0.08	219	108
43	9.23	222	670	5	45	0.23	0.20	0.23	111	115
43	9.24	222	1147	4	77	0.17	0.12	0.16	189	116
44	9.29	272	627	5	38	0.18	0.24	0.31	97	115
44	9.29	272	1187	4	72	0.08	0.09	0.08	183	118
45	9.30	262	987	5	61	0.19	0.19	0.15	154	113
45	9.30	262	1489	3	92	0.12	0.12	0.20	233	117
46	10.02	222	656	5	44	0.23	0.25	0.18	108	118
46	10.02	222	1132	4	76	0.11	0.16	0.10	187	115
47	10.06	92	1093	2	114	0.08	0.07	0.08	242	108
48	10.07	262	1020	5	63	0.15	0.16	0.09	159	112
48	10.07	262	1020	3	63	0.19	0.10	0.22	159	114
49	10.13	223	1090	4	73	0.13	0.11	0.11	180	114
49	10.13	223	642	5	43	0.22	0.20	0.15	106	116
50	10.14	282	1444	3	86	0.26	0.15	0.24	220	114
50	10.14	282	1142	5	68	0.20	0.16	0.12	174	112
51	10.15	202	1009	2	71	0.07	0.09	0.10	172	111
52	10.19	222	611	5	41	0.35	0.26	0.23	101	121
52	10.19	222	1043	4	70	0.13	0.11	0.13	172	120
53	10.22	262	1068	5	66	0.12	0.13	0.07	167	104
53	10.22	262	1408	3	87	0.16	0.16	0.16	220	112
54	10.29	222	611	5	41	0.22	0.20	0.31	101	120
54	10.29	222	1043	4	70	0.14	0.13	0.16	172	123
55	11.06	222	730	5	49	0.25	0.24	0.21	121	114
55	11.06	222	1043	4	70	0.18	0.13	0.18	172	113
56	11.13	262	1084	5	67	0.14	0.06	0.17	169	114
56	11.13	262	1408	3	87	0.12	0.10	0.11	220	113
57	11.16	352	1557	3	83	0.05	0.03	0.06	221	121
57	11.16	352	1032	2	55	0.12	0.11	0.12	146	113
58	11.18	222	745	5	50	0.27	0.18	0.20	123	114
58	11.18	222	1043	4	70	0.17	0.15	0.16	172	112
59	11.20	262	1101	5	68	0.15	0.12	0.09	172	115
59	11.20	262	1376	3	85	0.26	0.17	0.32	215	117

* SRSD = Square Root Scaled Distance and CRSD = Cube Root Scaled Distance.

** Inst. Loc. is the instrument location number as shown in the text.

†The carat symbol "^" denotes superscript. i.e. ^1/2 = "to the 1/2 power" or square root.

Table C-5. 1993 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #**	SRSD*, ft/lb^1/2†	Peak Particle Velocity, in/s H1	Vertical	H2	CRSD*, ft/lb^1/3†	Airblast, dB
1	2.05	262	1133	5	70	0.15	0.03	0.07	177	114
2	2.10	222	805	5	54	0.31	0.13	0.15	133	116
2	2.10	222	1043	4	70	0.13	0.11	0.15	172	113
4	3.25	102	353	3	35	0.51	0.89	0.31	76	120
5	3.31	418	1288	5	63	0.16	0.08	0.17	172	120
5	3.31	418	1186	3	58	0.14	0.18	0.14	159	122
6	3.31	207	1496	3	104	0.15	0.11	0.14	253	114
7	4.07	262	696	3	43	0.24	0.38	0.27	109	126
7	4.07	262	1797	2	111	0.05	0.05	0.05	281	113
8	4.12	443	989	5	47	0.20	0.20	0.13	130	122
8	4.12	443	1494	3	71	0.12	0.06	0.12	196	124
9	4.13	252	1175	5	74	0.14	0.18	0.16	186	112
10	4.14	207	878	5	61	0.38	0.27	0.18	148	115
11	4.16	102	353	3	35	0.58	0.46	0.29	76	117
12	4.12	242	887	5	57	0.17	0.21	0.16	142	111
13	5.19	357	1020	2	54	0.12	0.15	0.11	144	116
14	5.20	262	1327	3	82	0.12	0.25	0.22	207	117
14	2.20	262	1327	5	82	0.15	0.07	0.12	207	115
15	5.21	358	927	5	49	0.25	0.16	0.20	131	123
15	5.21	358	927	5	49	0.25	0.16	0.20	131	123
16	5.26	353	1785	3	95	0.15	0.14	0.15	253	119
16	5.26	353	902	5	48	0.26	0.18	0.12	128	112
17	6.02	404	945	5	47	0.22	0.11	0.20	128	119
17	6.02	404	1045	1	52	0.12	0.12	0.13	141	116
18	6.03	347	876	5	47	0.26	0.10	0.15	125	109
18	6.03	347	1788	3	96	0.13	0.15	0.10	254	120
19	6.04	242	1245	5	80	0.11	0.06	0.05	200	97
19	6.04	242	1291	3	83	0.16	0.11	0.13	207	115
20	6.09	408	1818	3	90	0.16	0.12	0.25	245	125
20	6.09	408	808	5	40	0.32	0.21	0.21	109	109
21	6.10	187	492	3	36	0.49	0.38	0.34	86	120
21	6.10	187	2051	2	150	0.10	0.06	0.12	359	97
22	6.11	407	1009	5	50	0.17	0.06	0.14	136	120
22	6.11	407	1735	3	86	0.11	0.10	0.15	234	118
23	6.15	242	793	5	51	0.39	0.15	0.17	127	113
23	6.15	242	1851	3	119	0.12	0.09	0.14	297	122
24	6.22	242	747	5	48	0.27	0.14	0.22	120	112
24	6.22	242	1867	3	120	0.23	0.26	0.23	300	123
25	6.23	417	1041	1	51	0.08	0.08	0.09	139	111
25	6.23	417	1695	3	83	0.15	0.16	0.14	227	117
26	6.28	372	1022	2	53	0.10	0.09	0.08	142	113
26	6.28	372	1601	3	83	0.11	0.10	0.10	223	115
27	6.29	252	746	5	47	0.20	0.09	0.12	118	114
27	6.29	252	1889	3	119	0.13	0.15	0.17	299	122
28	7.01	242	1789	5	115	0.28	0.18	0.21	287	115
28	7.01	242	1789	3	115	0.05	0.09	0.12	287	117
29	7.01	146	1003	1	83	0.04	0.04	0.05	190	103
30	7.07	452	1042	1	49	0.07	0.04	0.06	136	113
30	7.07	452	1765	3	83	0.13	0.13	0.13	230	118
31	7.09	242	747	5	48	0.31	0.17	0.23	120	114
31	7.09	242	1789	3	115	0.12	0.17	0.15	287	126
32	7.16	262	826	5	51	0.27	0.22	0.24	129	115
32	7.16	262	1700	3	105	0.05	0.12	0.12	266	118
33	7.19	252	651	3	41	0.45	0.42	0.48	103	124
33	7.19	252	1905	2	120	0.12	0.05	0.07	302	104
34	7.23	242	716	5	46	0.46	0.30	0.26	115	117

Table C-5. 1993 Peak Ground Vibration and Airblast Measurements at McCoy Compliance Stations (cont.)

Shot Number	Date, mo.day	Max. charge weight per delay, lbs	Distance, ft	Inst. Loc., #**	SRSD*, ft/lb^1/2†	Peak Particle Velocity, in/s			CRSD*, ft/lb^1/3†	Airblast, dB
						H1	Vertical	H2		
34	7.23	242	1805	3	181	0.06	0.07	0.12	290	126
35	7.27	102	353	3	246	0.61	0.38	0.42	76	121
36	7.29	182	499	3	37	0.65	0.37	0.29	88	124
37	8.04	462	924	5	43	0.23	0.14	0.21	120	116
38	8.06	252	794	5	50	0.22	0.16	0.25	126	115
38	8.06	252	1714	3	108	0.02	0.01	0.01	271	128
39	8.09	102	353	3	35	0.55	0.54	0.36	76	123
40	8.11	359	853	1	45	0.09	0.10	0.11	120	114
41	8.11	322	1615	2	90	0.14	0.13	0.14	236	115
42	8.17	242	747	5	48	0.24	0.16	0.15	120	114
42	8.17	242	1742	3	112	0.12	0.11	0.12	280	115
43	8.20	102	343	3	34	0.47	0.67	0.48	73	116
44	8.26	448	1058	1	50	0.09	0.06	0.07	138	113
44	8.26	448	1651	3	78	0.13	0.08	0.11	216	117
45	9.03	242	731	5	47	0.19	0.21	0.19	117	111
45	9.03	242	1711	3	110	0.06	0.05	0.07	275	119
46	9.16	242	809	5	52	0.20	0.16	0.13	130	118
47	9.20	242	716	5	46	0.33	0.36	0.27	115	109
47	9.20	242	1742	3	112	0.12	0.12	0.15	280	122
48	9.24	242	716	5	46	0.27	0.31	0.30	115	111
48	9.24	242	1789	3	115	0.12	0.07	0.11	287	119
49	9.29	247	1713	3	109	0.07	0.09	0.13	273	121
50	9.29	247	79	5	5	0.27	0.22	0.15	13	114
50	9.29	247	1823	3	116	0.10	0.08	0.09	291	117
51	9.30	122	353	3	32	0.33	0.69	0.35	71	119
52	10.01	117	400	3	37	0.25	0.37	0.31	82	124
53	10.06	242	1571	3	101	0.13	0.10	0.13	252	109
54	10.12	242	824	3	53	0.08	0.08	0.10	132	115
54	10.12	242	824	5	53	0.18	0.14	0.15	132	NR‡
55	10.14	127	361	3	32	5.59	0.48	0.51	72	119
56	10.15	243	701	5	45	0.33	0.24	0.21	112	118
56	10.15	243	1512	3	97	0.16	0.11	0.20	242	109
57	10.18	182	499	3	37	0.52	0.45	0.50	88	125
58	10.26	242	1602	3	103	0.12	0.09	0.23	257	107
59	10.29	483	1033	1	47	0.12	0.04	0.05	132	113
59	10.29	483	1626	3	74	0.09	0.09	0.09	207	110
60	11.12	242	856	5	55	0.30	0.16	0.20	137	113
60	11.12	242	1742	4	112	0.07	0.13	0.15	280	99
61	11.18	242	824	5	53	0.19	0.20	0.29	132	115
61	11.18	242	1182	4	76	0.06	0.09	0.08	190	107
63	11.30	132	368	3	32	0.40	0.39	0.29	72	120
64	12.01	242	902	5	58	0.14	0.00	0.13	145	116
64	12.01	242	1633	3	105	0.06	0.09	0.23	262	115
65	12.03	242	1493	2	96	0.14	0.12	0.15	240	106
66	12.07	242	1587	2	102	0.10	0.14	0.20	255	111
67	12.08	247	644	3	41	0.34	0.34	0.19	103	123
67	12.08	247	1902	2	121	0.08	0.04	0.06	303	109
68	12.10	112	392	3	37	0.39	0.38	0.30	81	118
69	12.16	423	843	5	41	0.25	0.00	0.17	112	122
69	12.16	423	1131	4	55	0.12	0.07	0.07	151	117
70	12.20	243	920	5	59	0.21	0.24	0.16	147	116

* SRSD = Square Root Scaled Distance and CRSD = Cube Root Scaled Distance.

** Inst. Loc. is the instrument location number as shown in the text.

†The carat symbol "^" denotes superscript. I.e. ^1/2 = "to the 1/2 power" or square root.

‡NR = No Record.

Table D. Peak Ground Vibrations at Limestone Quarries from Bulletin 656 [Nichols et al., 1968]

Peak Particle Velocity, in/s	SRSD*, ft/lb^1/2†	Frequency, Hz	Peak Particle Velocity, in/s	SRSD*, ft/lb^1/2†	Frequency, Hz	Peak Particle Velocity, in/s	SRSD*, ft/lb^1/2†	Frequency, Hz
0.02	344	40	0.16	43	7	0.31	28	23
0.03	236	50	0.17	46	36	0.31	23	29
0.03	79	36	0.17	60	19	0.31	46	22
0.05	184	42	0.17	61	19	0.32	34	18
0.06	73	29	0.17	48	23	0.32	17	26
0.06	140	50	0.17	49	16	0.33	64	16
0.06	117	44	0.18	34	20	0.33	64	16
0.06	105	16	0.18	82	42	0.33	33	19
0.07	89	24	0.18	82	42	0.33	33	33
0.07	50	15	0.18	73	37	0.33	50	16
0.07	62	48	0.18	73	37	0.33	45	20
0.07	170	14	0.18	51	50	0.33	23	21
0.07	123	63	0.18	45	11	0.33	41	28
0.08	122	16	0.18	57	25	0.34	44	32
0.08	150	56	0.19	47	20	0.34	44	32
0.08	66	56	0.19	55	30	0.34	32	30
0.08	64	23	0.20	46	45	0.34	31	29
0.08	142	25	0.20	94	29	0.34	57	14
0.09	166	43	0.20	35	45	0.34	57	14
0.09	81	28	0.21	48	48	0.34	35	23
0.09	58	33	0.21	38	21	0.34	43	32
0.09	66	23	0.22	39	19	0.35	43	14
0.09	66	16	0.22	35	25	0.35	52	23
0.10	67	38	0.22	74	45	0.36	33	16
0.10	64	21	0.23	73	45	0.36	33	16
0.10	106	29	0.23	73	45	0.36	28	16
0.10	52	42	0.23	53	24	0.36	32	19
0.10	55	42	0.23	33	16	0.37	39	20
0.10	34	38	0.24	54	24	0.37	32	30
0.11	64	29	0.24	62	8	0.38	29	32
0.11	57	12	0.24	50	16	0.38	29	31
0.11	46	16	0.25	35	11	0.38	40	14
0.12	80	14	0.25	30	33	0.38	21	16
0.12	56	32	0.25	46	25	0.38	31	16
0.12	56	32	0.25	41	17	0.38	27	30
0.12	67	17	0.25	45	48	0.38	25	20
0.12	52	56	0.26	26	23	0.39	37	28
0.12	52	56	0.26	47	24	0.39	30	19
0.13	64	24	0.26	52	15	0.39	22	15
0.13	66	48	0.26	46	24	0.39	22	15
0.13	66	48	0.26	41	24	0.39	18	71
0.14	60	23	0.26	29	19	0.39	29	19
0.15	60	15	0.27	26	14	0.39	29	19
0.15	93	42	0.27	41	24	0.40	49	22
0.15	93	42	0.27	37	23	0.40	41	15
0.15	52	21	0.28	29	28	0.40	28	29
0.15	59	12	0.28	58	19	0.41	32	17
0.15	79	26	0.28	21	26	0.41	51	16
0.15	68	32	0.28	39	20	0.42	53	37
0.15	78	28	0.29	38	24	0.42	53	37
0.15	120	38	0.29	38	26	0.42	33	24
0.15	78	28	0.30	26	11	0.44	36	20
0.16	44	13	0.30	48	16	0.44	40	50
0.16	71	18	0.30	31	18	0.44	40	50
0.16	28	36	0.30	59	29	0.44	38	20

Table D. Peak Ground Vibrations at Limestone Quarries from Bulletin 656 [Nichols et al., 1968] (cont.)

Peak Particle Velocity, in/s	SRSD, ft/lb^1/2	Frequency, Hz	Peak Particle Velocity, in/s	SRSD, ft/lb^1/2	Frequency, Hz	Peak Particle Velocity, in/s	SRSD, ft/lb^1/2	Frequency, Hz
0.45	33	26	0.69	28	22	1.07	21	28
0.45	52	13	0.69	27	15	1.09	18	34
0.45	35	29	0.69	25	20	1.09	17	22
0.47	35	29	0.69	24	28	1.09	15	-
0.47	39	24	0.71	17	19	1.10	16	31
0.48	23	42	0.71	17	19	1.10	23	19
0.48	39	22	0.71	19	21	1.10	11	24
0.48	19	10	0.73	25	18	1.12	37	16
0.48	30	27	0.73	34	21	1.15	23	28
0.49	33	23	0.73	29	30	1.16	17	28
0.49	14	27	0.74	37	36	1.18	20	20
0.49	32	23	0.75	18	83	1.18	20	25
0.51	29	30	0.75	42	16	1.20	16	12
0.52	15	43	0.77	26	26	1.20	25	16
0.52	38	29	0.77	25	13	1.23	12	8
0.53	26	17	0.78	23	20	1.23	12	19
0.53	33	17	0.78	13	42	1.23	14	33
0.53	19	30	0.79	20	31	1.25	15	25
0.53	27	14	0.82	28	23	1.28	15	19
0.54	34	23	0.83	43	19	1.28	24	29
0.54	25	16	0.83	13	25	1.29	9	42
0.54	32	67	0.83	21	29	1.29	15	24
0.55	20	37	0.84	15	20	1.29	12	23
0.55	32	26	0.85	34	23	1.29	12	23
0.56	23	32	0.86	21	23	1.30	16	38
0.56	33	21	0.87	25	30	1.30	19	62
0.57	25	18	0.87	28	25	1.31	15	45
0.57	23	31	0.88	29	14	1.31	16	36
0.57	29	28	0.89	12	34	1.34	11	14
0.57	33	24	0.90	19	59	1.35	20	24
0.58	23	15	0.90	16	15	1.38	13	25
0.58	30	20	0.91	49	16	1.41	9	30
0.59	22	63	0.91	49	16	1.41	10	31
0.59	34	22	0.92	17	20	1.42	15	23
0.60	22	26	0.93	24	26	1.45	16	24
0.60	34	19	0.93	48	42	1.45	20	27
0.61	47	13	0.94	26	25	1.45	18	50
0.61	23	26	0.94	26	14	1.45	10	29
0.63	18	28	0.94	26	14	1.47	13	25
0.63	22	25	0.94	30	20	1.47	14	9
0.63	34	23	0.95	21	15	1.49	13	20
0.63	14	23	0.95	21	15	1.51	16	35
0.63	24	28	0.95	27	33	1.52	17	20
0.63	23	16	0.95	11	50	1.53	17	23
0.63	29	14	0.96	19	24	1.57	11	22
0.64	29	14	0.96	24	26	1.57	11	22
0.65	36	21	0.98	12	11	1.58	11	12
0.66	31	32	0.99	56	20	1.59	19	28
0.66	28	24	1.01	21	24	1.61	12	17
0.67	22	16	1.02	18	19	1.62	14	25
0.67	27	29	1.02	25	63	1.63	8	37
0.67	32	9	1.03	16	26	1.64	7	77
0.67	26	31	1.04	22	15	1.66	16	19
0.68	21	16	1.06	13	23	1.67	9	21
0.69	20	20	1.06	25	26	1.67	20	14

Table D. Peak Ground Vibrations at Limestone Quarries
from Bulletin 656 [Nichols et al., 1968] (cont.)

Peak Particle Velocity, in/s	SRSD, ft/lb^1/2	Frequency, Hz	Peak Particle Velocity, in/s	SRSD, ft/lb^1/2	Frequency, Hz	Peak Particle Velocity, in/s	SRSD, ft/lb^1/2	Frequency, Hz
1.68	19	18	2.01	9	24	2.76	13	40
1.70	15	21	2.01	9	10	2.85	7	22
1.72	12	23	2.01	16	22	3.08	9	42
1.72	16	16	2.01	8	26	3.34	13	23
1.73	12	30	2.04	8	20	3.61	6	50
1.74	13	27	2.05	8	40	3.64	9	20
1.76	17	56	2.07	20	24	3.68	12	33
1.77	11	40	2.08	21	19	3.77	8	20
1.79	13	16	2.11	10	50	4.15	7	12
1.80	11	22	2.15	13	19	4.32	7	9
1.80	7	48	2.17	6	28	4.65	7	14
1.85	9	22	2.19	11	22	4.92	6	22
1.85	9	22	2.19	7	36	5.10	6	16
1.86	15	62	2.19	11	42	5.15	15	36
1.86	8	24	2.19	7	26	5.58	8	15
1.86	10	9	2.19	7	26	5.68	8	25
1.87	18	10	2.19	17	24	5.76	9	17
1.88	12	37	2.25	14	26	6.67	11	22
1.89	10	24	2.25	14	26	6.92	5	15
1.90	10	24	2.34	12	50	7.46	6	28
1.90	10	24	2.34	9	27	8.73	3	19
1.92	13	21	2.57	14	16	9.26	6	20
1.97	10	24	2.60	15	25	10.20	10	30
1.98	8	20	2.61	11	19	15.00	5	13
2.00	13	50	2.63	15	25	20.90	4	16
2.00	9	21						

* SRSD = Square Root Scaled Distance and CRSD = Cube Root Scaled Distance.

†The carat symbol "^" denotes superscript. i.e. ^1/2 = "to the 1/2 power" or square root.

Table E-1. Blast Vibration Measurements at Individual Swedesburg Homes, May - December, 1992

House "G"

Shot Number	Date, mo.day	Time*, hours	Distance, ft	SRSD**, ft/lb^1/2†	Peak Particle Velocity, in/s	Frequency, Hz	CRSD**, ft/lb^1/3†	Airblast, dB
24	5.13	1149	1937	120	NR‡	NR	303	NR
25	5.19	1034	2100	130	NR	NR	328	NR
26	6.50	930	1475	95	NR	NR	237	NR
27	6.10	1024	1975	122	NR	NR	309	NR
28	6.12	938	1375	88	NR	NR	221	NR
29	6.16	1150	1850	114	NR	NR	289	NR
30	6.23	1122	1950	120	NR	NR	305	NR
31	7.17	900	2425	268	NR	NR	558	NR
32	7.30	1036	2250	169	NR	NR	401	NR
33	8.05	1148	1400	90	0.04	21	225	115
34	8.12	1138	1824	109	0.04	13	278	107
35	8.13	1113	1425	96	0.04	13	235	115
36	8.18	1103	1425	111	NR	NR	260	NR
37	8.24	958	1425	96	0.03	12	235	114
38	8.25	916	1325	89	NR	NR	219	NR
39	9.14	1237	1760	105	0.04	28	268	104
40	9.15	910	1525	102	NR	NR	252	NR
41	9.22	1023	1750	108	NR	NR	273	NR
42	9.23	1055	1550	104	NR	NR	256	NR
43	9.24	1052	1350	91	0.04	18	223	113
44	9.29	1051	1375	83	NR	NR	212	NR
45	9.30	1054	1750	108	0.04	27	273	97
46	10.02	1021	1300	87	0.04	23	215	114
47	10.06	1245	1425	149	NR	NR	316	NR
48	10.07	1000	1750	108	0.06	26	273	97
49	10.13	1047	1250	84	0.04	9	206	113
50	10.14	1050	1740	104	NR	NR	265	NR
51	10.15	906	1390	98	NR	NR	237	NR
52	10.19	1055	1225	82	NR	NR	202	NR
53	10.22	955	1750	108	NR	NR	273	NR
54	10.29	1014	1200	81	NR	NR	198	NR
55	11.06	1039	1150	77	NR	NR	190	NR
56	11.13	1023	1687	104	NR	NR	264	NR
57	11.16	1203	1600	85	NR	NR	227	NR
58	11.18	1052	1125	76	NR	NR	186	NR
59	11.20	1022	1685	104	NR	NR	263	NR

House "K"

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
24	5.13	1149	2600	161	0.05	6	406	97
25	5.19	1034	2500	154	0.04	47	391	109
26	6.50	930	2050	132	NR	NR	329	NR
27	6.10	1024	2650	164	NR	NR	414	NR
28	6.12	938	2050	132	NR	NR	329	NR
29	6.16	1150	2500	154	0.05	11	391	97
30	6.23	1122	2650	164	NR	NR	414	NR
31	7.17	900	2850	315	NR	NR	656	NR
32	7.30	1036	2650	199	NR	NR	472	NR
33	8.05	1148	2100	135	0.04	21	337	108
34	8.12	1138	2475	147	0.04	12	377	97
35	8.13	1113	2100	141	0.04	14	347	107
36	8.18	1103	1775	139	NR	NR	324	NR
37	8.24	958	2125	143	0.02	18	351	97

Table E-1. Blast Vibration Measurements at Individual Swedesburg Homes, May - December, 1992: House "K" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
38	8.25	916	2025	136	0.04	20	334	107
39	9.14	1237	2450	146	0.05	45	374	93
40	9.15	910	2275	153	NR	NR	376	NR
41	9.22	1023	2450	151	0.04	12	383	97
42	9.23	1055	2250	151	NR	NR	372	NR
43	9.24	1052	2025	136	0.04	11	334	93
44	9.29	1051	2025	123	0.05	25	313	99
45	9.30	1054	2400	148	0.04	20	375	97
46	10.02	1021	1960	132	0.04	11	324	93
47	10.06	1245	1750	182	NR	NR	388	0
48	10.07	1000	2425	150	0.04	25	379	97
49	10.13	1047	1925	129	0.03	10	317	93
50	10.14	1050	2375	141	0.04	24	362	97
51	10.15	906	1700	120	0.03	18	290	93
52	10.55	1055	1900	128	0.06	12	314	93
53	10.22	955	2375	147	0.04	18	371	101
54	10.29	1014	1875	126	0.03	49	310	114
55	11.06	1039	1900	128	0.04	51	314	93
56	11.13	1023	2375	147	0.04	25	371	93
57	11.16	1203	1635	87	0.05	22	232	99
58	11.18	1052	1865	125	0.05	17	308	99
59	11.20	1022	2362	146	0.04	25	369	97

House "M"

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
24	5.13	1149	2675	165	NR	NR	418	NR
25	5.19	1034	2300	142	NR	NR	359	NR
26	6.50	930	2150	138	NR	NR	345	NR
27	6.10	1024	2750	170	NR	NR	430	NR
28	6.12	938	2200	141	0.03	15	353	115
29	6.16	1150	2600	161	NR	NR	406	NR
30	6.23	1122	2750	170	NR	NR	430	NR
31	7.17	900	2625	290	NR	NR	604	NR
32	7.30	1036	2450	184	0.02	17	436	110
33	8.05	1148	2250	145	0.03	14	361	115
34	8.12	1138	2575	153	0.05	14	393	109
35	8.13	1113	2260	152	0.02	NR	373	112
36	8.18	1103	1480	116	0.04	14	270	109
37	8.24	958	2275	153	NR	NR	376	NR
38	8.25	916	2100	141	0.03	8	347	114
39	9.14	1237	2550	152	0.04	28	389	97
40	9.15	910	2375	159	NR	NR	392	NR
41	9.22	1023	2525	156	0.04	29	395	109
42	9.23	1055	2425	163	NR	NR	400	NR
43	9.24	1052	2125	143	0.04	15	351	114
44	9.29	1051	2200	133	NR	NR	340	NR
45	9.30	1054	2490	154	0.04	16	389	99
46	10.02	1021	2100	141	NR	NR	347	NR
47	10.06	1245	1500	156	NR	NR	332	NR
48	10.07	1000	2475	153	0.04	23	387	109
49	10.13	1047	2075	139	NR	NR	342	NR
50	10.14	1050	2450	146	0.04	25	374	108
51	10.15	906	1475	104	0.05	14	251	109
52	10.55	1055	2050	138	NR	NR	339	NR

Table E-1. Blast Vibration Measurements at Individual Swedesburg Homes, May - December, 1992: House "M" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
53	10.22	955	2425	150	0.06	27	379	109
54	10.29	1014	2025	136	NR	NR	334	NR
55	11.06	1039	2025	136	NR	NR	334	NR
56	11.13	1023	2425	150	0.06	28	379	97
57	11.16	1203	1400	75	0.07	22	198	111
58	11.18	1052	1990	134	NR	NR	329	NR
59	11.20	1022	2400	148	0.06	19	375	111

House "P"

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
24	5.13	1149	2175	134	0.06	47	340	97
25	5.19	1034	2975	184	NR	NR	465	NR
26	6.50	930	1750	112	0.04	26	281	109
27	6.10	1024	2075	128	0.04	27	324	109
28	6.12	938	1750	112	0.04	28	281	111
29	6.16	1150	2050	127	0.04	35	320	105
30	6.23	1122	2025	125	0.03	36	316	111
31	7.17	900	3250	359	NR	NR	748	NR
32	7.30	1036	3125	235	NR	NR	557	NR
33	8.05	1148	1700	109	NR	NR	273	NR
34	8.12	1138	1975	118	0.08	35	301	101
35	8.13	1113	1690	113	0.06	38	279	99
36	8.18	1103	2500	195	NR	NR	457	NR
37	8.24	958	1700	114	0.07	38	281	97
38	8.25	916	1650	111	NR	NR	273	NR
39	9.14	1237	1930	115	0.06	37	294	103
40	9.15	910	1725	116	NR	NR	285	NR
41	9.22	1023	2550	158	0.06	21	399	93
42	9.23	1055	1720	115	NR	NR	284	NR
43	9.24	1052	1690	113	NR	NR	279	NR
44	9.29	1051	1675	102	NR	NR	259	NR
45	9.30	1054	2050	127	NR	NR	320	NR
46	10.02	1021	1650	111	0.09	43	273	109
47	10.06	1245	2535	264	NR	NR	562	NR
48	10.07	1000	2100	130	0.06	51	328	97
49	10.13	1047	1625	109	0.06	64	268	97
50	10.14	1050	2100	125	NR	NR	320	NR
51	10.15	906	2525	178	NR	NR	430	NR
52	10.55	1055	1600	107	0.08	13	264	109
53	10.22	955	2125	131	0.07	28	332	97
54	10.29	1014	1575	106	0.10	51	260	116
55	11.06	1039	1665	112	0.06	28	275	99
56	11.13	1023	2170	134	0.06	29	339	97
57	11.16	1203	2525	135	NR	NR	358	NR
58	11.18	1052	1675	112	NR	NR	277	NR
59	11.20	1022	2187	135	NR	NR	342	NR

* Time is in military time. e.g. 1138 = 11:38 a.m.

** SRSD = Square Root Scaled Distance and CRSD = Cube Root Scaled Distance.

†The carat symbol "^" denotes superscript. I.e. ^1/2 = "to the 1/2 power" or square root, and ^1/3 = "to the 1/3 power" or cube root.

‡NR = No Record. Either the seismograph did not trigger or the event was not recorded because data storage capacity was full.

Table E-2. Blast Vibration Measurements at Individual Swedesburg Homes, February - December, 1993

House "K"

Shot Number	Date, mo.day	Time*, hours	Distance, ft	SRSD**, ft/lb^1/2†	Peak Particle Velocity, in/s	Frequency, Hz	CRSD**, ft/lb^1/3†	Airblast, dB
1	2.05	1126	2350	145	NR	NR	367	NR
2	2.10	1111	1840	123	NR	NR	304	NR
3	3.01	1256	1650	89	NR	NR	236	NR
4	3.25	1038	2850	282	NR	NR	610	NR
5	3.31	1013	2880	141	0.04	36	385	116
6	3.31	1556	1832	127	0.04	11	310	101
7	4.07	1145	2500	154	0.04	15	391	97
8	4.12	1057	2825	134	0.04	48	371	116
9	4.13	1050	2355	148	0.04	6	373	97
10	4.14	1015	1805	125	0.04	8	305	103
11	4.16	1034	2850	282	NR	NR	610	NR
12	4.21	1130	2625	169	NR	NR	421	NR
13	5.19	1008	1675	89	0.03	15	236	99
14	5.20	1021	2370	146	0.04	50	370	97
15	5.21	947	1800	95	0.04	19	254	97
16	5.26	1153	2645	141	NR	NR	374	NR
17	6.02	1114	1775	88	0.03	14	240	108
18	6.03	958	2665	143	0.04	19	379	93
19	6.04	931	2387	153	0.05	51	383	97
20	6.09	1042	2560	127	0.04	19	345	99
21	6.10	1047	2700	197	0.04	26	472	103
22	6.11	1018	1745	86	0.03	14	235	97
23	6.15	906	2500	161	0.05	58	401	97
24	6.22	1042	2450	157	0.08	41	393	93
25	6.23	1203	1740	85	0.03	10	233	99
26	6.28	1105	1705	88	0.04	23	237	103
27	6.29	925	2415	152	0.04	55	382	93
28	7.01	1004	2415	155	0.04	41	388	93
29	7.01	1145	1775	147	NR	NR	337	NR
30	7.07	1044	1725	81	NR	NR	225	NR
31	7.09	959	2880	185	0.04	14	462	97
32	7.16	1133	2225	137	0.05	56	348	93
33	7.19	1119	2520	159	0.04	28	399	110
34	7.23	1108	2255	145	0.04	9	362	93
35	7.27	945	2850	282	NR	NR	610	NR
36	7.29	905	2700	200	0.04	53	476	97
37	8.04	1052	1900	88	0	0	246	0
38	8.06	1024	2210	139	0.05	54	350	93
39	8.09	935	2830	280	NR	NR	606	NR
40	8.11	1145	1590	84	0.03	8	224	93

Table E-2. Blast Vibration Measurements at Individual Swedesburg Homes, February - December, 1993: House "K" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
41	8.11	1150	1715	96	0.03	12	250	103
42	8.17	950	2375	153	0.05	22	381	93
43	8.20	1300	2840	281	NR	NR	608	NR
44	8.26	1011	1725	81	0.04	9	225	103
45	9.03	1040	2150	138	0.04	42	345	99
46	9.16	958	2375	153	0.04	30	381	93
47	9.20	949	2110	136	0.06	54	339	101
48	9.24	945	2075	133	0.04	42	333	99
49	9.29	1005	2360	150	NR	NR	376	NR
50	9.29	1327	2060	131	0.04	19	328	93
51	9.30	928	2835	257	NR	NR	572	NR
52	10.01	1150	2675	201	NR	NR	476	NR
53	10.06	953	2040	131	NR	NR	327	NR
54	10.12	935	2345	151	0.04	62	376	101
55	10.14	935	2835	252	0.04	49	564	97
56	10.15	935	2015	129	0.04	12	323	105
57	10.18	1100	2680	199	0.04	18	473	99
58	10.26	1132	2000	129	0.04	54	321	109
59	10.29	1035	1710	78	0.04	12	218	105
60	11.12	1033	2340	150	0.04	50	376	101
61	11.18	1210	1970	127	0.09	49	316	101
62	11.22	1100	2115	216	NR	NR	462	NR
63	11.30	931	2850	248	NR	NR	560	NR
64	12.01	1052	2320	149	0.04	51	372	101
65	12.03	1149	1950	125	0.05	12	313	101
66	12.07	1254	1945	125	0.04	19	312	101
67	12.08	1049	2515	160	0.04	20	401	103
68	12.10	852	2875	272	NR	NR	596	NR
69	12.16	1232	1900	92	0.05	47	253	111
70	12.20	1155	2300	148	0.04	54	369	93

House "M"

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
1	2.05	1126	2375	147	NR	NR	371	NR
2	2.10	1111	1955	131	NR	NR	323	NR
3	3.01	1256	1400	76	NR	NR	200	NR
4	3.25	1038	2645	262	NR	NR	566	NR
5	3.31	1013	2940	144	NR	NR	393	NR
6	3.31	1556	1940	135	NR	NR	328	NR
7	4.07	1145	2280	141	0.03	19	356	112

Table E-2. Blast Vibration Measurements at Individual Swedesburg Homes, February - December, 1993: House "M" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
8	4.12	1057	2915	138	NR	NR	382	NR
9	4.13	1050	2385	150	0.03	19	378	93
10	4.14	1015	1905	132	0.03	17	322	109
11	4.16	1034	2645	262	NR	NR	566	NR
12	4.21	1130	2775	178	0.04	14	445	112
13	5.19	1008	1410	75	0.06	12	199	113
14	5.20	1021	2380	147	NR	NR	372	NR
15	5.21	947	1880	99	0.04	19	265	114
16	5.26	1153	2785	148	NR	NR	394	NR
17	6.02	1114	1840	92	NR	NR	249	NR
18	6.03	958	2815	151	NR	NR	401	NR
19	6.04	931	2385	153	0.04	22	383	93
20	6.09	1042	2710	134	0.04	14	365	93
21	6.10	1047	2465	180	0.03	14	431	112
22	6.11	1018	1800	89	0.04	15	243	111
23	6.15	906	2645	170	NR	NR	424	NR
24	6.22	1042	2600	167	NR	NR	417	NR
25	6.23	1203	1785	87	NR	NR	239	NR
26	6.28	1105	1415	73	0.05	14	197	112
27	6.29	925	2565	162	NR	NR	406	NR
28	7.01	1004	2555	164	NR	NR	410	NR
29	7.01	1145	1850	153	NR	NR	351	NR
30	7.07	1044	1765	83	NR	NR	230	NR
31	7.09	959	2400	154	NR	NR	385	NR
32	7.16	1133	2315	143	NR	NR	362	NR
33	7.19	1119	2290	144	NR	NR	363	NR
34	7.23	1108	2380	153	NR	NR	382	NR
35	7.27	945	2625	260	NR	NR	562	NR
36	7.29	905	2465	183	0.03	16	435	110
37	8.04	1052	1920	89	0.05	9	248	112
38	8.06	1024	2310	146	0.04	15	366	110
39	8.09	935	2600	257	NR	NR	556	NR
40	8.11	1145	1600	84	NR	NR	225	NR
41	8.11	1150	1420	79	NR	NR	207	NR
42	8.17	950	2510	161	NR	NR	403	NR

Table E-2. Blast Vibration Measurements at Individual Swedesburg Homes, February - December, 1993: House "M" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
43	8.20	1300	2600	257	NR	NR	556	NR
44	8.26	1011	1740	82	NR	NR	227	NR
45	9.03	1040	2255	145	NR	NR	362	NR
46	9.16	958	2490	160	NR	NR	400	NR
47	9.20	949	2215	142	NR	NR	355	NR
48	9.24	945	2200	141	NR	NR	353	NR
49	9.29	1005	2475	157	NR	NR	394	NR
50	9.29	1327	2180	139	NR	NR	347	NR
51	9.30	928	2600	235	NR	NR	524	NR
52	10.01	1150	2440	183	NR	NR	435	NR
53	10.06	953	2170	139	NR	NR	348	NR
54	10.12	935	2450	157	NR	NR	393	NR
55	10.14	935	2600	231	NR	NR	517	NR
56	10.15	935	2140	137	NR	NR	343	NR
57	10.18	1100	2440	181	NR	NR	431	NR
58	10.26	1132	2120	136	0.04	15	340	111
59	10.29	1035	1705	78	0.05	12	217	113
60	11.12	1033	2440	157	0.04	36	392	97
61	11.18	1210	2080	134	0.04	18	334	103
62	11.22	1100	2020	206	NR	NR	441	NR
63	11.30	931	2600	226	NR	NR	511	NR
64	12.01	1052	2415	155	NR	NR	388	NR
65	12.03	1149	2050	132	0.04	8	329	115
66	12.07	1254	2045	131	0.04	23	328	109
67	12.08	1049	2290	146	NR	NR	365	NR
68	12.10	852	2580	244	NR	NR	535	NR
69	12.16	1232	2000	97	0.04	44	266	115
70	12.20	1155	2375	152	0.04	16	381	109

House "P"

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
1	2.05	1126	2185	135	NR	NR	341	NR
2	2.10	1111	1695	114	NR	NR	280	NR
3	3.01	1256	2575	139	NR	NR	368	NR
4	3.25	1038	3290	326	NR	NR	704	NR
5	3.31	1013	2440	119	NR	NR	326	NR
6	3.31	1556	1705	119	NR	NR	288	NR
7	4.07	1145	3000	185	NR	NR	469	NR
8	4.12	1057	2260	107	NR	NR	296	NR
9	4.13	1050	2225	140	NR	NR	352	NR

Table E-2. Blast Vibration Measurements at Individual Swedesburg Homes, February - December, 1993: House "P" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
10	4.14	1015	1745	121	NR	NR	295	NR
11	4.16	1034	3290	326	NR	NR	704	NR
12	4.21	1130	2015	130	NR	NR	323	NR
13	5.19	1008	2590	137	NR	NR	365	NR
14	5.20	1021	2255	139	NR	NR	352	NR
15	5.21	947	1780	94	NR	NR	251	NR
16	5.26	1153	2000	106	NR	NR	283	NR
17	6.02	1114	1800	90	NR	NR	243	NR
18	6.03	958	1995	107	0.07	42	284	103
19	6.04	931	2995	193	NR	NR	481	NR
20	6.09	1042	1925	95	0.07	14	260	103
21	6.10	1047	3165	231	0.04	64	553	111
22	6.11	1018	1825	90	0.04	10	246	111
23	6.15	906	1905	122	0.08	38	306	106
24	6.22	1042	1850	119	NR	NR	297	NR
25	6.23	1203	1870	92	NR	NR	250	NR
26	6.28	1105	1680	87	NR	NR	234	NR
27	6.29	925	1810	114	NR	NR	287	NR
28	7.01	1004	1870	120	NR	NR	300	NR
29	7.01	1145	1775	147	NR	NR	337	NR
30	7.07	1044	1915	90	NR	NR	250	NR
31	7.09	959	1837	118	NR	NR	295	NR
32	7.16	1133	1900	117	NR	NR	297	NR
33	7.19	1119	3025	191	NR	NR	479	NR
34	7.23	1108	1812	116	0.09	13	291	104
35	7.27	945	3290	326	NR	NR	704	NR
36	7.29	905	3185	236	NR	NR	562	NR
37	8.04	1052	1845	86	NR	NR	239	NR
38	8.06	1024	1855	117	0.05	36	294	104
39	8.09	935	3290	326	NR	NR	704	NR
40	8.11	1145	1920	101	NR	NR	270	NR
41	8.11	1150	2685	150	NR	NR	392	NR
42	8.17	950	1880	121	0.07	43	302	97
43	8.20	1300	3300	327	NR	NR	706	NR
44	8.26	1011	1950	92	NR	NR	255	NR
45	9.03	1040	1775	114	0.09	35	285	101
46	9.16	958	1910	123	0.08	26	306	107
47	9.20	949	1750	112	0.09	23	281	99
48	9.24	945	1725	111	0.06	12	277	99
49	9.29	1005	1925	122	0.07	29	307	99
50	9.29	1327	1740	111	0.06	19	277	99

Table E-2. Blast Vibration Measurements at Individual Swedesburg Homes, February - December, 1993: House "P" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
51	9.30	928	3300	299	NR	NR	665	NR
52	10.01	1150	3180	239	NR	NR	566	NR
53	10.06	953	1725	111	NR	NR	277	NR
54	10.12	935	1935	124	NR	NR	311	NR
55	10.14	935	2300	204	NR	NR	458	NR
56	10.15	935	1695	109	0.08	11	272	109
57	10.18	1100	3205	238	NR	NR	566	NR
58	10.26	1132	1750	112	0.07	27	281	106
59	10.29	1035	2000	91	NR	NR	255	NR
60	11.12	1033	1960	126	0.07	25	315	99
61	11.18	1210	1760	113	0.08	25	282	97
62	11.22	1100	2430	248	NR	NR	531	NR
63	11.30	931	2600	226	NR	NR	511	NR
64	12.01	1052	1950	125	NR	NR	313	NR
65	12.03	1149	1775	114	0.07	7	285	106
66	12.07	1254	1750	112	NR	NR	281	NR
67	12.08	1049	3055	194	NR	NR	487	NR
68	12.10	852	3340	316	NR	NR	693	NR
69	12.16	1232	1750	85	NR	NR	233	NR
70	12.20	1155	1910	123	0.08	25	306	97

House "V"

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
1	2.05	1126	1687	104	NR	NR	264	NR
2	2.10	1111	1125	76	NR	NR	186	NR
3	3.01	1256	1625	88	NR	NR	232	NR
4	3.25	1038	2565	254	NR	NR	549	NR
5	3.31	1013	2115	103	NR	NR	283	NR
6	3.31	1556	1125	78	NR	NR	190	NR
7	4.07	1145	2250	139	NR	NR	352	NR
8	4.12	1057	2010	95	NR	NR	264	NR
9	4.13	1050	1712	108	NR	NR	271	NR
10	4.14	1015	1130	79	NR	NR	191	NR
11	4.16	1034	2565	254	NR	NR	549	NR
12	4.21	1130	1780	114	NR	NR	286	NR
13	5.19	1008	1615	85	NR	NR	228	NR
14	5.20	1021	1735	107	NR	NR	271	NR
15	5.21	947	1137	60	NR	NR	160	NR
16	5.26	1153	1790	95	NR	NR	253	NR
17	6.02	1114	1150	57	0.06	18	156	112

Table E-2. Blast Vibration Measurements at Individual Swedesburg Homes,
February - December, 1993: House "V" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
18	6.03	958	1800	97	0.1	27	256	110
19	6.04	931	1770	114	NR	NR	284	NR
20	6.09	1042	1710	85	0.07	15	231	104
21	6.10	1047	2430	178	NR	NR	425	NR
22	6.11	1018	1140	57	0.07	26	154	111
23	6.15	906	1660	107	0.07	22	266	109
24	6.22	1042	1600	103	0.09	11	257	109
25	6.23	1203	1165	57	0.07	11	156	112
26	6.28	1105	1750	91	0.08	11	243	109
27	6.29	925	1565	99	NR	NR	248	NR
28	7.01	1004	1585	102	0.07	30	254	110
29	7.01	1145	1105	91	NR	NR	210	NR
30	7.07	1044	1185	56	NR	NR	154	NR
31	7.09	959	1500	96	0.1	33	241	112
32	7.16	1133	1475	91	0.07	17	231	110
33	7.19	1119	2265	143	0.05	18	359	119
34	7.23	1108	1455	94	0.08	17	233	110
35	7.27	945	2575	255	NR	NR	551	NR
36	7.29	905	2440	181	0.04	27	431	113
37	8.04	1052	1290	60	0.07	18	167	114
38	8.06	1024	1410	89	0.08	32	223	111
39	8.09	935	2550	252	NR	NR	546	NR
40	8.11	1145	1125	59	0.05	21	158	116
41	8.11	1150	1750	98	0.04	12	255	113
42	8.17	950	1560	100	0.08	19	250	111
43	8.20	1300	2570	254	NR	NR	550	NR
44	8.26	1011	1200	57	0.07	10	157	117
45	9.03	1040	1400	90	0.1	34	225	111
46	9.16	958	1570	101	0.07	28	252	114
47	9.20	949	1360	87	0.1	9	218	109
48	9.24	945	1330	85	0.07	26	213	107
49	9.29	1005	1570	100	0.09	27	250	108
50	9.29	1327	1310	83	0.09	20	209	111
51	9.30	928	2575	233	NR	NR	519	NR
52	10.01	1150	2425	182	NR	NR	432	NR
53	10.06	953	1280	82	0.09	12	205	112
54	10.12	935	1560	100	0.07	17	250	110
55	10.14	935	2575	228	NR	NR	512	NR
56	10.15	935	1250	80	0.1	19	200	111
57	10.18	1100	2450	182	0.04	7	432	93
58	10.26	1132	1250	80	0.11	23	201	112

Table E-2. Blast Vibration Measurements at Individual Swedesburg Homes, February - December, 1993: House "V" (cont.)

Shot Number	Date, mo.day	Time, hours	Distance, ft	SRSD, ft/lb^1/2	Peak Particle Velocity, in/s	Frequency, Hz	CRSD, ft/lb^1/3	Airblast, dB
59	10.29	1035	1230	56	0.05	6	157	116
60	11.12	1033	1565	101	0.07	16	251	110
61	11.18	1210	1230	79	0.09	26	197	110
62	11.22	1100	1700	174	NR	NR	371	NR
63	11.30	931	3340	291	NR	NR	656	NR
64	12.01	1052	1550	100	0.09	25	249	111
65	12.03	1149	1215	78	0.1	31	195	116
66	12.07	1254	1200	77	NR	NR	193	NR
67	12.08	1049	2275	145	NR	NR	363	NR
68	12.10	852	2575	243	NR	NR	534	NR
69	12.16	1232	1200	58	NR	NR	160	NR
70	12.20	1155	1540	99	NR	NR	247	NR

* Time is in military time. e.g. 1138 = 11:38 a.m.

** SRSD = Square Root Scaled Distance and CRSD = Cube Root Scaled Distance.

†The carat symbol "^" denotes superscript. i.e. ^1/2 = "to the 1/2 power" or square root, and ^1/3 = "to the 1/3 power" or cube root.

‡NR = No Record. Either the seismograph did not trigger or the event was not recorded because data storage capacity was full.

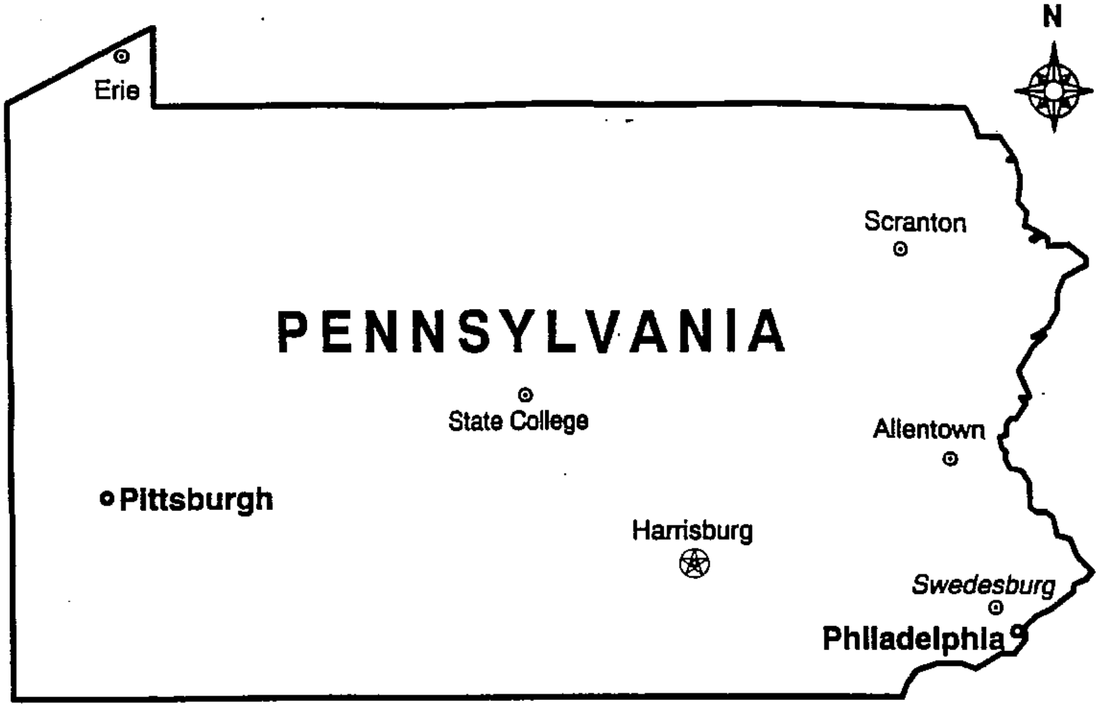


Figure 1. Map of Pennsylvania showing location of Swedesburg relative to other cities.

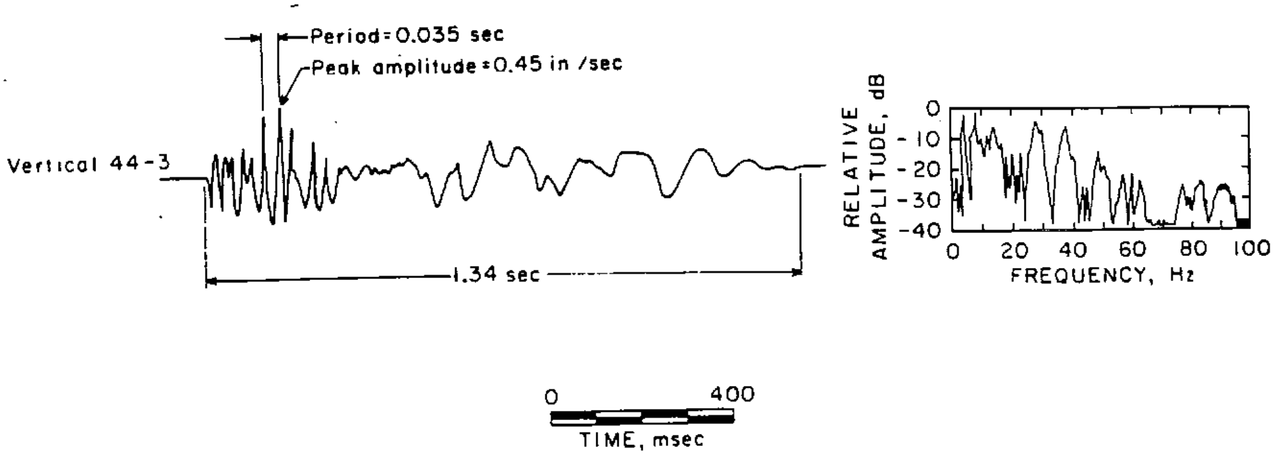


Figure 2. Ground vibration time history (left) and Fourier amplitude spectra. Notation on the time history (seismogram) points out waveform duration, peak amplitude (peak particle velocity) and period of the peak amplitude portion of the waveform [after Siskind et al., 1980b].

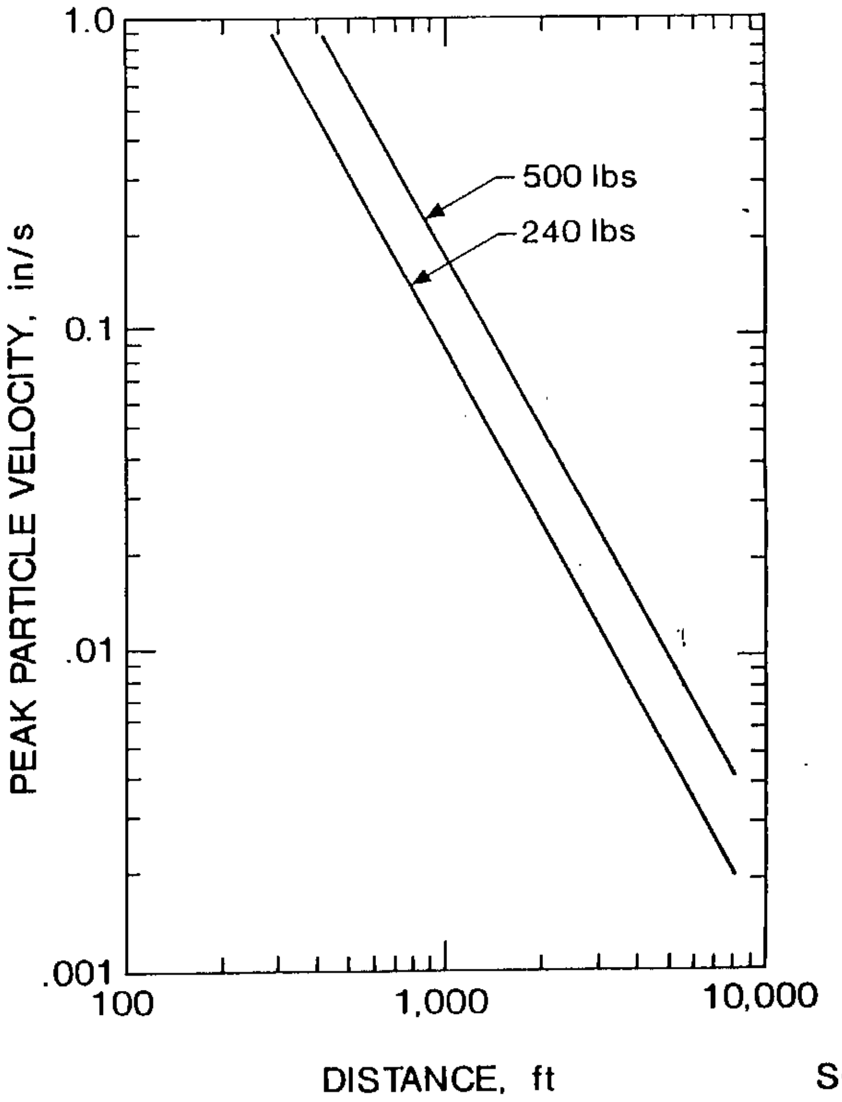


Figure 3. Propagation plot regressions of vibration amplitudes versus distance for two sizes of quarry blasts, in lbs per delay, derived from Nicholls et al. [1971].

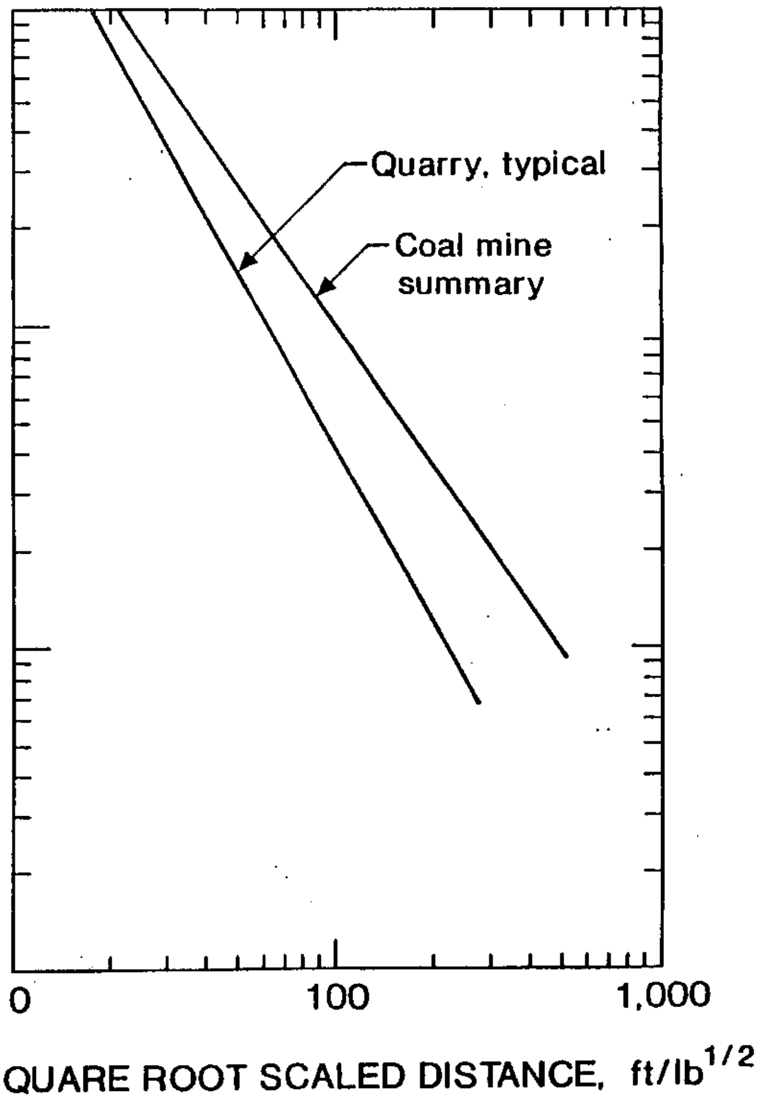


Figure 4. Propagation plot regressions representing peak vibration amplitudes as functions of scale distances for two types of blasts, adopted from Siskind et al. [1980b].

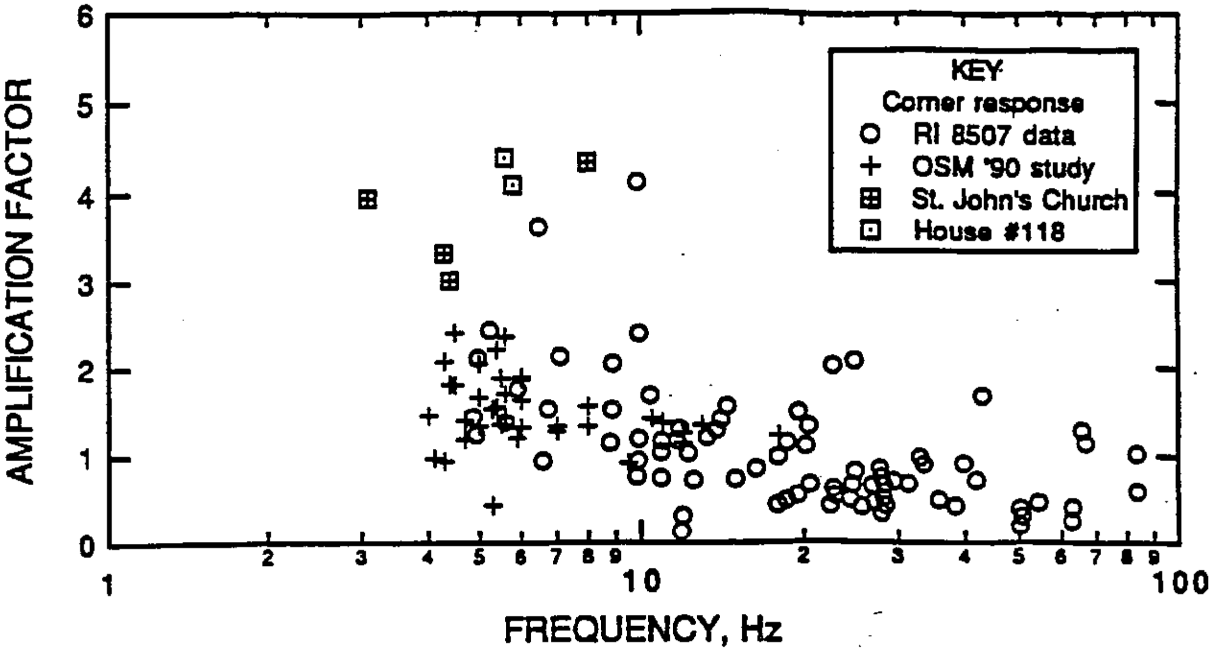


Figure 5. Corner responses of one to three story structures from mine blasting showing frequency dependence of amplification, from Crum and Siskind [1993].

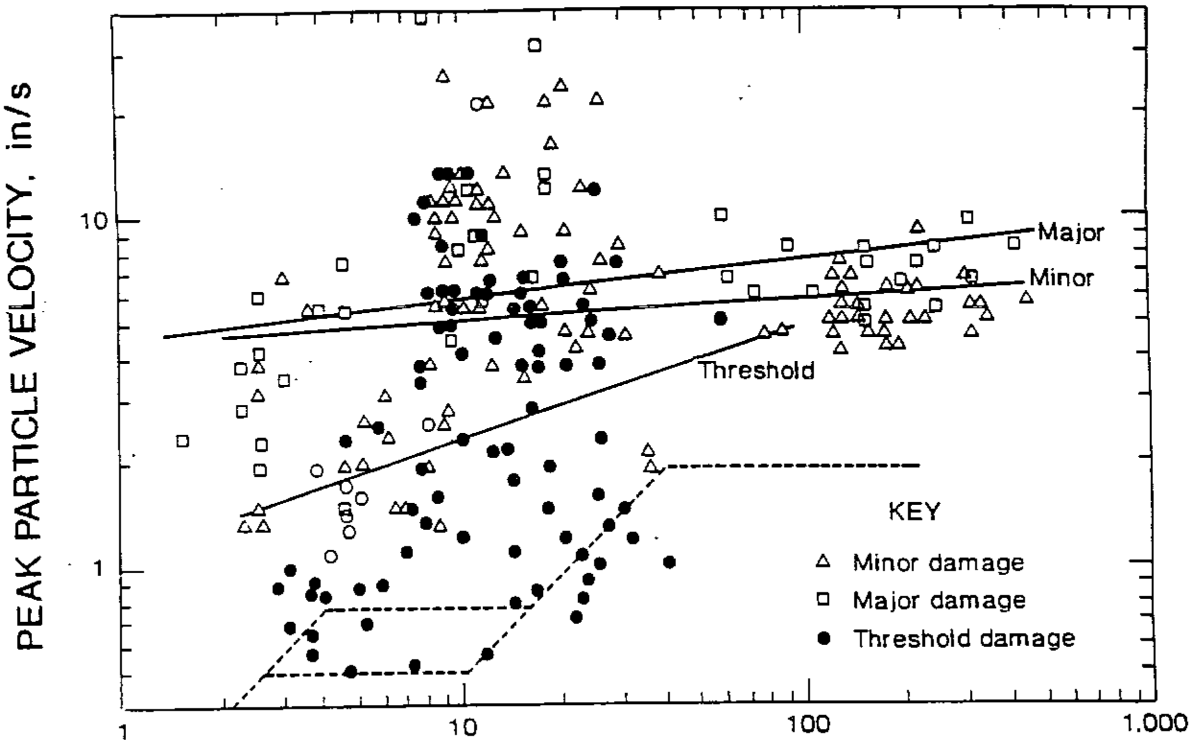
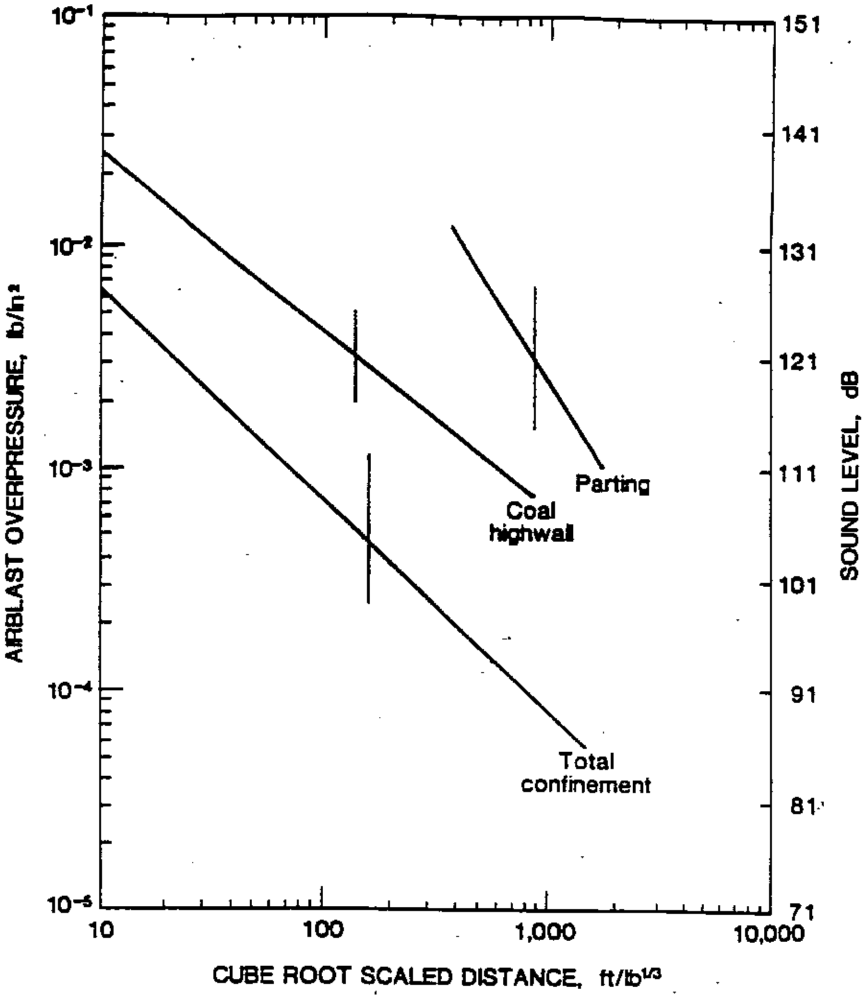


Figure 6. Ground vibration damage summary adopted from RI 8507 [Siskind et al., 1980b]. Dashed line defines the Bureau of Mines recommended safe level limits using a combination of velocity (horizontal lines) and displacement (angled lines) criteria.

Figure 7. Propagation plot regressions of airblast from surface mining [Siskind et al., 1980a].



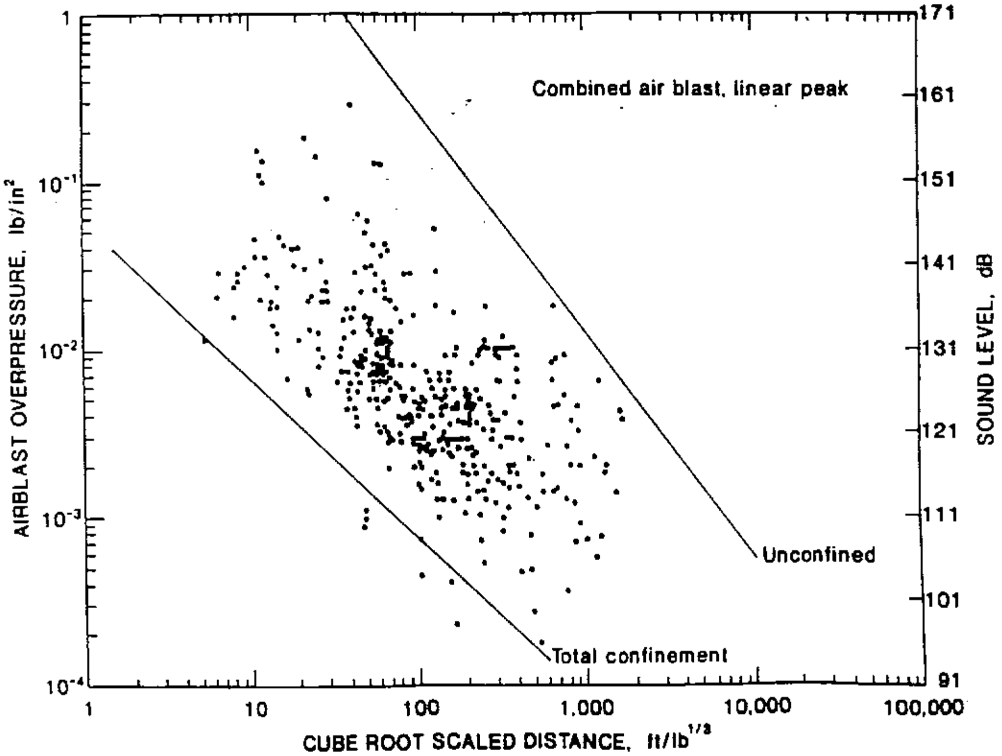


Figure 8. Combined mining and quarrying airblasts from all sites, adapted from RI 8485 [Siskind et al., 1980a].

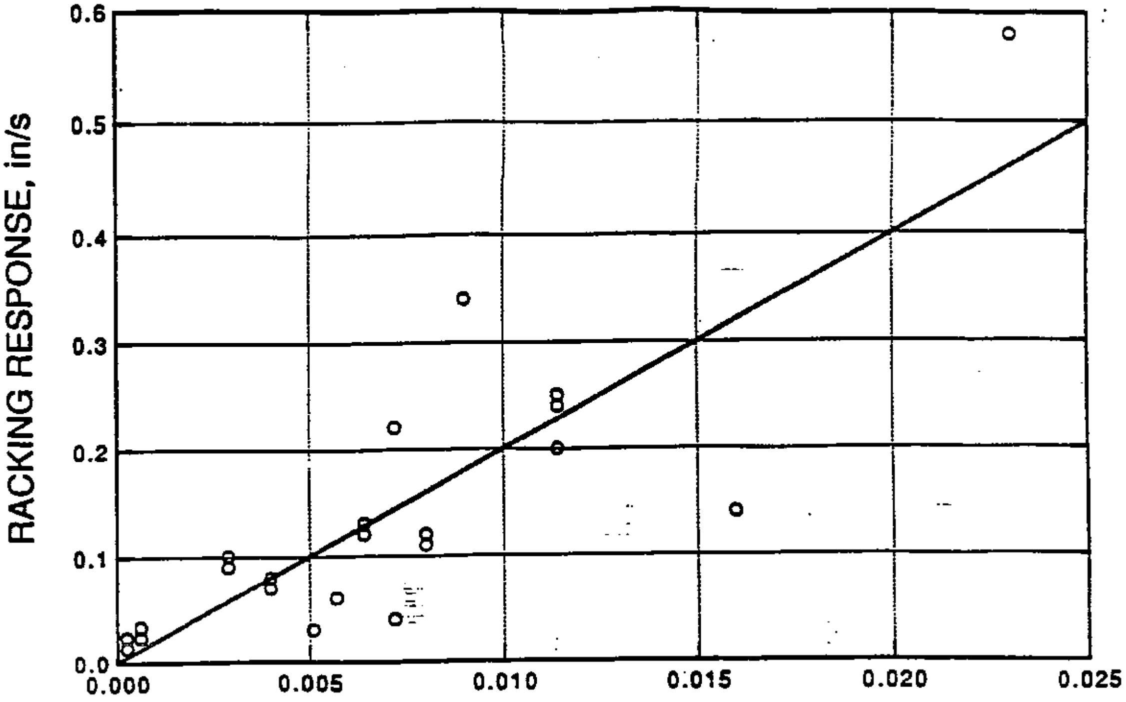


Figure 9. Corner, or structural racking, responses of homes from airblasts. The solid line is prediction from RI 8485 data [Siskind et al., 1980a]. An overpressure of 0.025 lb/in² is equivalent to 139 dB.

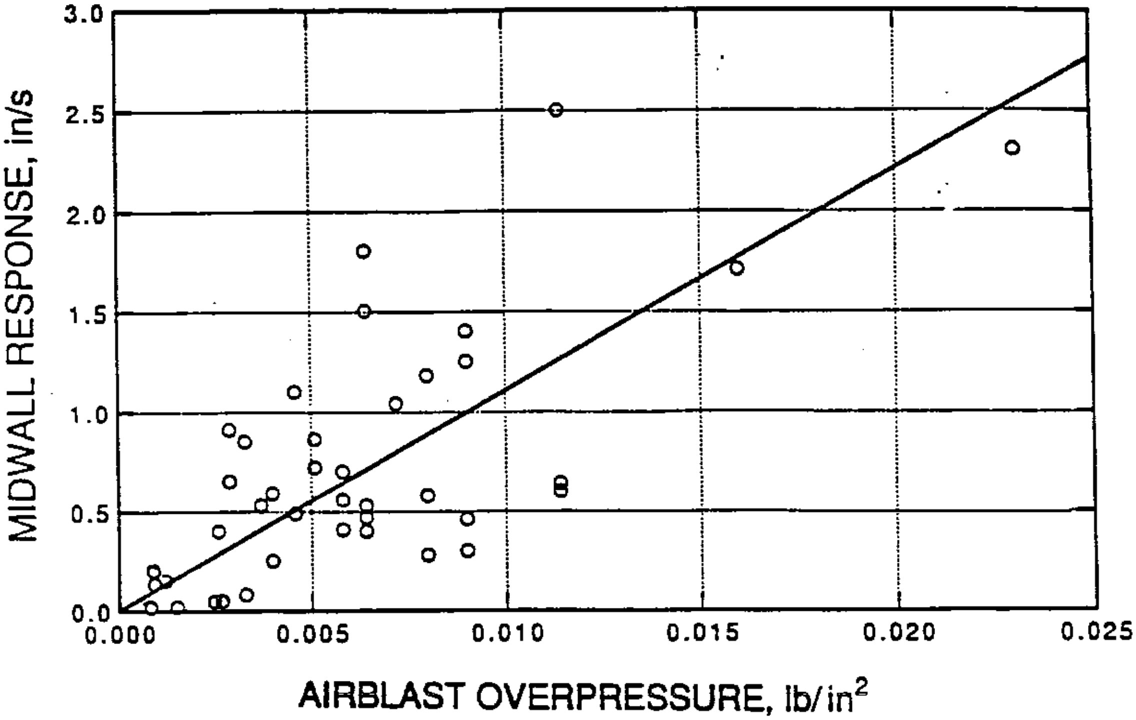


Figure 10. Midwall responses of homes from airblasts. The solid line is prediction from RI 8485 data [Siskind et al., 1980a]. An overpressure of 0.025 lb/in² is equivalent to 139 dB.

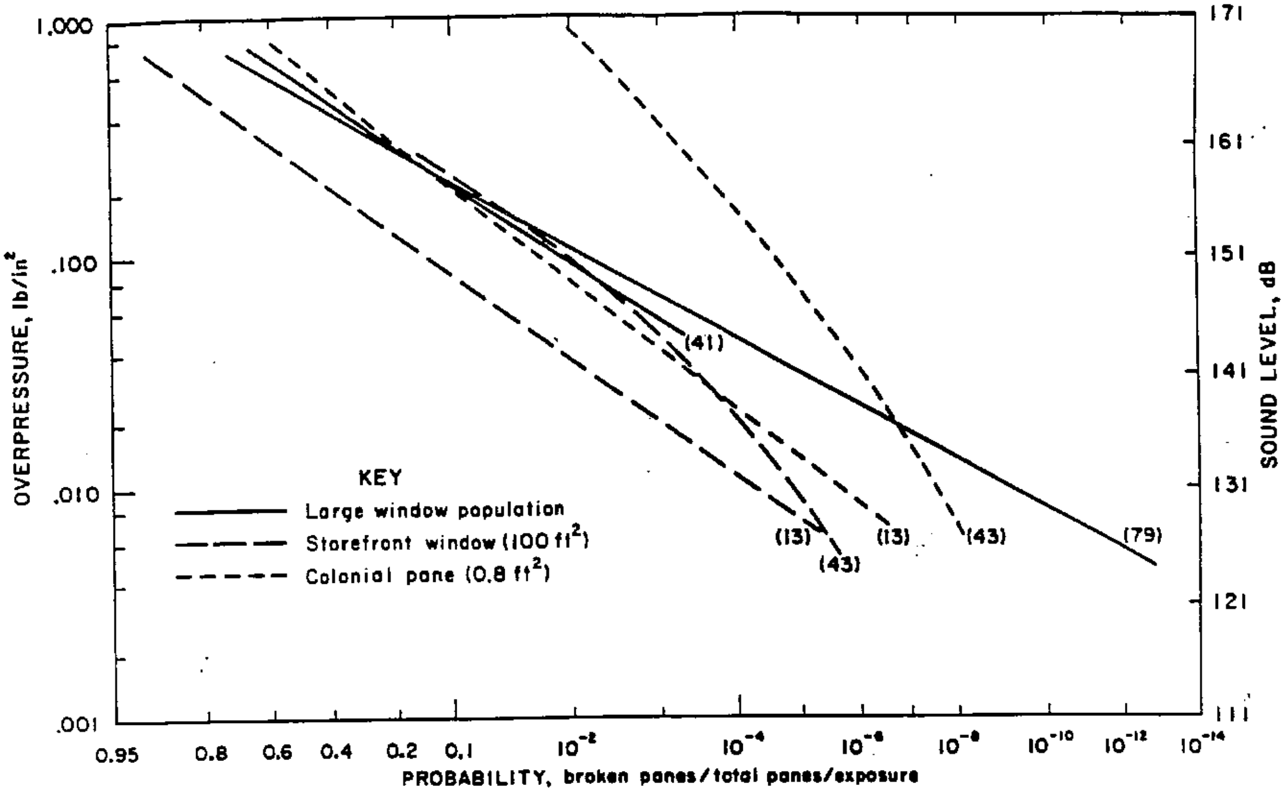


Figure 11. Glass breakage probability from sonic booms and airblasts. Numbers in parentheses are references in Bureau of Mines RI 8485 [Siskind et al., 1980a].

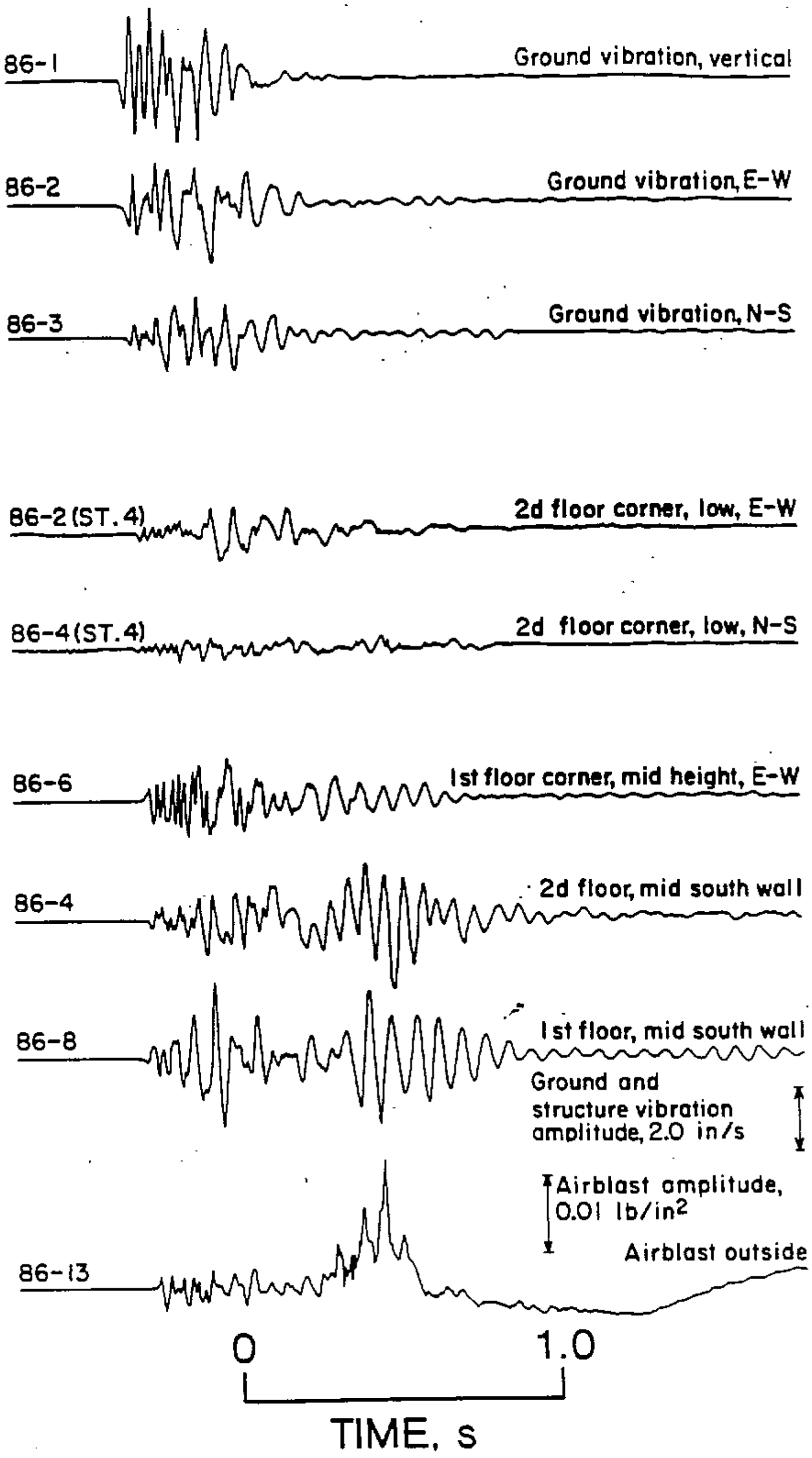


Figure 12. Ground vibrations, structures vibrations, and airblast from a coal mine highwall blast [Siskind et al., 1980b].

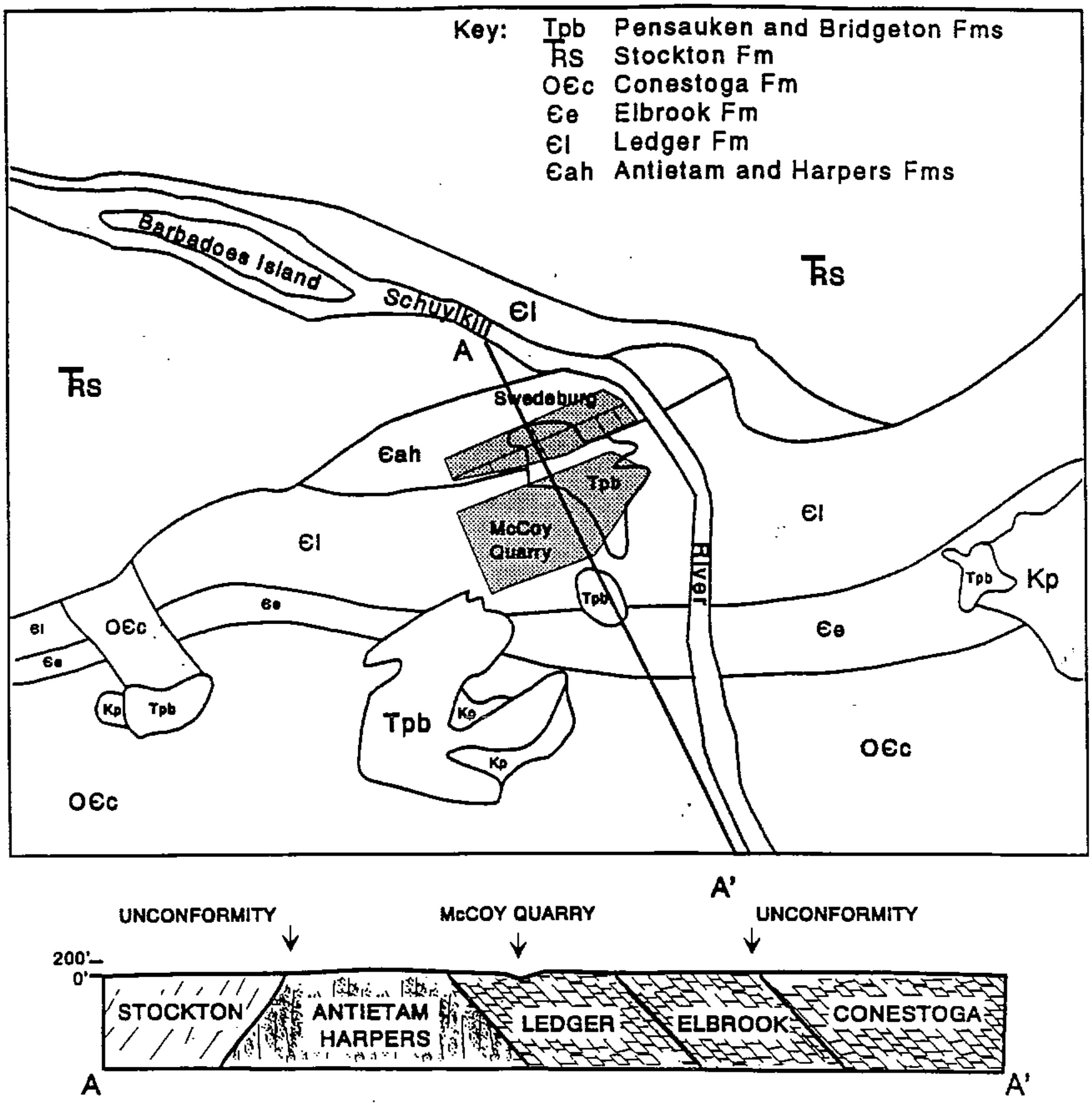


Figure 13. Generalized surface geology and geologic cross section in the vicinity of the McCoy Quarry and Swedesburg, PA.

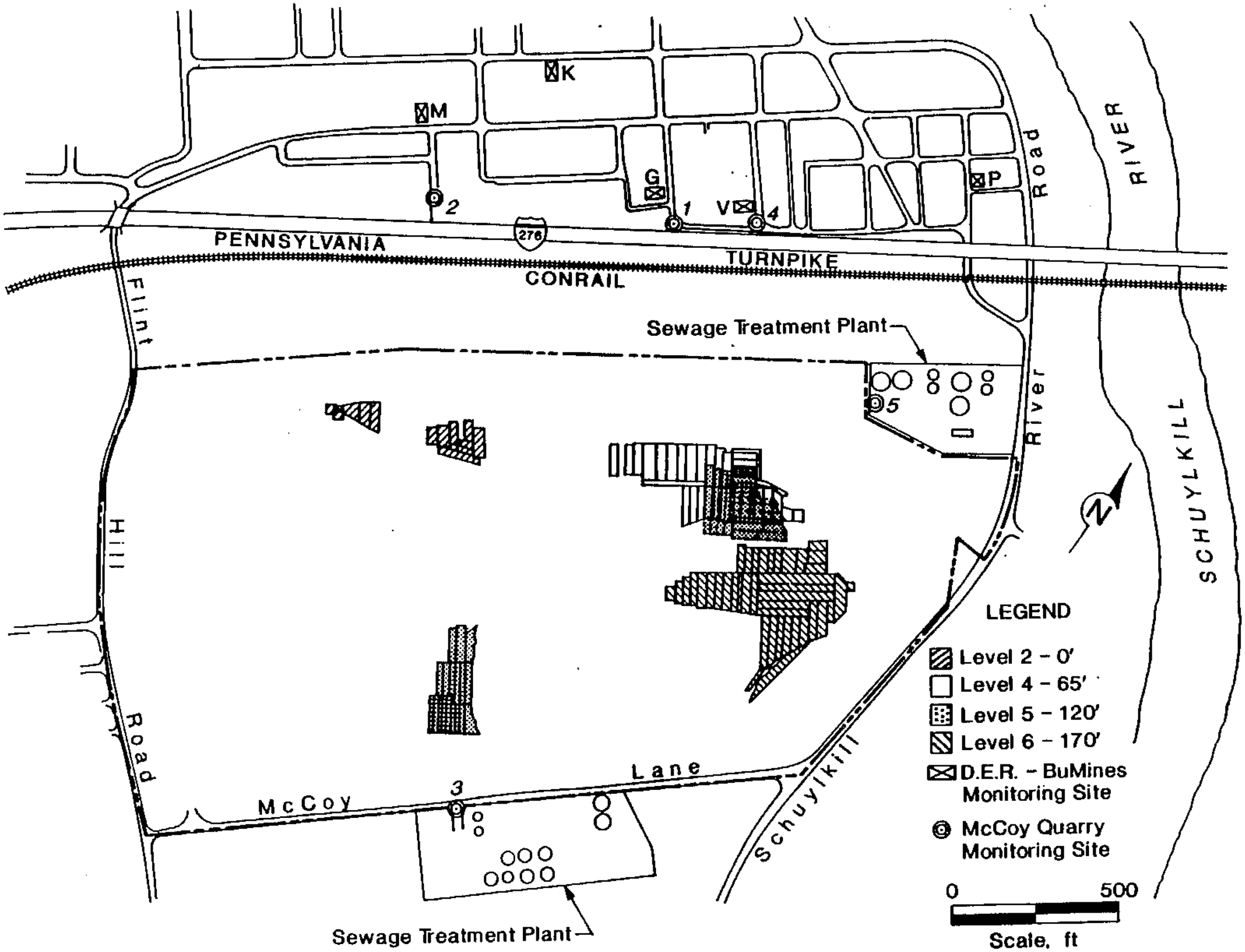


Figure 14. Plan map of the McCoy Quarry showing the relative locations of Swedesburg, monitored homes in the town, McCoy compliance stations, and the blasts detonated from May, 1992 to December, 1993.

Figure 15. House "M" monitored in Swedesburg.

Figure 16. House "K" monitored in Swedesburg.

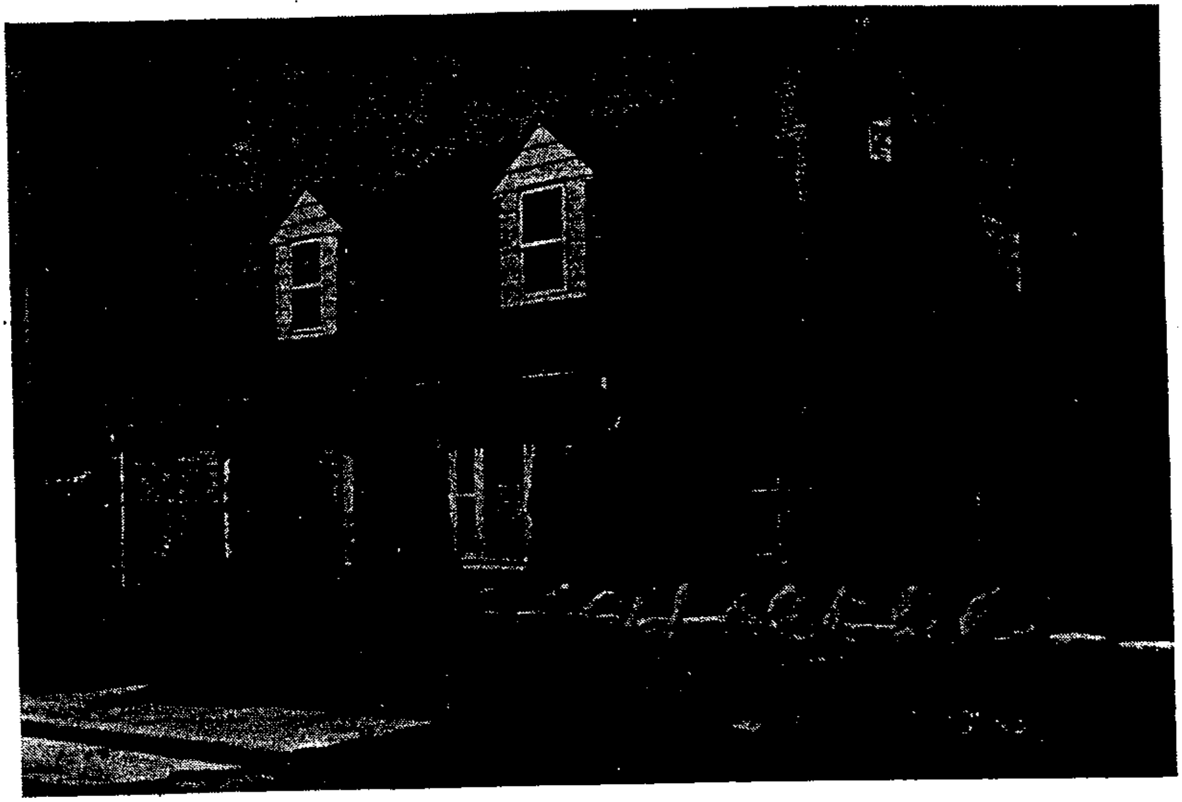
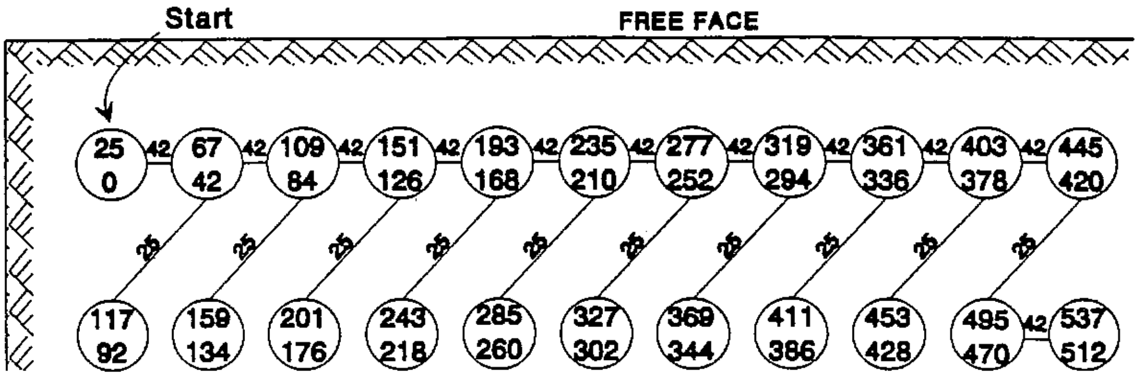


Figure 17. House "P" monitored in Swedesburg.

Figure 18. House "V" monitored in Swedesburg.



Surface delays: 42 ms between holes in rows and 25 ms between rows.
Down hole delays: 25/0 ms front row, 50/25 ms back row.

Figure 19. Schematic representation of the typical type of blast design used at the McCoy Quarry throughout the DER-Bureau study.

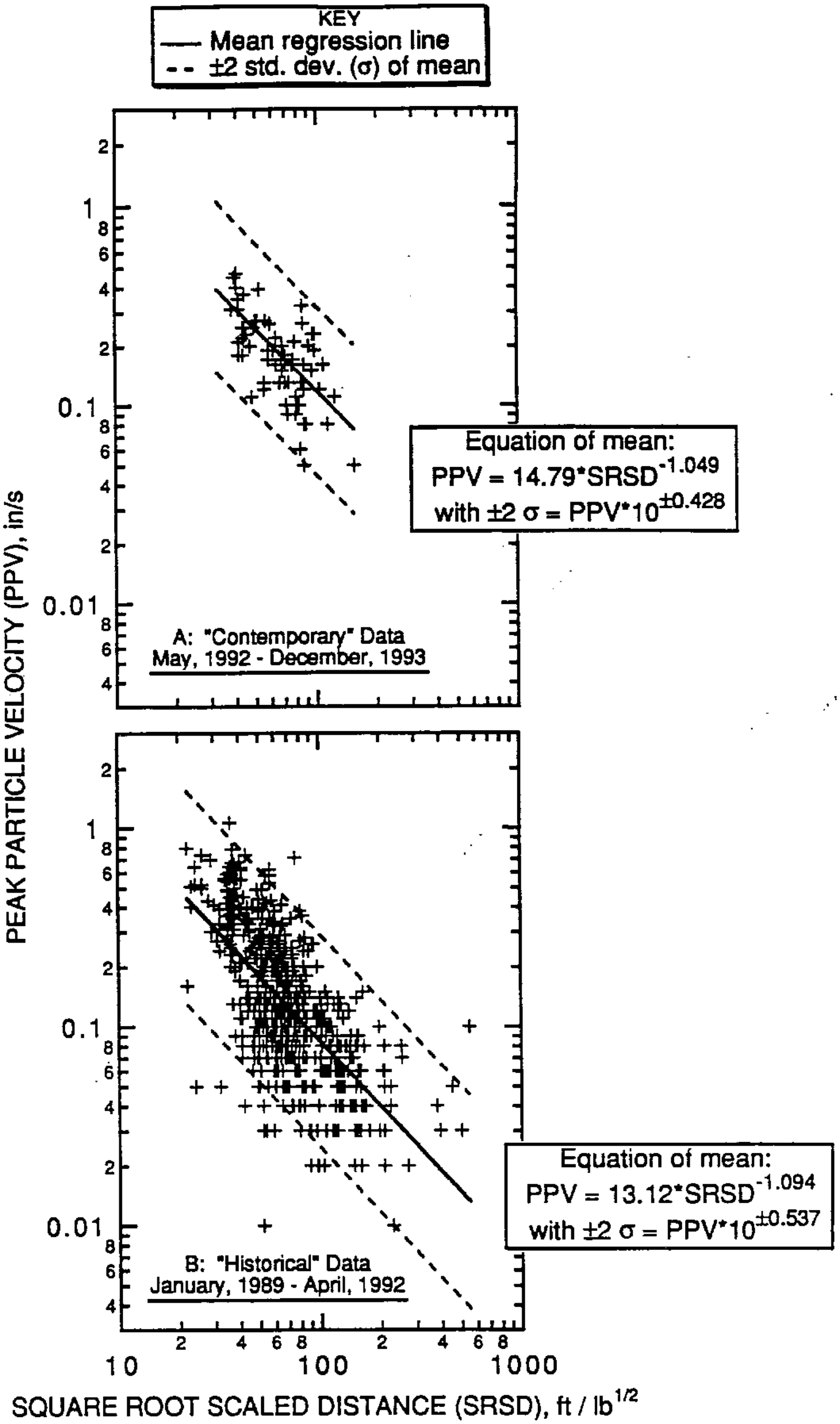


Figure 20. Peak ground vibrations from McCoy compliance stations.
A: "Contemporary" data collected from May, 1992, to December, 1993, during the DER-Bureau study; B: "Historical" data from January, 1989 to April, 1992, before the DER-Bureau study began.

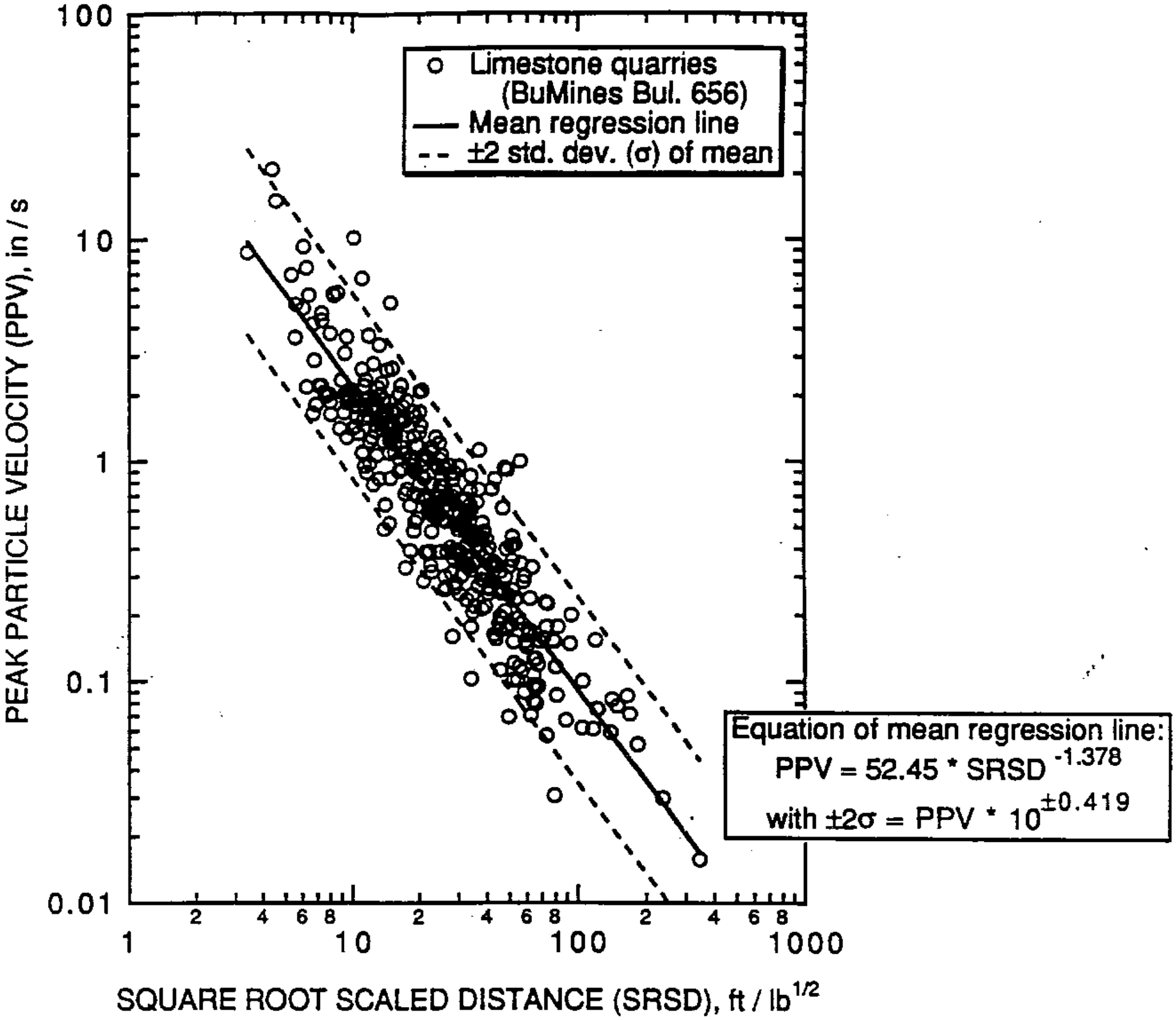


Figure 21. Collective peak ground vibration amplitudes from Bureau of Mines Bulletin 656 [Nichols et al., 1971] for limestone quarries. Equations for the mean and standard deviation lines are shown on the figure.

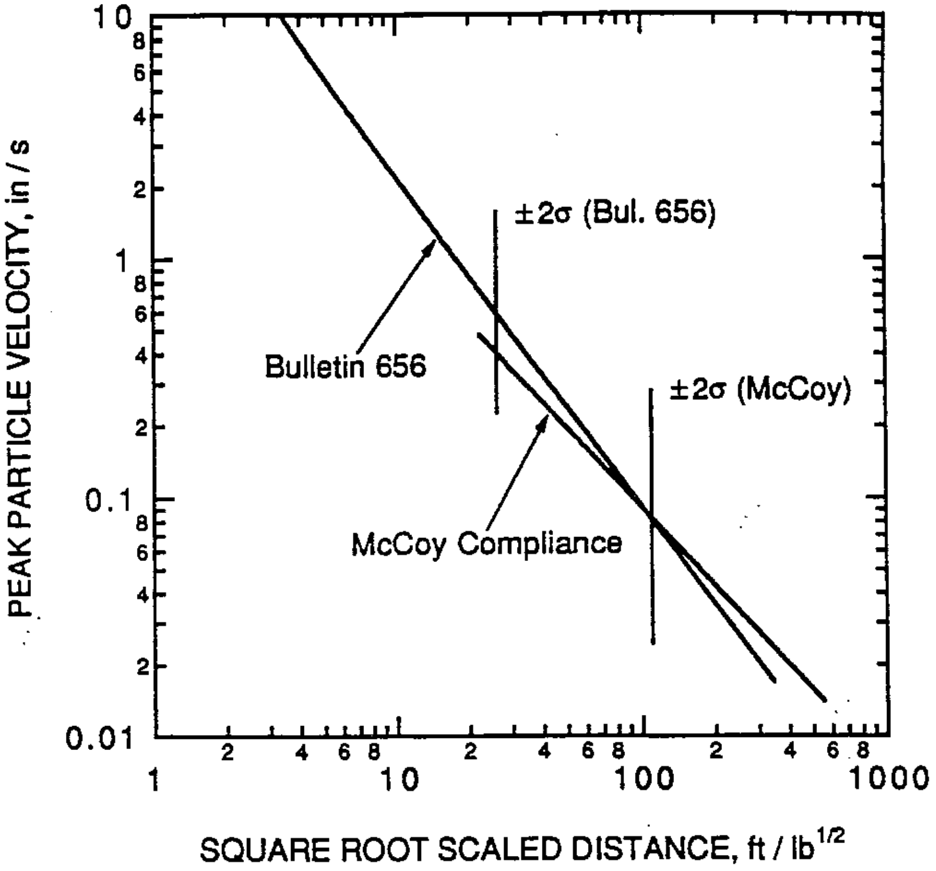


Figure 22. Comparison of representative mean regression lines and plus-minus two standard deviation bars for the Bulletin 656 data (figure 21) and the combined McCoy Quarry contemporary and historical compliance measurements (figures 20-A and 20-B). The equation for the mean regression line for the composite McCoy compliance data is: $PPV = 14.45 \times SRSD^{-1.101}$ with $\pm 2\sigma = PPV \times 10^{\pm 0.527}$.

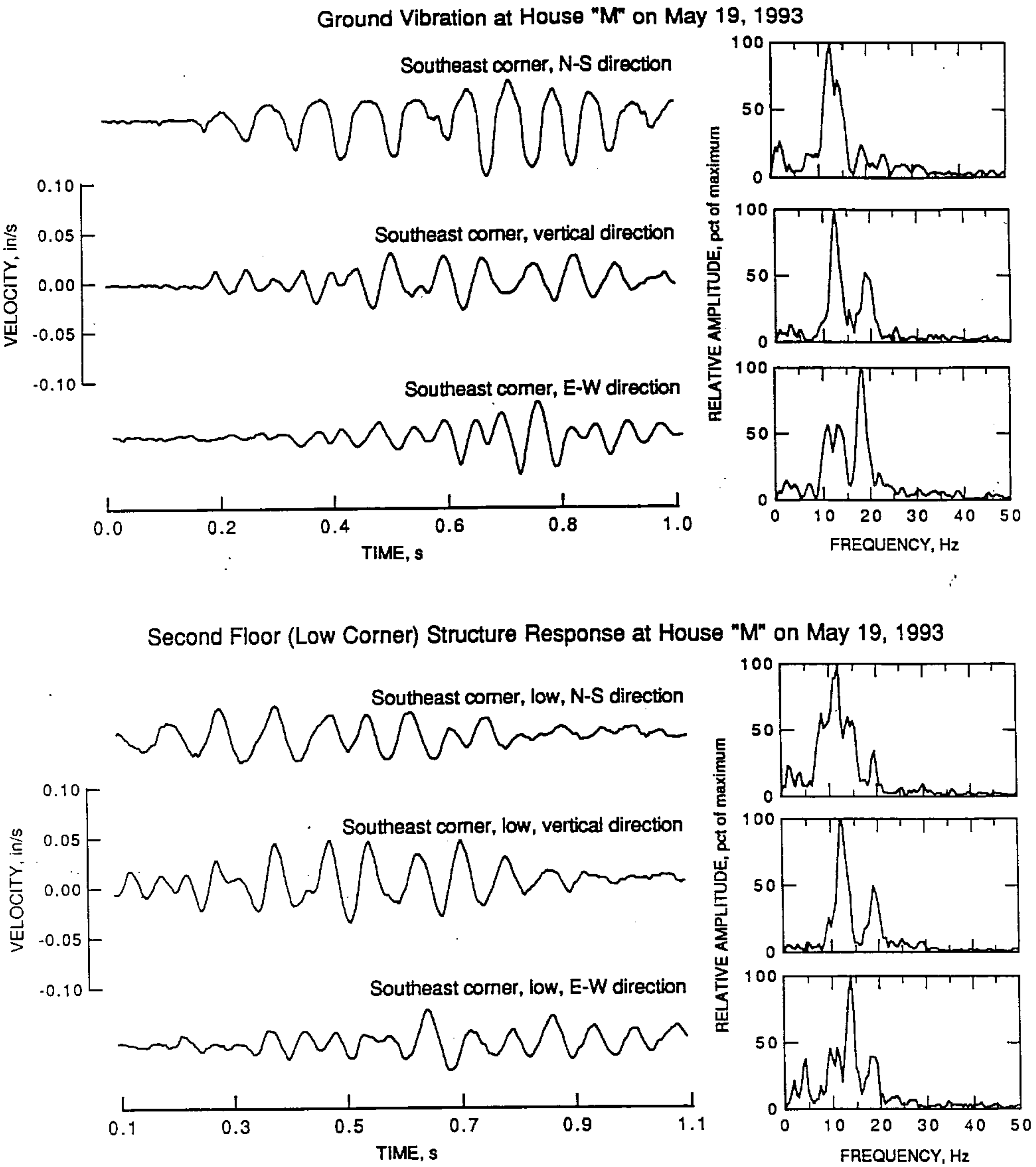


Figure 23. Ground vibration (top) and structure response (bottom) at house "M" for the blast on May 19, 1993. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

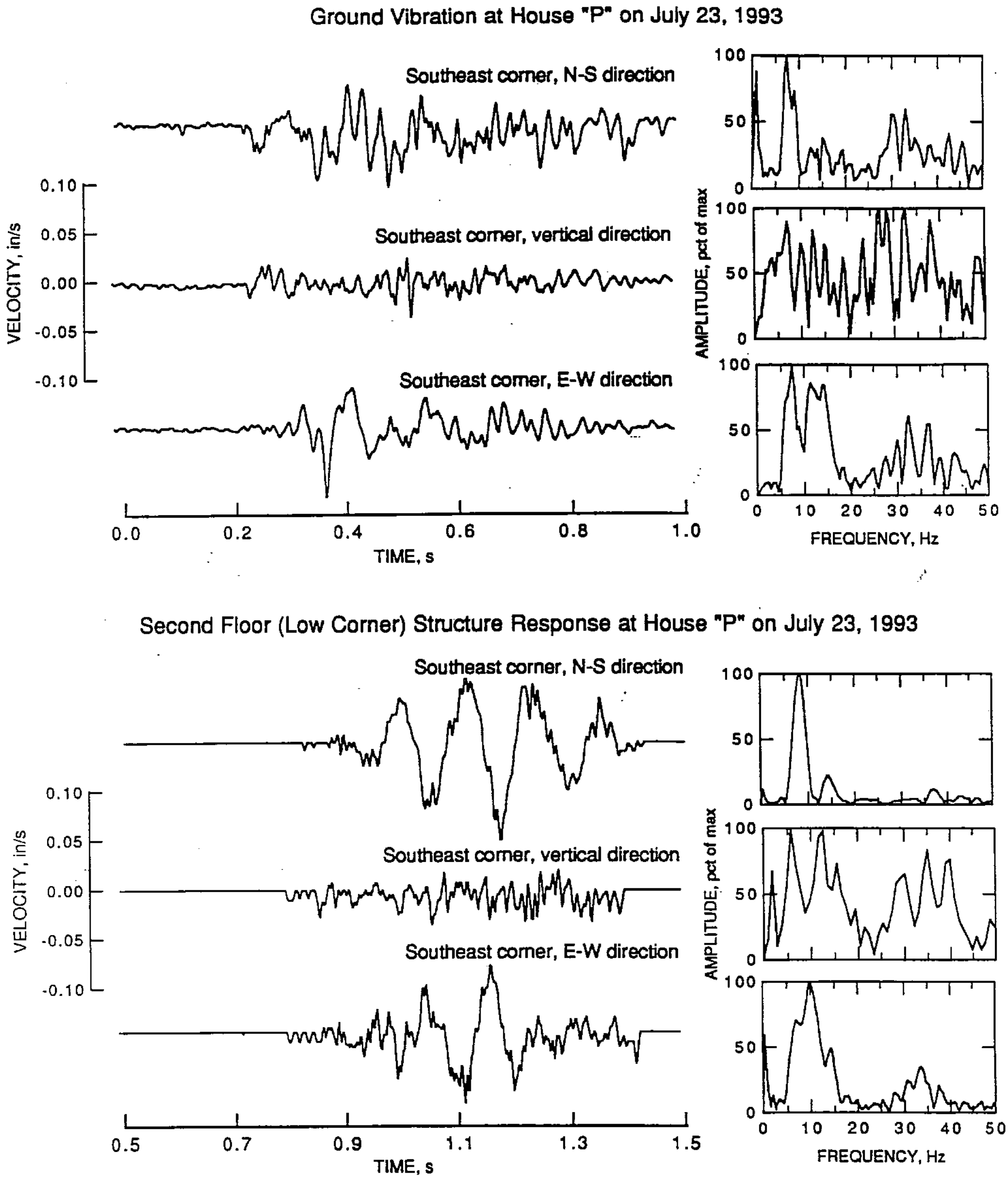


Figure 24. Ground vibration (top) and structure response (bottom) at house "P" for the blast on July 23, 1994. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

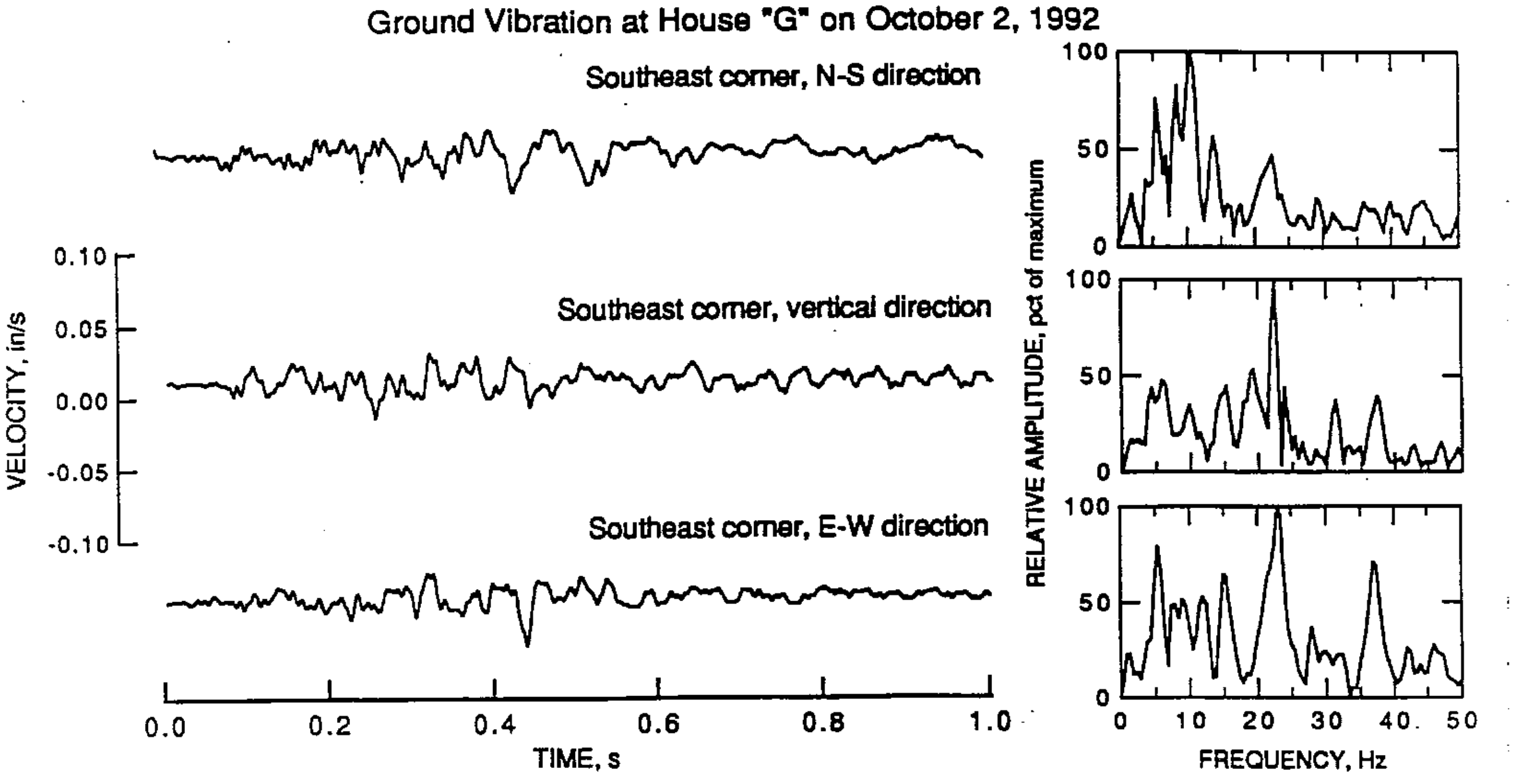


Figure 25. Ground vibration at house "G" for the shot on October 2, 1992. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

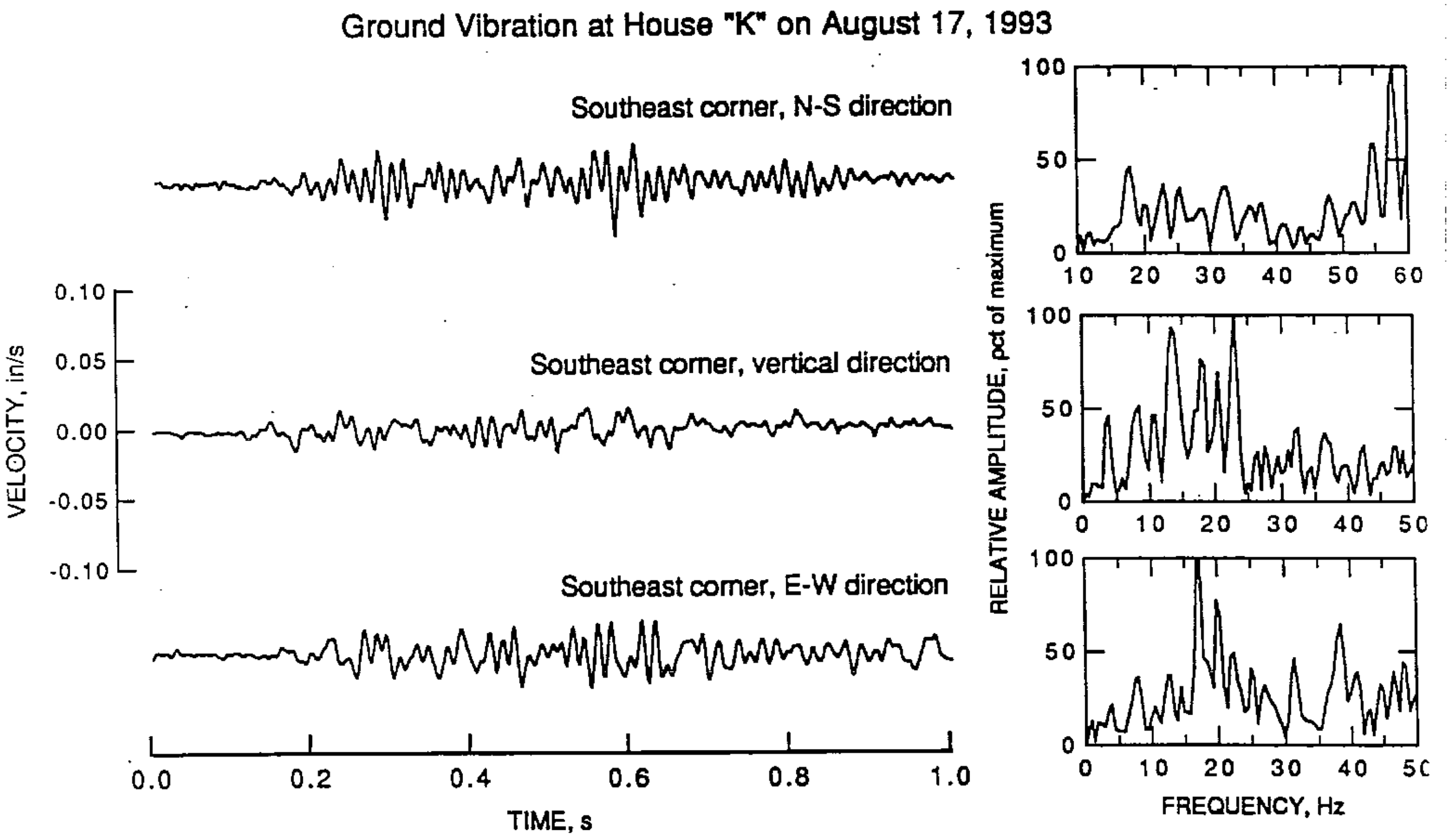


Figure 26. Ground vibration at house "K" for the shot on August 7, 1993. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

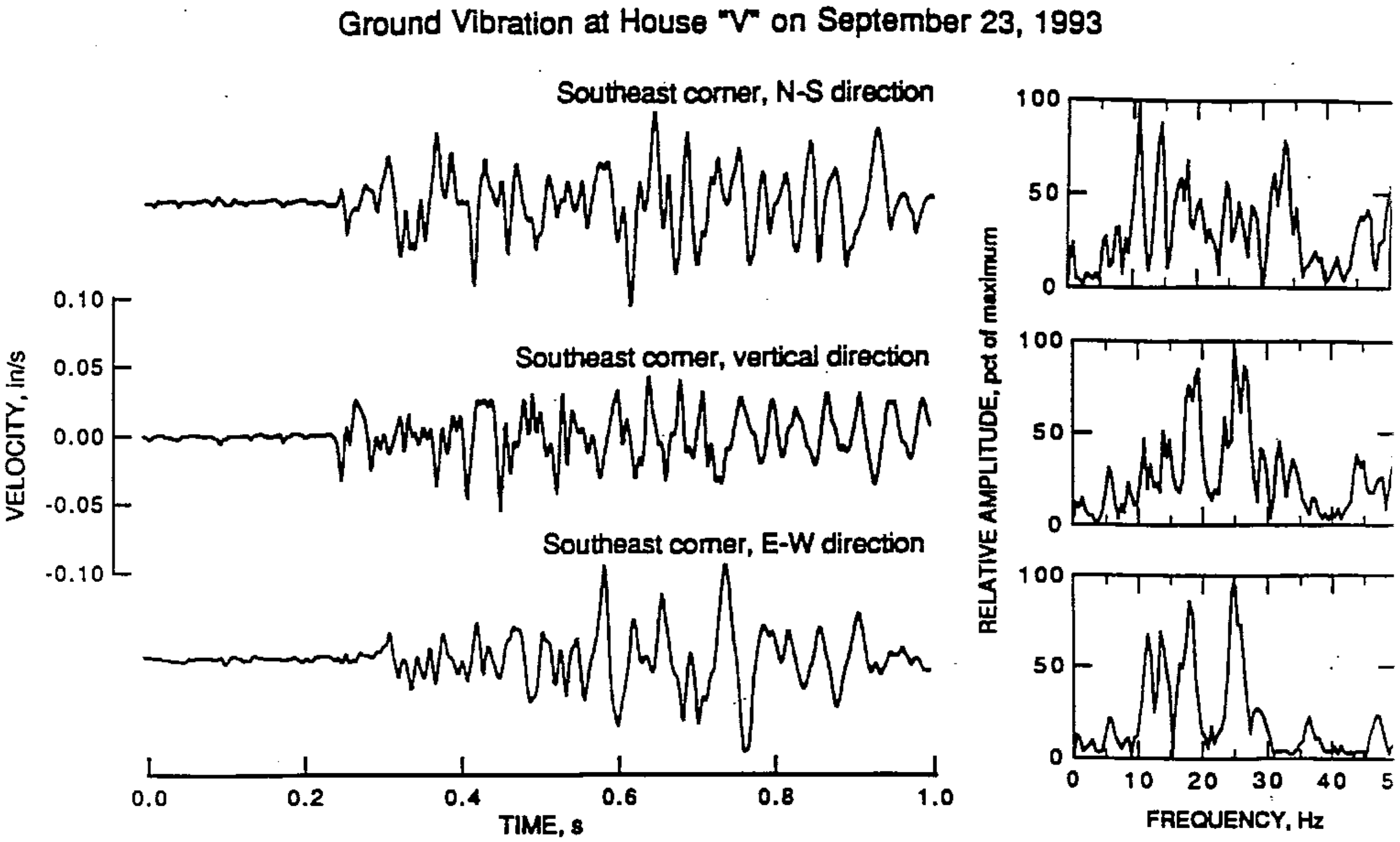


Figure 27. Ground vibration at house "V" for the shot on September 23, 1993. Corresponding FFT amplitude spectra are shown to the right of each vibration waveform.

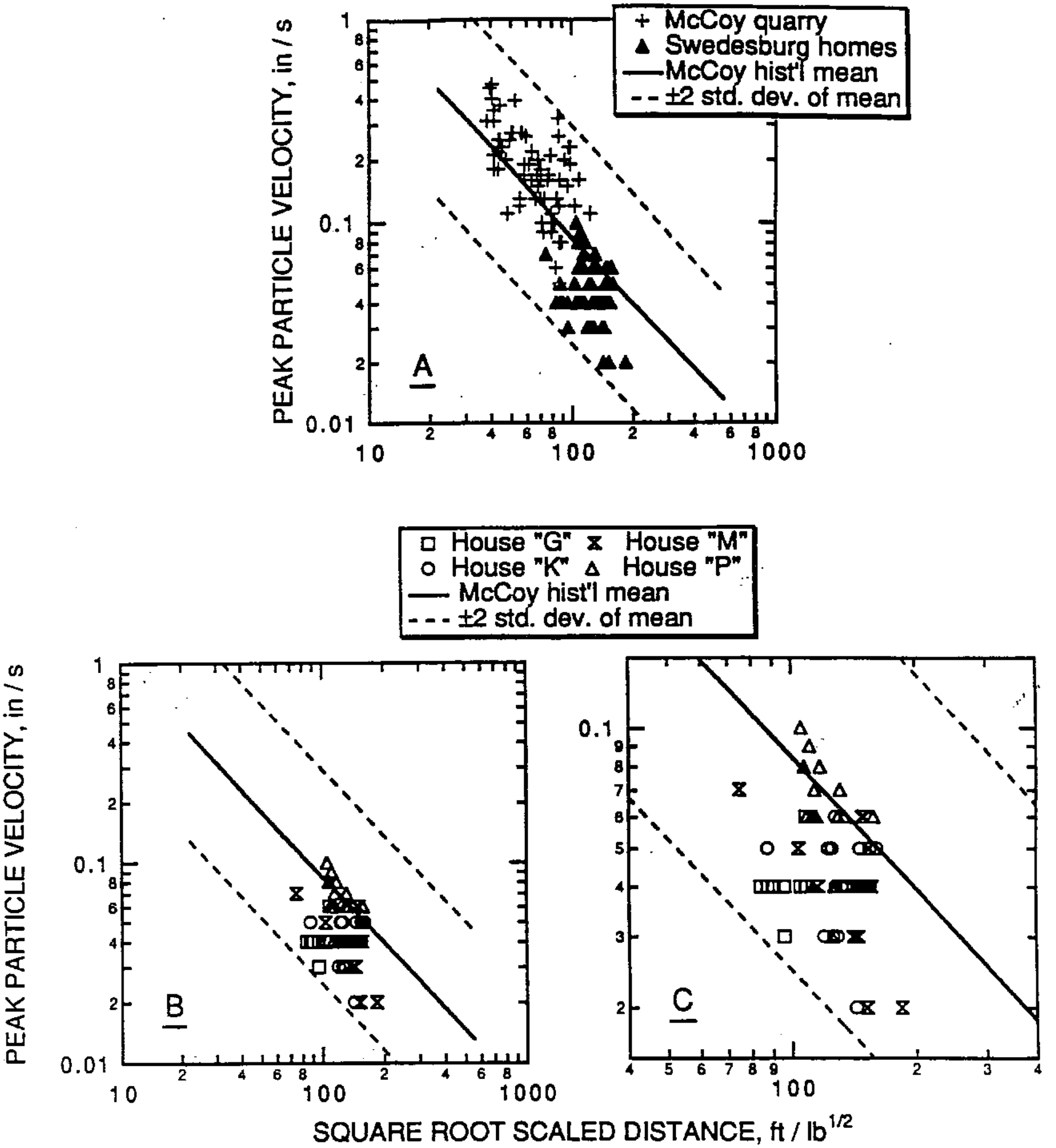


Figure 28. Peak particle velocity versus scaled distance from May to December 1992. A: McCoy Quarry compliance monitoring and DER-Bureau monitoring at the homes in Swedesburg ; B: Individual Swedesburg homes; and C: Expanded-scale view of B. The solid and dashed lines are the mean regression line and ±2 standard deviation envelope, respectively, from the McCoy historical (figure 20-B).

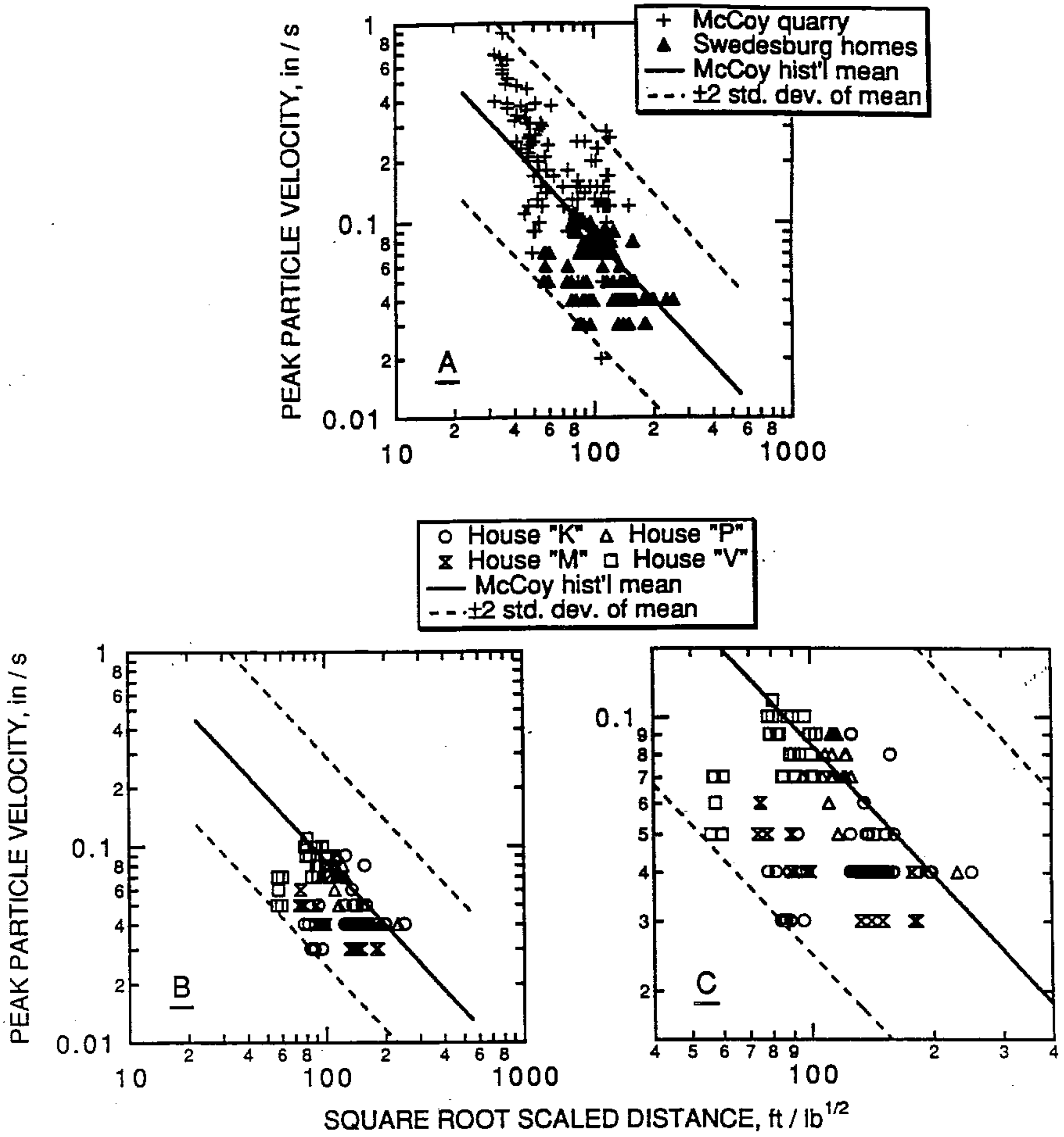


Figure 29. Peak particle velocity versus scaled distance from March to December, 1993. A: McCoy Quarry compliance and DER-Bureau monitoring at the homes in Swedesburg ; B: Individual Swedesburg homes; and C: Expanded-scale view of B. The solid and dashed lines are the mean regression line and ±2 standard deviation envelope, respectively, from the historical McCoy compliance data (figure 20-B).

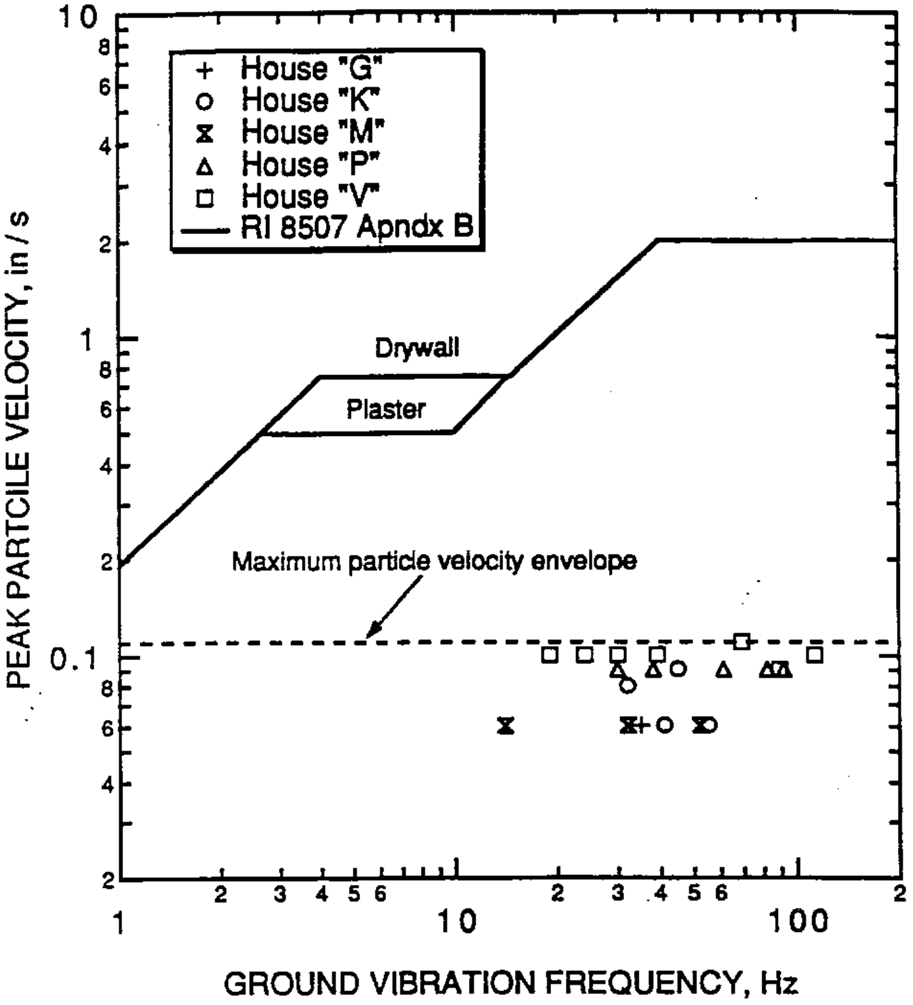


Figure 30. Worse-case Peak particle velocity versus frequency for ground vibrations recorded at Swedesburg homes from plotted against the RI 8507 [Siskind et al., 1980b] Appendix B threshold criteria for prevention of cracking in homes.

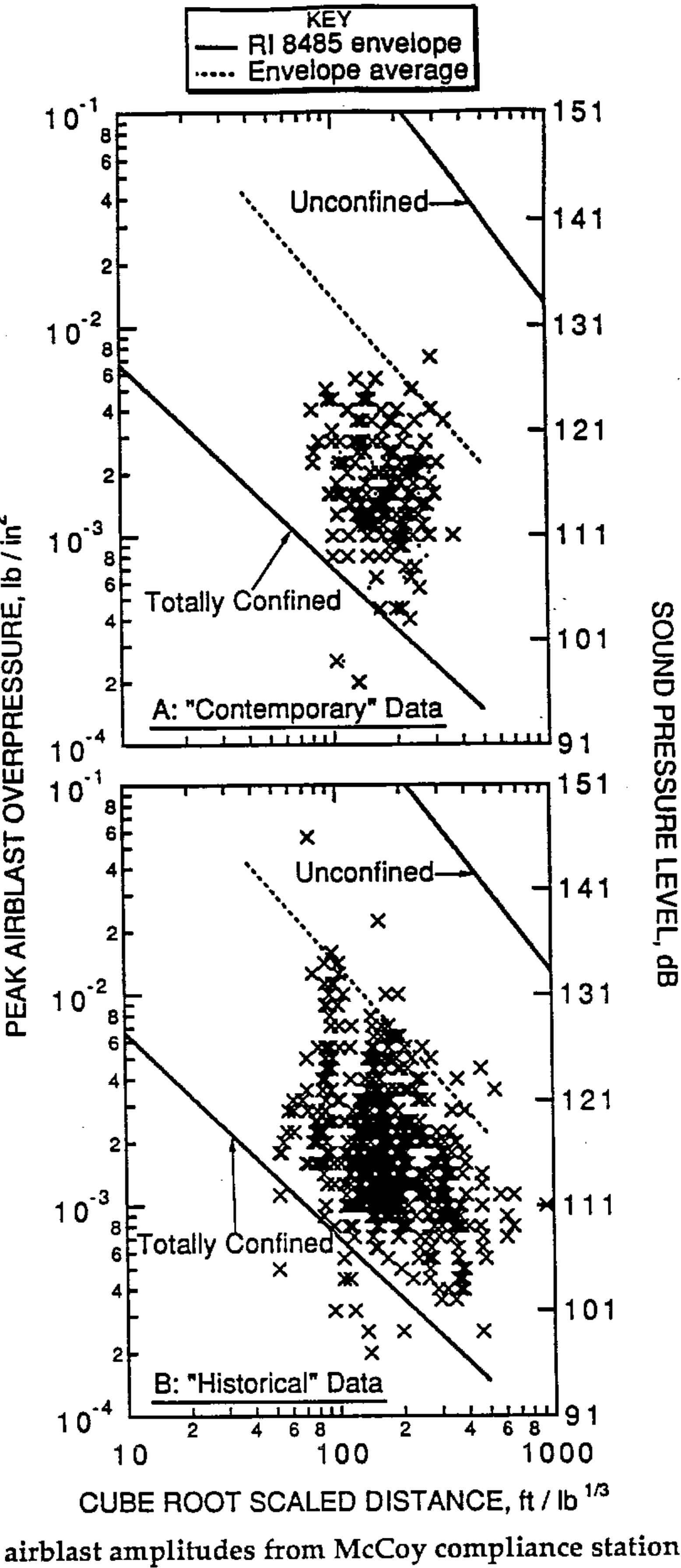


Figure 31. Peak airblast amplitudes from McCoy compliance stations.
A: "Contemporary" data collected from May, 1992, to December, 1993, during the DER-Bureau study ; B: "Historical" data from January, 1989, to April, 1992, before the DER-Bureau study began.

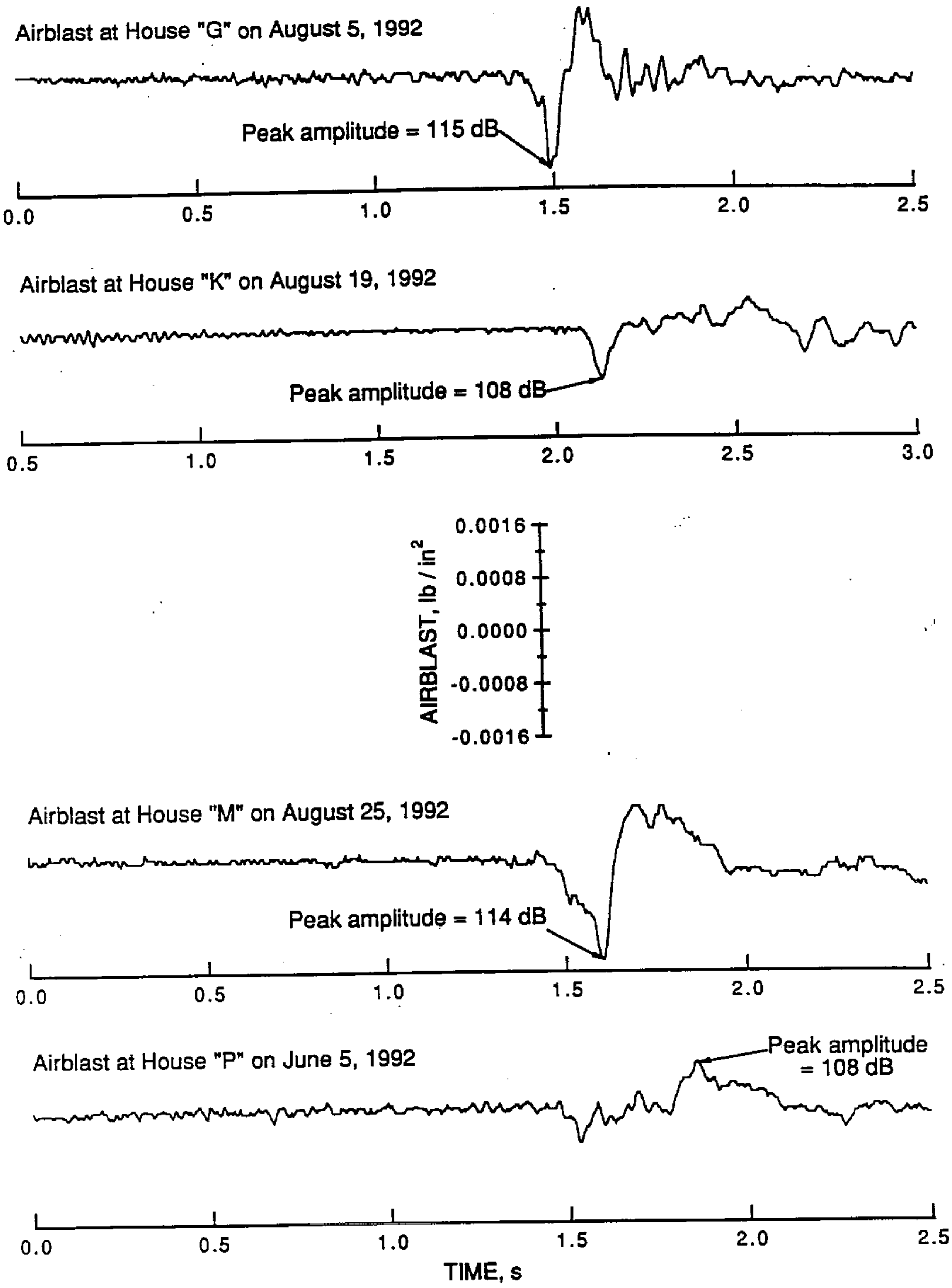


Figure 32. Airblast overpressure time histories from DER-Bureau monitoring in Swedesburg (5-Hz highpass recording system).

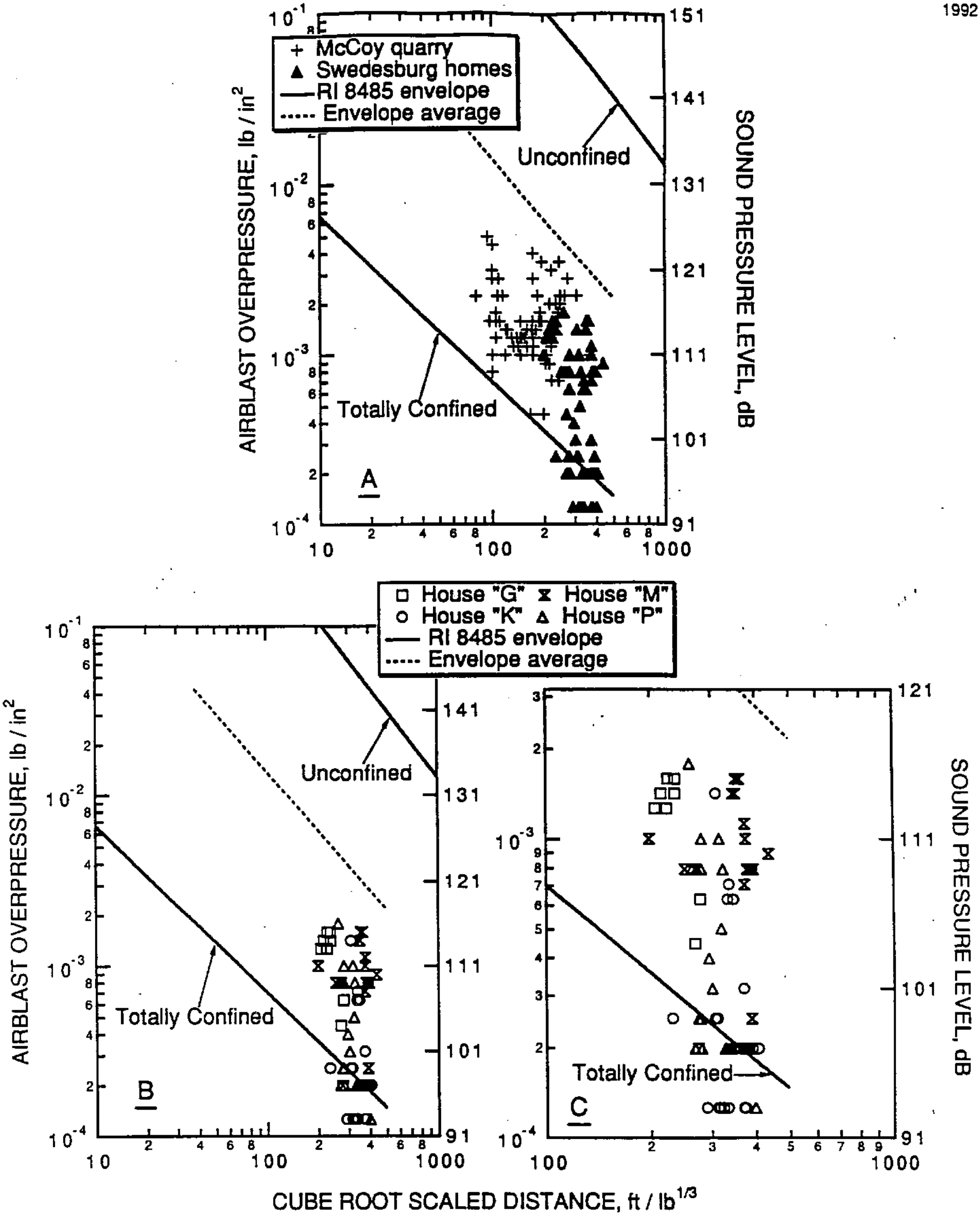


Figure 33. Peak airblast measurements from May to December, 1992. A: McCoy Quarry compliance and DER-Bureau monitoring in Swedesburg; B: Measurements at the individual Swedesburg homes; C: Expanded-scale view of the Swedesburg data shown in B. The solid and dashed lines are the maximum and minimum airblast bounds and their average, respectively, as described in figure 31.

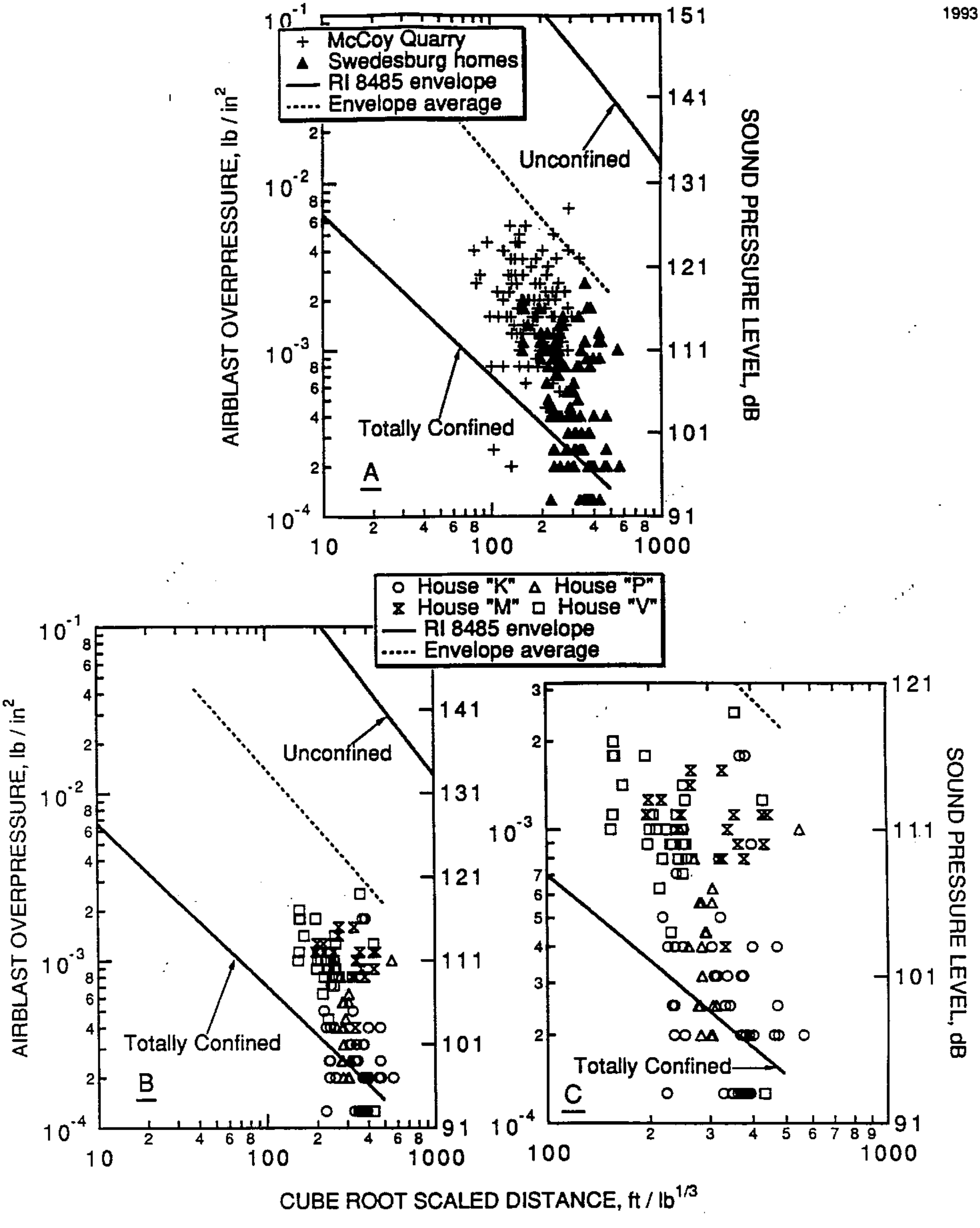


Figure 34. Peak airblast measurements for March - December, 1993. A: McCoy Quarry compliance monitoring and DER-Bureau monitoring in Swedesburg; B: Measurements at the individual Swedesburg homes; C: Expanded-scale view of the Swedesburg data shown in B. The solid and dashed lines are the maximum and minimum airblast bounds and their average, respectively, as shown in figure 31.

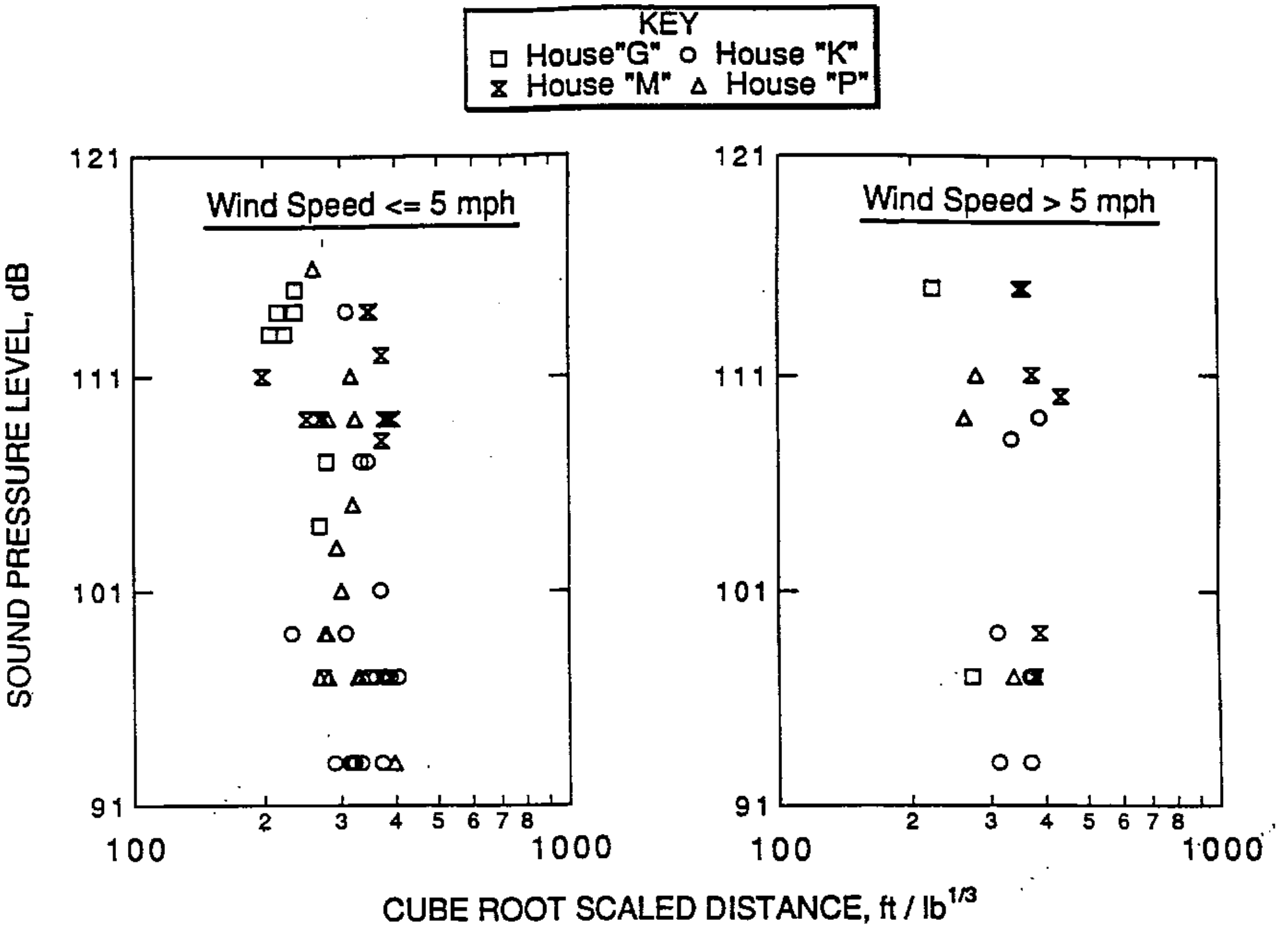


Figure 35. Peak airblast at Swedesburg homes versus wind speed on the bench at the time of the blast for May - December, 1992.

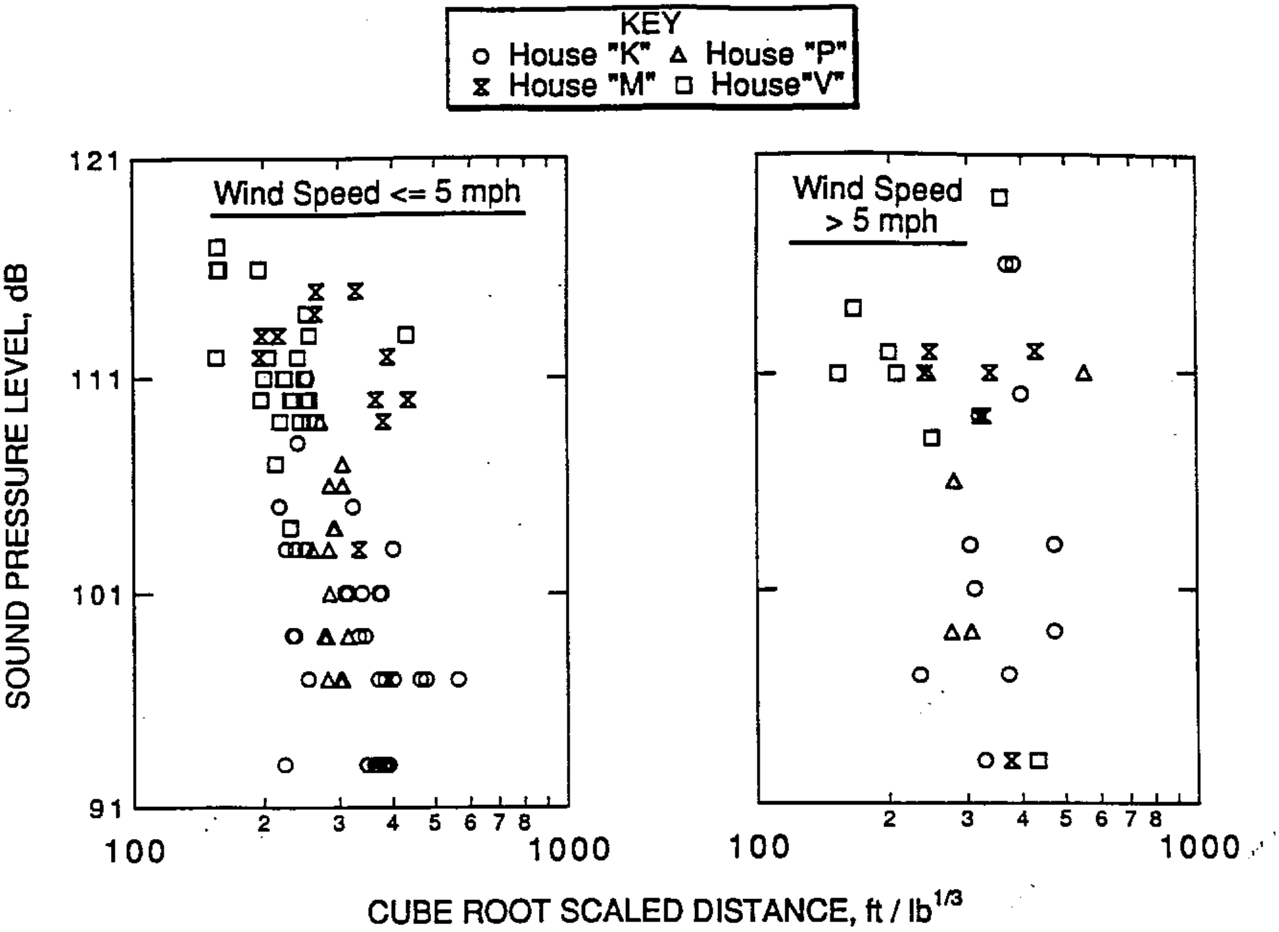


Figure 36. Peak airblast at Swedesburg homes versus wind speed on the bench at the time of the blast for March - December, 1993.

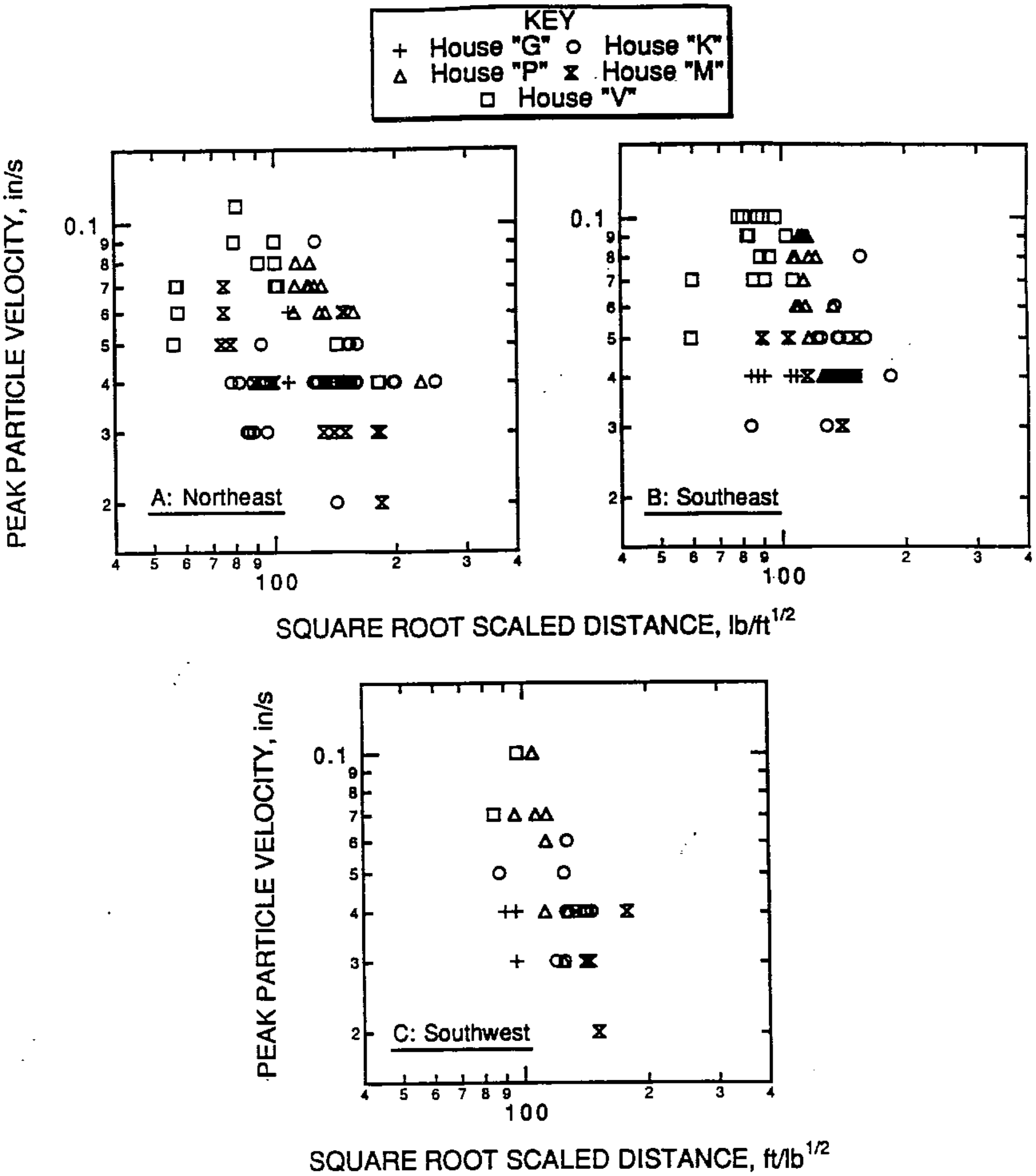


Figure 37. Peak particle velocity versus scaled distance from monitoring in Swedesburg grouped according to face orientation of the blast (all data).

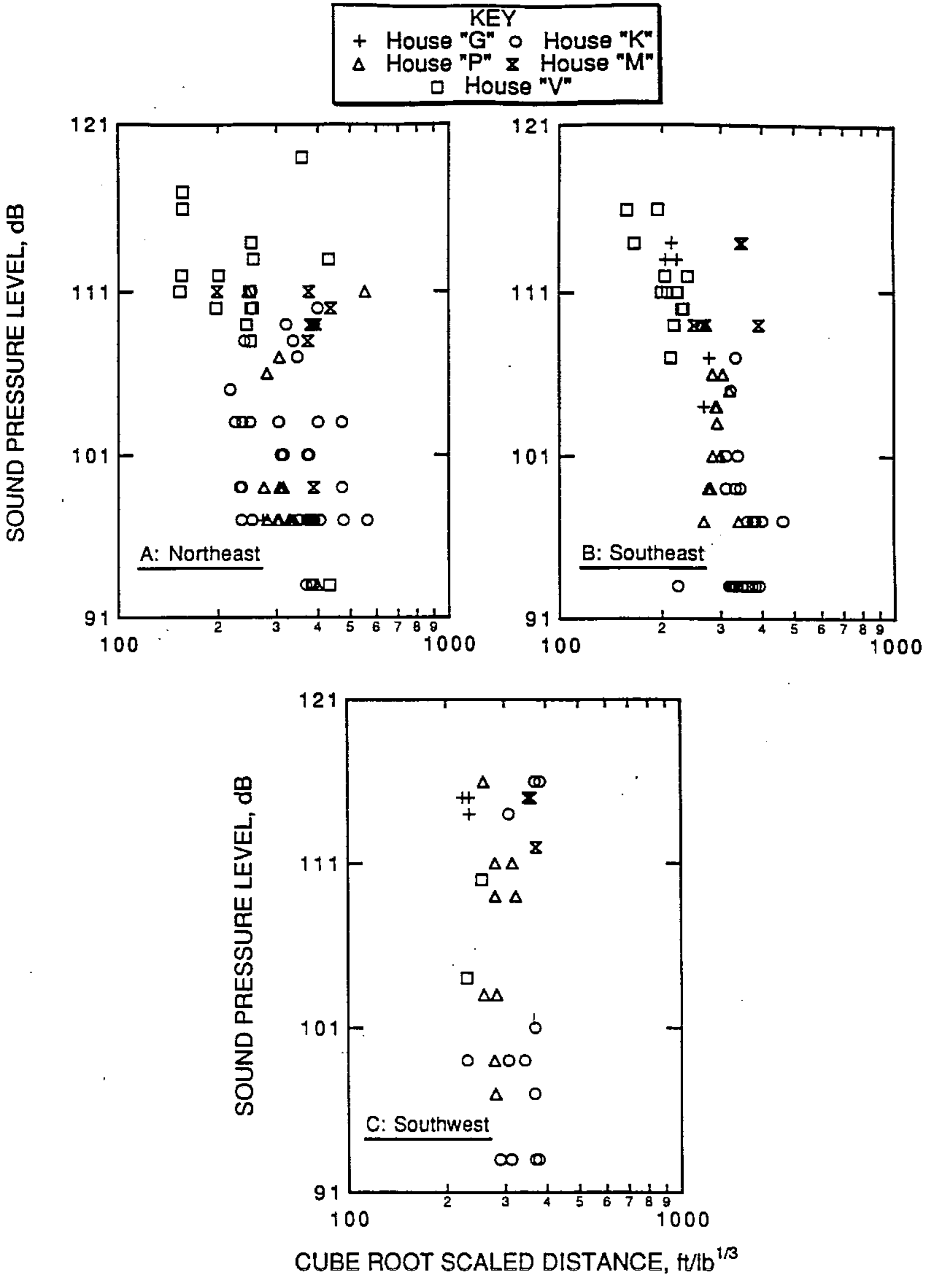


Figure 38. Peak airblast versus scaled distance from monitoring in Swedesburg grouped according to face orientation of the blast (all data).

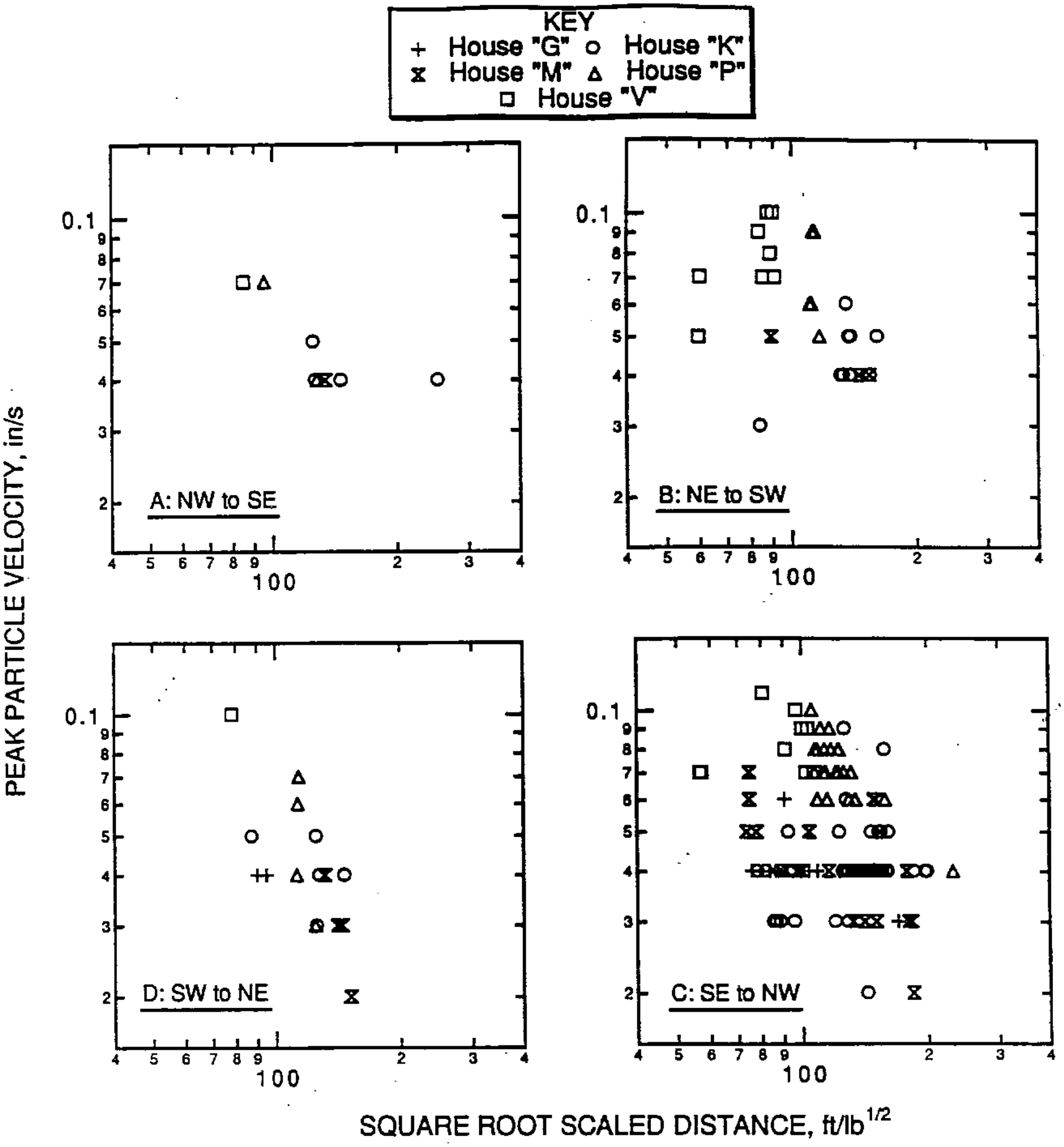


Figure 39. Peak particle velocity versus square root scaled distance from monitoring in Swedesburg grouped according to direction of blast initiation (all data).

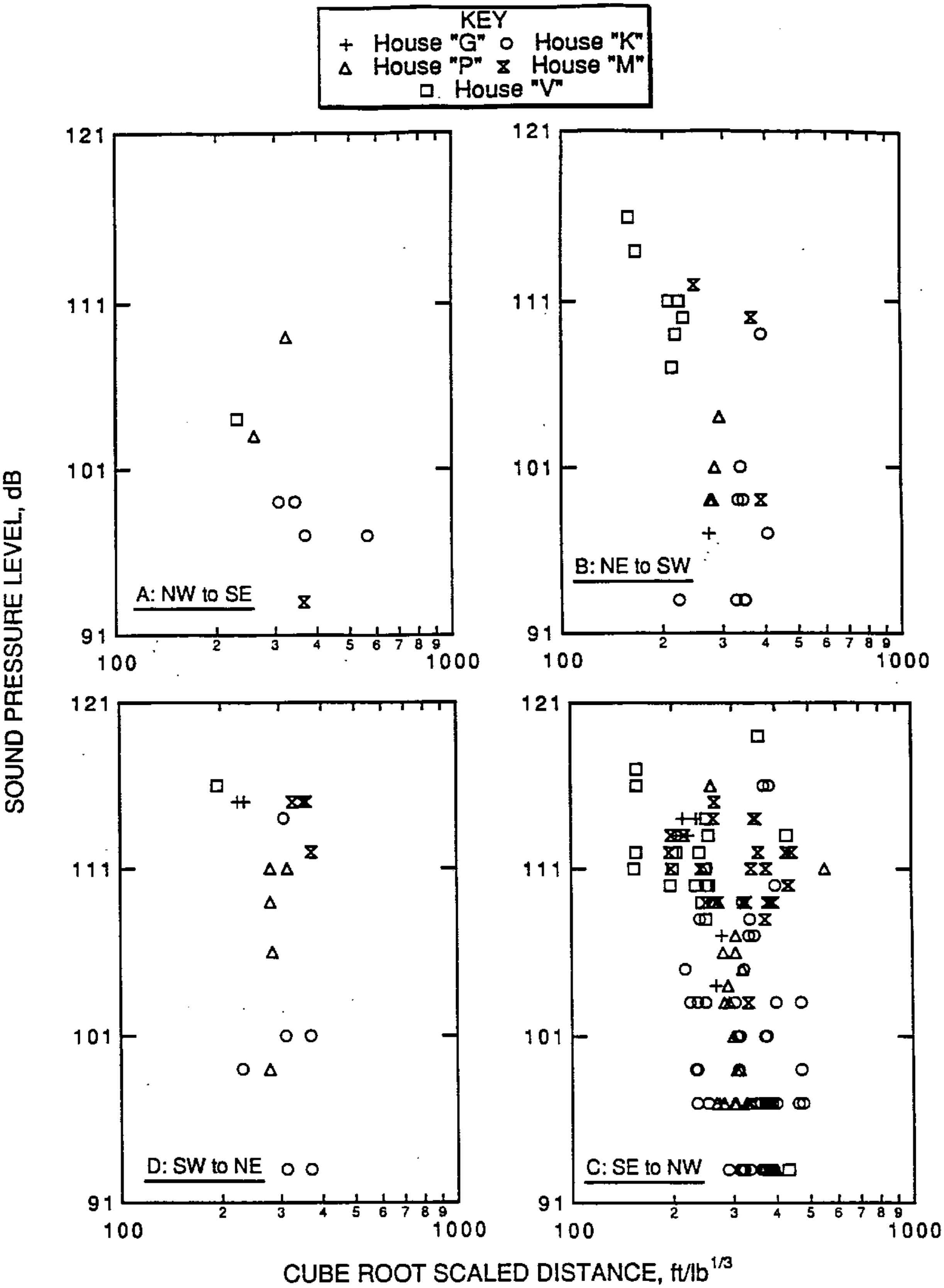


Figure 40. Peak airblast versus cube root scaled distance from monitoring in Swedesburg grouped according to direction of blast initiation (all data).

all

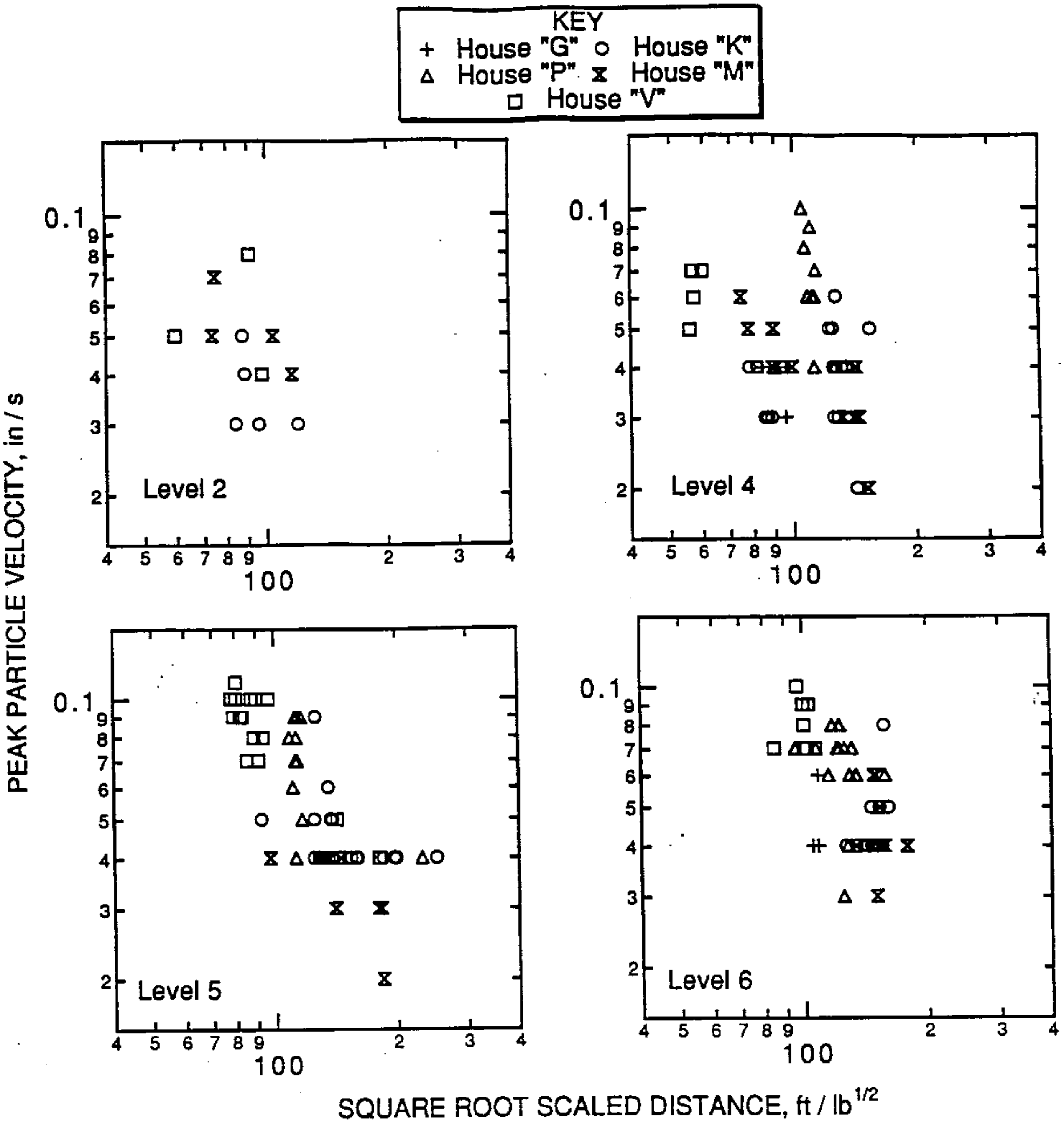


Figure 41. Peak particle velocity versus scaled distance from monitoring in Swedesburg grouped according to bench level where the blast occurred (all data).

all

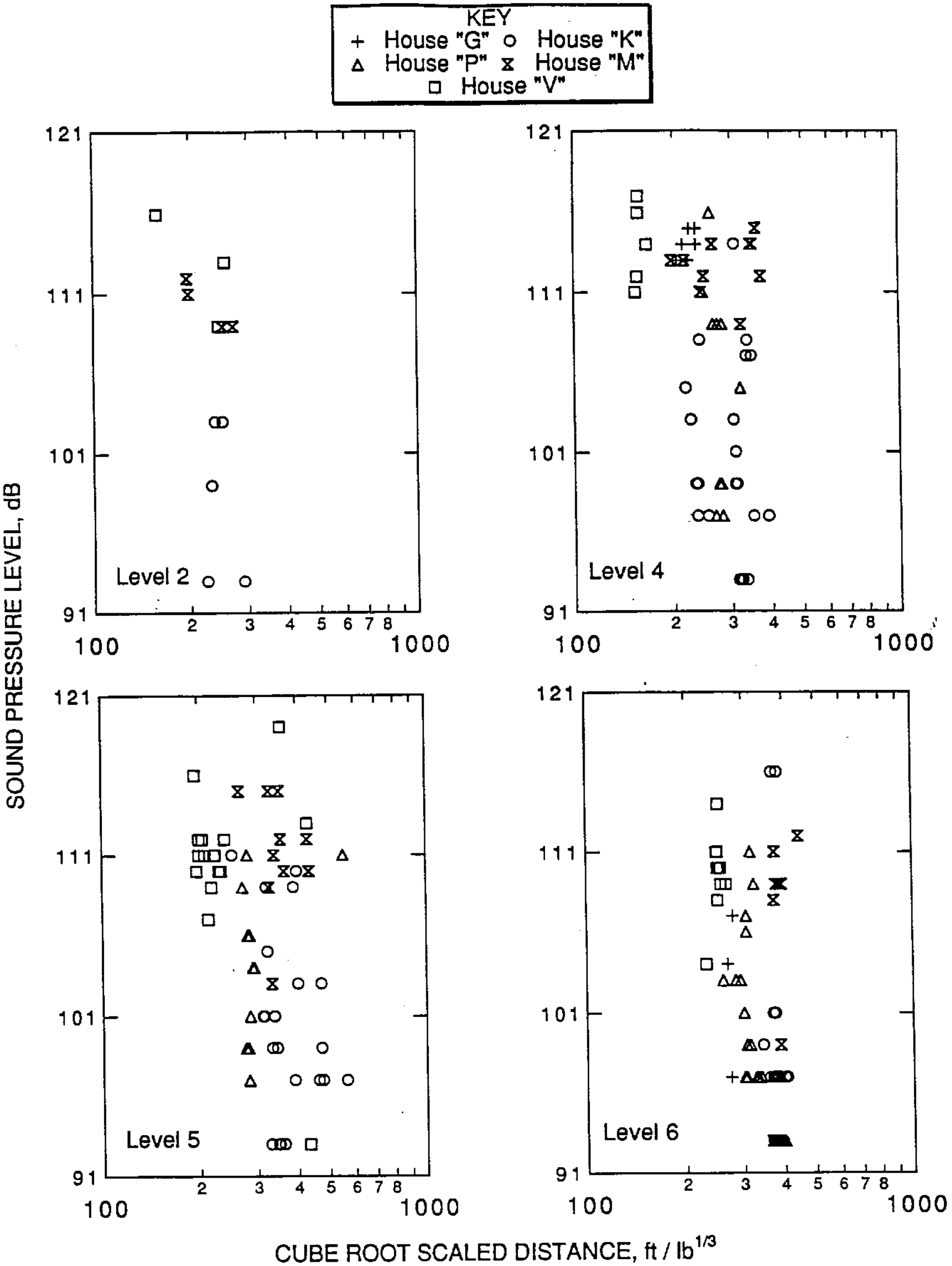


Figure 42. Peak airblast versus scaled distance at homes in Swedesburg grouped according to bench level where the blast occurred (all data).