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RECLAMATION AND ENFORCEMENT
TECHNICAL REPORT/1994

INVESTIGATION OF DAMAGE TO STRUCTURES IN THE M^{c}CUTCHANVILLE-DAYLIGHT AREA OF SOUTHWESTERN INDIANA

Volume 2 of 3

Part II: Geologic and Unconsolidated Materials in the McCutchanville-Daylight Area.
Part III: Blast Design Effects on Ground Vibrations in McCutchanville and Daylight, Indiana from Blasting at the AMAX, Ayrshire Mine.
Part IV: Vibration Environment and Damage Characterization for Houses in McCutchanville and Daylight, Indiana.
Part V: Racking Response of Large Structures from Airblast, A Case Study.
Part VI: Investigation of Building Damage in the McCutchanville-Daylight, Indiana Area.

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Office of Surface Mining Reclamation and Enforcement

Part IV

Vibration Environment and Damage Characterization For Houses in McCutchanville and Daylight, Indiana.

Errata

The U.S. Bureau of Mines has identified a few minor errors to Part IV as follows:

1) p. 19, line 6: Change from November 16 to November 6, 1989 at 1110.

2) p. 103: Structure responses for 11-14-89 are incorrect. Change as follows:

   .0024 to .010

   .007 to .028

   .024 to .108

   as per RI 9455 (p. 41)

3) p.106: Velocity for 11-01-89 at 1342 should be .02, not .20, for radial component.

CONTRACT RESEARCH REPORT
FEBRUARY 1990

VIBRATION ENVIRONMENT AND DAMAGE CHARACTERIZATION FOR HOUSES IN McCUTCHANVILLE AND DAYLIGHT, INDIANA

Interagency Agreement EC68-IA9-13259
U.S. Department of the Interior, Bureau of Mines, Twin Cities Research Center
David E. Siskind, Steven V. Crum and Matthew N. Plis

DEPARTMENT OF THE INTERIOR
OFFICE OF SURFACE MINING

VIBRATION ENVIRONMENT AND DAMAGE CHARACTERIZATION FOR HOUSES IN MCCUTCHANVILLE AND DAYLIGHT INDIANA

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INTRODUCTION

The Bureau of Mines was asked by the Federal Office of Surface Mining to conduct a damage evaluation study in two communities west of the active Ayrshire surface coal mine operated by the AMAX Mining Company north of Evansville, Indiana (Figure 1). A large number of residents in these communities of Daylight and McCutchanville had been complaining of blast vibration impacts on their homes. They attributed damage ranging from cosmetic superstructure cracks to collapsing basement walls to the blasting at distances of two to five miles. Additionally, some complaints had been received at widely varying locations up to 10 miles, suggesting abnormal propagations for vibration, airblast, or both.

The Bureau was to determine if the damage was being caused by the blasting through a program of blast monitoring and crack inspections. Included in the study were assessments of vibration characteristics, such as frequency and duration, in addition to particle velocity amplitudes. Airblast impacts, possible settlement and subsidence, effects of the propagating media on the vibrations structure response, and vibration sources other than blasting were also examined. If the blasting was found not to be the cause of damage, the Bureau was to propose alternative explanations.

In Indiana, the Department of Natural Resources (DNR) controls blasting effects by enforcing regulations approved by the Office of Surface Mining (OSM) for surface coal mining. In response to these complaints, the DNR conducted a study of Ayrshire mine blasting and a permit review (1). This undated study was completed around August 1989 and found that blasting was not a likely cause of damage to homes in these communities. The study also noted that a significant number of "events" complained about were not blasts at all, at Ayrshire or at other farther-away mines. The DNR continues its program of monitoring Ayrshire mine blasting. A permanent seismograph station is in

ABSTRACT

The Bureau of Mines studied seven homes near Evansville, Indiana with varying degrees of structural and cosmetic cracking which the owners were attributing to vibrations from blasting in a nearby surface coal mine. Researchers monitored the vibration and airblast impacts in McCutchanville and Daylight, Indiana for two months including pre- and post-blast crack inspections and dynamic structural responses from both the blasting and other sources such as nearby aircraft operations and human activity within the homes. Level-loop surveys were performed to quantify possible settlement and subsidence. These results were combined with a year's worth of state and coal company historical measurements to determine if vibration characteristics, propagations, or structural responses are typical of historical studies which provided regulatory criteria.

Researchers found that the blasting vibrations were occasionally of low frequency, down to 3 Hz, and durations as long as 10 seconds, making them unusually noticeable and potentially more dangerous. The relatively low levels of vibration measured by the Bureau during the course of this study indicate that phenomena other than blasting are responsible for the structural damage observed in the study area. None of the blasts produced significant changes in the 45 inspection areas within the homes.

The nature of the damage, a preliminary soil test, and available information on soils from nearby southern Illinois suggest that expansive clays are primarily responsible for the structural damage with possible drainage and slope contributions. Occasional airblasts from the larger casting blasts are greatly influencing the perceptibility of the blasts at larger distances.

place at one McCutchanville home and blasting practices at the mine are in continual review.

One recent effort by the DNR verified that production blasts during the period of the Bureau's monitoring, November 1, 1989 through January 3, 1990, were typical and as large as previous blasts including periods of high complaint levels. The DNR also noted that the mine was varying minor factors in the blast design, such as initiation delay intervals and pattern designs. The effects of such changes on vibration characteristics at the large distances of concern for this study (2 to 4 miles) are expected to be minor. Because of typical vibration propagation equations (given later), it is expected that even a major change, such as a doubling of the per-delay-period charge weight, will have, at worst, a corresponding doubling of vibration amplitude.

OSM also became directly involved because of the number of claims of damage and the seriousness of the implications for both its regulations and the coal mining industry should the blasting be responsible for such damage. OSM officials conducted a comprehensive damage inspection program which included about 115 area homes. Following that survey, they initiated a multifaceted research program involving the Bureau of Mines' monitoring (subject of this report), an Indiana Geologic Survey (IGS) core drilling and logging program to characterize local geology, and engineering tests on local soils by both the IGS and the Corps of Engineers. It is anticipated that OSM will assimilate all these efforts and publish an overall program report in the Summer of 1990.

This research was done at the request of OSM Eastern Field Operations and was partly funded by OSM through Interagency Agreement EC68-IA9-13259. The OSM technical project officer was Louis L. McGee.

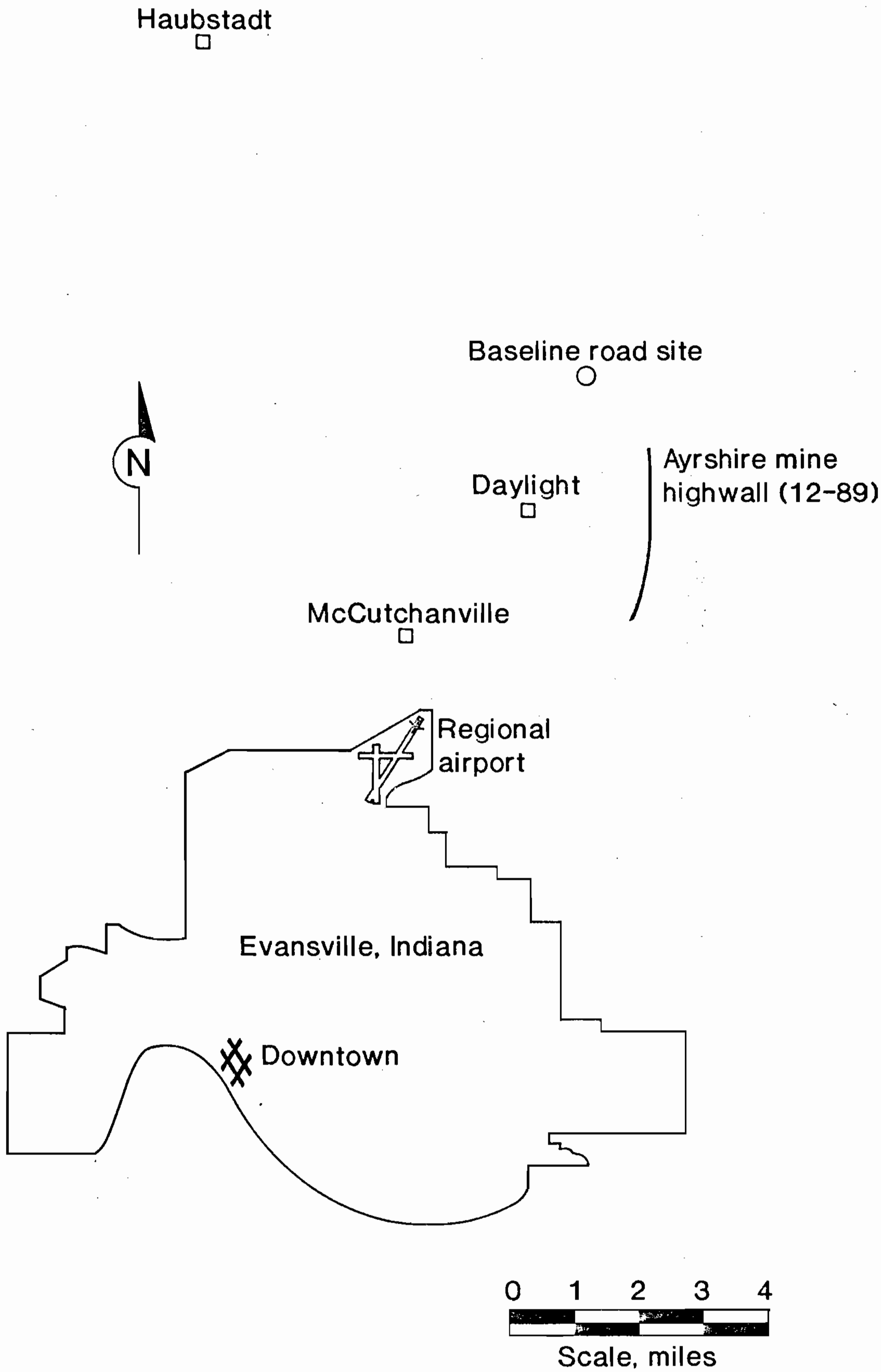


Figure 1. - Mine and monitoring locations west of Ayrshire mine near Evansville, Indiana.

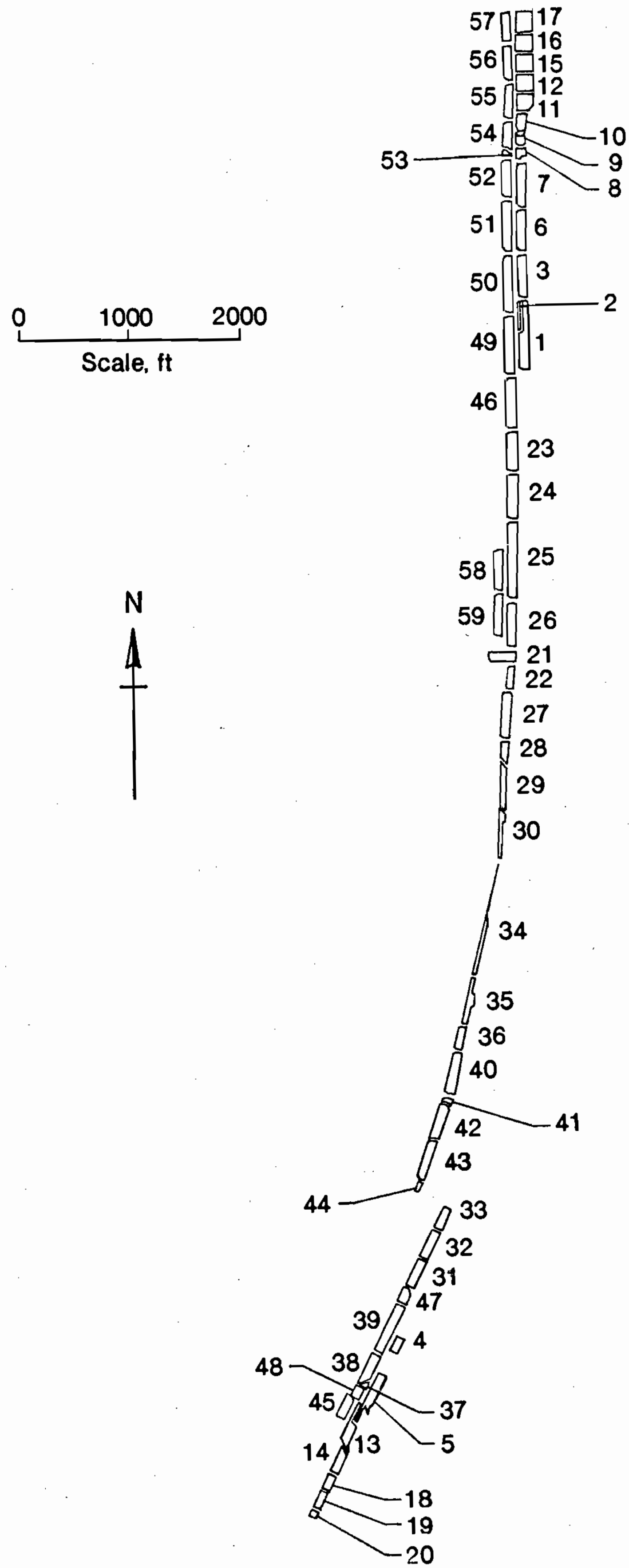


Figure 2. - Ayrshire mine highwall showing blasts during the Bureau of Mines monitoring program, November and December 1989.

BACKGROUND - GROUND VIBRATIONS AND AIRBLAST

Ground vibrations from blasting have been the subject of many studies back to at least 1942. Two Bureau of Mines' reports contain detailed summaries of vibration generation, Bulletin 656 on quarry blasting (2) and the more recent and comprehensive RI 8507 mainly on coal mine blasting (3). 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) of commercial explosives per year and expose large numbers of neighbors to the resulting vibrations (seismic waves). Although these relatively well-confined blasts are intended to fragment and move rock, they do produce some ground vibrations and airblast as wasted energy.

Appendix A describes previous relevant research on blast vibration generation, propagation, impacts on structures and human response. Appendix B similarly covers airblast and its effects.

SITE DESCRIPTIONS

AYRSHIRE MINE

The AMAX Company Ayrshire coal mine is a surface mining operation about 10 miles northeast of downtown Evansville, Indiana (figure 1). Like all such mines in the U.S., Ayrshire blasts break up the overburden rock to allow easy digging and removal. About March, 1988, they adopted cast blasting for the northern areas of their nearly three-mile-long highwall. Shown in figure 2 are production blasts detonated during the Bureau of Mines' monitoring period between November 1, 1989 to January 3, 1990, with a listing of blasts given in Appendix D.

The communities objecting to the blasting vibrations are all behind the highwall in the westward directions. The open pit spoils and reclaimed land are all on the east side. Previous studies at the mine did identify it as a location favoring the generation of low-frequency vibrations toward the west.

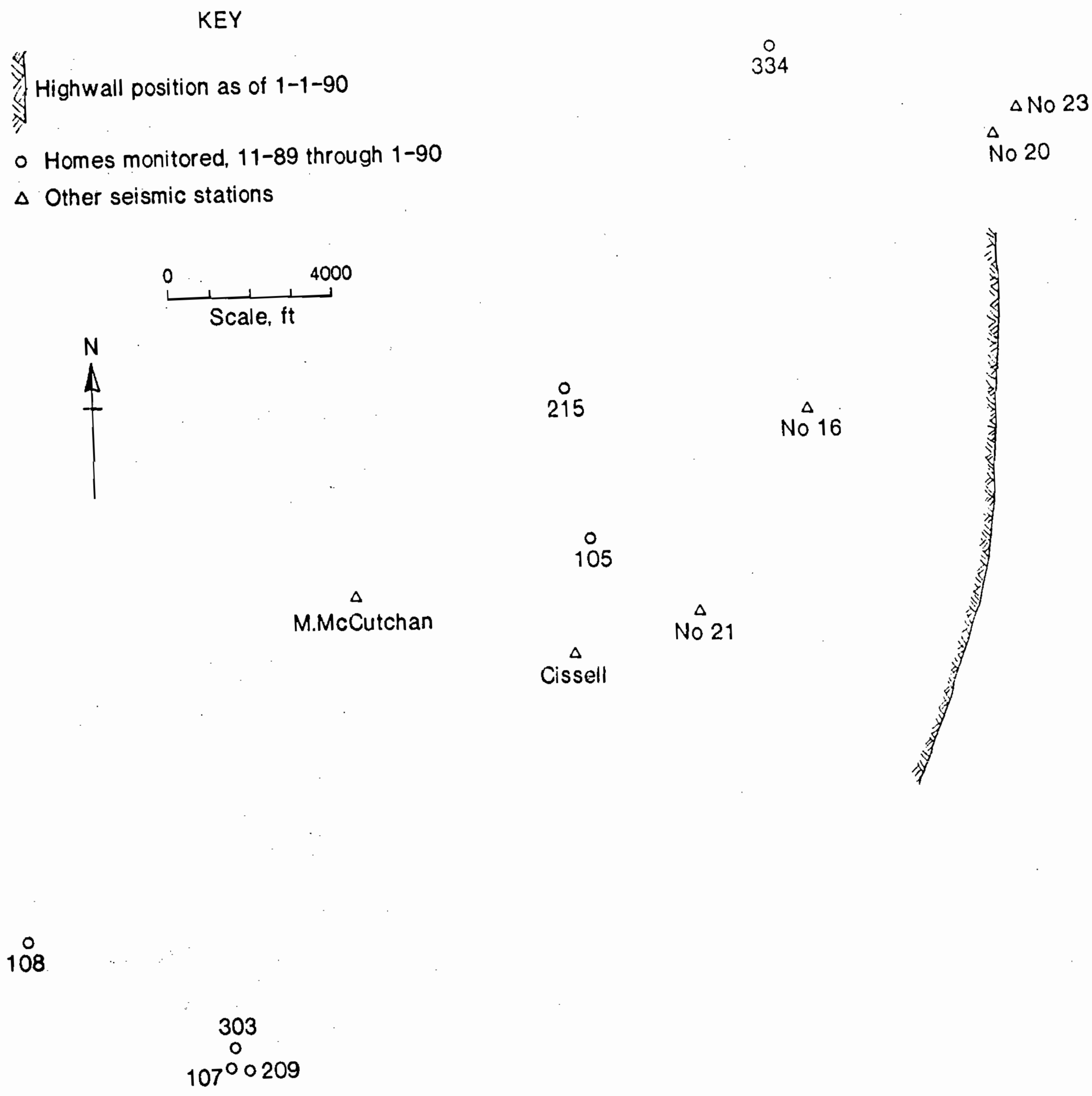


Figure 3. - Monitored homes and additional seismic stations west of the Ayrshire mine highwall.

Several Bureau studies were done at the Ayrshire mine. Some of the monitoring for RI 8507 (3) and 8485 (4) were in homes near this mine. All the field work phases for the blasting fatigue study, RI 8896 (5), and the blast design study, RI 9026 (6), were done there. It was also one of the sites studied in the 1987 survey of Indiana mines done for OSM and published in RI 9226 (7).

TOWN AREAS

General Description

Daylight is the closest community to the west of the Ayrshire mine (see figure 1). This is a flat lying area developed on old glacial lake beds. Homes and a few commercial structures in Daylight range up to 100 years old and are mostly one story. Typical home-to-blast distances are 2 miles.

McCutchanville is a suburb of Evansville, Indiana. It consists of older homes and a few larger new homes. Two and sometimes three stories tall, most of the homes examined are located on slopes. Virtually all of McCutchanville is heavily wooded and hilly with a relief of about 75 ft. The McCutchanville homes range from 3 to 5 miles from the mine. A few of the homes are within 0.30 miles of the end of the most active runway of the Evansville Regional Airport, which has regular commercial jet service.

Scattered homes and farmsteads are also located along county and township roads. Northwest of the mine is an area labeled "Baseline Road Sites." The homes in this area are closest to the pit's northern end which is usually cast blasted and can have tight box cuts (low relief and potentially higher vibrations). The town of Haubstadt is also northwest of the mine. The Haubstadt school (at about 10 miles from the Ayrshire mine), was monitored by AMAX for a short period as a result of complaints from the school staff that the blasting was noticeable and alarming. Figure 3 shows locations of homes monitored and additional seismic stations installed by AMAX.

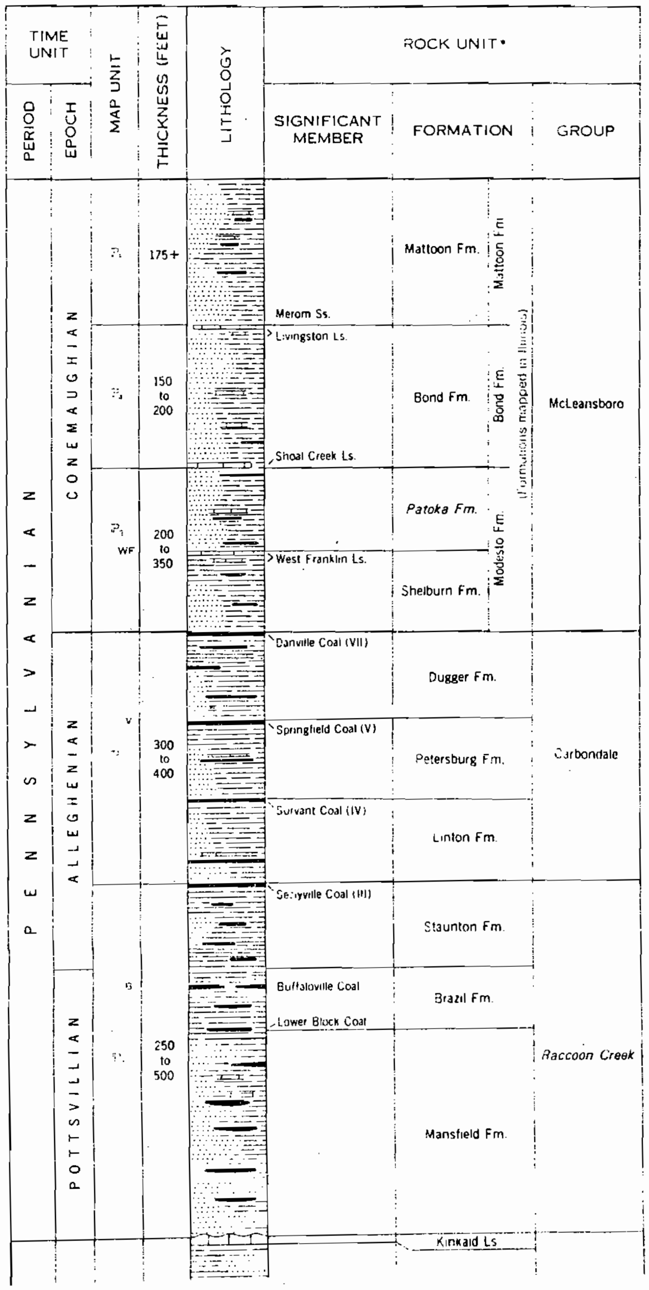


Figure 4. - Columnar section of Pennsylvania bedrock units in Southwestern Indiana (9).

locations of homes monitored and additional seismic stations installed by AMAX.

Geology of the OSM Study Area

The near-surface geology of the OSM study area consists of Pennsylvanian shales and sandstones, with thin beds of limestone, clay and coal of the McLeansboro and Carbondale Groups (figure 4). These units are in general overlain by loess in the bedrock-cored uplands surrounding McCutchanville. Lacustrine clays and silts occupy the flats near the Warrick County line and the Ayrshire Mine to the northeas (figures 5 and 6). Modern soils derived from these materials are fine-grained, composed mainly of silt- and clay-sized particles, and are classified as a silt loam throughout much of the area (8). A generalized cross-section through McCutchanville and the Ayrshire Mine is illustrated in figure 7.

Bleuer, in reference (8) describes three levels of local landscape called the upper, middle, and lower surfaces. The upper surface generally corresponds to the presence of the West Franklin Limestone Member of the Shelburn Formation, which forms narrow ridge tops with steeply sloping sides. The middle surface is related to the underlying shale of the Shelburn Formation, which forms the gently sloping flanks adjacent to the upper surface. The relatively flat lower surface is formed of lacustrine deposits of a deeper basin cut into the shale. This basin is referred to as the "lake plain."

The unconsolidated soil materials in the study area range in thickness from less than 10 feet at some upper and middle surface locations, to greater than 80 feet in the lower surface. The soil profile in the upper surface generally consists of modern soils containing a fragipan overlying loess. The loess may be composed of upper and lower units which in turn grade downward into a sandy loam or shale. The transition to bedrock is commonly abrupt. The

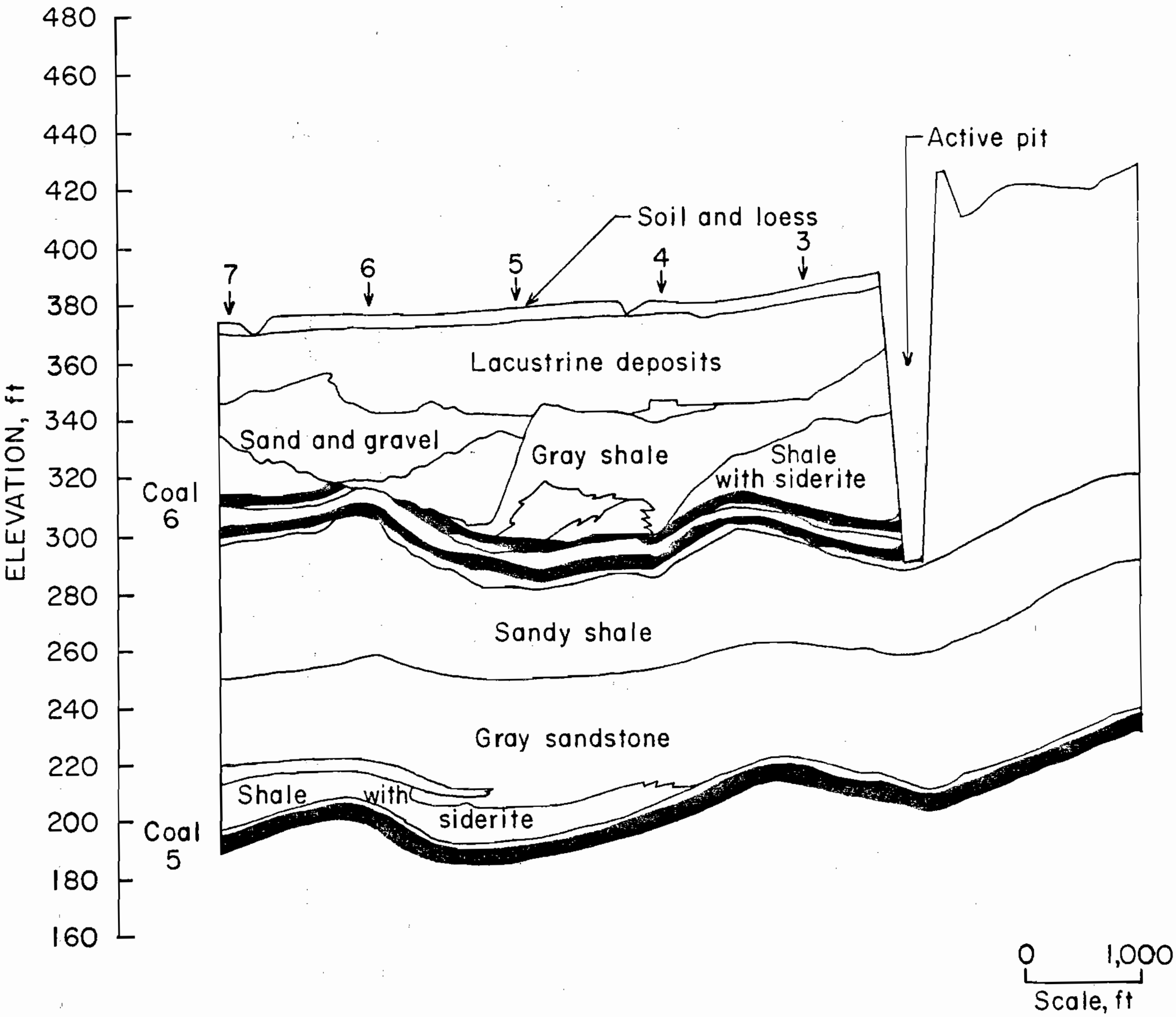


Figure 6. - Generalized sectional view of the Ayrshire mine trending west (left) to east (right) (7).

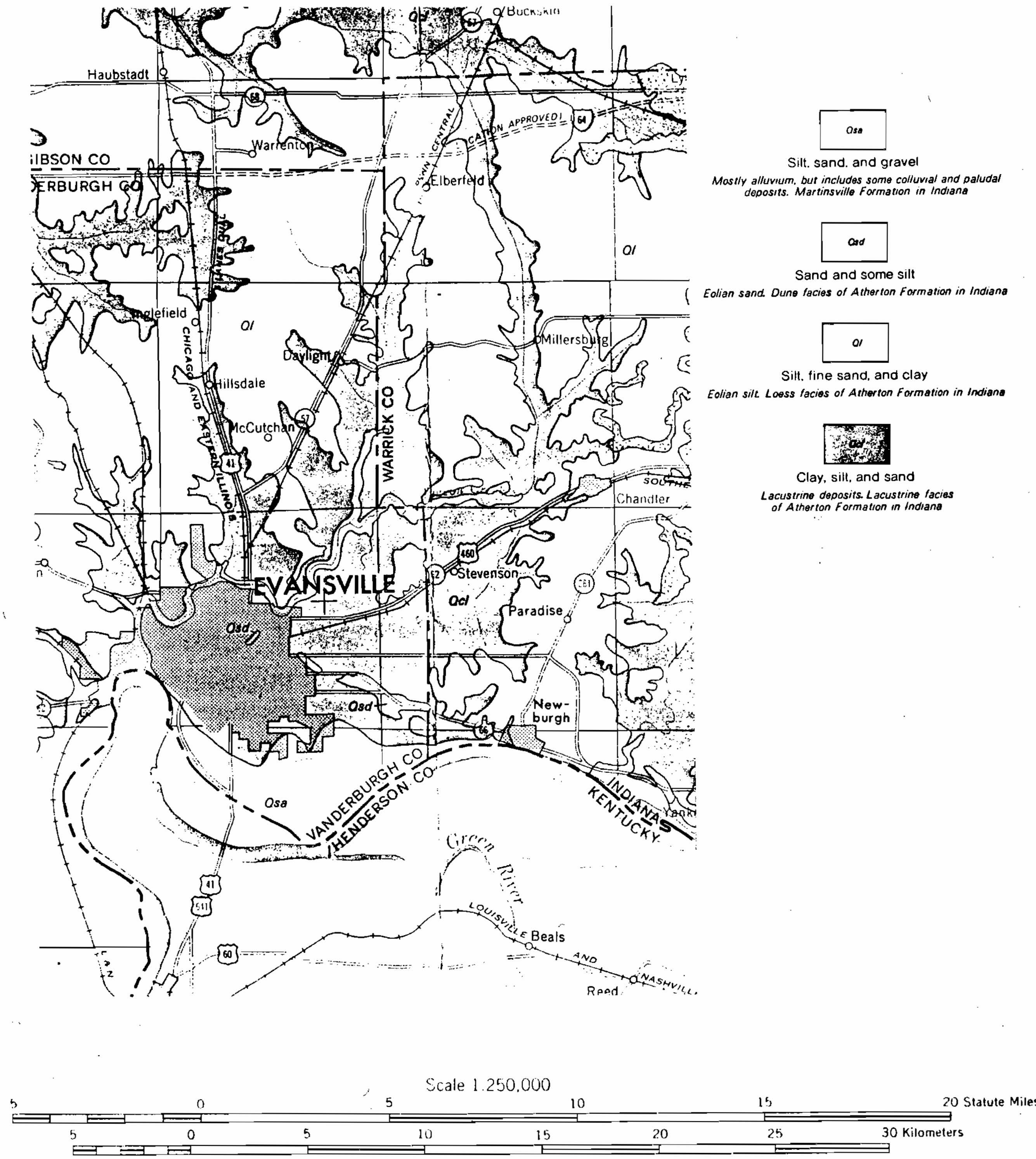


Figure 5. - Generalized map illustrating the surface geology in the Daylight and McCutchanville study area (9).

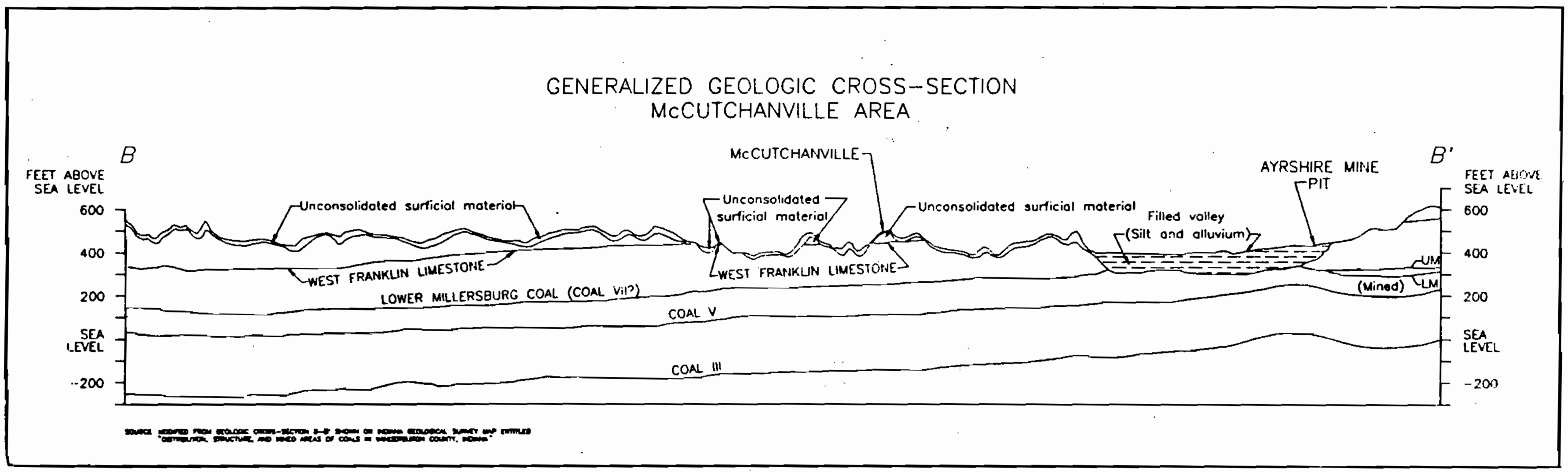


Figure 7. - Generalized sectional view of the McCutchanville area (1).

weathered material just above the contact reflecting the variable composition of the underlying West Franklin bedrock unit. The soil materials in the middle surface exhibit a less loess and a thicker shale transition. This is interpreted to be the result of a thickening wedge of sheetwash sediment forming the slope below the upper surface as a result of weathering and erosion. Finally, the soil profile in the lower surface consists of deep, gleyed modern soils overlying large-scale sedimentation units composed in general of clay and silty clay, silt, sand, and silty clay in turn (8).

As part of the OSM study, the Indiana Geological Survey drilled and sampled the unconsolidated soil materials at a number of locations throughout the study area (8). The soils were described and classified using USDA terminology and grouped for engineering purposes according to the Unified Classification System. Five holes were drilled near structures monitored by the Bureau. Table 1 contains a summary list of sample intervals and associated engineering group names for each location. The USDA system was used to describe the soil at house 334 as the engineering data were unavailable.

Table 1. - Soil Types Encountered at Bureau Test Houses

House 209

Depth (ft)	Soil group
1.0-6.0	Lean clay
6.0-6.9	Silt
6.9-8.7	Lean clay
8.7-10.7	Fat clay

House 105

Depth (ft)	Soil group
0.8-1.3	Lean clay
1.7-2.2	Fat clay
2.5-3.0	Lean clay
4.5-5.0	Silt
7.0-12.0	Lean clay

House 108

Depth (ft)	Soil group
0.8-3.0	Lean clay
3.5-4.0	Lean clay with sand
4.5-5.0	Sandy lean clay
5.3-8.2	Fat clay
9.5-11.5	Lean clay

House 334

Depth (ft)	Soil group
0.0-7.7	Silt loam
7.7-8.5	Silty clay loam
8.5-9.2	Clay
9.2-9.5	Loamy sand

House 215

Depth (ft)	Soil group
0.2-0.6	Lean clay
1.3-1.8	Fat clay
2.8-6.4	Lean clay
5.0-10.0	Loess? (most of sample lost)

SELECTION OF HOUSES FOR STUDY

A review was made of the 115 homes inspected and catalogued by OSM. Of these, 16 were selected as candidates for instrumenting and preliminary level-loop surveying (figure 8). Selection criteria were based on representative samples for both damage condition and location. Regular accessibility was important for both damage inspections and access to instrumentation. In McCutchanville, two homes were located on east-facing slopes (towards the mine) for maximum airblast-induced structure responses. The full two-month inspection and monitoring program was done for 6 homes, 3 of which were in McCutchanville. One additional home had been under constant monitoring by the DNR (#108), and during the study, two additional McCutchanville homes with serious cracking were subjected to walk-through inspections. Table 2 describes nine homes studied. Locations of the homes relative to the highwall were shown previously in figure 3.

Figure 8. - Survey crew performing level-loop with an automatic level.

Table 2. - Descriptions of homes studied by the Bureau of Mines, October 1989 through January 1990.

OSM id. number	Location	Closest distance to mine, miles	Number of stories	Basement walls	Year built	OSM damage description
105	Daylight	1.80	1	Concrete block	1966	Numerous thin cracks in garage, interior and exterior. 1/4-inch drop of cabinets in kitchen. Horizontal crack in basement, 1/4-in on one wall.
107	McCutch-anville	3.47	2	Concrete block	1953	Pervasive thin cracks, especially in the exterior. Wide cracks, separations involve porch frame frame separating from house and a mortar joint crack in the work-shop.
108	McCutch-anville	4.12	1,2	Concrete block	1967	Exterior-wide cracks in south wall and patio. Upper portion of house appears shifted about 1 inch. Numerous nail pops and thin cracks in main floor inter-ior. Extensive wide cracks in basement.
201	McCutch-anville	4.20	2	Concrete block	1980	Numerous cracks and separations in exterior walls, basement, and some interior rooms. Long and wide mortar cracks in basement and exterior. Planking and plastic sheets placed on basement walls to avoid additional movement and moisture.
209	McCutch-anville	3.41	1,2	Concrete block	1950	A few hairline cracks in each of living, dining, and 2 bedrooms. All around frames and corners. A few thin cracks in basement. Includes a long floor crack.
215	Daylight	1.97	1	Concrete block	1962	Sporadic, short and frame-related thin cracks in the interior. A few long wall and floor cracks in the basement and garage.
303	McCutch-anville	3.43	1	Concrete block	1952	Mostly frame and corner thin cracks on basement and garage north wall and floors. A few thin and short exterior wall cracks.

308	McCutch-anville	3.47	1,2	Concrete block	1952	Widespread thin cracks in interior. Not limited to frames (sic) and corners and a few are, considerable in length. Apparently nothing in basement (if there really is one) and garage. Not much on exterior. Lack of major failures contribute to "1." Almost "2" (on an OSM damage scale of 1 to 3).
334	Baseline Road	1.37	1	Concrete block	1965	Average of 1 or 2 thin cracks on east exterior and basement wall.

CITIZEN'S CONCERNS AND COMPLAINTS

Home owners near the mine have been concerned about the Ayrshire mine blasting and there is no question that many homes, particularly in McCutchanville, have extensive cracks. Because blasting produces occasional house rattling, citizens have attributed the cracking to the blasting and are complaining accordingly. The DNR report listed all complaints between September 1, 1988 and May 30, 1989, a period of 296 Ayrshire mine blasts, and noted that 36 pct of complaint times did not match blasting times (1).

Generally, there was no indication from the complaints about the severity of the "event" and also no monitoring near enough to provide a vibration or airblast to compare to the noticed "event." There was a serious lack of airblast recordings. This made it impossible to obtain a complete analysis because of airblast variability with regard to focusing, topography, and different shot-to-shot practices cannot be quantified . Some measurements were made by AMAX in McCutchanville near the areas of most complaints. These were requested by the Bureau but not made available in anticipation of their use by AMAX in a citizen's lawsuit. There are a few cases where noticed or recorded blasts are not from the Ayrshire mine, but rather the much farther Peabody Coal Company Lynville mine at about 9 miles. This very long range propagation is airblast as shown by two events of 121 dB recorded one each at two different McCutchanville sites: September 19, 1989 at 0915 (09:15 am) and October 17, 1989 at 0803.

Some homeowners claim that all damage occurred since cast blasting was begun (March 1988) while at least one admitted that some cracks were older than three years. A neighbor near house #334 stated that the blast of November 16, 1989 at 1108 was the "worst ever." That blast generated a peak vibration of 0.092 in/s and 102 dB at the monitored structure, far below any historical levels of concern for damage.

Bureau personnel examined complaint data from the period preceding its own monitoring because of claims that blasting had previously been more severe. There is a lack of a recognizable pattern to the complaints. For example, blasts labeled "severe" in one location are not noticed elsewhere, without regard to simple criteria such as blast location and simple or scaled distance. Some complaints received were from large distances: Downtown Evansville, Eastland Shopping Mall, and the town of Haubstadt. For at least one of these "events" examined, there was no blast at any of the local mines.

The DNR received a few complaints while the Bureau was monitoring. Table 3 lists those events and the vibrations recorded at the nearest monitored

Table 3. - Complaints filed with the Regulatory Agency, Indiana DNR, during the Bureau's monitoring.

Date	Time	Location of complainer	Nearest monitoring	
			Vibration, in/s	Airblast
11-03-89	1145	Daylight, 3/4 mile north of #215	0.05	97
	1330	"	.06	104
11-04-89	1035	"	.04	None
	1110	"	.06	97
	1159	"	.04	100
	1307	"	.03	99
11-09-89	1008	"	No trigger	No trigger
11-23-89	1110	McCutchanville, 1/4 mile east of #108	No blast	No blast
	1150	"	"	"

structure. The fact that complaints were received during this period conflicts with some homeowner's observations that the blast vibrations were relatively insignificant during the Bureau's study as compared to previous blasts. It underscores the subjectivity of complaint data.

ANALYSIS AND FINDINGS

VIBRATION AND AIRBLAST

Monitoring

The Bureau's monitoring and inspection program is summarized in table 4. Six homes had Bureau-owned self-triggered seismographs, Dallas Instruments ST4's with airblast channels. A seventh home (#108) was being monitored by The Indiana DNR since March 1989 and those data were supplied to the Bureau. An OSM-loaned seismograph was also used at house 209, as a backup. Additionally, one home each in Daylight and McCutchanville was monitored with 7-channel tape systems allowing measurement of structure response while also serving as wide-band back-ups for the seismographs. The self-triggering

Table 4. - Monitoring and inspection of Evansville area homes by the Bureau of Mines, November 1989 - January 1990.

OSM id. number	Location	Settlement, 2 level-loop surveys	Monitoring of vibration and airblast	Regular crack monitoring	Structure response	Visual inspection
105	Daylight	X	X	X	X	X
107	McCutch-	X	X	X	X[1]	X
108	anville	X	X[2]			X
201	McCutch-					X
209	anville	X	X	X	X	X
215	Daylight	X	X	X		X
303	McCutch-	X	X	X		X
308	anville					X
334	Baseline	X	X	X		X
	Road					

[1] A few measurements were made with a back-up seismograph.
[2] Monitoring by Indiana DNR.

seismographs were in continual operation for the monitoring period; however, the two tape systems required operators and were run for a sampling of blasts.

Figures 9 through 12 show the vibration sensors, high-gain integrating signal conditioning amplifiers and 7-channel FM tape recorders in place, plus seismographs and a digital oscilloscope for data retrieval. Ground vibration transducers were either mounted on the inside of the foundation at ground level or buried next to the foundation, depending on outside accessibility. Bureau studies of vibration monitoring procedures found that exact locations were not critical for low levels (8). Airblast microphones were mounted high up on the house walls facing the mine and under the eaves (figure 13). Although not ideal because of possible reflection-enhancement of the airblast, it was done to reduce weather exposure. A more ideal but impractical placement would be high up in an open field.

Structure responses were measured at two of the homes by mounting pairs of horizontal transducers high-up in the structural corners facing the mine. At one house, #209 in McCutchanville, midwall response measurements was also made. Time correlation of recordings allowed determination of the relative impacts of vibration and airblast.

Most of the project emphasis was on measuring blast-produced vibrations and airblasts and analyzing their impacts. However, the scope of the project also called for comparisons between blasting and other sources. It was immediately evident, upon working in some of the homes, that aircraft operations at the nearby Evansville airport cause structural rattling that could be both felt and heard. In addition, the houses are often rattled by normal human activities such as walking, jumping, and door closing. Recordings were made of such activities primarily effecting superstructure vibrations. In general, seismographs with buried or foundation-mounted transducers will not be triggered by such activity. All vibrations collected

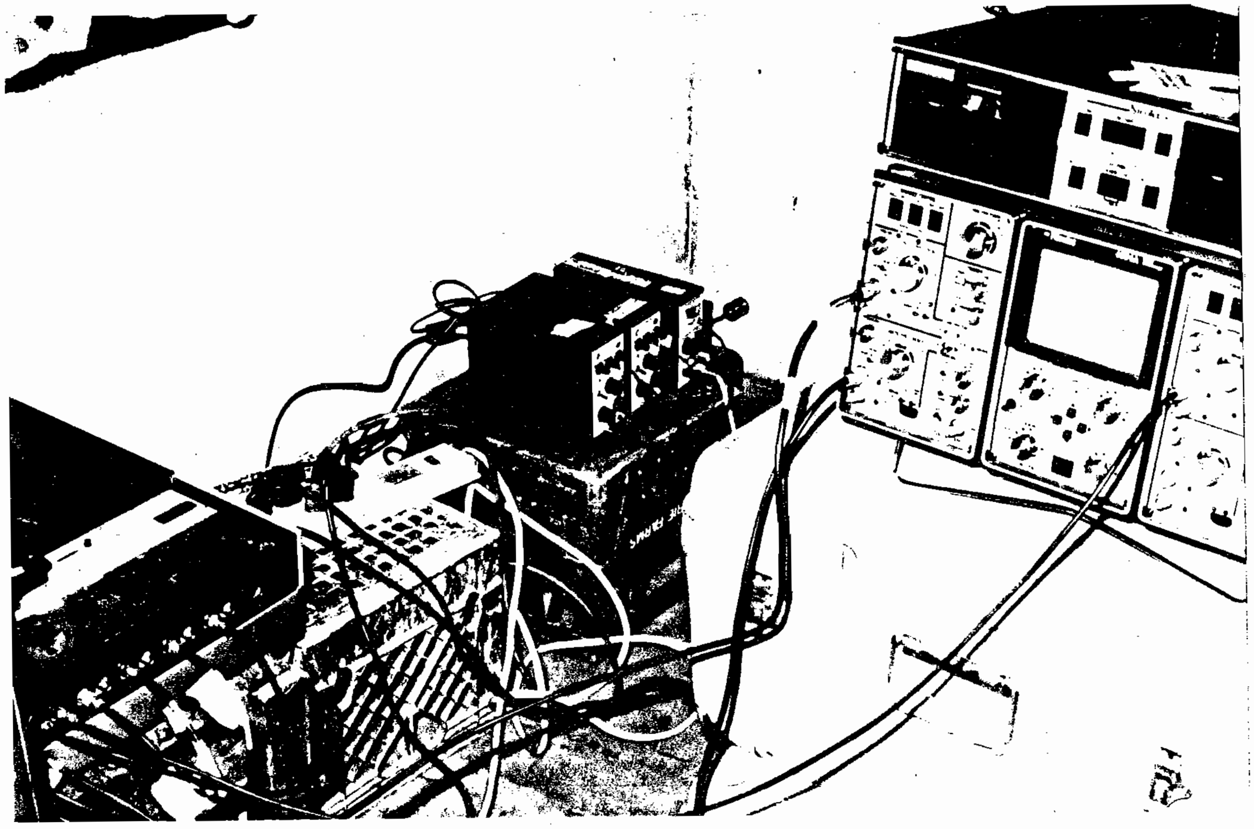


Figure 9. - Vibration monitoring system in house 209 including digital oscilloscope for data retrieval (R) and seven-channel FM recorder (L).

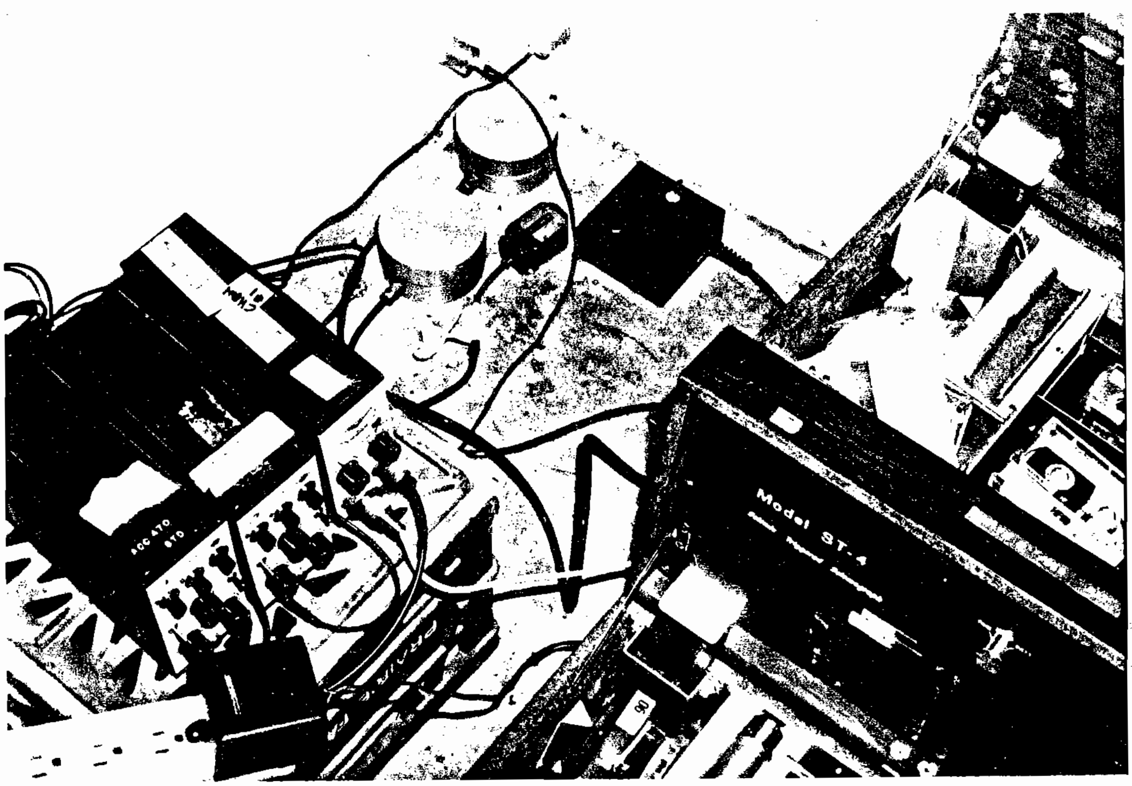


Figure 10. - Vibration transducers in basement corner of 209 ground level. The larger cylindrical and square seismograph transducer contain three geophones each.

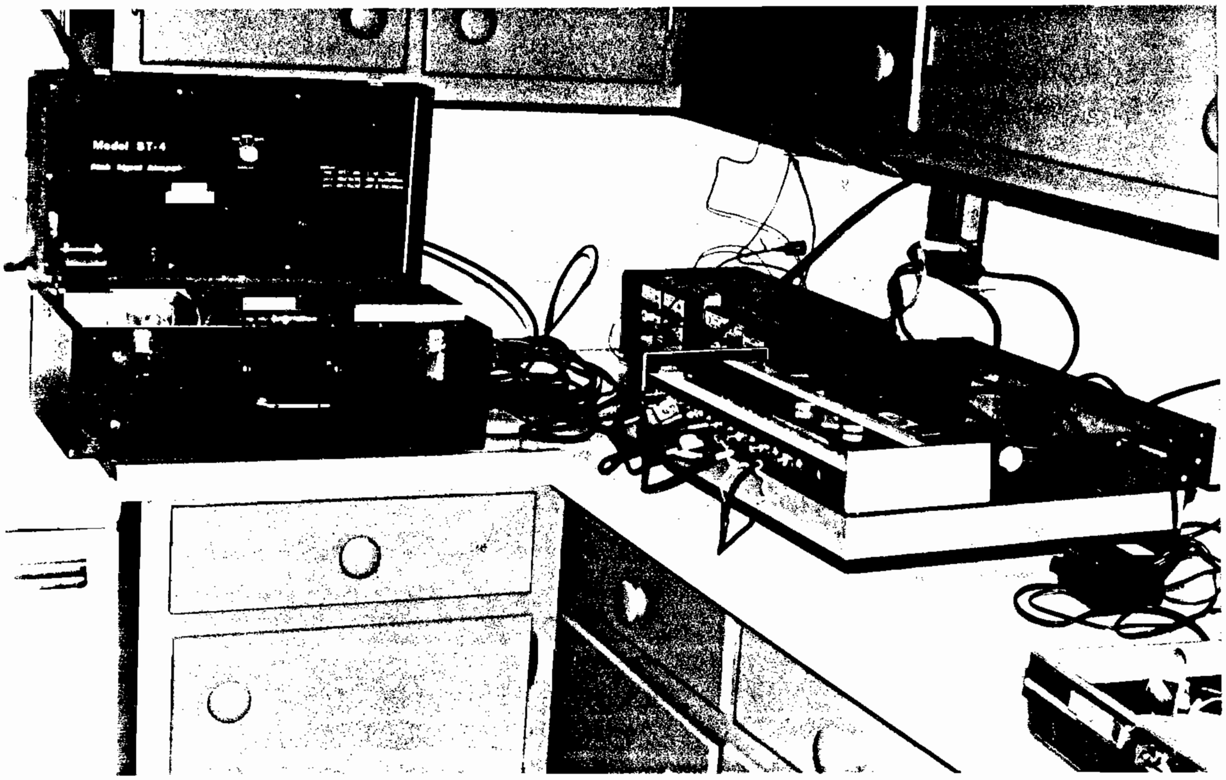


Figure 11. - Seismograph and recorder in house 105.

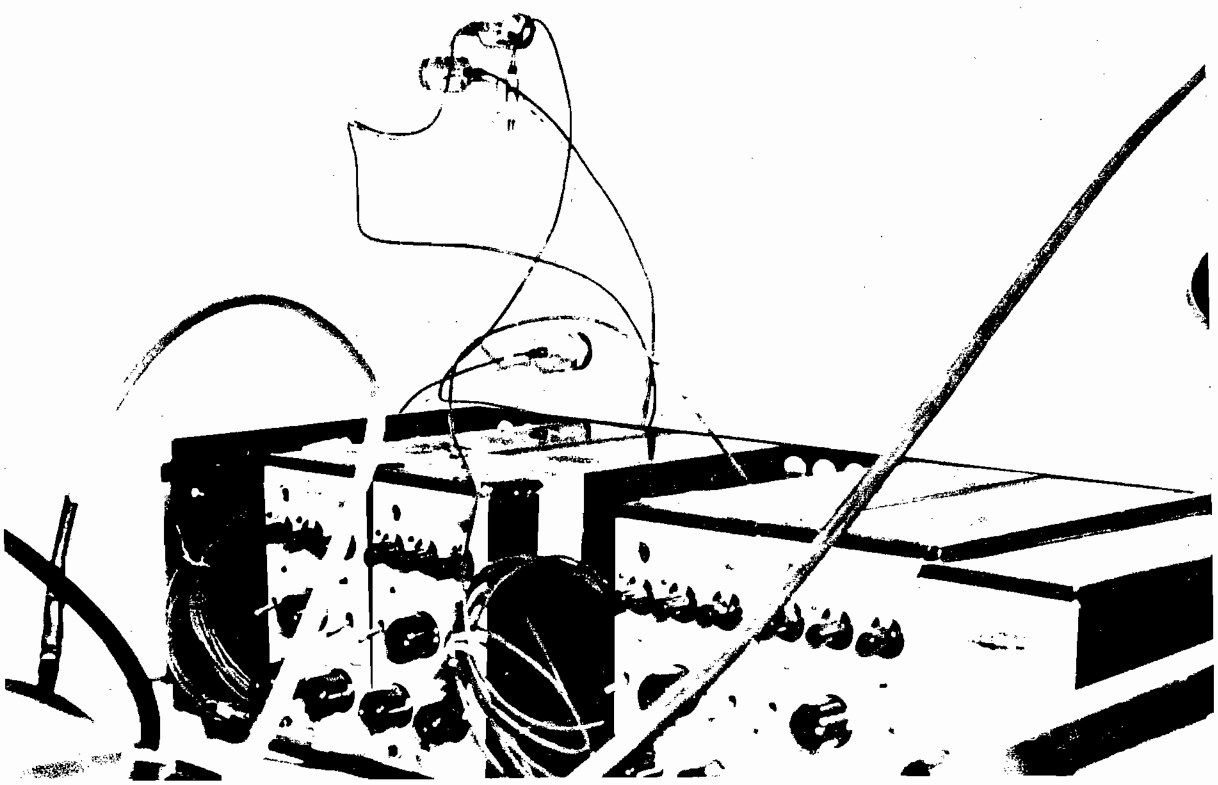


Figure 12. - Close up of accelerometers and integrating amplifiers giving wide-band velocity measurements in house 105.

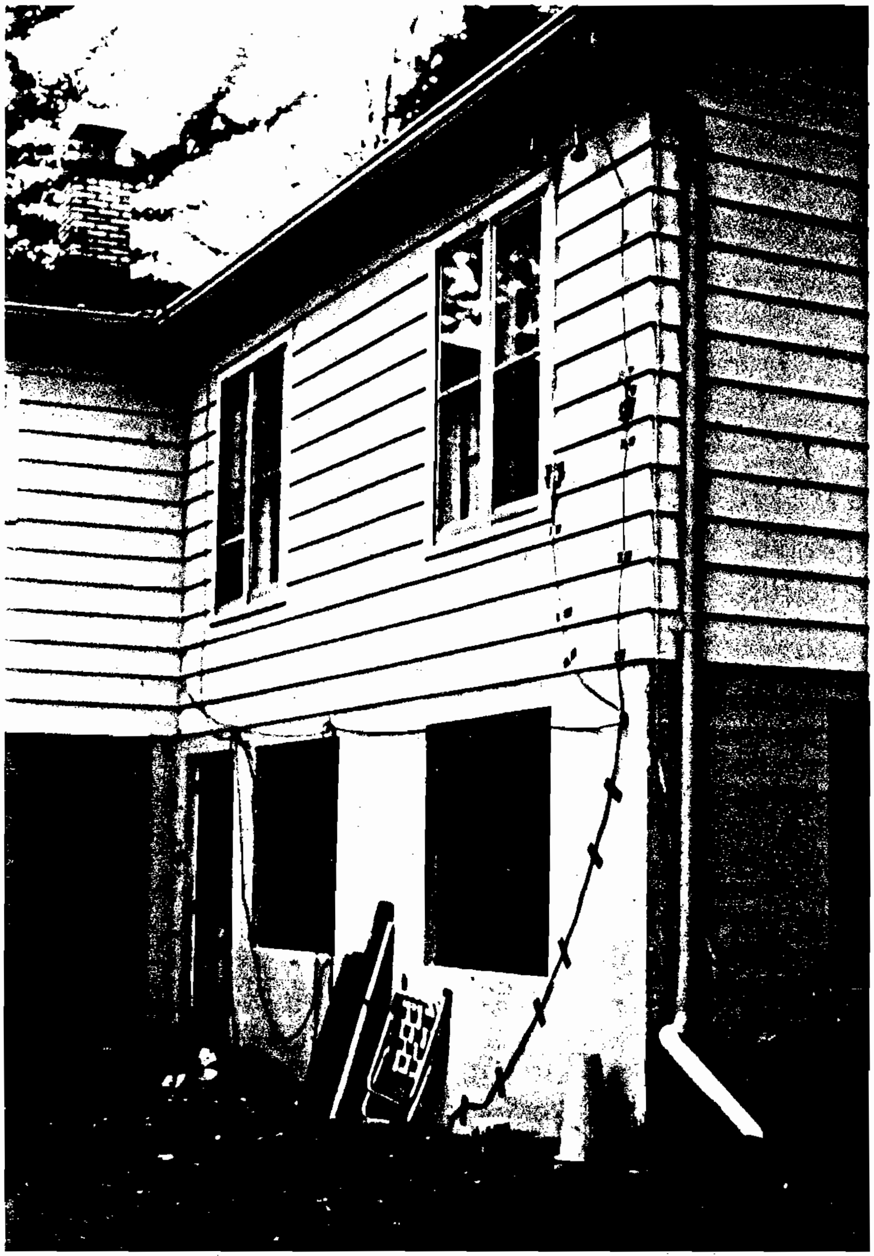


Figure 13. - Rear view of house 209 showing height and microphone placement.

by the Bureau are in Appendix C and the list of blasts for this period is in Appendix D.

Historical Blasting Data

In addition to the collection of new vibration data, Bureau researchers obtained many peak values and a few records for historical blasts, defined here as any prior to November 1, 1989. Home owners were claiming that certain dates or periods of time were bad, and researchers sought as much information on these events as was available. The DNR report contained a great amount of information up to the Spring of 1989 (1). The DNR also provided additional records from their continual monitoring at house 108. AMAX was asked for much information; however, most of their monitoring was at compliance seismographs closer to the blasts than the homes of the complainers. With one exception, already mentioned, AMAX complied with requests for information.

The historical data were divided into three sets, corresponding to the three distinct directions from the mine: S.W. toward McCutchanville, W. toward Daylight and N.W. towards Baseline Road and Haubstadt. Depending on the blast location, a particular monitoring station would belong to one case or another at different times. For example, the station at Cissell's is in an western direction for blasts along the southern half of the highwall, but S.W. for far-north blasts or approximately in line with McCutchanville. The general idea was to prepare three propagation plots corresponding to the three distinct directions, with measurement locations approximating linear arrays. Appendices 13-15 list all the historical data values.

Ground Vibrations

Waveform Analysis

A time-correlated set of the vibrations recorded at house 105 is given in figure 14 and a set for house 209 is presented in figure 15. Both sets of time-histories are from blast #25, a cast-blast design detonated on November

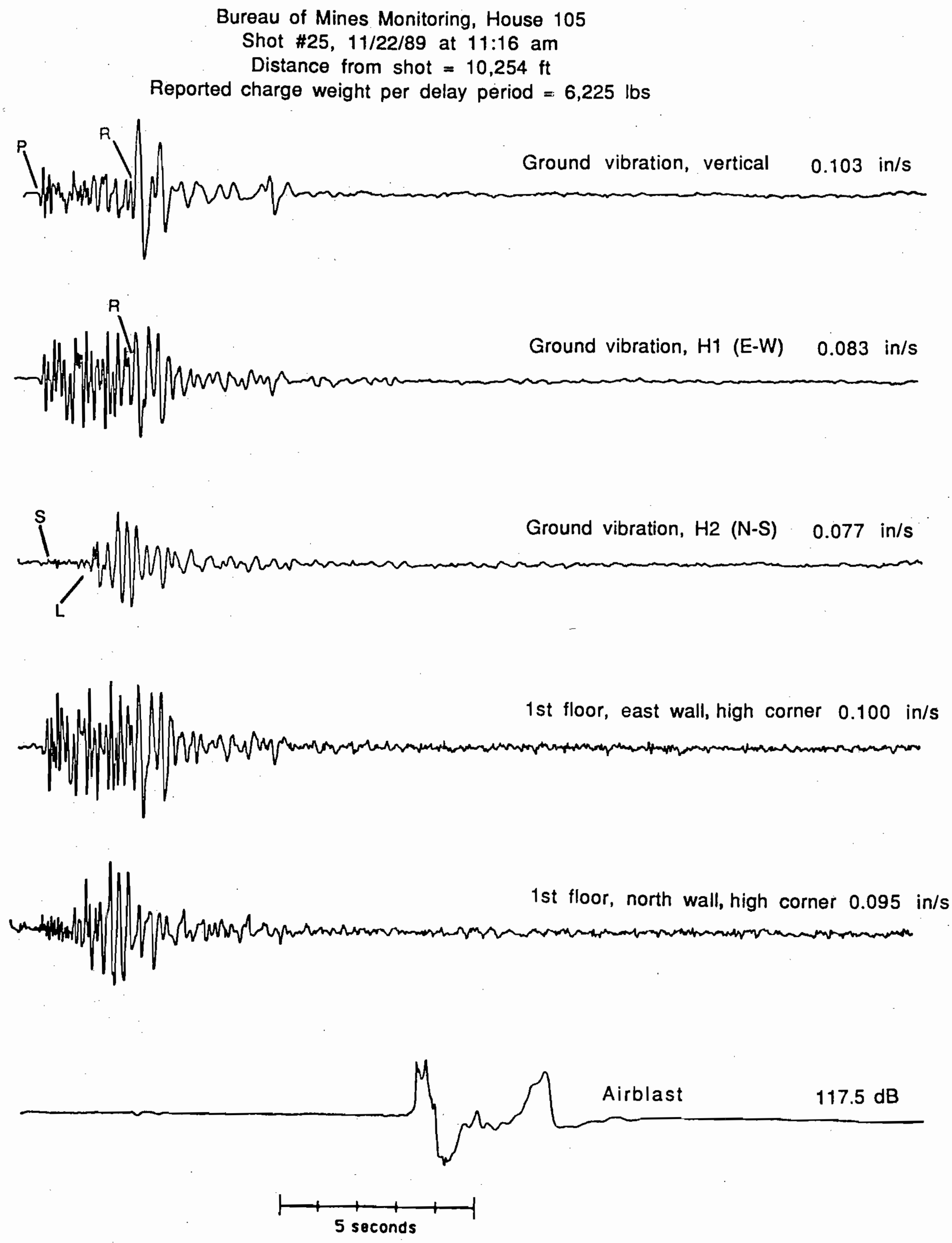


Figure 14. - Ground vibrations, structure response and airblast overpressure time-histories at house 105 for shot #25. For the ground motion time-histories, "P" = P-wave arrival, "S" = S-wave arrival, "R" = Rayleigh wave arrival and "L" = Love wave arrival.

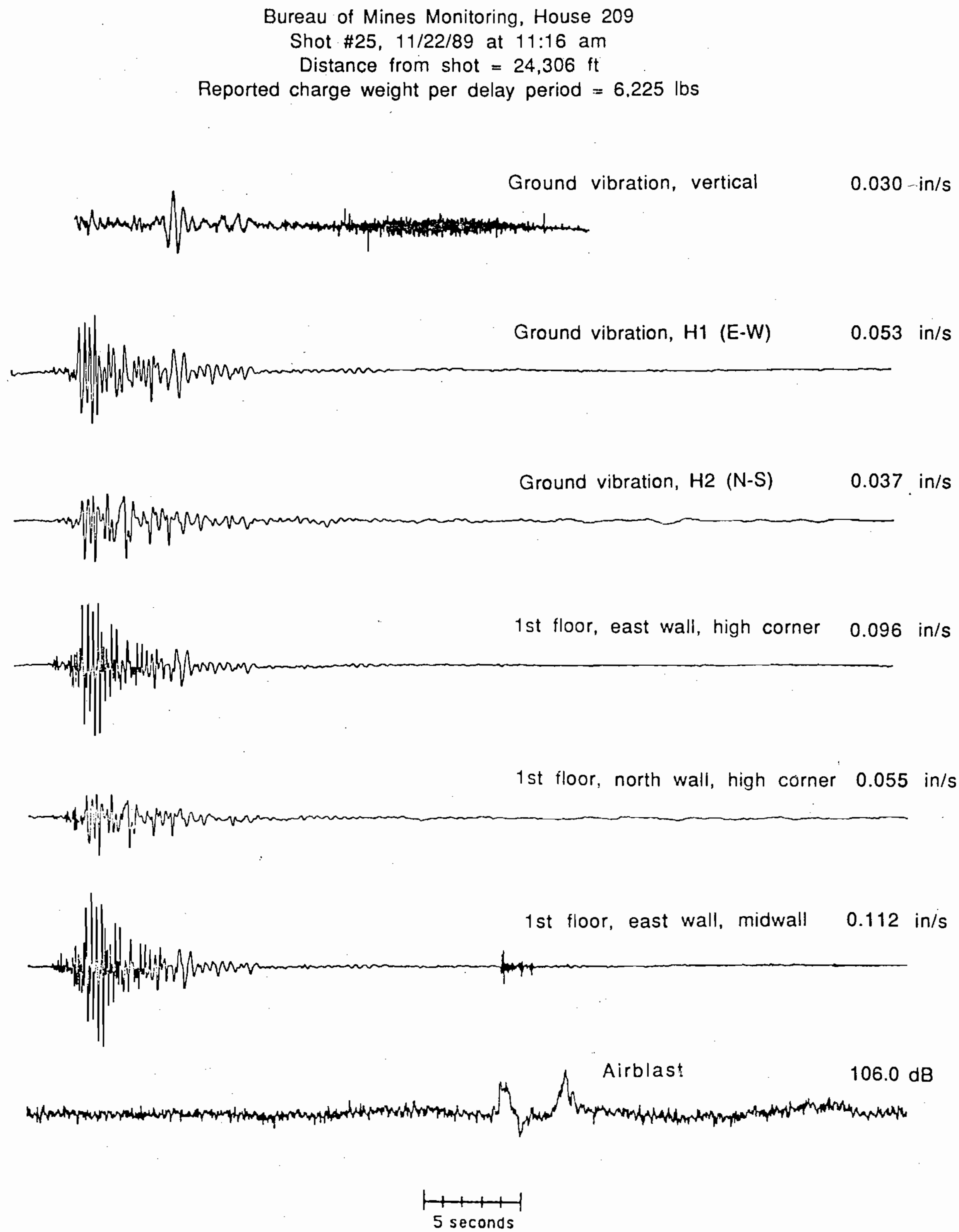


Figure 15. - Ground vibrations, structure response and airblast overpressure time-histories at house 209 for shot #25.

22, 1989 at 1116. House 105 was 10,254 ft (1.9 miles) from the blast and house 209 was at a distance of 24,306 ft (4.6 miles). This blast produced one of the largest ground vibrations recorded during the Bureau's monitoring period and is representative of a "worst case" vibration with respect to this study. These waveforms presented in figures 14 and 15 were recorded on the 7-channel FM recording systems described earlier in the text. Values listed to the right of the waveforms are peak amplitudes. The first floor vibrations are discussed in the structural vibrations' section later in this report.

Seismic waves from blasting contain several different types of waves, in particular P-, S-, Rayleigh and Love waves. P- and S-waves are commonly called body waves because they penetrate deepest into the earth. Rayleigh and Love waves propagate mostly in the relatively near-surface rock strata and are hence often referred to as surface waves. The wave types have theoretically distinct directional characteristics and can sometimes be identified by comparing and contrasting the time histories recorded on the three individual components of ground motion.

Shot #25 was located about 17 degrees to north from the east-orientated H1 ground-motion transducer at house 105. Considering the large distance involved between the shot and house, the record presented in figure 14 should give a good representation of the true directional characteristics of the ground vibration. Therefore, for house 105 the H1 component approximates the longitudinal, or radial, direction and the H2 component the transverse.

The first arrival on the vertical and H1 (longitudinal) components signals the wave arrival. The peak amplitude phase (i.e. wave part that contains the peak amplitude) from shot #25, arriving about 2.1 seconds after the first P-wave arrival, is dominant on the vertical component and can also be identified on the H1 (longitudinal) component of motion. These directional characteristics, low frequency content and relative arrival time suggest that the peak amplitude wavelet is part of a Rayleigh wave. Rayleigh waves are created by the sharp acoustic impedance found at the interface between the surface of the earth and the atmosphere. They travel at speeds of about nine-tenths of the shear wave velocity of the substratum for longer wavelengths, and at speeds of the uppermost geologic layers for shorter wavelengths (11). The actual wavelengths of the shot #25 vibrations were not measured as part of this project and are difficult to estimate because of the complex seismic velocity structure of the area which has not been sufficiently characterized. Vertical profiling of the seismic energy, a project outside the realm of this report, would aid in the further understanding of surface wave phenomena.

The small amplitude S-wave arrival on the H2 component is indicated in figure 31. The subsequent lower frequency, higher amplitude wave-packet may be identified as the Love wave. Love waves are usually dominant in the transverse direction and arise from seismic energy that is trapped in a layer bounded by two interfaces of high acoustic impedance such as a low velocity surface layer over much higher velocity strata. This type geologic of condition exists in the McCutchanville/Daylight area and is generally typical of the southwestern Indiana coal region. Love waves travel at the shear wave speed of the lower medium for large wavelengths. Based on the differences in arrival time it appears that Love waves travel faster than Rayleigh waves in the strata between the mine and Daylight.

For house 209, shot #25 was positioned about 39 degrees to the north of the east-orientated H1 (longitudinal) ground-motion sensor. This rotation may be too great to allow for proper waveform identification since ground motion will not be distinct in the longitudinal and transverse directions relative to the blast. For example, the distinct separation of P- and S-wave arrivals inferred from the differences in the H1 and H2 records, respectively, at house 105 is not evident in the recording from house 209.

As the distance from the blast becomes greater, the differences in wave speeds and seismic travel-paths cause the duration of the ground vibration to increase. Wave amplitudes (particle velocities decrease with increasing distance since seismic energy is continually absorbed by the earth. The frequency content is generally shifted to the lower end of the spectrum as high frequencies are more readily attenuated than low frequencies although particular site characteristics will also influence the waveforms. If frequencies are near the characteristic resonant frequency of the ground they can endure over relatively long distances and the associated seismic energy may be absorbed at a slower-than-expected rate.

The ground vibrations at house 209 (figure 15), located in McCutchanville at a distance of 4.6 miles from the blast, last perhaps twice as long, or more, than those observed at house 105 in Daylight, about 2 miles from the blast. Peak amplitudes are about half at house 209 compared to house 105, but dominant ground motion is now located on the horizontal components (H1 and H2) and not associated with the Rayleigh-wave phase as before. The peak vertical ground motion at house 209, which is mimicked in the H1 component, is probably Rayleigh-wave vibration. Also, the character of the early portion of the H1 component at house 209 is very similar to the Love-wave phase identified on the H2 component at house 105. Perhaps the Love wave travels more efficiently than the Rayleigh wave and its motion is being recorded more on the H1 than the H2 component because of the large orientation angle of 39 degrees between the H1 direction and the shot. Additional studies, designed to specifically to look at surface wave generation and propagation are needed in order to better understand these observations from a seismological standpoint.

Because of their low frequency energy and efficient propagation, surface waves have the greatest potential for structural damage at distances greater than a few hundred feet from the blast. Much of the damage from the 1985

Mexico City and 1989 San Francisco earthquakes were attributed to surface-wave vibrations in lower velocity near-surface strata. Further research regarding the characteristics of surface waves generated from mine blasting would help to better understand and perhaps effectively control blast vibrations. But, for the amplitudes shown here, these ground vibrations will create little more than a possible temporary annoyance to those inside the house.

Vibration Amplitudes

Peak ground vibration and airblast overpressure amplitudes were obtained by the Indiana DNR and Ayrshire Mine during the 9-month period from October 1988 to June 1989. These were used in conjunction with recently collected Bureau of Mines data (November 1989 to January 1990) to construct propagation plots in three directions for the McCutchanville/Daylight area: a McCutchanville direction, trending southwest away from the mine; a Daylight direction, trending west from the mine; and a Base Line Road direction, trending northwest from the mine. This gives a "historical" perspective of the vibrations during this period and a comparison to "current" measurements, as well as some inferences to the seismic propagation characteristics of the area.

Historical Data--Propagation Plots of Vibration Amplitudes

Figures 16 through 18 show the relation between square-root scaled distance and peak ground vibration particle velocity. This scaled distance is used so that the data presented can be easily compared to previously published Bureau of Mines research. The position of the recording stations are fixed so changes in the scaled distance arise from differing shot locations along the highwall and changes in the charge weight per delay used in the blast design. A peak value represents the highest amplitude particle velocity for all three components so that only one peak value is used from a station for a particular blast. Peak amplitudes were usually, but not always, horizontal components.

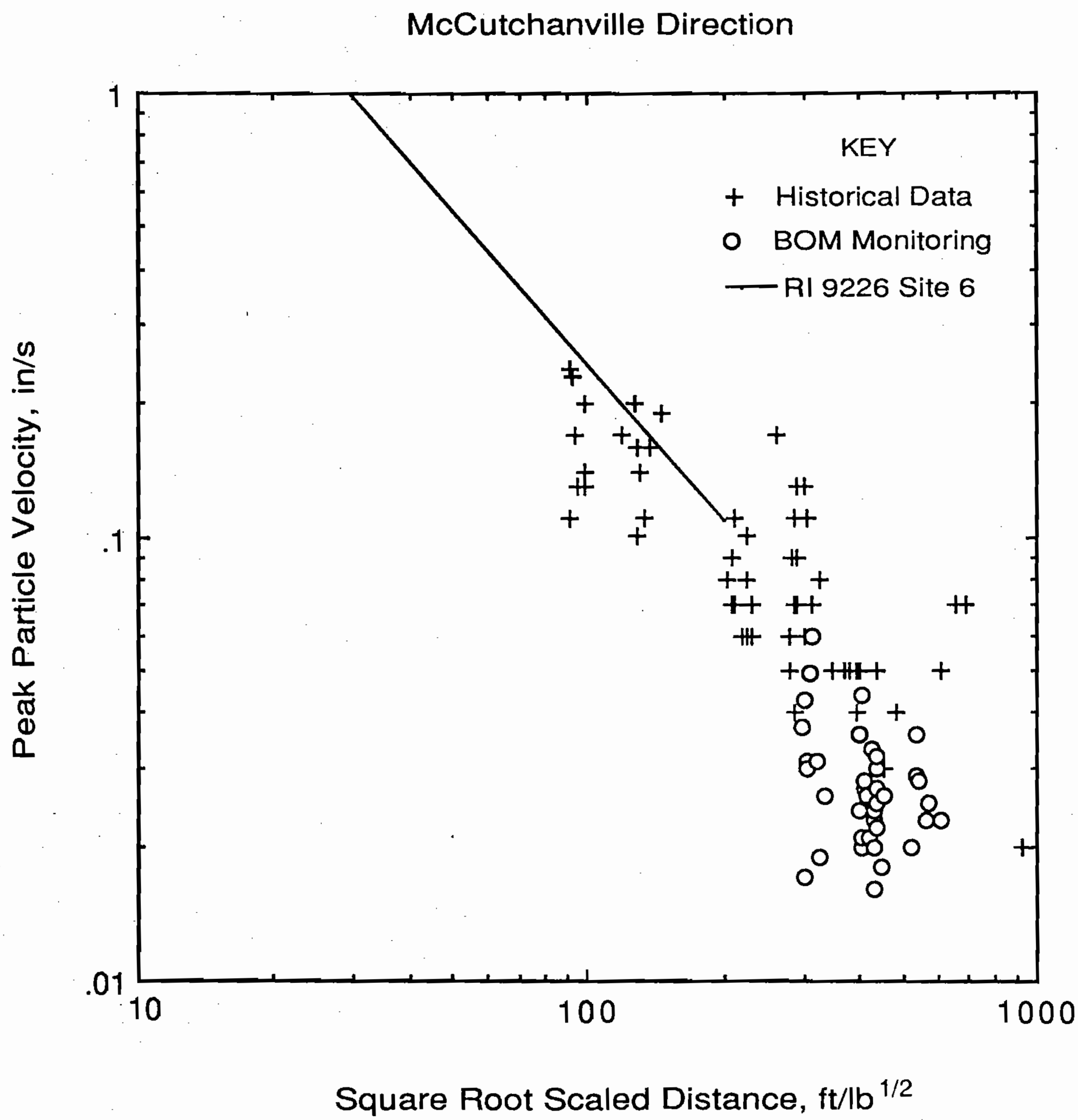


Figure 16. - Historical and recent Bureau of Mines (BOM) peak particle velocity data in the McCutchanville (southwest) direction.

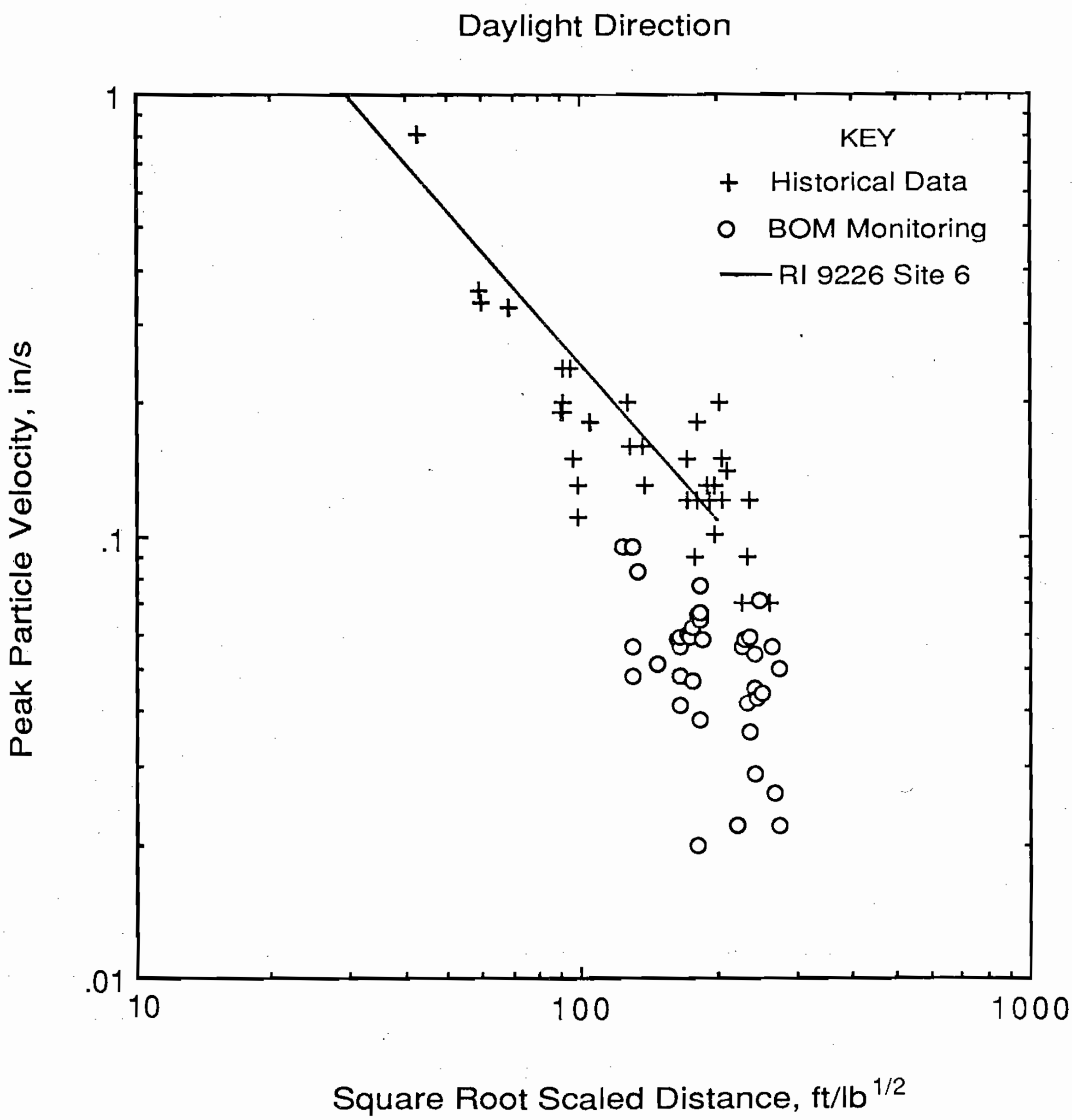


Figure 17. - Historical and recent Bureau of Mines (BOM) peak particle velocity data in the Daylight (west) direction.

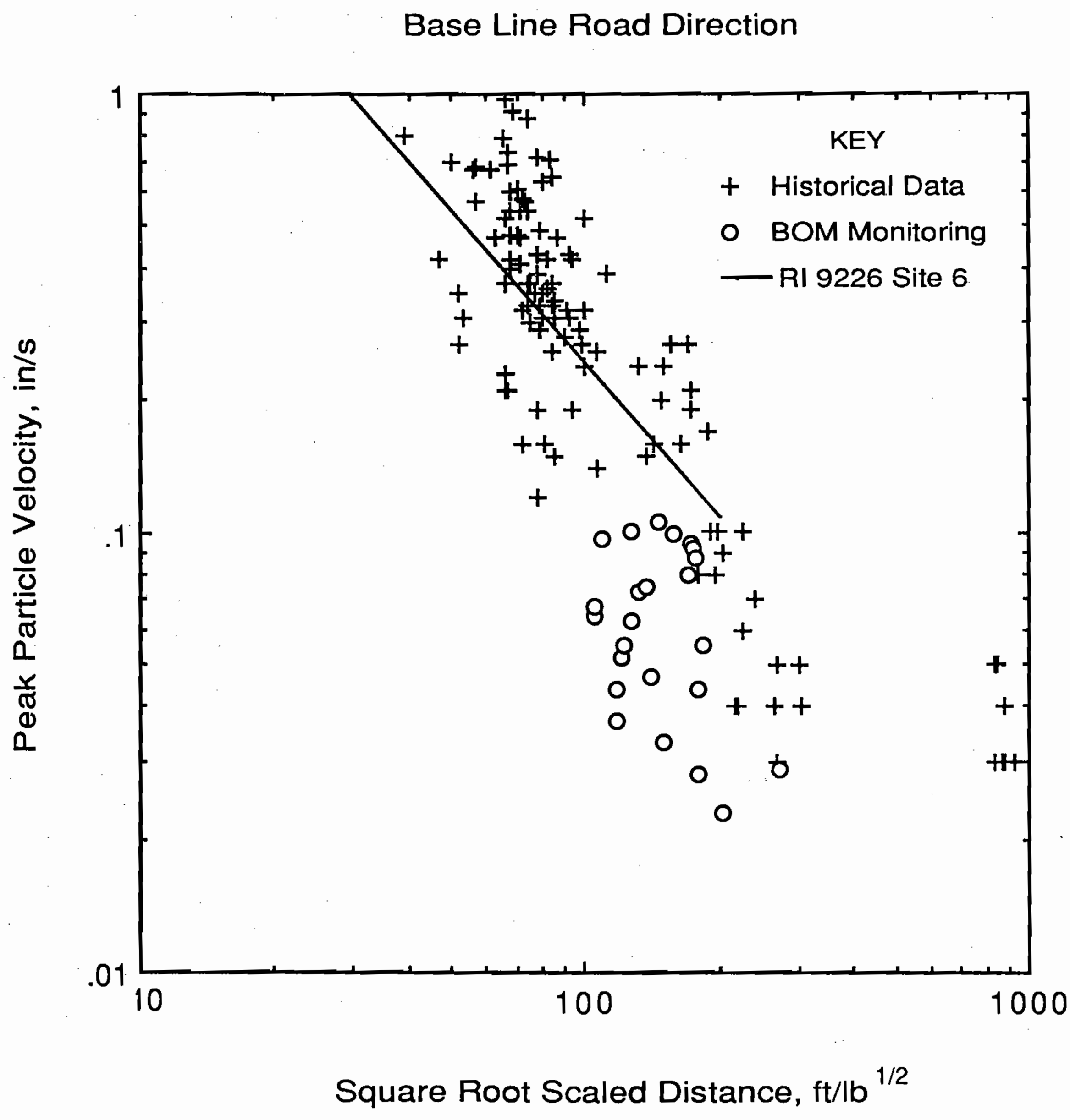


Figure 18. - Historical and recent Bureau of Mines (BOM) peak particle velocity data in the Base Line Road (northwest) direction.

The three directions are defined by recording stations locations and are listed along with all vibration values in appendix E. The relation between the historical stations and directions was devised to create an ad hoc array of recording stations to show how amplitude levels varied with distance in the direction of Bureau of Mines monitoring. For the historical data, the peak levels were chosen from shots that were somewhat "in-line" with the array.

Peak vibration levels from houses monitored by the Bureau were superimposed on the historical data. The orientation of the ground-vibration sensors were aligned so that the H1 direction was eastward, in the direction of the mine and were not realigned to adjust for shot relocation along the north-south trending highwall. Because of the large distances between the shot and recording stations, imprecise directional alignment of the transducers did not greatly effect peak-level measurements. Data for house 108, collected during the time of the Bureau's monitoring, was supplied by the DNR.

The propagation line from RI 9226 in figures 16-18 is the least squares regression fit to peak-production-blast amplitudes recorded from an earlier study at the Ayrshire Mine (7). Data was collected for this earlier study from an east-west array of seismic stations that extended from close-in to the blast to about 6000 ft west of the highwall in the Daylight direction. The line is included as reference and extrapolation to larger scaled distances may not be appropriate.

Figures 16 and 17, representing the McCutchanville and Daylight directions, respectively, show very good correlation between the RI 9226 line and the historical data. Peak particle velocities in the McCutchanville direction are between 0.25 in/s at a scaled distance of 80 ft/lb$^{1/2}$ and 0.02 in/s at 900 ft/lb^{2}. In the Daylight direction, historical peak levels range from 0.8 in/s at a scaled distance of near 20 ft/lb$^{1/2}$ to 0.06 in/s at about

250 ft/lb$^{1/2}$. Because of the narrow range of scaled distances involved, the data are quite clustered, but where scaled distances overlap, the peak levels are similar. The Bureau of Mines-monitored data show consistently lower particle velocities as compared to the historical data at similar scaled distances in both directions.

The propagation plot for the Base Line Road direction, figure 18, indicates particle velocities that are somewhat higher than expected for the historical data as compared to the other two directions. Peak levels were observed from about 1 in/s at a scaled distance of approximately 65 ft/lb$^{1/2}$ to 0.03 in/s at a scaled distance of about 1000 ft/lb$^{1/2}$. The series of crosses to the far right of the graph represent the Haubstadt School, about 10 miles away from the blasts. Peak particle velocities of 0.02 to .05 in/s recorded at this site are unusually high for such a large distance. Ground resonance near the characteristic frequency of the earth in this area may explain this unexpected occurrence.

The plot of the historical data in the Base Line Road direction suggests a different type of seismic propagation, relative to the Daylight and McCutchanville area, because of the higher peak levels observed at common scaled distances and because of the vibrations recorded at the Haubstadt School. The Base Line Road and McCutchanville plots have many of the same blasts in common or have a basically similar design, so differences in blast design do not appear responsible for the amplitude differences. In-depth blast design analysis was not part of the project so this conclusion is speculative. Again, the Bureau's recent measurements in the Base Line Road direction (house 334 only) are comparatively lower than the historical peaks, but contrary to the historical observations, are very similar to the peak values obtained in the McCutchanville area. Researchers do not believe that lower vibration amplitudes were measured at house 334 because of a shadowing effect on the NE corner transducer location.

For all three directions, the peak particle velocities from the recent Bureau of Mines monitoring project appear to be consistently lower than the historical data for the same scaled distance. Even though peak ground vibration levels have been consistently reasonable and low near the Ayrshire Mine, it appears that they were somewhat lower during the Bureau's monitoring program than the previous monitoring period.

Bureau of Mines Data--Propagation Plots of Vibration Amplitudes

Figures 19 and 20 plot the specific results from all of the shots recorded by the Bureau from November 1989 to January 1990, with each house identified by a separate symbol. House 334, previously included in the Base Line Road direction (figure 18) is now grouped with the other Daylight data in figure 20. Data recorded by the tape systems were used where available, otherwise peak levels were obtained from the less accurate ST 4 seismograph recordings. The regression line for RI 9226 site 6 (Ayrshire Mine) is again included for reference.

The maximum peak ground vibration level recorded in the Daylight area was about 0.1 in/s and in the McCutchanville area 0.06 in/s. The McCutchanville data (figure 19) are clustered between a scaled distance of about 300 to 650 ft/lb$^{1/2}$ and the Daylight (figure 20) data from near 90 to 300 ft/lb$^{1/2}$. The peak values overlap at the common scaled distance of 300 ft/lb$^{1/2}$ and are near or lower than the reference given by the RI 9226 study. Relative position of the blast in conjunction with the particular differences in site characteristics - surface geology, physical characteristics of the house, etc. can most likely account for the slight differences in peak particle velocity within an area. Generally there was nothing unusual about the peak vibration levels.

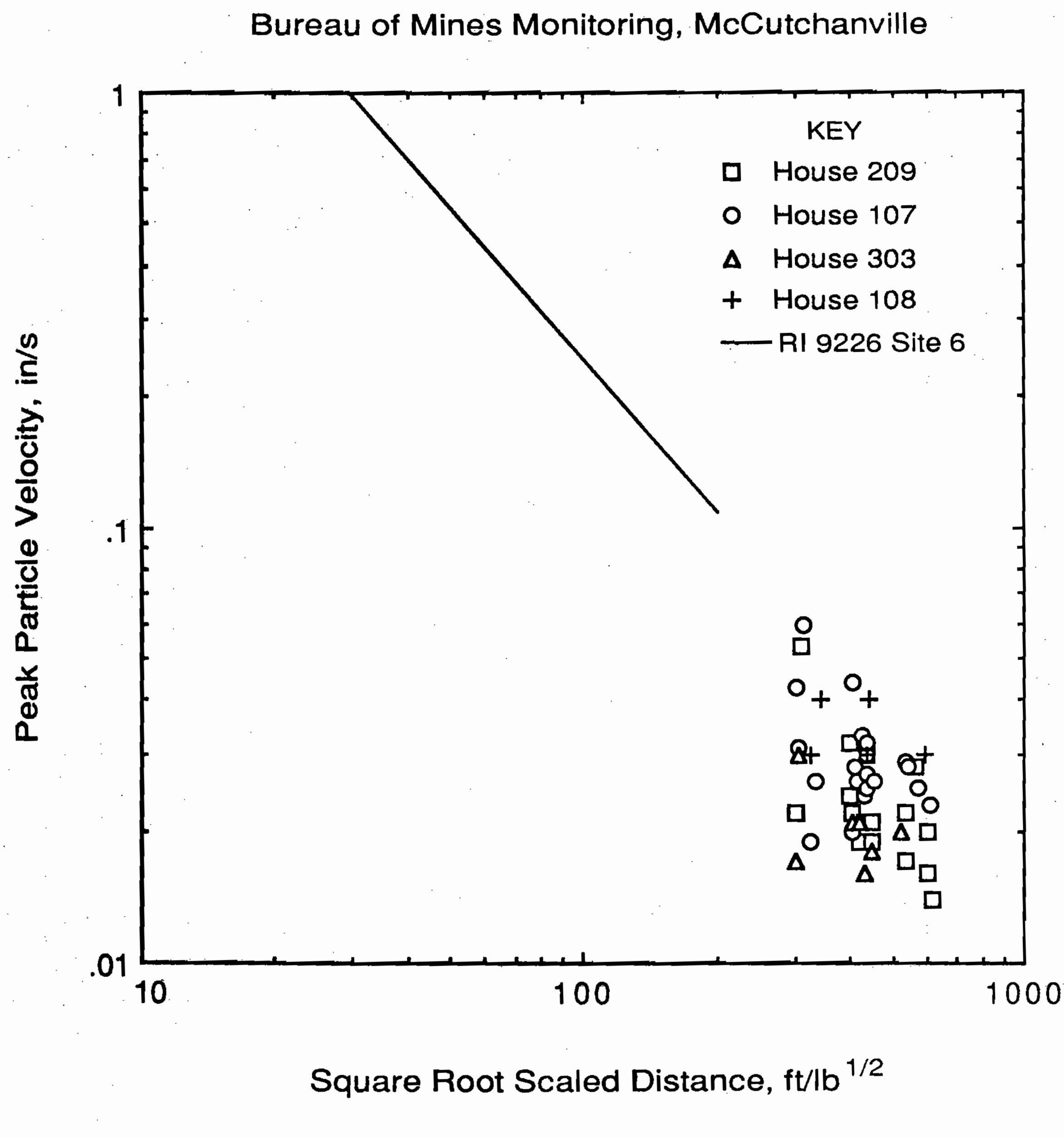


Figure 19. - Recent Bureau of Mines peak particle velocity data for homes monitored in McCutchanville.

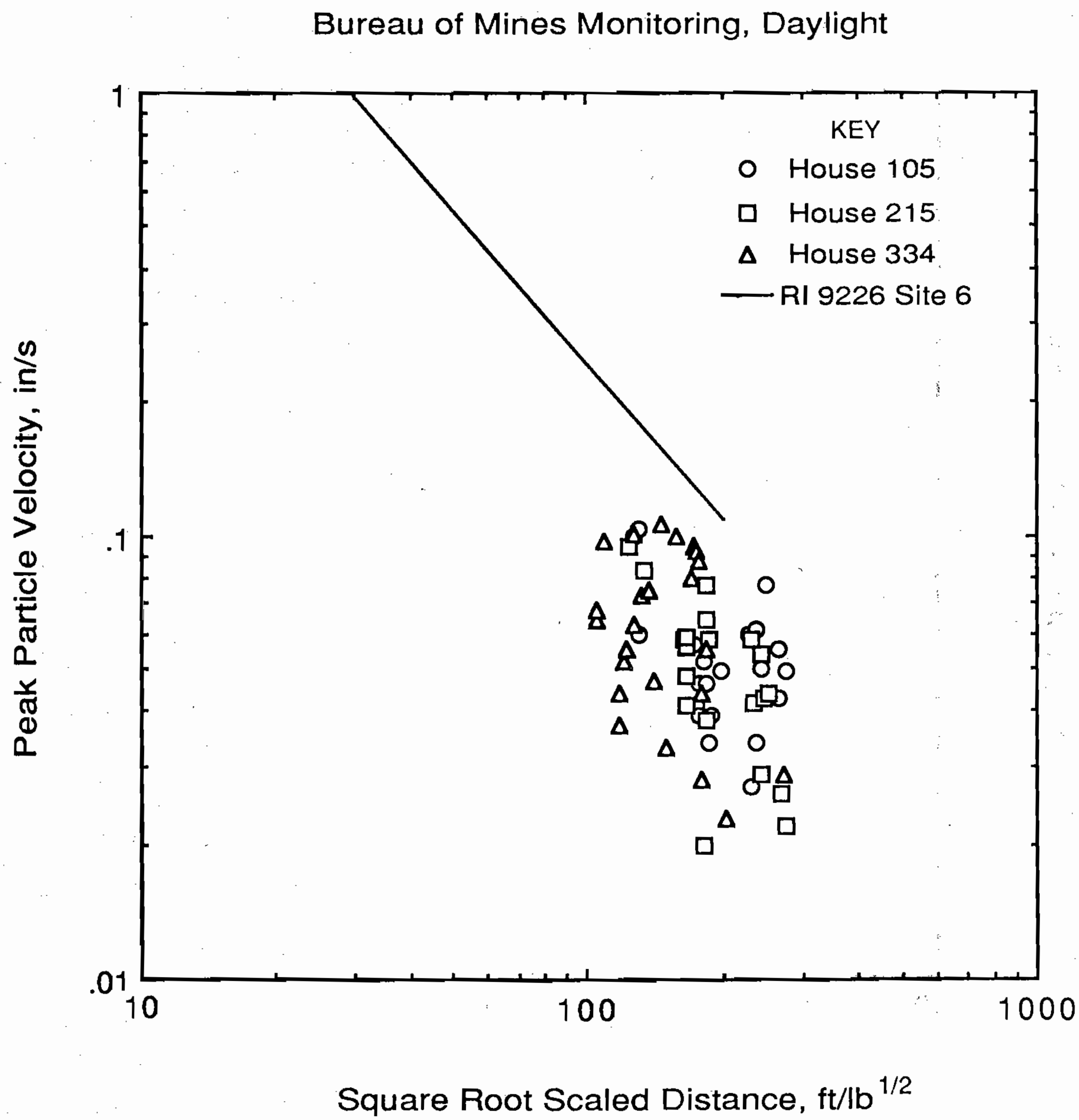


Figure 20. - Recent Bureau of Mines peak particle velocity data for homes monitored in Daylight.

Vibration Frequencies

Figures 21 and 22 depict frequency versus peak ground vibration particle velocity levels in McCutchanville and Daylight, respectively. The frequencies were obtained from the ground vibration time-histories and calculated as the inverse of the period (in seconds) of the corresponding peak velocity wavelet. The curve in the upper left-hand corner of each plot is the recommended Bureau of Mines limits from Appendix B in RI 8507 which relates threshold damage levels to frequency and peak ground vibration particle velocity (3). The ST 4 seismographs have a flat response from about 2 to 200 Hz and the tape recording systems from 1 to 5000 Hz for ground (and structure) vibration. No frequency data were available for house 108.

The ground vibrations in McCutchanville (figure 21) had a narrow frequency range between 4 to 8 Hz with highest velocity observations (0.03 to 0.06 in/s) occurring at about 5 Hz for houses 209 and 107. House 303 is not in the immediate vicinity of houses 209 and 107 which may account for the different peak velocities, i.e., the site characteristics are different. The anomalous measurements below 3.5 Hz are of questionable validity because they are too close to the frequency cut-off of the ST 4 instrument. All vibration amplitudes are well below Bureau of Mines suggested limits. Because of the nature of the distribution of peak level frequencies, the characteristic frequency of the ground in this area may be at 5 Hz.

Figure 22 shows that homes in Daylight experience a frequency range from about 3 to 20 Hz which is broader than in McCutchanville. Peak velocity levels of 0.1 in/s occur at about 5 Hz for house 105 and about 11 Hz for houses 215 and 334.

Considering the frequency characteristics observed in the study area, the homes in McCutchanville should experience a greater amount of narrow band, lower frequency vibrations than in Daylight. This condition probably results

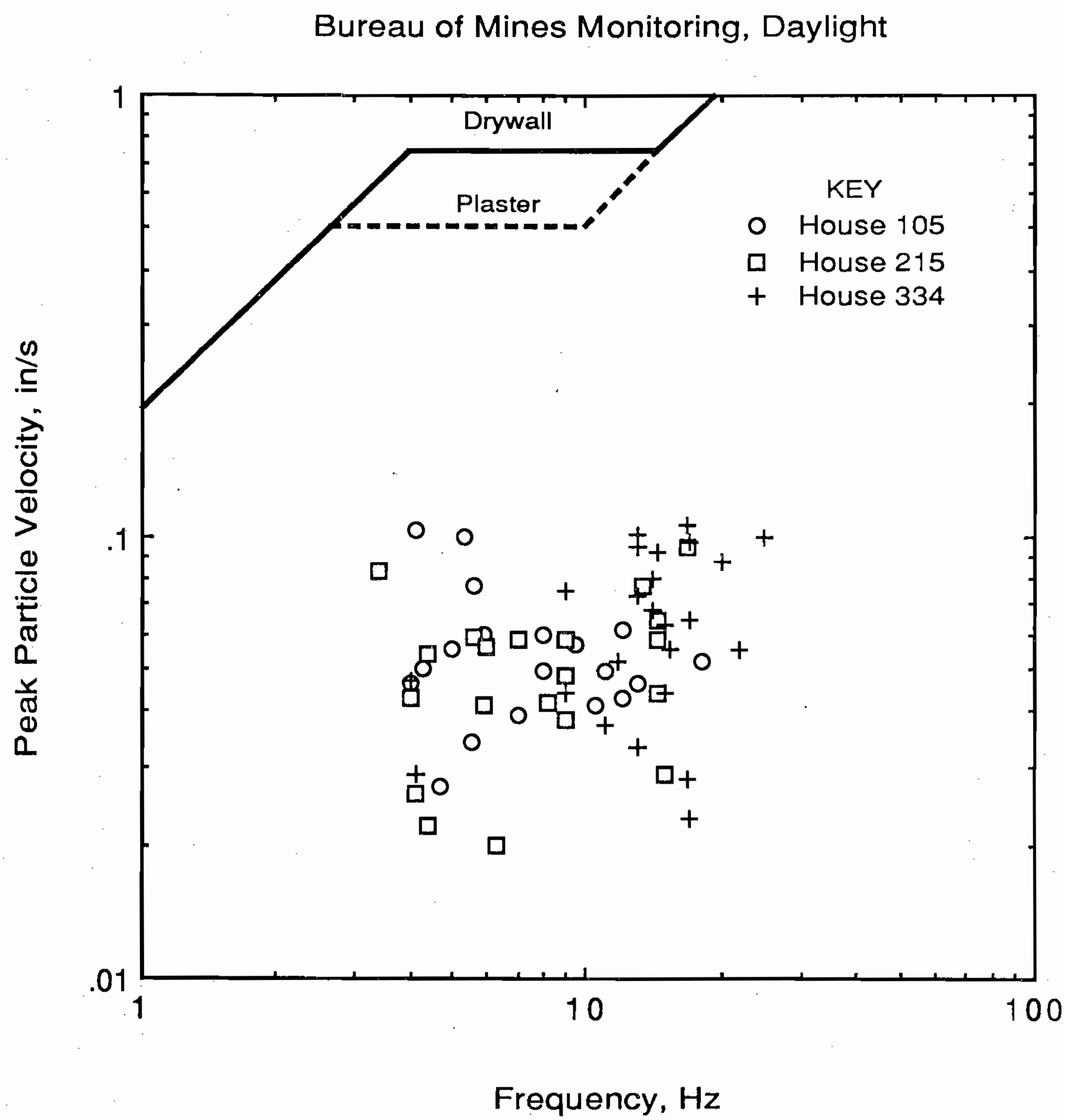


Figure 22. - Peak particle velocity and associated frequency relations for recent Bureau of Mines monitoring in Daylight. The curve in the upper-right corner is from Appendix B of RI 8507 and represents the safe limits recommended by the Bureau of Mines (3).

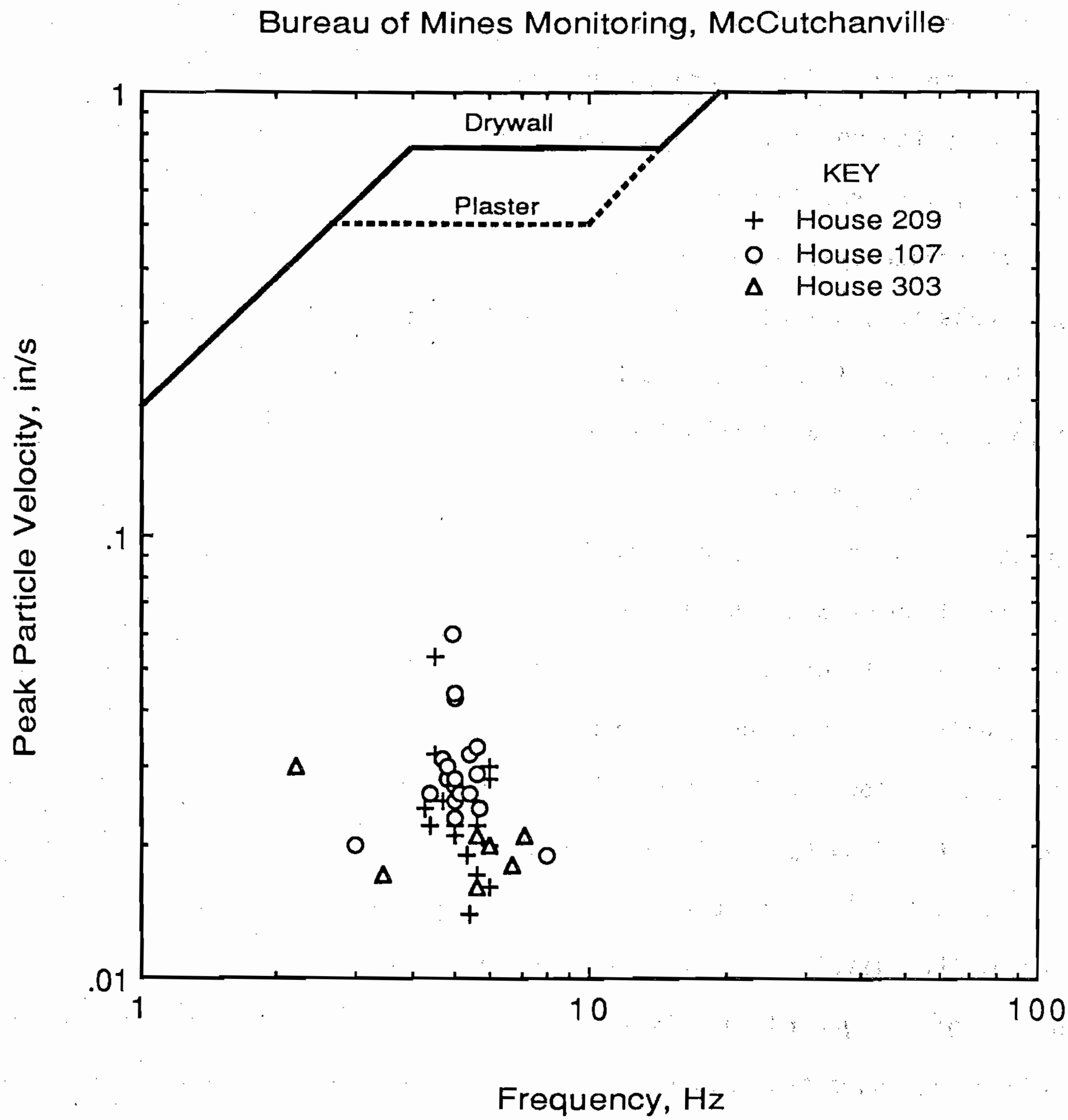


Figure 21. - Peak particle velocity and associated frequency relations for recent Bureau of Mines monitoring in McCutchanville. The curve in the upper-right corner is from Appendix B of RI 8507 and represents the safe limits recommended by the Bureau of Mines (3).

from the large distances from the blast and also influence from the local geology (and possibly topography). The peak vibration frequencies are concentrated near 5 Hz, which is close to the natural frequencies of the homes, making these ground vibrations more noticeable. At these particle velocity levels, there is negligible chance of structural damage, but, complaint numbers may be higher from the McCutchanville area because of the low frequencies there.

Natural Seismicity in the Study Area

On June 10, 1987, a 5.0 magnitude earthquake occurred in southeastern Illinois that was recorded by portable seismographs located in Daylight. Earthquakes are usually lower frequency and longer duration events than ground vibrations from blasting and therefore may impose a greater threat to structures. R. Street, et al. (1988) reported peak particle velocity levels from the June 10, 1987 earthquake recorded at four stations located in Daylight (12). The frequencies associated with the peak velocities were within 2 Hz of the cutoff frequencies of the seismographs and therefore may actually be higher than reported. The peak amplitudes for the individual stations ranges from 0.2 in/s at 3 Hz to 0.44 in/s at 6 Hz. The amplitudes are two to over four times the peak blasting levels recorded by Bureau researchers in this area, although still within the safe limits established in RI 8507.

Airblasts

Historical data and Bureau of Mines monitoring of airblast overpressure recorded in the McCutchanville direction are given in figure 23 and in the Daylight direction in figure 24. Airblast data correspond to the same group of blasts used in the previous ground-vibrations analysis (see figures 33 and 34 and discussion thereof), with house 334 included in the Daylight group

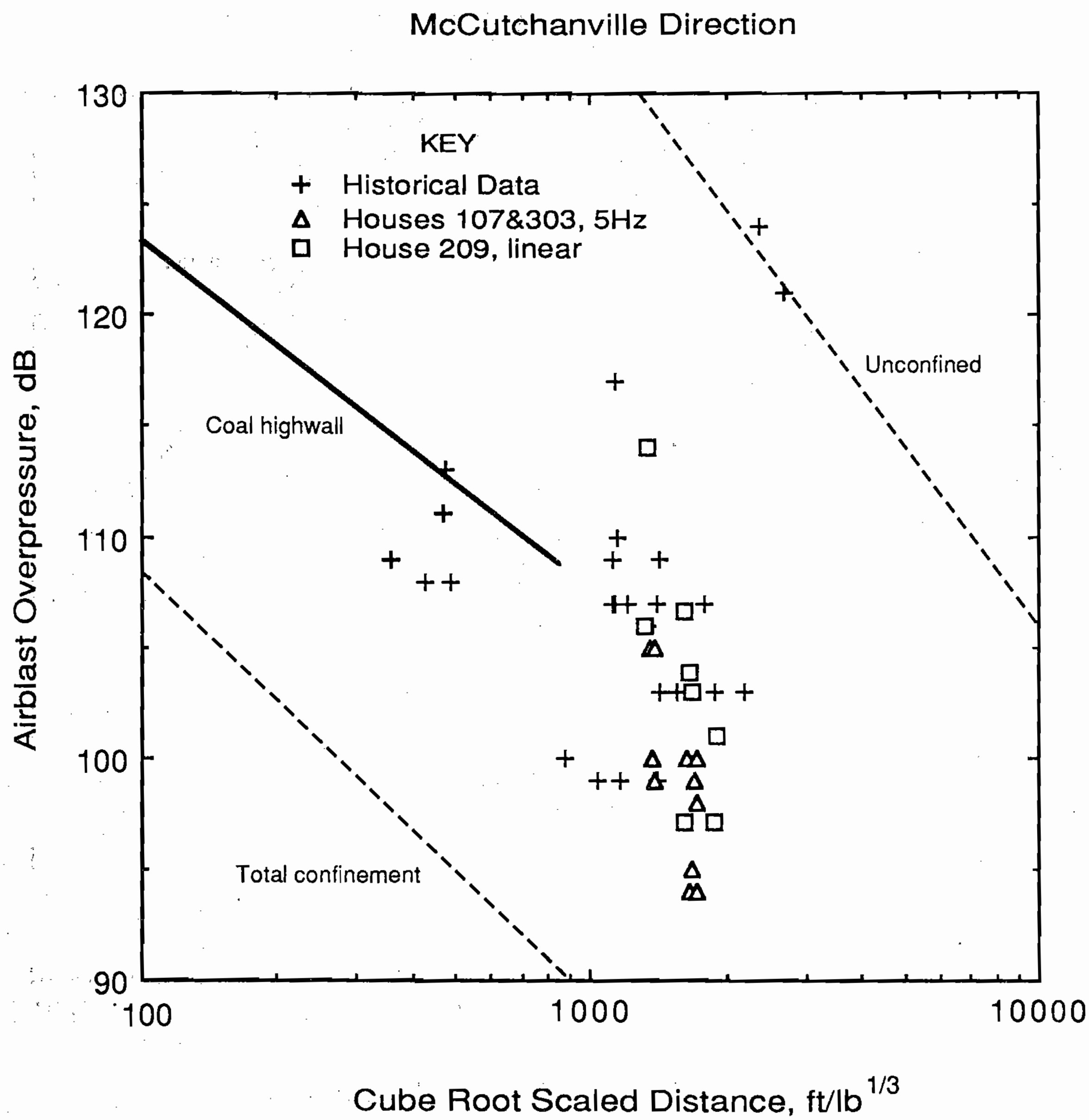


Figure 23. - Historical and recent Bureau of Mines airblast overpressures for the McCutchanville (southwest) direction. Reference lines and explanations about the plot key are discussed in the text.

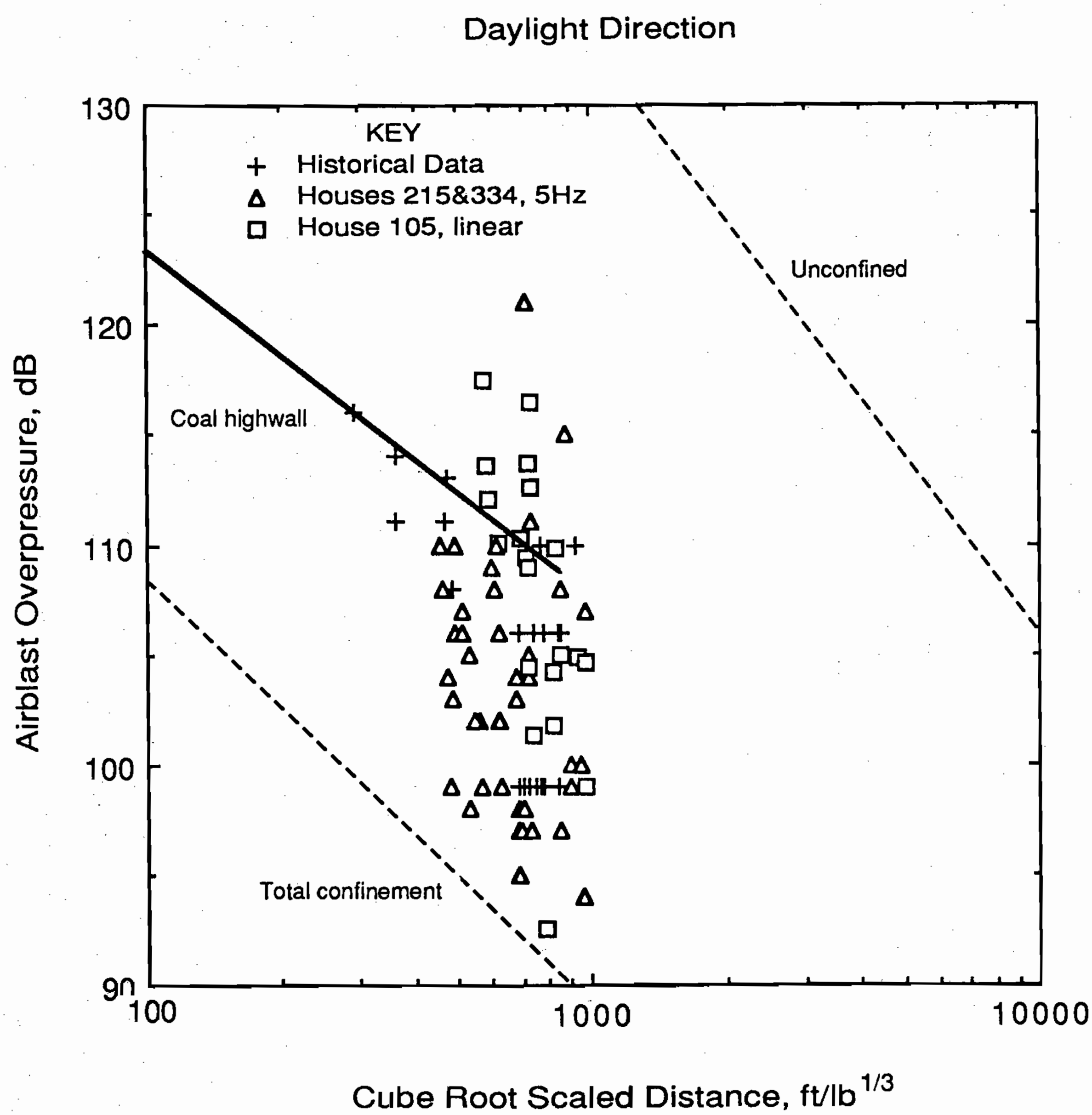


Figure 24. - Historical and recent Bureau of Mines airblast overpressures for the Daylight (west) direction. Reference lines and explanations about the plot key are discussed in the text.

since no historical airblast data were available in the Base Line Road direction.

The dashed lines of figures 23 and 24 represent upper and lower historical reference bounds for airblast levels for a totally confined blast (lower line) and unconfined blast (upper line) which could be paramount to a "blow-out." The solid black line is the regression line fit to other historical data from typical surface coal mine blasts, given in Appendix B, figure B-1. Peak level obtained from the ST 4 recorders are identified in the plot key as "5 Hz" because this is the frequency roll-off of the airblast channel on these instruments. "Linear" refers to the sonic boom detectors with the tape recorder systems which have flat responses from 0.1 to 8,000 Hz. Airblast levels obtained from the 5-Hz system are about 8 dB lower than the levels measured with the linear system for the low-frequency airblasts observed from the relatively distant Ayrshire Mine. All of the subsequent plots do not correct for this difference, although the type of system used is stated. Peak airblast values used in this report are also given in Appendices C & E. Airblasts with values stated as <100 dB were plotted at 99 dB.

The airblasts recorded in each direction are highly variable even within a relatively narrow scaled distance range. The vast majority peak airblast levels for all of the McCutchanville and Daylight measurements are between 90 and 120 dB, falling between the confined and unconfined bound, with most being near or below the expected coal highwall-type blasts and also below 110 dB. The highest airblast overpressure recorded by Bureau researchers was 121 dB at house 334 using a 5-Hz system.

In figure 23, the recent Bureau of Mines monitoring shows peak airblast levels comparable to, and often lower, than the McCutchanville direction historical measurements. Two comparatively large events between 120 and 125 dB were recorded by the DNR in the McCutchanville area that are near the unconfined bound and so could be indicative of a blow-out (see figure 23). The time and date of these events coincides approximately with actual mine blasts. Bureau researchers examined one of the actual time-histories but it is uncertain if these events are blasts or if they are a coincident "non-events" because other non-correlatable events of similar magnitude were sometimes recorded.

Bureau of Mines monitoring in the Daylight area recorded several airblasts with peak levels higher than the historical measurements. The 121 dB airblast, recorded on a 5-Hz machine is a very noticeable airblast although below the 129 dB criterion established by the Bureau of Mines in RI 8485 (4).

Moderately perceivable airblast noise would extend the total duration of transient annoyance to the homeowner which could be as long as 10 seconds in Daylight and 20 seconds in McCutchanville. Increased duration is related to increased human perception. Therefore, even low-level benign airblasts could generate complaints, with more possibly originating from the McCutchanville area.

Climatological Data

Weather data for the Evansville airport were requested from the National Climatic Data Center in Asheville, NC 28801. Rainfall data were sought as an aid in understanding water-soil interactions and their role in the observed foundation cracking. Wind direction and velocity were requested for specific dates in an attempt to explain long-range airblast propagation. Appendix F contains selected airblasts and shows that long range airblast from the distant Lynville mine corresponded to wind conditions from that direction, north and northeast. The two Ayrshire "blasts" of 04-06-89 @ 1254 and 07-21-89 @ 1443 did not have tailwind conditions.

STRUCTURAL VIBRATIONS

Ground Vibrations - Induced Responses

As discussed previously, houses 105 and 209 were instrumented to monitor above-ground structure motion induced from the blast vibrations. Structure response sensors for corner motion were placed in the main living areas of the homes directly over the corresponding sensors used to monitor ground motion.

Figure 14 shows the first floor, upper wall "corner response" in the same direction as the horizontal ground motion sensors as recorded at house 105; a one-story dwelling. Structure response from ground motion is identified within the approximate time frame as the ground vibrations. The respective ground motion and structure response time-histories are very similar except for a slight particle velocity amplification.

House 209 has a "walk-out" basement on this side of the structure so the sensors were located essentially two stories above ground-level, directly over and in the same directions as the horizontal ground motion transducers (figure 13). The second-story corner response of house 209, as seen in figure 15, is again very similar to the ground motion except for structure amplification of the particle velocity. In addition, some high frequency "bumps" are observed on the time history which are probably modifications induced by specific characteristics the structures such as by the materials and methods used in construction.

Monitoring of house 209 response was supplemented by a third transducer placed several feet away from the corner on an inside window-frame located on the east-facing wall (H1 direction) which gave an indication of the "midwall response" of the upper-level house motion. The midwall response to the ground motion in the H1 (east-west direction) is almost identical in shape and duration to the east-wall corner motion except for an amplification of the ground motion by a factor of two. The upper-level structure amplification of the ground vibration observed for houses 105 and 209 with respect for shot #25 are normal for one- and two-story residential structures (see RI 8507).

Corner amplifications for the two homes monitored for structure response are shown in figure 25. House 209 in McCutchanville had ground-to-structure amplifications averaging nearly 2.0. House 105 was shorter, at one story, and had typical amplification factor of 1.3 and a maximum of 1.6. This house was also subjected to a much wider range of vibration frequencies, as was already mentioned for all the Daylight homes. Midwall amplifications were also measured in house 209 and ranged up to 3 (figure 26). All response values are within the bounds of previously studied homes (shown in Appendix, figures A-6, A-7) and cannot be considered abnormal in terms of their responses to blasting vibrations.

Airblast Responses

The airblast overpressure for shot #25 at houses 105 and 209, shown in figures 14 and 15, respectively, were recorded using the wide-band sonic-boom system explained earlier. Because sound usually travels much more slowly through the air than through the ground, the airblast arrival will follow the ground vibration by a time proportional to the distance from the blast. The airblasts shown here are characteristic of overpressures recorded at large distances with most of the signal energy near or below 1 Hz. The respective peak amplitudes of 117.5 and 106.0 dB can be noticed by persons inside a home, but will not induce damage.

Airblast-induced structure responses were obtained for a few blasts in the two instrumented homes. Because of their relatively low dominant frequencies (less than 1 Hz and consistent with long distance and behind-face direction), they produced responses on the low side of the historical data (given in Appendix B-7, 8). Table 5 lists the measured responses for house 105, corner

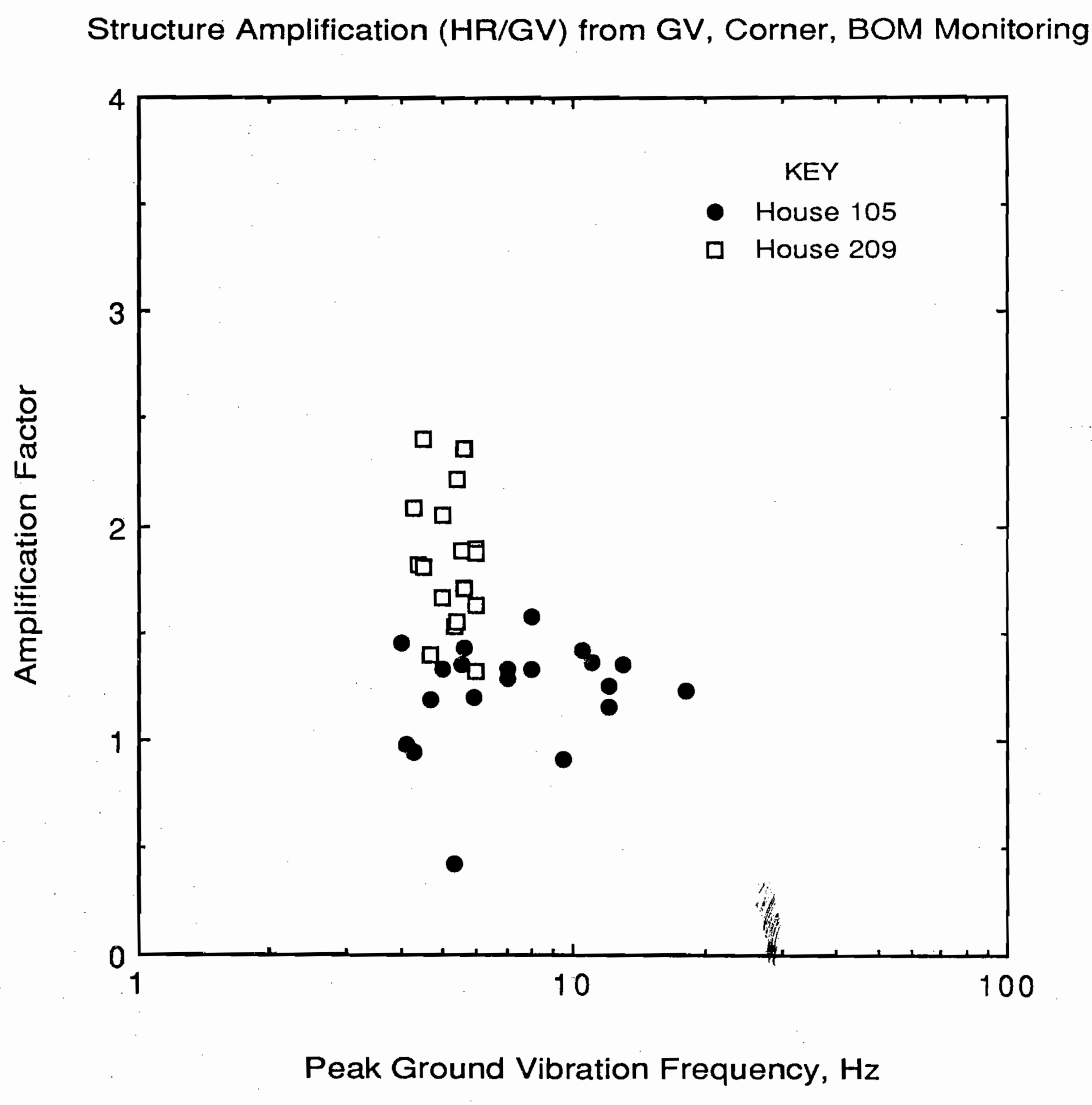


Figure 25. - Amplification factors for blast-produced corner responses for houses 105 and 209.

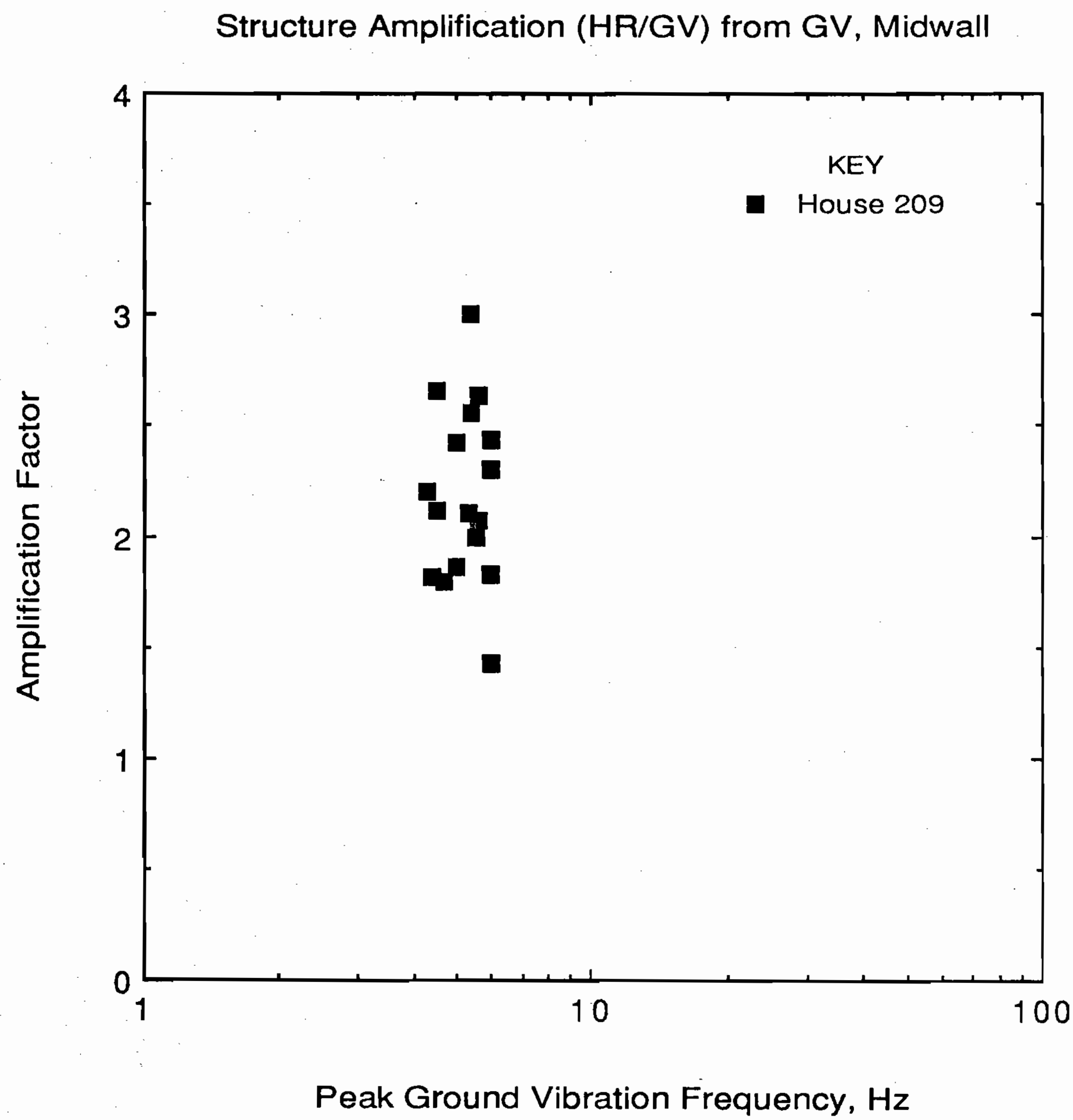


Figure 26. - Amplification factors for blast-produced midwall response for house 209.

only, and for 209, corner and midwall. The low height of 105 probably contributed to its small response.

Table 5. - Structure vibration responses from airblasts.

House	Airblast		Structure response, in/s	
	lb/in^2	dB	Corner	Midwall
105	.00216	117.5	.004	-----
209	.00058 .00145	106 114	.005 .008[1]	.031 .037[1]

[1] These convert to 5.5 and 25.5 in/s per lb/in^2 respectively, as compared to average responses in RI 8485 (4) of 16 and 84.

Responses From Human Activity

While the instruments were in place in the McCutchanville home 209, researchers measured a variety of responses to aircraft operations and human actions, table 6. Aircraft-induced rattling was noticeable and produced midwall vibrations comparable to, but somewhat lower in amplitude than, the worst blasts of the monitoring period. Most significant is the human activity, comparable to the strongest blasts for corners and far worse than the blasting for midwalls. These are entirely consistent with previous studies (3, 5).

Table 6. - Structure vibration responses in house 209 from aircraft operations and human activity, in/s.

Activity	Corner responses	Midwall responses
Aircraft takeoffs, 3 cases	.004-.009	.012-.034
Children's activity	----	.026-.032
Moderate door close	.007-.015	.006
Jumping on floor	.026-.039	0.38
Wall pounding, e.g., nailing	.023-.055	0.36

CRACKING AND DAMAGE IN HOMES

Monitoring Period Inspections

A total of 45 areas were selected in the six monitored homes for regular inspections before and after every blast when Bureau researchers were present. Effects of blasting and possible long-term changes, such as seasonal climatic influences, were being sought. Table 7 lists the areas under inspection. Each area in each home was examined 38 times between November 1, 1989 and January 3, 1990. Inspections were carefully done with a 7-power optical comparitor and strong side-lighting for contrast. Resolution was about 0.05 mm. On several occasions, the mine scheduled a series of closely-timed blasts

Table 7. - Inspection areas in the monitored homes.

OSM ID number	Location	Areas pre- and post-inspected for changes		
		Crack tips	Crack widths	Uncracked areas
105	Daylight	4	1	1
107	McCutch-anville	5	2	0
209	McCutch-anville	3	2	2
215	Daylight	2	2	3
303	McCutch-anville	3	4	0
334	Baseline Road	4	1	7

Table 8. - Crack changes in homes during Bureau of Mines monitoring period, November 1, 1989 through January 3, 1990.

House	Crack width changes, mm	Extensions, mm	Maximum blast vibrations in period, in/s	Location in home
105	+.10	None	.067	Over inside doorway
	-.10	None	.066	"
	+.10	None	None	"
	+.10	None	.094	"
	+.10	None	.056	"
	-.10	None	Unknown	"
107	None	Amount not known	.031	Basement ceiling
209	-.05	None	None	Below livingroom window
	+.05	None	Unknown	"
	-.05	None	.027	"
215	+.05	None	.081	Over doorway-outside
	-.10	None	None	"
	+.10	None	.038	"
	+.10	None	.054	"
	+.10	None	.077	Over inside doorway
	-.10	None	None	"
	+.10	None	.092	"
	+.10	None	None (cold spell)	"

requiring quick work for researchers who had responsibility for 3 homes each and - in Daylight, having to drive from home to home - and also having to record digital readings from the seismographs. Nonetheless, inspections were done regardless of vibration levels.

Selection of inspection areas concentrated on those with the highest estimated risk, such as above doorways, and those with high promise of visible change. All were inside the homes and most involved cracks in wallboard. A few masonry cracks were monitored; however, the rough surface textures made for difficult assessments of crack tip locations. This was less of a problem for crack widths, however. In all, over 1700 inspections were done and documented in addition to the operation of the recording systems and coordination with the mine blasting.

<u>Damage Changes Observed During Monitoring Period</u>

Of the six homes under crack monitoring, four had some minor changes in widths and one an extension of a crack which was not one of those preselected for monitoring. Table 8 summarizes the observations. Generally, the cracks cycled open and close with no regard to the blasts, which as already mentioned, were of low amplitude. For example, house 105 had a crack which appeared wider after a blast (by a very minor 0.1 mm or .004 in) and then was back to its original width upon inspection the next morning. For three successive inspections, this crack appeared to be widening steadily until it was observed to reverse and return to its original width.

House 107 had a ceiling crack extension which was not under inspection but cut through a mark placed to identify a nearby crack tip. The highest vibration level during the period when this occurred was 0.031 in/s. The highest blast at this home during the monitoring period was .06 in/s, which produced no observed changes.

House 209 had a crack which cycled just at the threshold of measurement, ± .05 mm. At least one change occurred during a period of no blasts. Another crack in this home all but disappeared after a very cold spell of -19°F. At the same time, a concrete driveway outside the walk-in basement lifted enough to prevent the opening of a door which had been in use. A few weeks later, and 60° warmer, the door could be opened.

House 215 had two cracks which cycled by an amount of ± .10 mm. This house, like the others, would have cracks both widen and close at times of blasting and, in 3 of the 8 cases do the same at other non-blasting times. Again, there appeared to be a reaction to the cold spell.

Although it is difficult to properly assess blasting impacts over such a relatively short study and particularly for a period representing only a fraction of a complete seasonal cycle, there is no clear correlation between blasting and the observed crack changes. A definite cause for these cycling crack behaviors is beyond the scope of this study, but a previous Bureau investigation of vibrational fatigue in homes suggests weather-related influences (5). Long-term crack changes are discussed later in the section dealing with soils and foundation interaction.

Some displacement gauges had been distributed by OSM to homeowners and in place during the Bureau's study. Figures 27 and 28 show two such gauges across cracks in the outside brick of houses #108 and #201. These relatively low-resolution gauges were not regularly checked although researchers noticed that several in houses #105, 107 and 215 showed no changes during the three month study.

Inspections of Existing Damage

Bureau researchers examined the homes being monitored plus three others for existing damage (as of October 1989). The Bureau's project for OSM called for an assessment of that damage and explanations for causes should they be

Figure 27. - Displacement gauge placed across a residential crack in house 108 prior to the Bureau's study.

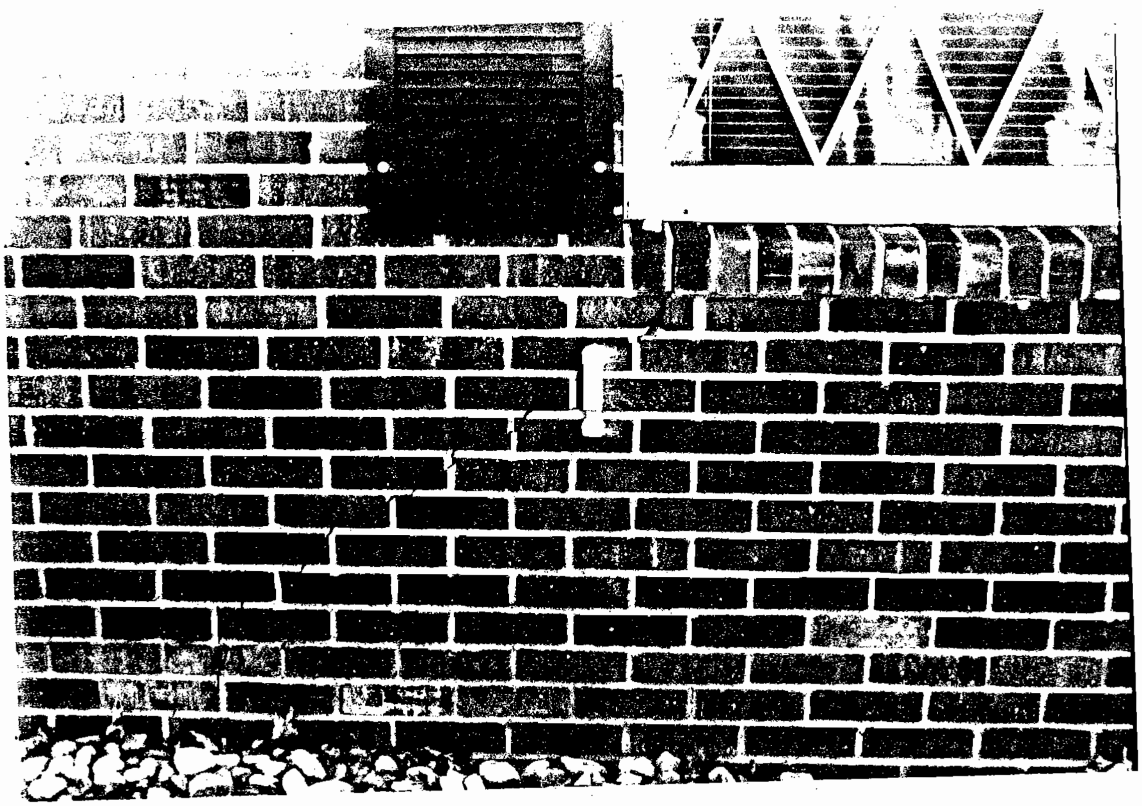


Figure 28. - Displacement gauge across a crack beneath a window of house 201.

judged unrelated to blasting. Although mentioned previously, it is worth repeating that the Bureau's part of this study had a limited scope, particularly in time. It was not possible or practical to tear apart foundation walls, excavate down to footings or do more than a cursory soil evaluation. Therefore, definitive causes of preexisting damage must be primarily the authors' opinions based on the observations, discussion with others knowledgeable in the field, and a few tests performed in the limited time available. The authors believe that OSM is looking into this problem in greater depth.

House 105 has two types of damage, minor horizontal cracks in the concrete block basement wall just below ground level and a few superstructure cracks including one over the center wall doorway and parallel to the house's long axis. The horizontal block cracks appear to occur on both sides of the house (only one wall was well exposed). Because the brick facade also begins at ground level, the block thickness appears to be reduced here in order to provide both room and support for the bricks. This is a likely point of weakness.

House 107 has cracks throughout both the basement and superstructure, including separation cracks behind the massive brick fireplace. A few cracks in the living room appear to be from compression. For example, it appears that wallpaper was used to cover an existing crack, which later closed somewhat, buckling the paper. This home was built in stages, part on footings (with a crawl space) and part over a basement. It is likely that different parts of the house are experiencing different forces particularly from any soil changes and also possibly complicated by the shallow slope.

House 108 is on a steeper slope and, as with 303, has evidence of down-slope foundation failure. Here are large cracks (some about 1/2-in in width) in both the outside brick walls and in the concrete basement floor. On the east end, where the worst outside cracks occur, the bricks near the ground are muddy. This indicated that rain water had been splashing directly on the walls (or that the gutters were not doing their job properly). In addition, the homeowner reported that water sometimes appeared in the basement floor cracks. Any assessment of damage in this house would have to consider the influence of water.

House 201 is the only one examined which has severe structural failure with major basement wall cracks and wood bracing to prevent the wall from falling inward. This house is on a hill top. The most seriously falling wall faces north and is a plain concrete block wall about 60-ft long with a full 8-ft height and completely below ground level (figure 29). This wall had no intersecting walls except at the two ends and also no visible reinforcing pilasters. Outside and above this wall was an uncovered patio. This patio had a perceptible tilt toward the wall and appears to have settled about 2-inches on the end against the house (figures 30 and 31). Again, rain and water must be considered in any damage assessment of this home.

House 209 is on a hillside and has numerous superstructure cracks, most being hairline. House 215 is in a flat area in Daylight and had both a few superstructure cracks and a few basement block wall cracks similar to those in house 105 discussed previously.

House 303 is on a hillside in McCutchanville and had many cracks throughout. Previous basement damage had been repaired prior to these studies and the adoption of casting by the mine. This required new brick and block work on the down-slope side of the home which was again showing signs of cracking. Some large ceiling cracks had been plastered over at one time and then buckled when the cracks closed. New cracks continue to appear in this house including a large one visible both inside and outside which the owner thought occurred recently (during the Bureau's study period).

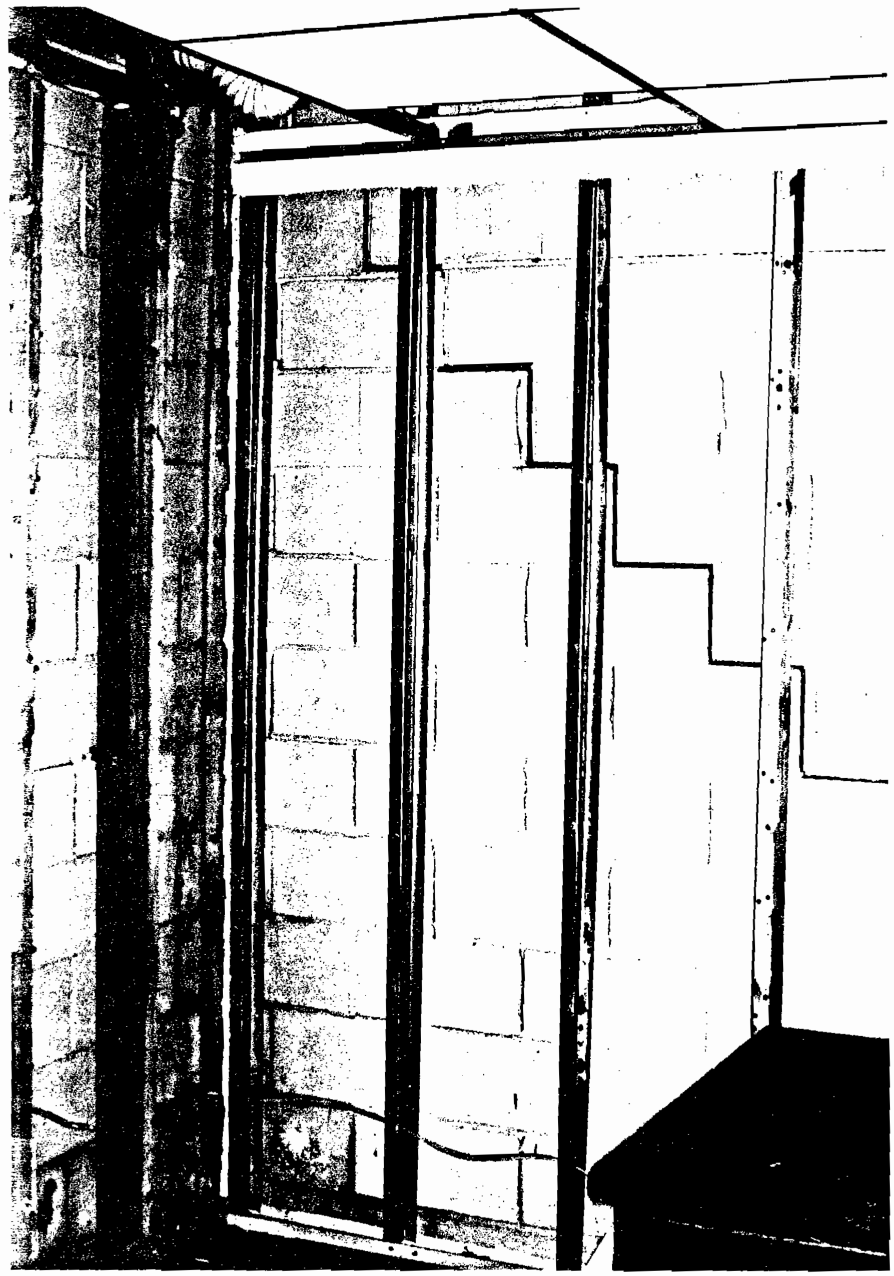


Figure 29. - Basement block wall crack on east wall of house 201.

Figure 30. - Uncovered patio at house 201 with perceptible tilt toward house's north wall.

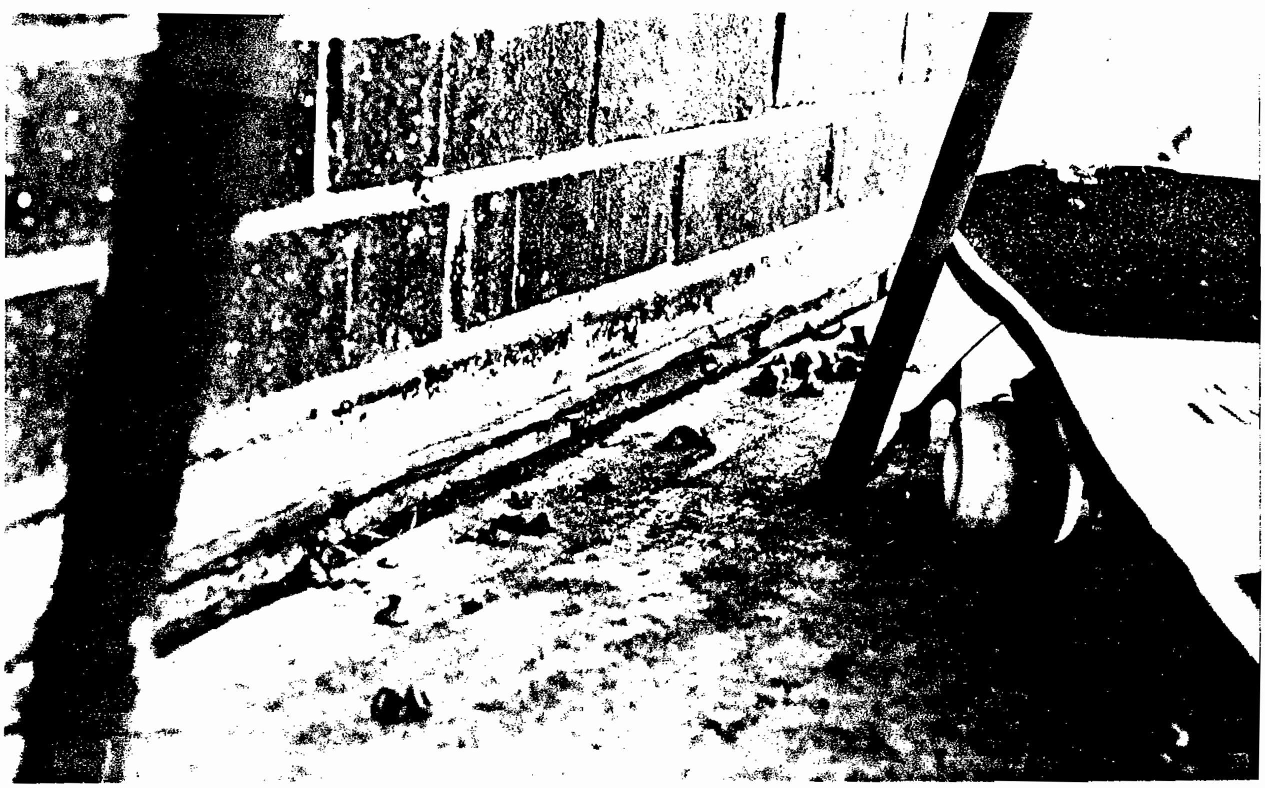


Figure 31. - Junction of north wall and patio of house 201 showing evidence of settlement.

House 308 had extensive superstructure cracks throughout most rooms but with little visible outside. This house is on a hillside and, like 107, has parts with a crawlspace and others over a basement-like walk-out. The owner admitted that some cracks are over 3 years old.

House 334 in Daylight had the fewest and most superficial cracking of all homes studied, despite being the closest to the blasting. It also has horizontal cracks near ground level, as noticed in the other two Daylight homes. However, these are very fine by comparison. The cracks in this house, as well as many of the cracks in the other homes studied, are typical of cracks observed in all homes regardless of location.

Assessment of Damage

This is always a difficult problem because of the similarity of damage from blasting and various short and long term causes of strains and cracking in homes. The frustration for homeowners is that elimination of noncauses is far easier than finding definitive causes. This is underscored by a publication of the American Insurance Association which describes the many ways that cracks form in homes (13), and a section of Wiggens Sonic Boom text which similarly discusses cracks in houses (14).

The worst damage was in McCutchanville homes and most of those were on slopes. Major cracks were consistent with some kind of down slope failure, possibly as a contributing factor. Construction practices are also a likely factor in some cases. For example, houses which have more than one kind of foundation will be subject to varieties of differential strains, #107 and 308 being good examples. By contrast, similar homes on level ground (e.g., in Daylight) have little or no damage although closer to the blasting. Houses with the worst damage (#108 and 201) have evidence of water intrusion along the foundation. The apparent lack of pilasters in #201 plus water intrusion was also noted earlier.

It is not possible to assess the damages with precise regard to causes; however, it is most likely and plausible that foundation responses from soil and water interactions are the largest forces on the homes. This is consistent with observations that much of the cracking exhibits cyclic rather than progressive behavior (table 8). A complete discussion of soil and geological influences follows the next section.

LEVEL LOOP SURVEYS

Bureau researchers performed pairs of level loop surveys for the seven homes being monitored for blast vibrations (figure 8). Such surveys can reveal gross differential settlement, subsidence, and slope failure, to a resolution of about 0.01 ft. Comparisons between the pairs of measurements made 3 months apart can show non-cyclic changes associated with ongoing processes.

The seven homes surveyed for settlement are shown in figures 32 through 38 and results are summarized in table 9. These results are relative elevations

Table 9. - Summary of two level-loop surveys of seven daylight and McCutchanville houses, October 1989 and January 1990.

House	Maximum elevation change between two surveys, ft	Maximum angular distortion[1]	Total angular distortion for house	Notes
105	-.02	1:430	1:680	
107	-.03	1:80	1:174	Roof line survey. Down slope end is low.
108	-.03	1:220	1:432	Down slope end is low.
209	±.01	1:171	1:258	Down slope end is low.
215	+.01	1:338	1:1730	
303	+.03	1:107	1:226	Down slope end is low. (on north side)
334	-.03	1:253	1:549	

[1]1:430 = Distortion of 1 part in 430, etc.

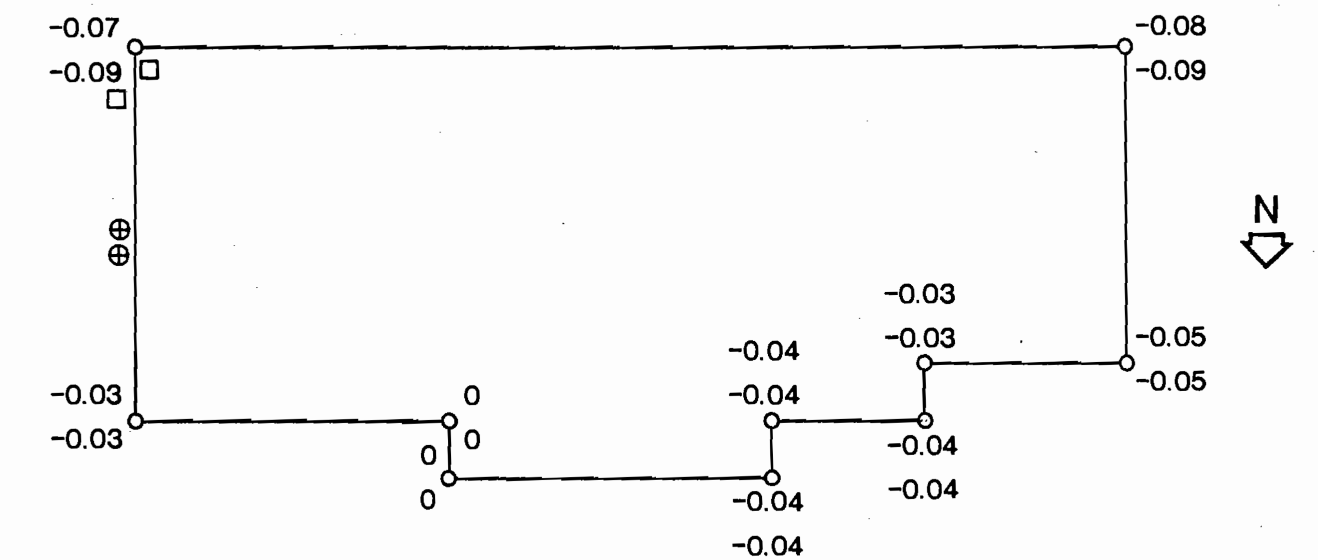
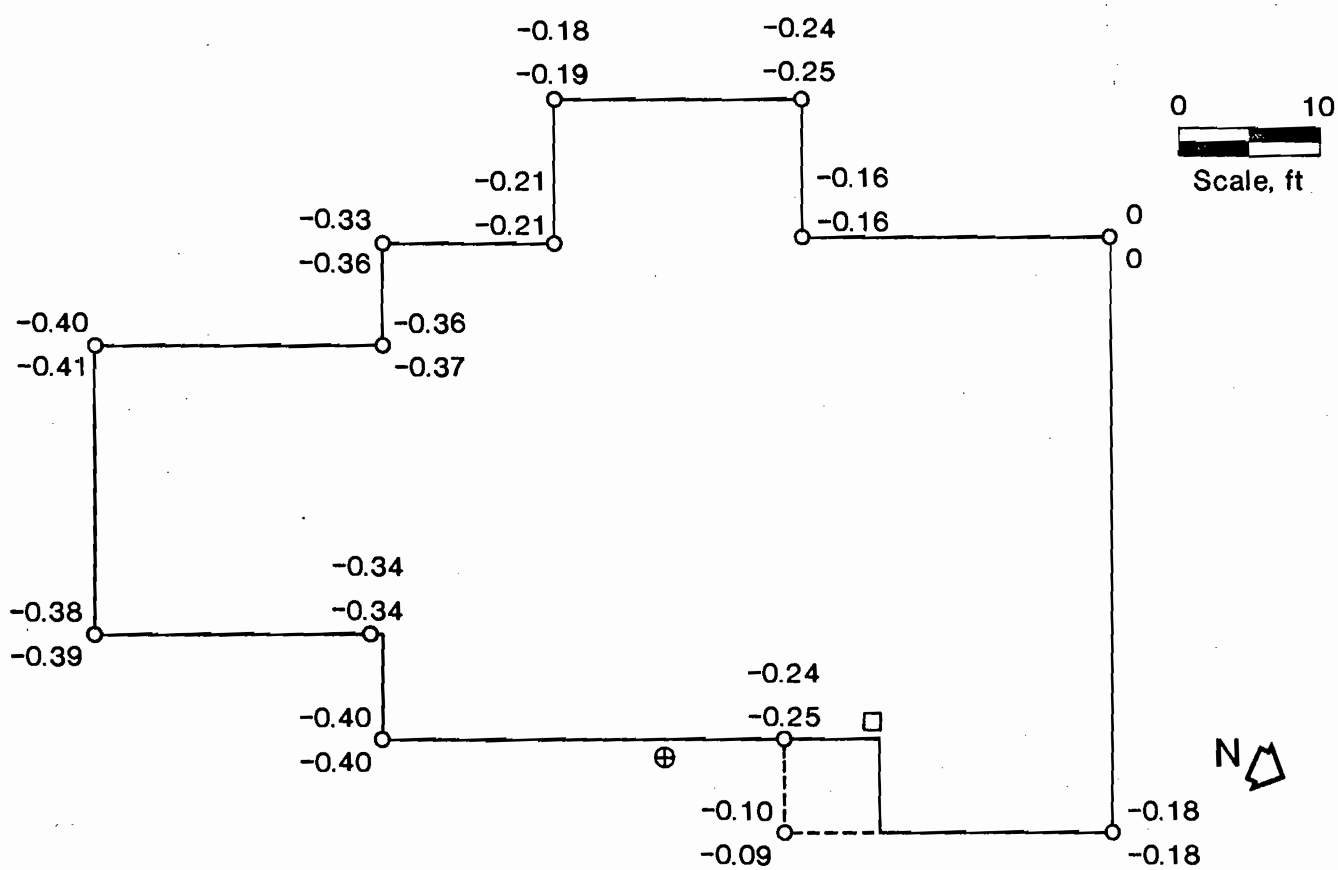


Figure 32. - House 105 and level loop surveys.



Top number is survey of October 1989

Bottom number is survey of January 1990

All elevations are in feet

Transducer: Vibration □

Transducer: Airblast ⊕

Figure 33. - House 107 and level loop surveys.

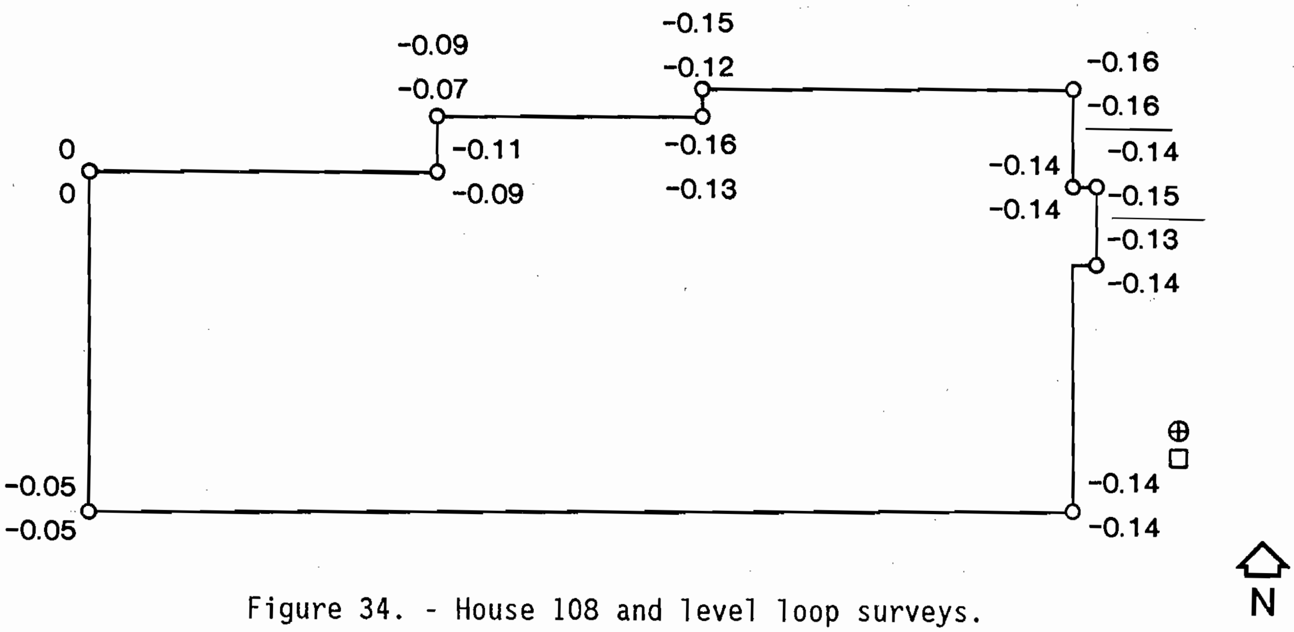


Figure 34. - House 108 and level loop surveys.

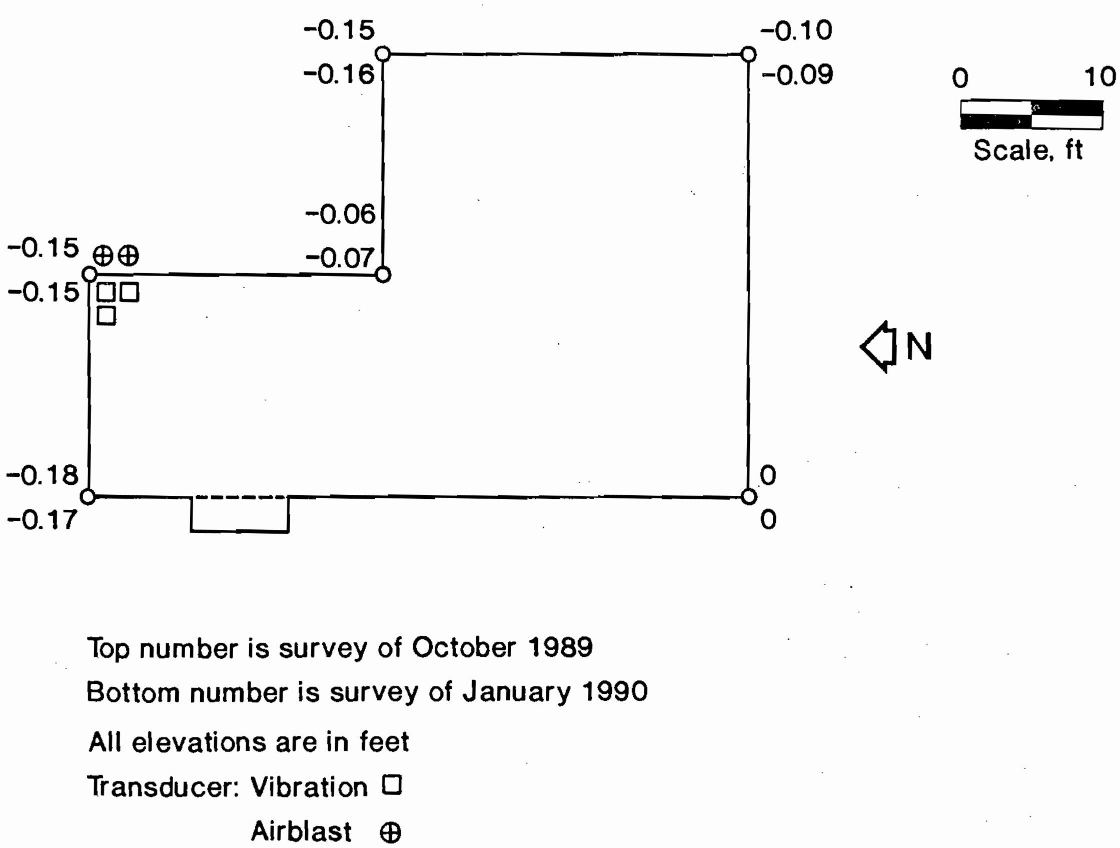


Figure 35. - House 209 and level loop surveys.

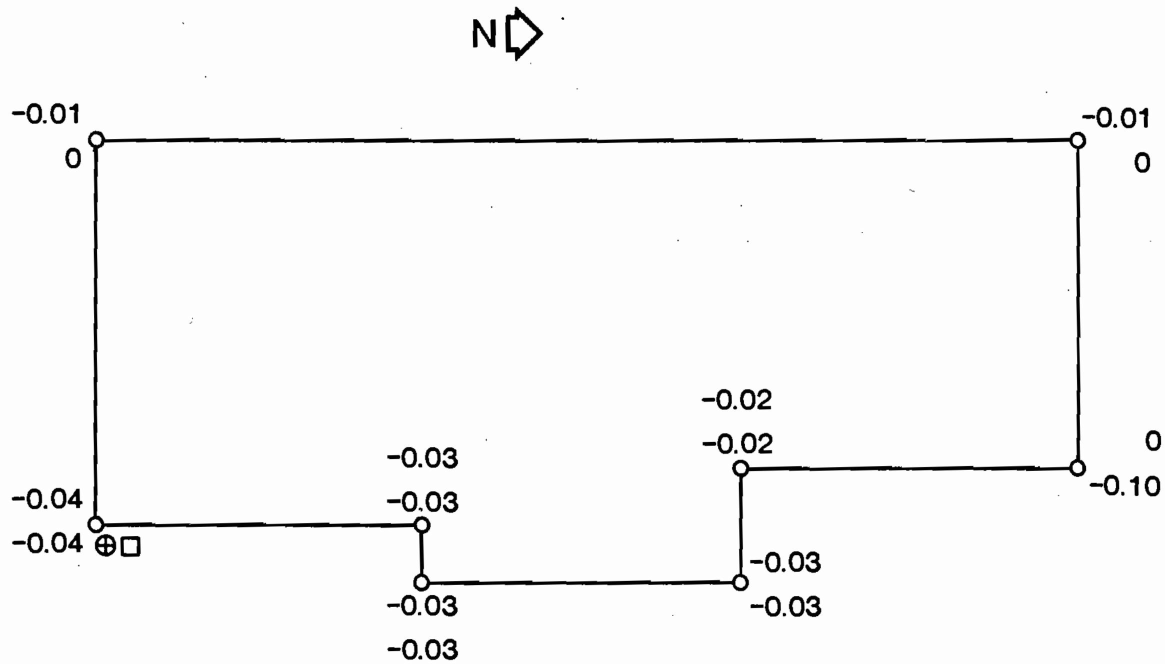


Figure 36. - House 215 and level loop surveys.

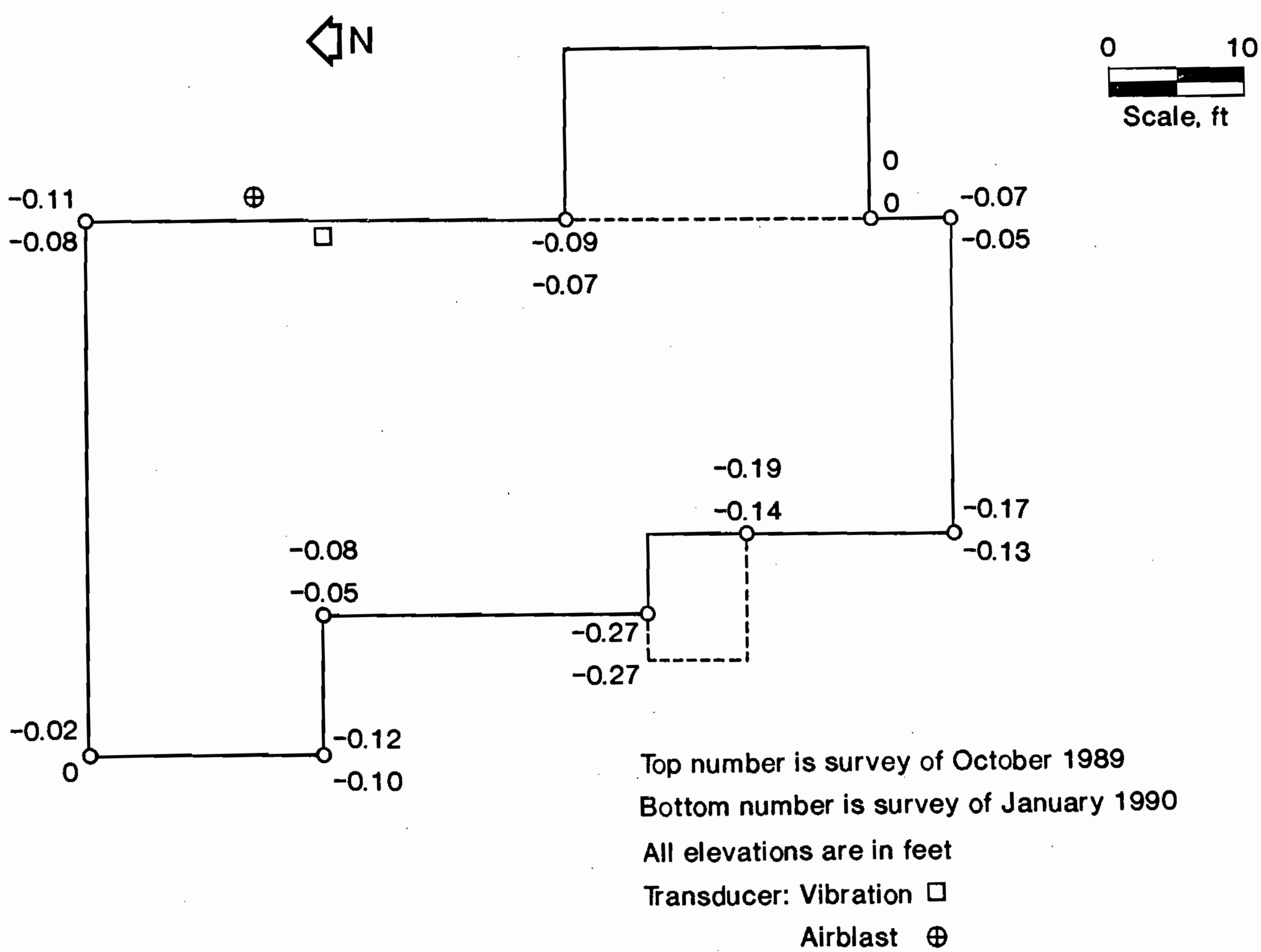


Figure 37. - House 303 and level loop surveys.

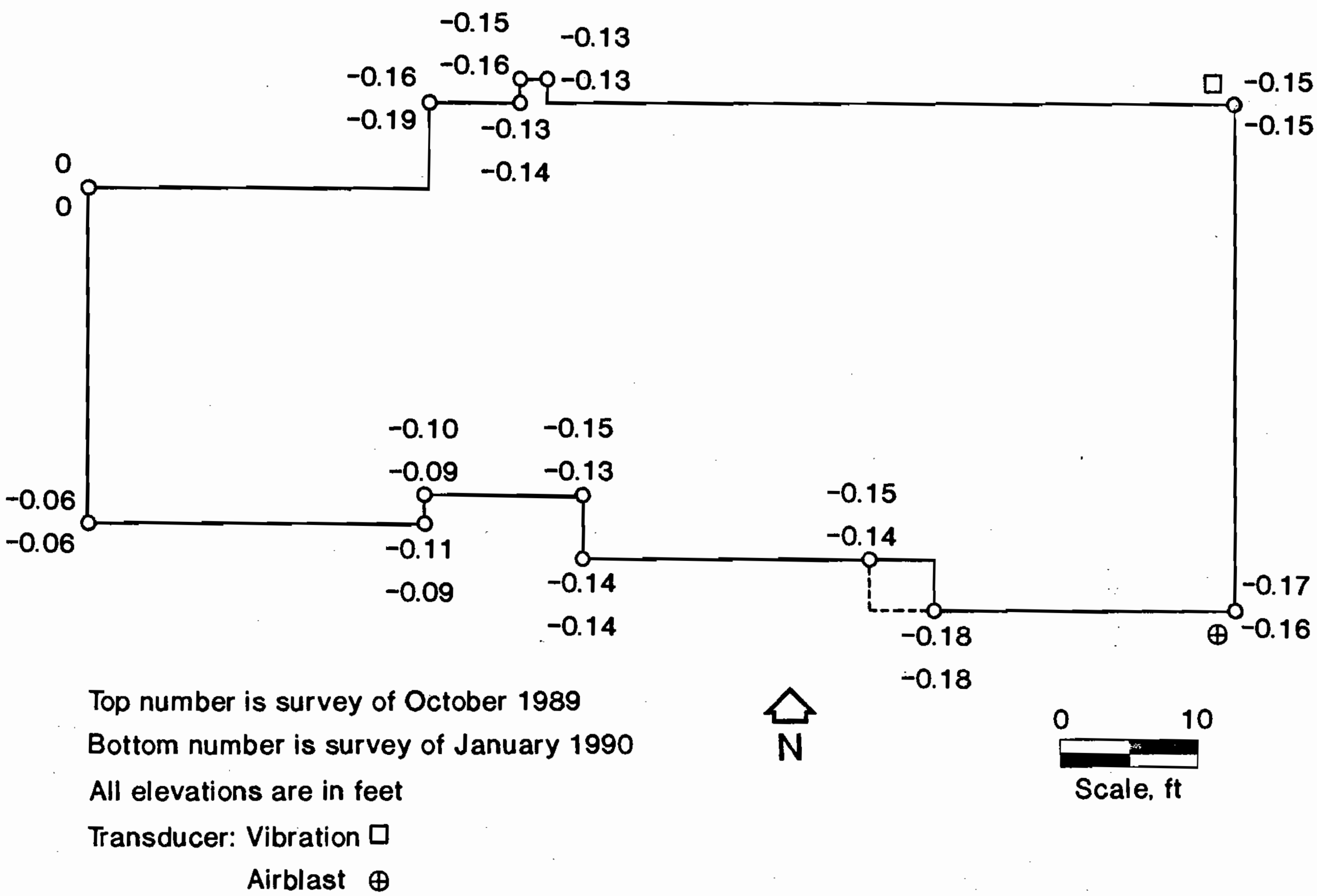


Figure 38. - House 334 and level loop surveys.

and do not directly indicate that the structure is under strain. Measured deviations could be due to differential settlement or the structures could have been built slightly out of level and free of strain, not having moved at all. If they were originally level most of these distortions are high enough for a substantial risk of cracking. Boscardin (15) cites the following ratio criteria in terms of angular distortions:

Structural damage...........................1:150

Cracking of panel and load-bearing walls....1:300

Noncracking case............................1:500

These are relatively high values. For example, the 1:226 for house 303 corresponds to the cracked north wall and means that the down-hill corner (NE) is 0.10 ft (1.2 in) lower than the uphill (NW) corner 23 ft away. All four houses on hills had their down-hill ends low as if there had been some down-slope slippage. The survey for house 107 had to be done using the roof eave as a survey horizon, making the data less reliable than homes with a traceable foundation or brick course. Additionally, house 215 has an elevation value which is so far off that it looks like a transcription or reading error: the 0.10-ft reading in the NE corner. There was no cracking damage corresponding to this very large "change" so it is being considered erroneous.

SOIL CHARACTERISTICS AND FOUNDATION FAILURE

The relatively low levels of vibration measured by the Bureau during the course of this investigation indicate that phenomena other than blasting are responsible for the structural damage observed in the study area. One clue to a possible cause is found in the report describing the proceedings of the informal public conference held, as part of the review of AMAX's mining permit, in McCutchanville on May 4-5, 1989 (1). It was stated that "a point of general agreement was the relatively recent time frame for the escalation of these problems. A number of speakers noted that they had either been lifelong residents or had been in the neighborhood for more than ten to fifteen years and that serious problems have only been noted since 1987-88." One speaker stated that she had lived in the area 34 years and had never had any cracked windows until the period between the spring and fall of 1988 when 10 occurred. Although the introduction of cast blasting at Ayrshire in March, 1988 has been offered by others as an explanation for the recent increase in damage complaints, given the Bureau's vibration measurements and available historical data, a more probable cause is the extremely dry conditions and the accompanying soil volumetric changes that manifested as a result of the drought of 1988.

Near the end of the Bureau's monitoring program, researchers realized that soil and foundation conditions may be important for understanding the observed damage in McCutchanville and Daylight. Researchers were aware that OSM was having tests run on local soils. However, the details of those tests and analyses weren't known nor expected to be available for this report. In addition, the agreement between OSM and the Bureau stated "if the blasting is not found to be responsible for the observed damage, researchers will try to determine the likely causes." Consequently, the Bureau examined the question of soil-structure interaction as applies to the north Evansville area and collected a sample for testing. Results are described in detail in Appendices G through I.

BLAST DESIGNS

A detailed analysis of blast design influences was beyond the scope of this study, although it was included in a second phase proposal which was not funded. Specifically of concern is the vibration and airblast from cast blasting, a potentially stronger source for these effects as described in the Appendices A and B. During the Bureau's study, the Indiana DNR reviewed blasting done at the Ayrshire mine and found that blasts detonated during the first week of monitoring ranged up to 7500 lbs/delay and 280,000 lbs per blast total. These are comparable to previous periods including those corresponding to times of high complaint numbers.

Using the site 6 propagation equation given previously in the Background section suggests that a doubling of charge weight will increase vibration amplitudes by a factor of about 1.50. Because amplitudes are low at the larger monitoring distances, typically .03 in/s, they would still be low even from such a large change in charge weight.

A variety of initiation delays were in use at different times as the mine continually experimented for acceptable and also productive blasting. Generally, little influence is expected from initiation design changes at the large distances of concern here, but this is admittedly an area needing additional research.

CONCLUSIONS

Many homes north of Evansville, Indiana, in the communities of Daylight and McCutchanville, have cracks in both superstructures and foundations. In some cases, the damage is far from cosmetic, being extensive exterior wall cracks up to and including basement wall collapse.

The Bureau of Mines studied the damage states in these two communities including an assessment of the vibration environment (current and past, blasting and other sources), and damage evaluations for a sampling of homes.

1. Vibration Amplitudes: Some were found to be high relative to the large blast-to-structure scaled distances. McCutchanville amplitudes ranged up to 0.06 in/s, somewhat high for the over four-mile distance. Some previous measurements at 10 miles (in Haubstadt) were well beyond expectations at about 0.04 in/s.

2. Vibration Frequencies: As expected from previous work at this site, frequencies were low primarily because of the nature of the near-surface

geology and aggravated by the long blast-to-receiver distances (note that these long distances also reduce vibration amplitudes). Measurements in Daylight ranged from 4 to 20 Hz while those in McCutchanville clustered closely around 4 to 5 Hz. These low frequencies are abnormally noticeable both directly by persons and by their relative efficiency in producing structure rattling.

3. Structure Responses: An examination of blasting and other vibration sources found that these structures responded similarly to other previously studied structures. Other impulsive vibration sources, such as human activity, local aircraft operation, etc. also produced comparable structural responses, another result consistent with previous studies (3, 5).

4. Airblast Effects: No significant airblasts occurred during the monitoring period. A proper assessment of past airblast impacts cannot be done. This is because airblast measurements either do not exist for most of the dates labeled "severe" by the homeowners, or were obtained too far away to be of any use. Airblasts must remain a possible contributing factor in perceptibility and even possibly in some cosmetic effects. However, the lack of widespread glass breakage makes it unlikely that 140 dBL has ever been exceeded, a value that also represents a threshold chance of plaster cracking (4). There is no chance that airblasts below that glass breakage threshold of 140 dB would cause foundation cracks.

The use of cast blasting does produce a potential airblast problem through both high relief (possible blowouts) and severe rock throw-producing APP-type airblast. The relationships between blast design (particularly casting) and airblast needs investigating. The variability of casting-produced airblast combined with weather conditions favoring long-range sound propagation appear to account for occasional anomalous "events" such as the distant Peabody

Lynville mine blasts measured in McCutchanville. Climatological data support the idea of occasional long range airblast propagation in the Evansville area.

There is no way to tell if the airblasts measured by the Bureau are representative of past airblasts because of their variability and the lack or inaccessibility of available records in the area of concern.

5. Cracks in Homes: Inspections and surveys conducted during the 64-day blast monitoring period found very minor changes in crack widths and relative elevations that had no correlation to the blasting. All level-loop survey results were consistent with down-slope slippage for those homes on slopes. Cyclic changes and their causes are ambiguous as they were not monitored long enough to encompass a complete one year weather cycle. Researchers noticed that some of the biggest crack-width changes and related effects occurred during a period of two very large temperature swings.

Blast vibrations measured by the Bureau were at least two orders of magnitude below the 5-10 in/s required to crack concrete walks, driveways and foundations and to cause major superstructure cracks. Because there are no conceivable blast design changes that could even begin to account for this vast difference, researchers conclude that blasting vibration is not responsible for the damage that is inarguably present. Airblast is admittedly more variable, however, researchers saw no evidence that levels have ever been high enough to account for the magnitude of damage. Although little data exist outside of military studies, a reasonable beginning value for airblast damage to masonry and concrete is 5 lb/in^2 (note that a 131 dB airblast is .01 lb/in^2). This 5 lb/in^2 would be expected from a surface blast of 400 lb at a distance of about 66 ft, and is why the bombing destruction of concrete fortifications require at least a very near-miss.

A preliminary soil engineering analysis and tests on a single soil sample suggest that expansible clay-containing soils activated by weather extremes may be the primary cause of major cracking in area homes. This mechanism is possibly assisted by other soil properties and construction designs, such as partial basements, that place differential soil-foundation forces on homes with non-uniform foundations located on slopes.

The most seriously-damaged homes are in McCutchanville as contrasted to Daylight and the NW direction also examined. This suggests a geographical correlation with damage rather than a simple distance from the mine rule. Two of the most seriously damaged homes show evidence of water intrusion. Wet and dry cycles are going to continually "work" homes on the clay-containing soils in the study area. The simpler Daylight homes appear less susceptible to these forces because of complete basements, uniform home designs, and level ground.

At this time, there is no more plausible explanation than unusual soil forces for the observed damage, particularly cracks occurring in concrete and foundations, caving basement walls, collapsing pipes, steps pulling away and other down-slope failures.

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APPENDIX A. - GROUND VIBRATIONS

Generation and Propagation

Vibration amplitudes (expressed as particle velocities, in/s) have been found to mainly depend on two simple factors, charge weights per delay and distances. Most equations describing vibration amplitudes include only these factors as exemplified by the coal mine summary propagation prediction from RI 8507 (3):

$$V = 119\ (D/W^{1/2})^{-1.52}$$

where V is the particle velocity at a monitoring site in in/s at a distance (D) in ft from a charge (W) in lbs of explosive per delay.

A third factor of less importance than charge weight and distance is the degree of confinement, expressed in various ways such as "depth of burial" in loose material and "burden" in rock. In standard coal mining echelon blasting, the rock is well confined and is primarily fractured in place. The relatively new techniques of cast blasting use smaller burdens and long between-row delays to throw a significant portion of the overburden across the pit. There is no question that casting improves productivity by reducing handling costs. Casting blasts often use large explosive weights and typically full-column charges. Offsetting the effects of the large charge weights is the smaller burden and some believe this reduces vibrations. A previous study of Indiana surface coal mine blasting appears to support this supposition, with lower vibration amplitudes on a charge weight per delay basis (7).

A potentially serious side effect from casting is a less predictable airblast and an enhanced air pressure pulse (APP), defined as an airblast component produced by the piston effect of the moving rock, as described in RI 8485 (4). Both the APP and increased chance of a blow-out suggest that casting increases the risk of occasional high airblast; However, this has not been studied. Airblasts are described in more detail in the next section.

Vibration propagation examples are shown in figure A-1 for six Indiana surface coal mines, scaled according to square root of charge weights per 8-ms delay. Line 6 represents a westward-oriented seismic array at the Ayrshire mine, the same general direction of concern for this study. The propagation equation for line 6 is:

$$V = 51\ (D/W^{1/2})^{-1.16}$$

Note the low values of the exponent as compared to the earlier coal mine summary from RI 8507, showing a lesser attenuation with distance, in fact, this is the shallowest slope of all six mines represented by figure 2. The Ayrshire mine parameters for the line 6 data are as follows:

1. Distances of seismographs..............................100 to 6000 ft.
2. Charge weight per delay................................1350 lbs
3. Hole diameter..12-1/4 in
4. Initiation design..............................17- by 100-ms Echelon
5. Time of monitoring...................................April 1987

Dates are given because of the mine is continually moving, westward in this case. An earlier study of vibration and airblast from Ayrshire mine blasting was done by the Bureau when the mine was considerably to the east and the geology was different (6). These earlier measurements examined blast design effects on vibrations; however, casting was not in practice at that time, between 1980 and 1983.

Vibration Effects on Structures

Cosmetic Cracking in Homes

The most comprehensive study of blasting vibration impacts on homes is the Bureau of Mines RI 8507 on ground vibration (3), published in December 1980. Supplementing this was a follow-up study of repeated long-term vibration

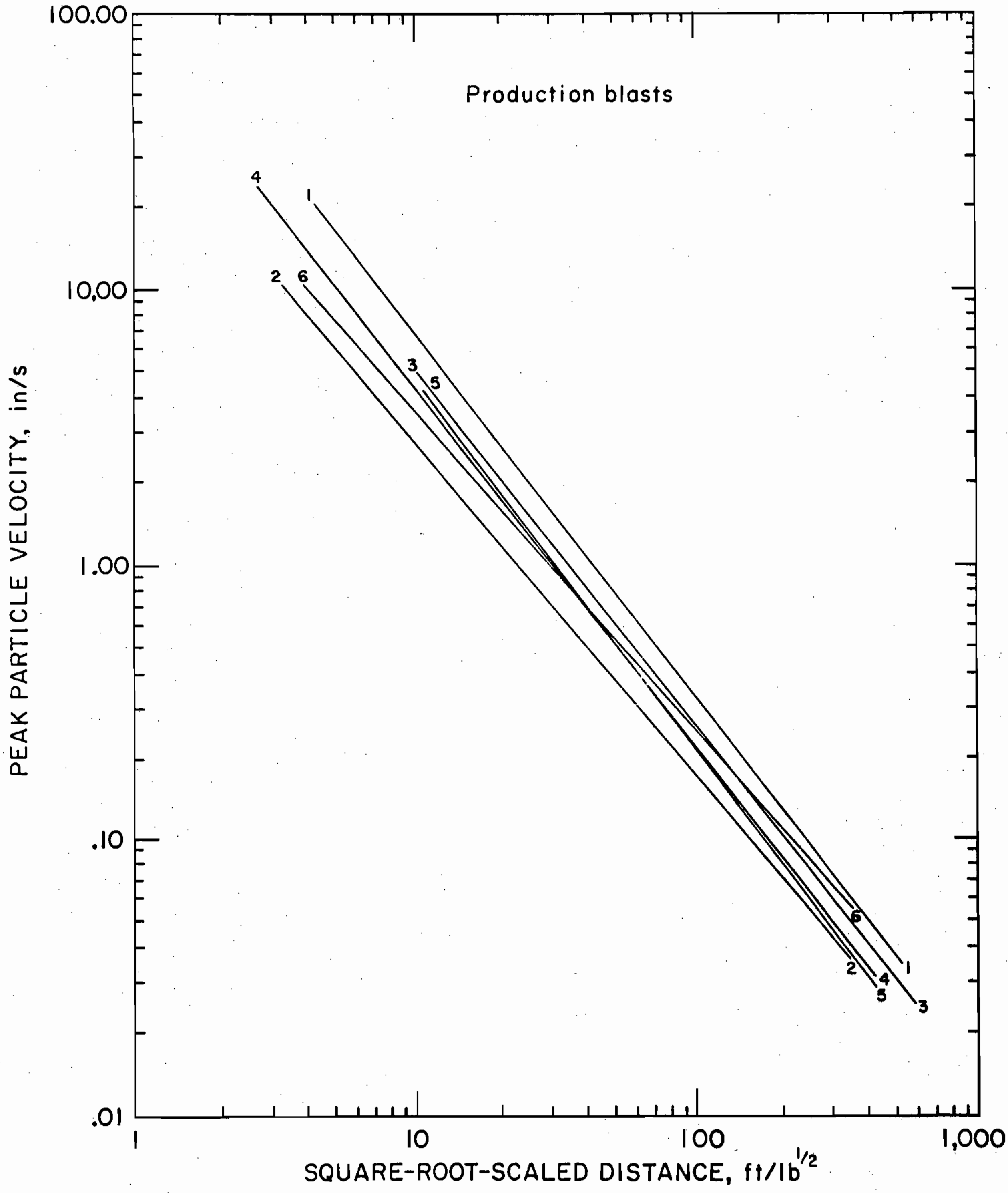


Figure A-1. - Propagation plot regressions for production blasts for six Indiana coal mines monitored by the Bureau of Mines, from Bureau of Mines RI 9226 (7).

effects on a single structure, components and materials, RI 8896 (5). These two studies summarize all available and appropriate observations of low-level blast-produced cracking. Their scopes of study were low-rise residential type structures from small to moderate size blasts (up to about 4,000 lb/delay) and moderate distances of a few miles.

A major finding in RI 8507 was the importance of vibration frequency to both structural response and damage potential. Figure 21 shows the Bureau-developed "safe-envelope" including reduced levels at low frequencies. Most serious for the Indiana blasting situation is the small amount of new and reliable low-frequency data in RI 8507 and, in particular, no Bureau damage values below 10 Hz (Figure A.2). The exact damage risk at low frequencies, especially below 4Hz, should be considered as approximated by the Bureau's evelope. RI 8507 discusses the special problems of low frequency sources, such as earthquakes, and use of the old 0.030-in displacement criterion (3).

Structural Response

Structures shake from blasting according to the characteristics of both the vibration and the structure (see RI 8507 for detailed discussion). For low-rise residential structures, typical amplifications in their natural frequency range of 4-12 Hz are 1.5-2 times. Midwall responses can be higher and correspond to high secondary noises, such as window sash rattling. They definitely contribute to vibration and airblast perceptibility.

Cracking of Concrete

Massive concrete is understandably very resistant to vibration-induced cracking. Oriard recommends restrictions for new (green) concrete which has not yet fully cured, estimating a safe level of 2-4 in/s after 7-10 days (9). In actual tests, he 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 also lists TVA criteria for mass concrete which specify a level of 12 in/s for

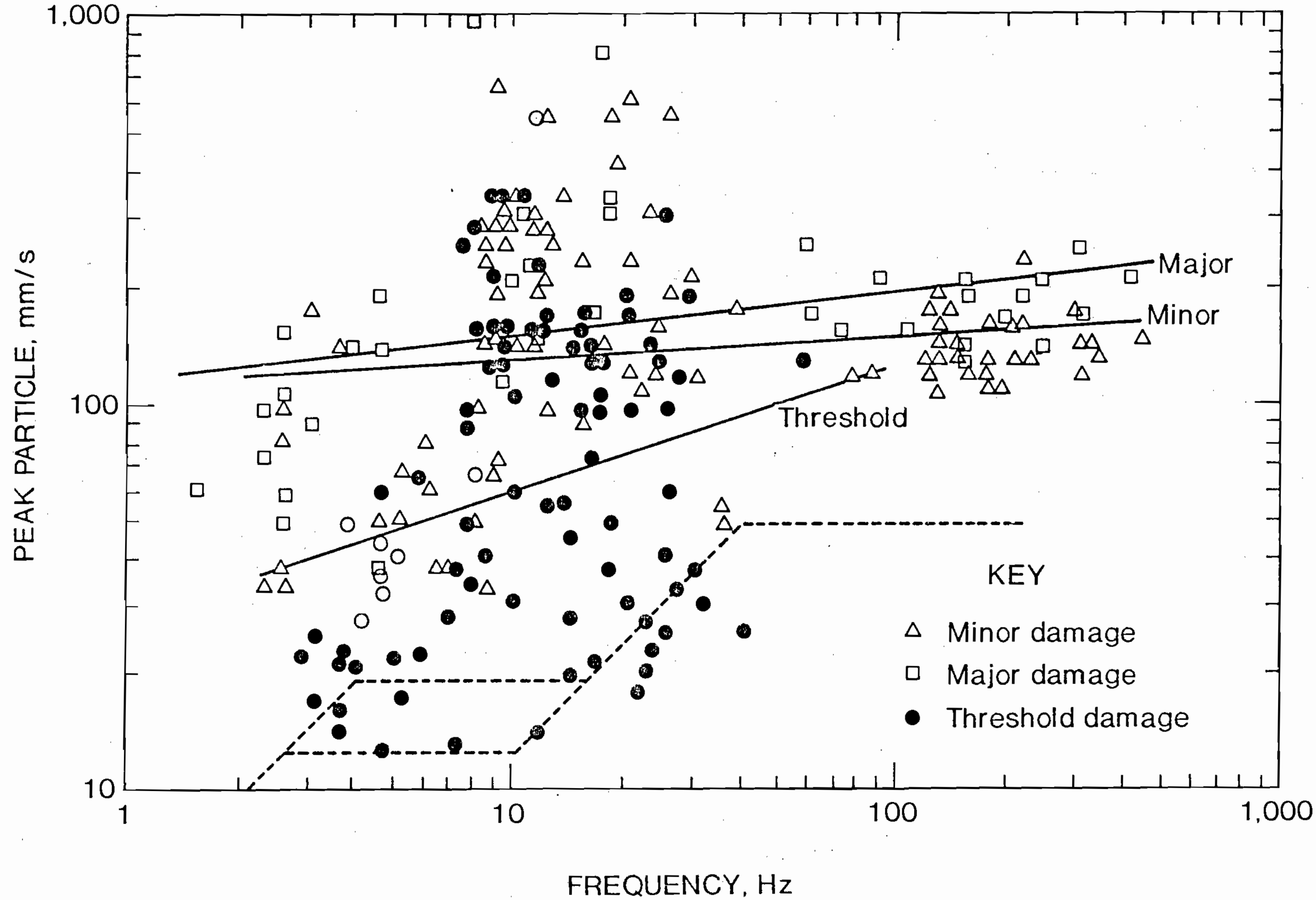


Figure A-2. - Vibration damage summary from Bureau of Mines RI 8507 (3). Envelope defining safe level limits uses a combination of velocity and displacement from Appendix B of RI 8507.

concrete over 10 days old at distances beyond 250 ft. Closer distance allowed higher vibrations, e.g., up to 20 in/s within 50 ft. The American Concrete Institute recommended similar values for peak vibrations (up to 2-7 in/s). Obviously, these vibration levels are orders of magnitude above what the superstructures could withstand and not of concern outside the immediate vicinity of a blast (a few feet).

A small amount of data were collected on basement wall concrete block cracks by the Bureau in its studies of vibrations impacts on homes (5, 7). Three observations of cracks in these walls occurred at 6-11 in/s and frequencies were about 12 Hz (figure A-4).

Ambient Vibrations

Although only suspected at the time of publication of RI 8507, the 0.5 in/s vibration level criterion was found to have special significance in that it approximates typical existing ambient conditions in houses. Human activity such as walking, door closing, etc. and also weather influences such as wind gusts, temperature and humidity cycles produce internal strains equivalent to about 0.5 in/s (5). With a regular immersion in such an environment, it is not surprising that no blast-produced cracking was observed for tests below 0.5 in/s. As a result, Bureau researchers concluded that vibration levels below 0.5 in/s were insignificant except for two possible cases: Particularly sensitive devices, such as scientific instruments, which are vibration-isolated (shock-mounted), and vibrations with frequencies below those studied for blasting (less than 4 Hz). Examples of the latter are earthquakes or other teleseismic events such as nuclear tests.

Human Response to Vibrations

Whole Body Vibrations

Vibration effects on persons are also covered in the comprehensive RI 8507 (3). 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 effects.

The American National Standard, ANSI S3.18-1979 addresses whole-body vibration concerns for the general population (20). The ANSI guidelines are basically for steady-state rather than transient vibrations and address issues of health, task proficiency, and comfort. They are given in table A-1.

Table A-1. - Human tolerance to whole-body vibration of 1-minute duration, after ANSI S3.18-1979 (20).

Frequency, Hz	Vibration levels, in/s		
	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 inside buildings respond differently than persons trying to perform a task or remain comfortable within a vibration environment. They developed a separate standard for this case which implicitly includes the factors of attitudes, fears of damage, and feelings of intrusiveness in a private situation (one's home). This standard is ANSI S3.29-1983 (21). Here, people are not responding directly to the vibration, but to the structure's response to the vibration, including all the secondary effects of window rattling, superstructure's groan and creaks, loose items on shelves, pictures on walls, etc.

Table A-2 lists values of peak particle velocity for transients of less than one second duration for worst-case combined vertical and horizontal motion.

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 the 0.5 in/s of table A-2, 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 whenever the incoming (outside measured vibration) exceeds about 0.1 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 A-2 correspond to the threshold of perceptibility which is roughly 0.01 in/s. For these sensitive cases, any amount of noticed vibration could be judged unacceptable by homeowners.

Table A-2. - Human tolerance to vibrations in buildings, combined curve for frequencies of 8-80 Hz, after ANSI S3.29-1983 (21).

Area of concern	Peak vibration levels, in/s		
	One per day	12 per day	26 per day
Critical	0.0050	0.0027	.0019
Residences, day	.50	.25	.17
Residences, night	.008	.0038	.0026
Office	.71	.35	.24
Workshop	.71	.35	.24

APPENDIX B. - AIRBLASTS

Generation and Propagation

Blasting produces both groundborne energy (ground vibrations) and airborne energy called airblast overpressure or impulsive sound. As with ground vibrations, charge size per delay and distances are important prediction parameters. The degree of confinement is far more important for airblast than it is for vibration. The airblast wavefront is also influenced by weather conditions, particularly wind and temperature inversions. For these reasons, airblast overpressures for a given charge and distance can vary by two orders of magnitude (a factor of 100). In a parallel effort to its mine-blasting vibration studies, the Bureau also monitored airblasts and airblast-produced structure responses, summarizing its effort in the report RI 8485 (4).

Degree of Confinement

Although RI 8485 contains propagation curves for a variety of blast designs, these are only approximately applicable to the Ayrshire mine casting blasts because of the importance of confinement on airblast generation. "Standard" surface mine blasts studied in RI 8485 and RI 8507 are echelon or variations thereof. The Bureau has not studied the effects of casting on vibration and airblast.

As already mentioned, confinement is important for controlling airblast. Generally, mining blasts have sufficient confinement to insure 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 the air-pressure pulse (APP) discussed previously. When confinement is insufficient or deliberately designed to be low, explosive products 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 (thin and hard rock layers), conventional bench blasts with seams of weakness or other easy paths for an explosive breakthrough, and secondary blasting such as mudcapping a boulder. Casting blasts are designed for good rock-throw and, hence, have low confinement. Therefore, cast blasting can produce high airblast in two ways, through its strong rock-throw producing a high APP which is directional (strongest in front) and the increased risk of direct venting or blow out conditions.

Figure B-1 summarizes mining airblasts for three cases: 1) Total confinement (deep burial), 2) mining highwall bench blasts, and 3) slightly

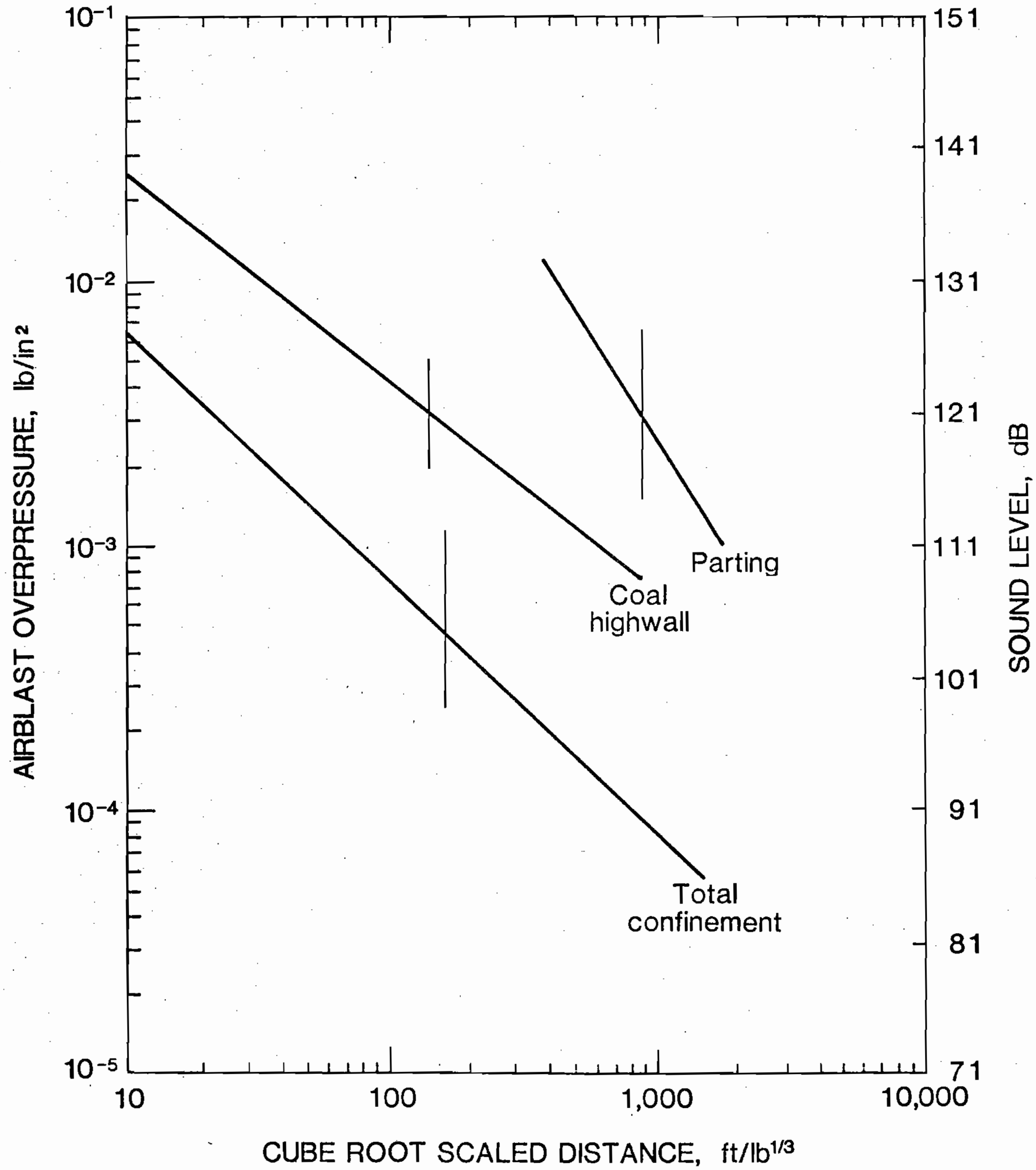


Figure B-1. - Airblast propagation from surface mining, from Bureau of Mines RI 8485 (4).

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 B-1. Casting would be somewhere between coal highwall and parting.

Figure B-2 summarizes all the mining airblasts including a minimum line presenting total confinement and a maximum line for unconfined surface blasts derived from a Ballistic Research Laboratory study (23). This figure is adopted from RI 8485 figure B-5 which has 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 blasts at 3,000 ft could produce from 0.00026 to .060 lb/in^2 (99 to 146 dB). This is an enormous range of uncertainty for prediction of airblast levels for a mining blast with only the knowledge of charge sizes and distances. When blast designs are known or fixed, however, predictions are considerably improved as shown by the reasonable standard deviation bars in figure B-1.

Table B-1. - Propagation equations for airblasts from mining type blasts in figure 8 and Table B-1 from RI 8485 (4).

Type of blasting	Equation	Correlation coefficient	Standard error, pct
Parting	$AB = 169\ (D/W^{1/3})^{-1.623}$	.587	120
Coal highwall	$AB = 0.162\ (D/W^{1/3})^{-0.794}$	.739	88
Total confinement	$AB = .061\ (D/W^{1/3})^{-0.956}$	NA	130

AB in lb/in^2, D in ft and W in lb of explosive per delay

Weather Influences

Both RI 8485 (4) and ANSI S2.20-1983 (24) on explosions in air discuss weather conditions effects on the propagation of airblasts. Two atmospheric

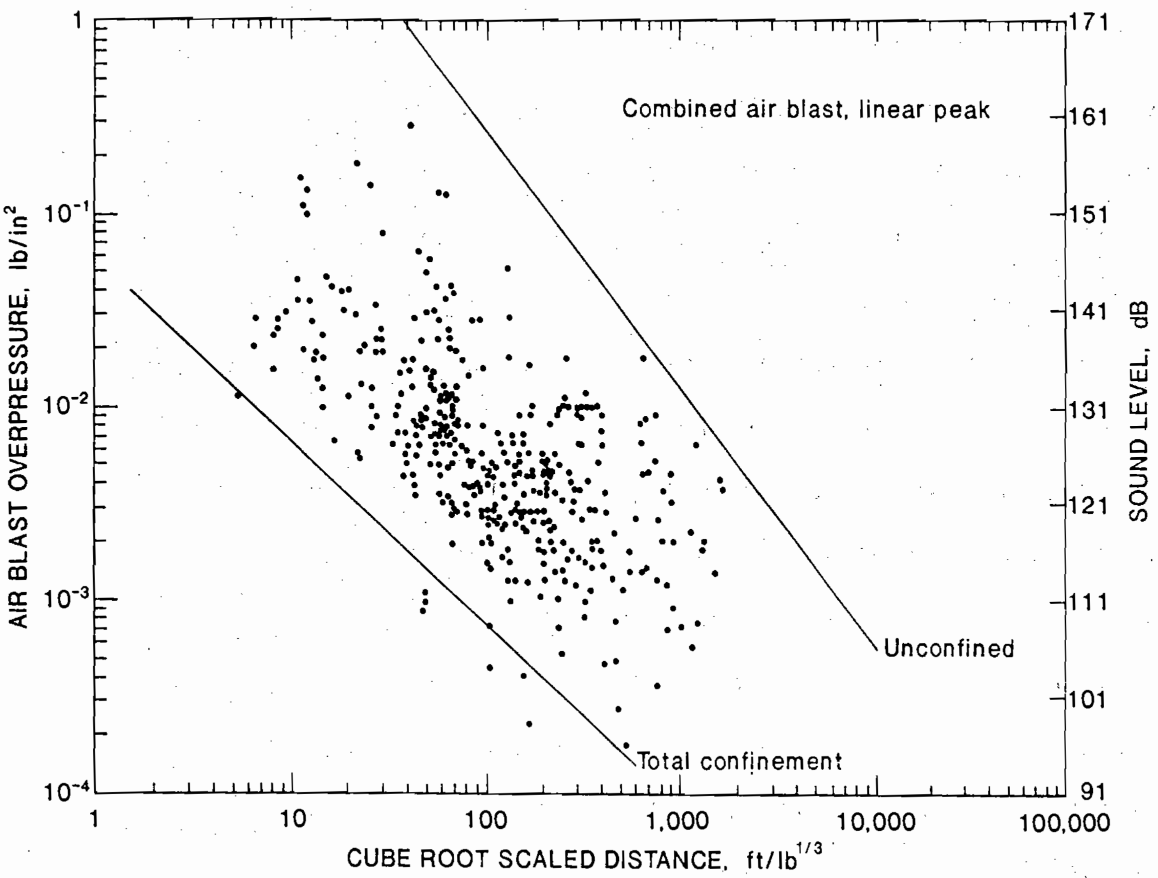


Figure B-2. - Combined mining airblast measurements for all sites, from Bureau of Mines RI 8485 (4).

conditions are significant, temperature inversions and wind (direction and strength). Both of these conditions can increase airblast levels above what would normally be found at a given scaled distance. They do not produce additional airblast energy, but only effect its distribution.

Temperature inversions are situations where warm air overlays cooler air. This is the reverse of the normal situation of steadily falling temperatures with altitude up to about 35,000 ft (24). 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 (or caustics) at large distances from the blast. A focus location will be an area of abnormally high airblast with a relatively silent zone between the focus and the source.

A review of cases in RI 8485 describes predicted inversion-produced sound intensifications of up to three times and averaging 1.8 times (=5.1 dB) (4). An ANSI Standard also reports some tests of atmospheric focusing and compared measured values with a linear probability distribution in its figure 20 (24). Tests showed a 1 pct chance of a two times amplification above the standard curves.

Temperature inversions are common in the mornings and evenings as the ground surface and air heat and cool at different rates. This is one reason surface mines tend to blast near the middle of the day. The DuPont Blaster's Handbook (25) has examples of inversion effects on airblast waves, reproduced here in figures B-3 through B-5.

Wind is the second significant weather influence on airblast propagation. Both RI 8485 and ANSI S2.20-1983 discuss wind effects. Examples of wind effects are 10 to 15 dB increases of sound level down-wind as compared to cross- or no-wind conditions for close-in quarry blasts, and a change of the propagation decay exponent proportional to wind velocity (4). The DuPont

Blaster's Handbook also discusses wind effects and has an example of down-wind airblast enhancement, shown in figure B-6.

Airblast Effects on Structures

Structure Response

As with ground vibrations, airblasts can produce structure rattling and, in extreme cases, cracking and other damage. The already-mentioned Bureau summary airblast report, RI 8485, includes plots of residential structure response to airblasts for a variety of measurement methods (4). Figures B-7 and B-8 show measured mean and maximum responses of structures to a variety of mining blasts for wide-band monitored airblast. Wide-band here means these peak overpressures were detected by a system with a flat response from 0.1 to at least 500 Hz and unfiltered. This insured that the responses were being compared to complete and undistorted airblast recordings.

Figure B-7 shows racking or whole-structure response as measured by corner-mounted transducers. Because cracking of structure walls results from strains in the plane of the wall, this type of response is significant to damage potential. For mining blasts, worst cases equivalencies 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 (3, 4).

Figure B-8 shows midwall responses to airblasts with considerably larger responses than racking from a given incident overpressure. As discussed in detail in RI 8485, this midwall response is not significant to cracking potential of structure walls with the exception of window glass. Indeed, cracking of 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 pictures, clocks, etc. being knocked askew or even occasionally off the wall. Although not significant to structural risk, these situations result in much

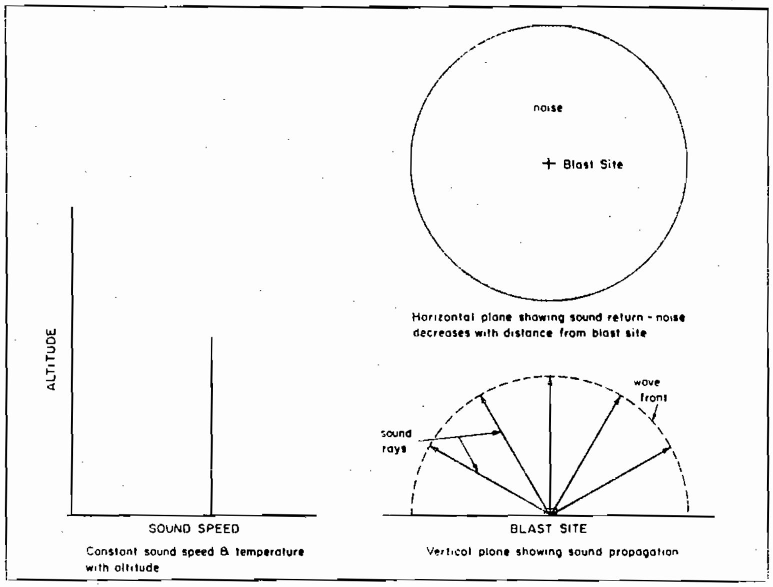


Figure B-3. - Sound propagation from an isothermal condition (speed is constant with altitude), from DuPont Blaster's Handbook (25).

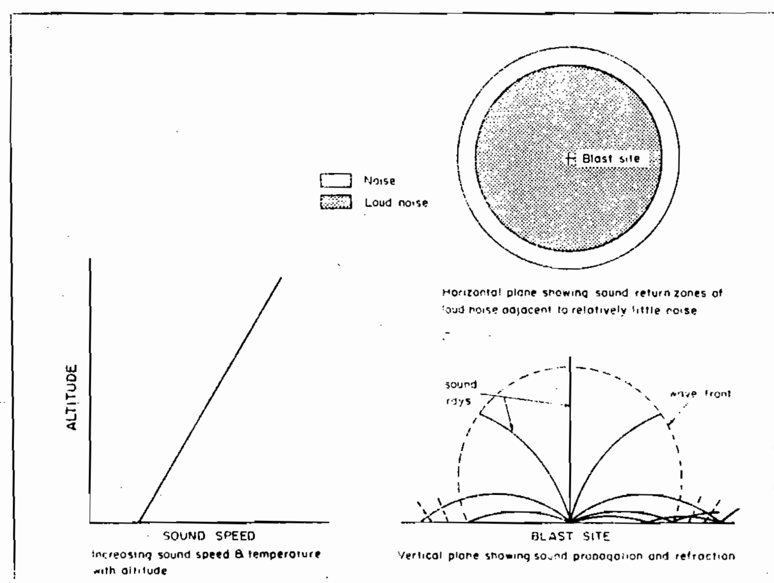


Figure B-4. - Sound propagation from a positive thermal gradient (speed increases with altitude), from DuPont Blaster's Handbook (25).

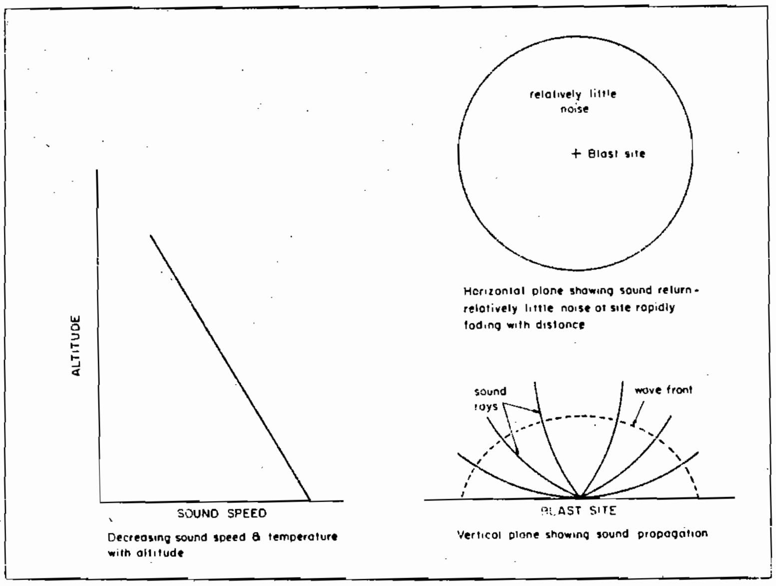


Figure B-5. - Sound propagation from a negative thermal gradient (speed decreases with altitudes), from DuPont Blaster's Handbook (25).

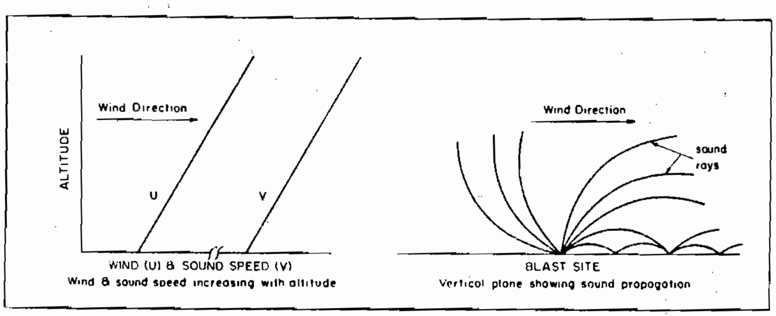


Figure B-6. - Sound propagation from a positive wind gradient (speed increasing with altitude), from DuPont Blaster's Handbook (25).

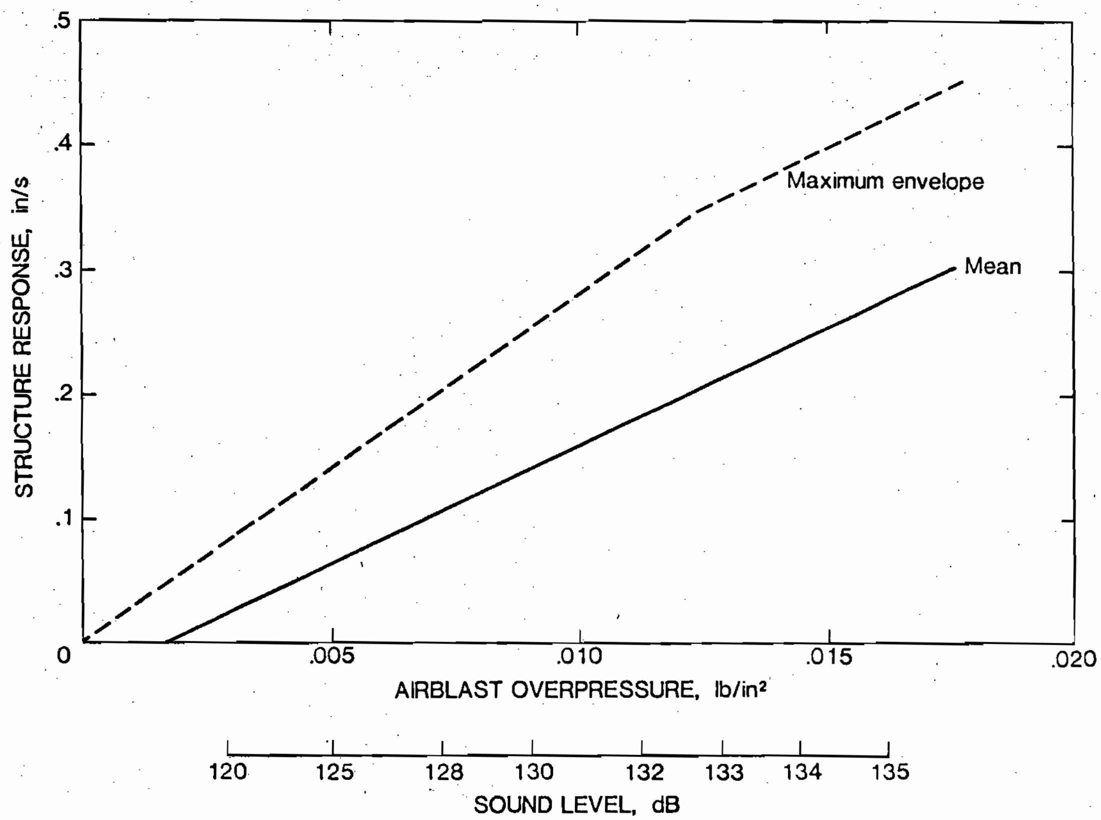


Figure B-7. - Structural response of low-rise structures from airblast overpressures, from Bureau of Mines RI 8485 (4).

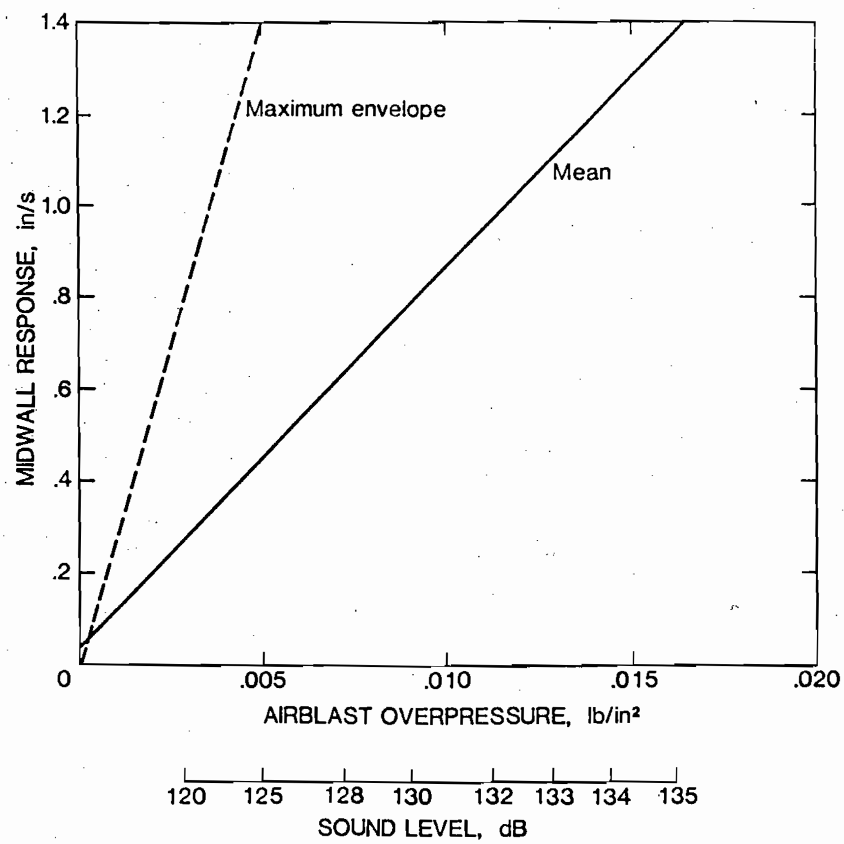


Figure B-8. - Midwall responses of low-rise structures from airblast overpressures, from Bureau of Mines RI 8485 (4).

of the neighbors' concerns that something serious and dangerous is happening to their homes.

Much research has been done on sonic boom-produced structure response. RI 8485 authors compared six boom studies to those 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 (28):

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

where p is pressure in lb/ft^2 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 comparable in amplitude to a strong airblast, its effects are not as noticeable because of the relatively slow rate of wind change and corresponding minor or nonexistent rattling, compared to the rapid rise time of an airblast transient.

Cosmetic Cracking and Glass Breakage

Bureau RI 8485 contains a summary of 18 older studies plus new analyses of airblast damage risks (4). A few very minor observations of damage 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 vibrations effects). Most of the studies in table B-2 concluded that an impulsive event sound level of 140 dB represents a good glass and plaster damage threshold.

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 vastly increased overpressures required to produce such damage. Napadenski gives structural failure probabilities of 10 pct for the following cases (29):

Framed construction 1 to 3 stories............1.5-2 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 "claims for damages such as cracked concrete foundations or broken pipes are invalid."

Human Response

Response of people to airblast is very much like that from 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. Blasting complaints from citizens almost always involve persons experiencing the "vibration" while in their homes rather than being outside. Consequently, they are actually responding to the structure's rattling, groaning, etc. In reality, people do not usually feel the direct ground vibration and sometimes do not even hear the direct airblast, which actually arrives about one second after the initial ground vibration for every 1,000 ft of source-to-receiver distance. For this reason, blast researchers measure all three quantities, vibration, airblast, and structure response on time-correlated multichannel systems. In this way, they can tell if and how much the structure responds to both the ground vibration and airblast. Figure B-10 shows such a set of records from RI 8507 (3) with structure responses from both vibrations and airblast.

As an example, a long-range blast may produce noticeable airblast response. 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, the house has a natural vibration frequency near 5 Hz and will respond to the airblast and produce a considerable amount 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 vibration arrived unnoticed 10 or more seconds earlier.

APPENDIX C.--VIBRATION DATA

Table C-1. - Bureau of Mines monitoring of Ayrshire Mine blasts: digital vibration amplitudes, in/s.

Date	Time	209	107	303	105	215	334
11-01-89	1252	.04	.04				
	1342	.04	.07				
	1540	.06	.05		.08	.08	
11-02-89	1150	(1)					
	1222						
11-03-89	1144				.07	.04	.07
	1329	.04	.03		.08	.06	.11
11-04-89	1028					.04	.08
	1110	.04	.03		.08	.05	.09
	1153		.05		.07	.03	.05
	1300					.02	.10
11-06-89	1108				.05	.04	.10
11-08-89	1403						
	1416						
11-09-89	1008						.10
	1126						.11
11-10-89	1049						.11
	1326						
	1344						
11-13-89	1111						
11-14-89	1452		.05	.03	.11	.05	
11-20-89	1410		.05		.10	.06	.04
11-21-89	1229	.04	.07	.05	.08/.07	.08	.05
	1453	.04	.05		.10/.08	.07	.07
11-22-89	1116	.05	.06	.05	.10	.09	.06
	1437		.05				
11-29-89	1110						
	1120						
11-30-89	1104				.05	.03	
	1140						
12-04-89	1019						
	1220						
	1233						
12-05-89	1212						
12-07-89	1113	.04			.07	.06	
	1319				.03	.04	
12-08-89	1200						
	1210						
	1345						
12-09-89	1357		.06		.06		
	1425						
	1452						

(1) Blank spaces are blasts for which seismographs did not trigger

Table C-1. - Cont.

Date	Time	209	107	303	105	215	334
12-11-89	1133						
	1154						
12-12-89	0951						
12-13-89	1450						.04
12-14-89	1240						
	1244						
12-23-89	1209	.06			.07		.07
	1404		.08	.04	.07	.11	.08
12-26-89	1200	.04	.04				.08
12-27-89	1029	.05	.06	.07		.07	.08
	1408						.05
	1418						.06
	1600		.05				.07
12-28-89	1126						.09
	1454		.04			.06	.09
01-03-90	1125		.05	.04			
	1450		.07	.03	.05	.06	.03

Table C-2. - Bureau of Mines monitoring of Ayrshire Mine blasts: digital airblast amplitudes, 5-Hz microphone, dB.

Date	Time	209	107	303	105	215	334
11-01-89	1252	104	100				
	1342						
	1540	94	94		104	104	
11-02-89	1150						
	1222						
11-03-89	1144				106	100	106
	1329	100	94		104	100	94
11-04-89	1028					94	104
	1110		94		94	94	
	1153		94		94	104	106
	1300					100	100
11-06-89	1108				94		94
11-08-89	1403						
	1416						
11-09-89	1008						106
	1126						104
11-10-89	1049						108
	1326						
	1344						
11-13-89	1111						
11-14-89	1452		100		106	108	
11-20-89	1410		94		94	112	108
11-21-89	1229	100	94	100	108	104	106
	1453	104	94		110	106	106
11-22-89	1116	106	104	108		110	104
	1437		104				
11-29-89	1110						
	1120						
11-30-89	1104				104	94	
	1140						
12-04-89	1019						
	1220						
	1233						
12-05-89	1212						
12-07-89	1113	94			106	104	
	1319				106	94	
12-08-89	1200						
	1210						
	1345						
12-09-89	1357		94		104		
	1425						
	1452						

Table C-2. - Continued

Date	Time	209	107	303	105	215	334
12-11-89	1133						
	1154						
12-12-89	0951						
12-13-89	1450						
12-14-89	1240						
	1244						
12-23-89	1209	94			104		100
	1404		94	100	100	104	94
12-26-89	1200	94	94				100
12-27-89	1029	94	94	100		94	94
	1408						106
	1418						104
	1600		94				104
12-28-89	1126						100
	1454					100	94
01-03-90	1125			94			
	1450		94	100	108	118	108

Table C-3. - Monitoring of surface coal mine production blasts, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Dallas ST 4 seismograph, structure 105, Daylight.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-01-89	1540	V R (E) T (S)	.037 .054 .060	5.5 12, 5 10, 6	5 3.5 2.3			103	11,260	4,234	173
11-03-89	1144	V R T	.017 .059 .043	3.8 10, 8.8 8	5.5 5 4.5			100	11,462	4,292	175
11-03-89	1329	V R T	.030 .062 .062	4.3 14, 5 4				102	11,665	4,408	176
11-04-89	1110	V R T	.025 .071 .060	5.7,3.4 5.5 5.4	4 3 3.8			<100	11,885	2,275	249
11-04-89	1153	V R T	.019 .040 .056	5.6 5.7 5.4				<100	11,976	2,015	267
11-06-89	1108	V R T	.05 .05 .05					<100	12,212	1,972	275
11-14-89	1452	V R T	.012 .022 .008	33 11.1 12.0				99	9,924	2,016	221
11-20-89	1410	V R T	.048 .056 .032	4.8 4.6 4.8				98	9,971	1,919	228
11-21-89	1229	V R T	.036 .067 .040	25 13.3 10.0				104	10,526	3,285	184

Table C-3. - Continued

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Freq-uency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-21-89	1453	V R T	.058 .066 .034	14.3 13.3 16.7				109	10,397	3,285	181.4
11-22-89	1116	V R T	.092 .094 .075	4.1 8.7 4.9				N/A	10,253	6,225	130
11-30-89	1140	V R T	.045 .041 .014	6.4,11. 5.5 6.5				N/A	9,748	1,625	242
12-07-89	1113	V R T	.026 .059 .034	10.5 10.5 9.5				<100	9,541	1,625	237
12-07-89	1319	V R T	.027 .036 .021	6.1 11.8 10				102	9,514	3,915	152
12-09-89	1357	V R T	.029 .051 .026	9.1 11.1 8.0				<100	9,505	4,140	148
12-23-89	1209	V R T	.024 .036 .056	5.4 11.8 11.1				99	10,874	7,004	130
12-23-89	1404	V R T	.047 .048 .055	5.3 5.3 7.4				97	11,111	7,352	130
01-03-90	1450	V R T	.040 .047 .020	15.4 10.0 11.7				111	9,981	3,190	177

Table C-4. - Monitoring of surface coal mine production blasts, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Dallas ST 4 seismograph, structure 107, McCutchanville.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Freq-uency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-01-89	1252	V R (NE) T (NW)	.038 .043 .040	2 5 6.6	8 10 8				25,973	7,482	300
11-01-89	1342	V R T	---- .027 .012	5 6	6 6				26,080	3,596	435
11-01-89	1540	V R T	.008 .044 .020	2.2 5 3	8 10 9.5				26,349	4,234	405
11-03-89	1329	V R T	.007 .012 .020	2.2 3, 5.5 2.8,5.9					26,930	4,408	406
11-04-89	1110	V R T	.006 .025 .017	2.4, 5 4.8 2.9	6.5 7 7				27,222	2,275	571
11-04-89	1153	V R T	.0057 .023 .014	5 5					27,339	2,015	609
11-14-89	1452	V R T	.004 .029 .013	5.6 5.6 6.45		.0024 .007 .024			23,911	2,016	533
11-20-89	1410	V R T	.010 .028 .019	2.1 4.8 4.4					23,858	1,919	545
11-21-89	1229	V R T	.005 .025 .019	14.3 5 11.6					25,184	3,285	439
11-21-89	1453	V R T	.0038 .030 .012	5.3 4.8 3.9				100	24,933	3,285	435

Table C-4. - Continued

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-22-89	1116	V R T	.025 .060 .030	2.1 4.9 5.3	8			105	24,609	6,225	312
11-22-89	1437	V R T	.004 .028 .0088	2.07 5 6.1				100	24,225	3,470	411
12-09-89	1357	V R T	.0067 .026 .011	4.55 5.13 5.26	4.3			102	21,354	4,140	332
12-23-89	1404	V R T	.0092 .031 .021	4.65 2.86				<100	26,202	7,352	306
12-26-89	1200	V R T	.0037 .014 .019	10.5 5.71 8.0					26,583	6,668	325
12-27-89	1029	V R T	.0053 .026 .026	2.18 4.44 6.25				<100	26,875	4,234	413
12-27-89	1600	V R T	.0037 .024 .014	5.71 5.26					27,402	4,060	430
12-28-89	1454	V R T	.022 .032 .015	5.40					27,654	4,002	437
01-03-90	1125	V R T	.0039 .026 .014	5.40 6.7					24,391	2,900	453
01-03-90	1450	V R T	.0060 .033 .0093	5.6 6.5					24,129	3,190	427

Table C-5. - Monitoring of surface coal mine production blasts, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Dallas ST 4 seismograph, structure 108.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-01-89	1251	V R T	.03 .03 .02					103	28,046	7,482	325
11-01-89	1537	V R T	.01 D .03 D .02 D					NA	28,324	4,234	435
11-14-89	1450	V R T	.02 .03 .02					103	26,465	2,016	589
11-22-89	1113	V R T	.04 .04 .03					103	27,003	6,225	342
12-27-89	1024	V R T	.02 .04 .02					102	28,691	4,234	441

Table C-6. - Monitoring of surface coal mine production blasts, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Dallas ST 4 seismograph, structure 209.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-01-89	1252	V R (E) T (N)	.017 .037 .032	2 4.8 5, 3.3	 4 4			104	25,677	7,482	297
11-01-89	1342	V R T	 .20 .018	 5.1 6	 3.6 3.6			NA	25,785	3,596	430
11-01-89	1540	V R T	.007 .036 .022	4 4.6 4.7				104	26,055	4,234	400
11-03-89	1329	V R T	.008 .024 .020	3 6.25,2.3 5, 12.6	 7.5 8			NA	26,638	4,408	401
11-04-89	1110	V R T	.005 .024 .024	2.0 5.3 6.1	5.6 5.3 7.4			NA	26,932	2,275	565
11-21-89	1229	V R T	.010 .022 .018	2.1 4.5				NA	24,885	3,285	434
11-21-89	1453	V R T	.008 .023 .024	2.9 4.9 5.7				104	24,633	3,285	430
11-22-89	1116	V R T	.030 .049 .037	2.2 4.6 4.9				102	24,305	6,225	308
12-07-89	1113	V R T	.019 .036 .010	2.0 1.75 3.13				< 100	21,514	1,675	534

Table C-6. - Continued

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
12-26-89	1200	V	-					< 100	26,291	6,668	322
		R	.021								
		T	.031	6.3							
12-27-89	1029	V	.009					< 100	26,585	4,234	409
		R	.027	6.3							
		T	.020	6.3							

Table C-7. - Monitoring of surface coal mine production blasts, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Dallas ST 4 seismograph, structure 215.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-01-89	1540	V R (E) T (S)	.050 .081 .050	4.6 5.6, 15 15.8				103	10,708	4,234	165
11-03-89	1144	V R T	.028 .048 .035	3.9 9.5 11	5.5 5.5 4			97	10,785	4,292	165
11-03-89	1329	V R T	.057 .058 .038	4.5 9 10, 4.3				104	10,869	4,408	164
11-04-89	1028	V R T	.030 .038 .030	6.9 9.5 7.7	3 3 3			-	10,944	3,592	183
11-04-89	1110	V R T	.028 .058 .043	3.6 6.9 4.9	4.5 4.5 5			97	10,977	2,275	230
11-04-89	1153	V R T	.030 .038 .043	5.9 5.7 4.2				100	11,020	2,015	245
11-04-89	1300	V R T	.023 .029 .028	25 15.4 10	4 4 3.5			99	11,110	2,070	244
11-06-89	1108	V R T	.033 .044 .040	15.4 14.3 14.3	3			-	11,172	1,972	252
11-14-89	1452	V R T	.021 .042 .021	6.25 8.25 13.3				108	10,510	2,016	234
11-20-89	1410	V R T	.054 .040 .031	4.4 4.3 4.3				115	10,622	1,919	243

Table C-7. - Continued

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-21-89	1229	V R T	.031 .077 .047	15.4 13.3 14.3				104	10,489	3,285	183
11-21-89	1453	V R T	.033 .064 .035	14.3 14.3 14.3				105	10,484	3,285	183
11-22-89	1116	V R T	.092 .083 .066	4.7 3.4 4.7				112	10,513	6,225	133
11-30-89	1140	V R T	.026 .016 .007	4.1 4.3				100	10,878	1,625	270
12-07-89	1113	V R T	.019 .022 .022	6.5 6.1 5.4				107	11,171	1,625	277
12-07-89	1319	V R T	.020 .010 .014	6.3 5.1 5.0				97	11,246	3,915	180
12-23-90	1404	V R T	.038 .095 .047	3.9 16.7, 10 16.7				102	10,572	7,352	123
12-27-89	1029	V R T	.042 .059 .047	5.9 5.6 5.4				95	10,756	4,234	165
12-28-89	1454	V R T	.017 .041 .036	5.0 5.9 5.9				97	11,160	4,524	166
01-03-90	1450	V R T	.029 .058 .029	6.5 14.3 5.6				111	10,440	3,190	185

Table C-8. - Monitoring of surface coal mine production blasts, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Dallas ST 4 seismograph, structure 303.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-14-89	1452	V R (E) T (N)	.002 .013 .020	6					23,496	2,016	523
11-21-89	1229	V R T	.005 .016 .016	5.6				98	24,739	3,285	432
11-22-89	1116	V R T	.030 .024 .036	2.2 3.8				105	24,178	6,225	306
12-23-89	1404	V R T	- .017 .011	3.45 8.33				100	25,364	7,004	303
12-27-89	1029	V R T	- .016 .021	3.70 7.14				95	26,393	4,234	406
01-03-90	1125	V R T	- .018 .019	6.7				< 95	23,962	2,900	445
01-03-90	1450	V R T	- .017 .021	5.9 5.6				< 95	23,706	3,190	420

Table C-9. - Monitoring of surface coal mine production blasts, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Dallas ST 4 seismograph, structure 334.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-03-89	1144	V R (S) T (E)	.056 .073 .070	22.2 13.3 14.3	3.5 5.3 5.5			105	8,666	4,292	132
11-03-89	1329	V R T	.058 .091 .10	13 13 12.5				107	8,362	4,408	126
11-04-89	1028	V R T	.038 .067 .075	16 13 8.7				98	8,155	3,596	136
11-04-89	1110	V R T	.032 .068 .080	7 15.4, 6 14.3, 5	3.2 4 5			110	8,084	2,275	169
11-04-89	1153	V R T	.034 .041 .044	5.3, 12 6.5, 9 8.7				99	7,974	2,015	178
11-04-89	1300	V R T	.021 .094 .064	16.7, 7 13.3 13.3	3.5 3.5 3.4			106	7,880	2,070	173
11-06-89	1110	V R T	.064 .087 .092	28.6 14.3 14.3				102	7,767	1,972	175
11-09-89	1008	V R T	.073 .088 .065	20 20 13.3				< 100	7,945	2,030	176
11-09-89	1126	V R T	.077 .106 .097	16.7 16.7 14.3	3.5			102	7,528	2,668	146

Table C-9. - Continued

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Compo-nent of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-10-89	1049	V R T	.099 .084 .090	25 16.7 14.3				< 100	7,400	2,204	158
11-20-89	1410	V R T	.029 .023 .014	4.1 4.2 4.4				94	11,933	1,919	272
11-21-89	1229	V R T	.020 .028 .025	18.2 16.7 13.3				98	10,227	3,285	178
11-21-89	1453	V R T	.030 .055 .043	15.4 15.4 15.4				98	10,532	3,285	184
11-22-89	1116	V R T	.037 .047 .036	3.8 4.0 4.2				109	10,959	6,225	140
12-13-89	1450	V R T	.024 .033 .029	17 13 13				108	9,839	4,319	150
12-23-89	1209	V R T	.023 .044 .036	 15 14				110	9,410	7,004	112
12-23-89	1404	V R T	.041 .064 .048	11 17 17				108	8,965	7,352	105
12-26-89	1200	V R T	.057 .068 .068	17 14 14				110	8,552	6,668	105

Table C-9. - Continued

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
12-27-89	1029	V R T	.036 .063 .059	15 12				106	8,238	4,234	127
12-27-89	1408	V R T	.022 .026 .037	11 14 11				< 100	8,072	4,756	117
12-27-89	1418	V R T	.041 .049 .052	17 13 11.8				106	7,961	4,292	121
12-27-89	1600	V R T	.055 .052 .051	22 12 10				103	7,766	4,060	122
12-28-89	1126	V R T	.055 .081 .086	25 13 13				105	7,513	4,002	119
12-28-89	1454	V R T	.036 .097 .080	15 17 15				104	7,294	4,524	109
01-03-89	1450	V R T	.017 .023 .022	14 17 15				121	10,440	3,190	202

Table C-10. - Monitoring of surface coal mine production blasts and structure response, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Store 7 recorder, structure 105.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-01-89	1252	V R (E) T (S)	.099 .059 .080	5.3 4.2 6		.041 .042		113.6	11,027	7,482	127
11-01-89	1342	V R T	.029 .034 .027	5.2 5.5 5		.046 .040		101.3	11,075	3,596	185
11-01-89	1540	V R T	.029 .047 .057	4.4 4.4 9.5		.052 .034		109.4	11,260	4,234	173
11-03-89	1144	V R T	.026 .041 .035	20 10.5 9.1		.058 .048		109	11,462	4,292	175
11-03-89	1329	V R T	.034 .044 .046	4.3 11.6, 5.1 4		.057 .067		116.5	11,665	4,408	176
11-04-89	1028	V R T	.026 .044 .049	22, 9 8 8		.025 .077		92.6	11,823	3,596	197
11-04-89	1110	V R T	.030 .077 .071	5.9 5.6 5.5		.090 .110		104.8	11,885	2,275	249
11-04-89	1153	V R T	.020 .039 .055	5.5 5.4 5.0		.043 .073		104.6	11,976	2,015	267
11-04-89	1300	V R T	.025 .043 .037	22 12 9.5		.054 .054		99.0	12,104	2,070	266

Table C-10. - Continued

Date	Time	Component of motion	Velocity in/s	Frequency Hz	Duration s	Corner in/s	Midwall in/s	Airblast, dB	Distance, ft	Charge per delay, lb	Source root scaled distance
11-06-89	1108	V R T	.044 .049 .042	20 11 10		.062 .067			12,212	1,972	275
11-20-89	1410	V R T	.057 .060 .032	4.4 5.9 5.4		.072 .045		101.7	9,971	1,919	228
11-21-89	1229	V R T	.032 .046 .042	5 13 6		.055 .062		112.6	10,526	3,285	184
11-21-89	1453	V R T	.037 .052 .026	20 18 5.4		.064 .048		113.7	10,397	3,285	181
11-22-89	1116	V R T	.103 .083 .077	4.1 4.9 4.4		.100 .095		117.5	10,253	6,225	130
11-30-89	1104	V R T	.027 .024 .017	4.7 3 4.8		.032 .030		104.2	9,787	1,798	231
11-30-89	1140	V R T	.050 .037 .021	4.3 5.1 5		.047 .027		105.0	9,748	1,625	242
12-07-89	1113	V R T	.029 .061 .035	9 12 7.7		.070 .055		109.8	9,541	1,625	237
12-07-89	1319	V R T	.029 .034 .022			.040 .027		110.1	9,514	3,915	152

Table C-10. - Continued

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
12-23-89	1404	V R T	.042 .051 .060	2.6 12 8		.080 .080		112	11,111	7,352	130
01-03-90	1125	V R T	.025 .039 .032	6.7, 29 7 6		.050 .052		104.4	10,077	2,900	187
01-03-90	1450	V R T	.025 .039 .027	5 7 7		.050 .047		110.3	9,981	3,190	177

Table C-11. - Monitoring of surface coal mine production blasts and structure response,, AMAX Ayrshire Mine, November 1, 1989 to January 3, 1990, Store 7 recorder, structure 209.

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
11-01-89	1252	V R (E) T (N)							25,677	7,482	297
11-01-89	1342	V R T	< .01 .021 .012	5 6		.035 .017	.039	-	25,785	3,596	430
11-01-89	1540	V R T	.012 .032 .021	4.5 5		.077 .031	.085	-	26,055	4,234	400
11-02-89	1222	V R T	< .01 .0063 .0055			.0078 .0075	.017	-	19,013	325	1,054
11-03-89	1144	V R T	< .01 .022 .018	10.5 5.6 8.0	11 2.3	.052 .040	.058	106.6	26,349	4,292	402
11-03-89	1329	V R T	.024 .021	4.3 6.0	7.7 10.5	.045 .050	.053	-	26,638	4,408	401
11-04-89	1028	V R T	.006 .021 .016			.058 .024	.062	-	26,851	3,596	448
11-04-89	1110	V R T	.005 .028 .020	7.0 6.0 6.0		.037 .035	.040	-	26,932	2,275	565
11-04-89	1153	V R T	< .01 .020 .013	6.0 5.6		.038 .017	.046	-	27,051	2,015	603

Table C-11. - Continued

Date	Time	Ground vibration: Component of motion	Ground vibration: Velocity, in/s	Ground vibration: Frequency, Hz	Ground vibration: Duration, s	Structure response: Corner, in/s	Structure response: Midwall, in/s	Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
11-04-89	1300	V R T	.006 .016 .009	11 6 6.5		.030 .024	.039	-	27,204	2,070	598
11-06-89	1108	V R T	.004 .014 .014	5.0 5.4 6.0		.031 .027	.042	-	27,341	1,972	616
11-20-89	1410	V R T	.022 .020	4.4 5.0		.040 .027	.040	101	23,552	1,919	538
11-21-89	1229	V (ST4) R T	.030 .018	6.0 4.4		.049 .026	.055	103	24,885	3,285	434
11-21-89	1453	V R T	.008 .025 .019	4.7 5.6		.035 .025	.045	103.9	24,633	3,285	430
11-22-89	1116	V R T	.005 .053 .037	4.5 5.0		.096 .055	.112	106.0	24,305	6,225	308
11-30-89	1104	V R T	.009 .007	5.4 12.5		.014 .012	.023	97.1	22,885	1,789	540
11-30-89	1140	V (ST4) R T	.002 .009 .008	3 5.5 6.0		.017 .011	.018	-	22,624	1,625	561
12-07-89	1113	V R T	.019 .015 .017	5.1 5.6		.029 .021	.031	-	21,514	1,625	541

Table C-11. - Continued

Date	Time	Ground vibration				Structure response		Airblast, dB	Distance, ft	Charge per delay, lb	Square root scaled distance
		Component of motion	Velocity, in/s	Frequency, Hz	Duration, s	Corner, in/s	Midwall, in/s				
12-07-89	1319	V R T								3,915	
12-23-89	1209	V R T									
12-23-89	1404	V R T	.019 .022	4.3 5.0		.045 .039	.046	114.0	25,908	7,352	302
12-26-89	1200	V R T									
12-27-89	1029	V R T									
01-03-90	1125	V R T	.019 .019			.036 .028	.037		24,089	2,900	447
01-03-90	1450	V R T	.004 .019 .017	4.5 5.3 5.6		.029 .025	.040	97.1	23,825	3,190	422

APPENDIX D - Production blasts monitored by the Bureau of Mines, November 1, 1989 through January 3, 1990.

Shot no.	Date	Time	Type of blast	Northing	Easting	Tot/lbs	Lbs/delay
1[1]	11-01-89	1255	Casting	219,177	393,316	279,500	7,482
2	11-01-89	1346	"	219,376	393,279	38,377	3,596
3	11-01-89	1538	"	219,740	393,309	210,923	4,234
4	11-02-89	1145	Conventional	210,104	391,893	4,817	325
5	11-02-89	1220	"	209,683	391,674	18,031	325
6	11-03-89	1145	Casting	220,154	393,322	225,602	4,292
7	11-03-89	1331	"	220,562	393,328	241,311	4,408
8	11-03-89	1028	"	220,854	393,339	61,742	3,596
9	11-04-89	1110	"	220,960	393,347	75,265	2,275
10	11-04-89	1155	"	221,120	393,354	66,550	2,015
11	11-04-89	1300	Box	221,295	393,395	126,724	2,070
12	11-06-89	1110	"	221,473	393,408	136,169	1,972
13	11-08-89	1403	Conventional	209,389	391,474	21,833	462
14	11-08-89	1416	"	209,078	391,359	15,330	294
15	11-09-89	1008	Box	221,644	393,797	137,399	2,030
16	11-09-89	1126	"	221,822	393,401	153,490	2,668
17	11-10-89	1049	"	222,016	393,399	167,233	2,204
18	11-10-89	1326	Conventional	208,902	391,271	15,078	420
19	11-10-89	1344	"	208,738	391,186	17,178	210
20	11-13-89	1111	"	208,618	391,114	5,460	210
21	11-14-89	1452	"	216,307	393,022	106,969	2,016
22	11-20-89	1410	Casting	216,118	393,098	87,393	1,919
23	11-20-89	1230	"	218,126	393,188	193,725	3,285
24	11-21-89	1452	"	217,757	393,171	230,423	3,285
25	11-22-89	1116	"	217,257	393,162	325,588	6,225
26	11-22-89	1437	"	216,692	393,122	196,103	3,470
27	11-29-89	1107	"	215,762	393,061	186,927	2,842
28	11-29-89	1117	Conventional	215,447	393,033	28,923	1,740
29	11-30-89	1106	"	215,119	393,004	66,642	1,798
30	11-30-89	1140	"	214,708	392,972	50,421	1,625
31	12-04-89	1019	"	210,759	392,100	14,735	350
32	12-04-89	1220	"	210,990	392,226	14,649	350
33	12-04-89	1233	"	211,234	392,351	13,245	365
34	12-05-89	1212	"	213,937	392,805	75,075	2,210
35	12-07-89	1113	"	213,187	392,639	57,944	1,625
36	12-07-89	1319	Casting	212,866	392,553	83,790	3,915

[1]Shot numbers are keyed to map, Figure 19.

APPENDIX D - Continued

Shot no.	Date	Time	Type of blast	Northing	Easting	Tot/lbs	Lbs/delay
37	12-08-89	1200	Conventional	209,757	391,598	2,485	280
38	12-08-89	1210	"	209,903	391,648	8,980	245
39	12-08-89	1345	"	210,244	391,833	9,520	280
40	12-09-89	1357	Casting	212,543	392,470	179,297	4,140
41	12-09-89	1425	"	212,307	392,412	34,881	2,436
42	12-09-89	1452	"	212,107	392,344	125,870	2,552
43	12-11-89	1133	"	211,771	392,222	146,685	4,830
44	12-11-89	1154	Conventional	211,526	392,132	18,495	1,665
45	12-12-89	0951	"	209,575	391,425	12,670	280
46	12-13-89	1450	Casting	218,580	393,174	173,723	4,319
47	12-14-89	1240	Conventional	210,541	391,979	4,810	130
48	12-14-89	1244	"	209,698	391,537	4,815	225
49	12-23-89	1208	Casting	219,104	393,181	277,125	7,004
50	12-23-89	1404	"	219,659	393,183	296,572	7,352
51	12-26-89	1200	"	220,198	393,198	294,507	6,668
52	12-27-89	1029	"	220,614	393,201	227,560	4,234
53	12-27-89	1408	"	220,848	393,212	35,721	4,756
54	12-27-89	1418	"	221,017	393,230	160,717	4,292
55	12-27-89	1600	"	221,310	393,250	184,943	4,060
56	12-28-89	1126	"	221,669	393,243	182,883	4,002
57	12-28-89	1454	"	221,981	393,231	157,333	4,524
58	01-03-90	1125	"	217,083	393,023	153,129	2,900
59	01-03-90	1448	"	216,673	393,014	179,497	3,190

APPENDIX E - Summary Vibration Data

Table E-1. - Vibration and airblast from Ayrshire Mine blasting (SW of mine), McCutchanville direction: Cissell, M. McCutchan (N. blasts), R. McCutchan, stations 16 and 17.

Date	Time	Charge weight per delay, lb	Charge weight, total lb	Monitor location	Distance ft	SRSD, ft/lb	Vibration in/s	Airblast, dB
01-05-89	1055	3,400	178,100	Cissell	12,379	212	.07	
01-05-89	1207	3,700	236,100	Cissell	12,560	207	.09	
01-10-89	1341	3,700	230,500	Cissell	12,744	210	.11	
01-12-89	1112	3,300	198,800	Cissell	12,915	225	.08	
01-17-89	1113	3,700	153,900	Cissell	13,293	219	.06	<100
01-18-89	1448	450	3,400	Cissell	13,980	659	.07	
02-14-89	1201	2,900	145,200	Cissell	12,175	226	.06	
02-14-89	1424	3,700	204,000	Cissell	12,342	203	.08	
02-17-89	1350	3,700	177,700	Cissell	12,706	209	.07	
02-20-89	1031	3,100	71,300	Cissell	12,853	231	.07	
02-24-89	1345	3,300	137,900	Cissell	12,965	226	.06	
02-27-89	1313	3,200	70,600	Cissell	13,075	231	.06	
04-13-89	1108	2,200	44,500	Cissell	13,405	286	.04	<100
06-16-89	1035	3,510	238,578	Cissell	13,329	225	.10	100
12-13-88	1421	3,900	87,700	M. McCUT	18,111	290	.07	110
12-15-88	1131	2,600	146,700	M. McCUT	16,622	326	.08	107
12-19-88	1440	1,900	98,600	M. McCUT	16,541	379	.05	106
01-10-89	1341	3,700	230,500	M. McCUT	17,170	282	.09	109
01-12-89	1112	3,300	198,800	M. McCUT	17,269	301	.06	<100
01-16-89	1058	3,600	123,800	M. McCUT	17,408	290	.09	112
01-16-89	1114	3,800	108,500	M. McCUT	17,348	281	.06	107
01-17-89	1113	3,700	153,900	M. McCUT	17,491	288	.07	107
01-17-89	1433	2,000	86,200	M. McCUT	17,594	393	.04	<100
01-18-89	0952	2,000	36,700	M. McCUT	17,675	395	.05	107
01-18-89	1344	2,000	39,900	M. McCUT	17,707	396	.05	<100
01-20-89	1337	2,000	57,600	M. McCUT	17,893	400	.05	109
02-14-89	1201	2,900	145,200	M. McCUT	16,803	312	.07	
02-14-89	1424	3,700	204,000	M. McCUT	16,886	278	.05	
02-17-89	1350	3,700	177,700	M. McCUT	17,091	281	.05	
02-24-89	1345	3,300	137,900	M. McCUT	17,239	300	.13	
02-27-89	1313	3,200	70,600	M. McCUT	17,304	306	.11	
02-04-89	1134	3,300	178,100	R. McCUT	24,981	435	.05	103
02-14-89	1424	3,700	204,000	R. McCUT	27,593	454	.03	107
04-06-89	1254	1,700	45,800	R. McCUT	28,413	689	.07	124
04-13-89	1108	2,200	264,000	R. McCUT	28,609	610	.05	103

Table E-1. - Continued

Date	Time	Charge weight per delay, lb	Charge weight, total lb	Monitor location	Distance ft	SRSD, ft/lb	Vibration in/s	Airblast, dB
05-15-89	1049	5,580	334,038	R. McCUT	27,563	369	.05	103
05-23-89	1319	5,040	296,514	R. McCUT	24,501	345	.05	103
06-16-89	1033	3,510	238,578	R. McCUT	28,565	482	.04	103
07-21-89	1433	600	19,616	R. McCUT	22,807	931	.02	121
11-16-88	1400	2,000	115,800	16	6,135	137	.16	108
11-17-88	1329	2,400	166,400	16	6,243	127	.20	111
11-18-88	0917	2,400	82,800	16	6,319	129	.16	113
12-08-88	0939	4,000	236,800	16	5,751	91	.24	114
01-12-89	1112	3,300	198,800	16	5,600	98	.20	
01-16-89	1058	3,600	123,800	16	5,657	94	.13	
01-16-89	1114	3,800	108,500	16	5,597	91	.11	
01-17-89	1113	3,700	153,900	16	5,682	93	.17	108
01-17-89	1433	2,000	86,200	16	5,754	129	.10	
01-18-89	1344	2,000	39,900	16	5,824	130	.14	
01-20-89	1434	2,000	91,600	16	5,931	133	.11	
02-27-89	1313	3,200	70,600	16	5,521	98	.13	
04-13-89	1108	2,200	44,500	16	5,562	119	.17	108
06-16-89	1035	3,510	238,578	16	5,477	92	.23	109
10-15-88	1207	1,600	60,700	17	3,921	98	.14	
12-10-88	1343	1,600	76,900	17	5,872	146	.19	
12-16-88	1124	250	2,850	17	4,570	289	.13	
12-16-88	1128	250	3,250	17	4,508	285	.11	
12-16-88	1137	300	12,900	17	4,563	263	.17	

Table E-2. - Vibration and airblast from Ayrshire Mine blasting, Daylight direction: Cissell, stations 16 and 19. (E. of mine)

Date	Time	Charge weight per delay, lb	Charge weight, total lb	Monitor Location	Distance ft	SRSD, ft/lb	Vibration in/s	Airblast, dB
12-15-88	1131	2,600	146,700	Cissell	11,587	227	.07	106
12-19-88	1440	1,900	98,600	Cissell	11,442	263	.07	110
12-20-88	0928	3,000	160,100	Cissell	11,250	205	.12	106
12-20-88	1032	3,000	134,900	Cissell	11,067	202	.20	110
12-20-88	1152	2,700	58,000	Cissell	10,903	210	.14	<100
12-23-88	1109	2,800	137,300	Cissell	10,905	206	.15	<100
12-23-88	1148	3,600	151,100	Cissell	10,840	181	.18	<100
12-29-88	1446	3,800	212,300	Cissell	10,688	173	.15	<100
12-30-88	1134	3,000	89,100	Cissell	10,567	193	.12	<100
12-30-88	1321	3,000	136,000	Cissell	10,452	191	.13	<100
01-30-89	1101	3,100	176,100	Cissell	10,976	197	.13	<100
01-31-89	1107	2,100	44,900	Cissell	10,865	237	.12	106
01-31-89	1454	2,100	60,300	Cissell	10,771	235	.09	<100
02-02-89	1019	3,600	196,500	Cissell	10,743	179	.09	<100
02-02-89	1250	3,800	253,400	Cissell	10,657	173	.12	106
02-02-89	1415	2,700	67,500	Cissell	10,322	199	.10	106
02-04-89	1130	3,300	178,100	Cissell	10,470	182	.12	<100
10-24-88	1006	2,600	155,400	16	7,087	139	.13	---
11-16-88	1400	2,000	115,800	16	6,135	137	.16	108
11-17-88	1329	2,400	166,400	16	6,243	127	.20	111
11-18-88	0917	2,400	82,800	16	6,319	129	.16	113
12-06-88	1014	3,600	217,400	16	5,726	95	.24	---
12-08-88	0939	4,000	236,800	16	5,751	91	.24	114
12-09-88	1034	4,000	241,500	16	5,770	91	.20	111
02-14-89	1201	2,900	145,200	16	5,584	104	.18	---
02-14-89	1424	3,700	204,000	16	5,507	91	.19	---
02-17-89	1350	3,700	177,700	16	5,467	90	.19	
02-20-89	1031	3,100	71,300	16	5,473	98	.11	
02-24-89	1345	3,300	137,900	16	5,496	96	.15	
02-27-89	1313	3,200	70,600	16	5,521	98	.13	
05-15-89	1049	5,580	334,038	16	5,189	69	.33	116
10-09-89	1140	6,888	319,836	16	4,885	59	.36	
10-09-89	1203	6,390	331,730	16	4,806	60	.34	
05-23-89	1319	5,040	296,514	19	3,088	43	.82	121

Table E-3. - Vibration and airblast from Ayrshire Mine blasting (NW of mine) Base Line road direction: C. Bohrer, Haubstadt, stations 12, 15 and 18.

Date	Time	Charge weight per delay, lb	Charge weight, total lb	Monitor location	Distance ft	SRSD, ft/lb	Vibration in/s	Airblast, dB
12-06-88	1014	3,000	217,400	Bohrer	13,176	220	.04	<100
12-08-88	0939	4,000	236,800	Bohrer	12,821	203	.09	
12-09-88	1034	4,000	241,500	Bohrer	12,469	197	.10	
12-10-88	0931	3,800	240,700	Bohrer	12,096	196	.08	
12-13-88	1012	3,800	208,900	Bohrer	11,759	191	.10	
12-13-88	1339	700	308,700	Bohrer	11,410	136	.15	
12-13-88	1421	3,900	87,700	Bohrer	11,185	179	.08	
12-23-88	1148	3,600	15,100	Bohrer	18,211	304	.04	
12-29-88	1446	3,800	212,300	Bohrer	18,495	300	.05	
01-05-89	1055	3,400	178,100	Bohrer	14,007	240	.07	
01-05-89	1207	3,700	236,100	Bohrer	13,617	224	.10	
01-12-89	1112	3,300	198,800	Bohrer	12,934	225	.06	
01-17-89	1433	2,000	86,200	Bohrer	12,077	270	.05	
01-17-89	1459	2,000	35,700	Bohrer	12,039	269	.03	
01-18-89	0952	2,000	36,700	Bohrer	11,881	266	.04	
02-17-89	1350	3,700	177,700	Bohrer	13,051	215	.04	
12-08-88	0939	4,000	236,800	Haubst	53,100	840	.05	
12-09-88	1034	4,000	241,500	Haubst	52,900	836	.03	
12-10-88	0931	3,800	240,700	Haubst	52,500	852	.05	
01-05-89	1207	3,700	236,100	Haubst	53,700	883	.04	
01-10-89	1341	3,700	230,500	Haubst	53,400	878	.04	
01-12-89	1112	3,300	198,800	Haubst	53,200	926	.03	
01-16-89	1058	3,600	123,800	Haubst	52,900	882	.04	
01-17-89	1113	3,700	153,900	Haubst	52,600	865	.03	
02-14-89	1424	3,700	204,000	Haubst	53,800	884	.03	
09-27-88	1038	2,200	105,500	12	4,682	99	.32	
09-29-88	1101	2,200	113,400	12	4,408	93	.42	
10-01-88	1425	2,400	141,800	12	4,158	84	.65	
10-01-88	1450	1,800	126,000	12	3,925	92	.43	
10-04-88	1330	1,800	124,700	12	3,617	85	.31	
10-05-88	1011	1,800	108,400	12	3,353	79	.49	
10-06-88	1018	2,200	109,000	12	3,084	65	.79	
10-07-88	1147	2,400	121,800	12	2,838	57	.68	
10-07-88	1205	2,400	29,300	12	2,818	57	.57	
10-08-88	1320	2,400	77,400	12	2,615	53	.31	
10-08-88	1336	2,400	48,000	12	2,592	52	.35	
10-08-88	1351	2,400	31,500	12	2,581	52	.27	
11-07-88	1400	1,800	28,000	12	4,711	111	.39	
11-07-88	1517	2,000	44,800	12	4,744	106	.14	
11-07-88	1534	2,000	67,900	12	4,753	106	.26	

Table E-3. - Continued

Date	Time	Charge weight per delay, lb	Charge weight, total lb	Monitor location	Distance ft	SRSD, ft/lb	Vibration in/s	Airblast, dB
11-07-88	1606	2,700	118,850	12	4,480	86	.47	
11-09-88	1404	2,700	208,100	12	4,189	80	.63	
11-12-88	1350	2,600	196,400	12	3,781	74	.54	
11-14-88	1151	2,600	137,500	12	3,503	68	.60	
11-15-88	1143	2,000	130,200	12	3,254	72	.58	
11-16-88	1344	1,800	28,500	12	2,978	70	.48	
11-16-88	1400	2,000	115,800	12	2,994	66	.97	
11-17-88	1329	2,400	166,400	12	2,734	55		
11-18-88	0917	2,400	82,800	12	2,519	51		
12-06-88	1014	3,600	217,400	12	4,683	78	.72	
12-08-88	0939	4,000	236,800	12	4,283	67	.74	
12-09-88	1034	4,000	241,500	12	3,896	61	.67	
12-10-88	0931	3,800	240,700	12	3,470	56	.67	
12-13-88	1021	3,800	208,900	12	3,088	50	.70	
12-13-88	1339	7,000	308,700	12	2,691	32	1.22	
12-13-88	1421	3,900	87,700	12	2,438	39	.80	
12-06-88	1014	3,000	217,400	15	10,124	169	.27	
12-08-88	0939	4,000	236,800	15	9,773	155	.27	
12-09-88	1034	4,000	241,500	15	9,425	149	.24	
12-10-88	0931	3,800	240,700	15	9,058	147	.20	
12-13-88	1012	3,800	208,900	15	8,729	142	.16	
12-13-88	1339	7,000	308,700	15	8,391	100	.24	
12-13-88	1421	3,900	87,700	15	8,174	131	.24	
01-05-89	1055	3,400	178,100	15	10,952	188	.17	
01-05-89	1207	3,700	236,100	15	10,562	173	.21	
01-12-89	1112	3,300	198,800	15	9,882	172	.19	
02-17-89	1350	3,700	177,700	15	9,996	164	.16	
01-12-89	1112	3,300	198,800	18	4,825	83	.71	
01-16-89	1058	3,600	123,800	18	4,431	73	.57	
01-16-89	1114	3,800	108,500	18	4,436	71	.54	
01-17-89	1113	3,700	153,900	18	4,086	67	.69	
01-17-89	1433	2,000	86,200	18	3,845	85	.34	
01-17-89	1459	2,000	35,700	18	3,827	85	.15	
01-18-89	0952	2,000	36,700	18	3,620	80	.31	
01-18-89	1000	2,000	5,400	18	3,501	78	.19	
01-18-89	1010	2,000	42,600	18	3,587	80	.35	
01-18-89	1022	2,000	13,500	18	3,635	81	.16	
01-18-89	1033	2,000	8,100	18	3,511	78	.12	
01-18-89	1159	2,000	51,300	18	3,360	75	.30	
01-18-89	1335	2,000	17,200	18	3,336	74	.37	
01-18-89	1344	2,000	39,900	18	3,347	74	.33	

Table E-3. - Continued

Date	Time	Charge weight per delay, lb	Charge weight, total lb	Monitor location	Distance ft	SRSD, ft/lb	Vibration in/s	Airblast, dB
01-18-89	1353	2,000	13,100	18	3,225	72	.16	
01-18-89	1448	450	3,400	18	2,807	132	.24	
01-20-89	1337	2,000	57,600	18	3,064	68	.42	
01-20-89	1434	2,000	91,600	18	3,083	68	.54	
01-20-89	1532	1,700	55,000	18	2,812	68	.48	
01-20-89	1629	1,700	52,300	18	2,795	67	.45	
02-17-89	1350	3,700	177,700	18	5,005	82	.42	
02-20-89	1031	3,100	71,300	18	4,696	84	.33	
02-24-89	1014	3,300	137,900	18	4,484	78	.43	
02-27-89	1313	3,200	70,600	18	4,267	75	.37	
03-01-89	1057	1,700	80,000	18	4,098	99	.52	
03-03-89	1014	1,700	59,100	18	3,838	93	.19	
03-03-89	1408	1,700	68,700	18	3,813	92	.31	
03-06-89	1109	1,700	50,000	18	3,514	85	.34	
03-06-89	1246	1,700	48,400	18	3,499	84	.37	
03-07-89	1118	1,700	41,200	18	3,260	79	.33	
03-07-89	1154	1,700	34,600	18	3,223	78	.39	
03-07-89	1416	1,700	84,500	18	3,070	74	.88	
03-09-89	0917	1,700	6,800	18	2,977	72	.32	
03-09-89	1030	1,700	47,600	18	2,895	70	.61	
03-09-89	1117	1,700	29,600	18	2,875	69	.92	
03-09-89	1325	1,700	6,000	18	2,785	67	.21	
03-09-89	1353	1,700	26,500	18	2,738	66	.52	
03-09-89	1414	1,700	11,700	18	2,723	66	.21	
03-09-89	1436	1,700	21,900	18	2,722	66	.23	
04-03-89	1417	3,600	102,400	18	4,277	71	.41	
04-05-89	0945	1,700	46,400	18	4,037	97	.29	
04-05-89	1403	1,700	42,400	18	3,751	90	.28	
04-06-89	1038	1,700	55,400	18	4,046	98	.27	
04-06-89	1254	1,700	45,800	18	3,766	91	.32	
04-07-89	1449	3,700	247,600	18	4,995	82	.36	
04-10-89	1044	3,300	187,700	18	4,566	79	.29	
04-13-89	1108	2,200	44,500	18	3,484	74	.33	
04-13-89	1205	1,700	55,000	18	3,473	84	.26	
04-13-89	1419	2,200	62,000	18	3,195	68	.40	
04-13-89	1448	1,700	67,300	18	3,193	77	.35	
04-17-89	1020	2,200	33,100	18	2,962	63	.47	
04-17-89	1042	1,700	37,400	18	2,937	71	.47	
04-17-89	1205	3,400	63,700	18	2,762	47	.42	
04-17-89	1322	1,700	56,400	18	2,752	66	.37	

Appendix F. - Selected high-level airblast incidents.

Date	Time	Airblast dB	Monitoring location, house	Yes	No	Distance m,[1]	Direction	Speed, mi./hr
04-06-89	1254	124	108	X		5	W	12
07-12-89	1724	123	108		X	-	SW	06
07-21-89	1443	121	108	X		5	W	05
09-19-89	0915	121	near 107	X		9	NE	06
10-17-89	0803	121	108	X		9	N	12
10-25-89	1811	128	108		X		N	03
10-30-89	1539	128	108		X		SW	11
12-02-89	0809	131	108		X	-	NW	11
12-06-89	0832	130	108		X	-	N	04
12-09-89	1238	127	108		X	-	-	0

[1]Distance of about 9 miles corresponds to Linville mine of Peabody Coal Company. Distance of about 5 miles corresponds to Ayrshire mine of AMAX Coal Company.

APPENDIX G. - SOIL-FOUNDATION INTERACTIONS

Illinois Studies

Murphy, et al. (30) tabulated 17 factors associated with foundation failures as part of a 6-year review of claims for the Illinois Mine Subsidence Insurance Fund. Six of the factors are especially relevant to the situation observed in the Daylight/McCutchanville area and are discussed here. Some of the remaining 11 items may be pertinent, though they are not considered here due to the lack of supporting information. The six relevant factors are: soil desiccation, soil shrink-swell, soil freeze-thaw, soil densification by vibration (liquefaction), piping of soils beneath foundations, and upward buoyancy of structures caused by a seasonal high water table. Also worthy of consideration are variations in the load-bearing capacity of soils found in this area.

The Illinois State Geological Survey (ISGS) reported in the Summer 1988 edition of Geonews (31) that its Water Survey scientists had examined rainfall amounts during the periods between January and June for the last 100 years. They averaged the 10 years with the lowest rainfall and found that 1988 rainfall was lower than that average. Although similar climatological data for Indiana are unavailable to the authors at the present time, given the close proximity of the two states it is reasonable to conclude that soil moisture conditions were generally the same in both. This information is significant in that ISGS scientists quoted in the aforementioned article reported therein that they had observed a link between soil behavior during the drought and damage in the form of cracked basement walls and, in extreme cases, collapsed foundations.

The mechanism explaining the drought-related foundation damage is as follows:

"Compression forces against foundation walls are most commonly developed by an increase of soil moisture after an extended dry period. During long, extremely dry weather, the soil shrinks and pulls away from the foundation, and soil particles fall into the resulting gap. Wind, animals, and rain may also push material into this gap. The return of moisture to the soil causes clay particles in the gap and in the adjacent soil to expand, exerting horizontal pressure on the foundation walls. Horizontal pressures push the foundation walls inward, forming a bow shape with the midspan of the wall pushed farthest inward. The foundation walls usually have horizontal cracks within 2 feet of the ground surface. We conclude that horizontal pressures are generally built up by a combination of wetting/drying and swelling/shrinking cycles. It may take many such cycles to exert enough pressure to damage the foundation, although the process can be accelerated by drought. According to members of the Small Homes Council of the University of Illinois, the number of damaged foundations (walls pushed inward) greatly increases after droughts," (32).

Rose (33) found that the horizontal cracks mentioned in the previous paragraph often occur at the level of the bottoms of the basement windows; such cracks were observed to be prominent in house 105, and evident to a lesser degree in houses 215 and 334, in the Daylight area when Bureau researchers visited these homes. Homes in the McCutchanville area (with the exception of house 201 in the vicinity of the Evansville airport and OSM test-hole #32, with a block foundation extensively cracked and bowed inward) in general had basement walls covered with some type of plaster, or were in some other way finished, so that damage of this type could not readily be assessed. In any case, soil conditions in these two areas are different, as explained in the corresponding Geology section of this report, and this mechanism may not have been as active in McCutchanville's soils as it appears to have been in the Daylight area.

Indicative of the relative severity of the drought-related foundation damage in Illinois is the press release (34) entitled "Protect Your Concrete Block Basement Walls From The Pressures Induced By Drought," published June 21, 1988, by the Small Homes Council - Building Research Council at the University of Illinois. This release instructs homeowners to keep the soil moist around their foundations during the drought by shading, mulching, covering, or watering if possible. Also, an article (35) entitled "Drought may wreak foundation damage," published in the September 21, 1988 issue of the Champaign-Urbana News-Gazette quotes a representative of the Small Homes Council as saying that those people who don't take such preventative measures could have problems. When foundation problems have occurred, it is stated that the usual solution is to excavate the soil around the foundation to relieve the earth pressure. Both the press release and the article are included as Appendix H as they might be difficult for the general reader to obtain.

Soil Shrink-Swell

Southern Indiana is not known for having highly-expansible soils, unlike areas of the western United States, and one would not generally expect to see there such problems as described above during times of average precipitation. A well-known example of an area having highly-expansive soils is that of Denver, Colorado, where in some locations soils containing the clay mineral bentonite have been found to cause extensive foundation cracking and buckling. Damage in these areas typically takes place within two years after the homes are completed, which is indicative of the highly active nature of the soils present (36). Most of the damage to the homes in the OSM study area, however, apparently occurred many years after they were built. This implies that the soils in Daylight/McCutchanville are not highly expansible in the usual sense.

Although the Bureau, as part of the OSM effort, was not responsible for determining soil properties, curiosity compelled the authors to take one soil sample from the ground surface near the most extensively cracked portion of the foundation of house 108. This sample was split three times prior to submitting it to the University of Minnesota's Soil Science Department for analysis. It was not otherwise specially prepared or handled. In general, the soil was classified as a silt loam following the USDA system, and it was found to have a moderate shrink-swell hazard due to the presence of expansible smectite and interlayered smectite/illite clays. The results from one sample are obviously not definitive, but they do indicate the possibility that soil expansibility could have been at least partially responsible for the damage to the foundation of house 108, and plausibly to other homes in the upland areas near McCutchanville. Further work by OSM to establish to credibility of this hypothesis for the entire study area is recommended. The complete report on the submitted soil sample is found in Appendix I.

There is one point regarding the shrinking and swelling of clay-containing soils worth emphasizing here. This is a cyclic process, as was previously mentioned in the quotation from Bauer (32). Once the soil surrounding a foundation has been disturbed by excavation and backfilling, it may take many cycles of prolonged wetting/drying for horizontal soil pressures to increase enough to damage that foundation. Research by Osipov, et al (37) shows the number of wet/dry cycles required to produce the maximum amount of expansion in disturbed soils varies from 3-4 in modern silts to 6-20 in lithified clays. Therefore, as most homes examined in the OSM study area are less than 40 years old, and serious foundation damage has occurred only recently, it is possible that the drought of 1988 was the last in the series of prolonged wet/dry cycles required to produce that effect. Construction techniques, soil characteristics, and landscape vary depending on the property of course, so that some homes will be affected to a greater or lesser degree than others.

Soil Freeze-Thaw

Another soil characteristic of consequence is its response to ambient temperature fluctuations above and below the freezing point of water. Silts are the deposits most susceptible to frost heaving (33). In fact, the relatively silty soils found in the upper and middle surfaces of the study area drain slowly (38), probably for a number of reasons given by Hester, et al. (8), thereby contributing to the frost-heaving hazard to structures situated in this soil. The climate in the area is generally moderate however, and this is a relatively minor problem in the Daylight/McCutchanville area because the depth of freezing in winter is not great (38). At risk of heaving and cracking though are poured floors in unheated garages, concrete driveways, patios, etc., and hypothetically during abnormally cold periods foundations whose footings lie relatively near the ground surface. This condition could possibly occur in homes located in the sloping portions of the study area, particularly with regard to footings on the downslope side of the house. Freeze-thaw action could also theoretically cause a gradual downhill creep of the soil and house. The most extensive cracking in house 108 occurred on the downslope side. Frost heaving could have played a role in causing that damage, though a more thorough examination by qualified professionals would be required to establish that as fact.

Soil Liquefaction

Soil liquefaction by vibrations has apparently been previously mentioned by others as a possible cause for the damage to the homes in the study area. Soil liquefaction is the vibration-induced loss of cohesion and bearing capacity of soil. It is caused by an increase of pore pressure from the shaking-induced rearrangement of particle grains into a more compact form. Saturated cohesionless soils are required, and fine dense sands with low permeability are the most susceptible. It is also a time-dependent phenomenon, starting at depth and moving upward. Seed (39) cited a case where liquefaction was observed after 10 cycles at 20 ft depth and 80 cycles at the surface from a 0.165-g horizontal vibration; the water table being was within 2-3 ft of the surface. This is equivalent to 1.0 in/s at 10 Hz and 2.6 in/s at 4 Hz (4 Hz being the dominant frequency measured by the Bureau in McCutchanville), using the S.H.M. assumption. Paolillo states that settlement due to liquefaction can occur in loose saturated cohesionless soils at 0.05-0.20 g, although the high end of this range would be a conservative criterion as it is unlikely that soil under existing buildings would be in loose condition (40).

Because of the short duration of blasting vibrations, seconds rather than minutes, they appear extremely unlikely to cause soil liquefaction at vibration levels usually encountered, less than 1 in/s, and particularly at the less than 0.1 in/s measured by the Bureau in the study area.

Piping of Soils

The piping of soils from beneath foundations is of particular interest as the loess, with its high silt content, found in the upper and middle surfaces of the study area is prone to exhibit this behavior. Rose (33) cites a case where a homeowner with a high water table installed a sump pump without filter fabric to dewater his basement, and consequently excavated four tons of the relatively freely-flowing saturated silt from beneath his footings. Bauer states that loess can easily be piped from along poorly-sealed subsurface drainage systems, which can lead to a differential lowering of the foundation and development of tensile cracks. This mechanism could be partially responsible for the damage observed in house 108 and, from the homeowners description possibly house 303, although the major damage in this house had already been repaired when the authors first inspected it. Without direct evidence, however, the existance of this mechanism must remain speculative.

Upward Buoyancy

The upward buoyancy of structures caused by a seasonal high water table (or the settlement of structures due to ground water level fluctuations) is a matter of concern in the study area, especially in homes having significant differences in their footing elevations. Should a home be built partly over a full basement and partly over a crawl space, for example, and the ground water level be near the footings, variations in the water level could cause portions of the house to settle differentially (41). This could cause cracks to appear in the walls and ceilings above ground level, and potentially in the foundation should it not settle evenly. A dense fragipan typically located at about 2.5 to 3 ft of depth in the upper surface of the study area has the potential for creating a seasonally perched water table that might activate this mechanism (8). House 107 is situated in this surface and at least some of the cracking observed in this house might thus be explained.

Soil Load-Bearing Capacity

The load-bearing capacity of the study-area soils varies and was loosely grouped into two categories by Straw, et al. (38). The lacustrine materials found in the lower surface were reported to provide poor foundation conditions for all but relatively light loads. The soils are stated to be saturated with field moisture contents well above the optimum moisture for proper compaction and maximum strength. House 105 was located in this surface near the lower-middle surface boundary, with houses 215 and 334 in the middle surface not far from that boundary. Damage to these homes was generally less severe than that found in homes in or near the upper surface, with the level-loop surveys indicating little movement away from level in the lower and near-lower surface homes. This implies that the bearing capacity of the lacustrine soils is sufficient to properly support the inspected homes situated therein.

The bearing capacity of the silty soils of the upper to middle surfaces was reported to be adequate for light to moderate foundation loads, and bedrock of good bearing capacity can be reached at shallow depth if necessary. The bearing capacity of the soil is commonly significantly less, however, when the material is saturated than when dry. This could be a problem if downspouts discharge along the corners of foundations during wet weather, saturating and reducing the bearing capacity of the silty soil. The foundation could consequently be cracked near the corners in stair-step fashion and lowered, with the corners rotating outward and downward (32). The damage observed in house 108 and that reported to have occurred in house 303 might be at least be partially attributed to this mechanism. Also, prolonged wet weather could saturate the material under the footings around the entire circumference of the house. Missing or leaky rain gutters would accelerate this process. If the house was located on a slope in the upper or middle surface, the upslope footings might be at or near bedrock and the downslope footings could be resting on several feet of silty soil. Upon becoming saturated the bearing capacity of the silty soil would decrease, possibly past the point required to induce foundation settlement. The downslope side of the house would thus settle more than the upslope side in this case, possibly causing foundation and superstructure cracks. The level-loop surveys show that the downslope side of house 209 is, in fact, lower than the upslope side, the trend being evident but not as definite in houses 108 and 303. Assuming these homes were originally built relatively level, the process described above could explain the apparent downslope movement measured by the surveys. One must keep in mind that it is difficult and uneconomical to build a house perfectly level and plumb; differences of as much as 1 in (0.08 ft) in level from corner to corner in a newly-constructed home are not unusual, principally due to variations in the quality control of the materials used.

There are obviously many soil-related factors potentially responsible for the variety of damage observed in the homes in the Daylight/McCutchanville area. In any one location several mechanisms could operate simultaneously making a proper assessment difficult. Additionally, construction techniques and quality vary from home to home. Each damage situation is therefore unique and deserves more than the cursory treatment received here to truly determine the causative elements at work.

Appendix H - Press release on drought effects on basement walls.

PRESS RELEASE

June 21, 1988

Small Homes Council-Building Research Council University of Illinois

Illinois State Geological Survey

PROTECT YOUR CONCRETE BLOCK BASEMENT WALLS FROM THE PRESSURES INDUCED BY DROUGHT

Staff of the Small Homes Council of the University of Illinois and the Illinois State Geological Survey have observed that multiple episodes of drought may cause some concrete block basement walls to crack and deform. Here's how:

Soil containing clay minerals will swell or shrink depending on whether it is wet or dry. Right now during the drought, the soil is very dry. So the soil around many house foundations, where it is exposed and unprotected, has shrunk away from the walls, creating a vertical separation which may be 1/2-inch wide at the top and 2-feet deep. This separation of the soil from the wall is not detrimental as long as it stays open and free of any debris which may be deposited by the wind, water (initial rainfalls or watering) or animals traveling next to the foundation. If dirt is allowed to accumulate repeatedly in the open crack, then concrete block basement walls may be headed for trouble. When the rains come again, the soil will try to swell back to its original dimension but is hindered by the debris that has accumulated in the crack. This increases the pressure on the walls after each dry period. Years of accumulation and pressure buildup can cause the walls to bulge inward and in extreme cases, can cause the basement walls to collapse.

To protect your basement walls against damage from drought:

--keep the soil moist around the foundation by shading, mulching, covering and watering if possible. Respect water use limitations during droughts.

When the rains come and the soil swells back, do not become alarmed if hairline cracks form in concrete block basement walls. If the inward deflection is greater than 2" for an 8-inch thick wall, the wall may need to be repaired.

For more Information contact Mr. William Rose at the Small Homes Council 217-333-1801.

Drought may wreak foundation damage

By W. DAVID BAIRD
News-Gazette Staff Writer

Some Midwest homeowners may experience problems with the foundations of their homes by next spring, experts are warning.

That's because this summer's hot, dry conditions have caused the soil to shrink. But when it rains, the soil around the foundation swells, and produces an inward pressure that can result in damage to foundations.

"Soil shrinking away from the foundations is more common on basement houses than on those with crawl spaces," said Henry Spies of the Small Homes Council-Building Research Council at the University of Illinois.

Spies said he has had numerous calls from homeowners reporting a space between the foundation and the soil of three-quarters of an inch to 2 inches, which he said is caused by the dry weather.

"In the case of extreme drought, the soil actually dries out and shrinks, causing those gaps," said Spies. "When it rains, the moisture will cause the soil to expand back to its original dimension. And if anything like sand or debris has fallen down those cracks around the foundation of a home, the pressure causes the foundation to lean inward."

Although Spies hasn't had any reports of problems yet, he added, "I fully expect to be getting lots of calls about horizontal cracks at or below ground level after the first good rain."

Homes built on a concrete slab will not be affected, according to Spies.

RESIDENTIAL CONTRACTOR Willie Gordon of J.J. Construction Co., 201 E. Roper, C, believes any problems with cracked foundations won't turn up until next spring, after "a few good rains."

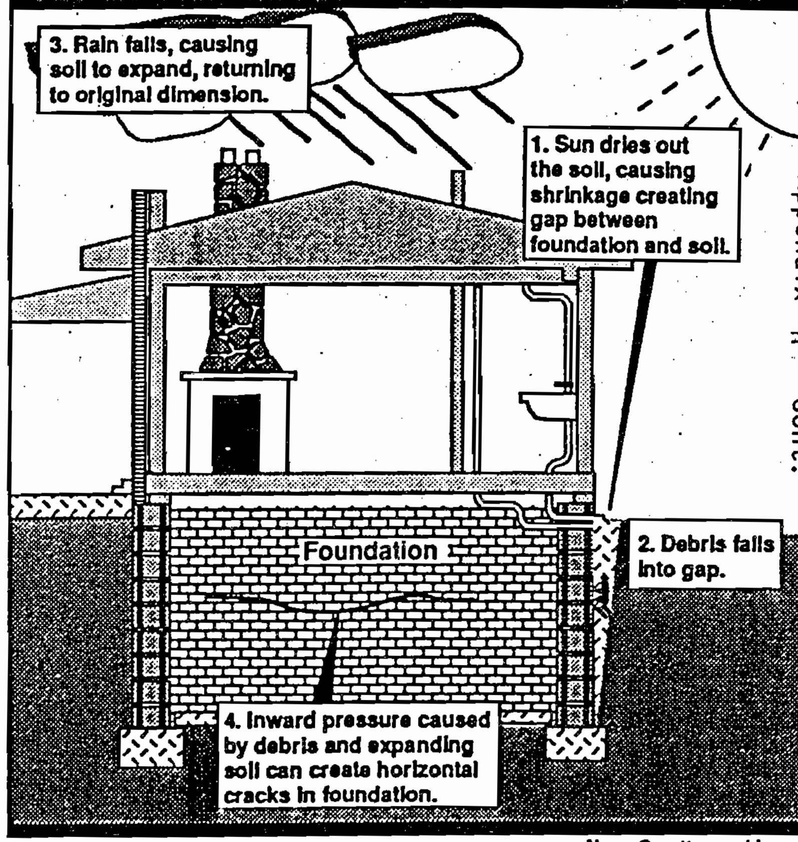
He said most homes built during the past 16 years in Champaign-Urbana probably won't develop serious problems because local building codes require contractors to follow construction guidelines that are designed to avoid such problems.

"With the reinforcement bars and the way home builders have to backfill around foundations, you're not going to get too much earth movement," he said.

Bruce Johnson, who owns American Concrete in Champaign, a residential builder specializing in foundations, footings and basements, said any damage caused by the soil shrinkage-swelling effect will be "superficial."

He said factors such as where the home is built, the type of foundation, the age of the home and the type of soil on which it is built all determine if there will be any damage.

Potential foundation damage caused by drought



News-Gazette graphic

TO AVOID THE PROBLEM, Spies said many homeowners water down the earth around the foundations in dry weather. Many don't, and they are the ones who could have problems, especially if debris has fallen into the cracks, he said.

The usual solution is to dig up the earth around the edge of the house foundation to relieve the earth pressure, said Spies. Depending on the severity of the problem, a contractor may be needed.

News Gazette 9/21/88 Urbana - Champaign

Appendix I - Soil test by University of Minnesota on a McCutchanville sample.

UNIVERSITY OF MINNESOTA
TWIN CITIES

Soil Science Department
Borlaug Hall
1991 Upper Buford Circle
St. Paul, Minnesota 55108

9 February, 1990

Matt Plis
U.S. Bureau of Mines
Twin Cities Research Center
5629 Minnehaha Ave S.
Minneapolis, MN 55417

Dear Matt;

Enclosed are results of the analyses of samples you provided. The samples were very similar, and the results are too.

The basic findings are that the soils have a moderate shrink-swell hazard, and that their clay fraction is dominated by smectite and interlayered smectite/illite clays. These are both expansible clays, and as such, contribute to the shrink-swell hazard. Probably the only thing that prevents these soils from having severe shrink-swell hazards is their relatively low (≈ 20 %) clay contents. If some horizon has a higher clay content, and it is similar in composition to that of the samples provided, then that horizon would probably have a higher shrink-swell hazard.

I hope that this information will be of use to you. I have included relevant citations of methods and interpretations where applicable. If you have any questions regarding the data, please do not hesitate to call me at (612) 625-1725.

An itemized bill is enclosed on the following page. Thank you.

Sincerely,

Edward A. Nater
Assistant Professor

Analytical Costs

Clay Mineral Analysis

Service	# Samples	Individual Cost	Total Cost
One-Time Handling Charge			20.00
X-ray Diffraction Analysis	3	30.00	90.00
Particle Size Analysis	3	12.00	36.00
Bulk Density and COLE	3	10.00	30.00
Surface Area	3	25.00	75.00
Total			251.00

Charged to U.S. Bureau of Mines P. O. # L3300673

PARTICLE SIZE ANALYSIS

Method: Sedimentation, pipette method.

Reference: Soil Survey Staff, 1972. *Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples.* Soil Survey Investigations Report No. 1, U.S. Government Printing Office, Washington, D.C.

Sample	Sand (0.05 - 2.00 mm) %	Silt (0.002 - 0.05 mm) %	Clay (< 0.002 mm) %	USDA Textural Class
N1	2.9	75.8	21.3	silt loam
N2	2.1	76.1	21.8	silt loam
N3	3.2	76.2	20.6	silt loam
Mean	2.7	76.1	21.2	silt loam

BULK DENSITY

Method: Saran-coated clods.

Reference: Soil Survey Staff, 1972. *Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples.* Soil Survey Investigations Report No. 1, U.S. Government Printing Office, Washington, D.C.

Sample	Bulk Density (g cm^{-3})
N1	1.44
N2	1.40
N3	1.48
N4	1.45
Mean	1.44

COLE VALUES

Method: COLE rod method.

Reference: Schafer, W. M., and M. J. Singer, 1976. A new method of measuring shrink-swell potential using soil pastes. *Soil Science Society of America Journal*, 40:805-806.

Sample	$COLE_{rod}$	$COLE_{std}$ (predicted)
N1	0.0366	0.0333
N2	0.0435	0.0372
N3	0.0460	0.0387
N4	0.0308	0.0300
Mean	0.0392	0.0348

Relation between shrink-swell hazard and $COLE_{std}$ values*

$COLE_{std}$	Shrink-swell hazard
0.00 - 0.03	slight
0.03 - 0.06	moderate
0.06 - 0.09	severe
> 0.09	very severe

*Soil Conservation Service, 1971. Guide for interpreting engineering uses of soils. USDA. U.S. Government Printing Office, Washington, D.C.

SPECIFIC SURFACE AREA OF THE CLAY FRACTION

Method: Monolayer adsorption of ethylene glycol monoethyl ether: Desorption method

Reference: Carter, D. L., M. D. Heilman, and C. L. Gonzalez, 1965. Ethylene glycol monoethyl ether for determining surface area of silicate minerals. *Soil Science*, 100:356-360.

Sample	Surface Area ($m^2 g^{-1}$)
N1	301
N2	322
N3	293
Mean	305

SEMI-QUANTITATIVE CLAY MINERAL IDENTIFICATION

Method: Peak Area of X-ray diffraction.

Reference: Jackson, M. L., 1965. *Soil Chemical Analysis: Advanced Course.* Published by the author. Madison, WI.

Quantitation of clay minerals is poor at best, due to several factors, including particle size, particle composition, degree of crystallinity, and particle orientation. Therefore, I cannot provide any quantitative data. I can provide broad ranges, however, and you may use these as a guide.

The following minerals were present in the clay fraction (< 2 μm effective particle diameter). Their approximate percentages, as estimated from their respective peak areas, are:

Mineral	% of Total
Quartz	10-20
Kaolinite	5-15
Illite	15-25
Smectite*	40-60
Interlayered Smectite/ Illite*	5-15

*Smectite and interlayered smectite/illite clays are expansible (swelling) clays. The other clay-sized materials are not expansible, and thus would not contribute to potential shrink-swell problems.