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INVESTIGATION OF DAMAGE TO STRUCTURES IN THE M^cCUTCHANVILLE-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.

US Department of Interior
Office of Surface Mining
Reclamation and Enforcement

Kenneth K. Eltschlager
Mining/Explosives Engineer
3 Parkway Center
Pittsburgh, PA 15220

Phone 412.937.2169
Fax 412.937.3012
Keltschl@osmre.gov

U.S. Department of the Interior

Office of Surface Mining Reclamation and Enforcement

Part V

Racking Response of Large Structures from Airblast, A Case Study.

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DECEMBER 1992

RACKING RESPONSE OF LARGE STRUCTURES FROM AIRBLAST, A CASE STUDY

Interagency Agreement EF68-IA 91-13795
U.S. Department of the Interior, Bureau of Mines, Twin Cities Research Center
David E. Siskind, Steven V. Crum, and Willard Pierce

DEPARTMENT OF INTERIOR
OFFICE OF SURFACE MINING

RACKING RESPONSE OF LARGE STRUCTURES FROM AIRBLAST, A CASE STUDY

BY

David E. Siskind[1]
Steven V. Crum[2]
Willard E. Pierce[3]

[1] Group Supervisor, Blasting Research, U.S. Bureau of Mines, Twin Cities Research Center

[2] Geophysicist, U.S. Bureau of Mines, Twin Cities Research Center

[3] Blasting Specialist, Indiana Department of Natural Resources

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*** UNITS OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	in/s	inch per second
ft	foot	lb/in^2	pound per square inch
Hz	hertz	mb	millibar
in	inch	s	second

***ABSTRACT

The Bureau of Mines studied three large structures near Evansville, Indiana to quantify structure vibration responses from airblast resulting from blasting at a nearby surface coal mine. Over a period of 3-1/2 months, researchers monitored racking or distortion responses from production blasts plus impacting ground vibrations and airblasts at these three sites and at two other nearby locations. This research was part of a comprehensive assessment by the Office of Surface Mining on community concern about blasting impacts on homes.

Researchers found vibration and airblast levels to be low with relatively few blasts producing severe enough responses to trigger the seismographs at the more distant locations. Measurable airblast structural responses, were obtained for only one of the structures, a large church relatively close to the mine. Response levels were comparable to historical norms, or slightly greater. Because of the height and large exposed surface facing the blasts, a heightened response was expected. At this same church, sports activities in the large activities room generated numerous responses comparable to the strongest blasts.

***INTRODUCTION

The Bureau of Mines was asked by the Federal Office of Surface Mining Reclamation and Enforcement, OSM, to conduct a blasting response evaluation of structures near the Ayrshire surface coal mine operated by AMAX Coal Company north of Evansville, Indiana (Figure 1). This area is comprised of the communities of McCutchanville and Daylight with some scattered homes in between. It was the subject of previous studies by the Indiana Department of Natural Resources (*1*), the Bureau of Mines (*2,3*) and OSM (unpublished) which addressed community concerns about blasting impacts and potential damage to homes.

As a follow-up to the above studies, OSM requested assistance from several outside agencies to examine specific questions about dynamic responses, vibration characteristics, and soil behavior related to foundation and superstructure stability. The Bureau of Mines portion of this work, the subject of this report, was to address the following issues:

1. What is the dynamic response of large structures to impacting airblast?

2. Does an abnormal response occur at one relatively nearby and new structure, a large church, and is it possibly responsible for cracks in structural masonry?

3. What are the responses from airblast at larger distances, and how does the airblast amplitude change with weather influences?

In addition to structural responses from airblasts, researchers also collected responses resulting from ground-borne vibrations. These data were collected by the monitors as a no-cost by-product. Previous work at the site noted that some blasts produced low-frequency ground vibrations, down to 3.5 Hz. At some

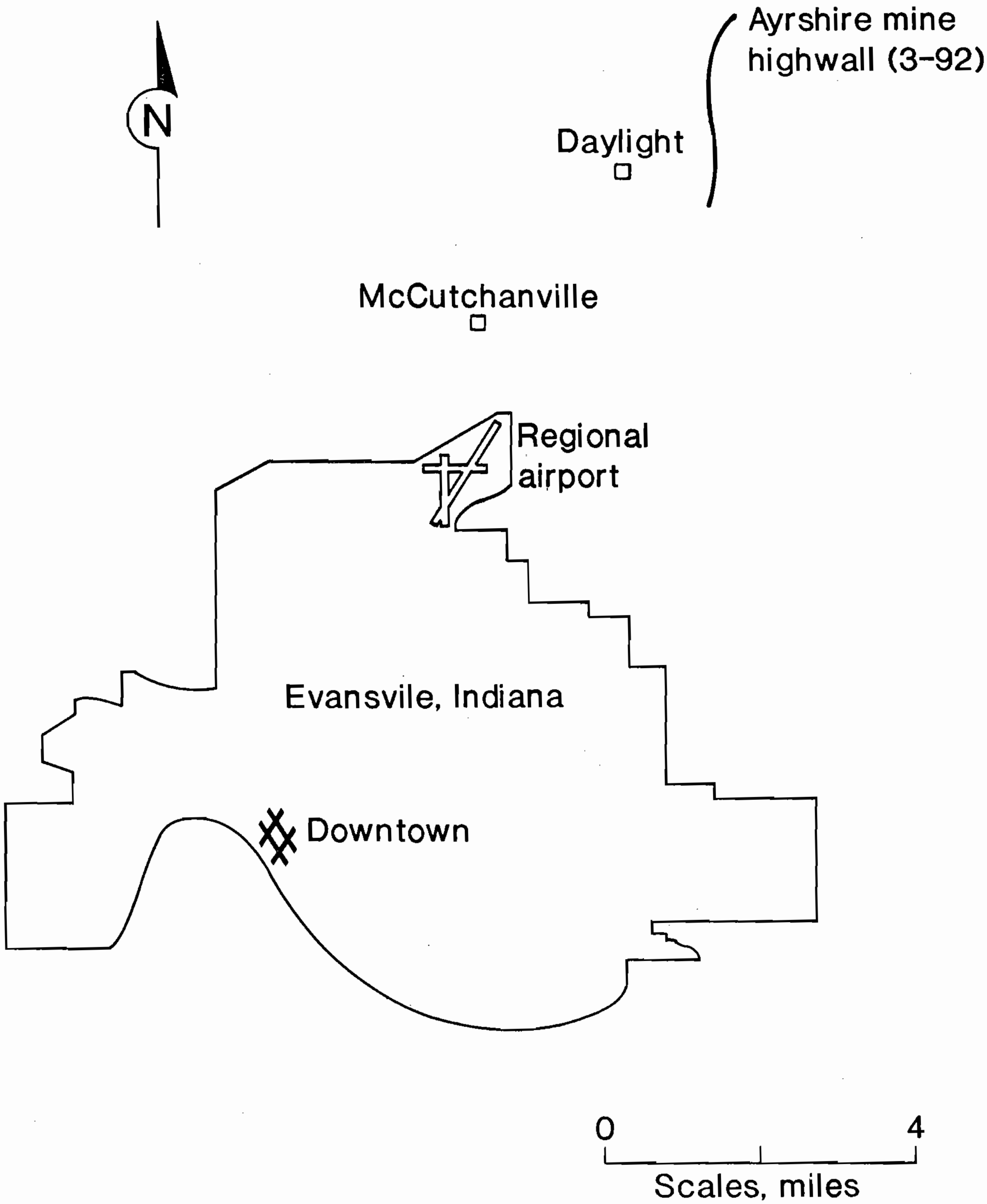

Figure 1.- Mine and monitoring locations west of Ayrshire mine near Evansville, Indiana

later date, responses will be compared to previous Bureau studies which had been used to provide general safe level criteria for blasting (*4,5*).

The mine's cooperation for this study was unnecessary as the seismographs were capable of airblast and vibration self-triggering.

This research was done at the request of the OSM Eastern Support Center and partly funded by OSM through Interagency Agreement EF68-IA91-13795. The OSM Technical Project Officer was Ken Eltschlager.

***SITE DESCRIPTIONS
AYRSHIRE MINE

The AMAX Coal Company Ayrshire 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 to break the overburden rock for easy digging and removal. About February, 1988, they adopted cast blasting for the northern areas of their nearly three-mile long highwall. Casting uses explosive energy and gas pressures to throw the rock and reduce digging time and cost.

LOCAL COMMUNITIES

The communities objecting to the blasting vibrations are all behind the highwall in the westward direction. The open pit spoils and reclaimed land are all on the east side. Daylight is the closest community to the west of the Ayrshire mine (see figure 1). This is a flat-lying area developed, in part, on old glacial lake beds. The homes and few commercial structures in Daylight range up to 100 years old and are mostly one story. Typical home-to-blast distances are about 2 miles.

McCutchanville is a suburb of Evansville, Indiana, southwest of Daylight. It consists of both 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. Much of this highland area is wind-deposited fine silt. 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 toward the north and northwest. Some 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 geologic character of the area was summarized in the previous Bureau of Mines Study (*2*). In this study, Bureau researchers had hypothesized that soils erosion and/or expansion were responsible for structural damages. Therefore, OSM arranged for the collection and analysis of additional soil samples and also commissioned the Corps of Engineers to run soil engineering tests coincidentally with this dynamic response study (for results on the latter, see Hadala's report).

Monitored Sites

The Bureau chose sites for the response study for geographical diversity and to test responses of structures which are larger than homes studied previously (figure 2). The St. John's Catholic Church (#119) in Daylight is, a largespan, newly built structure relatively close to the highwall at about two miles (figure 3). Because of the large eastern-end activity room, its response to airblast was expected to be above average. Northwest of the mine is the Blue Grass Church (#224) also having a relatively large area of exposure because of a steep roof (figure 4). In McCutchanville, a large home, (Hoover house), on an exposed eastern slope was chosen to detect possible long-range airblast propagation (figure 5). Two other sites consisted of one seismograph each to provide data useful for propagation plots. These last sites are shown in figure 2 as site #16 (Marx) and site #202 (Richey). The former is very close to the highwall, being a compliance station, and the latter next to a residence on an exposed hillside beyond the Blue Grass Church.

***PROCEDURES
INSTRUMENTATION

Only one seismograph type was used for this study. Eight new Alpha-Seis seismographs manufactured by White Industrial Seismology were supplied by the Indiana Department of Natural Resources, Division of Reclamation, Technical Services (figure 6). These 4-channel self-triggered seismographs have frequency ranges of 2-200 Hz for both vibration and airblast, a 54-dB dynamic range, dual triggers with 0.01 in/s and 1 dB selectivity, a 1/2-second pretrigger, and sufficient solid-state memory for 300, 9-second events. Time-history records were down-loaded weekly and all blasts played back with the appropriate time and amplitude scales.

RESPONSE MONITORING

Researchers installed two seismographs at each of the three structures under study for structural response (118, 119, 224). One seismograph was used at ground level to monitor ground vibrations and airblast impacting the structure. The second was used to assess structure responses with the 3-component vibration sensor mounted high in an exterior corner, or at St. John's, at the peak near the roof line, plus an additional airblast microphone. Microphones were mounted high on the structures following standard procedures. Figures 7-11 show locations of transducer placement. The arrow shows the radial component or the structural axis closest to radial. With seismographs monitoring vibrations, and airblasts and structure response, and set to trigger from any channel, it was possible to tell which responses were blast-related and amount of structural response occurring. Note: Regardless of which channel triggered the seismograph, all four channels would be activated and record. The objective was to quantify racking (whole-structure distortional response) for these large structures and compare to historical data for both dynamic response and resultant cracking.

A key problem was setting seismograph trigger levels. Too sensitive triggers would fill memories with environmental "events" which could be more numerous than blasting. Examples of such events are traffic, human activity-induced vibrations (e.g., sports activities in St. John's), and wind turbulence on the

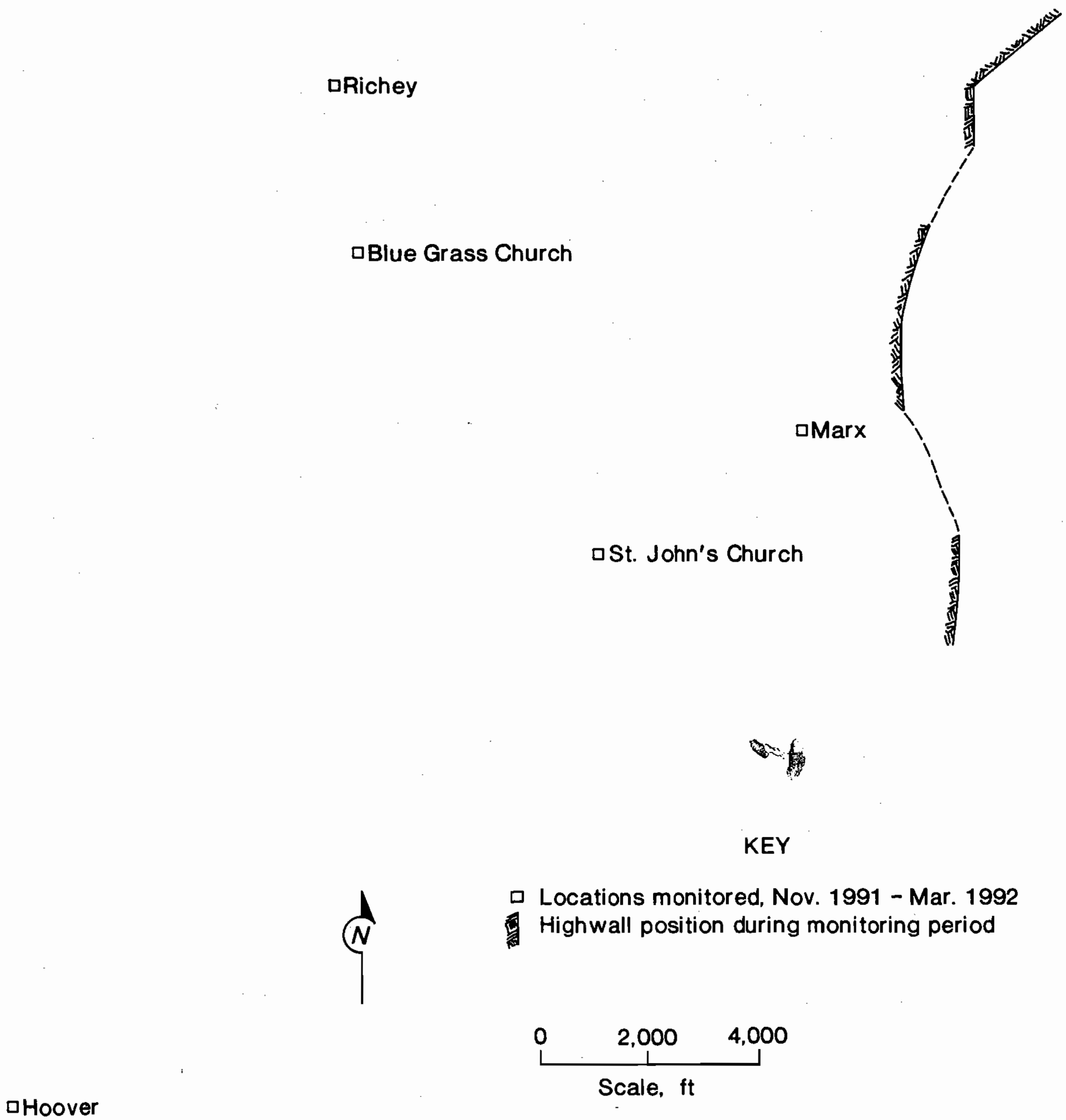

Figure 2.- Monitored sites west of the Ayrshire mine highwall

Figure 3.- St. Johns Church in Daylight (#119)

Figure 4.- Blue Grass Church NW of Daylight (#224)

Figure 5.- Hoover House in McCutchanville (#118)

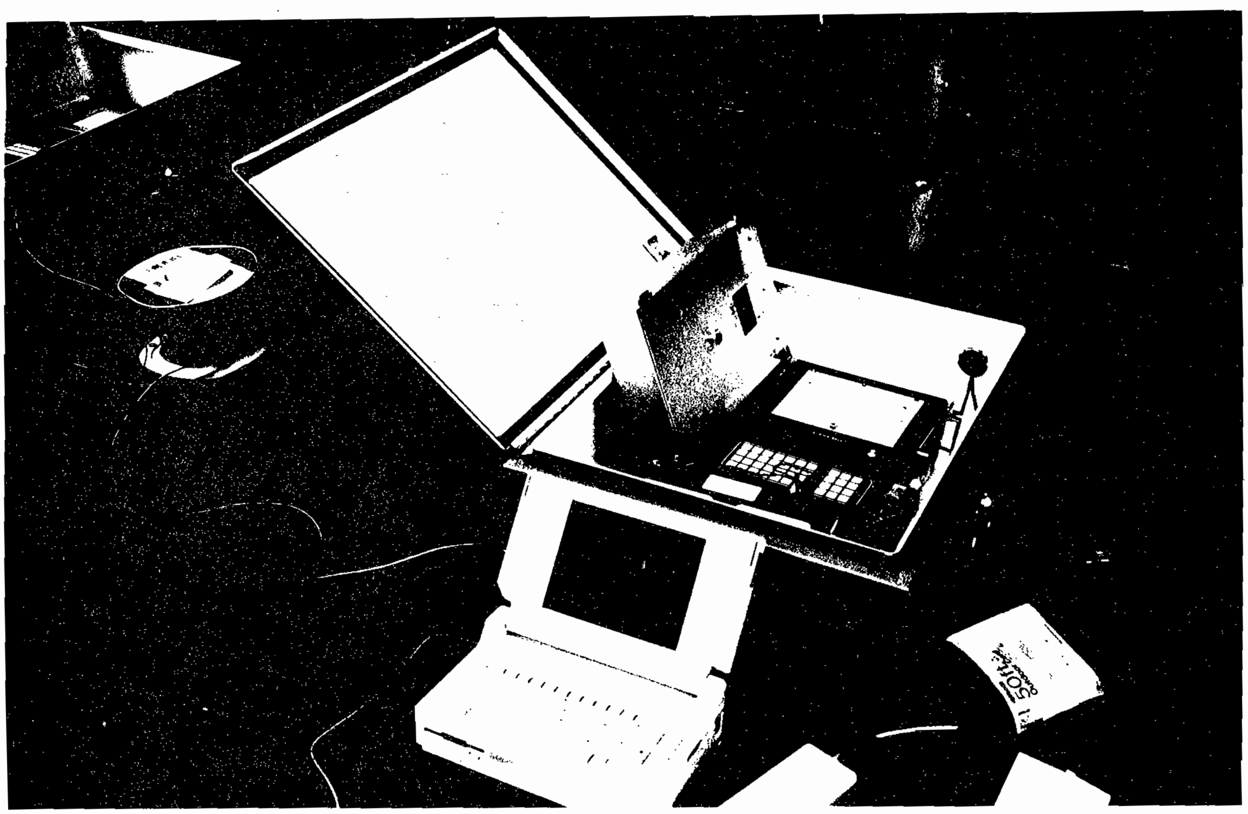

Figure 6.- Self-triggering seismograph and downloading computer

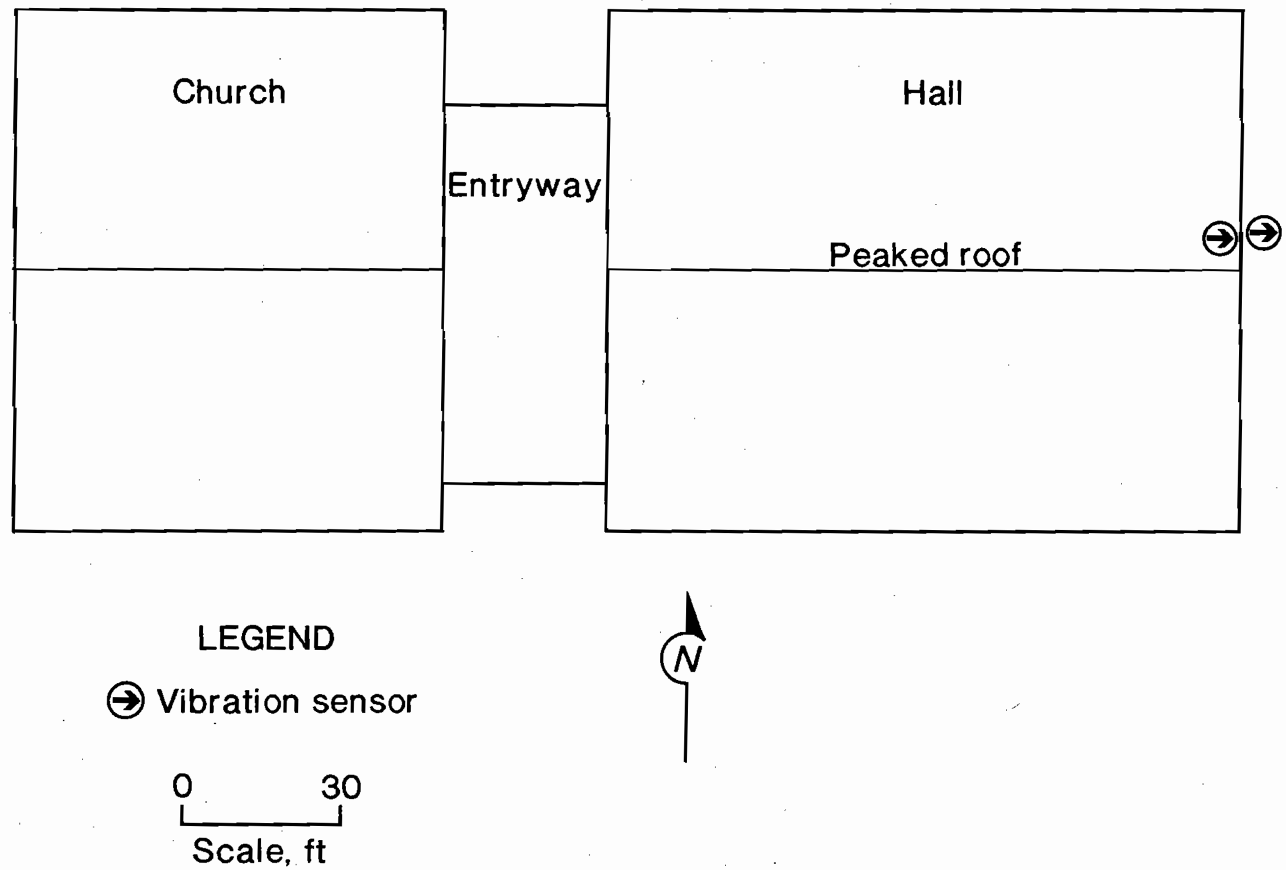

Figure 7.- Plan view of St. John's Church (#119)

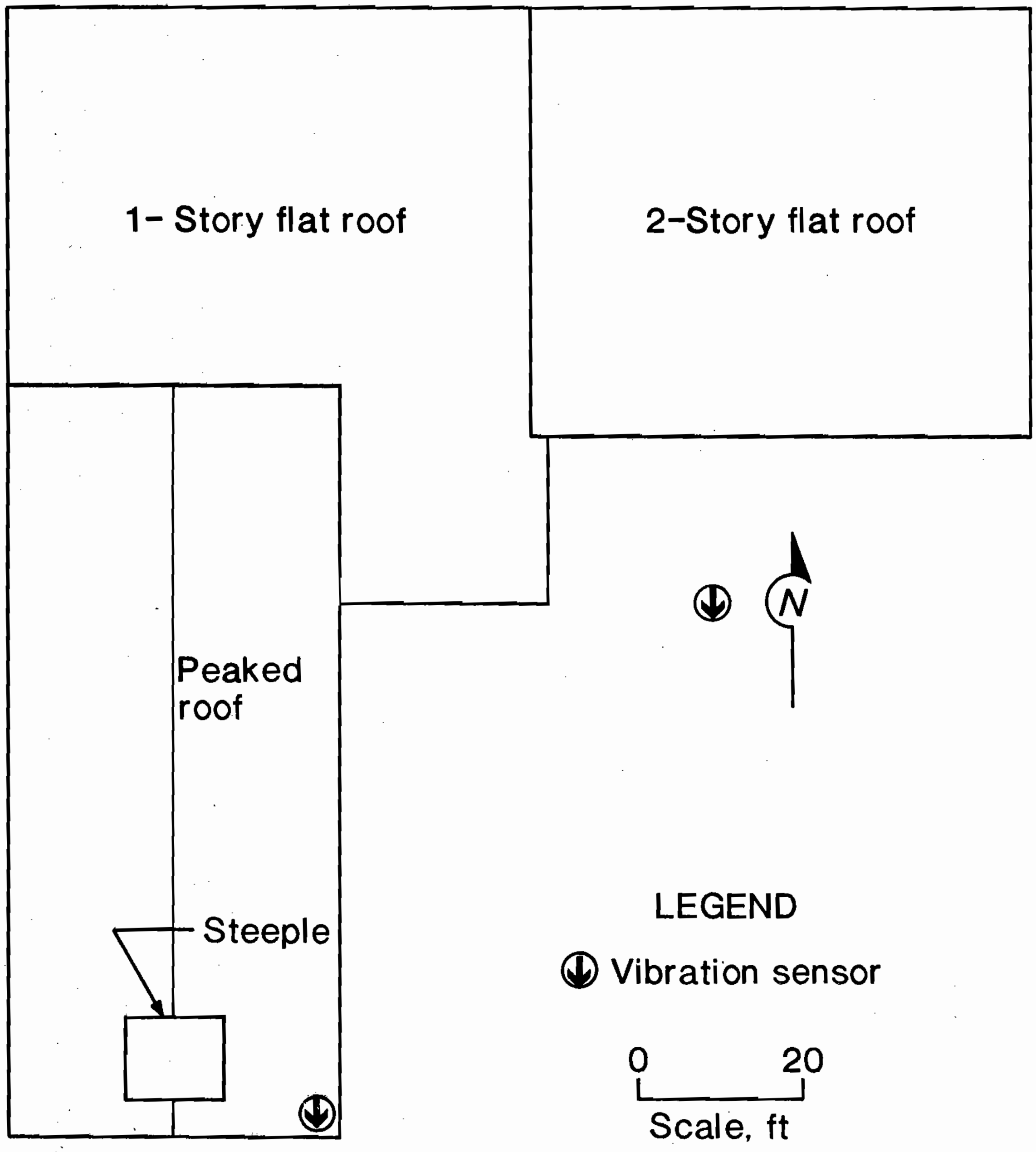

Figure 8.- Plan view of Blue Grass Church (#224)

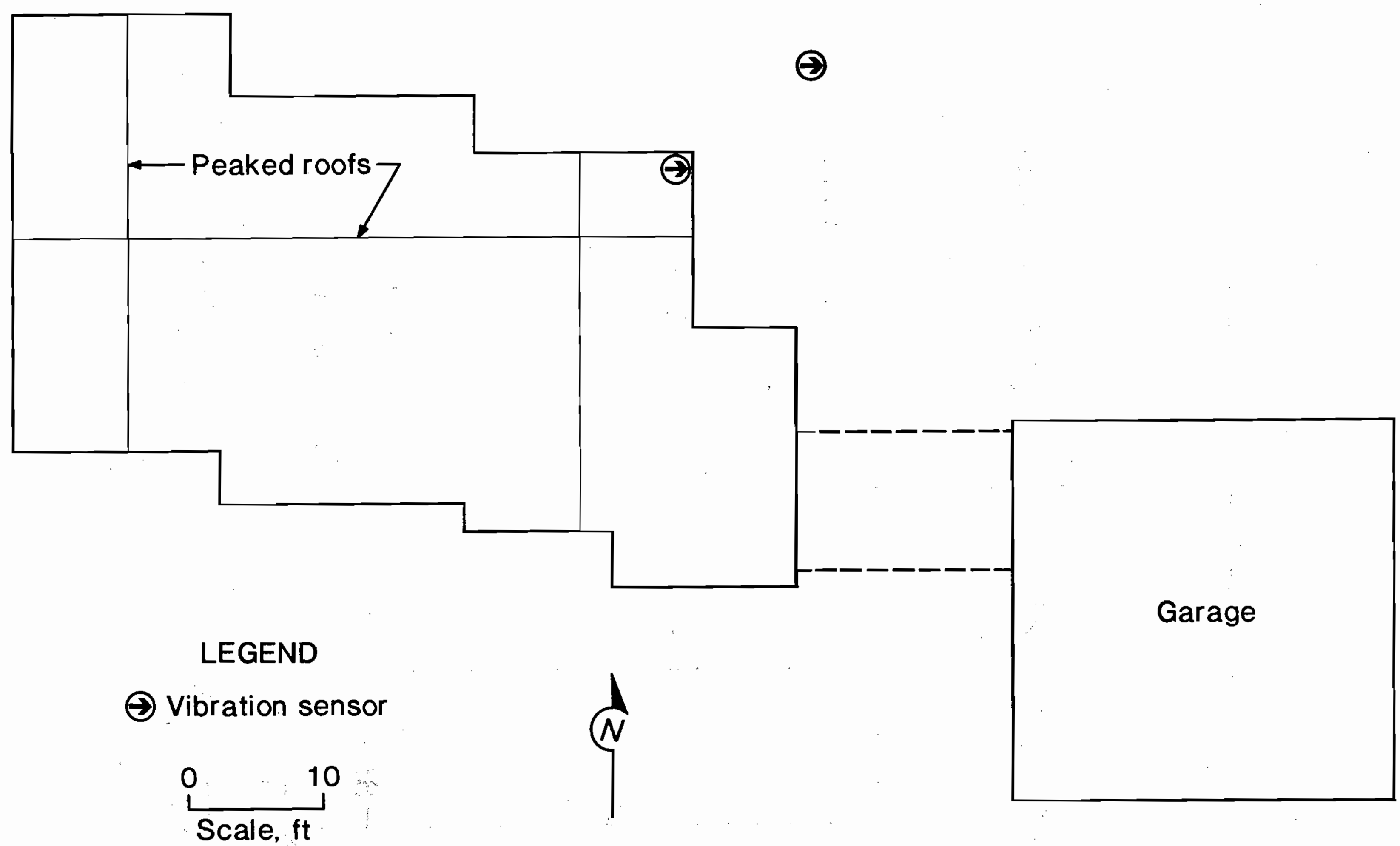

Figure 9.- Plan view of Hoover House (#118)

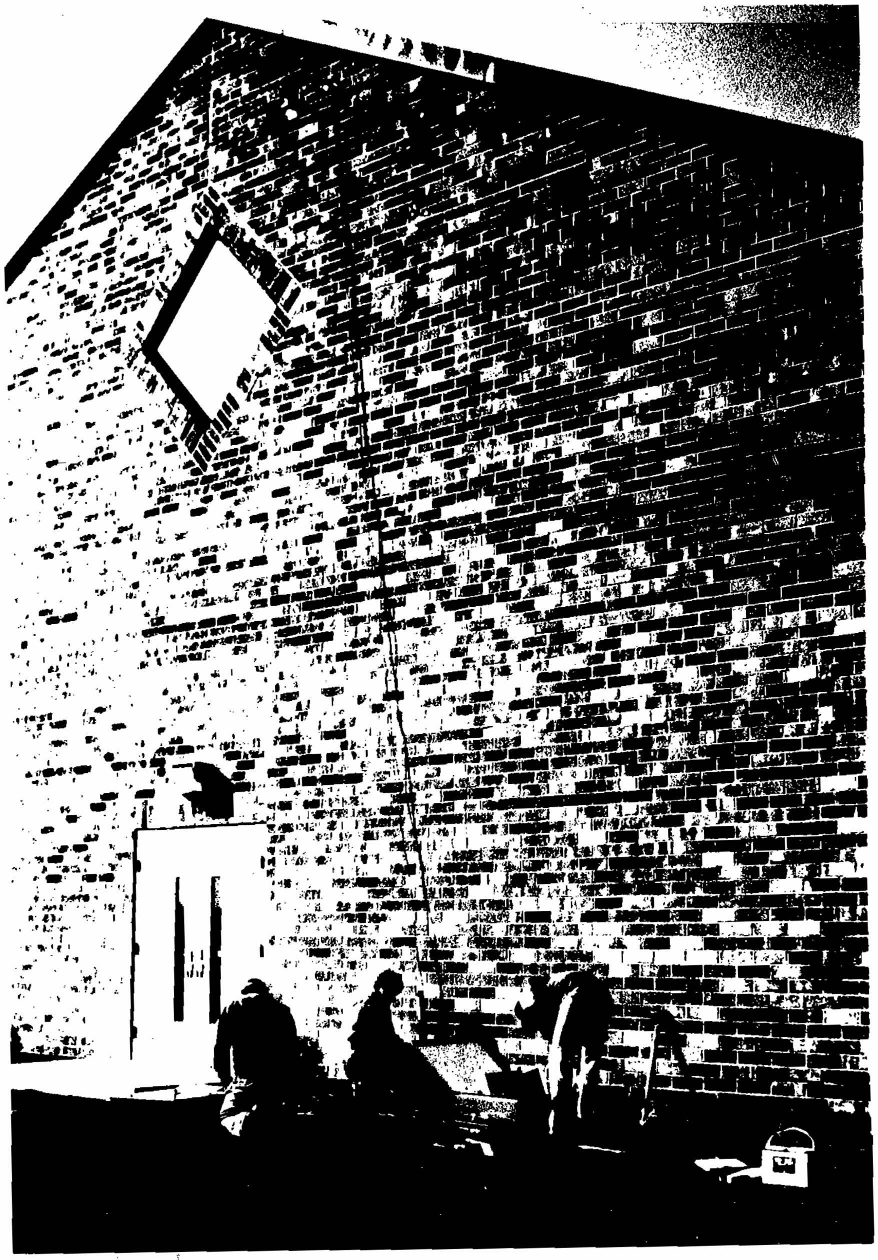

Figure 10.- Structure response transducer and microphone 30-ft high on east wall of St. John's Church

acoustic channel. For both ground vibrations and airblasts, there are always recordings which are unknown and do not correspond to blast times. Because some of the largest ones were not noticed by nearby persons, they must be instrumental glitches. Examples are given in Appendix C.

Initial trigger levels were set November 13, 1991, at 0.1 in/s for vibration and 125 dB for airblast. The relatively high airblast or acoustic trigger was needed to prevent wind noise from producing continual triggering and recording during blustery periods. After a review of initial results on January 9, 1992, some vibration triggers were adjusted. The three ground vibration seismographs and two of the structure vibration units were set to trigger at their lowest settings, 0.02 in/s. The structure response seismograph at St. John's was increased to 0.15 in/s to eliminate some of the triggers caused by basketball practices and games. There had been hundreds of these events per week and over 1500 total over the study period. Figure 12 shows the hoop and backstop mounted on the east wall. These levels were used until the study's termination in March, 1992.

Propagation

A second objective was to examine airblast propagation and compare to the principal weather factors of wind direction and speed. Two additional monitoring stations were used (#16 and 202) to provide data for this objective, roughly in line with the structure-monitoring stations (figure 2). These arrays is used to measure amplitude delay with distance. Figure 13 shows the seismograph at location 16, alongside instruments being operated by the mining company and other government agencies.

Production Blasts

Shot times, dates, weights per delay and coordinates were obtained from AMAX by INDR for this study. Date and times were needed to identify actual Ayrshire mine blasts, particularly at sites with numerous non-blast triggers. Charge weights were used to compute scaled distances for the propagation plots.

*** RESULTS

MEASUREMENTS

All measurements obtained during this study are tabulated in Appendix A. Instrument recordings of blast events are given in Appendix B and non-blast events in Appendix C.

St. John's Church (#119)

At this church, as at all other sites, very low airblasts were experienced. Researchers obtained only three measurable airblast-produced structural responses. A few ground vibration-induced structural responses were also obtained and more could have been recorded except for the high environmental "noise" and some bad choices of initial trigger settings.

Early in the study, there were 8 events with radial-component structural responses greater than 0.15 in/s. Only two of these triggered the ground

Figure 11.- Close-up of St. John's transducer and microphone

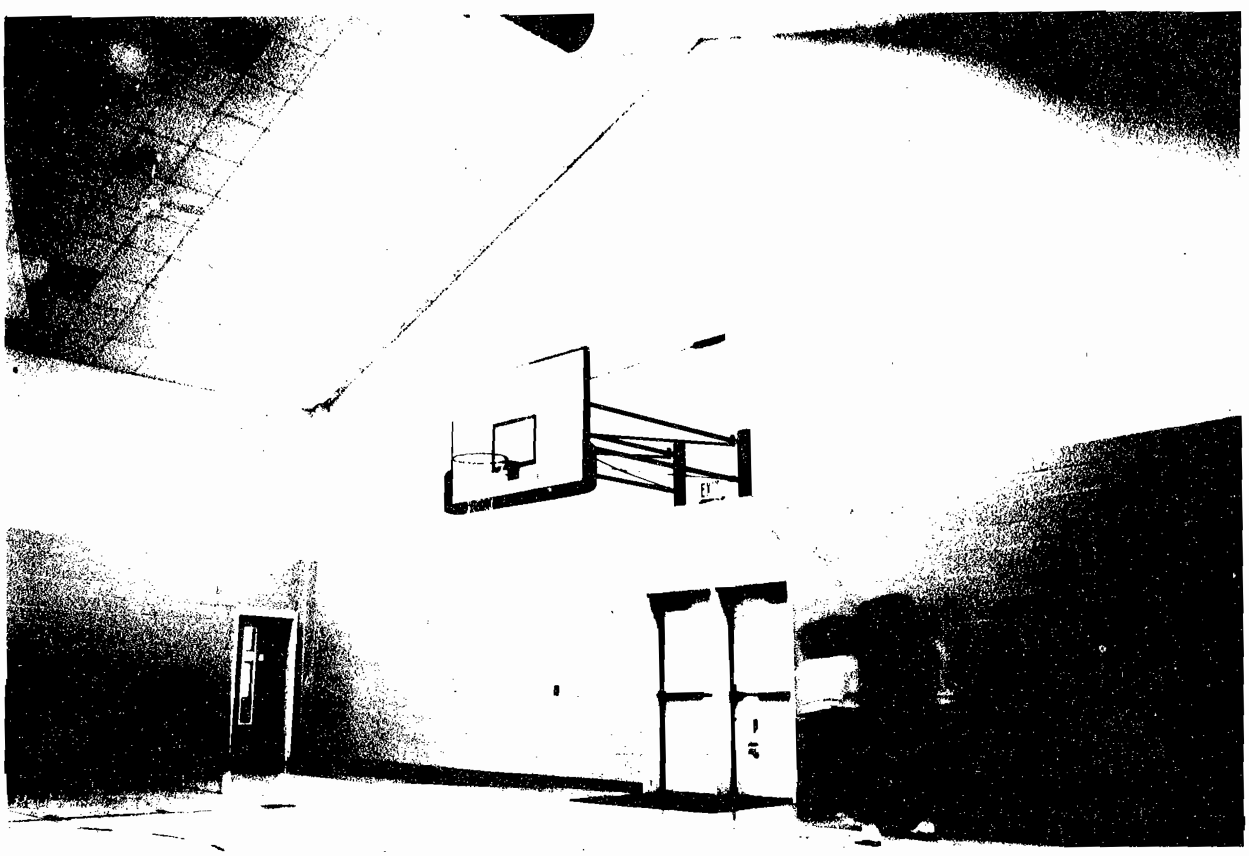

Figure 12.- Inside east wall of St. John's Church showing backstop mounted near midwall antinode

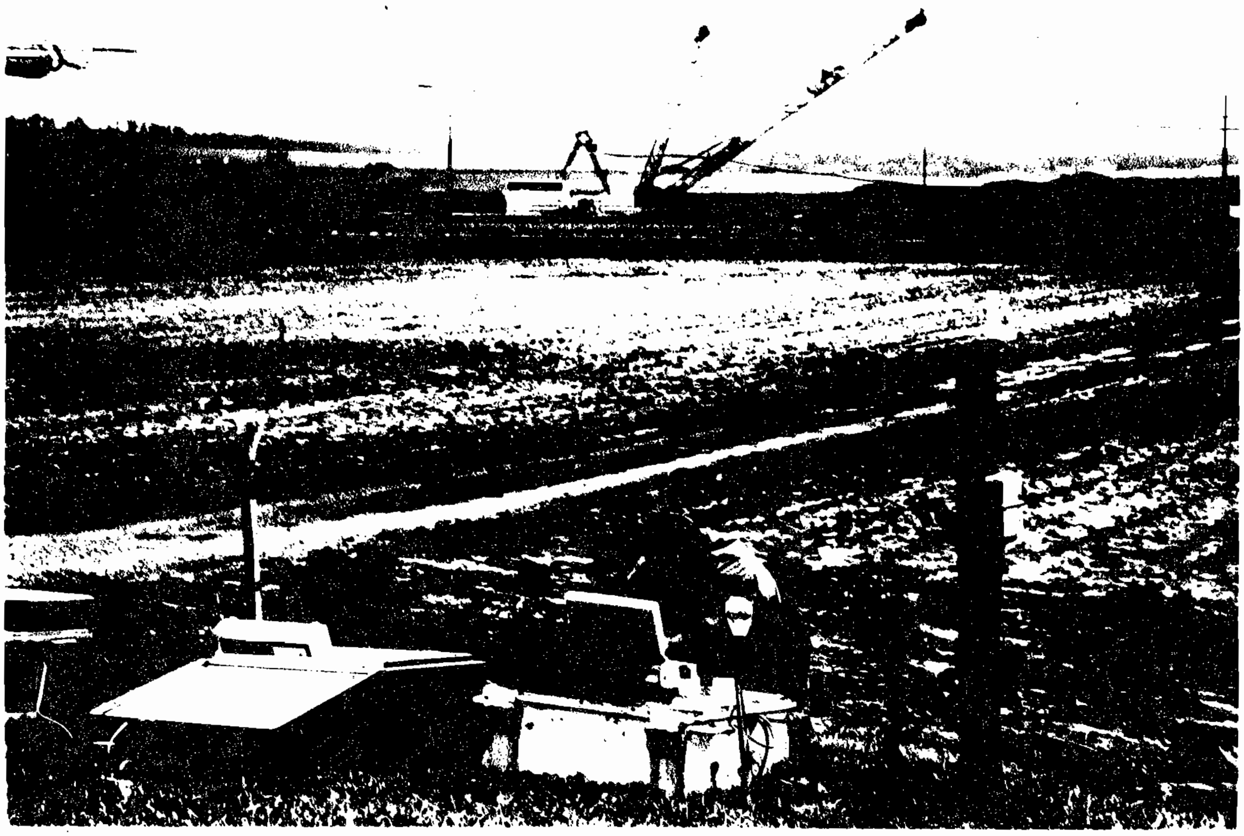

Figure 13.- Instrument set-up at closest structure, Marx house (#16): Equipment belonging to the mine and another government agency were also located here

vibration seismograph set to trigger at or above 0.1 in/s. As previously discussed, triggers were adjusted on January 9.

After these changes, only two blast-induced responses exceeded 0.15 in/s. In total, only five blasts were recorded with both vibrations and responses at St. John's. Considering the low blast vibration amplitudes and the relatively high ambient from human activity and other sources, such problems were not unusual for automated monitoring. In any case, ground vibration amplitudes and their induced structural responses were beyond the scope of this project.

At this site, as at all others during this study, no airblasts exceeded the trigger thresholds of 125 dB. Hence, all recorded airblasts and airblast responses were from seismographs already triggered by ground and/or structural vibrations and arriving within the 9-second time window.

Figure B1 and 2 show examples of ground vibration and structural responses at St. John's. Figure B-3 shows vibrations, airblast and responses from both of these at St. John's.

Hoover (#118)

This structure was the farthest monitored and only 10 usable record were obtained. Reported airblast values in table A-2 are not meaningful, being acoustic noise coincidental with ground vibration arrivals, e.g., Rock Pressure Pulse (RPP) as described in RI 8485 (*4*). Results from this lack of triggers are: 1) no airblast at this structure exceeded 125 dB and 2) no airblast-induced structure responses exceeded 0.1 in/s. Figures B-4 and B-5 show vibrations and responses for this structure.

Blue Grass Church (#224)

No structural responses exceeded the threshold triggering levels for this structure and all ground vibration amplitudes were low, at or below .04 in/s. As with House 118, the lack of triggers indicates no significant airblasts nor airblast-induced responses. Human activity-induced triggers during downloading visits verified that the seismographs here and at other sites were properly operating. Figure B-6 shows one of the largest blast events obtained at this site.

Marx (#16)

This structure is closest to the mine highwall and resulted in 58 vibration and airblast recordings. This was the only location where significant airblasts were measured, the highest being 0.2 mb (120 dB). A high reading listed in Table A-4 (2-25, 1401) is probably not from a blast even though close to blast time. The lack of a measurable ground vibrations and absence of triggers of any other seismographs makes this recording suspect.

Figures B-7 and B-8 show two vibrations with very different frequencies. Although clearly beyond the scope of this airblast study, careful analysis of such recordings could lead to techniques for controlling vibration characteristics through blast design, at least for moderate distances. Such studies have been proposed and some preliminary results of a blast deisign influence on vibration character in the Daylight-McCutchanville area exist (*3*).

Richey (#202)

This structure is far from the highwall and shares the trigger and monitoring problems and characteristics of sites #118 and #224. All airblast recordings in table A-5 are suspect because of a high acoustic turbulence on this hilltop location and the fact that any true airblast would likely be outside the 9-second window for a vibration-triggered event. However, whatever the maximums were, none were above the 125 dB airblast trigger threshold or the seismograph would have triggered again. Figure B-9 shows a blast recorded at this site.

AIRBLAST PROPAGATIONS

Interpreting anything meaningful from such sparse and low-level airblast data is beyond prudent extrapolative ability. Only the two closest structures, Marx and St. John's have airblast amplitudes which reliably represent the peaks. Airblasts recorded at different times cannot be pooled to establish losing distinctive weather conditions affecting the propagations. Taking the airblast values from Appendix A, the authors plotted amplitudes in figure 14 and 15. Lines connecting points are to show values measured at different sites for a given blast. They are <u>not</u> regression lines representing statistical averages. Figure 14 and 15 also show the historical values of 2-Hz measured airblast from RI 8485 plus extremes of total confinement and unconfined (*4*).

AIRBLAST-INDUCED STRUCTURE RESPONSES

Figure 16 shows airblast-induced structure responses with the bottom graph having a greatly expanded origin zone. The least-squares line is from RI 8485 (*4*). This least squares mean is an origin-based prediction curve and pertains to 2-Hz systems, as also employed for this study. This means flat amplitude response down to 2 Hz. The few structural response values obtained in this study are also plotted. All are from the St. John's monitoring, and all are very approximate at such low amplitudes. Points above the mean prediction suggest relatively high responses. This is not surprising and was originally hypothesized as possible because of the height of St. John's and the large area of exposed wall. If extrapolated proportionally according to Fig. 16, airblasts above 130 dB should produce responses as large as some of the bigger basketball-induced responses. However, such extreme extrapolation is not recommended.

GROUND VIBRATION RESPONSES AND PROPAGATIONS

A few ground vibration-induced responses were measured during this airblast study. Peak amplitudes are listed in the Appendix A tables. Because of limitations of time and project scope, these were not analyzed for structural amplification factors. This could be done at a later date using enhanced amplitude-playbacks and careful time-correlations.

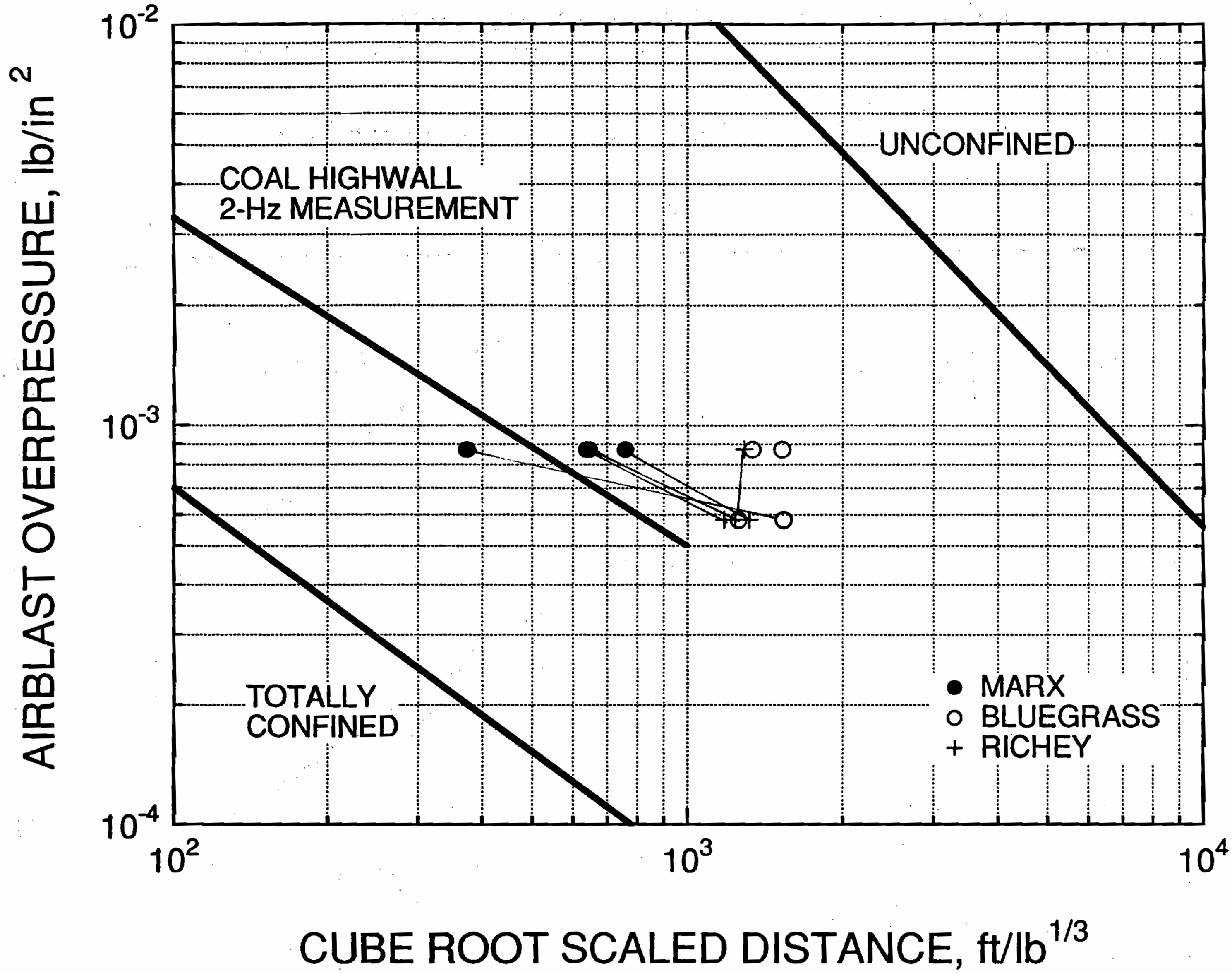

Figure 14.- Airblast amplitudes obtained in this study in the NW direction. Values collected from a given blast are connected

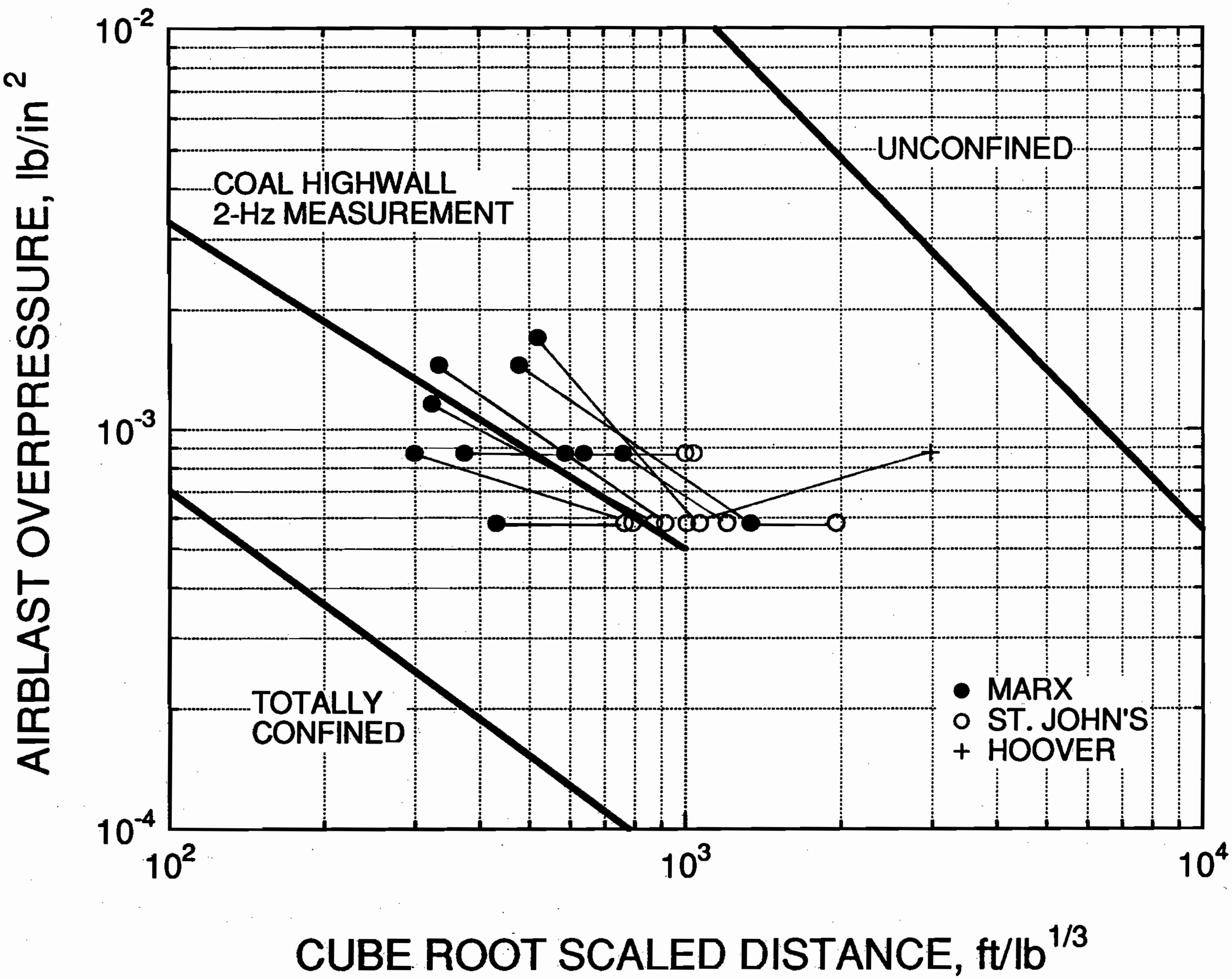

Figure 15.- Airblast amplitudes obtained in this study in the SW direction. Values collected from a given blast are connected

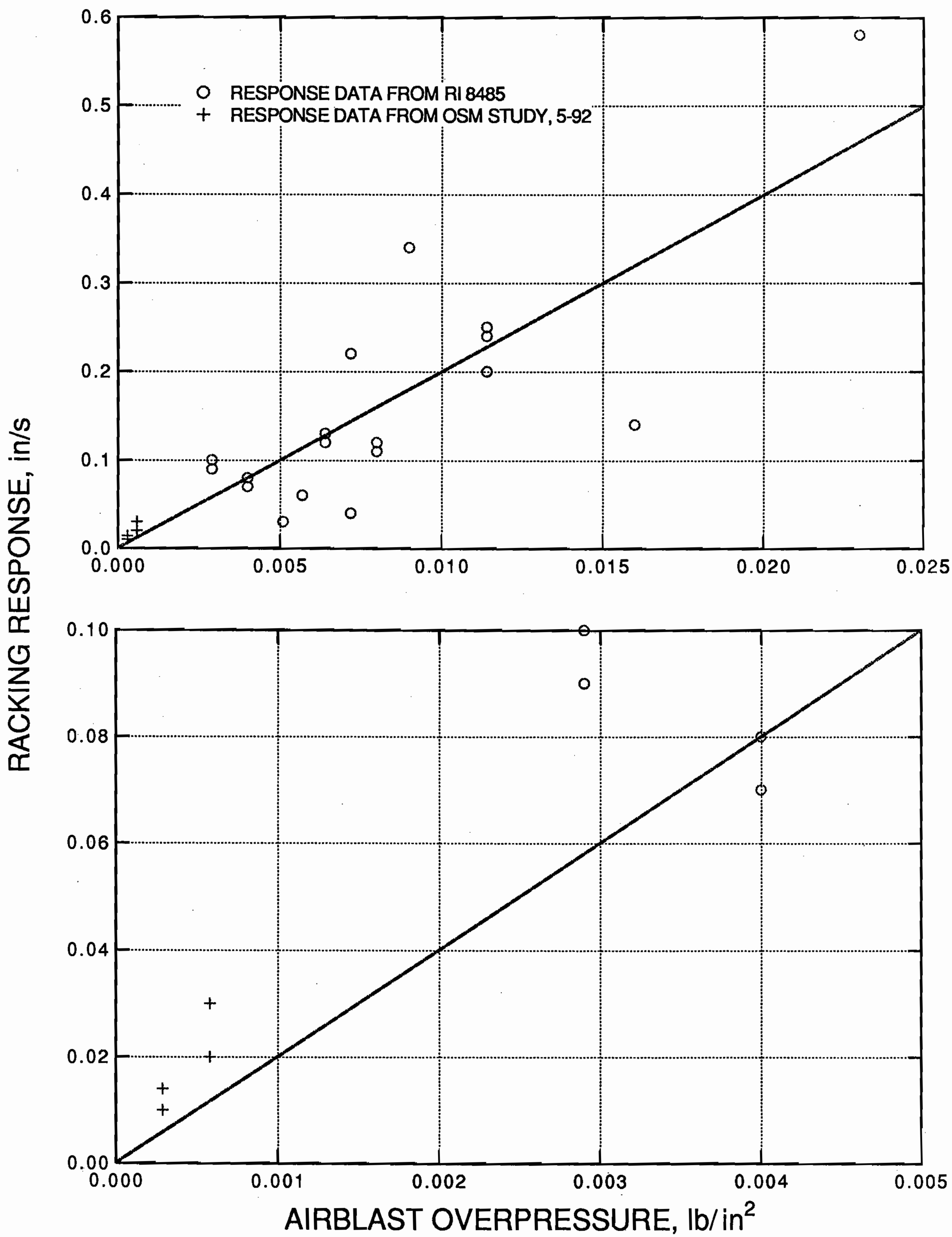

Figure 16.- Structure responses from airblast. Top is all data out to .025 lb/in^2 (139 dB) and bottom shows a greatly expanded origin zone. Solid line is least squares mean prediction for the RI 8485 (*4*) data

*** CONCLUSIONS

Very few significant airblasts were generated during this three-month monitoring period. The few producing measurable responses suggested a slightly greater structural responses than the average of homes studied previously and reported in BuMines RI 8485 (*4*). This agrees with the expectation for structures which are taller and/or have relatively large surface areas exposed to the airblast wavefront, compared to single-family homes.

St. John's Church is a recently built structure with a few cosmetic cracks in internal block walls in the large activity room towards the mine highwall (eastward end). With the few airblast responses obtained here, it is not possible to determine exactly how the vibrational responses scale up with increasing airblast levels or if the impact response ratio would be the same as reported in RI 8485. A significant environmental impact on the monitored east wall is the basketball and other human activity, producing hundreds of relatively high vibrational responses. Although extrapolation from the RI curve is necessarily approximate, the larger of these basketball-induced responses are equivalent to those which would result from airblasts in the range of 130 dB.

With the lack of high amplitude airblasts and associated responses this study is inconclusive. Measured responses, such as they are, are above average but not above the range of those measured previously. Consequently there is no reason to conclude that the guidelines in RI 8485, based on the worst case response scenario, are not still applicable.

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Table A-1.--Vibrations and Responses at St. Johns Church (#119)

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
11-13-91	1402										
11-16	1302				.02	.24	.03	.06			
11-16	1314				.02	.27	.08	.08			
11-16	1326				.02	.38	.06	.09			
11-19	1104				.02	.25	.05	.08			
11-19	1112				.04	.14	.03	.04			
11-21	1322	.08	.03	.10	.02	.35	.07	.13			
11-22	1138										
11-27	1414				.02	.12	.03	.04			
11-27	1425										
11-27	1436										
11-30	1324				.04	.11	.02	.04			
12-3	1440				.02	.15	.02	.04			
12-6	1022				.02	.13	.02	.03			
12-7	1011				.02	.11	.02	.03	.01		
12-13	1053				.04	.16	.04	.05	.03		
12-13	1100				.02	.26	.05	.08			
12-17	0941				.02	.10	.01	.03			
12-17	0950										
12-17	1531										
12-17	1616										
12-17	1624										
12-18	1103										
12-18	1122										
12-18	1509					Out of service					
12-21	1127	.10	.05	.06	.04	"	"	"			
12-21	1138					"	"	"			
12-31	1026										

Table A-1.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Air-blast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
1-2-92	0958										
1-3	1006	.03	.03	.03	.04	.13	.01	.03	.02		
1-6	0957	.02	.02	.03	.02	.11	.01	.04			
1-7	1006	.02	.02	.02	.08						
1-15	1125										
1-15	1140	.02	.01	.03	.02						
1-15	1147	.02	.01	.02	.02						
1-15	1159	.02	.01	.02	.02						
1-15	1207	.02	.01	.02	.02						
1-17	1103	.06	.02	.04	0	.15	.02	.06			
1-17	1111	.04	.03	.05	.02				.014		
1-22	0945	.02	.02	.03	0						
1-22	0952	.01	.01	.02	0						
1-22	1429	.02	.02	.02	.02						
1-22	1447	.04	.03	.05	.02						
1-23	1000	.03	.01	.02	.02						
1-23	1016	.03	.02	.04	.02						
1-23	1314	.03	.02	.03	.02						
1-28	1439										
1-29	1357	.02	.01	.02	.02						
1-29	1504										
1-30	1205										
1-31	0930										
2-3	1100	.02	.02	.02	.04						
2-3	1107	.02	.01	.01	.02						
2-5	0903										
2-6	0918	.04	.02	.04	.06						

Table A-1.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
2-6	1037	.03	.02	.02	.04						
2-7	0909	.03	.02	.03	.02						
2-7	1019	.05	.03	.04	.02						
2-10	1149										
2-11	1014	.02	0	.01	.04						
2-13	1140	.03	.03	.04	0						
2-13	1150	.03	.02	.03	.02						
2-14	1006	.02	.01	.03	.04						
2-14	1017	.03	.02	.04	.04						
2-14	1545	.04	.03	.04	.02						
2-17	1500	.05	.02	.05	.04						
2-18	1456	.03	.02	.03	.02						
2-18	1459	.02	.02	.02	.06						
2-18	1508	.05	.03	.04	0						
2-18	1544	.02	.01	.02	.02						
2-19	1332	.04	.04	.04	.02	.15	.05	.05			
2-21	1104	.04	.03	.07	.02						
2-21	1112										
2-21	1129	.03	.01	.03	.02						
2-21	1535	.03	.03	.01	.04						
2-24	1018										
2-24	1452										
2-25	1020										
2-25	1401										
2-26	1320	.02	.02	.01							
2-26	1547										
2-27	0906										
2-27	1514	.02	.01	.02	.02						
2-28	1519										
2-28	1539	.02	0	.01	.02						
3-3	0853										
3-3	1250										

Table A-2.--Vibrations and Responses at House (#118)

Shot Date and Time		Ground Vibration, in/s			Airblast, mb	Vibration-induced responses, in/s			Airblast-induced responses, in/s		
		R	V	T		R	V	T	R	V	T
11-13-91	1402										
11-16	1302										
11-16	1314										
11-16	1326										
11-19	1104										
11-19	1112										
11-21	1322										
11-22	1138										
11-27	1414										
11-27	1425										
11-27	1436										
11-30	1324					.06	.03	.12			
12-3	1440										
12-6	1022										
12-7	1011										
12-13	1053										
12-13	1100										
12-17	0941										
12-17	0950										
12-17	1531										
12-17	1616										
12-17	1624										
12-18	1103										
12-18	1122										
12-18	1509										
12-21	1127										
12-21	1138										
12-31	1026										

Table A-2.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
1-2-92	0958										
1-3	1006	.01	.03	.02	.06						
1-6	0957										
1-7	1006										
1-15	1125										
1-15	1140										
1-15	1147										
1-15	1159										
1-15	1207										
1-17	1103										
1-17	1111	.01	.01	.02	.02						
1-22	0945										
1-22	0952										
1-22	1429										
1-22	1447	.01	.02	.02	.02	.04	.02	.11			
1-23	1000										
1-23	1016										
1-23	1314										
1-28	1439										
1-29	1357										
1-29	1504										
1-30	1205										
1-31	0930										
2-3	1100										
2-3	1107										
2-5	0903					Out of Service					
2-6	0918					"	"	"			

Table A-2.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
2-6	1037					Out of service					
2-7	0909					"	"	"			
2-7	1019					"	"	"			
2-10	1149					"	"	"			
2-11	1014					"	"	"			
2-13	1140	.01	.01	.02	0	"	"	"			
2-13	1150					"	"	"			
2-14	1006					"	"	"			
2-14	1017					"	"	"			
2-14	1545	.01	.01	.02	0	"	"	"			
2-17	1500	.01	.01	.02	.02	"	"	"			
2-18	1456					"	"	"			
2-18	1459					"	"	"			
2-18	1508	.02	.01	.02	0	"	"	"			
2-18	1544					"	"	"			
2-19	1332	.01	.01	.02	.02	"	"	"			
2-21	1104										
2-21	1112										
2-21	1129										
2-21	1535										
2-24	1018										
2-24	1452										
2-25	1020										
2-25	1401										
2-26	1320										
2-26	1547										
2-27	0906										
2-27	1514										
2-28	1519										
2-28	1539										
3-3	0853										
3-3	1250										

Table A-3.--Vibrations and Responses at Blue Grass Church (#224)

Shot Date and Time		Ground Vibration, in/s			Airblast, mb	Vibration-induced responses, in/s			Airblast-induced responses, in/s		
		R	V	T		R	V	T	R	V	T
11-13-91	1402										
11-16	1302										
11-16	1314										
11-16	1326										
11-19	1104										
11-19	1112										
11-21	1322										
11-22	1138										
11-27	1414										
11-27	1425										
11-27	1436										
11-30	1324										
12-3	1440										
12-6	1022										
12-7	1011										
12-13	1053										
12-13	1100										
12-17	0941										
12-17	0950										
12-17	1531										
12-17	1616										
12-17	1624										
12-18	1103										
12-18	1122										
12-18	1509										
12-21	1127										
12-21	1138										
12-31	1026										

Table A-3.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Air-blast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
1-2-92	0958										
1-3	1006										
1-6	0957	.02	.01	.03	.02						
1-7	1006	.02	.02	.01	.02						
1-15	1125	.02	.01	.01	.06						
1-15	1147	.02	.02	.02	.04						
1-15	1147	.02	.01	.02	.06						
1-15	1159	.02	.01	.02	.04						
1-15	1207	.02	.01	.02	.02						
1-17	1103	.04	.02	.04	.02						
1-17	1111	.04	.02	.03	.02						
1-22	0945	.03	.02	.03	.02						
1-22	0952	.02	.01	.01	.02						
1-22	1429	.02	.02	.02	.04						
1-22	1447	.03	.02	.03	.02						
1-23	1000	.02	.02	.02	.02						
1-23	1016	.02	.01	.02	.02						
1-23	1314	.04	.02	.02	.04						
1-28	1439										
1-29	1357	.02	.02	.02	.02						
1-29	1504										
1-30	1205										
1-31	0930										
2-3	1100	.02	.02	.02	.02						
2-3	1107	.02	.02	.02	.02						
2-5	0903	.03	0	.02	.02						
2-6	0918	.02	.01	.02	.04						

Table A-3.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
2-6	1037	.02	.02	.02	.02	Out of service					
2-7	0909	.02	.02	.01	.02	"	"	"			
2-7	1019	.03	.02	.03	.02	"	"	"			
2-10	1149	.02	.01	.02	.02	"	"	"			
2-11	1014	.02	.02	.02	.02	"	"	"			
2-13	1140	Out of service				"	"	"			
2-13	1150	"	"	"		"	"	"			
2-14	1006	"	"	"		"	"	"			
2-14	1017	"	"	"		"	"	"			
2-14	1545	"	"	"		"	"	"			
2-17	1500	"	"	"		"	"	"			
2-18	1456	"	"	"		"	"	"			
2-18	1459	"	"	"		"	"	"			
2-18	1508	"	"	"		"	"	"			
2-18	1544	"	"	"		"	"	"			
2-19	1332	"	"	"		"	"	"			
2-21	1104	"	"	"		"	"	"			
2-21	1112	"	"	"		"	"	"			
2-21	1129	"	"	"		"	"	"			
2-21	1535	"	"	"		"	"	"			
2-24	1018	"	"	"		"	"	"			
2-24	1452	"	"	"		"	"	"			
2-25	1020	"	"	"		"	"	"			
2-25	1401	"	"	"		"	"	"			
2-26	1320	"	"	"		"	"	"			
2-26	1547	"	"	"		"	"	"			
2-27	0906	"	"	"		"	"	"			
2-27	1514	"	"	"		"	"	"			
2-28	1519	"	"	"		"	"	"			
2-28	1539	"	"	"		"	"	"			
3-3	0853	"	"	"		"	"	"			
3-3	1250	"	"	"		"	"	"			

Table A-4.--Vibrations at House #16

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
11-13-91	1402										
11-16	1302	.10	.14	.15	.06						
11-16	1314										
11-16	1326	.15	.13	.17	.10						
11-19	1104	.11	.11	.11	.08						
11-19	1112	.14	.15	.11	.06						
11-21	1322	.23	.23	.23	.08						
11-22	1138										
11-27	1414										
11-27	1425										
11-27	1436										
11-30	1324										
12-3	1440										
12-6	1022										
12-7	1011										
12-13	1053										
12-13	1100	.14	.09	.12	.06						
12-17	0941										
12-17	0950										
12-17	1531										
12-17	1616										
12-17	1624										
12-18	1103										
12-18	1122										
12-18	1509										
12-21	1127	.11	.16	.19	.08						
12-21	1138	.09	.10	.10	.06						
12-31	1026	.13	.07	.07	.06						

Table A-4.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
1-2-92	0958	.13	.12	.10	.08						
1-3	1006	.06	.06	.06	.12						
1-6	0957	.04	.04	.06	.06						
1-7	1006	.04	.05	.04	.14						
1-15	1125	.03	.02	.03	.02						
1-15 1140		.04	.02	.04	.02						
1-15	1147	.03	.02	.03	.04						
1-15	1159	.03	.03	.04	.04						
1-15	1207	.04	.03	.03	.04						
1-17	1103	.03	.05	.06	.08						
1-17	1111	.07	.06	.06	.06						
1-22	0945										
1-22	0952	.02	.02	.02	.02						
1-22	1429	.04	.04	.03	.06						
1-22	1447	.02	.02	.02	.06						
1-23	1000	.03	.03	.06	.06						
1-23	1016	.04	.03	.05	.10						
1-23	1314	.04	.03	.04	.04						
1-28	1439										
1-29	1357	.03	.04	.04	.02						
1-29	1504										
1-30	1205										
1-31	0930										
2-3	1100	.04	.04	.05	.12						
2-3	1107	.04	.03	.04	.08						
2-5	0903	.08	.08	.12	.06						
2-6	0918	.05	.08	.08	.06						

Table A-4.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
2-6	1037	.10	.06	.08	.10						
2-7	0909	.09	.06	.15	.06						
2-7	1019	.12	.10	.10	.10						
2-10	1149	.02	.01	.01	.02						
2-11	1014	.03	.04	.03	.04						
2-13	1140	.02	.01	.02	.02						
2-13	1150	.03	.05	.05	.04						
2-14	1006	.05	.05	.05	.10						
2-14	1017	.11	.09	.09	.20						
2-14	1545	.01	.02	.01	.02						
2-17	1500	.06	.05	.05	.06						
2-18	1456	.02	.02	.02	.04						
2-18	1459	.03	.03	.05	.06						
2-18	1508	.05	.08	.08	.04						
2-18	1544	.03	.02	.04	.02						
2-19	1332	.07	.09	.10	.06						
2-21	1104	.02	.01	.02	.02						
2-21	1112	.01	.02	.02	.04						
2-21	1129	.04	.04	.07	.06						
2-21	1535	.03	.04	.03	.06						
2-24	1018	.03	.03	.03	.04						
2-24	1452										
2-25	1020	.02	.02	.02	.06						
2-25	1401	.01	.01	.01	.38						
2-26	1320	.02	.03	.02	.04						
2-26	1547										
2-27	0906										
2-27	1514	.02	.02	.02	.02						
2-28	1519										
2-28	1539	.02	.02	.02	.02						
3-3	0853	.02	.02	.02	.02						
3-3	1250										

Table A-4.--Vibrations at House (#202)

Shot Date and Time		Ground Vibration, in/s			Airblast, mb	Vibration-induced responses, in/s			Airblast-induced responses, in/s		
		R	V	T		R	V	T	R	V	T
11-13-91	1402										
11-16	1302										
11-16	1314										
11-16	1326										
11-19	1104										
11-19	1112										
11-21	1322										
11-22	1138										
11-27	1414										
11-27	1425										
11-27	1436										
11-30	1324										
12-3	1440										
12-6	1022										
12-7	1011										
12-13	1053										
12-13	1100										
12-17	0941										
12-17	0950										
12-17	1531										
12-17	1616										
12-17	1624										
12-18	1103										
12-18	1122										
12-18	1509										
12-21	1127										
12-21	1138										
12-31	1026										

Table A-5.--Continued

Shot Date and Time		Ground Vibration, in/s			Airblast, mb	Vibration-induced responses, in/s			Airblast-induced responses, in/s		
		R	V	T		R	V	T	R	V	T
1-2-92	0958										
1-3	1006										
1-6	0957	.02	.01	.02	.02						
1-7	1006	.02	.02	.02	.02						
1-15	1125	.02	.01	.02	.04						
1-15	1140	.02	.02	.02	.04						
1-15	1147	.02	.01	.02	.02						
1-15	1159	.02	.02	.02	.08						
1-15	1207	.02	.01	.02	.10						
1-17	1103	.02	.01	.02	.02						
1-17	1111	.01	.01	.02	.02						
1-22	0945	.02	.01	.02	.04						
1-22	0952	.02	.02	.02	.02						
1-22	1429	.02	.02	.02	.06						
1-22	1447	.02	.02	.02	.04						
1-23	1000										
1-23	1016	.02	.02	.02	.04						
1-23	1314	.02	.01	.01	.02						
1-28	1439										
1-29	1357	.01	.02	.02	.02						
1-29	1504										
1-30	1205										
1-31	0930										
2-3	1100	.02	.02	.03	.02						
2-3	1107	.02	.02	.02	.02						
2-5	0903	.03	.02	.03	.02						
2-6	0918	.02	.02	.03	.02						

Table A-5.--Continued

Shot Date and Time		Ground Vibration, in/s R	V	T	Airblast, mb	Vibration-induced responses, in/s R	V	T	Airblast-induced responses, in/s R	V	T
2-6	1037	.02	.02	.02	.02						
2-7	0909	.03	.01	.02	.02						
2-7	1019	.03	.03	.03	.02						
2-10	1149	.05	.02	.05	.04						
2-11	1014	.03	.03	.04	.02						
2-13	1140	.02	.01	.02	.02						
2-13	1150	.05	.02	.03	.04						
2-14	1006	.02	.01	.01	.04						
2-14	1017	.02	.01	.02	.04						
2-14	1545	.02	.02	.02	.04						
2-17	1500	.06	.02	.05	.04						
2-18	1456	.04	.02	.03	.04						
2-18	1459	.05	.02	.03	.04						
2-18	1508	.07	.03	.03	.08						
2-18	1544	.03	.02	.02	.04						
2-19	1332	.08	.03	.05	.02						
2-21	1104	.05	.03	.04	.02						
2-21	1112	.02	.01	.01	.02						
2-21	1129	.03	.02	.02	.02						
2-21	1535										
2-24	1018	.04	.03	.04	.02						
2-24	1452										
2-25	1020										
2-25	1401										
2-26	1320										
2-26	1547										
2-27	0906										
2-27	1514										
2-28	1519										
2-28	1539										
3-3	0853										
3-3	1250										

Appendix B.--Blast event time history examples

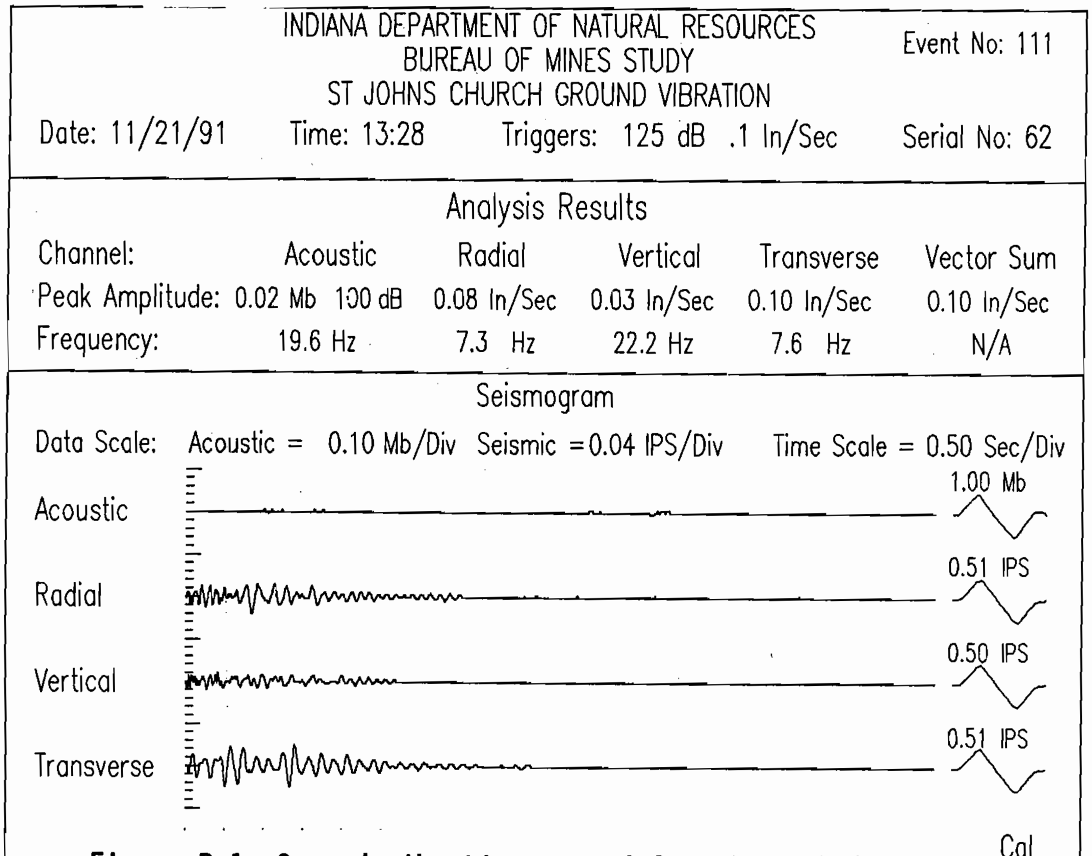

Figure B-1.-Ground vibration record from St. John's Church

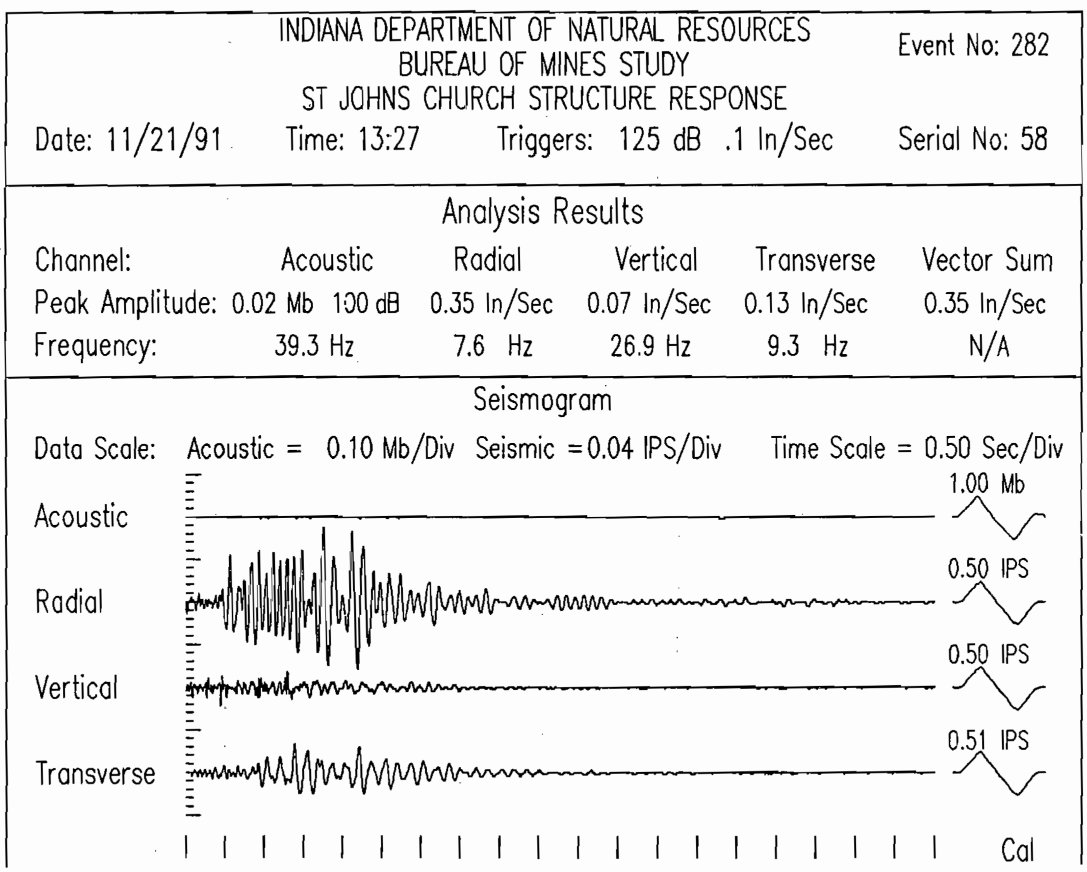

Figure B-2.-Structure response record from St. John's Church, same blast as Figure B-1

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
ST JOHNS CHURCH STRUCTURE RESPONSE

Event No: 200

Date: 1/ 3/92 Time: 10:11 Triggers: 125 dB .1 In/Sec Serial No: 58

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.04 Mb 106 dB	0.13 In/Sec	0.01 In/Sec	0.03 In/Sec	0.13 In/Sec
Frequency:	2.0 Hz	9.6 Hz	102.4Hz	11.6 Hz	N/A

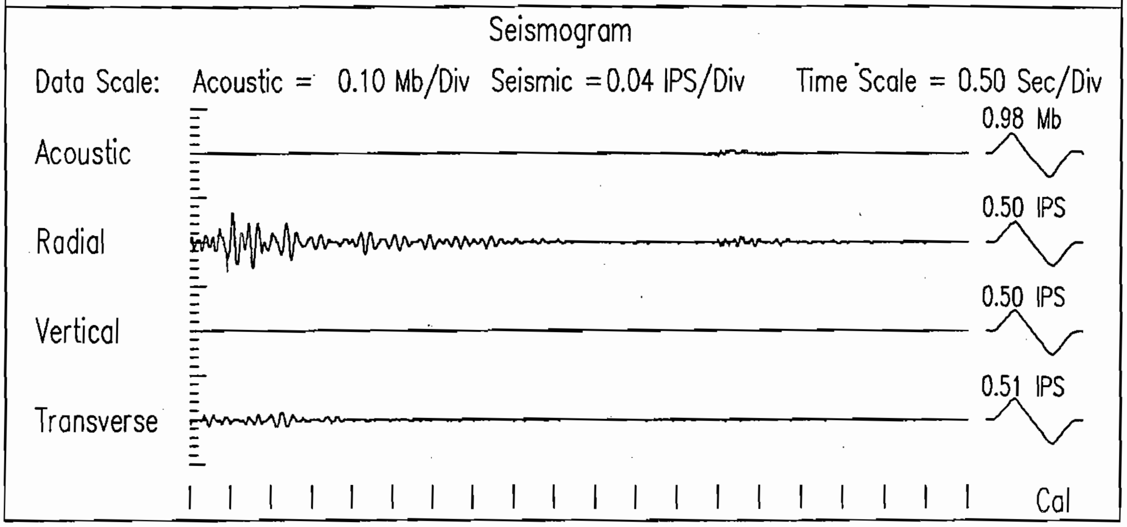

Figure B-3.-Structure response record from St. John's Church showing both vibration-and airblast-induced responses

Appendix B. --Continued

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
HOOVER RESIDENCE GROUND VIBRATION

Event No: 102

Date: 1/22/92 Time: 14:56 Triggers: 126 dB .02 In/Sec Serial No: 69

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.00 Mb 0 dB	0.01 In/Sec	0.01 In/Sec	0.02 In/Sec	0.02 In/Sec
Frequency:	102.4Hz	17.6 Hz	2.0 Hz	10.4 Hz	N/A

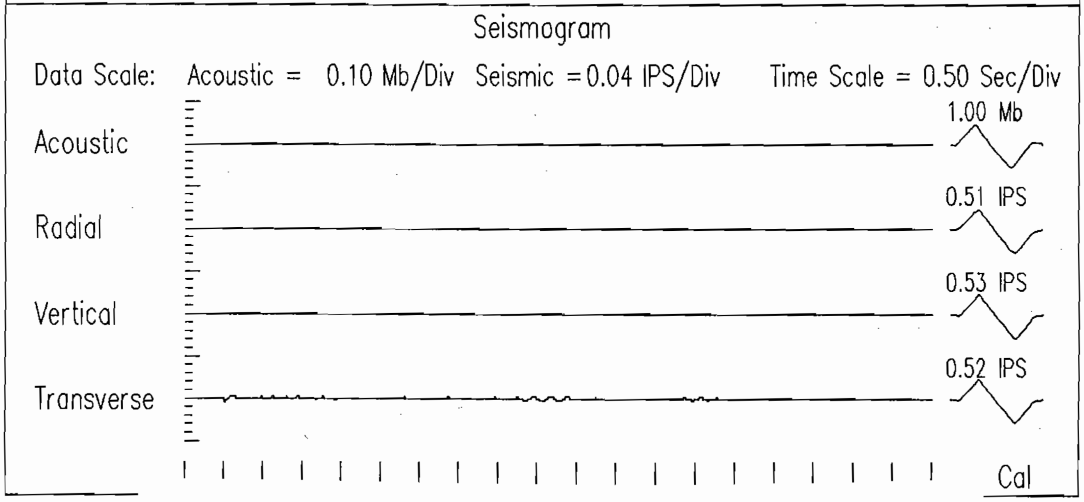

Figure B-4.-Ground vibration record from Hoover house

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
HOOVER RESIDENCE STRUCTURE RESPONSE

Event No: 199

Date: 1/22/92 Time: 14:55 Triggers: 125 dB .1 In/Sec Serial No: 60

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.02 Mb 100 dB	0.04 In/Sec	0.02 In/Sec	0.11 In/Sec	0.11 In/Sec
Frequency:	102.4Hz	7.3 Hz	10.8 Hz	5.5 Hz	N/A

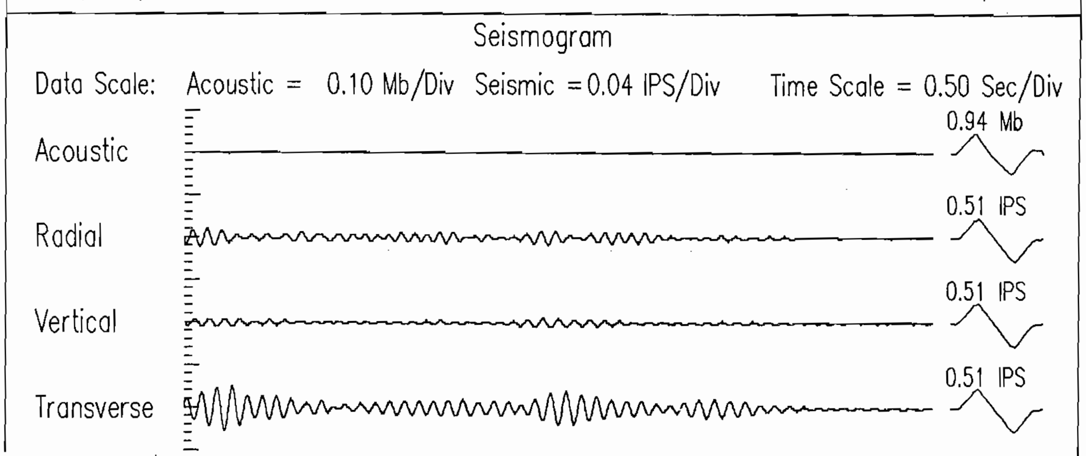

Figure B-5.-Structure response record from Hoover house, same blast as figure B-4

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
BLUE GRASS CHURCH GROUND VIBRATION

Event No: 195

Date: 1/22/92 Time: 14:53 Triggers: 126 dB .02 In/Sec Serial No: 59

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.02 Mb 100 dB	0.03 In/Sec	0.02 In/Sec	0.03 In/Sec	0.03 In/Sec
Frequency:	64.0 Hz	32.0 Hz	51.2 Hz	10.4 Hz	N/A

Seismogram

Data Scale: Acoustic = 0.10 Mb/Div Seismic = 0.04 IPS/Div Time Scale = 0.50 Sec/Div

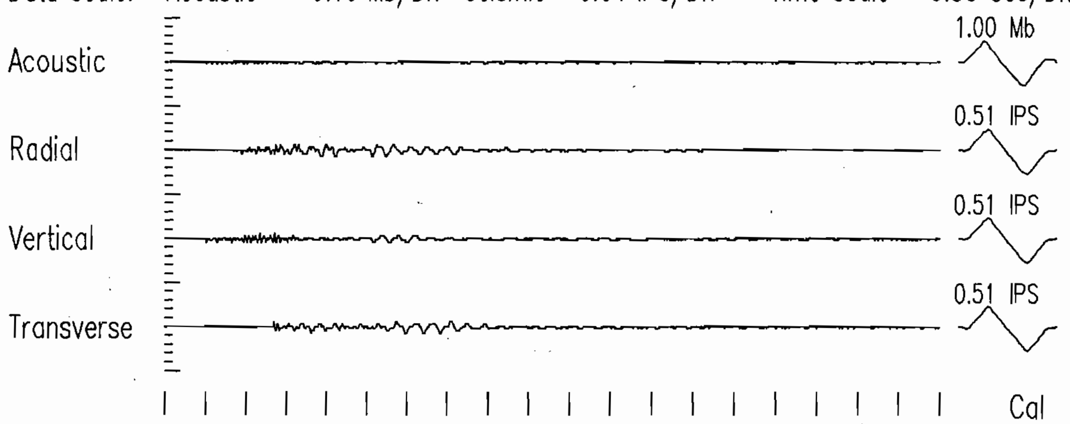

Figure B-6.-Ground vibration record from Blue Grass Church.

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
MARX RESIDENCE GROUND VIBRATION

Event No: 274

Date: 11/16/91 Time: 13:32 Triggers: 125 dB .1 In/Sec Serial No: 67

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.10 Mb 114 dB	0.15 In/Sec	0.13 In/Sec	0.17 In/Sec	0.21 In/Sec
Frequency:	13.8 Hz	15.0 Hz	9.3 Hz	13.1 Hz	N/A

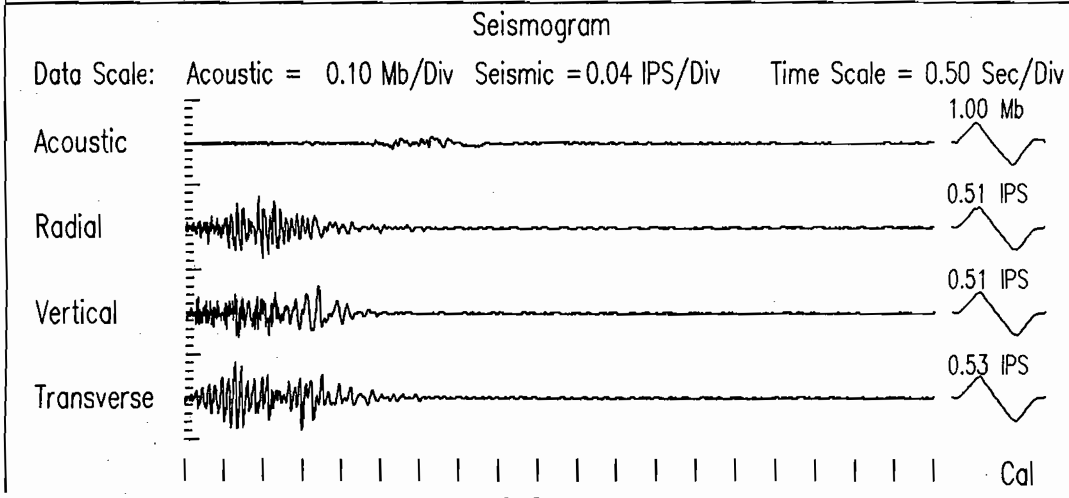

Figure B-7.-Ground vibration record from Marx house showing relatively high frequencies.

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
MARX RESIDENCE GROUND VIBRATION

Event No: 164

Date: 2/19/92 Time: 13:38 Triggers: 125 dB .02 In/Sec Serial No: 67

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.06 Mb 110 dB	0.07 In/Sec	0.09 In/Sec	0.10 In/Sec	0.10 In/Sec
Frequency:	2.0 Hz	5.8 Hz	5.3 Hz	6.4 Hz	N/A

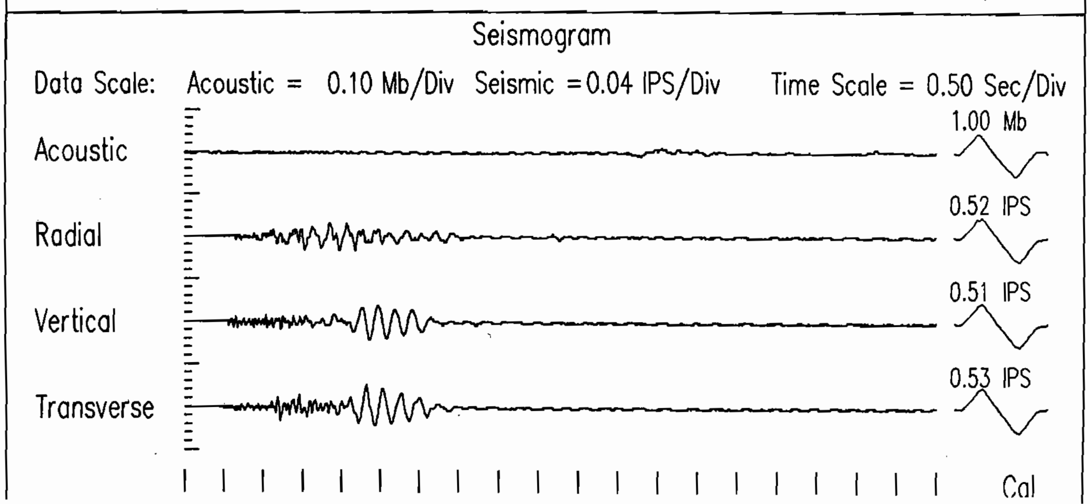

Figure B-8.-Ground vibration record from Marx house dominated by relatively low frequencies and contrasting with figure B-7

Appendix B. --Continued

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
RICHEY RESIDENCE GROUND VIBRATION

Event No: 091

Date: 2/18/92 Time: 15:14 Triggers: 125 dB .02 In/Sec Serial No: 57

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.08 Mb 112 dB	0.07 In/Sec	0.03 In/Sec	0.03 In/Sec	0.07 In/Sec
Frequency:	1.9 Hz	10.6 Hz	36.5 Hz	17.0 Hz	N/A

Seismogram

Data Scale: Acoustic = 0.10 Mb/Div Seismic = 0.04 IPS/Div Time Scale = 0.50 Sec/Div

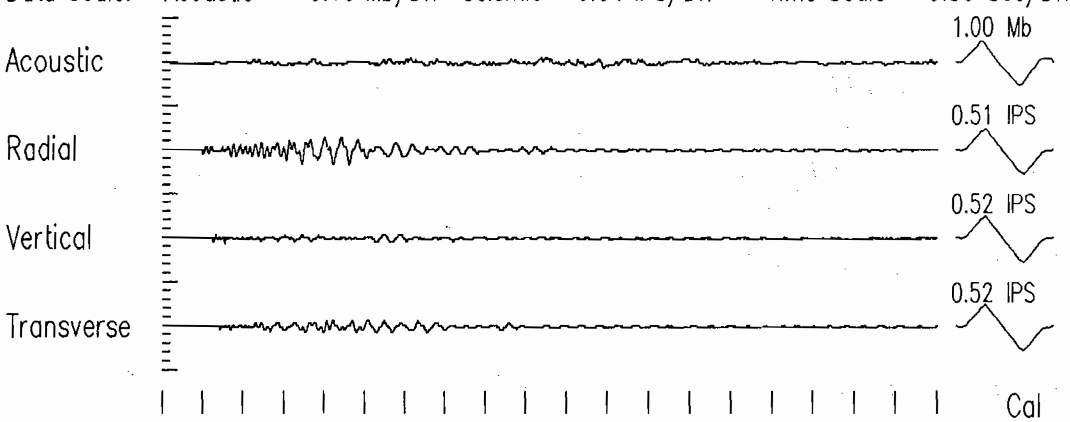

Figure B-9.-Ground vibration record from Richey house (#202)

Appendix C.--Non-blast event examples

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
ST JOHNS CHURCH STRUCTURE RESPONSE

Event No: 155

Date: 2/27/92 Time: 7:23 Triggers: 125 dB .15 In/Sec Serial No: 58

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.38 Mb 126 dB	0.01 In/Sec	0.01 In/Sec	0.01 In/Sec	0.01 In/Sec
Frequency:	9.1 Hz	102.4Hz	256.0Hz	102.4Hz	N/A

Seismogram

Data Scale: Acoustic = 0.10 Mb/Div Seismic =0.04 IPS/Div Time Scale = 0.50 Sec/Div

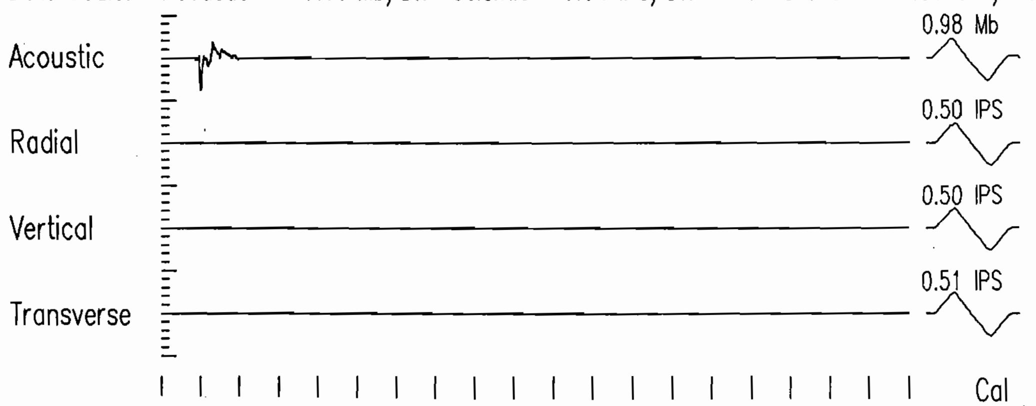

Figure C-1.-Acoustic non-blast recording at St. Johns, high frequency

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
ST JOHNS CHURCH STRUCTURE RESPONSE

Event No: 040

Date: 2/11/92 Time: 19:59 Triggers: 125 dB .15 In/Sec Serial No: 58

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.02 Mb 100 dB	0.36 In/Sec	0.05 In/Sec	0.02 In/Sec	0.36 In/Sec
Frequency:	102.4Hz	15.0 Hz	22.2 Hz	46.5 Hz	N/A

Seismogram

Data Scale: Acoustic = 0.10 Mb/Div Seismic =0.04 IPS/Div Time Scale = 0.50 Sec/Div

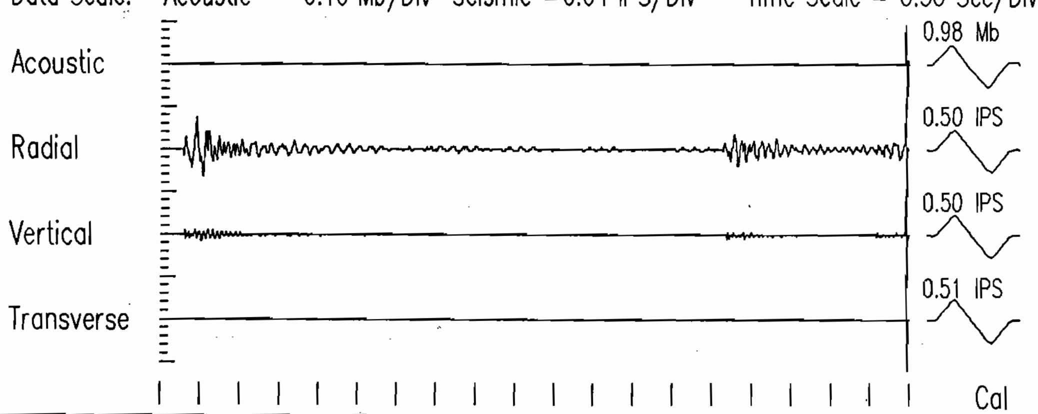

Figure C-2.-Vibration non-blast repetitive recording of stucture response at St. John's

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
ST JOHNS CHURCH STRUCTURE RESPONSE

Event No: 170

Date: 11/14/91 Time: 21:38 Triggers: 125 dB .1 In/Sec Serial No: 58

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.02 Mb 100 dB	0.62 In/Sec	0.06 In/Sec	0.03 In/Sec	0.62 In/Sec
Frequency:	102.4Hz	6.8 Hz	12.4 Hz	42.6 Hz	N/A

Seismogram

Data Scale: Acoustic = 0.10 Mb/Div Seismic = 0.20 IPS/Div Time Scale = 0.50 Sec/Div

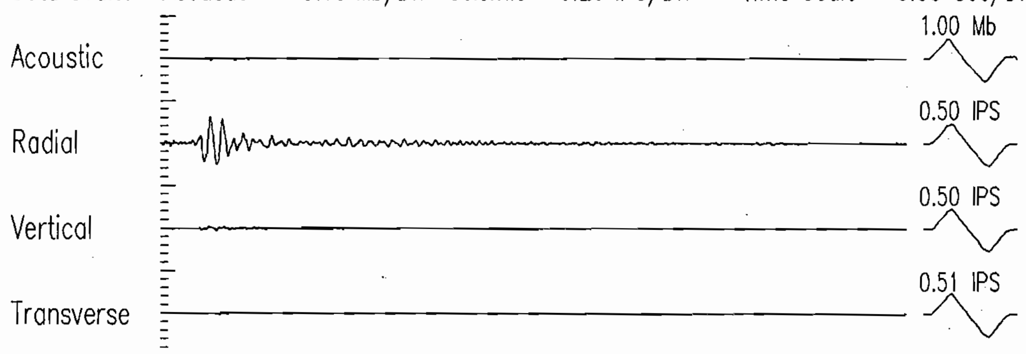

Figure C-3.-Vibration non-blast recording of structure response at St. John's, largest one during study period

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
HOOVER RESIDENCE STRUCTURAL RESPONSE

Event No: 179

Date: 11/25/91 Time: 7:28 Triggers: 125 dB .1 In/Sec Serial No: 60

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.98 Mb 134 dB	0.01 In/Sec	0.01 In/Sec	0.01 In/Sec	0.01 In/Sec
Frequency:	13.8 Hz	102.4Hz	102.4Hz	102.4Hz	N/A

Seismogram

Data Scale: Acoustic = 0.20 Mb/Div Seismic = 0.04 IPS/Div Time Scale = 0.50 Sec/Div

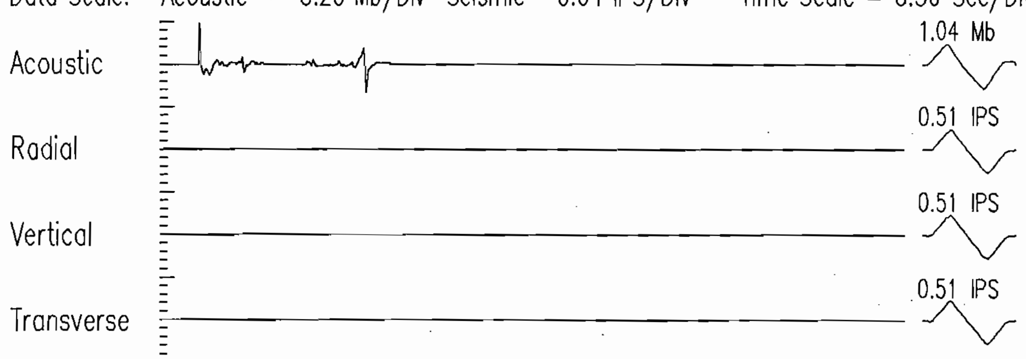

Figure C-4.-Acoustic non-blast vibration at Hoover house residence, high frequency

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
HOOVER RESIDENCE STRUCTURAL RESPONSE

Event No: 184

Date: 12/ 7/91 Time: 18:23 Triggers: 125 dB .1 In/Sec Serial No: 60

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.02 Mb 100 dB	0.13 In/Sec	0.02 In/Sec	0.06 In/Sec	0.13 In/Sec
Frequency:	102.4Hz	28.4 Hz	36.5 Hz	21.3 Hz	N/A

Seismogram

Data Scale: Acoustic = 0.10 Mb/Div Seismic = 0.04 IPS/Div Time Scale = 0.50 Sec/Div

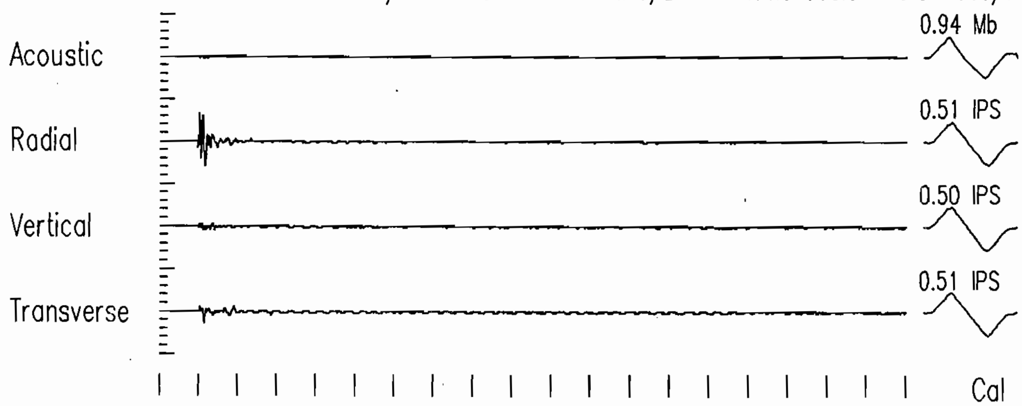

Figure C-5.-Vibration non-blast recording of structure response monitor at Hoover house #118.

INDIANA DEPARTMENT OF NATURAL RESOURCES
BUREAU OF MINES STUDY
BLUE GRASS CHURCH GROUND VIBRATION

Event No: 148

Date: 12/ 7/91 Time: 10:35 Triggers: 126 dB .1 In/Sec Serial No: 59

Analysis Results

Channel:	Acoustic	Radial	Vertical	Transverse	Vector Sum
Peak Amplitude:	0.64 Mb 130 dB	0.01 In/Sec	0.01 In/Sec	0.01 In/Sec	0.01 In/Sec
Frequency:	3.1 Hz	51.2 Hz	5.6 Hz	102.4Hz	N/A

Seismogram

Data Scale: Acoustic = 0.20 Mb/Div Seismic = 0.04 IPS/Div Time Scale = 0.50 Sec/Div

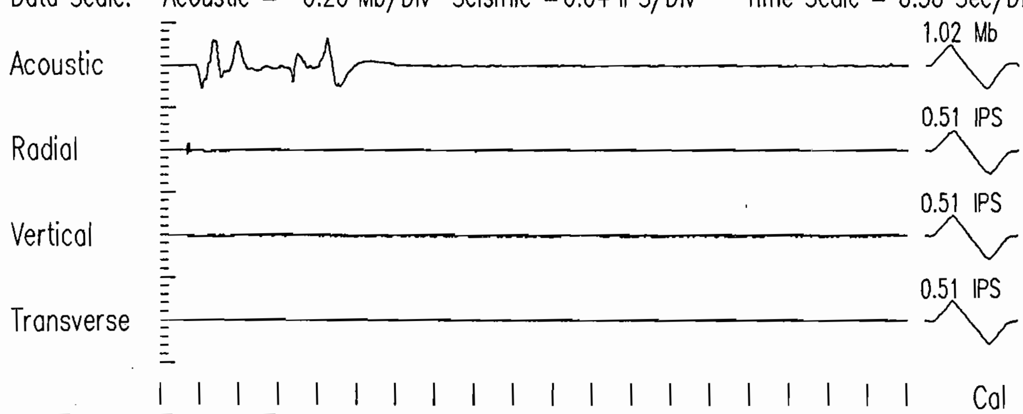

Figure C-6.-Acoustic non-blast recording at the Blue Grass Church