MICROSEISMIC ROOF FALL WARNING SYSTEM DEVELOPMENT

Field Trials and Commercial Prototype Fabrication

Prepared for

UNITED STATES DEPARTMENT OF INTERIOR
BUREAU OF MINES

by

Integrated Sciences, Inc.
1134 Francis Street
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FINAL REPORT

Contract No. H0272009
Field Trials of a Microseismic Roof Fall Warning System

May 30, 1980

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A microseismic roof fall warning system was field tested in Western and Eastern coal mines in the United States to better define the capabilities and limitations of the microseismic method in predicting roof fall. Microseismic event and energy type data were obtained and documented for twenty-three coal mine roof falls. Field test results indicate that both the microseismic event and energy methods, as applied in this development effort, have a high probability for successful application in a commercially practical roof fall warning system.

Based on the results and experience obtained during field testing, a commercial prototype microseismic roof fall warning system was designed and constructed. Although it was the intent of the program to field test the commercial prototype system, delays in equipment fabrication and contract time limitations did not permit field testing.

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FOREWORD

This report was prepared by Integrated Sciences, Inc. of Longmont, Colorado under USBM Contract Number H0272009. The contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of the Denver Mining Research Center, with Mr. Bernard J. Steblay acting as Technical Project Officer. Mr. David J. Askin was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as part of this contract during the period of August 1977 through December 1979. This report was submitted by the author on May 30, 1980.

The report presents the results of a two and one-half year program to provide services, material, and personnel to upgrade microseismic roof fall data collection equipment and design, fabricate, and field test a prototype microseismic roof fall warning system for commercial application. The principal effort was directed toward data collection and field testing in coal mines to evaluate the microseismic roof fall warning system's ability to predict roof fall.

Appendices are included to provide the interested reader with additional details on specific aspects of the program. The Volume I - Appendix C Data Collection Summary is included separately so that readers may have access to detailed field data listings for in-depth analysis.

The author wishes to acknowledge the efforts of Mr. Tom L. Finney, Mr. Thomas J. Burdick, Mr. Clarence B. Sparks, and Mr. George W. Crites of Integrated Sciences, Inc. who made major contributions to the roof fall warning system's design, and pursued the collection of field data with dedication and patience. Last, but not least, the author extends his sincere appreciation and gratitude to the Kaiser Steel Corporation, Plateau Mining Company, and Consolidation Coal Company, without whose cooperation the results of this effort would not have been possible.

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1.0 INTRODUCTION

The occurrence of roof fall continues to be a major problem in the coal mining industry. Preliminary statistics compiled by the Mine Safety and Health Administration (MSHA) for 1979 show a significant increase in fatalities and lost work days compared to 1978.* The number of deaths attributed to roof falls in 1979 was more than double the 28 deaths from falls in 1978. In addition to the tragic loss of human life, roof falls incur large economic losses to the mining companies through lost production and damage to costly mining equipment. The development of a commercially practical roof fall warning system would be of great benefit to the coal mining industry.

Under contract to the U.S. Bureau of Mines, Integrated Sciences, Inc. pursued the development of a commercially practical microseismic roof fall warning system. The 25 month effort (later extended to 30 months) was aimed at further defining the capabilities and limitations of the microseismic roof fall warning system, previously developed under U.S. Bureau of Mines Contract No. H0242045, in providing roof fall warnings, and to develop equipment prototypes suitable for commercial use. The highest program priority was to gain further field experience with the in-mine use of the microseismic roof fall warning system.

The program plan included a three phase effort to substantially upgrade and modify the previously developed microseismic roof fall equipment, develop a commercial prototype roof fall warning system, and field test both types of equipment under a variety of mining conditions. Equipment upgrading and modification were completed during the first quarter of 1978 with in-mine testing initiated in May 1978 at a Western coal mine test site. MSHA permissibility approval for the upgraded microseismic roof fall warning system was not secured until the middle of 1979.

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*"Death Rate from Roof Fall Rises", Coal Age, May 1980, pg. 25.

Uncertainties in the applicability of a microseismic energy method of roof fall prediction delayed the design and construction of a commercial prototype system until the latter part of 1979. Once a sufficient quantity of field data was obtained it was found that microseismic energy count, event count, and energy/event count ratio methods were suitable for roof fall prediction, although the energy count and event count methods were more limited in application. A commercial prototype microseismic roof fall warning system was designed and constructed prior to the end of the contract performance period, but was not field tested in coal mines.

During the field test program, over 4,000 hours of microseismic energy count and event count data were obtained using a one minute time window or sampling period. The data was obtained from longwall and room and pillar type coal mining operations at four coal mines, one of which was an Eastern coal mine. A total of 23 roof falls were recorded from pre-failure to post-failure and documented for this report.

The conclusion reached through the performance of this effort is that the microseismic roof fall warning system does provide an adequate method of predicting roof fall in coal mines and has a high probability for successful application as a commercially practical system. It is further concluded that, with additional field testing and equipment development, the energy count method used in conjunction with the energy/event ratio method of roof fall prediction can provide reliable, short range prediction of roof falls within the immediate area of the coal mine working face.

Continued field testing, evaluation, and hardware development of the commercial prototype microseismic roof fall warning system are recommended.

2.0 DATA COLLECTION SYSTEM

The data collection equipment used for this development effort is a modified version of the Roof Fall Warning System developed by Westinghouse Electric Corporation under U.S. Bureau of Mines Contract No. H0272009[1] during the years 1974 and 1975. The overall system design objective is to provide equipment capable of detecting and processing microseismic signals in coal mines, yet provide considerable flexibility in system controls to allow experimentation in optimizing system parameters to the roof fall prediction application.

Even though the principal program objective was to evaluate the capabilities and limitations of the microseismic technique in providing a warning of roof fall, the evolution of field equipment to a reliable, field worthy status assumed a major role in the program. In a very true sense, the quality of results depended greatly upon the quality of the equipment used to obtain data for analysis and evaluation. Putting aside any pretense to glib proverbs, significant and consistent field data collection was made possible only after equipment problems and limitations were identified through field testing with subsequent modifications to upgrade the system's performance.

A description of the data collection system in its final configuration is provided in the following sections with discussion of the requirements for modifications and their results being left to the discussion of the field testing program.

[1] Westinghouse Electric Corporation, Microseismic Roof Fall Warning System, Final Report, November 1976, 142 pp.

2.1 Measurement Concepts

The primary task of the data collection system is to detect and characterize microseismic events in terms of the number and relative energy of events as a function of time. This information, presented in an event count and energy count format, is derived from the straightforward detection scheme illustrated in Figure 2-1.

Microseismic event voltage waveforms, shown in Figure 2-1(a), are converted to equivalent amplitude voltage envelopes and compared to a fixed threshold level as illustrated in Figure 2-1(b) and Figure 2-1(c). The resulting well defined event pulses are counted during the sampling period or time window and forms the basis of the event count data. The use of a "threshold" detection scheme provides amplitude noise discrimination as well as low level microseismic event discrimination. Hence, the event count is defined as the number of microseismic events per time window with peak amplitudes equal to or greater than the threshold level.

A relative indication of the microseismic event energy is derived from knowing how long an event's amplitude remains above the threshold. Since the time duration of each event pulse is related to the peak amplitude and energy is proportional to peak amplitude, the time duration of the event pulse is also proportional to energy. The energy count is obtained by using the event pulse to gate a stable 300 kHz oscillator as illustrated in Figure 2-1(d). The 330 μsec. event pulse is translated into an energy count of 100 by counting the oscillator pulses at a rate of one

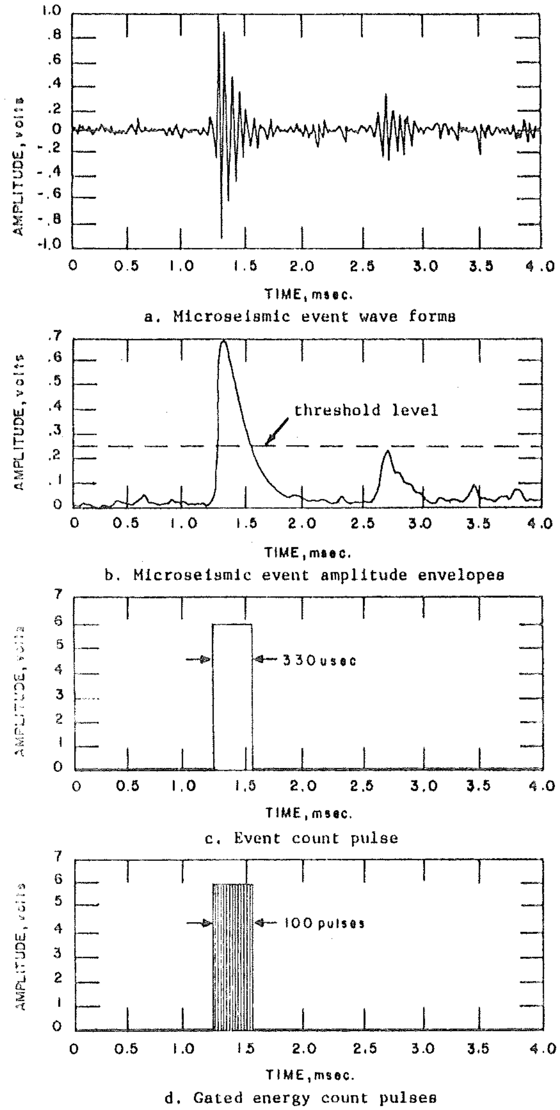

Figure 2-1. Method of Obtaining Event and Energy Count

pulse per 3.3 μsec. Using this method, the energy count is defined as the total energy per time window relative to the threshold energy level. No attempt has, however, been made to establish an absolute relationship between energy and the threshold level.

With a knowledge of system gain, threshold level, time of day, and coal mine roof activity, the relative merits of the energy and event count methods of roof fall prediction can be evaluated.

2.2 System Configuration

The Roof Fall Warning System is configured in three separate subsystems to permit data acquisition and data recording at widely separated locations in coal mines. A Data Acquisition Unit (DAU) forms one subsystem and two Digital Printer Units (DPU) comprise the remaining two subsystems. The two DPU's are used to separately record event count and energy count data. Table 1 gives a detailed list of the subsystems and their auxiliary components.

Data Acquisition Unit

The Data Acquisition Unit is a battery operated instrument designed for portability and ease of operation in working coal mines. A microseismic transducer, transducer preamplifier, battery pack, and telemetry transmitting antenna are the only components that are external to the DAU package. Figure 2-3 illustrates the DAU's overall functional organization.

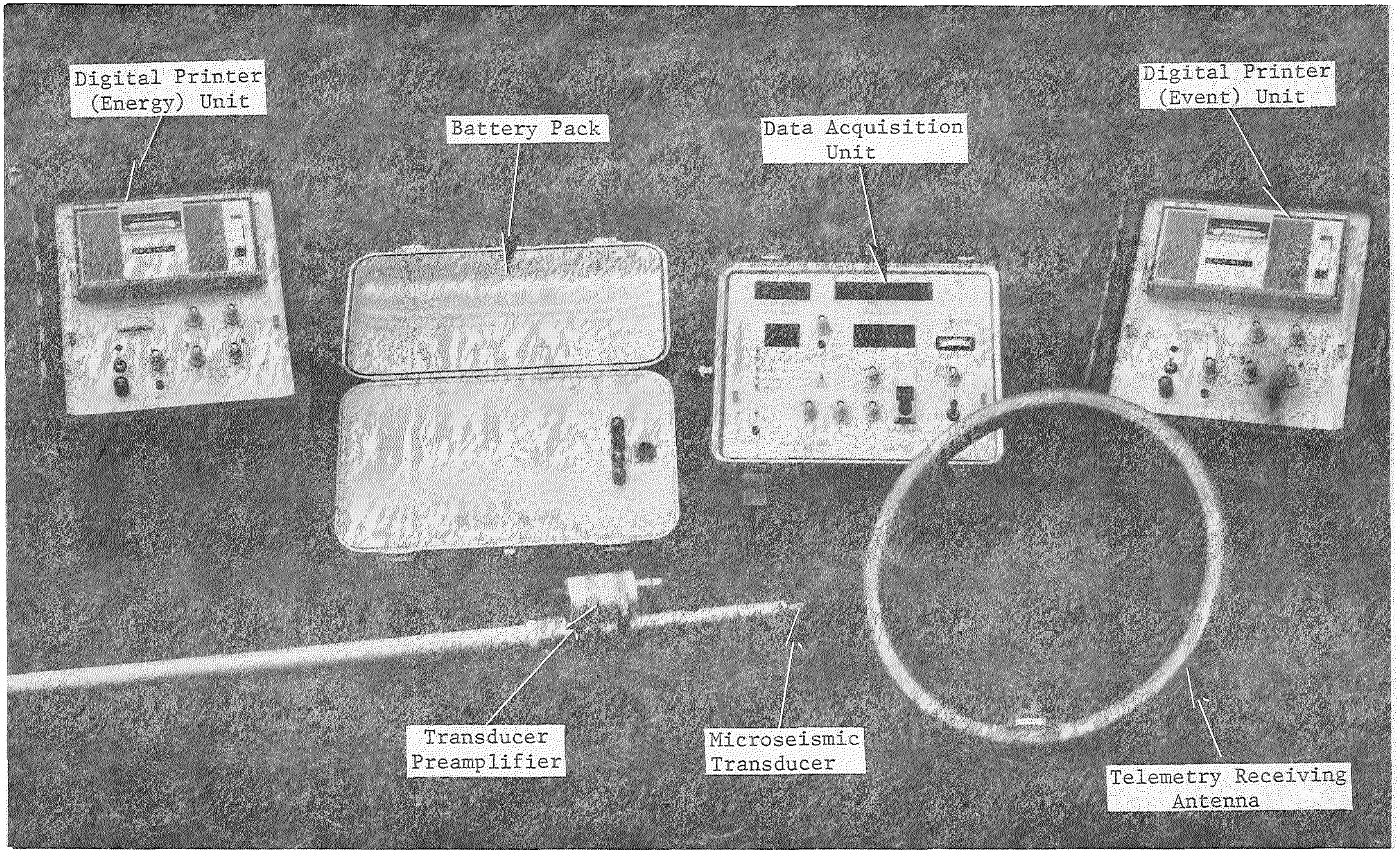

Figure 2-2. Microseismic Roof Fall Warning System

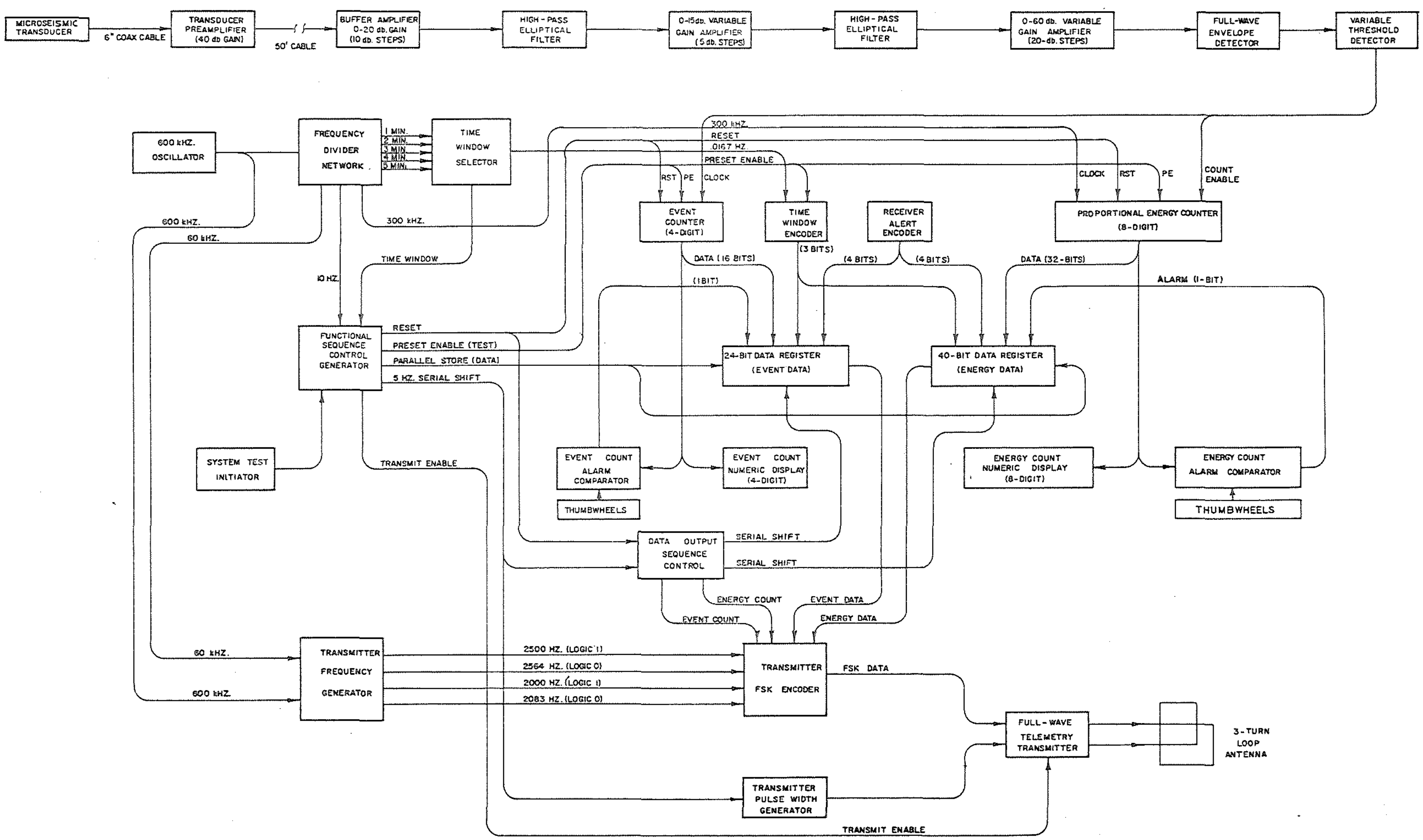

Figure 2-3. Data Acquisition Unit Function Organization

Table 2-1. Data Collection Subsystems and Components

A. Data Acquisition Unit, Model P-1412, Ser. Nos. 001 and 002.

1a. Transducer Preamplifier, Model P-1415, Ser. Nos. 001 and 002.
2a. Transducer Mounting Assembly.
3a. Transducer Connecting Cable (50 ft.).
4a. Battery Pack, Model P-1413, Ser. Nos. 001,002,003,004.
5a. Battery Connecting Cable (3 ft.).
6a. Battery Charger, Model P-1414, Ser. Nos. 001 and 002.
7a. Transmitting Antenna (100 ft.).
8a. Antenna J-Box and Connecting Cable.

B. Digital Printer Unit (Event), Model P-1410, Ser. Nos. 001 and 002.

1b. Air-Core Receiving Antenna.
2b. Receiving Antenna Connecting Cable.
3b. 115 vac Connecting Cable.

C. Digital Printer Unit (Energy), Model P-1411, Ser. Nos. 001 and 002.

1c. Air-Core Receiving Antenna.
2c. Receiving Antenna Connecting Cable.
3c. 115 vac Connecting Cable.

Microseismic events sensed by a lithium sulfate type transducer are converted to a voltage waveform and amplified by 40 dB in the transducer preamplifier prior to being driven over a 50 foot cable to the DAU. In the DAU, the microseismic signals are given additional amplification (selectable up to 95 dB) and high-pass filtered to strongly reject those frequency components below 36 kHz that are related to noise generated by mining equipment and rock cutting.

Figure 2-4 gives the DAU frequency response, including the microseismic transducer and preamplifier. The full-wave envelope detector removes all the alternating frequency components to prevent multiple triggering in the threshold detector.

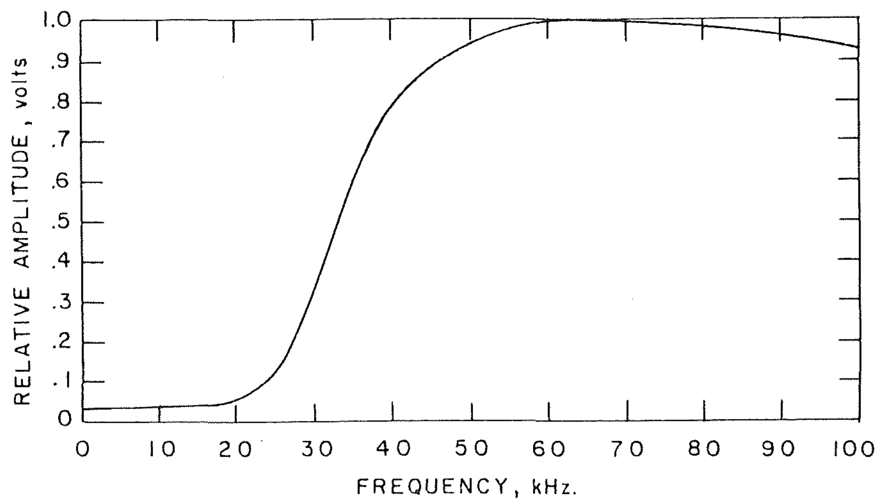

Figure 2-4. Data Acquisition Unit Frequency Response

The threshold detector compares the microseismic event's amplitude envelope to a voltage reference that is adjustable from zero to one volt. Since the threshold detector is in practice a two state device, either "on" or "off", it provides a convenient method of detecting microseismic events and the length of time each event remains above the threshold reference. The threshold detector's "on" state also controls when the energy counter counts the 300 kHz clock. Like the event counter, the energy counter accumulates counts over each time window. The maximum energy count per time window is limited to the time window in seconds times 300,000, whereas the event count has no basic system dependent limitation.

The DAU has five selectable time windows ranging from one minute to five minutes. At the end of each time window, the event count, energy count, and time window information are transmitted via a low frequency radio telemetry technique to their respective Digital Printer Units for recording.

An additional feature designed into the DAU provides on-site evaluation of the concept that an anomalously high event count or energy count provide a precursory indication of impending roof failure. To realize this design feature, digital comparators are employed to monitor the energy and event counters. When either the event or energy counters equal or exceed limits set by front-panel switches, the DAU activates a pulsating red light located on the exterior of the unit and sets the data transmission code so the printers print the current time window data in red ink. This also serves as a safety feature by alerting equipment operators to potentially hazardous mine conditions.

<u>Digital Printer Units</u>

The Digital Printer Units (DPU) are designed to receive and print narrow band telemetry information from DAU and requires an external 115 vac power source for operation. Figure 2-5 and Figure 2-6 illustrate the event count and energy count DPU functional organization, respectively. Since, functionally, the two DPU's are the same, only the event count DPU's operation is discussed.

The DAU transmits all data in a binary-coded-decimal (BCD) format using a frequency-shift-keying (FSK) technique to differentiate between binary "0's" and "1's". The DPU's loop antenna receives DAU data that is sorted according to frequency in the two bandpass filter sections. Data intended for the two Digital Printer Units is separated by using unique telemetry frequency pairs in each unit.

Telemetry information is converted to digital information by removing frequency components in the data pulse generators. The serial BCD data is then reassembled in its original order through a combination of operations performed by the shift pulse generator, decision logic, and binary bit counter. After the known number of data bits have been received, the count data, time window, and time-of-day are printed on paper tape.

2.3 Coal Mine Permissibility Certification

The federal Mine Safety and Health Administration (MSHA) requires, by law, that all electrical equipment used in gassy or gas producing areas of coal mines must be approved as permissible by the MSHA Approval and Testing Group. After substantially modifying the data collection system, a formal request for permissibility certification was submitted to the MSHA Approval and Testing Group in February 1978. Due to an extensive backlog of requests for approval investigations, MSHA could not respond and

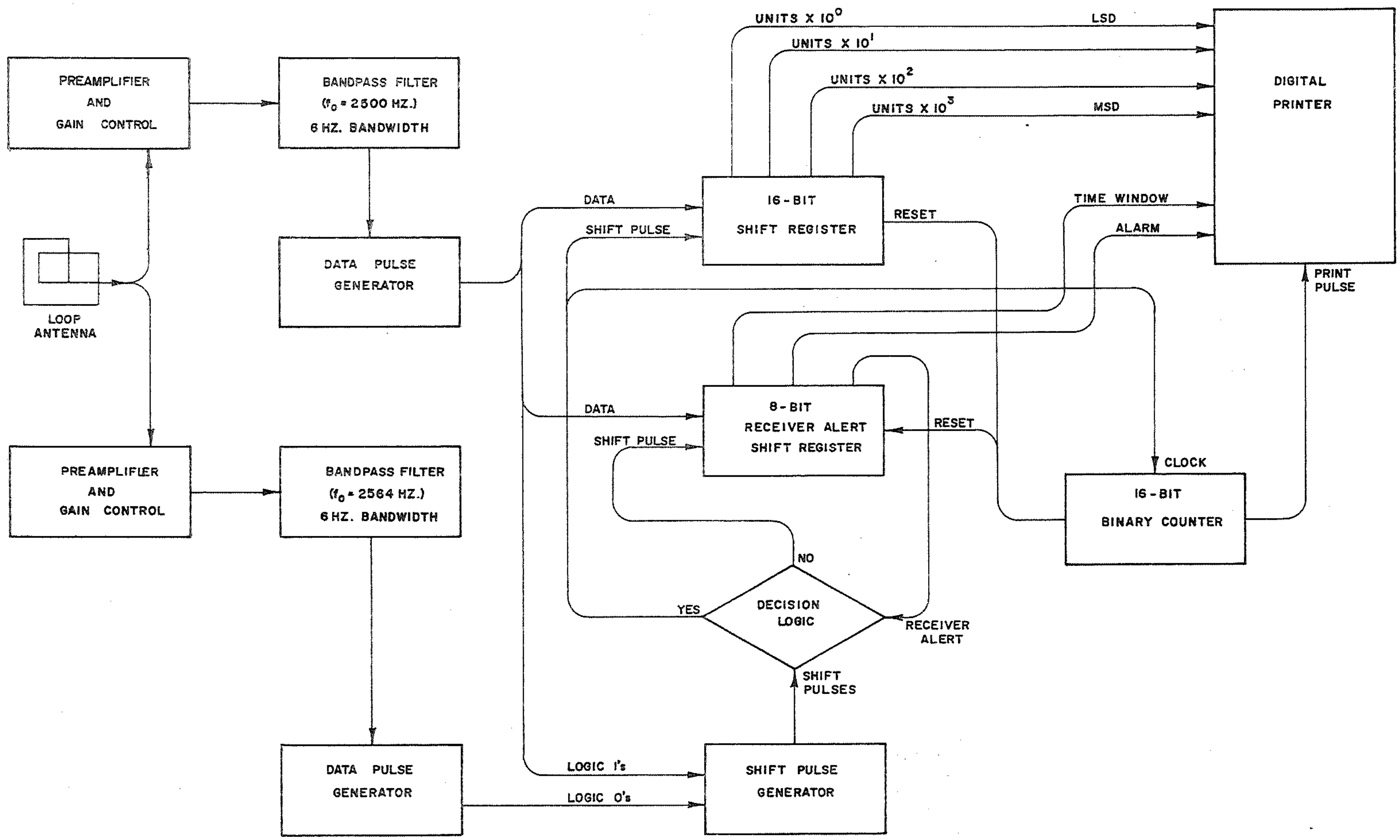

Figure 2-5. Digital Printer Unit (Event Count) Functional Organization

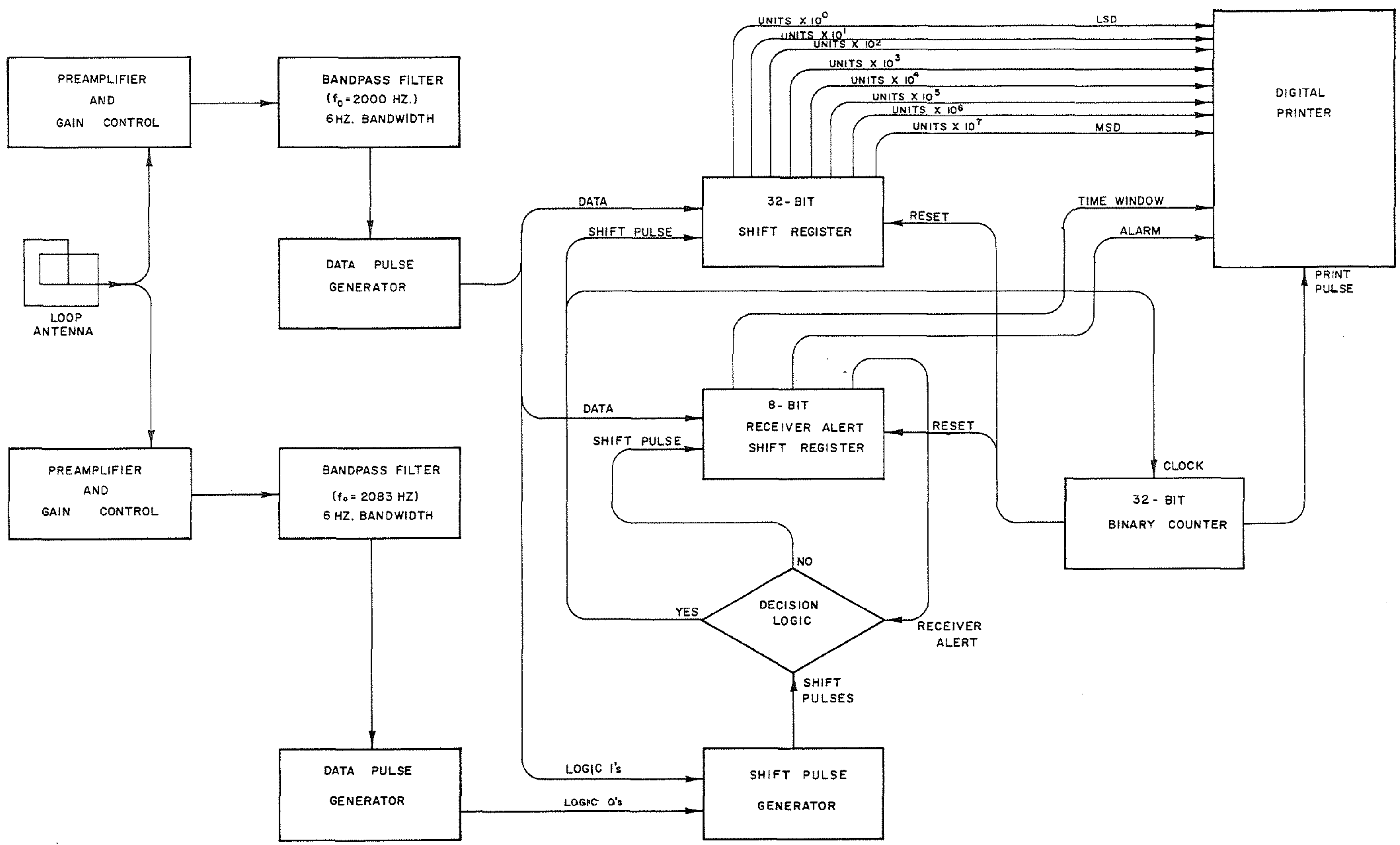

Figure 2-6. Digital Printer Unit (Energy Count) Functional Organization

begin the approval investigation until November 1978. As a result of the investigation, numerous modifications were required on the DAU to meet approval specifications.

Modifications were primarily directed toward the Battery Pack and establishing greater mechanical security of the units from possible tampering in the coal mine. The Battery Pack modifications included providing separate connecting cables for dc supplies, potting battery terminal areas, reconfiguring the battery charging connections, and installing a key-operated lock and special front-panel mounting screws. With modifications completed, certified, and documented, permissibility approval was granted in May 1979.

The fifteen month period required to acquire the data collection system's permissibility approval significantly delayed the progress of the field data collection activities. MSHA has recognized the problem their extensive backlog was generating and has since streamlined the approval procedure to the extent that testing and certification should not take more than six months to obtain.

Field testing was performed in Utah and Pennsylvania during the program. Unlike Utah, Pennsylvania requires state approval of equipment used in coal mines in addition to MSHA approval. This further aggravated the delay in field testing since MSHA approval was required before the Pennsylvania State Bureau of Coal Mine Safety would accept a request for state approval. Although the Pennsylvania approval was obtained in only three months, eastern coal mine testing in Pennsylvania could not be performed until August 1979, eighteen months after the initial MSHA permissibility request was submitted.

The Roof Fall Warning System's Data Acquisition Unit has been approved as permissible for use in gassy or hazardous coal mine environments by MSHA (Approval No. 9B-107-0) and the Pennsylvania State Bureau of Coal Mine Safety (Approval No. BFE-749-79). The Digital Printer Units have not been approved as permissible in gassy coal mine areas and are intended for use only in "fresh air" areas of coal mines. MSHA does not require approval of equipment used in fresh air areas; however, the state of Pennsylvania does and has granted approval of the use of the DPU's in fresh air (Approval No. BOTE-308-79). The Pennsylvania approval designations "BFE" and "BOTE" stand for "bituminous face equipment" and "bituminous open tunnel equipment", respectively.

2.4 Equipment Specifications

Data Acquisition Unit Model P-1412

Physical Dimensions:	14" x 11½" x 13".
Weight:	20 lbs.
Power Supply Voltages:	
Transmitter Circuits	+6 vdc.
Digital Circuits	+6 vdc.
Analog Circuits	+14 vdc. -14 vdc.
Frequency Response:	36 kHz to 100 kHz (±3 dB).
Signal Gain:	Selectable 0 to 95 dB.
Equivalent Input Noise Voltage, E_n:	3.5 nv(rms)/$\sqrt{Hz}$.
Event Threshold Level:	Variable 0 to 1.0 vdc.
Time Window:	1 to 5 minutes.
Alarm Threshold:	
Event	Variable 0 - 99,990 counts.
Energy	Variable 0 - 99,999,999 counts.
Count Range:	
Event	0 to 99,990 counts.
Energy	0 to 17,400,000 counts.

Digital Telemetry Frequencies:	
Event	2500 Hz (Logic 1).
	2564 Hz (Logic 0).
Energy	2000 Hz (Logic 1).
	2083 Hz (Logic 0).
Transmitting Antenna Current:	1.82 amperes (rms).

Microseismic Transducer

Type:	Lithium Sulfate.
Frequency Response:	10 kHz to 200 kHz (±3 dB).
Acceleration Sensitivity:	89 mv/g.

Transducer Preamplifier Model P-1415

Physical Dimensions:	4" x 2" dia.
Weight:	3 oz.
Power Requirements:	±14 v @ +11 ma and -8 ma.
Frequency Response:	30 kHz to 100 kHz (±3 dB).
Signal Gain:	40 dB.

Battery Pack Model P-1413

Physical Dimensions:	9-3/4" x 16" x 8-1/2".
Weight:	36 lbs.
Battery Life:	9 days.

Digital Printer Unit Model P-1410

Physical Dimensions:		14" x 11½" x 18".
Weight:		35 lbs.
Power Requirements		115 vac.
Digital Telemetry Receiver:		
Signal Gain:		Variable 0 to 110 dB.
Frequency	Channel #1	2500 Hz (Logic 1).
	Channel #2	2564 Hz (Logic 0).
Bandwidth		3 Hz (±3 dB).
Data Printout:		1. Time of Day. 2. Time Window. 3. Microseismic Event Count. 4. Alarm (red ink)/No Alarm (black ink).

Receiving Antenna:

Physical Dimensions	15" dia.
Weight	6 lbs.
Figure of Merit (Q)	Approx. 40.

<u>Digital Printer Unit Model P-1411</u>

Physical Dimensions:		14" x 11½" x 18".
Weight:		35 lbs.
Power Requirements:		115 vac.
Digital Telemetry Receiver:		
Signal Gain		Variable 0 to 110 dB.
Frequency	Channel #1	2000 Hz (Logic 1).
	Channel #2	2083 Hz (Logic 0).
Bandwidth		3 Hz (±3 dB).
Digital Printer:		(See Appendix A.)
Data Printout:		1. Time of Day. 2. Time Window. 3. Microseismic Energy Count. 4. Alarm (red ink)/No Alarm (black ink).

Receiving Antenna:

Physical Dimensions	15" dia.
Weight	6 lbs.
Figure of Merit (Q)	Approx. 40.

3.0 FIELD DATA COLLECTION

The primary field program objective was to obtain in-mine microseismic energy and event type data for subsequent evaluation of the method's roof fall prediction capabilities and limitations. Since the microseismic method and instrumentation used were relatively new and untested, major emphasis was placed on gaining additional field experience, especially in terms of signal gain, threshold level, and sensor mounting requirements. The ability of the equipment to yield usable data under the diverse range of mining conditions and geologic settings was also of prime interest.

The most important aspect in planning the field program was to obtain data for a sufficient number of roof falls such that reasonable conclusions could be made concerning the microseismic method's capabilities and limitations. Conventional mining methods employed in pillar extraction or retreat mining operations appeared to represent the best compromise between a semi-controlled environment, frequency of roof fall, and realistic mining conditions. As a consequence, roof fall data were obtained almost exclusively from room and pillar sections of coal mines actively involved in retreat mining or pillar extraction. Since operating coal mines are production oriented, a successful working relationship with mining personnel had to be based specifically on the ability to collect data without, in the slightest way, interfering with normal mining activities. Integrated Sciences personnel adhered strictly to this rule and, as a result, gained the cooperation and interested participation of mining personnel that was so necessary to the successful completion of the field test program.

Coal mines were selected from the western and eastern coal regions of the United States. Western region mines included Kaiser Steel Corporation's Sunnyside No.1 and Sunnyside No.3 mines, and Pleateau Mining Company's Star Point No.1 mine. The Consolidation Coal Company's Renton mine was selected as the eastern region coal mine.

The Sunnyside mines are operated in the Lower Sunnyside seam of the Utah Book Cliffs coal field. The Lower Sunnyside seam has an average thickness of 8 to 14 feet and is an important source of coking coal. The seam dips at an average of 4 to 8 degrees, but in some localities increases to 15 degrees. Although there is considerable faulting in the Sunnyside area, generally, there is considerable space between faults. One important aspect of these mines is that the use of more advanced coal mining technology and coal economics is inducing companies to mine deeper coal and may soon push the 3,000 foot limit to realize the additional, large reserve tonnage.

The Star Point No.1 mine is operated in the Hiawatha seam of the Utah Wasatch Plateau coal field and has an average thickness of 6 to 17 feet. Structurally, the coal seam is gently inclined but is cut by fault zones. Other problems include thick overburden, burned coals, and water problems. Wasatch Plateau coal contains resins which are important as a binder in printing ink, in paints, and as a tackifying agent in adhesives.

The Consolidation Coal Company's Renton mine is located near Pittsburg, Pennsylvania, in the Central Bituminous District. The Renton mine is operated in the

Upper Freeport seam which has an average seam thickness of 17 feet. The mine is considered a "deep mine" for the area with an overburden depth on the order of 600 to 700 feet. More importantly, the Renton mine is well known for its frequent, large roof fall associated with new development work. Ground water, channel sands, kettle bottoms, and numerous faults all contribute to roof problems in this coal mining region.

3.1 Sunnyside No.1 Mine

The Sunnyside No.1 mine is located near the small mining town of Sunnyside, approximately 32 miles east of Price, Utah. Data collection was conducted in the Sunnyside No.1's 3rd-Right Outside Raise Longwall Section as illustrated in Figure 3-1 and represents the single exception to conducting field tests in room and pillar sections.

The mine's 500 foot overburden consists of an alternating series of structurally competent shales and sandstones, with sandstones representing the major portion of the overburden material. The longwall section is mined to a height of 71 to 100 inches across a 600 foot working face. Approximately 15 minutes was required to make a single cutting traverse along the working face. Figure 3-1 also indicates the total progress of the longwall face during the 3 month data collection period.

The roof fall data collection system was installed in the mine on May 22, 1978. Throughout the 3 months of data collection, data records were intermittent with no periods of continuous data longer than 72 hours being obtained. A majority of the equipment's "down time"

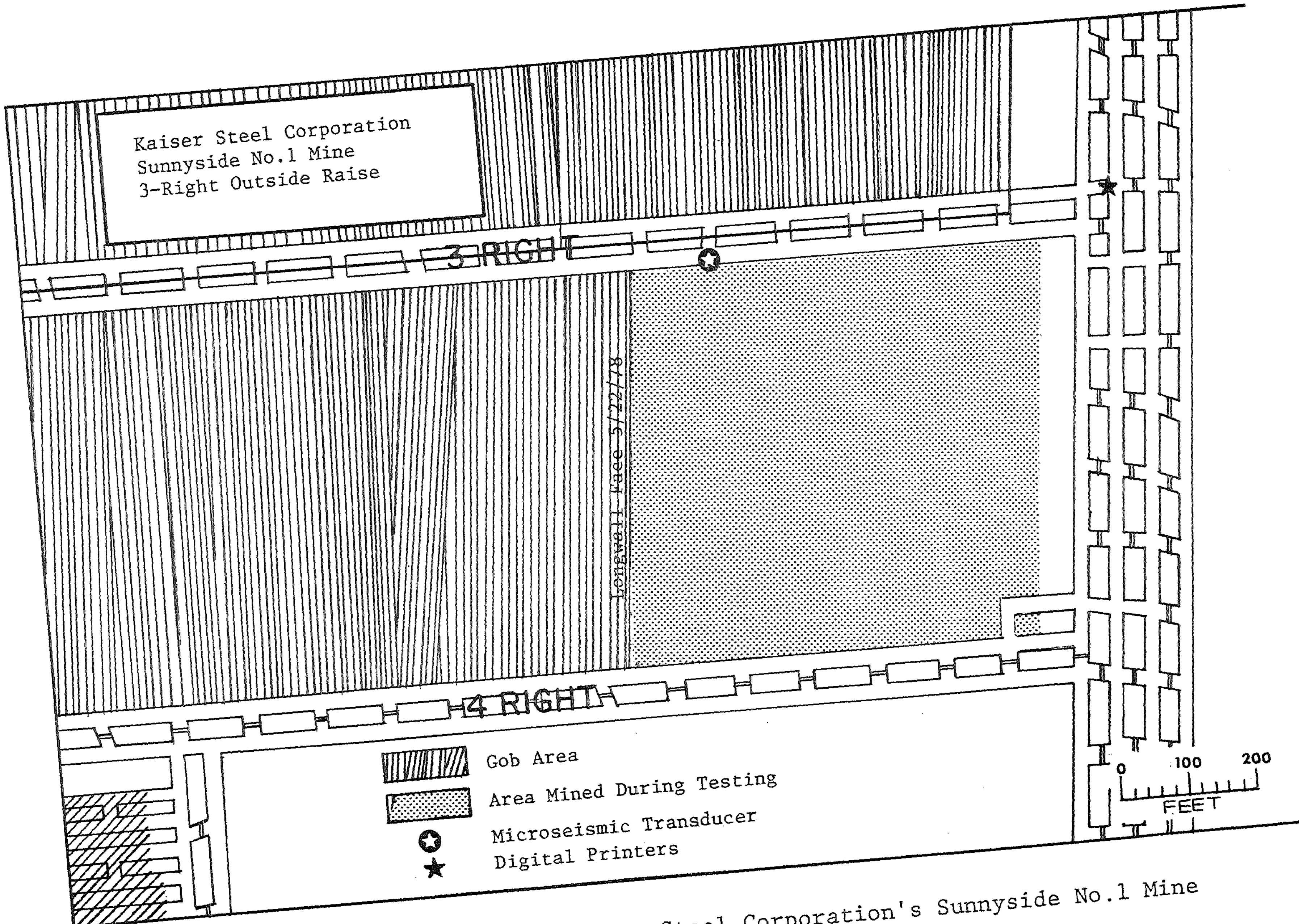

Figure 3-1. Longwall Test Site at Kaiser Steel Corporation's Sunnyside No.1 Mine

resulted from mine inspectors turning off the equipment's primary power source during their late hour inspections of the working section. Since the 115 vac power was not normally used in the mine, the inspectors routinely turned it off as a matter of good safety practice. Equipment damage, malfunctions, and a scheduled 2 week mine vacation accounted for the remaining down time.

Roof fall data collection was performed using the microseismic roof fall warning system. The Data Acquisition Unit (DAU), operated in a fresh-air entry, was normally located within 150 feet of the longwall face and transmitted information to the Digital Printer Units (DPU's) via a cable telemetry link. Use of the radio telemetry capability was not practical due to the limited space available to deploy the 25 foot square transmitting antenna and the risk of antenna damage from mining traffic. The microseismic transducer was placed against the coal mine roof using an aluminum pole between the mine floor and roof. A spring assembly, in the top of the pole, held the transducer securely against the roof material with a force of approximately 8 pounds. The transducer pole mounting configuration, however, met with difficulties during this test period - being knocked down repeatedly by mining traffic and coal sluffing from the ribs as a result of heavy mine bounces.

Data was typically obtained using 100 dB of signal gain and, initially, a 3 minute time window or sampling period. Both the microseismic energy and event count data showed good response to the cyclic loading induced by the longwall cutting shear transversing the 600 foot working face. When mining stopped, energy and event count data would, presumably, show a corresponding decrease as the roof material's dynamic distribution of loading reduced local roof stress.

Caving behind the longwall was usually good. On occasions, the roof temporarily "hung" behind the longwall and then abruptly fell. This situation, being somewhat more dangerous and of concern to mining personnel, was studied more thoroughly to determine if the abrupt failure of the roof material could be predicted. Energy count data did show a consistent pattern of gradual increase up to the time of fall and a subsequent rapid decrease with the fall. It did not, however, show a uniquely anomalous behavior, e.g., the magnitude of response was easily masked by the response to normal mining activity. The event count data showed little correlation with the energy count data and, in general, was quite erratic. The poor correlation between event count and energy count data, and the very erratic behavior of the data, gave rise to concern over possible equipment problems.

A major effort was directed at identifying whether equipment problems were contributing to the erratic nature of the microseismic event count data. After an exhaustive evaluation of the system, no major problems could be identified other than an awareness that the equipment's battery packs were not accepting a full charge during recharging cycles. This simply meant that battery packs would have to be recharged more frequently, at least temporarily. The search for what appeared to be equipment problems became even more confusing when good, consistent results were obtained using a Functional Test Set designed to test the system's performance while installed in the coal mine. It was not until the end of the 3 month test period that the key to the problem was finally brought to light.

The DAU is equipped with visual display readouts for both energy and event count circuits to allow observation of data accumulation during each time window. While observing the event count data accumulation during in-mine data collection, a project engineer noted that the event count display was counting up to its maximum 4-digit capacity and resetting to zero several times during a time window. With this knowledge, it became obvious that the problem was not related to system performance but rather to a basic underestimate of the system's required event count capacity. By manually transferring field data to digital magnetic tape storage and using an interactive computer graphic system, event count data was later corrected for event counter overflow.

Prior to the realization that the DAU's event count capacity was insufficient, data had been recorded during two instances of severe roof sag. Since it had been suspected that a phenomena known as "continuous emission" would occur just prior to roof failure, data was subjected to computer analysis to see if a corresponding energy/event ratio peak could be detected.* The energy/event ratio peak was indeed observed and, in conjunction with an observed anomalous energy count, gave the first positive indication of the microseismic technique's prediction potential.

Roof Sag, July 12, 1978

The longwall face had progressed approximately 450 feet by July 12, 1978 with only about 150 feet of the longwall panel remaining. As the panel size decreased, the severity and frequency of mine bounces also increased,

*The reader is referred to Appendix A for a more complete discussion of continuous emission and the energy/event ratio concept.

indicating that the remaining panel was seeing an increase in loading. The roof area in the vicinity of the longwall tailgate and lower longwall jacks began to yield and sag under the increased load.

Figure 3-2 shows the microseismic data obtained at a distance of 62 feet from the area of roof sag during the entire sag sequence. From Figure 3-2, it appears that the roof started sagging around 2200 on July 12, 1978. The somewhat stepwise response of the microseismic data shows good correlation with the cyclic load-yield-load sequence that would be expected as the sagging progressed. Particularly interesting is the decrease in both energy and event counts from 0930 to 1000 on July 13, 1978, that shows the subsequent drop in loading as the roof gained support from the lower longwall jacks. During the period from 1000 to 1340 the roof continued to sag, compressing the jacks before the roof itself began to show signs of imminent failure.

Mining personnel reported that the sagged roof developed a large number of cracks at approximately 1400 on July 13, 1978. Although the roof did not fall, mining personnel characterized the roof as "broken to the point of being mushy". Both the microseismic energy and event count data exhibited a uniquely anomalous behavior prior to the roof's reported failure. This is especially encouraging since a rapid decrease in the data values occurred prior to the time when mining personnel observed roof failure. Note that a large, singular peak in the computed energy/event ratio occurred at 1345, also prior to the observed advent of roof failure.

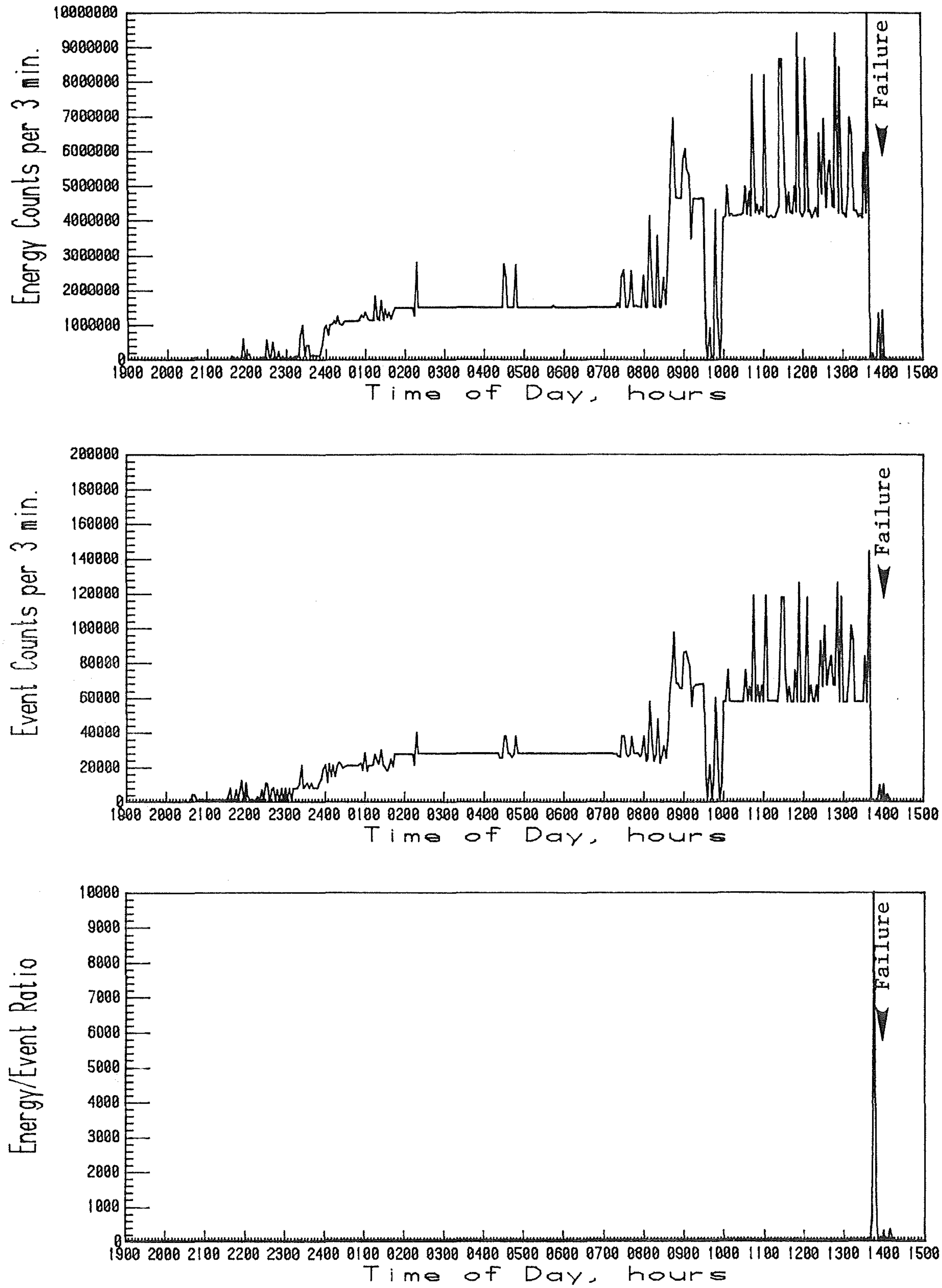

Figure 3-2. Microseismic Roof Sag Data in Longwall Section (July 12, 1978 to July 13, 1978)

It should be noted that the event data shown in Figure 3-2 has been computer corrected for event counter overflow and that the large energy/event ratio peak was found in both the corrected and uncorrected data computations. The energy count data is presented as originally recorded at the mine site.

Roof Sag, August 15, 1978

As completion of the mining on the longwall panel neared, the mining plan was to leave the last 50 feet of coal to protect the entry to the rear of the panel and roof bolt 30 feet outby the longwall face. During execution of this plan, concern over signs of high stress in the entry on the lower end and to the rear of the longwall panel developed. At the request of the mining personnel, the microseismic roof fall warning system was relocated to specifically monitor the lower entry's roof activity.

Additional 4' x 4' cribbing and timber supports were installed in anticipation of roof problems in the area. Beginning about 0100 on August 15, 1978, the roof in the lower entry began to sag and continued to do so during the next 8 hours. Figure 3-3 shows the microseismic data obtained during the entire roof sag period. Note that the data plot's character is very similar to the July 12, 1978 roof sag data. Like the July 12, 1978 roof sag, the August 15, 1978 roof sag ultimately resulted in roof failure.

During roof sag, the wooden cribbing was compressed several feet. Mining personnel reported that at about 0900 on August 15, 1978 the sagged roof broke in several places but was held securely in place by the support of

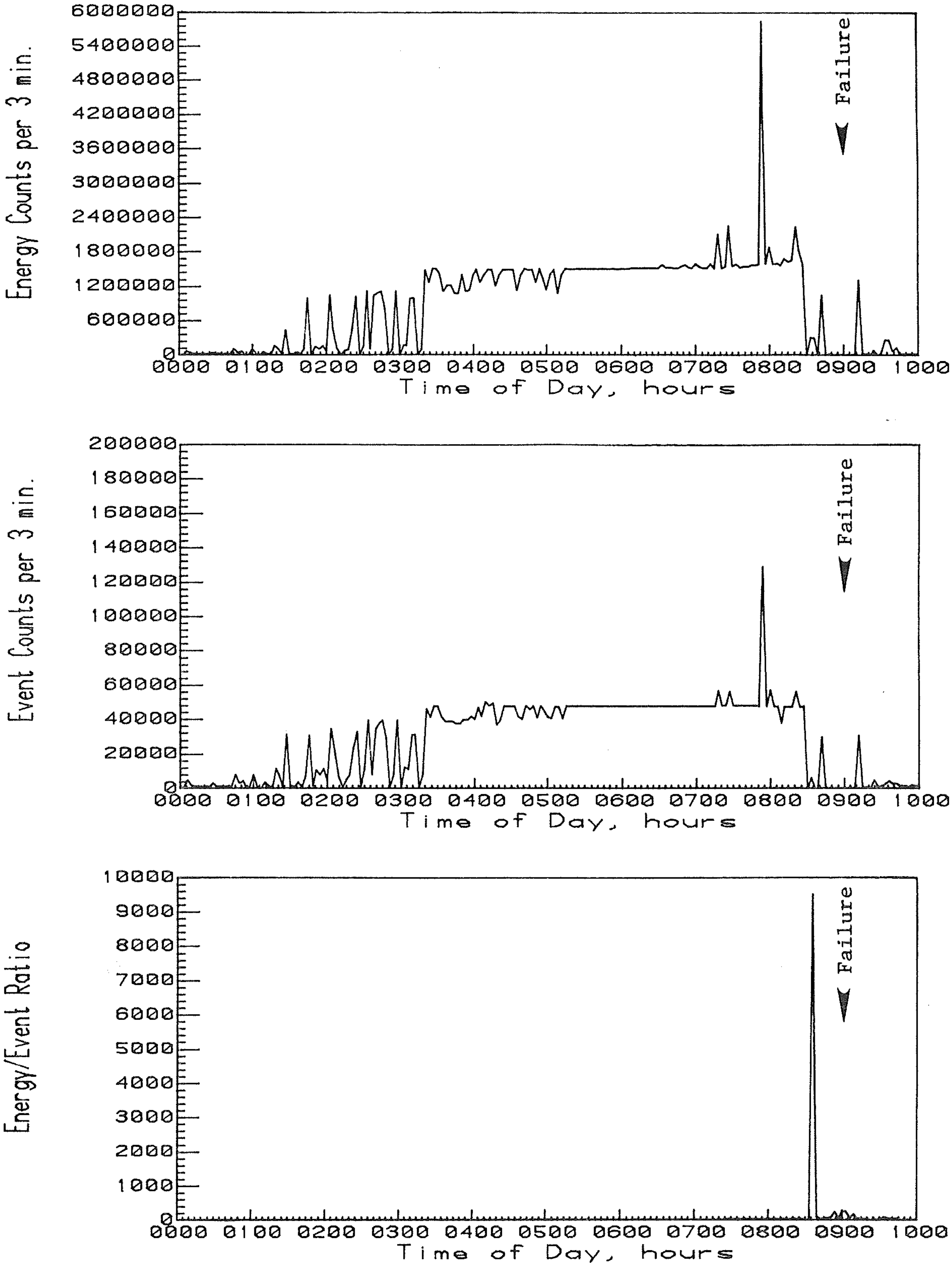

Figure 3-3. Microseismic Roof Sag Data in Longwall Section (August 15, 1978)

the cribbing. After this, more timbers and cribbing were installed to allow continued access to the longwall face and operation of the conveyor belt running under the sagged roof.

Again, it should be noted that the event count data shown in Figure 3-3 has been computer corrected for event counter overflow and that the large energy/event ratio peak was also evident in computations using the uncorrected data. The energy count data is presented without modification or correction.

The microseismic roof sag data presented in Figure 3-3 was also significant in that it showed a positive response to a deformation process that ultimately lead to roof failure and that it may be possible to identify specific precursory behavior associated with different failure mechanisms. The anomalous period of high energy count rapidly decreased 30 minutes prior to the reported time of roof failure and remained at a relatively low level thereafter. The computed energy/event ratio peak occurred approximately 10 minutes prior to the reported time of failure - an easily distinguishable event. The microseismic transducer was located approximately 20 feet from the area of roof sag during acquisition of the microseismic data shown in Figure 3-3 as opposed to 62 feet for the data shown in Figure 3-2.

Although no other significant events were observed, a total of 650 hours of microseismic energy and event count data were recorded prior to terminating the Sunnyside No.1 longwall section's testing on August 22, 1978. The results of the effort were, however, significant in terms of gaining a sound understanding of and familiarity with the field equipment's operational limitations. More specifically, experimentation with microseismic signal gain, transducer mounting and coupling, and proper tuning of the telemetry receivers increased confidence in the system's capabilities and set the stage for more significant results.

3.2 Sunnyside No.3 Mine

The Sunnyside mine management notified ISI that plans were being made to begin retreat mining in the Sunnyside No.3 15-Right R&P section during the later part of August 1978. Since the potential for obtaining roof fall data is much greater in retreat mining areas, arrangements were quickly made to shift the microseismic test site to the Sunnyside No.3 mine.

The Kaiser Steel Corporation's Sunnyside No.3 mine is located in the immediate area of the Sunnyside No.1 and is also operated in the Lower Sunnyside coal seam. A small canyon, cutting into the Book Cliffs, separates the Sunnyside No.1 from the Sunnyside No.3 mine. The Sunnyside No.3 is predominately a room and pillar mine that drives deep into the Book Cliffs, as deep as 1,300 feet in some sections. The 15-Right R&P section is approximately 1,200 feet deep with a seam thickness on the order of 7 to 8 feet. Faulting, a steep slope, and high overburden pressure are the primary problems dealt with in mining the 15-Right R&P section.

Retreat mining began approximately August 21, 1978. Due to a misunderstanding concerning the in-mine requirements for 115 vac power in relation to the working face, the microseismic roof fall warning system was not installed in the 15-Right R&P section until after the first suite of rooms had been developed and pillar extraction was nearly complete. Figure 3-4 illustrates the physical layout of the mine site and the mining progress during the period of microseismic data collection. The basic test plan was to locate the microseismic transducer such that the mining operation would progress toward it over a one to two week period, thus allowing undisturbed data collection which would be useful in evaluation of the technique's sensitivity and roof fall detection range. However, since the pillar extraction on the first suite of rooms was nearly complete, the microseismic transducer's initial location was within 300 feet of the anticipated fall areas.

Roof Fall, September 13, 1978

The roof fall system was installed in the mine on September 13, 1978 with a large roof fall occurring during the afternoon hours of the same day. The equipment performed flawlessly, recording the entire roof fall sequence and showing exactly the type of response that was hoped for. Figure 3-5 shows the microseismic data prior to, during, and after the fall sequence using a 1 minute time window and 90 dB signal gain. The fall was located approximately 300 feet from the microseismic transducer and covered an area of 6,500 square feet (6 feet high). No exact time of fall was, however, obtained since the day shift crew left the area at about 1430 and the swing shift crew did not arrive back in the area until approximately 1730 (an unusually late arrival due to mechanical problems with the in-mine transportation vehicles). The

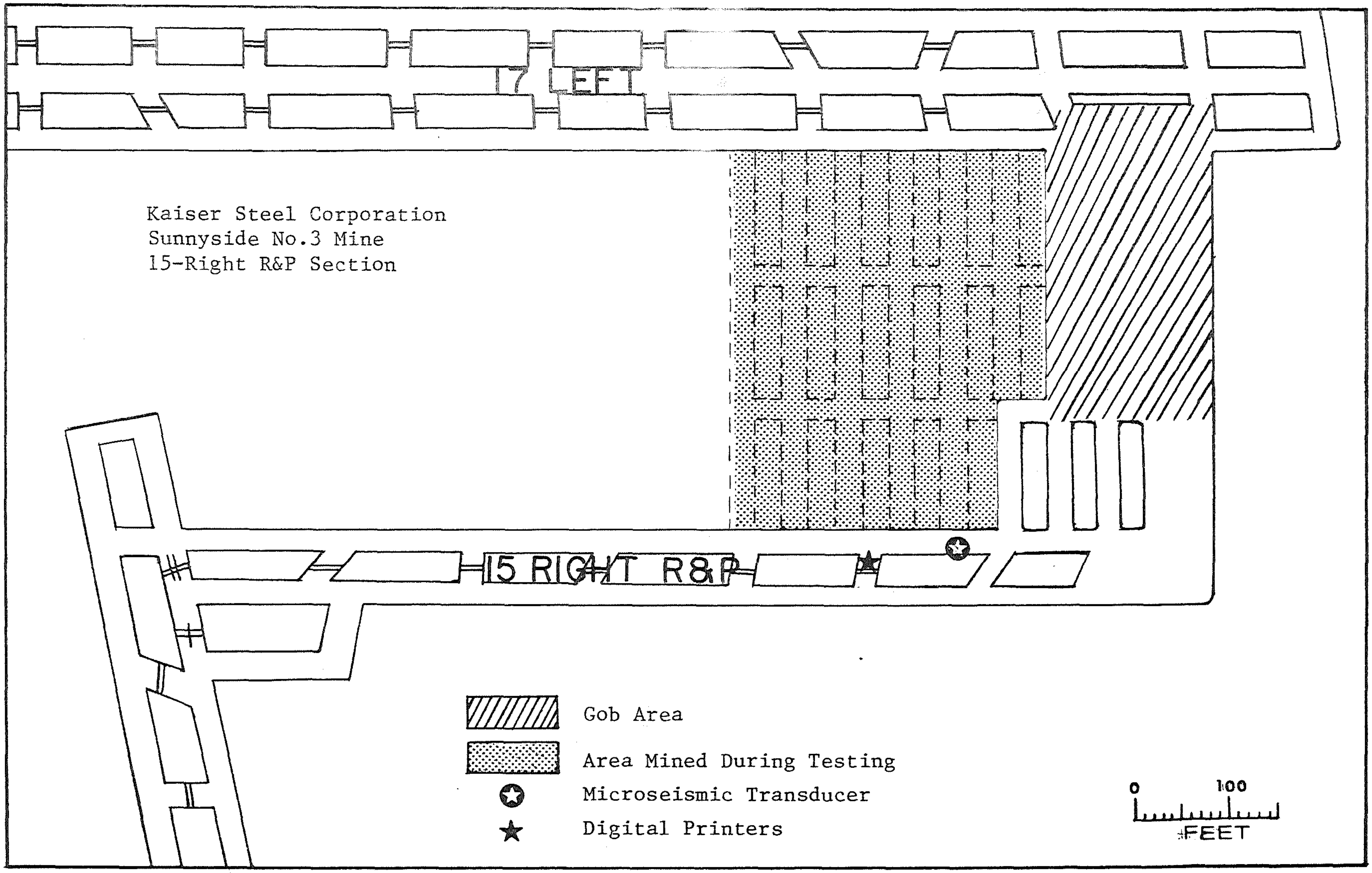

Figure 3-4. Roof Fall Test Site at Kaiser Corporation's Sunnyside No.3 Mine (September 13, 1978 to November 30, 1978)

fact that the fall had occurred during the work shift change was verified by the swing shift foreman.

The microseismic activity prior to 1400 is in response to normal mining activity at a distance of approximately 250 feet. Observation of the microseismic activity during pillar extraction showed a high sensitivity to changes in roof load, even to the extent that an increase in activity occurred each time the continuous miner cut coal to fill a shuttle car. A short time delay (a few seconds) would occur before activity would increase in response to the miner cutting coal and then would rapidly decrease after the miner stopped cutting coal.

The microseismic activity showed a pronounced increase beginning at 1412, presumably in response to the complete removal of the nearby coal pillar's support, and remained high for 53 minutes as the roof yielded under the overburden pressure. It is assumed that the high level of microseismic activity ceased at or before the time the roof structurally failed and that the fall occurred shortly after 1500. Note that the computed energy/event ratio showed a well defined peak 7 minutes before the rapid decrease in energy and event count data.

Roof Falls, September 15, 1978

When the microseismic system was initially installed in the 15-Right R&P section, there were only two coal pillars left to be pulled before a new suite of rooms would be developed. The last of the two pillars was pulled on September 14, 1978 leaving an 8,000 square foot area of roof unsupported. During the morning hours of the next day, the unsupported roof fell in three sections,

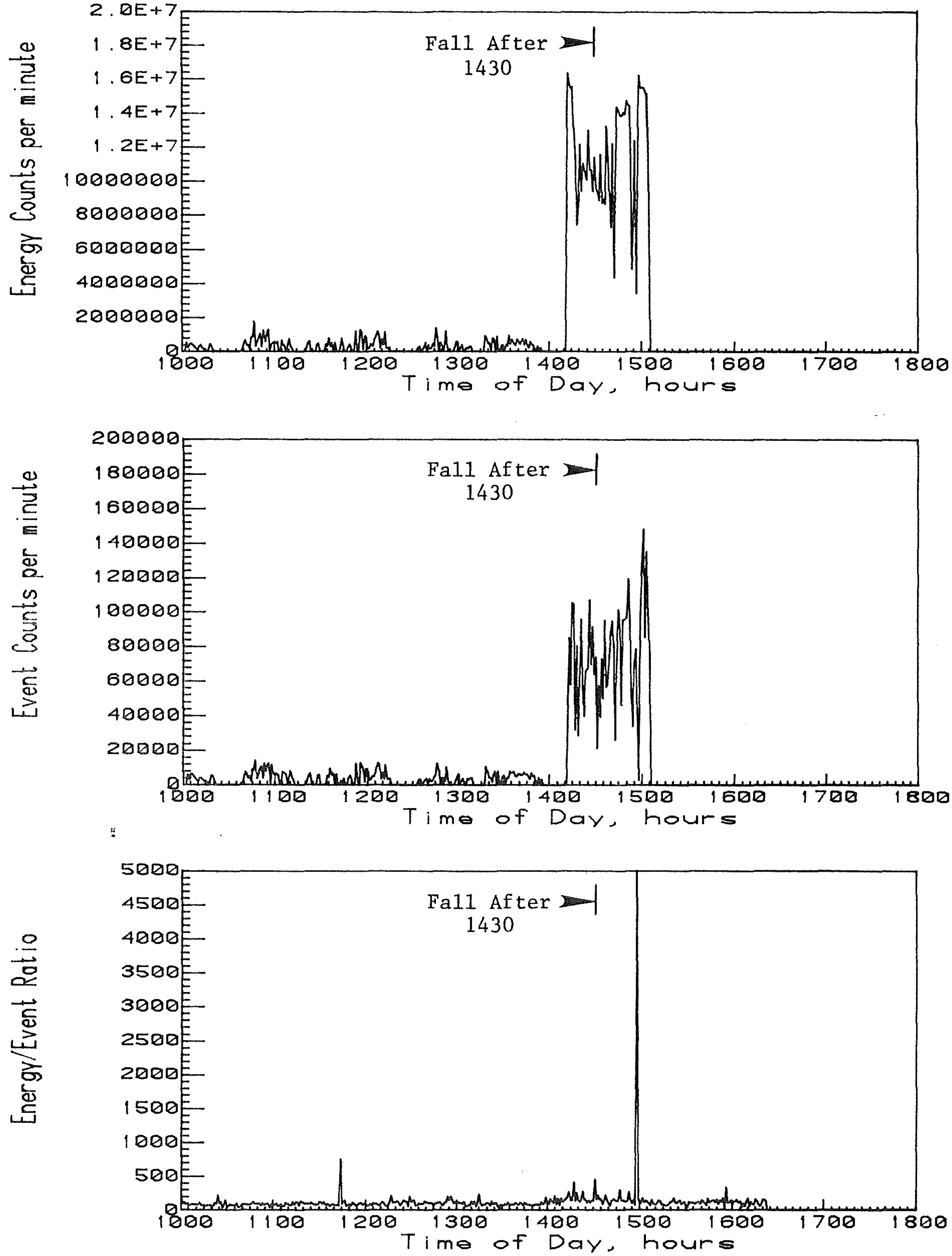

Figure 3-5. Microseismic Roof Fall Data from the Sunnyside No.3 Mine (September 13, 1978)

with the exact time of fall for each of the three falls noted and reported by the day shift foreman.

Figure 3-6 shows the microseismic data recorded during the three roof falls on September 15, 1978. The mining crew was mining coal outby the coal pillar adjacent to the fall area and in the 15-Right entry (approximately 200 feet from the microseismic transducer's location). The three roof falls occurred in succession over a 4 hour period beginning at 1015 and ending at 1334. Note that no obvious change in the character of the microseismic energy and event count data occurred in relation to the reported fall times. In fact, when compared with the data shown in Figure 3-5, the level of activity was no greater than what previously resulted from a response to normal mining operations. This was the first indication that a possible relationship existed between fall size, distance, and microseismic activity levels.

More significant, the computed energy/event ratio showed three clearly distinguishable peaks closely associated with and prior to the reported fall times. The first energy/event ratio peak occurred at 0948, 27 minutes before the reported fall time of 1015. This fall was 160 feet from the microseismic transducer and approximately 4,000 cubic feet in volume. The second energy/event ratio peak occurred at 1110, just 5 minutes prior to the fall at 1115, located 200 feet from the microseismic transducer, and approximately 6,000 cubic feet in volume. The third energy/event ratio peak occurred at 1334, 6 minutes prior to the last fall reported at 1340, 250 feet from the microseismic transducer and approximately 10,000 cubic feet in volume.

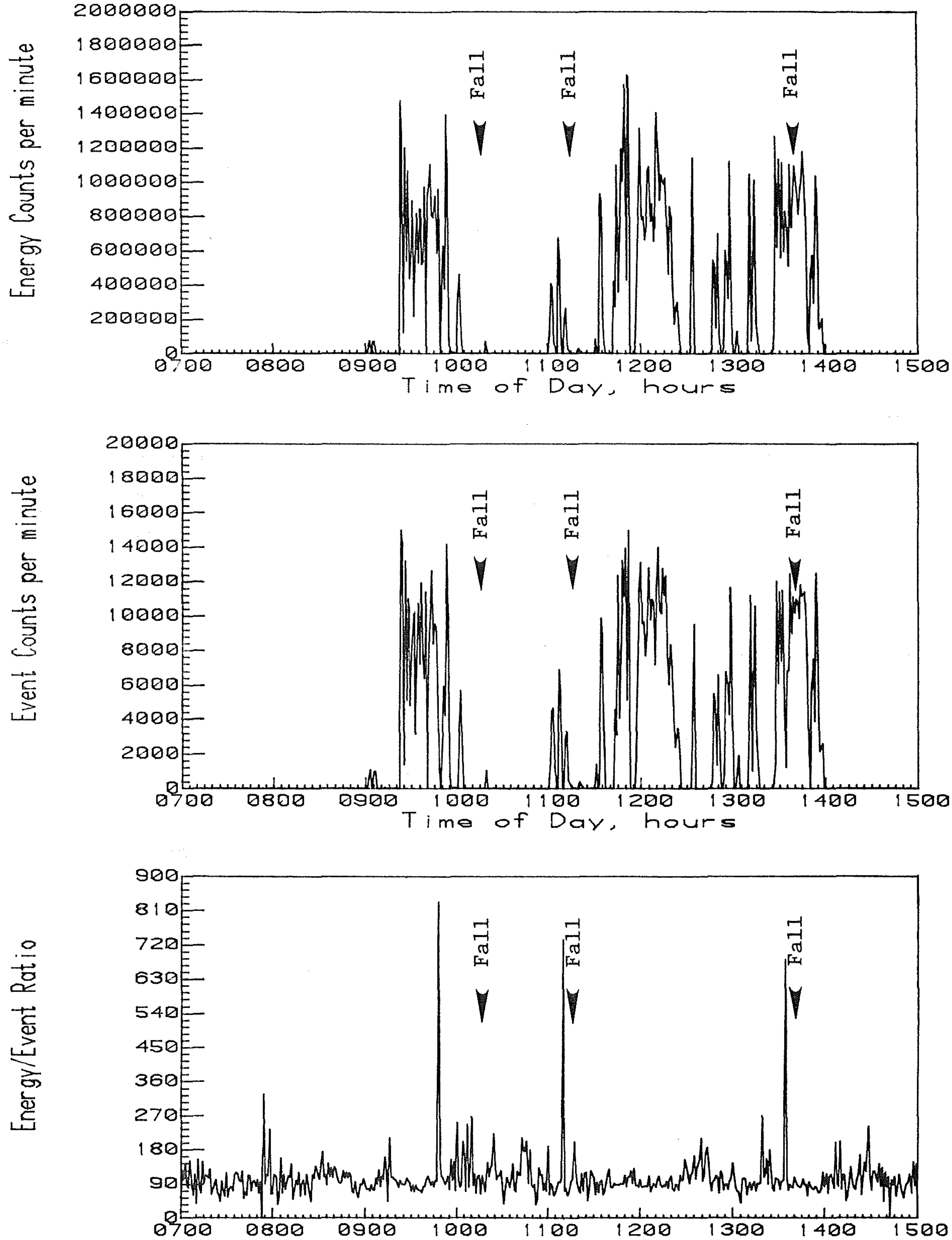

Figure 3-6. Microseismic Roof Fall Data from the Sunnyside No.3 Mine (September 15, 1978)

Mining personnel reported that the extent of mining for the day was below normal as a result of high roof fall activity.

Roof Fall, September 18, 1978

During the day shift on September 18, 1978, half of the last chain pillar in the 15-Right entry was mined before proceeding with new pillar development and pillar extraction. The second shift relocated mining equipment to begin the new pillar development and, in response, the microseismic roof fall warning system's transducer was relocated to avoid interference with mining equipment traffic. Microseismic data collection was resumed at approximately 1724.

Toward the end of the second shift, a small section of roof adjacent the half of the chain pillar mined by the day shift fell. The fall occurred approximately 140 feet from the microseismic transducer's location at 2212 and covered an area of about 1,932 square feet (5 feet high). The location and size of the fall were difficult to determine accurately and are here given as rough estimates.

Figure 3-7 shows the microseismic roof fall data during the time of fall. Since no coal mining was performed during the second shift, the energy count and event count data are assumed to be in response to roof activity associated with the reported fall. As noted for the roof falls that occurred on September 15, 1978, no significant indication that a roof fall was forthcoming is seen in the energy count or event count data. The computed energy/event count ratio did, however, give a well defined indication at 2205, just 7 minutes prior to the reported

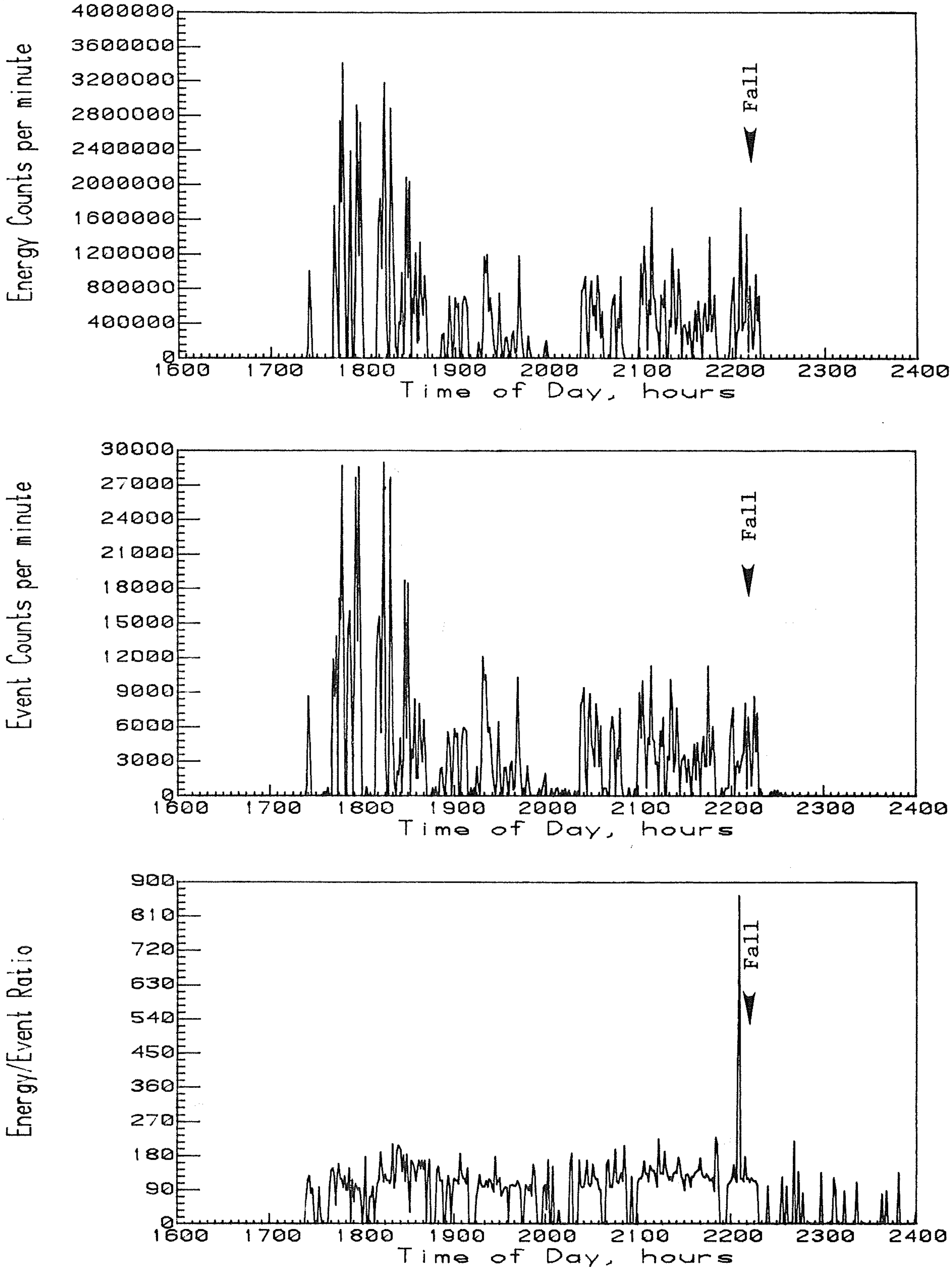

Figure 3-7. Microseismic Roof Fall Data from the Sunnyside No.3 Mine (September 18, 1978)

time of fall. Again the data seems to be indicating that the energy count and event count data responses are more strongly influenced by the fall size and the distance between the microseismic transducer and the fall than is the energy/event count ratio's response.

Roof Fall, September 19, 1978

The day shift began pillar development mining on September 19, 1978. During the work shift, approximately 50 feet of new entry had been driven into the coal panel. Although a few normally expected mine bounces were reported during the day, no roof falls were reported by day shift personnel. The day shift crew departed the 15-Right section at approximately 1430.

Upon arrival in the 15-Right section, the second shift crew noted that a fall had occurred in the area immediately adjacent to the fall reported on September 18, 1978. The fall covered a 1,680 square foot area (5 feet high) and was located about 130 feet from the microseismic transducer. Since the day shift crew reported no falls up to 1430, it is assumed that the fall occurred sometime between 1430 and the time the second shift crew arrived in the working section, or 1600.

Figure 3-8 shows the microseismic roof fall data during the assumed time of fall on September 19, 1978. Neither the energy count nor event count data gave an indication of impending roof failure except for the brief, but sharp, increase in the energy count data at 1214. The computed energy/event count ratio also gave a definitive response in conjunction with the increase in energy count data at 1214. This response was at least 2 hours and 16 minutes prior to the assumed time of fall.

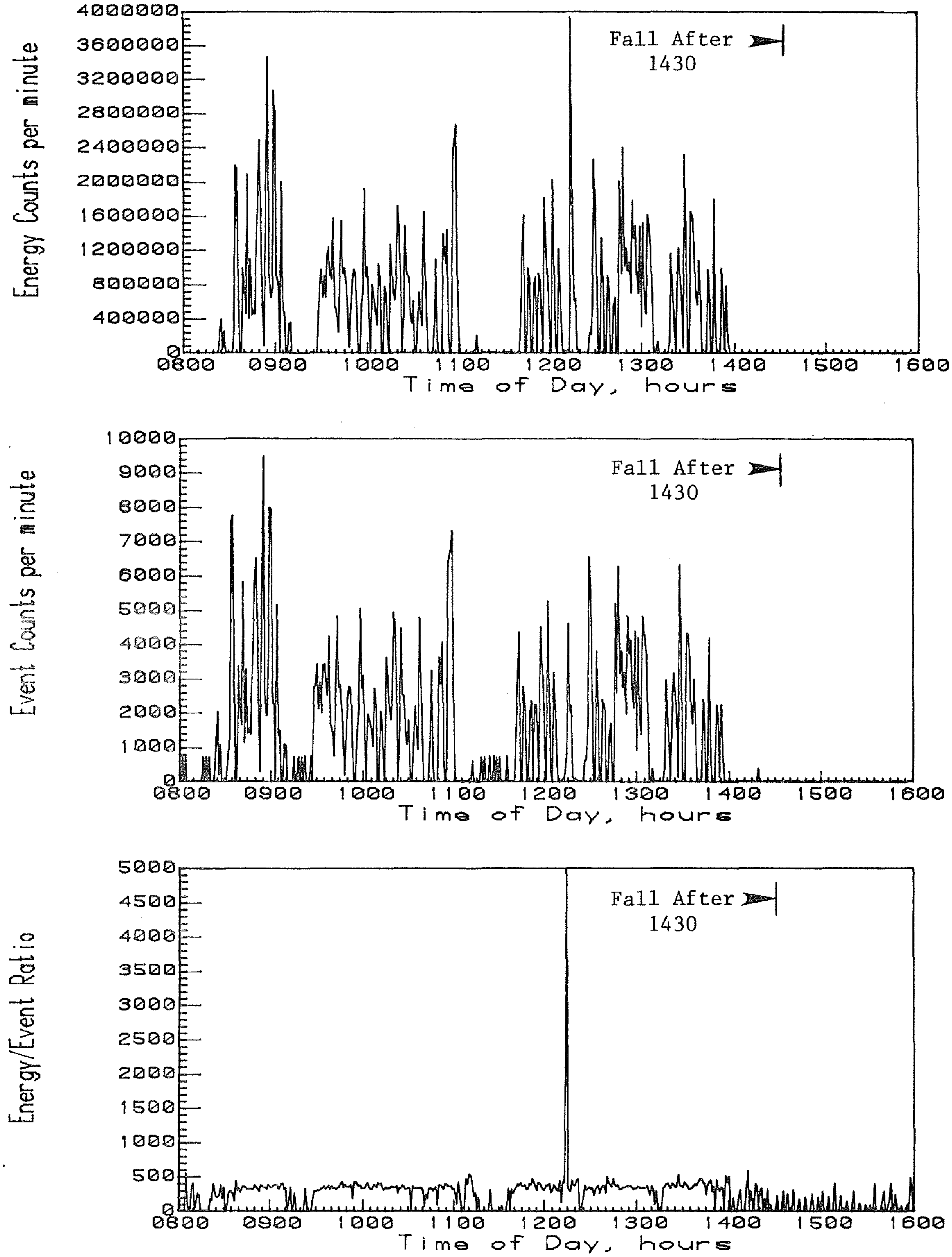

Figure 3-8. Microseismic Roof Fall Data from the Sunnyside No.3 Mine (September 19, 1978)

Although the "prediction" time associated with this fall seems excessively long, it may be an indication that the microseismic data responds more specifically to rock failure and that the time of "failure" could be appreciably different than the time of "fall". In any event, it is certain that a fall did occur sometime between the hours of 1430 and 1630, and that the energy/ event count ratio did give a clearly defined response prior to the time when the fall could have occurred.

Roof Falls, November 29, 1978

Pillar development continued through October 10, 1978, with no roof falls or other significant events occurring. However, during the process of pillar development, heaving of the mine floor and concern over maintaining good ventilation over gobbed areas, induced the mine personnel to leave two rows of pillars standing to provide a fresh air corridor into the gob area. Pillar extraction was then begun on October 10, 1978, three pillar rows outby the fall area noted on September 19, 1978. Even through November 2, 1978, no roof falls occurred due to the additional roof support provided by the two rows of pillar left standing for air ventilation.

More pillar development began on November 3, 1978 and continued through November 18, 1978. The large unsupported roof area generated by pillar extraction in October 1978 finally caved during a two day period beginning November 3, 1978. Although numerous roof falls were reported during the two-day caving period, the microseismic roof fall warning system had been removed from the mine for evaluation and repair. Subsequently, no microseismic data were obtained for the falls.

Pillar extraction was resumed on November 19, 1978 and continued until mining in the section was discontinued on November 30, 1978 for an indefinite period. Prior to continuing the pillar extraction on November 19, 1978, the microseismic roof fall warning system was removed from the mine and returned to the Integrated Sciences' laboratory for modifications to extend the event count capability of the system. The data collection system was returned to the mine site and reinstalled in the 15-Right R&P section on November 28, 1978.

On the morning of November 29, 1978, the day shift crew had completed removal of two of the last four pillars in the section. As a result of a noticeably high roof activity, the crew moved all mining equipment away from the anticipated fall area and waited for it to cave. The area caved at approximately 0930.

Figure 3-9 shows the microseismic roof fall data obtained during the morning hours of November 29, 1978. The 0930 roof fall covered a large area of about 18,900 square feet (4 feet high) and was located 220 feet from the microseismic transducer's location. From Figure 3-9, it is apparent that the energy count, event count, and computed energy/event count ratio all gave very good responses to the forthcoming fall. Both the energy count and event count data increased by an order of magnitude at 0841 and remained at the anomalously high levels until 0915. The rapid increase in microseismic activity occurred approximately 49 minutes prior to the reported time of fall. The high activity continued for 33 minutes and then reapidly decreased 15 minutes prior to the time of fall. The computed energy/event count ratio, on the other hand, showed a single, distinct peak at 0914, 16 minutes prior to the reported time of fall.

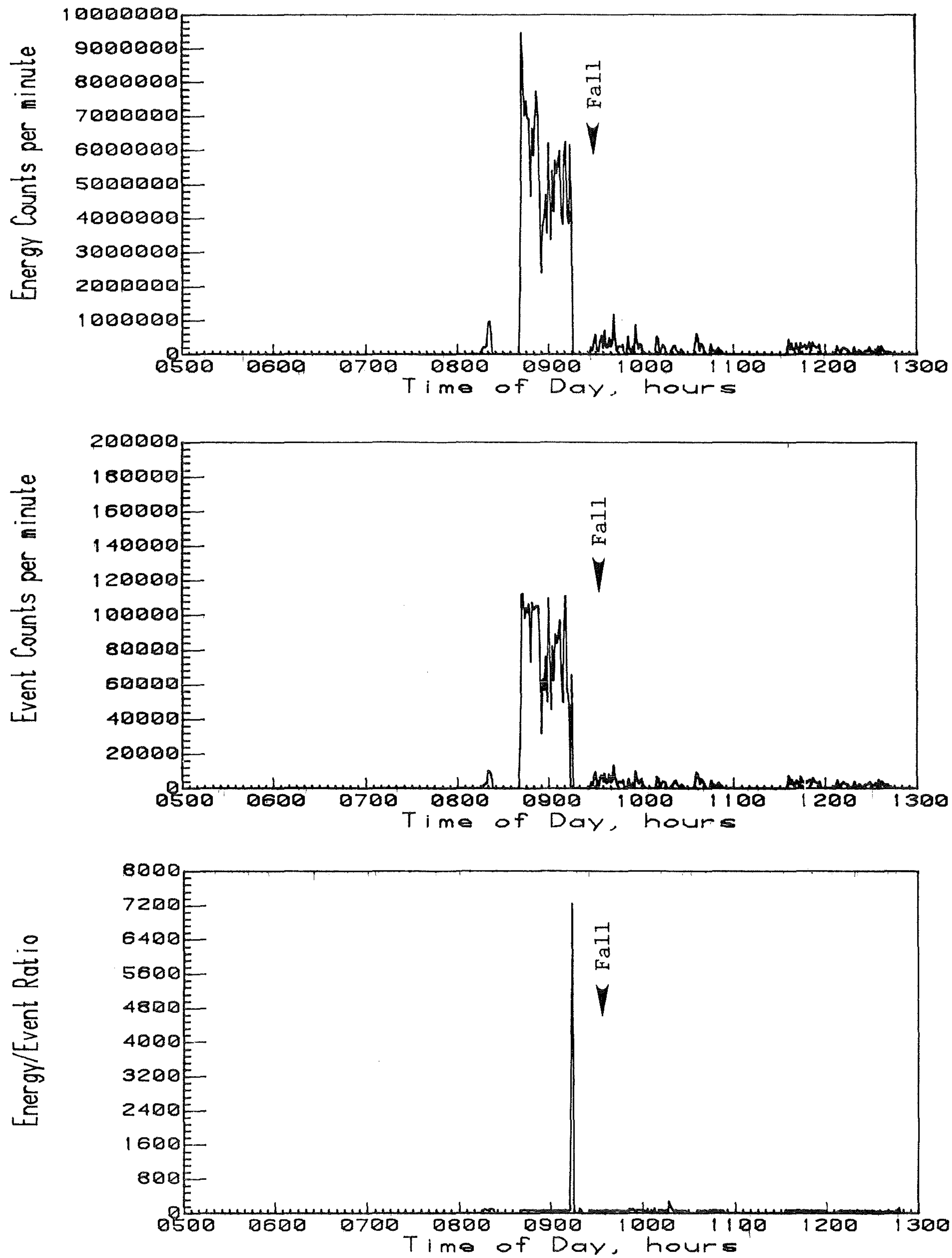

Figure 3-9. Microseismic Roof Fall Data from the Sunnyside No.3 Mine (November 29, 1978)

Mining continued after the fall on a coal pillar immediately adjacent to the fall area but was slow due to secondary caving in the nearby fall area. Since no response is seen in the microseismic data that can be associated with the secondary caving, it is assumed that, once a primary failure has occurred, little microseismic activity is generated in the process of the roof material working loose so as to fall under its own weight.

With a noticeable increase in roof activity, the second shift mining crew moved the continuous miner to the lower end of the coal pillar currently being mined, set additional timbers, and resumed mining coal. The action was well taken since the roof on the upper end of the pillar fell 2 hours later at 2025.

Figure 3-10 shows the microseismic roof fall data during the fall on the evening hours of November 29, 1978. The fall covered an area of approximately 3,000 square feet (3 feet high), 160 feet from the microseismic transducer's location. Both the energy count and event count data showed a short, but distinctly noticeable, increase at 1932, 53 minutes prior to the reported fall time of 2025. The computed energy/event count ratio also gave a singular peak, but at time 1943, 42 minutes prior to the reported fall time of 2025.

After the fall at 2025, the mining crew moved back to the upper end of the pillar, adjacent to the fall area, and mined the remaining portion of the pillar. A portion of the last coal pillar's upper end was also mined by the second shift before leaving the working section at about 2300.

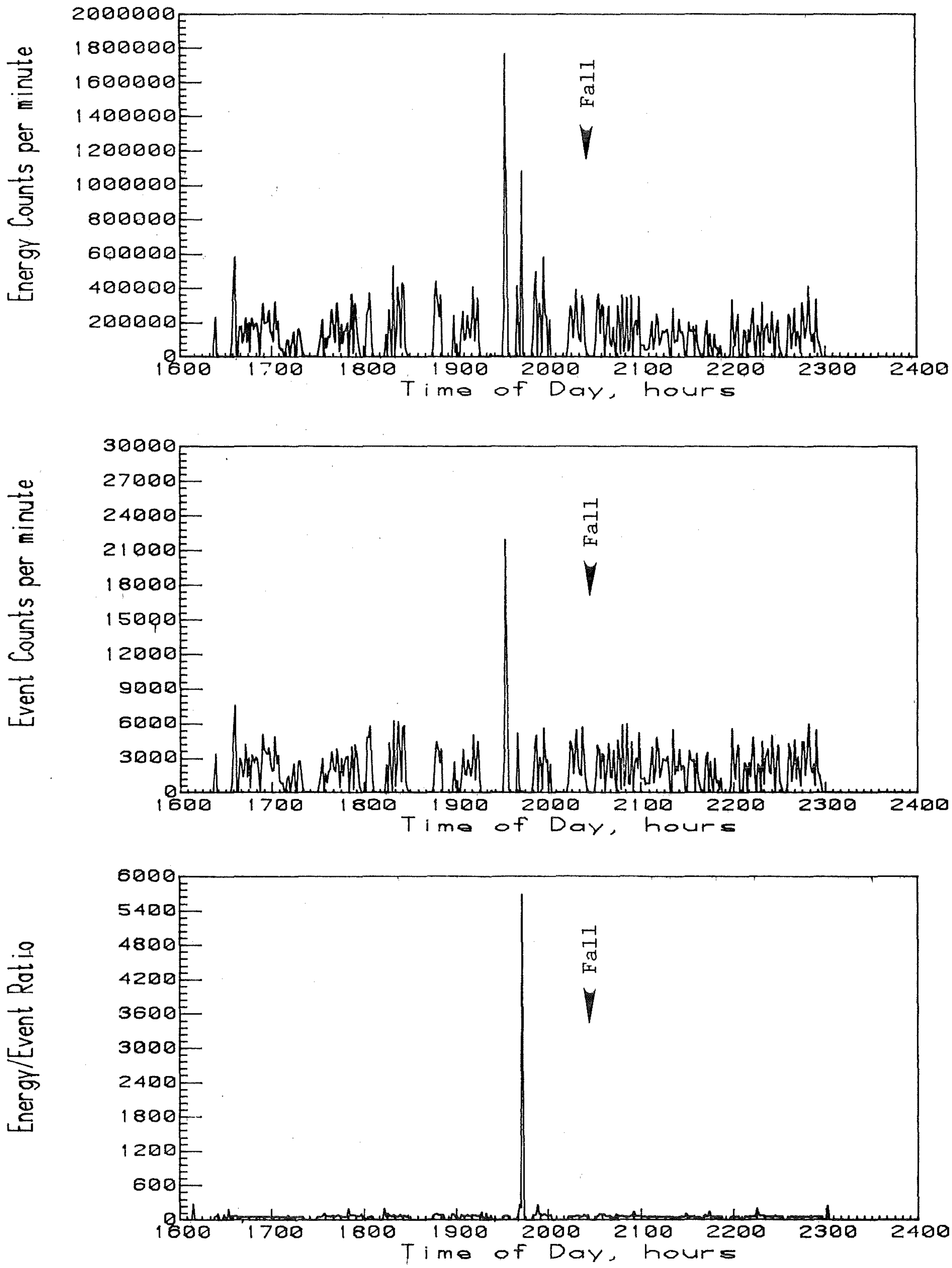

Figure 3-10. Microseismic Roof Fall Data from the Sunnyside No.3 Mine (November 29, 1978)

Roof Fall, November 30, 1978

The day shift on November 30, 1978 completed mining the last pillar in the working section. A section of roof over the upper end of the last pillar fell at approximately 0900 on the morning of November 30, 1978. The fall covered an area of 2,750 square feet (3 feet high) and was located about 130 feet from the microseismic transducer's location.

Figure 3-11 shows the microseismic data obtained during the reported fall. No indication of the potential fall is seen in either the energy count or event count data. The activity shown starting at about 0820 is due to mining the lower end of the pillar at the start of the day shift. The computed energy/event count ratio did give a singular, well defined peak at time 0815, 45 minutes prior to the reported time of fall.

The day shift crew completed pulling the last pillar prior to the end of the work shift. The resultant unsupported roof area fell just as the second shift arrived in the working section. Microseismic data were not obtained for the last fall since the day shift crew disconnected power to the recording system before leaving the working section. November 30, 1978 was the last day of microseismic roof fall data collection in the Sunnyside No.3 mine.

Microseismic roof fall data collection in the Sunnyside No.3 mine contributed important and encouraging results to the field program effort. With the 1,067 hours of microseismic energy and event count data obtained on a one minute time window, nine roof falls were recorded in sufficient detail to begin evaluating the microseismic

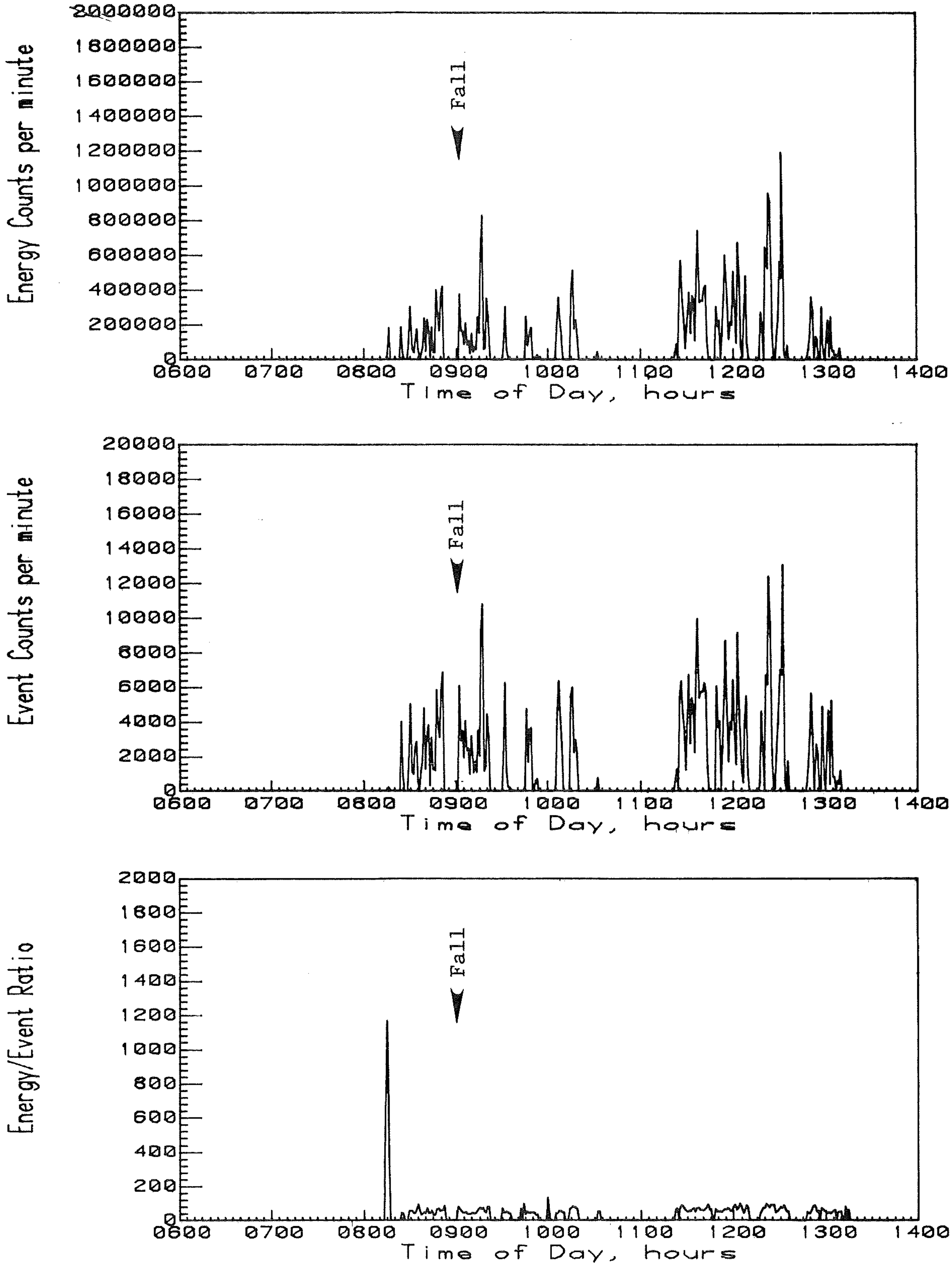

Figure 3-11. Microseismic Roof Fall Data from the Sunnyside No.3 Mine (November 30, 1978)

roof fall warning system's capabilities and limitations in predicting roof fall. Data indicated that the energy count and event count methods may have prediction limitations that are a combined function of fall size, fall distance, and system gain. For roof falls of relatively large size, in excess of 10,000 cubic feet in volume, the energy and event count methods gave a well defined response prior to the time of fall. The computed energy/event count ratio, on the other hand, shows a singular, well defined response prior to all roof falls for which data had been obtained.

Also, during the Sunnyside No.3 mine test period, the roof fall warning system was modified to correct the event counter overflow, battery supply, and digital printer problems identified during the course of field testing. The field worthiness and operational stability of the equipment were greatly improved as a result. Field testing in the Star Point No.1 mine, then, began with a much higher degree of confidence in the equipment's capabilities.

3.3 Star Point No.1 Mine

Since no other Sunnyside mine room and pillar sections were scheduled for mining in the near future, an alternate Western mine test site was pursued. Interest was expressed by the Plateau Mining Company's Star Point management to participate in the roof fall warning system's test program and, subsequently, resulted in the establishment of a third Western coal mine test site.

The Star Point No.1 mine is located on the eastern slope of the Wasatch plateau near the small town of Wattis, Utah. The Star Point No.1 is operated in the Hiawatha coal seam and has a maximum overburden thickness of 1,500 feet. Mining is done using conventional room and pillar methods. The Hiawatha seam mined in the Star Point No.1 is referred to as the "bottom" seam since a second mine, the Star Point No.2, and a third mine, the Wattis No.1, are at two different levels above the Star Point No.1 mine.

Figure 3-12 shows the Star Point No.1 mine layout in the 3-South room and pillar section where microseismic roof fall warning system testing was performed from December 6, 1978 to February 2, 1979. Figure 3-12 also shows the progress of pillar extraction operations during the in-mine test period.

The microseismic roof fall warning system was installed in the 3-South working section on December 6, 1978 in the locations indicated in Figure 3-12. Mining activity was relatively slow due to a large number of hard mine bounces and working of the coal mine roof, i.e., convergence as evidenced by timbers cracking and splintering. Mining, however, continued at a constant pace during the mine's three working shifts. In the opinion of mining personnel, the working section's roof integrity was progressively deteriorating as mining continued.

Microseismic roof fall data during this period displayed a distinctly different character than that seen at previous mine test sites, even though the relative amplitude of data did not change significantly. The change in character was such that the data appeared to be excessively noisy, i.e., the normally observed variations in energy and event count were superimposed on rapid, large variations in the count rates.

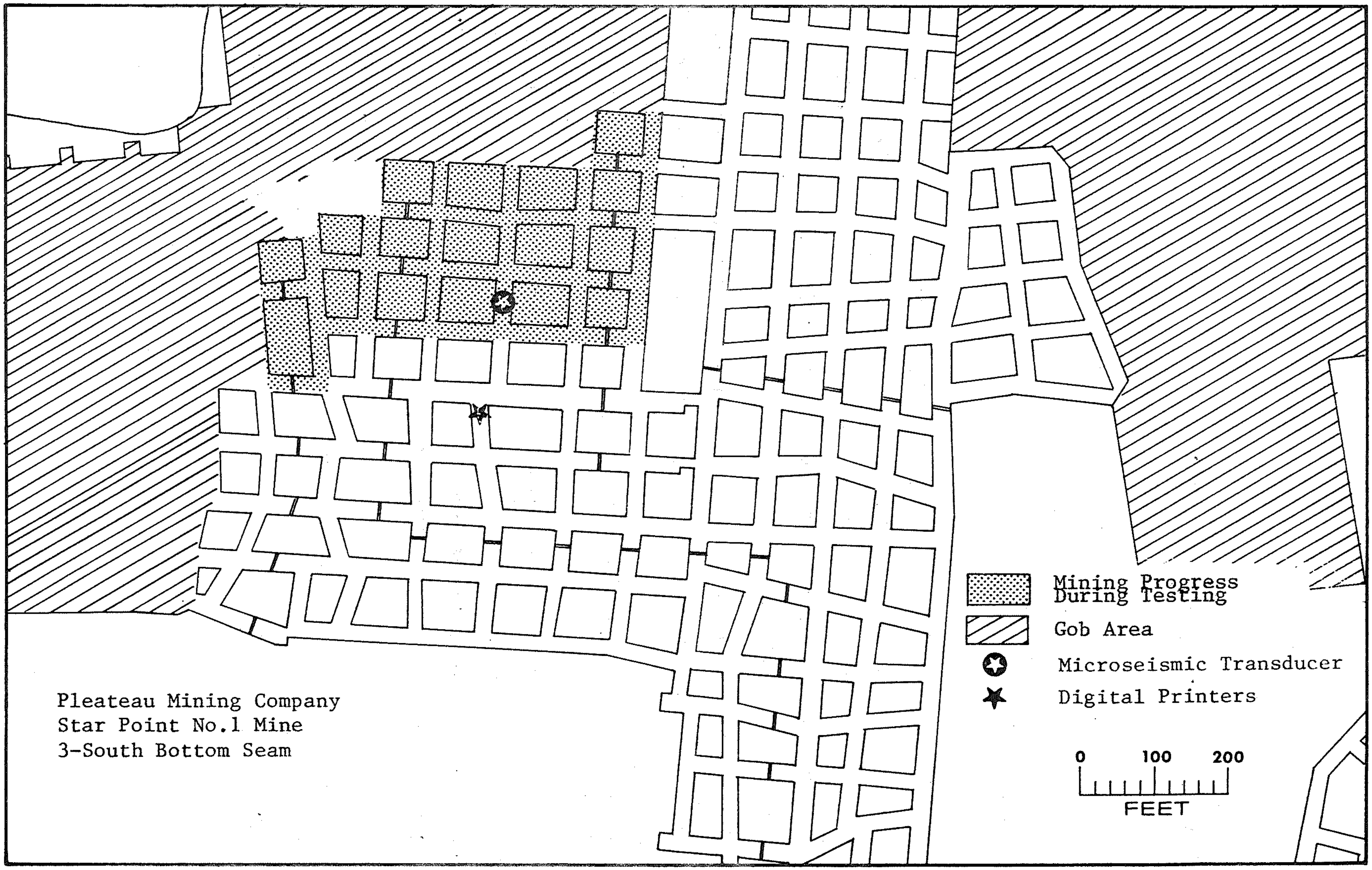

Figure 3-12. Roof Fall Test Site During Retreat Mining at Star Point No.1 Mine

Roof Fall, December 19, 1978

The first roof fall occurred during the second working shift on December 19, 1978. During the earlier part of the work day, mining had been repeatedly interrupted by heavy roof activity that was similar to the pre-fall indications that experienced miners have learned to respect. No fall, however, occurred until approximately 1900 of the same day. Figure 3-13 shows the microseismic roof fall data during the evening hours of December 19, 1978. The roof fall covered an area of 9,100 square feet (25 feet high) at a distance of 550 feet from the microseismic transducer's location.

Both the microseismic energy and event count data showed a large positive response well in advance of the reported time of fall. Note in Figure 3-13 that the response is similar to data presented previously with the exception of the somewhat noisy character. The energy and event count data increased by several orders of magnitude beginning at 1733 and maintained the high count rates, although erratic in nature, until 1810. The activity then rapidly decreased and remained low thereafter.

The computed energy/event count ratio also showed a positive response prior to the reported time of fall. It is interesting to note the atypical character of the energy/event ratio - most likely a result of the widespread deterioration in the roof's structural stability over the working section. The energy/event ratio did, however, display a specific peak at 1755, 65 minutes prior to the reported time of fall.

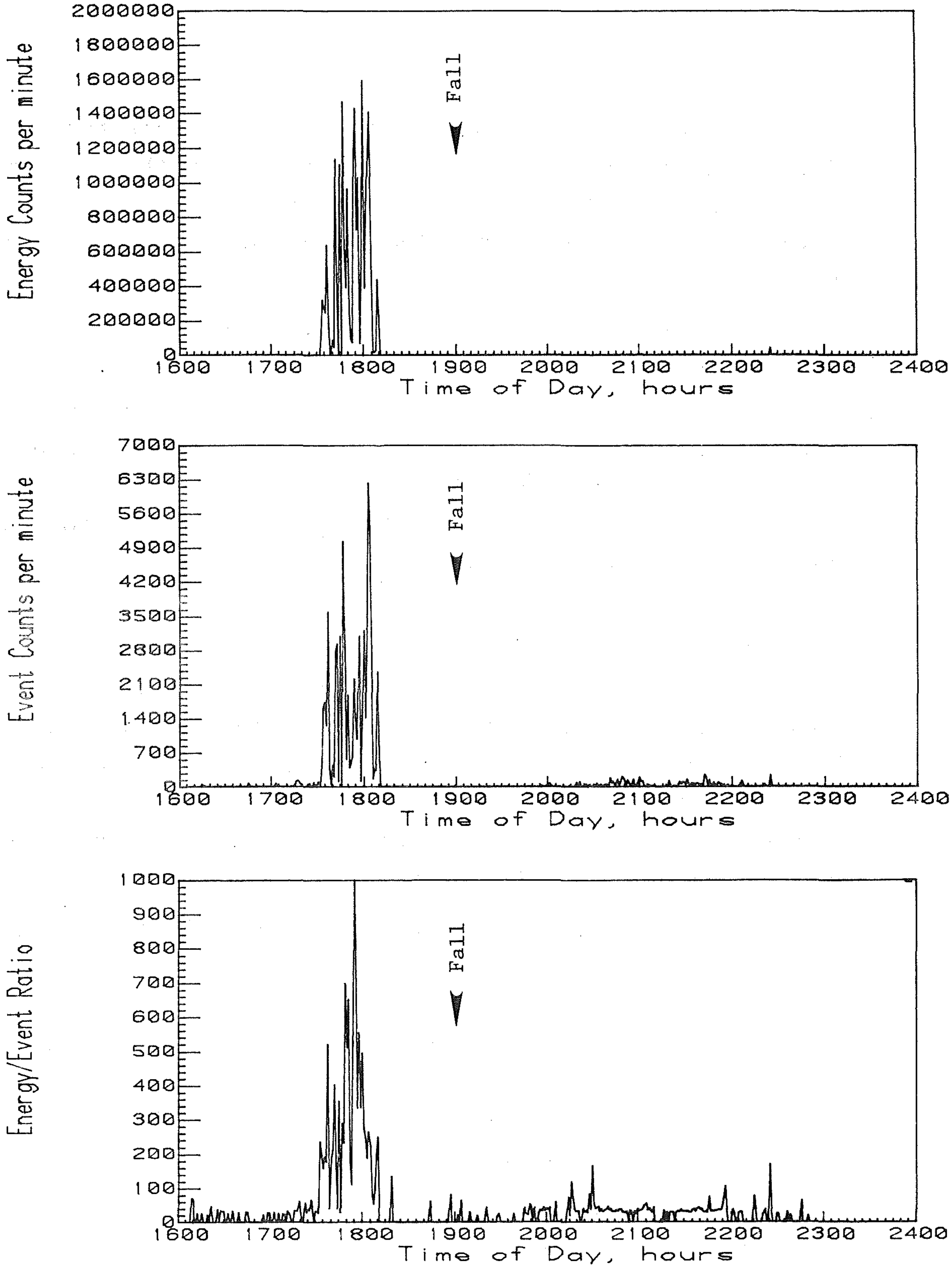

Figure 3-13. Microseismic Roof Fall Data from the Sunnyside No.1 Mine (December 19, 1978)

It should be noted that the Data Acquisition Unit's analog signal gain was increased from the previously used gain of 90 dB to 100 dB at the beginning of the Star Point No.1 mine tests. The 100 dB gain was used throughout the Star Point mine testing.

Figure 3-14 shows the actual caved area associated with the 0900 roof fall. The floor-to-roof height is approximately 15 feet. The photograph was taken from between two coal pillars and in front of a row of timbers that acted as a secondary breaker row. The clean break line shown at the top of the photograph resulted from the fall caving up the coal pillars.

Roof Fall, December 27, 1978

Heavy roof activity continued in the 3-South working section. The location of mine bounces seemed to be fairly widespread over the working section, indicating that roof stress was shifting and not remaining in the immediate vicinity of coal mining activity. Mining progressed cautiously but effectively.

The second shift crew completed pulling a large pillar and began mining coal from the coal barrier to the right of the cave line. Roof activity noticeably increased in the newly developed, unsupported roof area prior to the end of the work shift. Although roof convergence had begun, the roof did not cave by the time the miners left the working section at 2230.

The maintenance crew on the day shift reported that, during the night of December 27, 1978, the unsupported roof area had caved. The fall covered an area of 8,400 square feet (25 feet high) and was located 300 feet from

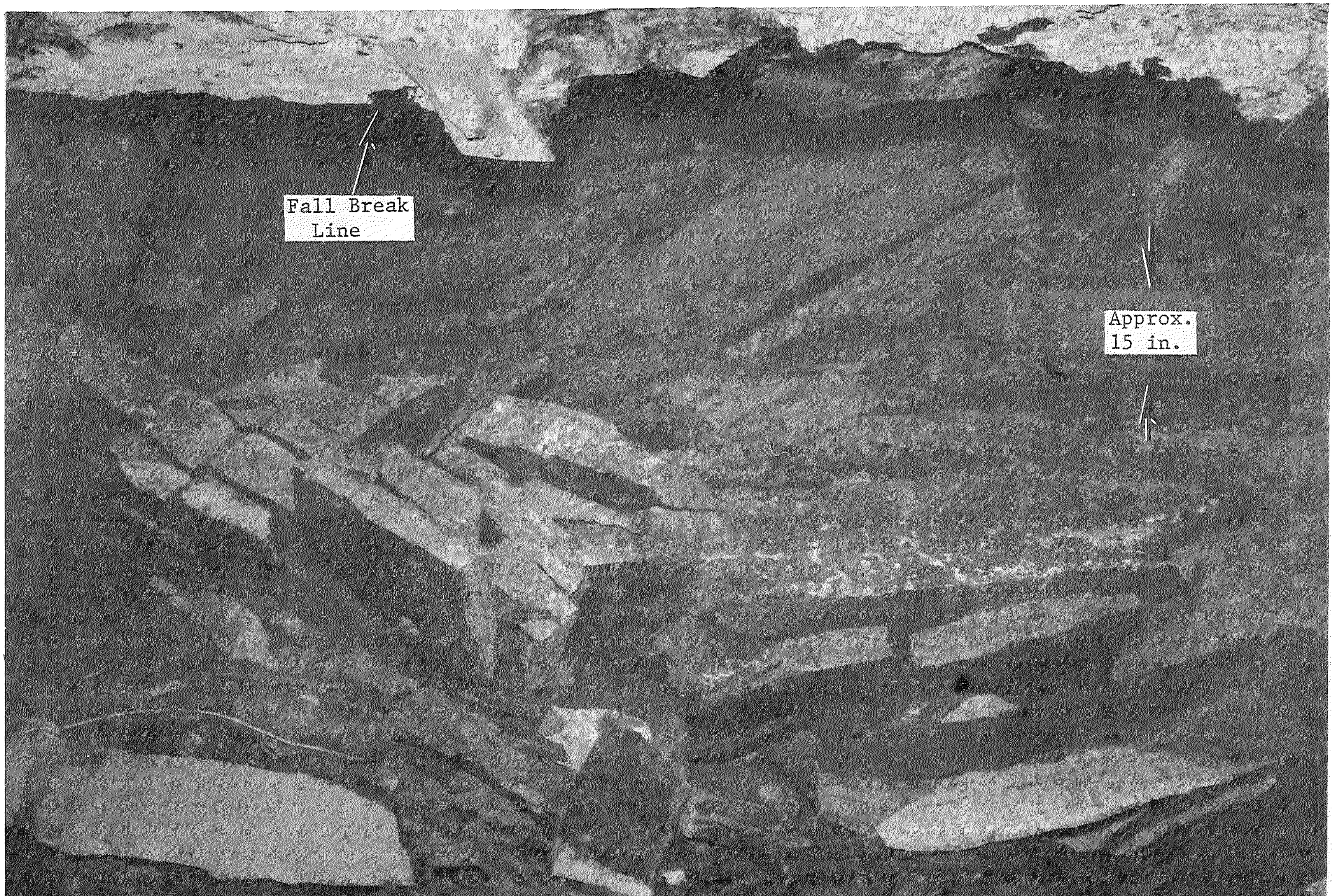

Figure 3-14. Roof Fall That Occurred at 0900 on December 19, 1978.

the microseismic transducer's location. Figure 3-15 shows the microseismic roof fall data obtained during the night of December 27, 1978.

Again, the energy and event count data showed a strong positive response prior to the assumed time of fall and displayed the same "noisy" character seen in the December 19, 1978 data. The computed energy/event count ratio shows a single well defined peak at 2222, a period in which the fall was known not to have occurred. In all three cases, it is certain that the positive responses occurred prior to the time of fall but, since the actual time of fall is not known, no specific estimate of prediction times can be given.

The structural integrity of the 3-South working section continued to progressively deteriorate. Mining personnel indicated that, in their opinion, the roof was shifting uniformly with a subsequent separation of the roof material at, perhaps, 6 to 10 feet up in the mine roof. Beginning on December 29, 1978, mining personnel became aware that the old mine workings above the 3-South section were caving. After this, the old mine workings in the Star Point No.2 mine could be viewed from below, through the roof fall areas in the 3-South section. A constant roar of activity from the upper, old mine workings could be heard for two days. Figure 3-16 shows the physical layout of the Star Point No.2 Mine (middle seam) directly above the 3-South working section.

Beginning on December 29, 1978, all detectable microseismic activity ceased. Both the energy and event count data remained at zero even with increasing the DAU's

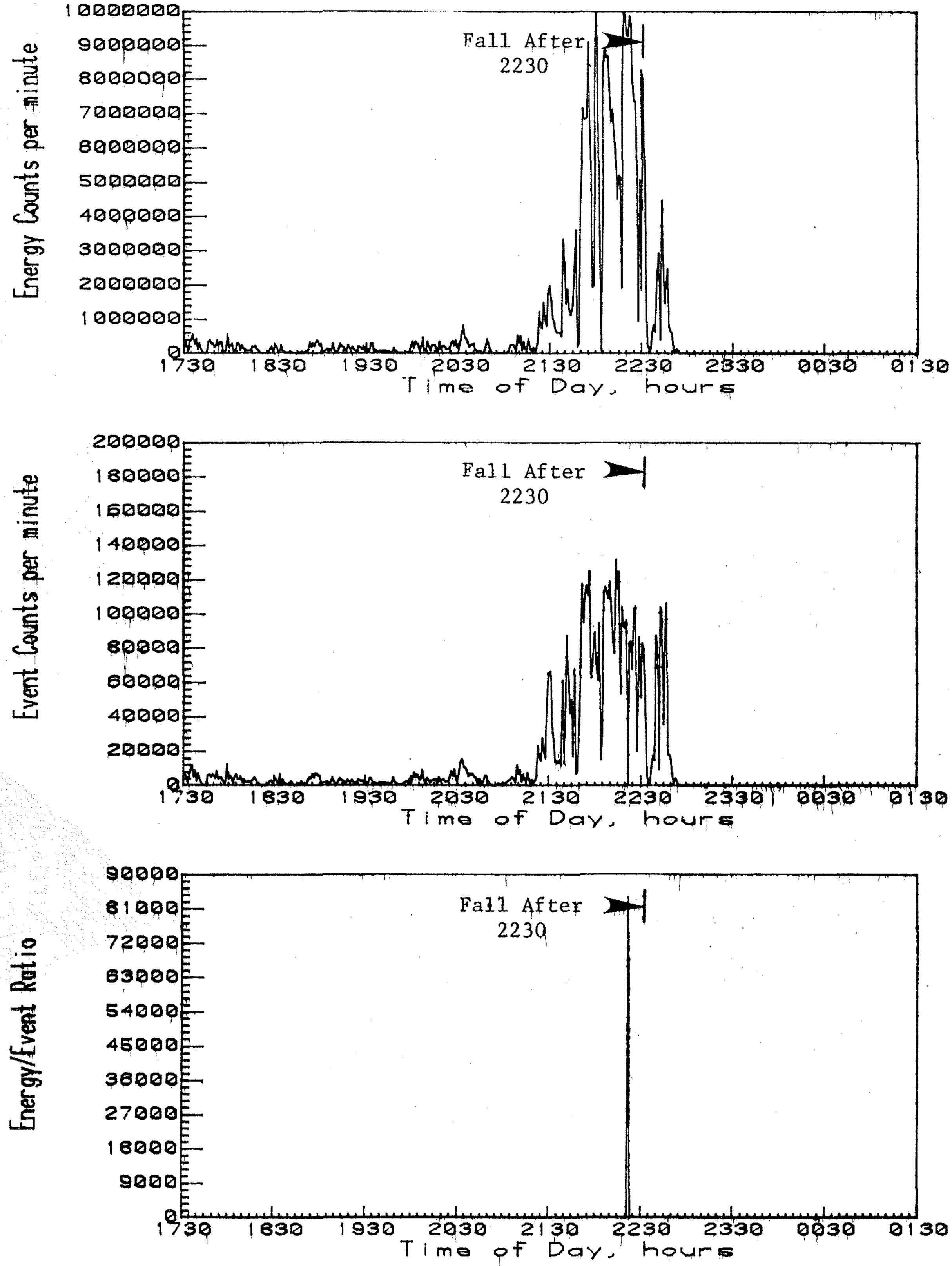

Figure 3-15. Microseismic Roof Fall Data from the Star Point No.1 Mine (December 27, 1978)

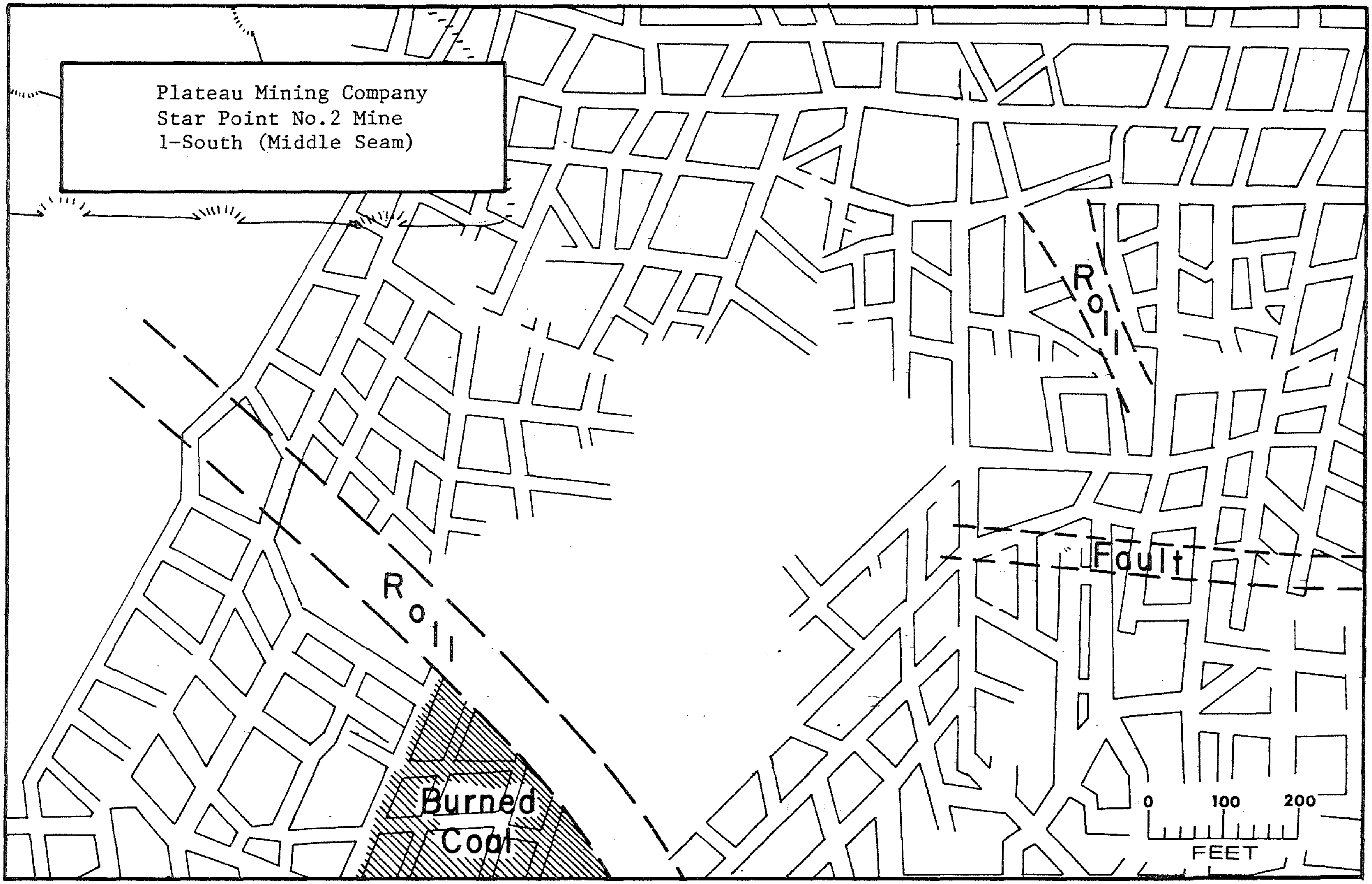

Figure 3-16. Old Abandoned Mine Workings Directly Above Roof Fall Test Site

analog signal gain. At first, this caused concern that the data collection equipment was malfunctioning since roof activity was still evidenced by audible sounds and mine bounces. Using the functional test set to inject microseismic signals into the roof near the microseismic transducer showed that the data collection equipment was operating properly. Convinced that "equipment problems" were not at fault, data collection was resumed even though the energy and event count remained at zero. Figures 3-17 through 3-19 show a typical in-mine roof fall warning system installation. The black substance on the microseismic transducer in Figure 3-17 is acoustic couplant contaminated with coal dust.

The lack of detectable microseismic activity continued throughout the remainder of the Star Point No.1 mine test period. Further examination of the 3-South section revealed that vertical cracks had developed in the mine roof. This can be reasonably linked to the loss of microseismic data by reviewing the possible effect of the old mine and the pillar extraction operation below it in the 3-South section.

As pillars in the 3-South section were being extracted, large unsupported roof areas were developed. The unsupported roof, being comprised of very competent sandstones, stayed together and acted (by virtue of its weight) as a lever whose folcrum was the line or row of coal pillars still to be mined. Since the old mine workings were only 25 to 50 feet above the 3-South working section, it presented little resistance to the action of the lever to lift the roof behind the fall line up into the old mine workings. This action separated the roof material so that the roof stresses generated in the fall

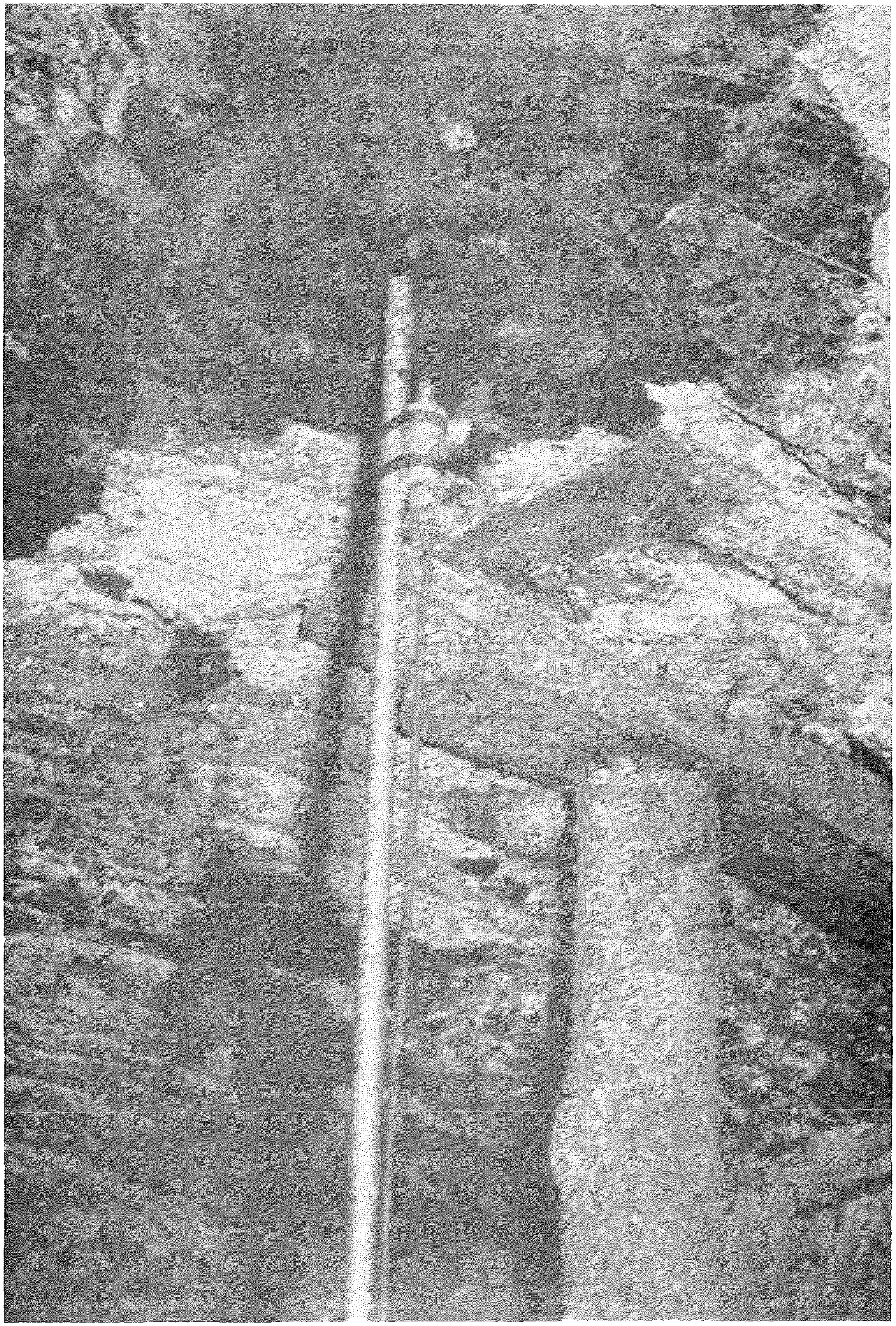

Figure 3-17. Microseismic Transducer Installed in the Star Point No.1 Mine Using Telescopic Mounting Pole

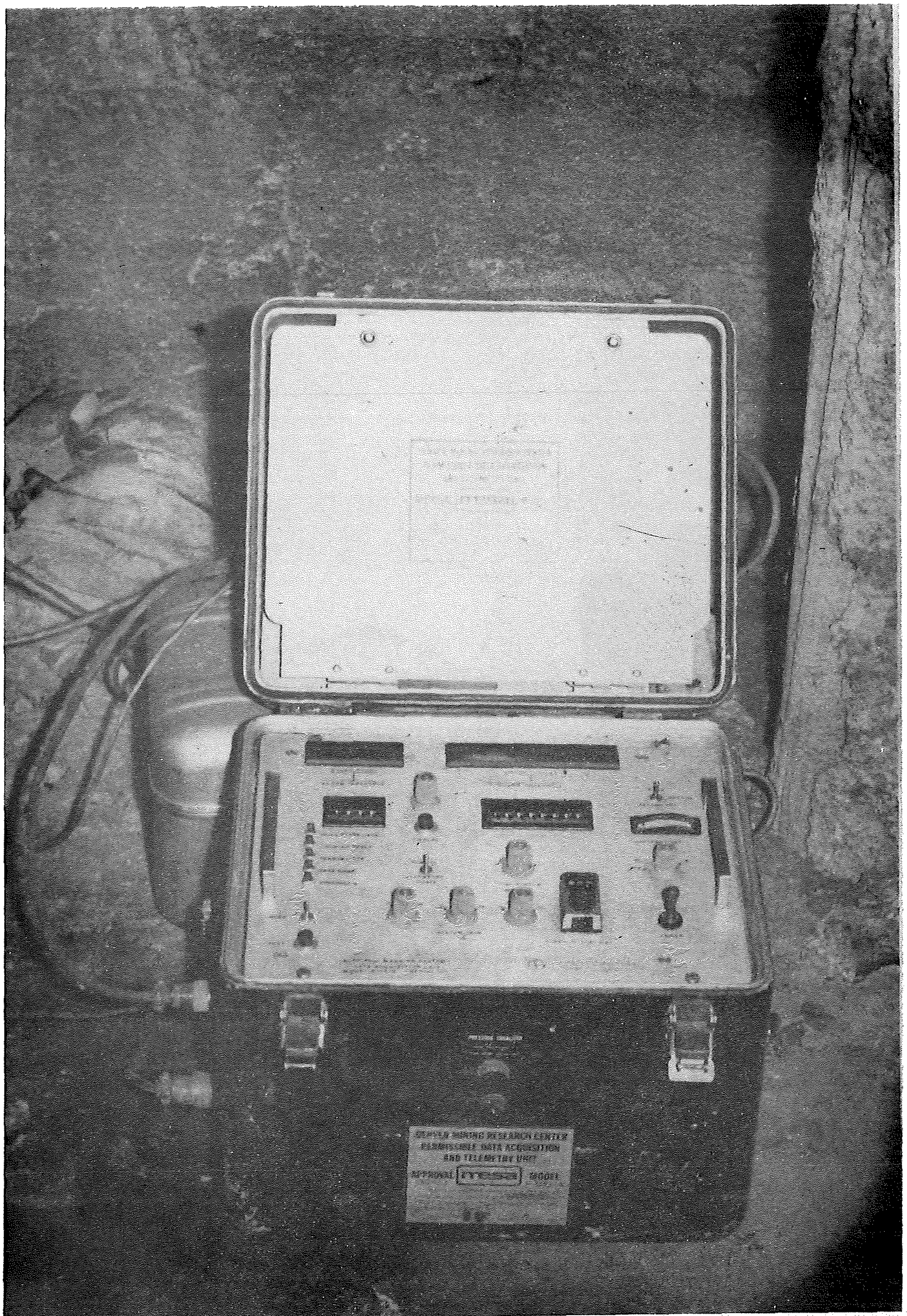

Figure 3-18. Data Acquisition Unit and Battery Pack in the Star Point No.1 Mine

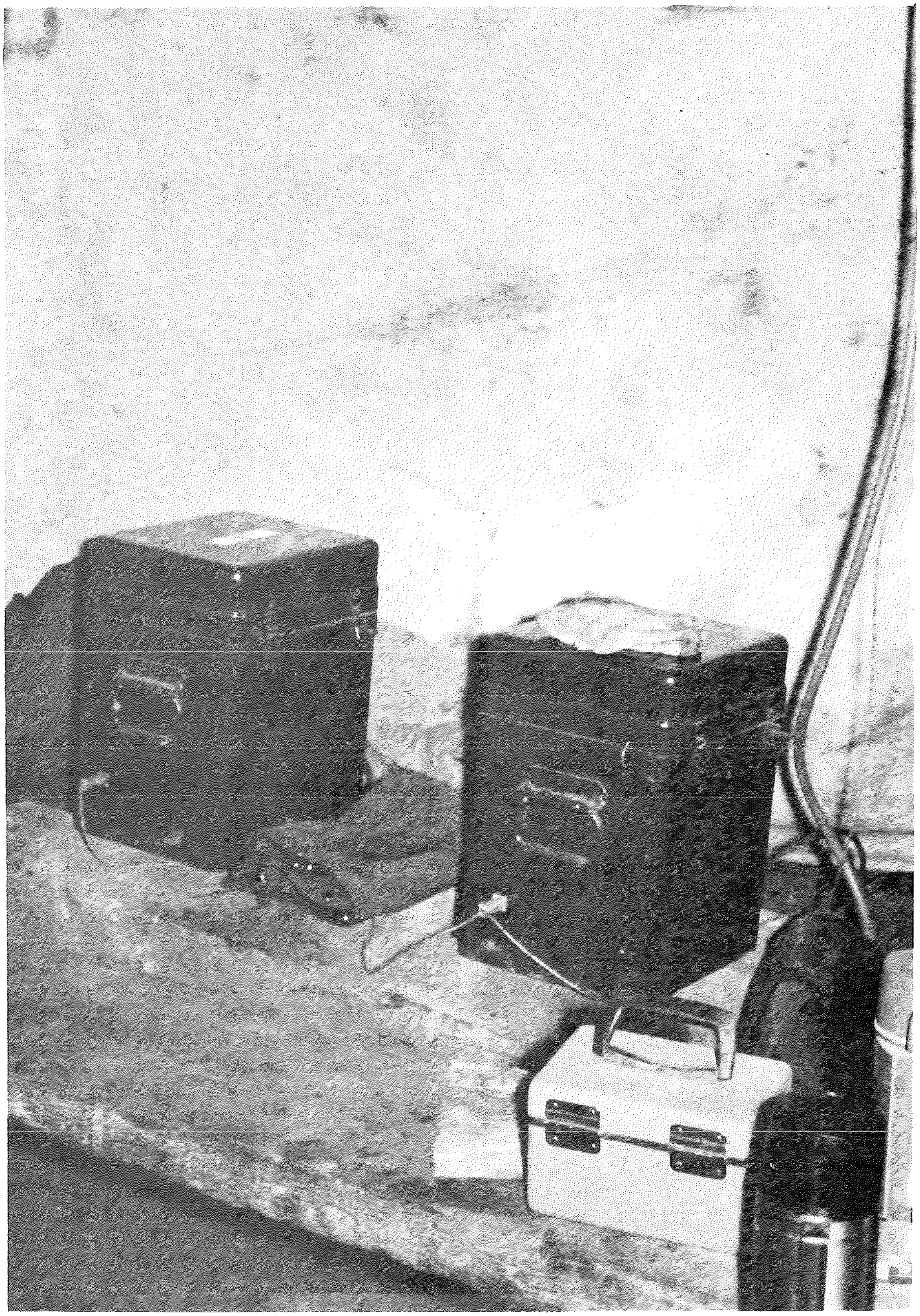

Figure 3-19. Digital Printer Units in the Star Point No.1 Mine

areas could not affect the roof at the microseismic transducer's location. Hence, even though roof activity continued, the information could not bridge the gap caused by the roof separation and, subsequently, no microseismic activity could be detected. Over time, of course, the unsupported roof yielded, developed cracks, and eventually caved. Since mining continued, more unsupported roof was being generated to replace areas that caved, maintaining the progressive growth of roof separation in the 3-South working section.

To illustrate how completely roof separation can block the detection of microseismic activity, with the microseismic transducer located within 2 feet of a large, potential fall area, not one event was detected during the fall sequence. This represents the state of microseismic roof fall data collection at the Star Point No.1 mine after December 29, 1978. Since no change could be anticipated in the mine conditions, roof fall testing was terminated on February 2, 1979.

During the test period at the Star Point No.1 mine, 1,083 hours of microseismic energy and event count data were obtained on a one minute time window.

3.4 Sunnyside No.1 Mine

Kaiser Steel Corporation had decided to retreat mine a section of the Sunnyside No.1 mine adjacent to the longwall section where roof fall testing was performed six months earlier. Upon learning of this, the roof fall test program was quickly relocated to the 4½-Right section in the Sunnyside No.1 mine. Figure 3-20 shows the physical mine layout at the time the microseismic roof fall warning

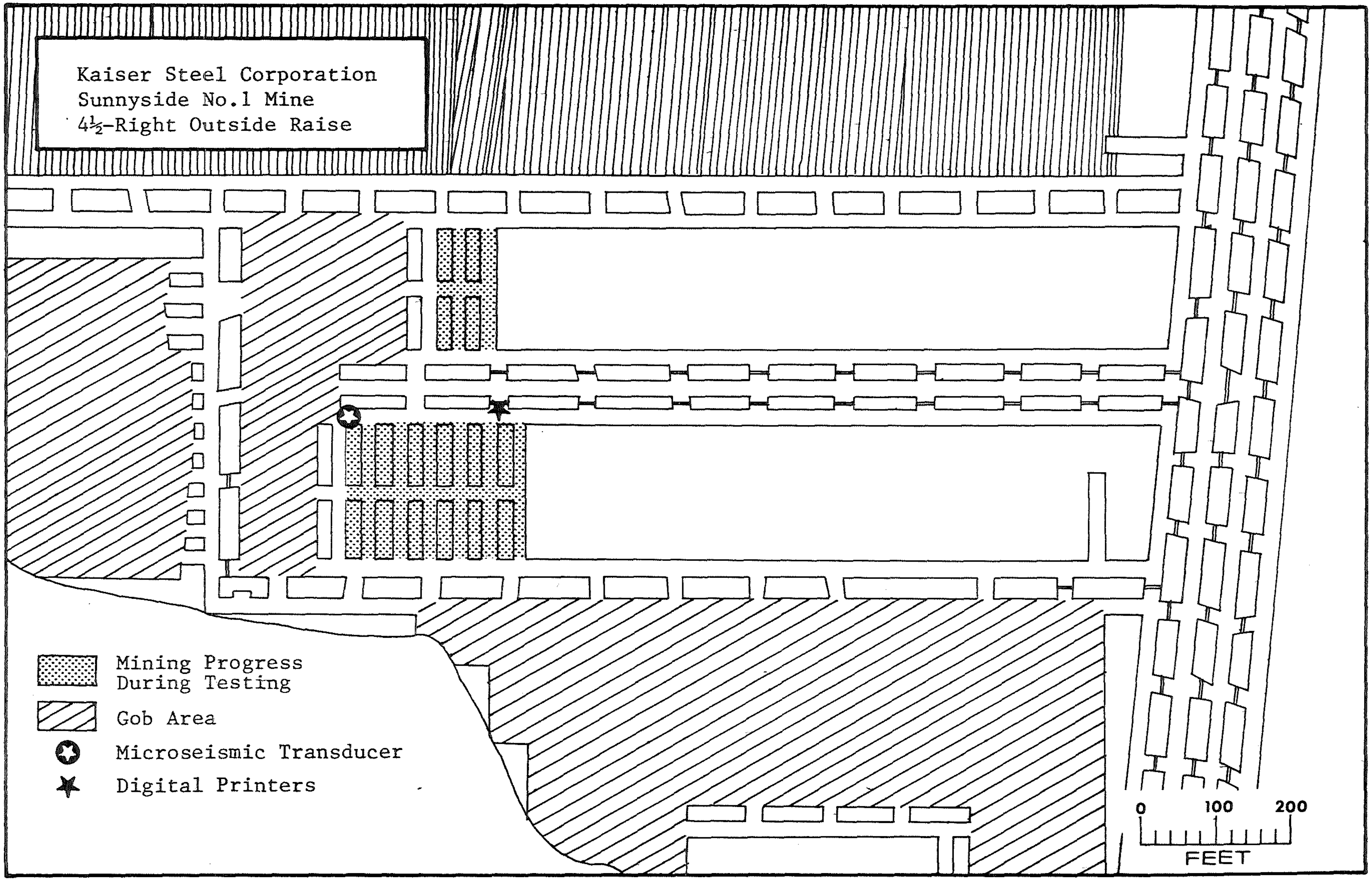

Figure 3-20. Roof Fall Test Site During Retreat Mining at the Sunnyside No.1 Mine

system was installed on February 5, 1979. The progress of room and pillar development during the two month test period is also shown in Figure 3-20.

Roof Fall, February 15, 1979

Mining in the 4½-Right section had progressed to the point where pillars had already been developed, extracted, and new development started by the time the roof fall warning system was installed. It took approximately nine days for the mining crew to develop a new suite of pillars and resume retreat mining. Pillar extraction started on February 15, 1979.

Before a complete pillar could be mined, roof activity escalated to the point that mining had to be temporarily halted. The mining crew set timbers and awaited the roof fall that soon caved at 1852. Figure 3-21 shows the microseismic data recorded during the roof fall reported on February 15, 1979. The roof fall covered an area of 2,000 square feet (15 feet high), 80 feet from the microseismic transducer's location. The DAU analog signal gain was still at 100 dB.

Even though the fall was relatively close to the microseismic transducer's location, no indication of a positive response is seen in the energy and event count data. The computed energy/event count ratio did show a primary response at 1808, 44 minutes prior to the reported time of fall. The higher average energy/event ratio is most likely due to the higher system gain used initially at this test site.

Pillar extraction continued soon after the fall. It was not until four days later that several more roof falls occurred.

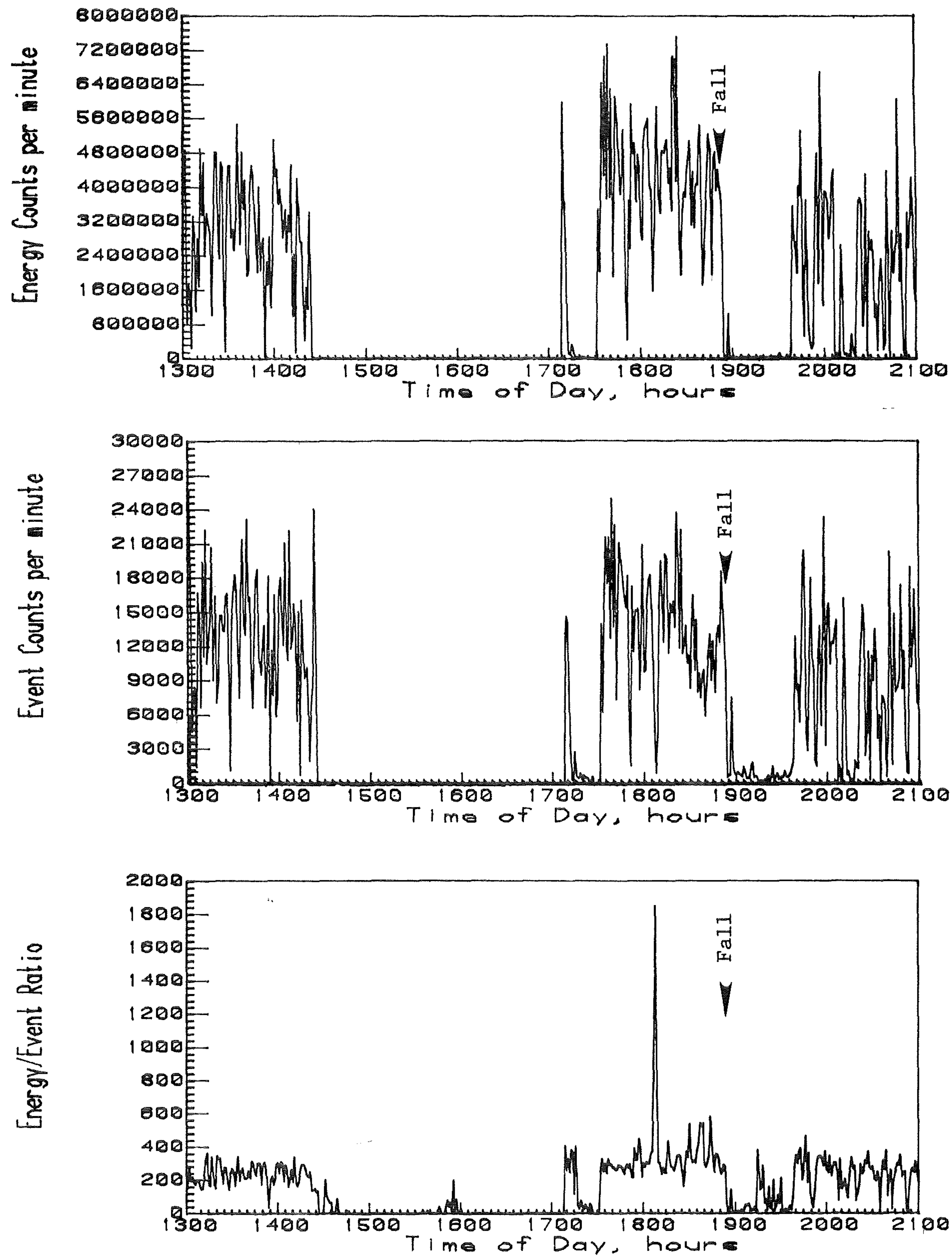

Figure 3-21. Microseismic Roof Fall Data from the Sunnyside No.1 Mine (February 15, 1979)

Roof Falls, February 19, 1979 (am)

Several falls occurred in succession during the afternoon hours of February 19, 1979 while pillar extraction was proceeding nearby. The three falls were witnessed at 1341, 1500, and 1509. The fall at 1341 was located 80 feet from the microseismic transducer and covered an area of 2,000 square feet (20 feet high). Figure 3-22 shows the microseismic data obtained during all three falls. It appears that, even though the energy and event count data did not clearly indicate that any of the three falls were forthcoming, the energy/event count ratio did give a response prior to, and in response to, the fall reported at 1341. In this particular instance, the energy/event ratio occurred at 1209, 92 minutes prior to the 1341 fall time.

There is no indication of the energy/event count ratio responding to the two falls at 1500 and 1509, respectively. Both these falls were relatively small and occurred in an entry between two pillars. The two entry falls were of approximately equal size (400 square feet by 20 feet high) and were located 160 feet and 175 feet, respectively, from the microseismic transducer's location - opposite in direction from the fall that occurred at 1341.

It is important to note that the DAU analog signal gain had been reduced to 90 dB prior to the recording of data on February 19, 1979. The inability of the roof fall warning system to detect the last two falls could be the result of lower system gain. However, it should also be kept in mind that the last two falls were small, compared with previously discussed falls.

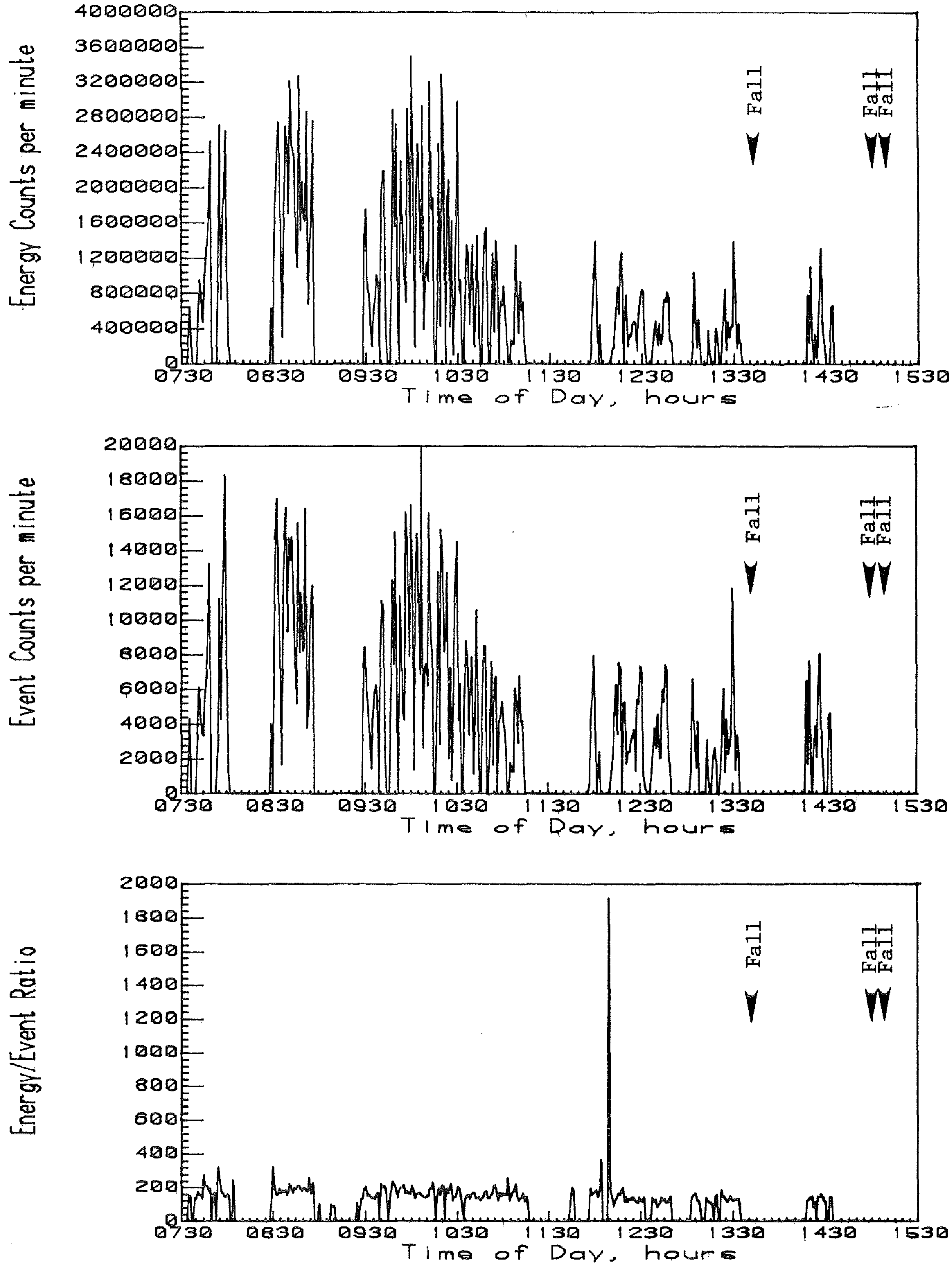

Figure 3-22. Microseismic Roof Fall Data from the Sunnyside No.1 Mine (February 19, 1979)

Roof Falls, February 19, 1979 (pm)

The day shift crew continued mining without further interruption from roof fall. The second shift crew began mining at approximately 1540 on the evening of February 19, 1979. At 1733, a small fall (500 square feet by 20 feet high) was witnessed in the area immediately adjacent to the fall reported at 1341 earlier in the day. The fall at 1733 was at a distance of 120 feet from the microseismic transducer.

A second fall was reported at approximately 2100 by mining personnel. This was a larger fall, covering an area of 5,500 square feet (20 feet high) and at a distance of 55 feet from the microseismic transducer. The fall was a large entry fall and was not associated with the area of unsupported roof generated by pillar extraction.

Figure 3-23 shows the microseismic data during the evening hours of February 19, 1979. No response in the data can be attributed to the small fall at 1733. The lack of response to this fall could be because the 1733 fall was actually secondary caving associated with the earlier fall at 1341. It could also be due to the lower system gain being used.

The computed energy/event count ratio did show the, apparently, typical response to the fall reported at 2100. The energy/event ratio peak occurred at time 1944, 76 minutes prior to the reported time of fall.

Roof Fall, February 20, 1979

Pillar extraction continued in the 4½-Right section during February 20, 1979. During the day work shift, a fall occurred that was reported at 1220 by mining

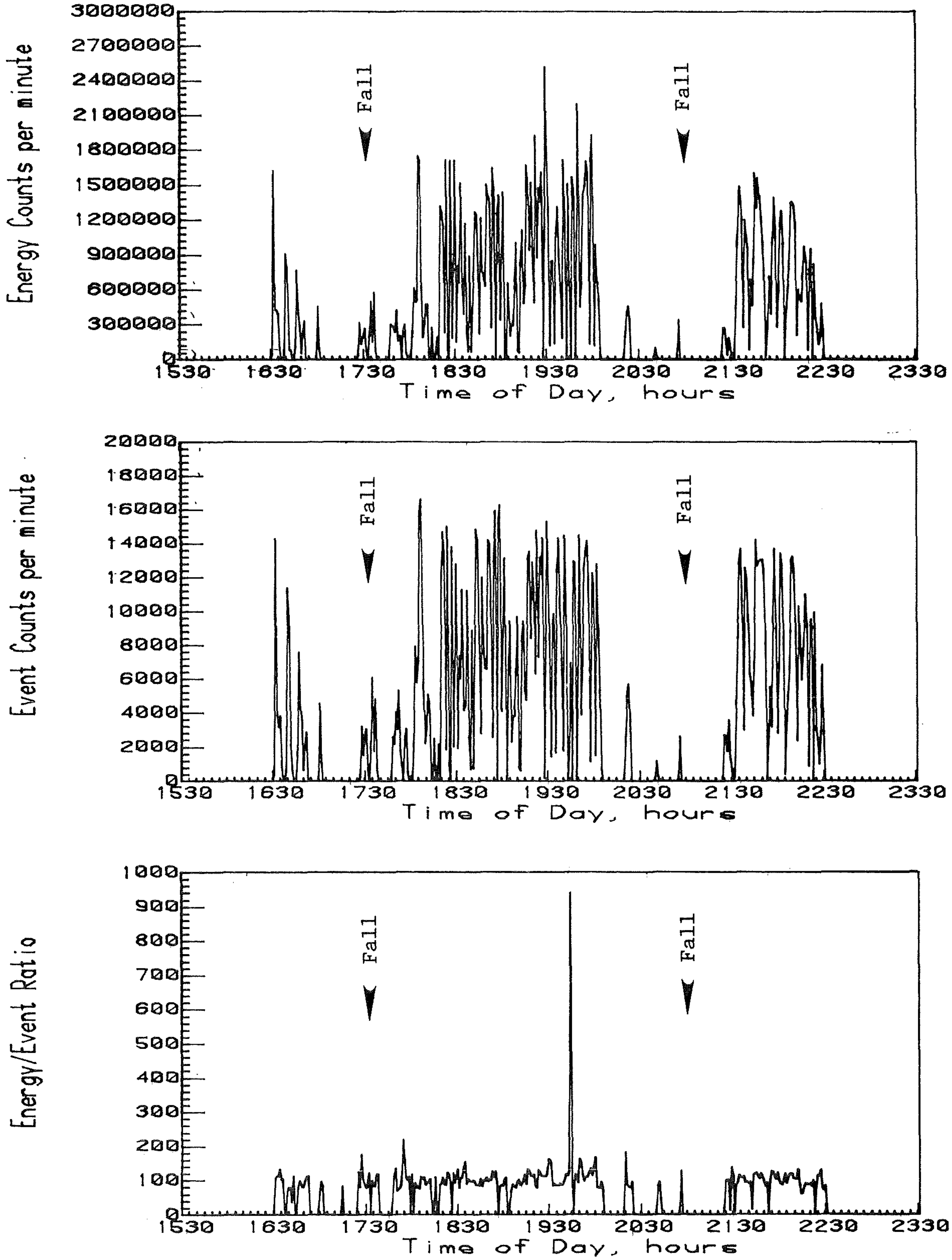

Figure 3-23. Microseismic Roof Fall Data from the Sunnyside No.1 Mine (February 19, 1979)

personnel. The fall covered a narrow area of 1,600 square feet (20 feet high), 80 feet from the microseismic transducer's location. Figure 3-24 shows the microseismic data obtained during the February 20, 1979 roof fall.

Again, no indication is seen in the energy and event count data that can be attributed to a response prior to the time of fall. The computed energy/event count ratio did, however, give a positive response at time 1136, 44 minutes prior to the reported time of fall.

Roof Fall, March 20, 1979

Pillar extraction continued through February 21, 1979. Mining activity shifted toward the development of a new suite of pillars beginning on February 22, 1979 and continued through February 27, 1979. Pillar extraction was started again and did not stop until March 5, 1979. Although roof falls were reported during the period between February 28, 1979 and March 5, 1979, equipment problems developed that, by coincidence, resulted in the equipment being out of the mine for repairs when most of the falls occurred. Those falls which were reported when the equipment was in the mine, did not have a sufficiently high credibility or confidence level to include in the report. The development of a new suite of pillars began again on March 5, 1979 and lasted until March 14, 1979.

Pillar extraction started in the 4½-Right section on March 14, 1979. On March 20, 1979, mining personnel on the day shift reported a fall at time 1220. The fall covered an area of 4,000 square feet (15 feet high), 86 feet from the microseismic transducer's location. Figure 3-25 shows the microseismic data during the March 20, 1979 roof

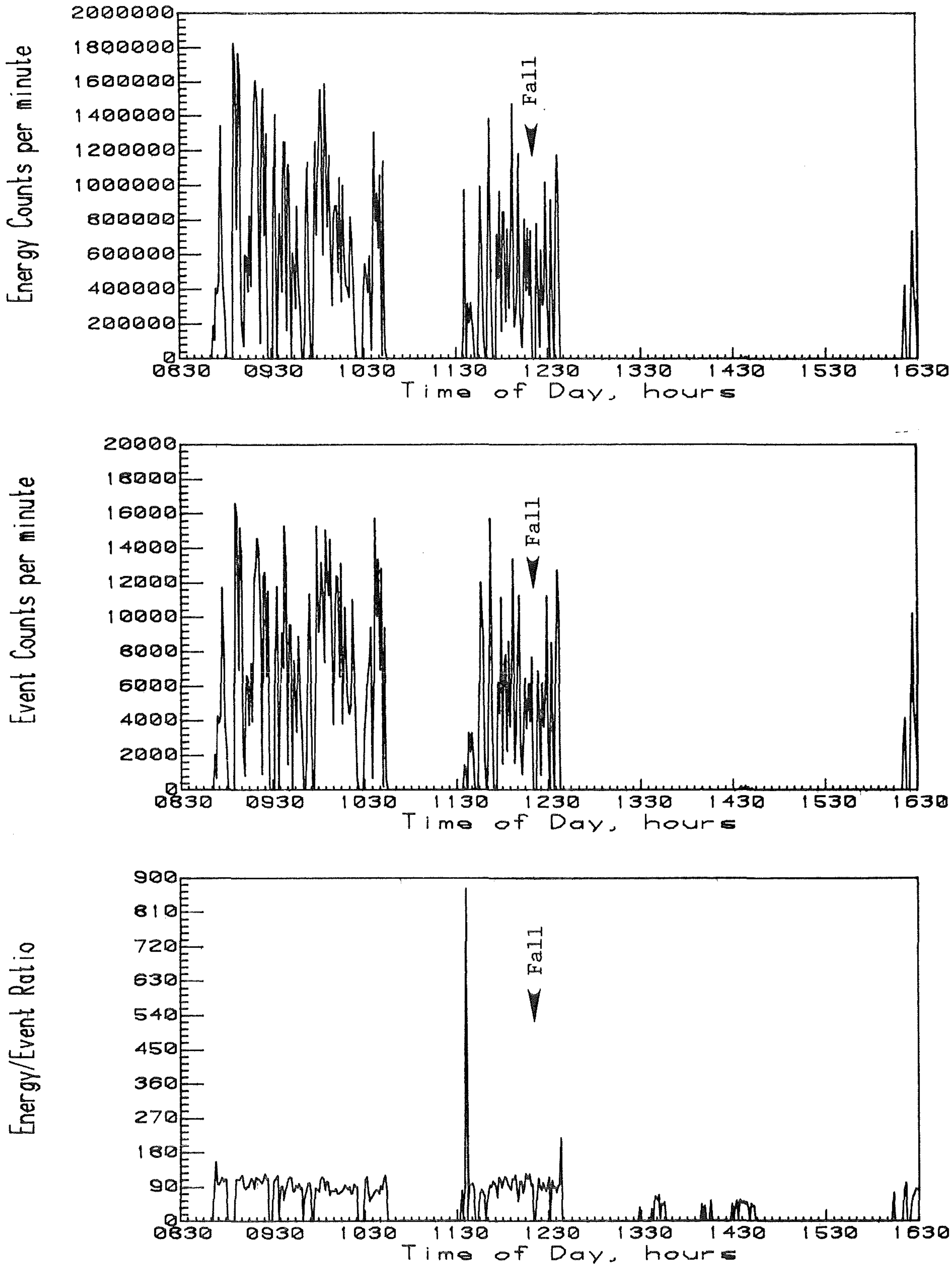

Figure 3-24. Microseismic Roof Fall Data from the Sunnyside No.1 Mine (February 20, 1979)

fall. Note that the DAU's analog signal gain was reduced from 90 dB to 85 dB at time 1940 in Figure 3-25.

With the analog signal gain reduced, no indication is given of the impending roof fall in the energy or event count data shown in Figure 3-25. The computed energy/event count ratio did give a particularly strong response at 2002, 14 minutes prior to the reported time of fall. No other roof falls were reported during March 20, 1979.

Roof Falls, March 21, 1979

Reduction of the DAU analog signal gain appeared to have a significant effect on the roof fall warning section's ability to detect roof fall related activity at a range of more than 90 feet. Two roof falls were witnessed during the day shift on March 21, 1980 with absolutely no response seen in the corresponding microseismic data.

The two falls occurred at 1407 and 1418, and covered areas of 1,000 square feet (20 feet high) and 2,250 square feet (20 feet high), respectively. The falls at 1407 and 1418 were 90 feet and 150 feet, respectively, from the microseismic transducer's location.

Since a magnetic tape recording of analog roof fall data had been obtained during the time over which the two falls occurred on March 21, 1979*, the opportunity was seized to see if the falls were not detected as a result of the lower system gain and, perhaps, reduced detection range. The taped roof fall data was played back into the

*See the Volume I - Appendix A, Analog Data Recording at the Sunnyside No.1 Mine, for more details.

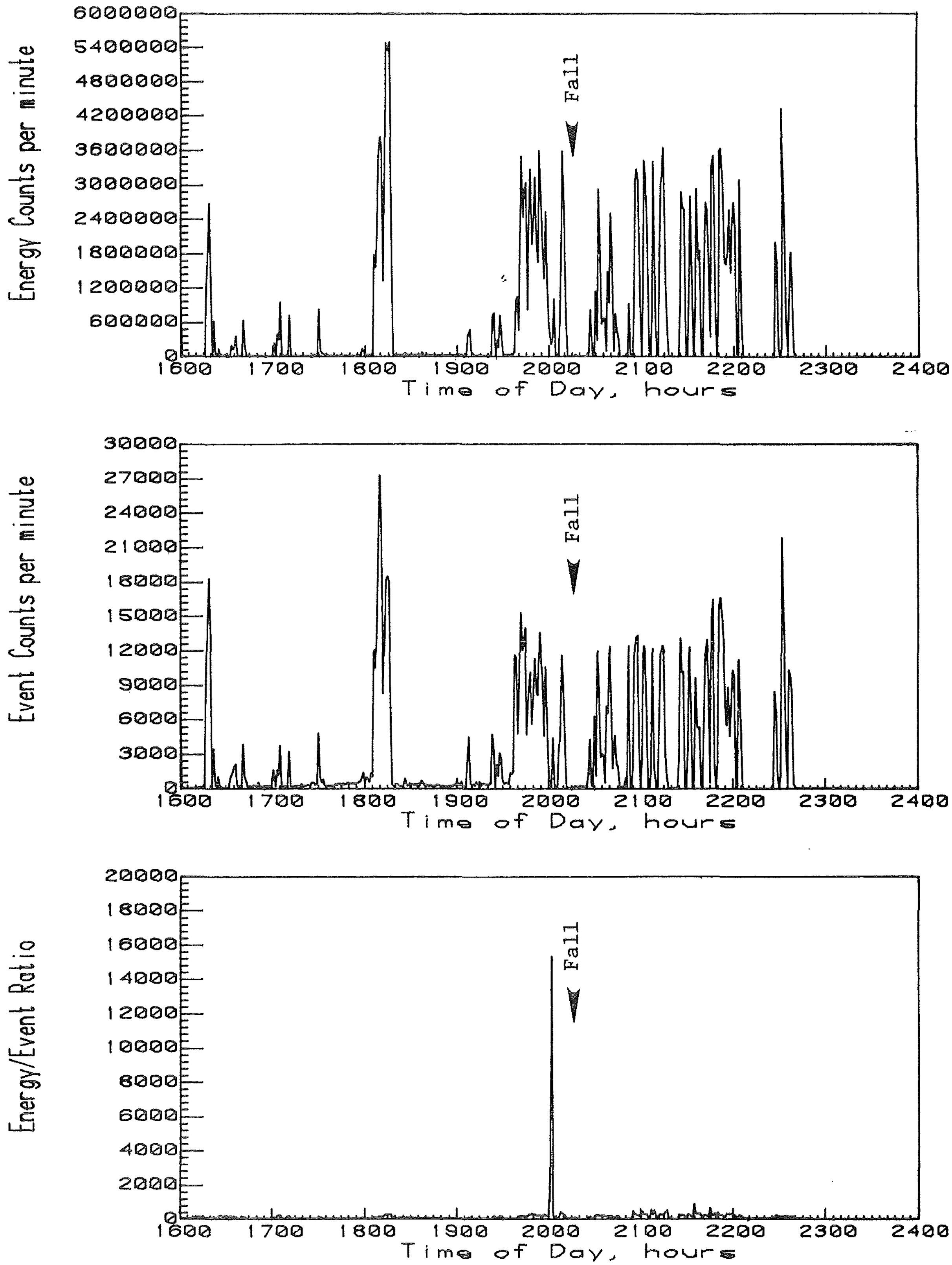

Figure 3-25. Microseismic Roof Fall Data from the Sunnyside No.1 Mine (March 20, 1979)

microseismic roof fall warning system with additional gain. Figure 3-26 shows the resulting data output.

Using a higher signal gain, the energy and event count data still did not give an indication of the impending roof falls. However, the computer energy/event ratio did respond in a manner consistent with previous experience. Well defined energy/event ratio peaks occurred at 1305 and 1339, respectively. It is assumed that these two peaks are associated with the reported roof falls. The first peak occurred 52 minutes prior to the 1407 roof fall. The second peak occurred 39 minutes prior to the second fall at 1418.

By the end of March 1979, the MSHA Approval and Testing Group had responded to the request for the microseismic roof fall warning system's permissibility certification. As a result of MSHA's approval investigation, major modifications to the roof fall warning system would be required. Since the field program also called for Eastern mine testing, it was decided to terminate the Western mine test program, modify the roof fall warning system to MSHA specifications, and then proceed with the Eastern mine test program.

The Sunnyside No. 1 mine tests were terminated on March 21, 1979. During the data collection period in the 4½-Right working section, 883 hours of microseismic energy and event count data were obtained on a one minute time window. In addition, ten roof fall sequences were recorded and documented.

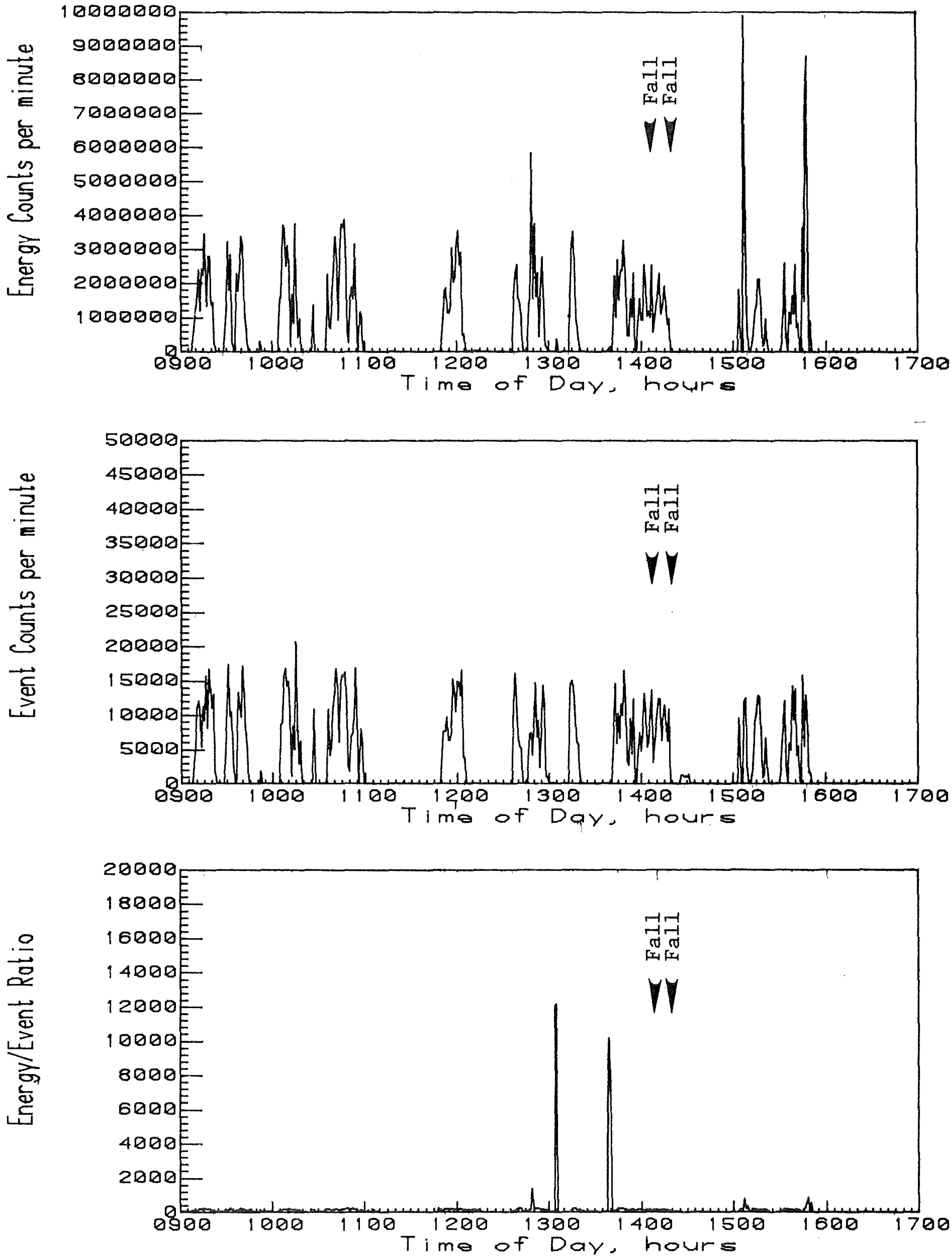

Figure 3-26. Microseismic Roof Fall Data from the Sunnyside No.1 Mine (March 21, 1979)

3.5 Renton Mine

The Consolidation Coal Company's Renton mine is located near the town of Renton, Pennsylvania, just 24 miles east of Pittsburg, Pennsylvania. The coal mine operates in the Upper Freeport seam and is accessed through a vertical shaft. The immediate roof in the Renton mine consists of approximately 12 feet of shale that is overlain with a thick, competent sandstone. The mine floor is composed principally of shales and fire clay that rest on a hard limestone basement.

After obtaining MSHA permissibility approval for the microseismic roof fall warning system on May 14, 1979, equipment and men were deployed to the mine test site to begin the Eastern coal mine test program. Upon arrival at the Renton mine, it was learned that retreat mining in the mine's 3-East working section was nearing completion and that the mine was scheduled to begin retreat mining in the 4-East section in the near future. It was also learned that, in addition to the requirement for MSHA permissibility approval to allow equipment to be installed in the mine, the Pennsylvania Bureau of Deep Mine Safety had to also approve and certify the equipment before it could be used in any coal mine in the state of Pennsylvania. This meant that the Eastern mine testing would have to be delayed until the Pennsylvania State approval could be obtained.

The Pennsylvania State Bureau of Deep Mine Safety was contacted and the formal approval proceedings initiated on May 19, 1979. The approval procedure required that the equipment and its operation be demonstrated before a state appointed committee. The committee would not be available until July 23, 1979.

On July 23, 1979, the Pennsylvania State Approval Committee reviewed the request for approval of the microseismic roof fall warning system and granted state approval on the condition that the state-appointed review committee be given an in-mine demonstration of the equipment's operation. The in-mine demonstration was scheduled for July 25, 1979 at the Renton mine test site.

By this time the Renton mine was just starting mine operations after the June 1979 mine vacation and experiencing the usual problems of "after vacation" start-up and, at the same time, trying to meet their demanding production schedule. As a result, the Renton mine management could not comply with the request for an in-mine demonstration of the microseismic roof fall warning system. Due to the heavy work load of the state review committee, the demonstration and field testing had to be delayed until early September 1979.

After a five month delay, the microseismic roof fall warning system was finally installed in the Renton mine's 4-East room and pillar section on September 4, 1979. New problems were, however, to be encountered and solved before data collection could proceed.

One of the major restrictions that MSHA had placed on the operation of the roof fall warning system was that the hard-wired cable telemetry link, normally used with the system, could not be employed under the approved, permissible configuration. The system had to rely, therefore, upon its through-the-earth radio (EM) telemetry capability to transfer data from the Data Aquisition Unit to the Digital Printers. A problem arose when it was determined that the nearest available in-mine power source for the Digital Printer Units (DPU's) was located 900 feet from the microseismic monitoring location. Since only marginal telemetry reception could be expected at this distance, it was decided that it would be better to locate the DPU's on the surface, 600 feet directly above the in-mine test site.

Arrangements were made to provide a surface recording location with a local resident who had a small work shed directly over the in-mine location of the DAU. The through-the-earth telemetry transmissions of this location were marginal due to the very high ambient EM noise levels of the mine. The intermittent data records were, to a large extent, unacceptable and led to a decision to increase the DAU's transmitting antenna moment and tune the DPU's receiver circuits more precisely. With the field changes completed, data collection resumed on October 2, 1979.

Pillar extraction operations did not actually begin in the Renton Mine's 4-East section until September 17, 1979. The microseismic roof fall warning system was located well ahead of the mining operation so that data could be obtained as long as possible without having to relocate the equipment. By October 10, 1979, the mining had progressed to within 300 feet of the microseismic transducer's location. No roof falls were detected during this period although roof falls were reqported at distances in excess of 400 feet from the microseismic transducer's location. Roof fall in the 4-East section occurred within 30 minutes of pillar extraction and were typically 25 to 40 feet high.

By the time the mining progress was such that roof fall data should have started to show a response to fall related activity, mining personnel requested that the roof fall warning system be moved to allow roof bolting to begin in its immediate area. This increased the distance between the microseismic transducer and potential fall areas by a sufficiently large amount such that the roof falls were out of range of the system's detection capability (at this mine, 300 feet appeared to be the detection limit). This process of moving ahead of roof bolting operations continued during the remainder of the Renton mine test period. Subsequently, no significant roof fall data were obtained from the Eastern mine test site. Even though no roof fall sequences were recorded, approximately 400 hours of energy and event count data were obtained on a one minute time window.

The Renton mine test program and the field test program, in general, were terminated on December 21, 1979.

3.6 Roof Fall Summary

Table 3-1 summarizes the significant parameters associated with the 23 roof falls discussed in this report. The symbols used in Table 3-1 include:

t_o = time of fall based on 24 hour time.
V = volume of fall in cubic feet.
d = distance to fall from the microseismic transducer in feet.
A = Data Acquisition Unit gain, in dB.
t_r = roof fall prediction time in minutes, based on the energy/event ratio peak.
N = maximum value of energy/event count data.

Fall Id.#	Date (day)	t_o (hour)	V (cu.ft.)	d (ft.)	A (dB)	Data Response Energy	Data Response Event	Data Response Ratio	t_r (min)	N (units)
1	07/12/78	1400	NA	62	100	YES	YES	YES	15	8,500
2	08/15/78	0900	NA	20	95	YES	YES	YES	20	10,072
3	09/13/78	>1430	39×10^3	300	90	YES	YES	YES	>15	5,025
4	09/15/78	1015	4×10^3	160	90	NO	NO	YES	27	832
5	09/15/78	1115	6×10^3	200	90	NO	NO	YES	5	734
6	09/15/78	1340	10×10^3	250	90	NO	NO	YES	6	681
7	09/18/78	2212	9.6×10^3	140	90	NO	NO	YES	7	864
8	09/19/78	>1430	8.4×10^3	130	90	NO	NO	YES	>86	5,097
9	11/29/78	0930	76×10^3	220	95	YES	YES	YES	16	7,245
10	11/29/78	2025	9×10^3	160	95	NO	NO	YES	52	5,683
11	11/30/78	0900	8.3×10^3	130	95	NO	NO	YES	45	1,171
12	12/19/78	1900	228×10^3	550	100	YES	YES	YES	65	1,009
13	12/27/78	>2230	210×10^3	300	100	YES	YES	YES	> 8	84,208
14	02/15/79	1852	30×10^3	80	100	NO	NO	YES	44	1,849
15	02/19/79	1341	40×10^3	80	90	NO	NO	YES	92	1,915
16	02/19/79	1500	8×10^3	160	90	NO	NO	NO		
17	02/19/79	1509	8×10^3	175	90	NO	NO	NO		
18	02/19/79	1733	10×10^3	120	90	NO	NO	NO		
19	02/19/79	2100	110×10^3	55	90	NO	NO	YES	76	941
20	02/20/79	1220	32×10^3	80	90	NO	NO	YES	44	872
21	03/20/79	2016	60×10^3	86	85	NO	NO	YES	14	15,348
22	03/21/79	1407	20×10^3	90	85	NO	NO	YES	62	12,181
23	03/21/79	1418	45×10^3	150	85	NO	NO	YES	39	10,052

Table 3-1. Coal Mine Roof Fall Summary

The column labeled "Data Response" indicates which of three data formats gave responses that could have been employed to predict each fall. Note that the use of the symbol ">" with t_o implies "after time" and indicates "greater than" when used with t_r.

4.0 CONCLUSIONS

Field test results from Western coal mines indicate that the microseismic technique can be applied successfully to roof fall prediction. Of the three data formats explored, all three formats are needed to give reliable fall prediction. The fall prediction time is not seen to be well defined in terms of when a warning of fall is given and the subsequent time of fall is observed. The condition of the mine roof can impose limitations on the method's ability to sense pre-fall activity, especially if a physical separation occurs in the roof material. In addition, equipment parameters such as signal gain and transducer coupling do affect energy count and event count data response. In spite of these limitations, the microseismic method can be used as an effective method of predicting roof fall or roof failure in a coal mine environment.

4.1 Roof Fall Sensitivity

The microseismic method shows a particularly high sensitivity to changes in roof load. This is evident in every plot of the data presented in this report. Normal small changes in roof load due to coal mining are clearly seen in the data, even at distances in excess of 300 feet from the location where mining is taking place. Both energy count and event count data show the same sensitivity to changes in roof load.

One unexpected result is that energy count and event count data are very well correlated in time and magnitude. This characteristic is even maintained during periods when their respective count rates increase prior to roof fall, and is due to microseismic event amplitudes staying fairly constant during the deformation process. Increases in energy count arise from an increase in the number of events per time window, and not because the amplitude of individual events increases. This implies that the energy/event ratio peak observed prior to roof fall is due either to the duration of events increasing dramatically, or that the events are occurring at a rate which is faster than the response time of the microseismic warning system. Analysis of analog recordings of roof fall data shows that the event duration does increase dramatically just prior to roof failure.

Subsequently, there is no particular advantage in using the energy method, as opposed to the event method, to predict roof fall. In addition, the observed energy/event count ratio peak is not generated due to specific equipment limitations.

The energy count method of roof fall prediction does not always give a definitive response prior to roof fall. Out of the twenty-three roof falls documented, energy count data showed an anomalous response for only six. It appears that the energy count (and event count) method's ability to predict roof fall is a function of fall size and distance, although field results do not show this to be strictly correct. Variations in microseismic transducer/mine roof coupling and microseismic system gain may be effecting the energy count data response. Although the absolute magnitude of the energy and event count data varies from one situation to another, relative changes in the energy count data are fairly constant with respect to the increases observed in response to roof fall. Energy data normally remains below 5,000,000 counts on a one minute time window in response to non-critical roof activity. In every case where there was a response to roof fall, the energy data increased above 10,000,000 counts. This would suggest that, if the energy count method were used, a roof fall warning threshold of 10,000,000 counts would be suitable with a one minute time window.

The energy/event count ratio method does show the most consistent response to roof fall under the varying transducer coupling and gain conditions. It does seem certain that the amplitude of the energy/event ratio peak response is a fuction of fall size and distance,with fall distance having the most influence. This can, of course, be directly related to the absolute amplitude of microseismic events which, besides being a function of fall distance, is also controlled through the microseismic system's gain and threshold level settings. The ability of the microseismic system to detect the energy/event count ratio peak is due to its large dynamic range, and that the basic property of event duration increases drastically prior to a fall, even at relatively low event amplitudes.

4.2 Physical Mine Limitations

Physical changes in the mine roof or environment that affected roof fall data collection were experienced in only one mine. Physical separation of the mine roof strata in the Star Point No. 1 mine effectively blocked the mechanism by which roof fall information is transmitted to the microseismic roof fall warning system.

Even though this points out a basic limitation in the application of the microseismic method for monitoring and predicting roof fall at relatively large distances, it does not present a limitation in applying the method in the immediate vicinity of the working face. The intended application of the microseismic roof fall warning system is to monitor and warn of roof fall within a radius of approximately 25 feet of the working face. In this application, it is very unlikely that roof separation will occur between the microseismic transducer location and the section of roof that presents a danger. This, of course, assumes that the immediate roof in the vicinity of the working face will generate microseismic activity during the process of failure. There has been no indication that this will not be the case.

Other physical conditions also affect the ability to detect microseismic activity. These conditions are primarily associated with placing the microseismic transducer in contact with already highly fractured or loose material in the immediate roof. Although this problem was encountered, it was specifically associated with monitoring in old room and pillar sections where deterioration of the immediate roof had occurred over time. The problem was easily overcome by removing loose roof material and placing the microseismic transducer in contact with more competent material. No problems were observed as a result of placing the transducer in contact with various types of roof material, i.e. sandstones, coal, shales, etc., as long as the material was structurally competent to begin with.

4.3 Equipment Considerations

The realization of a practical microseismic roof fall warning technique goes hand-in-hand with instrumentation configured to meet the specific requirements of the technique. The research roof fall warning system used to collect roof fall data was designed to allow experimentation with system gain, threshold level, time window, and alarm count thresholds. In addition, various methods of transducer mounting and coupling were explored during the test program.

Transducer coupling and mounting were of the greatest concern since the transducer is the most critical part of the equipment and the "weakest link" in terms of a practical, commercial application. The telescopic pole mounting configuration did not work well. Material breaking away from coal pillar ribs and movement of mining equipment easily dislodged the transducer. Roof sag and heaving of the mine floor changes the transducer coupling pressure, which may adversely affect the data quality as well as inflict physical damage on the transducer. A roof bolt mounting assembly was fabricated, tested, and proven to be a very satisfactory solution. Since roof bolts are in all mining areas, including the area immediately around the working face, no problems are seen in the general application of the roof bolt mounting assembly.

Various transducer couplants were field tested, including silicone gels, heavy grease, plastic materials, and no couplant at all. Of the methods tried, the use of no couplant was the least effective, and a thin sheet of polyethylene plastic was found to work the best. The silicone gels and grease were too susceptible to coal dust contamination to be effective for very long, especially when the transducer was relocated frequently. Although the polyethylene plastic gave the best coupling, it should be kept in mind that results were obtainable using no couplant, and this method may be more practical for application at the working face where falls will be within 25 feet of the transducer.

Microseismic signal gains of 90 dB to 100 dB appear to be most suitable in conjunction with a 0.50 volt threshold level for event and energy counting. A signal gain of 85 dB resulted in several roof falls not being detected at ranges in excess of 100 feet at the Sunnyside No. 1 Mine's 4½-Right working section. Signal gain may well be the primary method available to control roof fall detection range. Note, however, that detection of the energy/event count ratio peak appears to be dependent upon a relationship between signal gain and voltage threshold level. The nature of the gain/voltage threshold relationship has not been studied and defined at the time of this report.

The use of a comparator to determine when energy counts and event counts exceed a critical level has been the principal method of giving a warning of impending roof fall. In view of the response to roof fall seen in energy and event count data, the use of a "warning count threshold" is a useful and workable method of predicting large roof fall at close range.

The time window or data sampling period is an important variable in the microseismic method, especially when the energy/event count ratio is used for fall prediction. In terms of energy count, the time window does not make much difference since the energy count is generated by a fixed 300 kHz clock. Increasing the time window simply allows more energy counts to accumulate. Although the event count is not equipment generated, no significant change in character will be seen in the data with different time windows except for a time averaging effect on short period variations. The character of the energy/event count ratio will, however, change significantly with longer time windows.

Much of the data obtained from field testing was obtained on a one minute time window. The energy/event count ratio peak response to roof fall is, in almost every case, not longer than one minute. Using a time window greater than one minute will have the effect of averaging or smoothing the ratio peak, dramatically reducing the amplitude and detectability of the peak response. Since the energy/event count ratio method is the most consistently reliable method of predicting the roof falls of the methods studied, it would be reasonable to conclude that the one minute time window is the most advantageous.

One of the most significant aspects of the equipment and data is that high frequency microseismic events were detected at distances of several hundred feet from the area of failure or fall. Since events are clearly associated with distant fall areas, the source of observed microseismic signals must be localized about the sensor's location and have a high sensitivity or response to dynamic stress changes in the mine's roof material. The possibility of such a highly sensitive, direct response to stress change is encouraging. However, further study is required to better define such a relationship, if indeed it exists.

4.4 Comments From Mining Personnel

A specific effort was made to acquaint mining personnel with the microseismic roof fall warning system's operation and the data results at each mine test site. It was found that miners quickly learned to interpret roof conditions and gain a high degree of confidence in the system's operation by observing the system's digital numeric readout during mining operations. This invariably lead to the miners routinely checking to see if the equipment was operating properly at the beginning of the work shift, e.g. turning "on" the system if the previous work shift had disconnected the ac line power and righting printers that were knocked over. Due to this involvement, useful input was offered by mining personnel.

The main criticism offered by the miners centered around the length of prediction time and the lack of indication of where the fall would occur. Miners uniformly agreed that they would prefer seeing fall prediction times which were less than the 5 minutes to 30 minutes experienced in the mine. They indicated that 1 minute to 5 minutes was more than sufficient and would not tend to keep mining personnel idle while waiting for the fall once an alarm was sounded.

Much stronger was their concern over not knowing where the location of the fall would be, except that it would be in a radius of perhaps 300 feet to 500 feet of the transducer's location. Although this objection can be readily understood with such large detection ranges, miners still felt that it was necessary to know the exact location of fall, even if the detection range were effectively reduced to a 25 foot radius. The key context of this criticism lies in the miners' desire for a roof fall warning system that is definitive in its analysis of hazardous roof conditions, irrespective of the miner's personal evaluation and experience.

This points out the possibility that in making a commercial system available to mining personnel, it may be viewed with too much credibility, leaving mining personnel with the concept that the microseismic roof fall warning system can relieve them of the burden of personal responsibility toward safety. Through discussion with mining personnel, the author has observed that miners very much fear making the wrong decision when production and safety considerations conflict. The working section foreman's responsibility to make the right decision for the crew is a heavy burden. The magnitude of this responsibility may have significant implications associated with how a commercial roof fall warning system is applied in practice. Hopefully, it will be viewed as a supplemental input to safety decisions, a tool for making better decisions, and not as an alternative to the miner's responsibility to act in the best interest of safety.

5.0 COMMERCIAL PROTOTYPE SYSTEM

A commercial prototype microseismic roof fall warning system was designed and constructed. The experience gained through field trials has been applied to the commercial prototype system's design, especially in regards to the implementation of the energy/event count ratio method of roof fall prediction in conjunction with the energy count method. The commercial prototype system comprises three separate functional assemblies:

- Roof Bolt Mounting Assembly
- RFW Analyzer Unit
- RFW Receiver Unit.

5.1 RFW Analyzer

The RFW Analyzer includes the roof bolt mounting assembly and the RFW Analyzer Unit. This part of the commercial prototype system is designed for portable use in the area of a coal mine working face, and is equipped with audio-visual indicators to alert mining personnel to hazardous roof conditions. No facility is made for mining personnel to access the real-time microseismic data that the unit generates and constantly evaluates for indications of roof failure. The audio-visual indicators are the unit's only interface with mining personnel.

Figure 5-1 shows the physical appearance of the RFW Analyzer's roof bolt mounting assembly. This assembly includes the microseismic transducer, transducer preamplifier, and mechanical roof bolt mounting bracket. Transducer mounting is of major importance since it has the largest single effect on performance. The consistent, repeatable transfer of microseismic energy from the roof to the transducer relies on maintaining a firm, constant contact with the roof material.

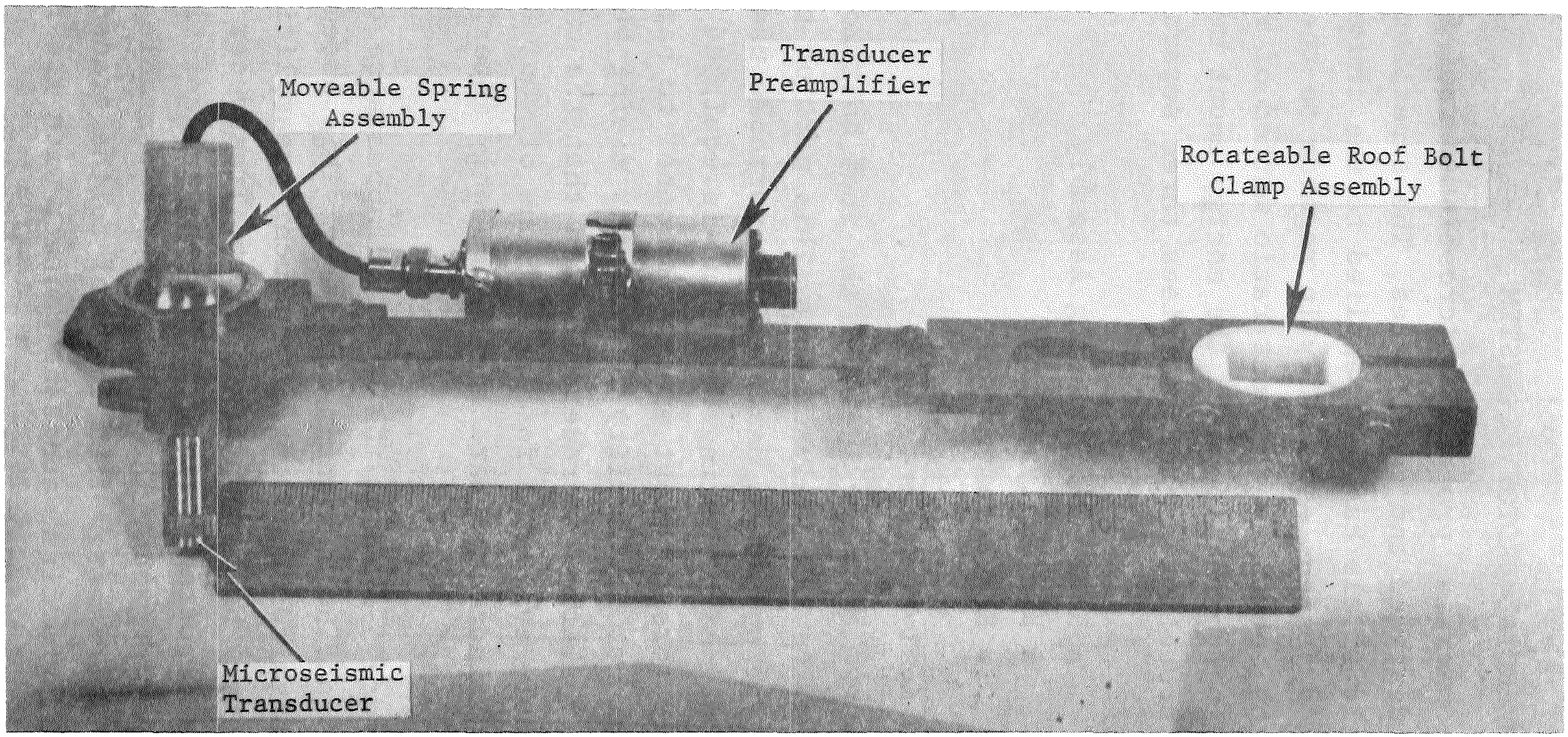

Figure 5-1. Roof Bolt Mounting Assembly

The lithium sulfate transducer senses time-varying microseismic events and converts them to an electrical signal. The electrical signals are amplified in the transducer preamplifier and transmitted to the RFW Analyzer Unit.

The design of the preamplifier is based upon a differential input and a synthesized differential output. The input circuit uses a J-FET operational amplifier arranged as a differential input. Differential performance is achieved by floating the transducer case and using it as an input terminal. This technique also reduces the potential for ground current loops. Identical operational amplifiers are used in a split configuration to provide a differential output, allowing a balanced cable input to the RFW Analyzer. The low driving impedance of this split scheme permits driving cable lengths up to 500 feet. The preamplifier has 40 dB voltage gain and operates from a $\pm$6 volt supply located in the RFW Analyzer. The frequency response of this preamplifier is dc to 250 kHz ($\pm$3 dB).

The RFW Analyzer Unit consists of four individual, yet fully integrated, compatible sections. Each one of these sections performs a specific function in obtaining energy and event count data, processing the data, and alerting mining personnel to dangerously high roof stress, or warning of impending roof failure. The four sections consist of:

1. Analog Section: The primary purpose of the analog section is to filter, amplify, and condition microseismic events in such a way that both the energy and event count data can be generated and formatted for input to the microprocessor section.
2. Microprocessor Section: The microprocessor section analyzes data trends and indicates whether a roof alert or fall warning condition has occurred, and activates the audio-visual indicators accordingly.

3. Transmitter Section: The transmitter section transmits the alert and warning signals to the mobile RFW Receiver Unit located on a miner's person. This device warns the miner that an alert situation exists, where high stress has developed in the roof and the probability of a roof fall occurring in the not too distant future is significant; or, that a warning situation has occurred and roof failure is imminent.

4. Battery Power Supply: The battery section consists of a ± 6 volt supply used to power the other three sections.

Figure 5-2. shows the physical appearance of the RFW Analyzer Unit with the front cover removed and the functional modules partially extended. The RFW Analyzer Unit is designed with strict attention to maintaining environmental integrity of the electrical circuits from moisture and coal dust contamination. Figure 5-3 illustrates the RFW Analyzer's function organization in block diagram form.

Analog Section

The analog module consists of several operational amplifier circuits, each accomplishing a small segment of the total operation. The input operational amplifier accepts a differential signal with frequencies from dc to 250 kHz. Input offset correction and wideband response precondition the signal for an initial gain of 40 dB. Successive amplifiers combine filtering and variable gain functions with a resulting bandwidth of 36 kHz to 100 kHz. Operational amplifiers were selected for low noise applications with the upper end roll-off of the response spectrum being a function of the amplifier's slew rate and gain-bandwidth product. Three additional operational amplifiers, as a true cascaded amplifier section, produce the remaining 20 dB of signal gain.

The microseismic event signals are then rectified and

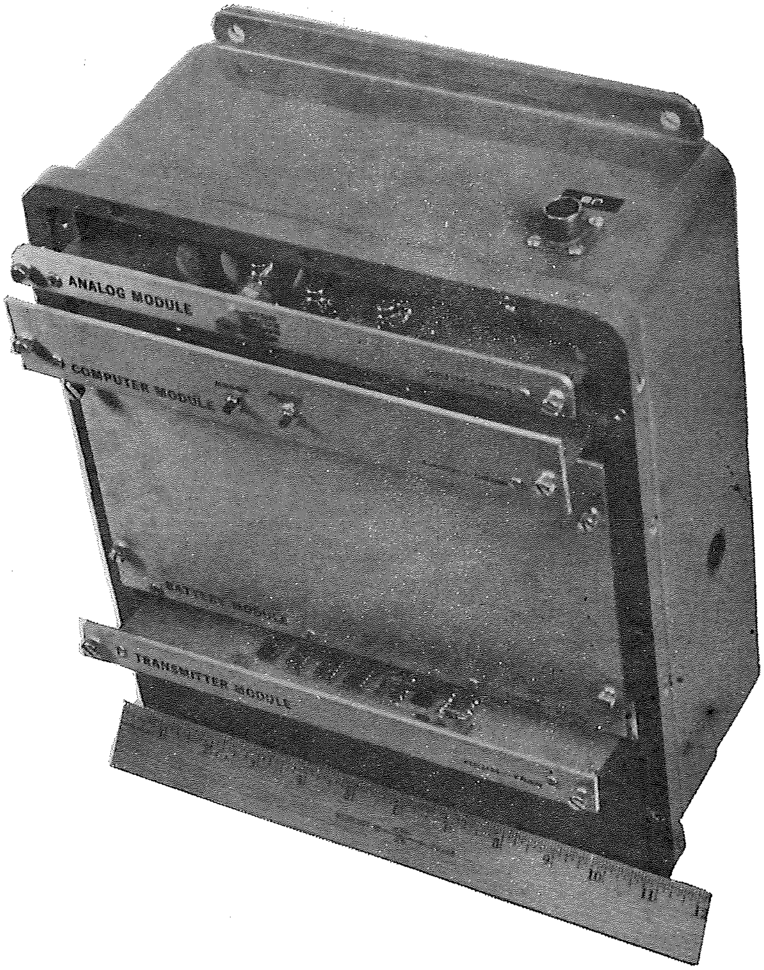

Figure 5-2. RFW Analyzer Unit with Cover Removed and Functional Modules Partially Extended.

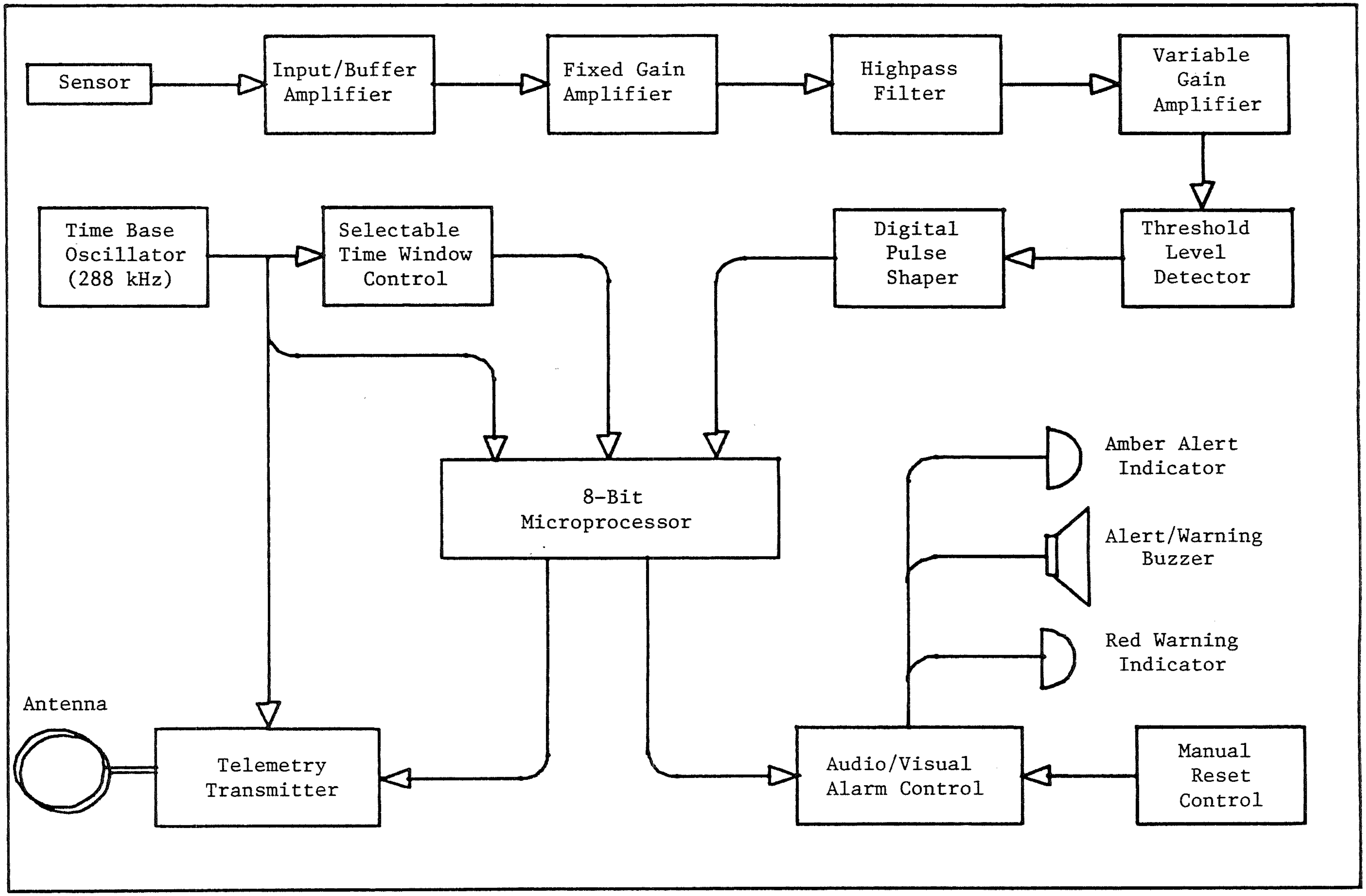

Figure 5-3. RFW Analyzer Functional Block Diagram

envelope detected. The last amplifier provides a means of selecting a predetermined threshold level. Operating as a variable level comparator, this amplifier provides a dc output signal each time the microseismic event's envelope exceeds the preselected voltage level.

Microprocessor Section

The microprocessor section processes the output of the analog section. A Schmitt trigger circuit is used to speed up the threshold detector's output rise and fall time, thereby generating a well defined signal to enable the digital counters. Two counters are cascaded and accumulate the microseismic event count over a preselected time window, i.e. how many times the threshold has been exceeded.

Three other counters are cascaded and clocked with a 288 kHz oscillator. These counters count the clock pulses when enabled by the threshold detector. This generates the energy count and is proportional to the energy of the microseismic events relative to the preset threshold level. The choice of a 288 kHz clock rate over the previously used 300 kHz clock rate is strictly a matter of convenience in hardware design. The 288 kHz oscillator is more suitable for generating several other important circuit timing references by binary division than is the 300 kHz oscillator reference.

The microprocessor acquires energy and event count data from the input counters every 15 seconds and stores it internally. At the end of the selected time window, the microprocessor analyzes the microseismic data. A rapidly increasing energy count trend initiates an alert; a subsequent decreasing trend initiates an alarm. For example, if, and only if, the energy count level is greater than or equal to the alert set count (EM1) for five consecutive time windows, an alert will be issued which indicates high roof stress (see Figure 5-4). At the end

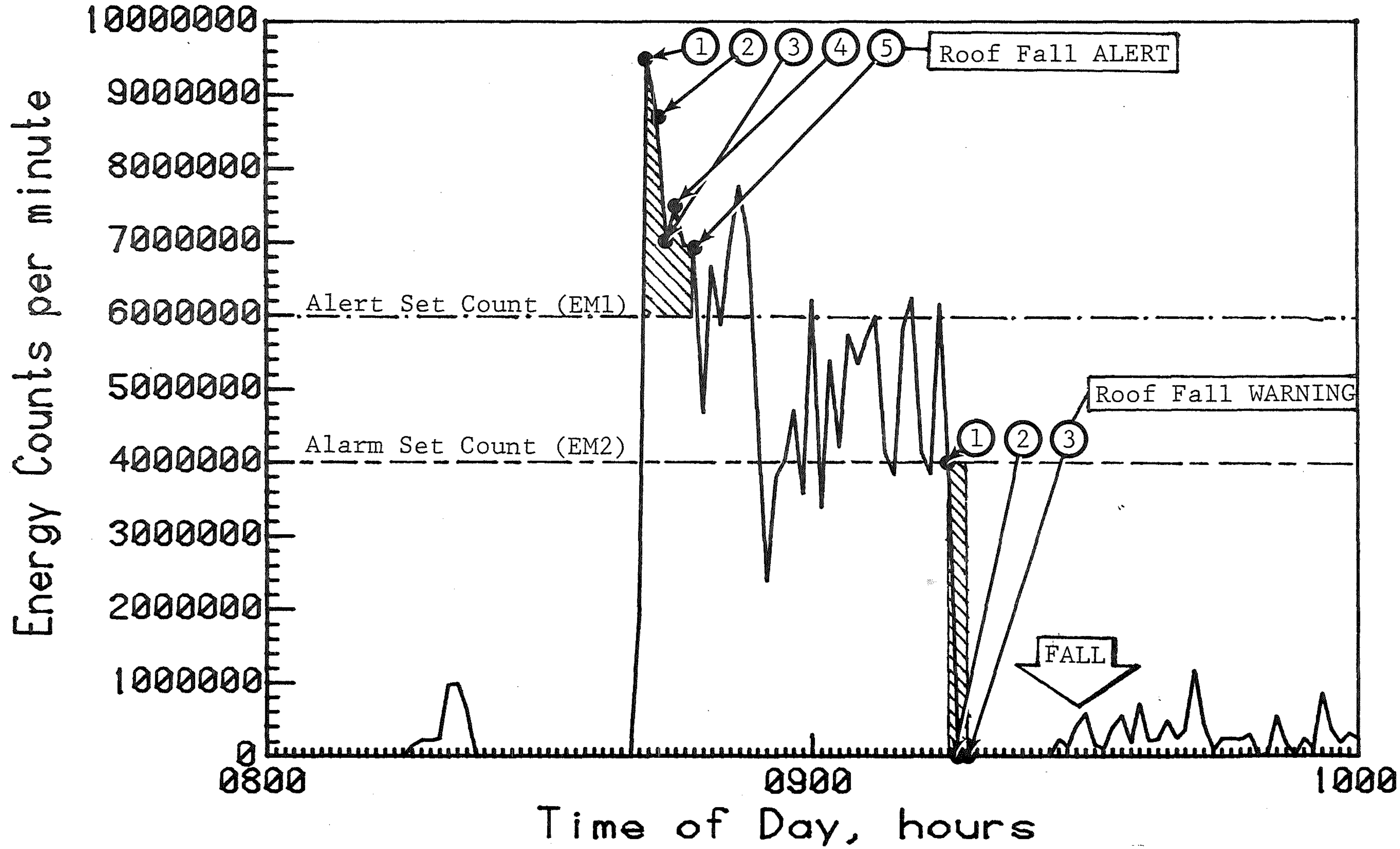

Figure 5-4. Roof Fall Alert and Warning Trend Analyzer Concepts.

of each time window the microprocessor also computes the energy/event count ratio. If the ratio equals or exceeds 1500, a roof fall warning command will be automatically issued regardless of the status of energy count data. Issuance of an alert or warning command will simultaneously activate the telemetry transmitter and the proper front panel indicators.

Transmitter Section

Upon acknowledgement of a roof fall alert or warning condition, the telemetry transmitter section commences to inform the RFW Receiver. Transmitter operations are performed in two distinct and individual modes:

(1) The alert mode consists of a 1 second transmission of a series of five 50 msec. pulses spaced 175 msec. apart with the fourth pulse blanked. After a 15 second delay, the sequence is repeated. The sequence again is repeated for a third time after another 15 second delay. At the time of the first transmission, the amber alert light and horn on the RFW Analyzer are activated at a 2.2 Hz rate. The horn may be deactivated by pushing the manual reset button. The light will continue to operate and will extinguish only when an alarm transmission is activated. This indication stays on as a reminder that a high roof stres condition exists.

(2) The warning mode information is transmitted the same as an alert except that the third pulse is blanked instead of the fourth. At the time of the first transmission, the amber alrt light is turned off; the red warning light and horn are then activated at a 4.4 Hz rate. Both the warning light and the horn may be disabled by pushing the manual rest button.

If the horn, activated by either mode, is not turned off within 20 minutes, the transmitter section will turn it off automatically in order to conserve power.

The transmitter section also monitors battery voltage. If this voltage drops below an acceptable level, the transmitter will automatically activate the horn and both lights for 1 second every 30 seconds to remind mining personnel that system maintenance is required.

The transmitter circuits use a new type component, a VMOS power FET in a parallel configuration. This device combines the speed of SCR's, low drive requirements of CMOS, and the current capability of power transistors. VMOS has a negative temperature coefficient, providing a degree of automatic output load compensation. The circuit performs as an analog gate SCR with the capability of being driven directly from digital CMOS components. To conserve power, the transmitter is operated on a 10% duty cycle.

5.2 RFW Receiver

The RFW Receiver is a companion unit of the RFW Analyzer that permits key mining personnel to move about the working face area and still keep in personal contact with the commercial prototype system's roof fall warning capability. The RFW Receiver is a small unit, comparable in size to a pocket calculator, that is designed to be carried in a miner's shirt pocket or attached to a waistband or belt. The unit's primary function is to provide audi-visual indications of roof instability or fall potential in a highly portable package. Audio-visual indicators are activated via low frequency telemetry commands from the RFW Analyzer.

The RFW Receiver, shown next to the RFW Analyzer in Figure 5-5, contains all the electronic circuitry necessary to receive telemetry transmissions from the RFW Analyzer, decode the digital commands, and activate the appropriate audio-visual devices. Figure 5-6 illustrates the RFW Receiver's functional organization.

The small, ferrite-core antenna receives telemetry signals from the RFW Analyzer. These command signals are amplified in a self-resonating high gain input amplifier. Additional signal gain is provided prior to bandpass filtering

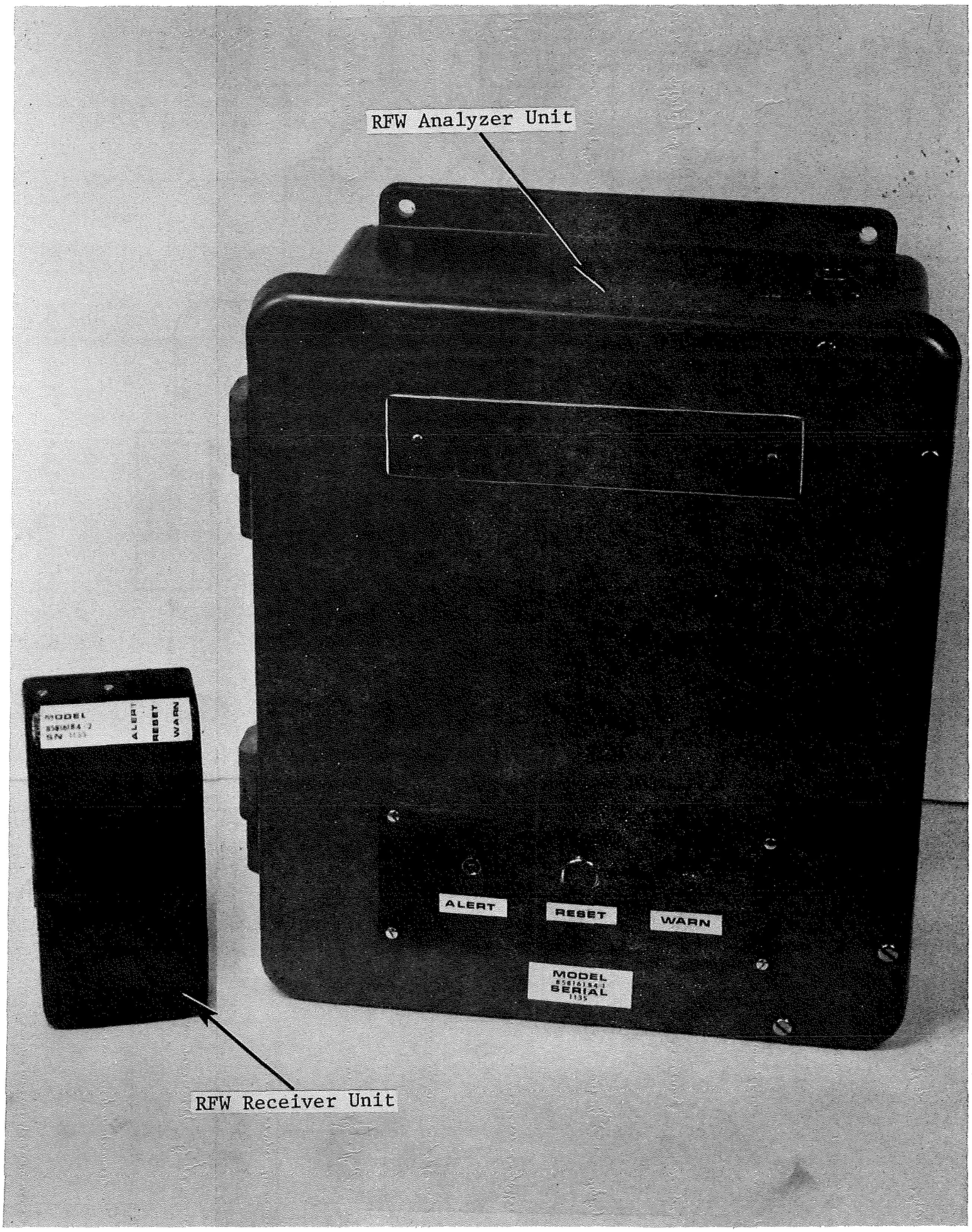

Figure 5-5. Mobile RFW Receiver Unit and RFW Analyzer

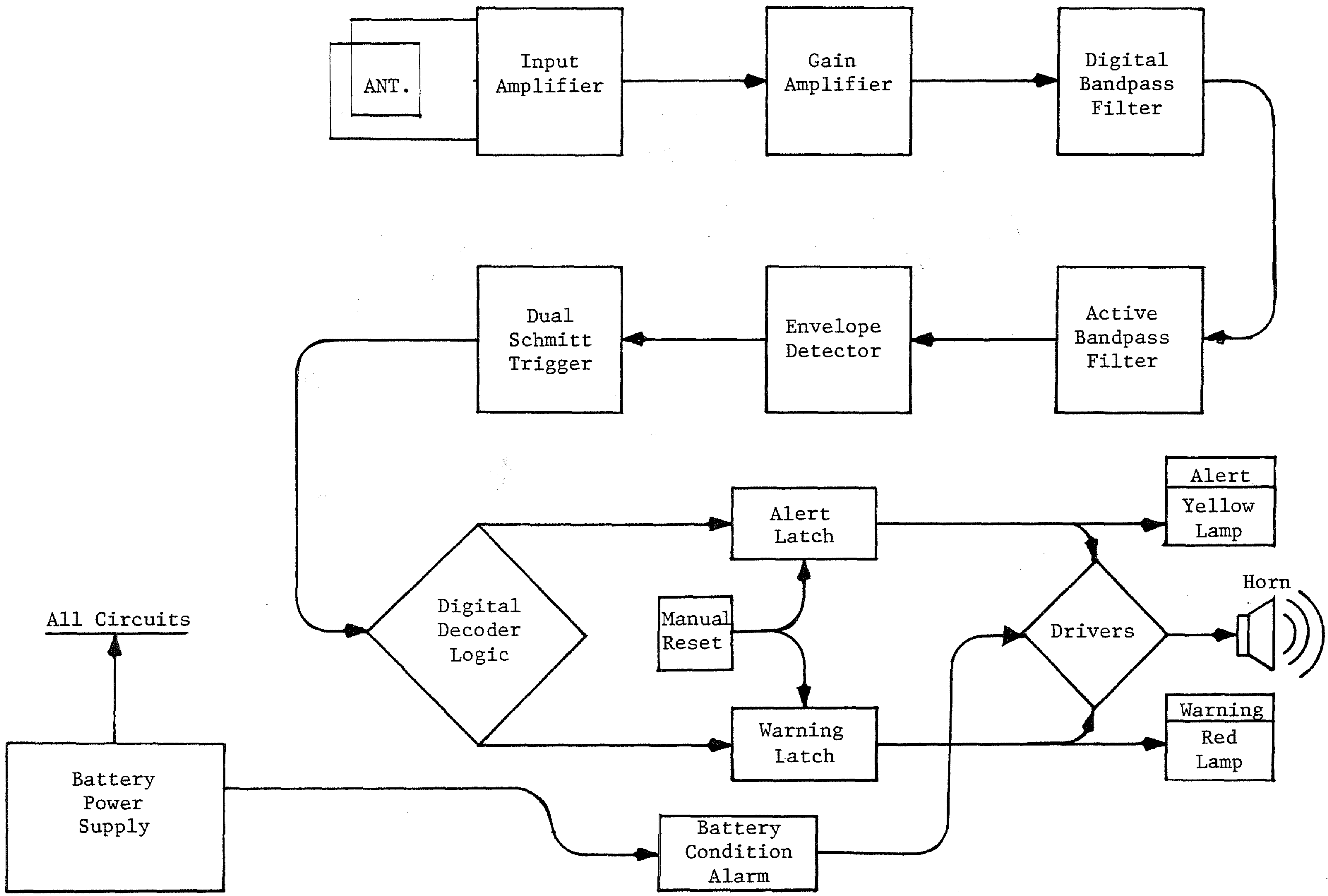

Figure 5-6. RFW Receiver Functional Block Diagram

in the next two operational amplifiers. A digital bandpass filter filters out unwanted frequencies quite effectively, having a Q of approximately 500. A second active bandpass filter stage provides further filtering and gain to compensate for losses in the digital filter.

Two additional operational amplifiers are used to rectify and envelope detect the signals. A Schmitt trigger receives the output of the envelope detector and speeds up the rise and fall times, thereby generating a well defined digital event.

The received digital events are continually decoded by serially inputting them into a 4-bit serial-in/parallel-out shift register. The parallel information is monitored continually to determine if the proper codes have been received in a predetermined time period. If the proper alert or warning codes are detected, the appropriate alert or warning indicators are activated. For example, if an alert code is received, the unit activates the amber light and buzzer at a 2.2 Hz rate; if a warning code is received, the red light and buzzer are activated at a 4.4 Hz rate. Pushing the manual reset button turns off the lights and buzzer.

The RFW Receiver also monitors its own battery voltage. If this voltage drops below an acceptable level, the unit automatically sounds the buzzer and flashes its lights for 100 msec. every 12 seconds to remind mining personnel that maintenance is required.

5.3 System Specifications

<u>Microseismic Transducer</u>

Type:	Lithium Sulfate
Frequency Response:	10 kHz to 200 kHz ($\pm$3 dB)
Acceleration Sensitivity:	89 mv/g.

Transducer Preamplifier

Physical Dimensions:	4" x 2" dia.
Weight:	3 oz.
Power Requirements:	$\pm$6 vdc.
Frequency Response:	dc to 250 kHz ($\pm$3 dB)
Signal Gain:	40 dB

RFW Analyzer

Physical Dimensions:	6" x 12" x 14"
Weight:	24.5 lbs. (including battery pack)
Power Requirements:	$\pm$6 vdc.
Frequency Response:	36 kHz to 100 kHz ($\pm$3 dB)
Signal Gain:	Selectable 60 dB to 90 dB
Event Threshold Level:	Variable 0.1 to 1.0 vdc.
Energy Count Threshold:	
Alert (EM1)	Variable 5 x 10^6 to 18 x 10^6
Warning (EM2)	Variable 15 x 10^6 to 4 x 10^6
Time Window:	1 to 10 min.
Count Range:	
Event	0 to 999,999
Energy	0 to 17,280,000
Battery Life:	170 hours (rechargeable)

RFW Receiver

Physical Dimensions:	3" x 6" x 1.5"
Weight:	0.5 lb.
Power Requirements:	$\pm$9 vdc.
Signal Gain:	80 dB
Receiver Frequency:	2250 Hz
Bandwidth:	4 Hz ($\pm$3 dB)
Operating Range:	50 ft. (min.)
Battery Life:	250 Hours (non-rechargeable)

6.0 RECOMMENDATIONS

There is no doubt that the results of this effort support a recommendation to continue further development and field testing of a commercial prototype roof fall warning system. The commercial prototype system has not been field tested in either Western or Eastern coal mines in the United States.

A program to field test the commercial prototype system in mining conditions similar to those under which this effort was performed is recommended. This will, at least initially, substantiate the commercial prototype's design concepts under conditions for which a partial data base has been developed. Roof fall data collection in conjunction with the commercial prototype system's field testing would provide an invaluable aid in documenting the system's performance, as well as broaden the data base.

During the course of the data collection effort, over 680,000 data elements were obtained and manually entered into an interactive computer system for evaluation. As a result of data collection system improvements that reduced equipment down-time, the practice of manual data transfer for processing rapidly became impractical both in terms of cost and labor. Subsequently, it is recommended that the research microseismic roof fall warning system be modified to incorporate a magnetic tape cartridge recording capability which is directly compatible with small interactive computing systems.

A clear determination of the relationships between equipment parameters such as signal gain, voltage threshold level, and transducer coupling, with roof fall detection range and prediction time was not achieved during the reported field test effort. Further research should be more specifically directed at defining these relationships and implementing any improvements in the commercial prototype system dictated by the results.

Roof fall data was obtained for relatively large roof falls that resulted from retreat mining or pillar extraction in coal mines. Although this data is significant and useful in developing confidence in the roof fall system's capabilities, it is not truly representative of the roof fall characteristics known to cause fatalities in coal mines. Almost all roof fall related fatalities are associated with roof fall whose volume is less than 10,000 cubic feet, and within 25 feet of a working face. A "small fall" field program should be iniated to run in parallel with the prototype system's development to allow long term (3 to 5 years) data collection in a single, roof fall prone mine. This would provide a data base to close the gap between exploration of the technique's fall prediction capabilities and the practical, user related equipment development effort.

The microseismic roof fall warning system developed as a result of this effort has a great potential for successful commercial application in underground mines. No other method or technique being researched at present has shown such a strong positive correlation with roof fall or the potential for practical hardware implementation that meets the requirements for MSHA permissibility approval. With further research and development, the microseismic roof fall warning system can provide the mining industry with a practical and important method of preventing human tragedy and economic loss due to roof fall.

MICROSEISMIC ROOF FALL WARNING SYSTEM DEVELOPMENT

Field Trials and Commercial Prototype Fabrication

APPENDIX A: Analog Data Recording at Sunnyside No.1 Mine

1.0 INTRODUCTION

Analog signal recordings of microseismic roof fall data were made in the Kaiser Steel Corporation's Sunnyside No. 1 Mine on March 21, 1979. Magnetic tape recording equipment was installed in the mine's 4½-Right working section and operated during pillar extraction. Microseismic roof fall data in the 15 kHz to 100 kHz frequency range were obtained for two roof fall, including pre-failure, failure, and post-failure periods.

Data playback and analysis indicates that the microseismic event character displays three specific modes which may be used to uniquely define the dynamic process of roof deformation and failure. These modes are themselves characterized by event duration, frequency components, and frequency sweeping characteristics. In particular, microseismic events with durations of from 5 msec. to 20 msec. and frequency components greater than 45 kHz are observed just prior to roof failure.

One of the most important results was that no appreciable travel time could be seen from simultaneous recordings of microseismic events at various distances from a fall area. Although more testing is required to confirm this result, it does indicate that the source mechanism for such events may be other than the normally assumed propagation of elastic waves from a single failure or crack within the fall area.

The main conclusion is that a continuous emission type microseismic event does exist and forms the basis for the microseismic energy/event count ratio peak observed in data obtained with the BuMines microseismic roof fall warning system. Secondly, roof failure would be more precisely and uniquely determined using microseismic instrumentation with a flat high pass frequency response of 45 kHz to 100 kHz and employing the energy/event count ratio method of roof fall prediction.

2.0 RECORDING EQUIPMENT

Microseismic roof fall data was recorded on a multi-channel magnetic tape recorder located in the 4½-Right working section of the coal mine. Lithium sulfate type transducers were used to detect microseismic events in the frequency range of 10 kHz to 250 kHz. The transducer's output was amplified by a 40 dB gain preamplifier and transmitted over twisted-pair cables to the recording location. Variable gain buffer amplifiers were used to adjust microseismic event amplitudes to levels suitable for input to the magnetic tape recorder.

The magnetic tape recorder used a 1 inch tape and provided 14 independent channels for recording. Three channels were used to record microseismic events from lithium sulfate transducers located approximately 50 feet apart and in a direction which was away from the potential roof fall area. A digitally coded time-of-day encoder was used to establish an accurate time reference and was recorded on a fourth channel. The magnetic tape recorder was operated at a recording speed of 15 inches per second to reduce the number of times data recording would have to be interrupted to change tapes. This resulted in the recorder having a rather limited dynamic range of 20 dB and a flat frequency response of 15 kHz to 100 kHz.

Figure A-1 shows the recording equipment located in the mine. The multi-channel tape recorder is shown at the left-center of the photograph.

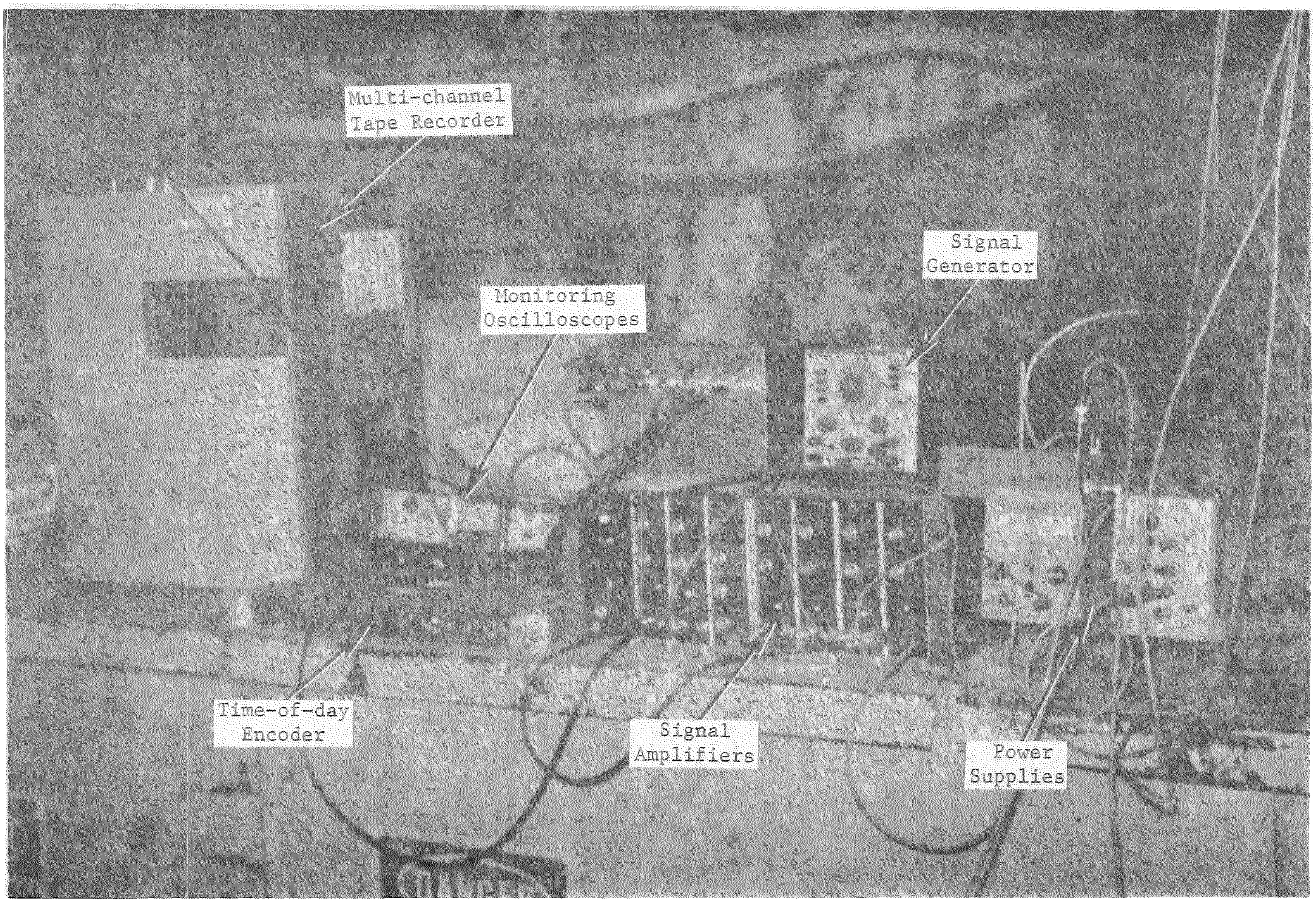

Figure A-1. Analog Microseismic Recording Equipment in the Sunnyside No. 1 Mine.

3.0 RESULTS

Two roof falls occurred in the mine during acquisition of analog data recordings.* The two falls occurred at 1407 and 1418, respectively, on March 21, 1979. For the purposes of this report, data is shown and discussed which is related to the fall at time 1407 only, since similar data characteristics were observed for both falls.

The data discussed was recorded from a microseismic transducer 140 feet from the roof fall location. Both time and frequency plots of microseismic events were obtained by playing back the recorded roof fall data through a digital, fast fouier transform analyzer and plotting the results using a digital x-y plotter. Figure A-2 illustrates the plot formats used for data presentation and discussion.

All the data plots presented in this section show an "I.D. Number" in the lower left hand corner of the time and spectrum plots. This I.D. Number gives the relative order in time of the microseismic signals as the time of fall is approached. Since the intent is to illustrate the different microseismic event characteristics that are observed as the time of fall approaches, no attempt has been made to secure data plots that are equally spaced in time between samples, although the plots are arranged in order of progressing time of day.

Three distinct types of microseismic events were observed prior to the time of fall. The most common event character observed is the pulse type that appears to be associated with non-critical roof stress build up and release. Figures A-3 through A-9 illustrate the various types of non-critical pre-failure event pulses observed.** These microseismic events are typically 25 μsec to 50 μsec in duration and are primarily made up of frequency

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* See Section 3.4 Sunnyside No. 1 Mine, Roof Falls, March 21, 1979, for a more detailed description.

** Note that a 25 kHz highpass filter was used to remove low frequency components during data playback and plotting.

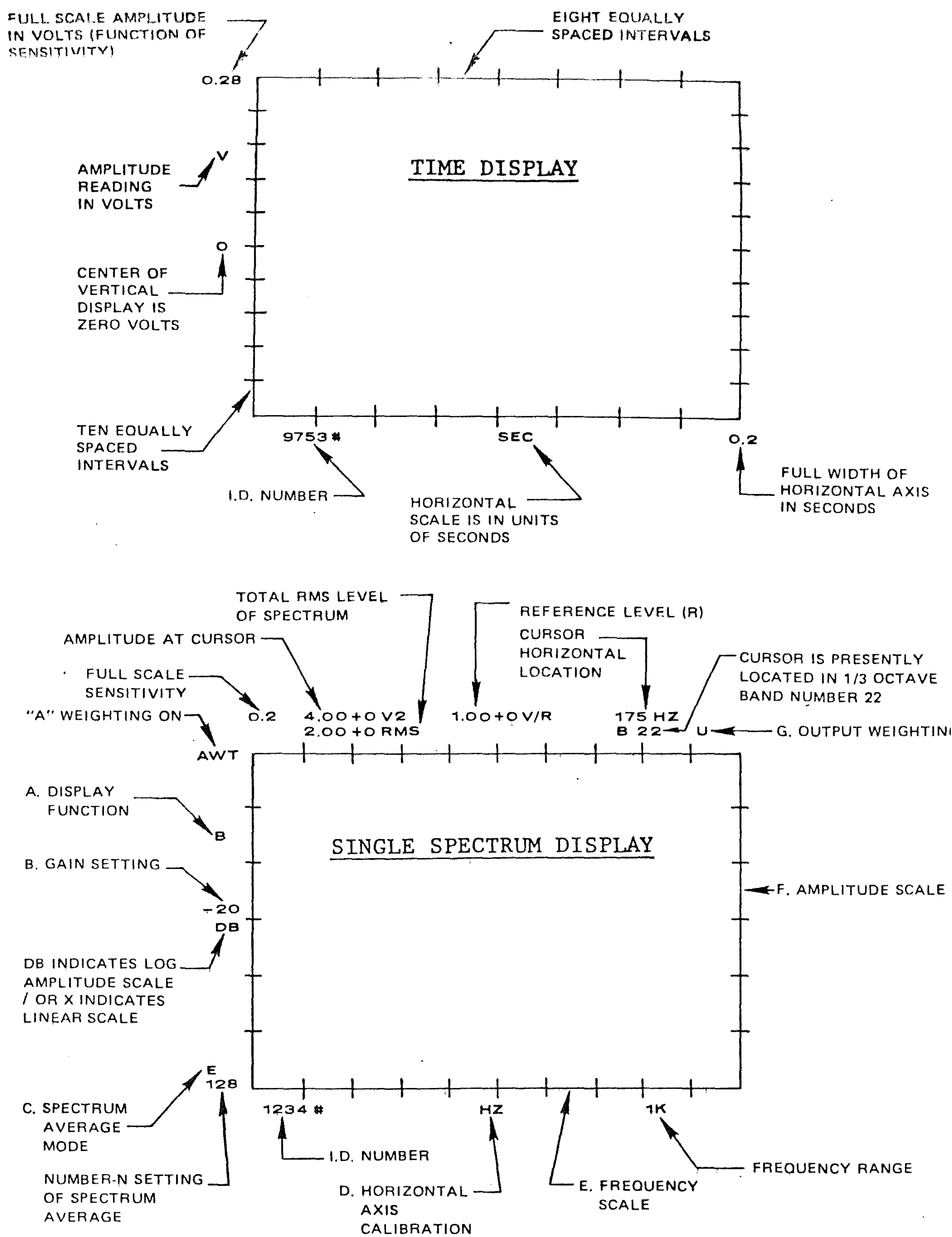
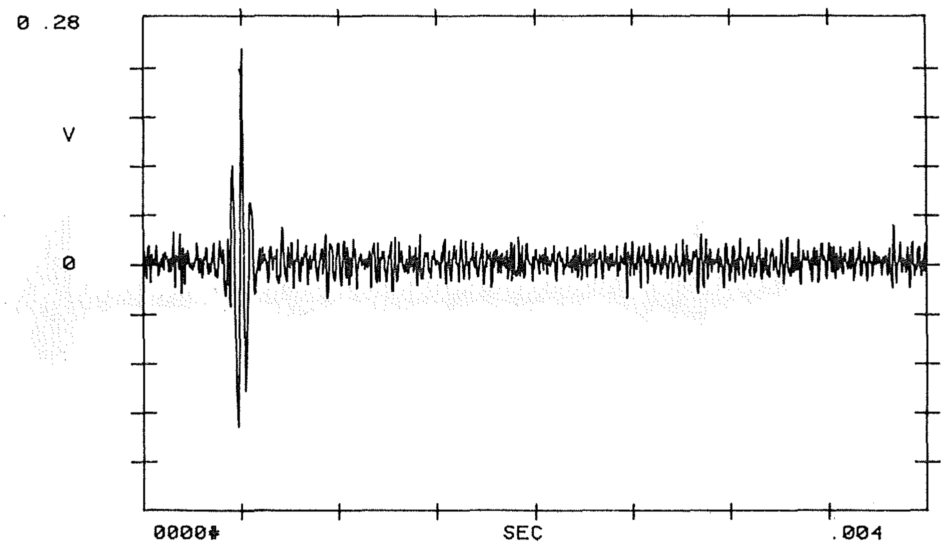
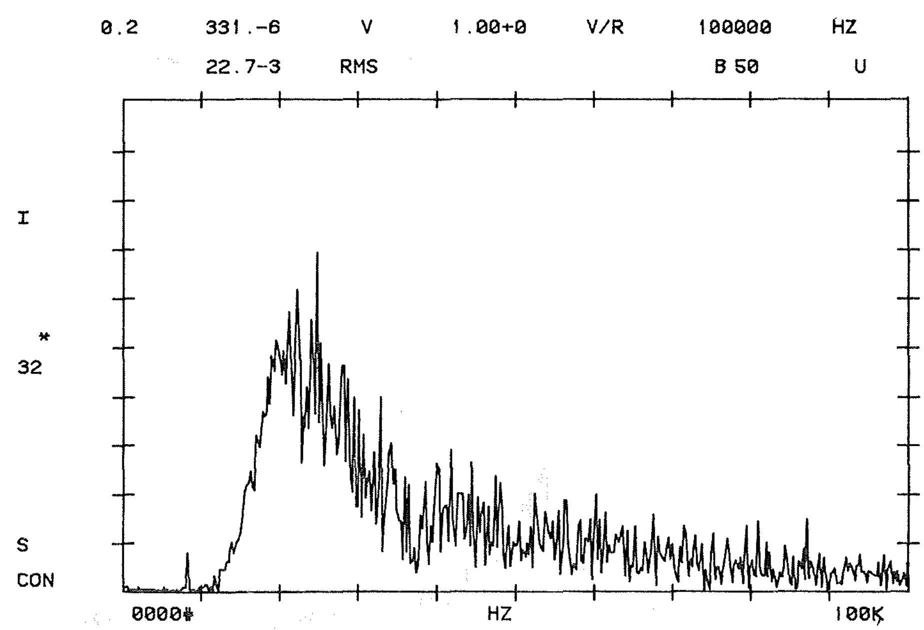


Figure A-2. Microseismic Event Data Plot Format

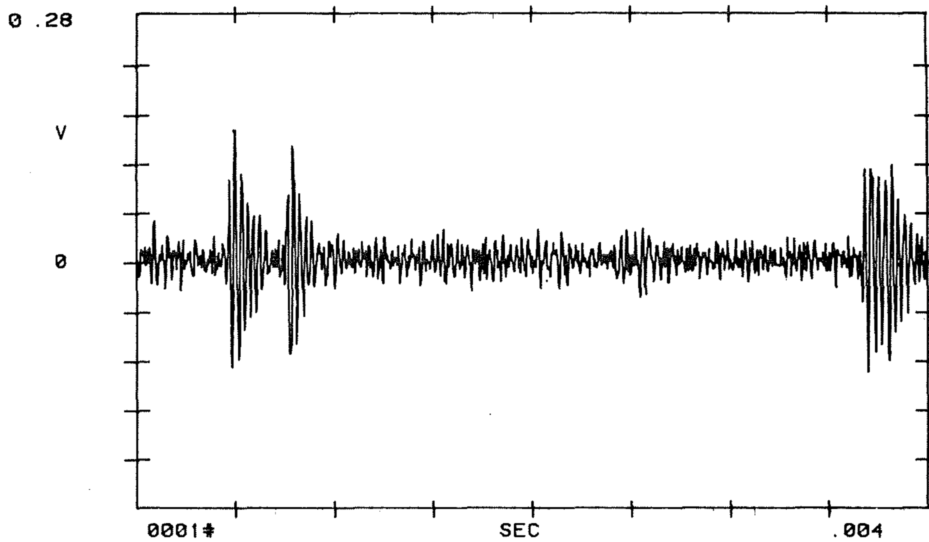


a. Amplitude vs. Time Plot

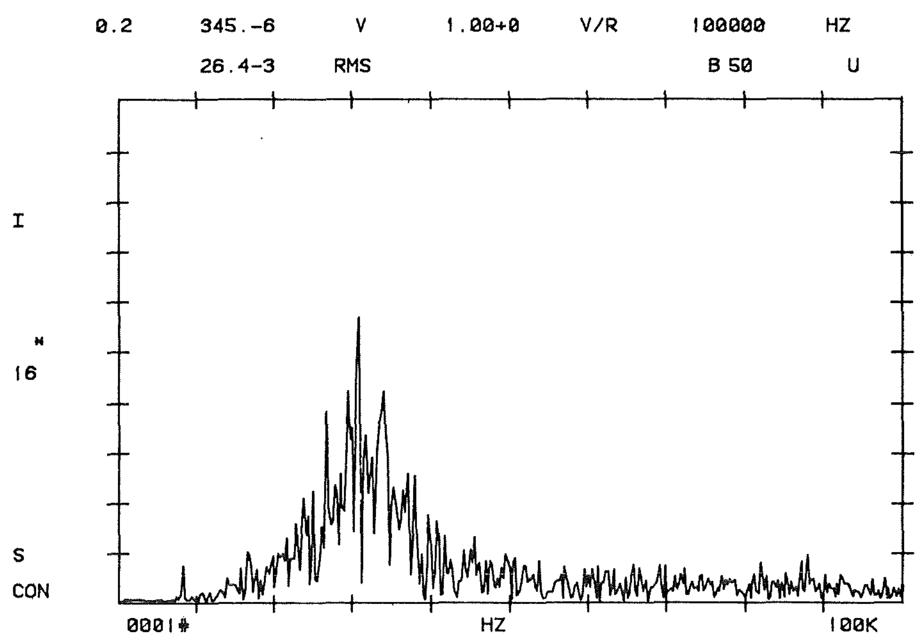


b. Amplitude vs. Frequency Plot

Figure A-3. Microseismic Event - Pre-Failure Pulse Data

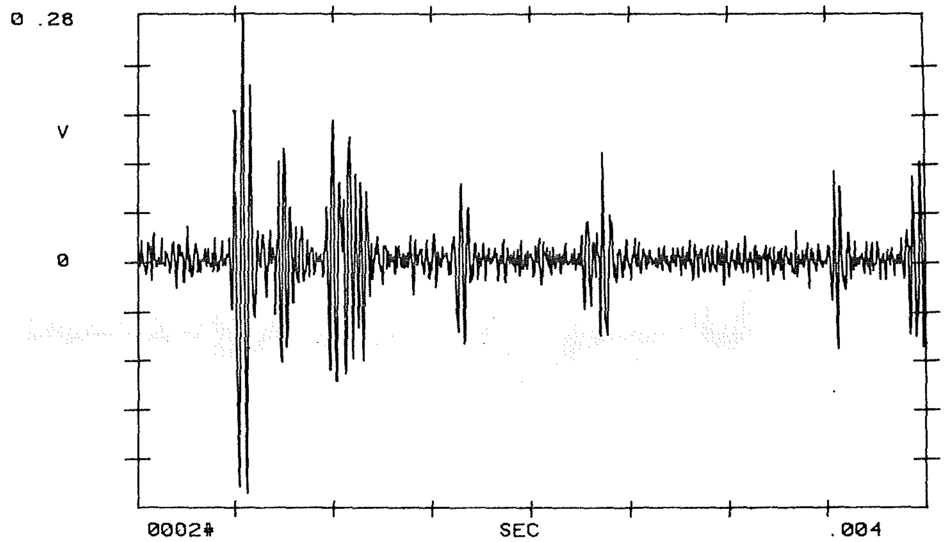


a. Amplitude vs. Time Plot

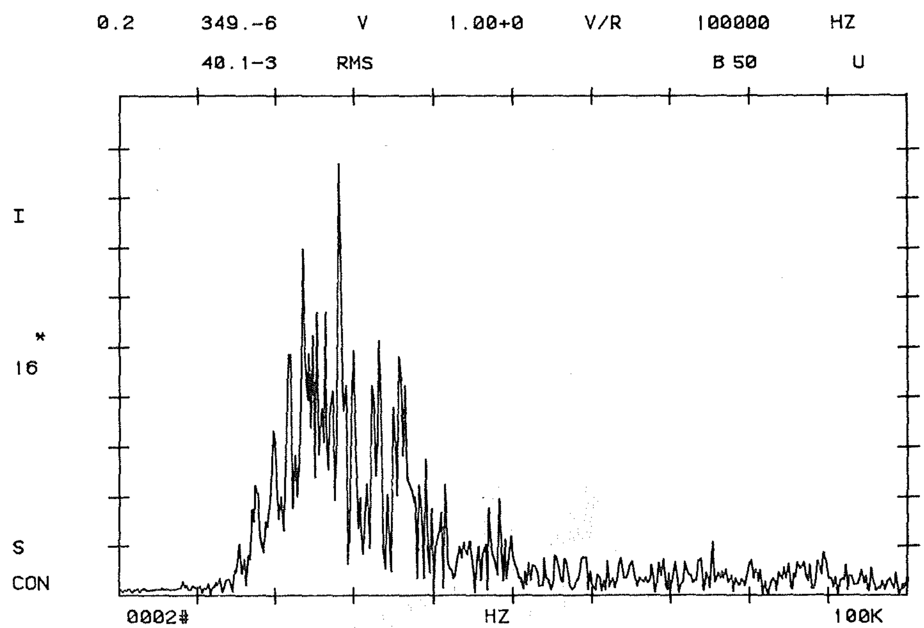


b. Amplitude vs. Frequency Plot

Figure A-4. Microseismic Event - Pre-Failure Pulse Data

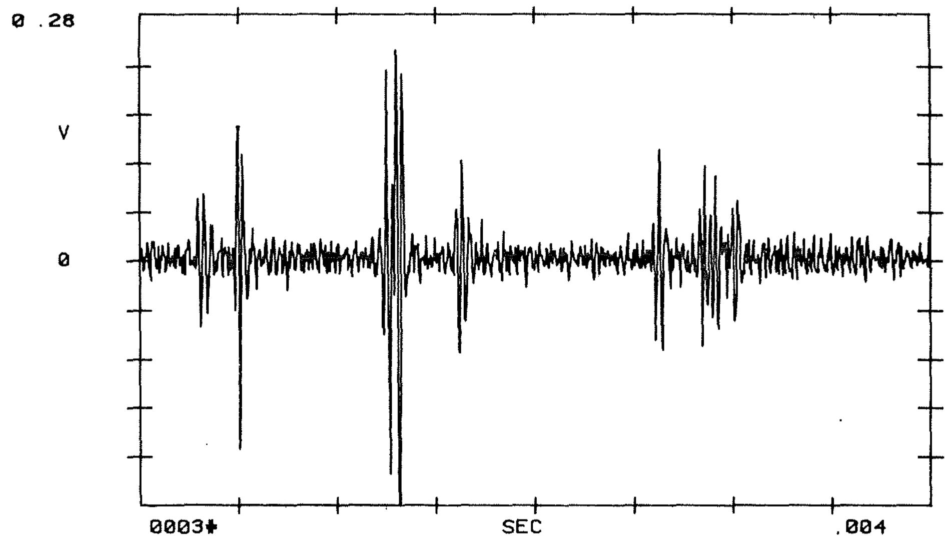


a. Amplitude vs. Time Plot

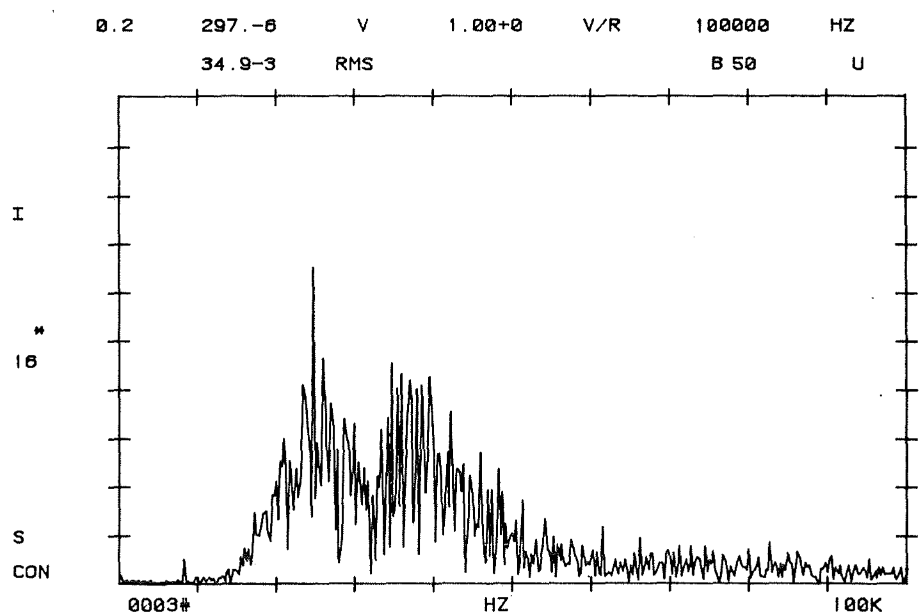


b. Amplitude vs. Frequency Plot

Figure A-5. Microseismic Event - Pre-Failure Pulse Data

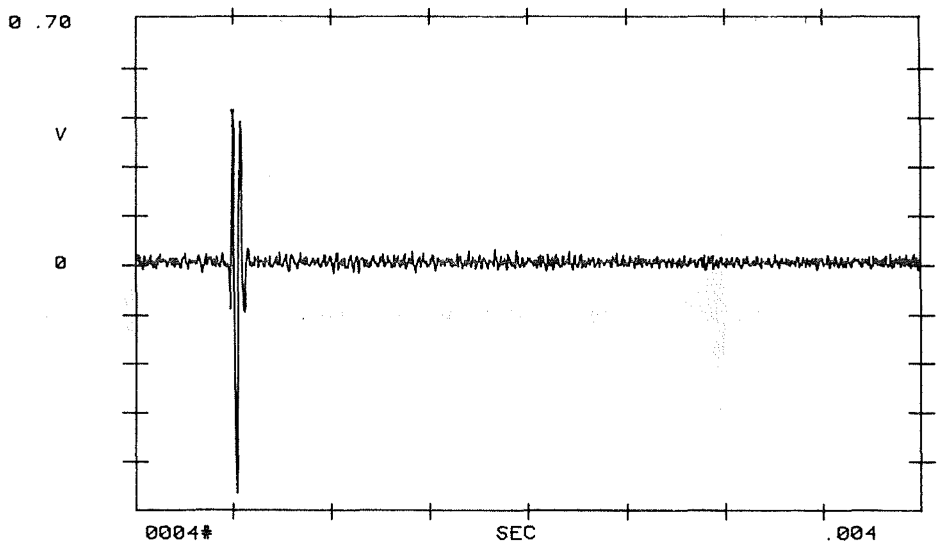


a. Amplitude vs. Time Plot

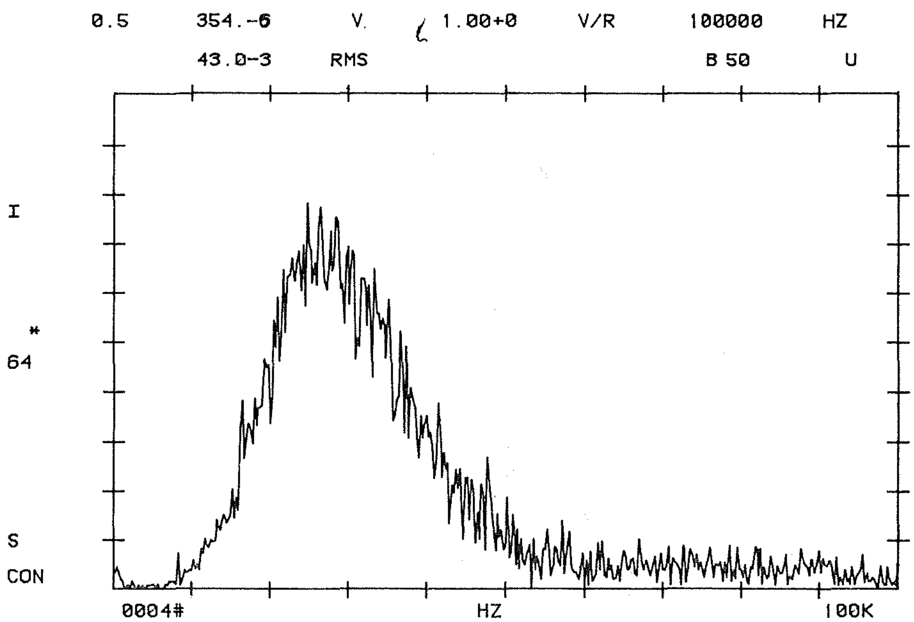


b. Amplitude vs. Frequency Plot

Figure A-6. Microseismic Event - Pre-Failure Pulse Data

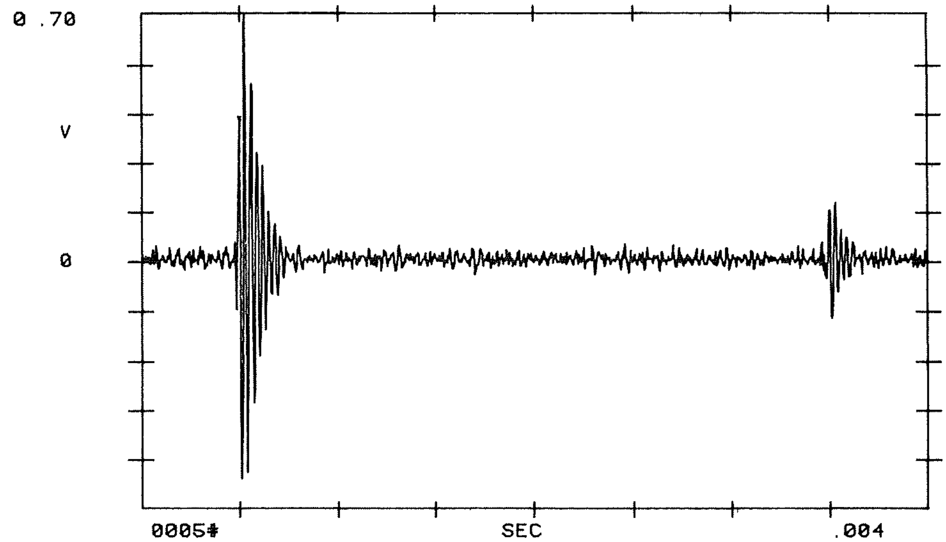


a. Amplitude vs. Time Plot

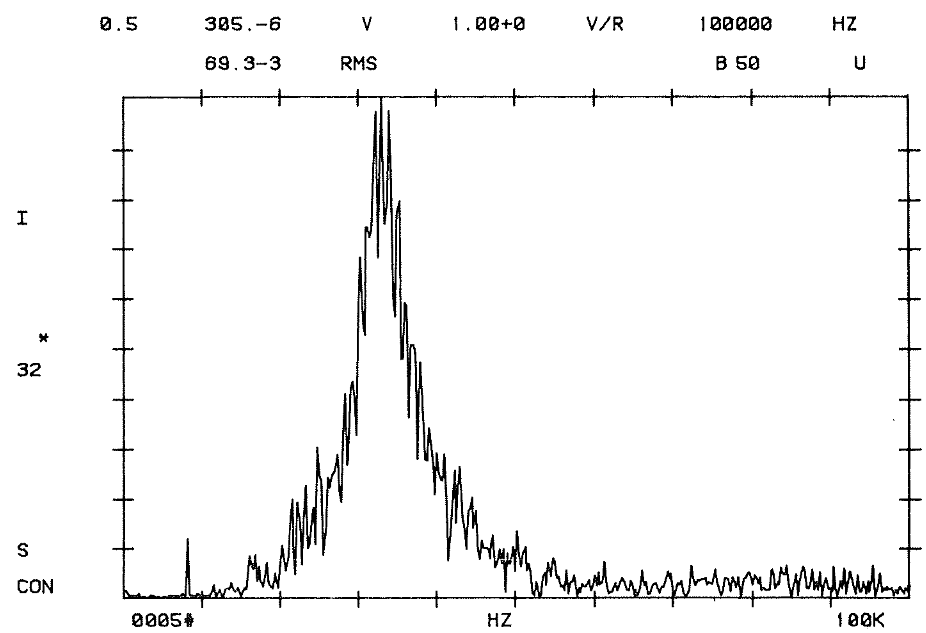


b. Amplitude vs. Frequency Plot

Figure A-7. Microseismic Event - Pre-Failure Pulse Data

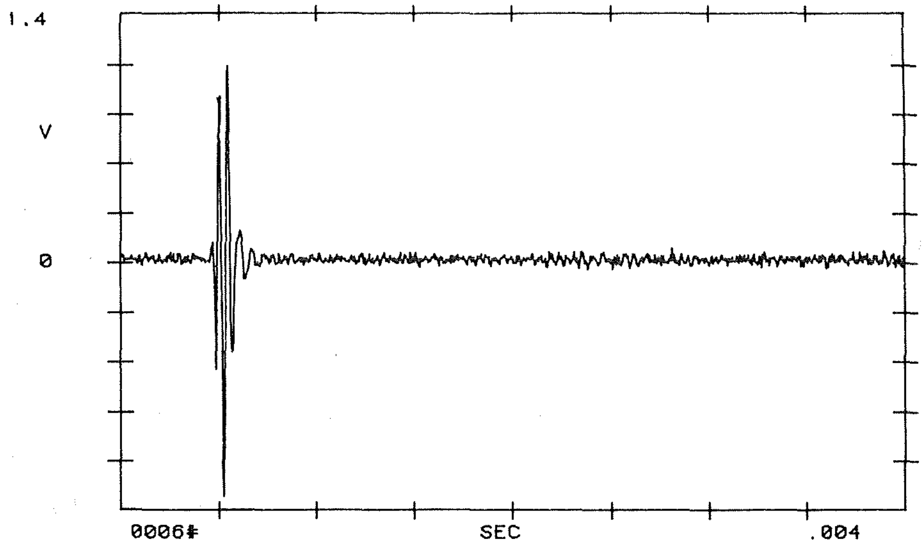


a. Amplitude vs. Time Plot

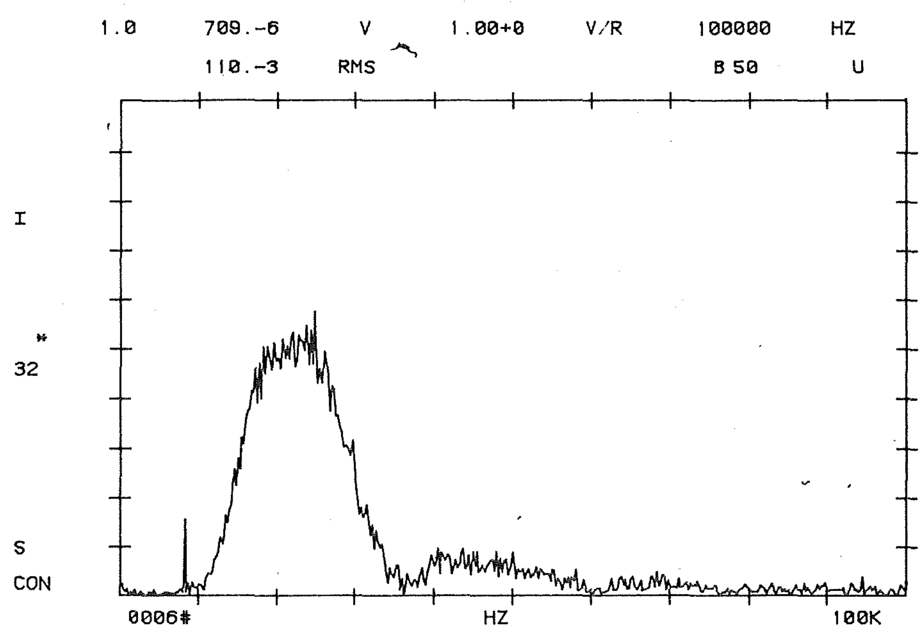


b. Amplitude vs. Frequency Plot

Figure A-8. Microseismic Event - Pre-Failure Pulse Data



a. Amplitude vs. Time Plot



b. Amplitude vs. Frequency Plot

Figure A-9. Microseismic Event - Pre-Failure Pulse Data

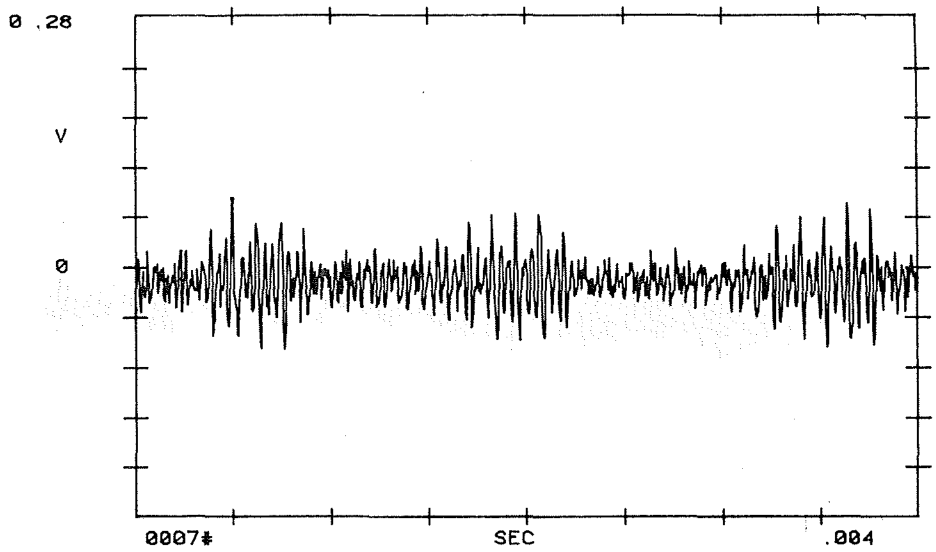
components of less than 40 kHz. Literally thousands of these events are observed over about a one hour period. In comparison with the microseismic roof fall warning system's energy/event count ratio data using a 300 kHz reference for energy count, the time duration of these event pulses would correspond to an energy/event ratio of from 75 to 150. This is consistent with microseismic data collected during the field test program.

It is interesting to note that the amplitude of events does tend to increase with time as the second major type of events approaches. In addition, a slight increase in the frequency is observed as a function of time. Once the second type of microseismic event begins to occur, the short duration events all but disappear with only a few isolated pulses being observed. Figures A-10, A-11, and A-13 illustrate the basic character of the second major type of microseismic events observed.

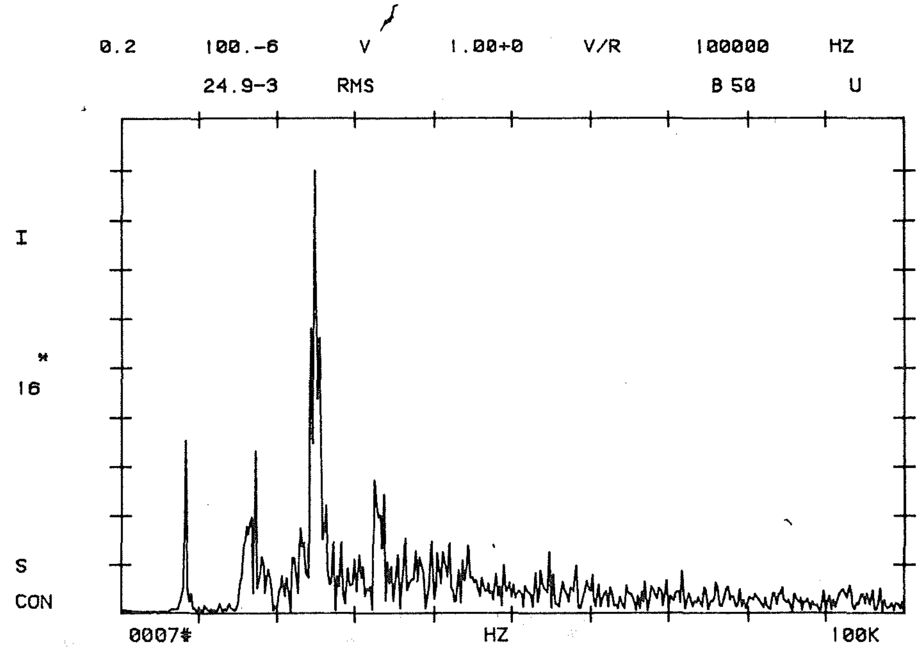
The second type of events appears to be related to development of critical roof stress where, perhaps, the ability of the roof material to relieve strain is being taxed by the rapid rate of stress build-up. These events are characterized as groups of short duration events lasting on the order of 75 μsec to 150 μsec and having discrete frequency components of less than 50 kHz.

The second type of events were predominant during a one-half hour period with a continuous train of the events observed during the period. These events did increase in amplitude with time, as illustrated in Figures A-10 through A-12. The third major type of event abruptly interrupted the second type for approximately 5 minutes. The second type of event then continued for about 10 minutes and then ceased, as did all activity, approximately 25 minutes prior to the time of fall.

Figures A-13 and A-14 illustrate the third major type

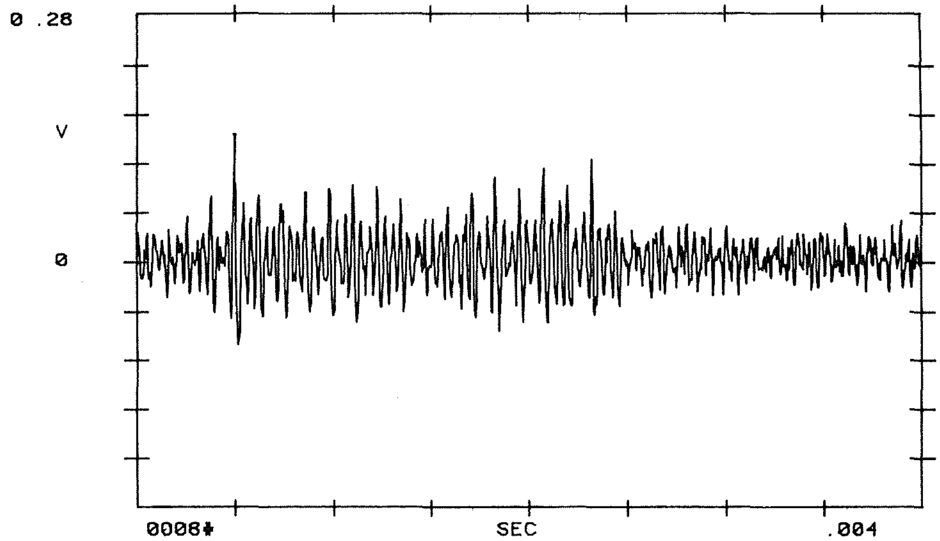


a. Amplitude vs. Time Plot

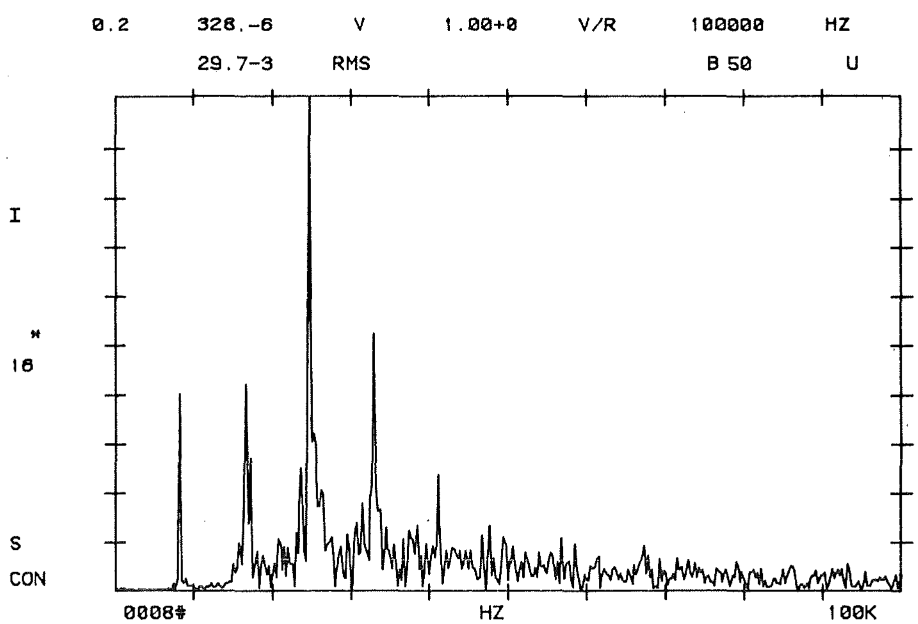


b. Amplitude vs. Frequency Plot

Figure A-10. Microseismic Event - Near-Failure Pulse Data

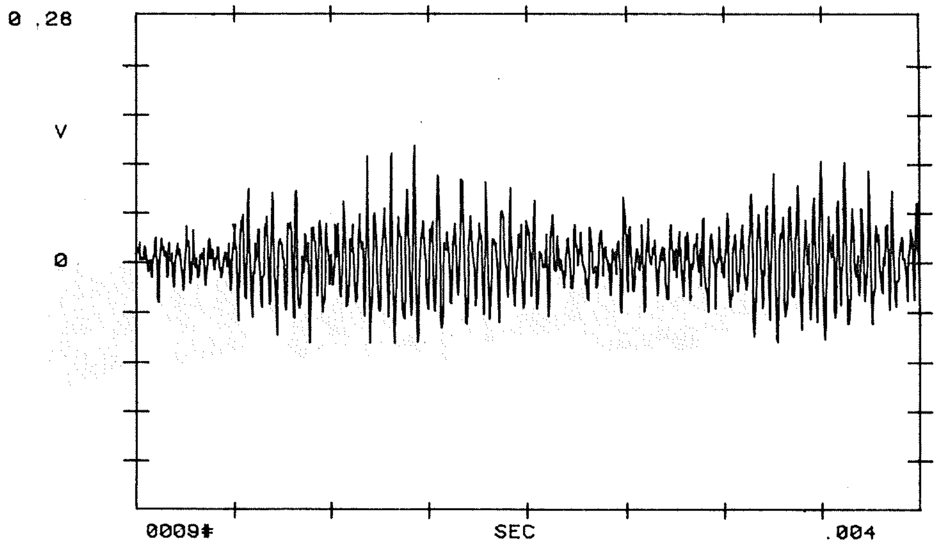


a. Amplitude vs. Time Plot

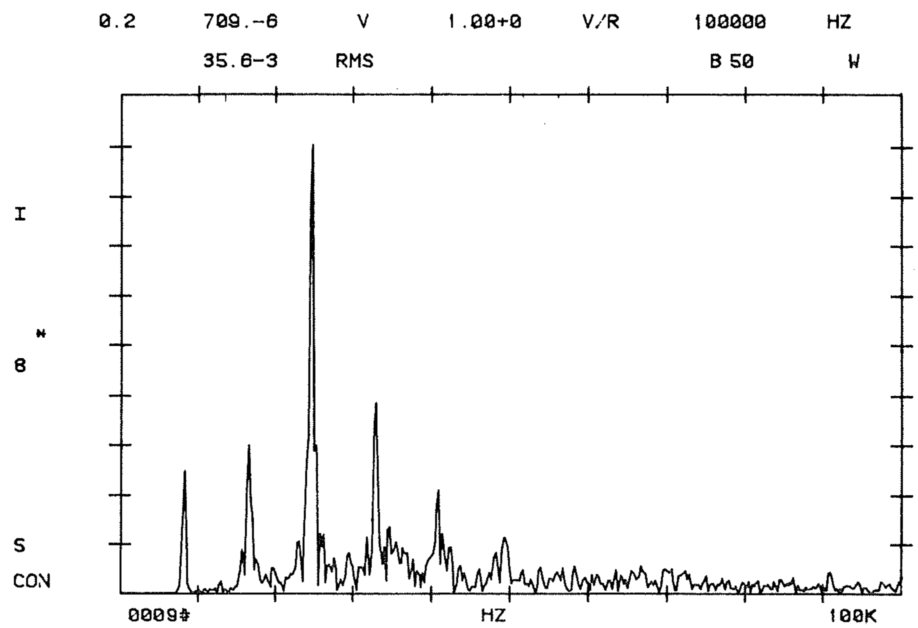


b. Amplitude vs. Frequency Plot

Figure A-11. Microseismic Event - Near-Failure Pulse Data

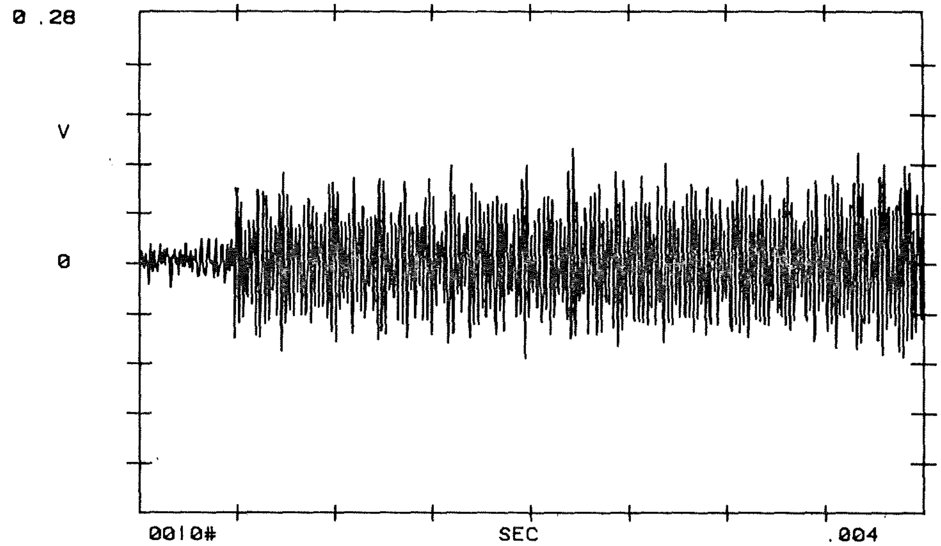


a. Amplitude vs. Time Plot

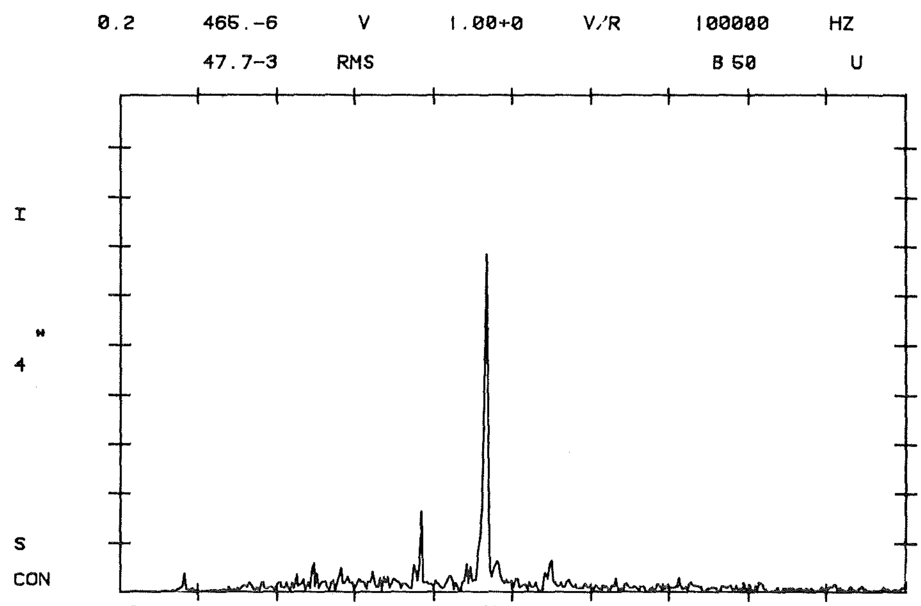


b. Amplitude vs. Frequency Plot

Figure A-12. Microseismic Event - Near-Failure Pulse Data

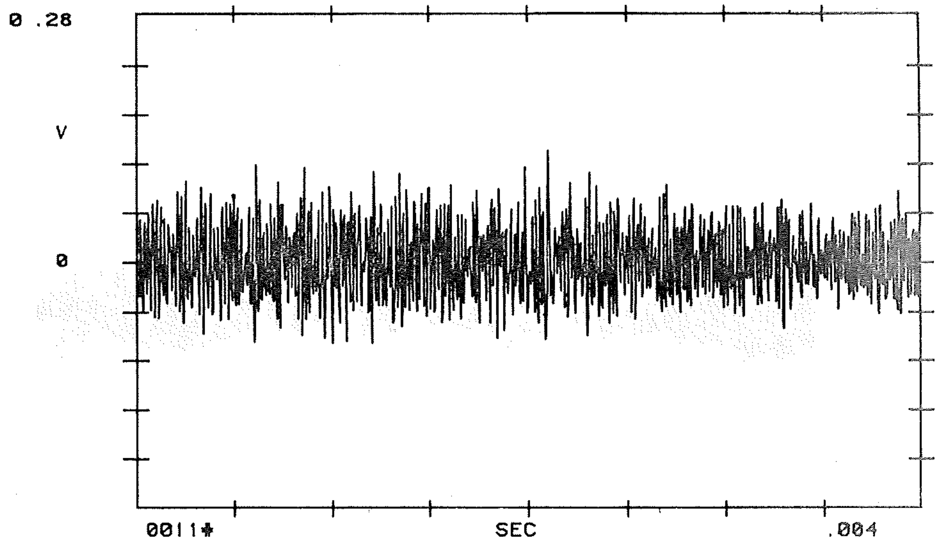


a. Amplitude vs. Time Plot

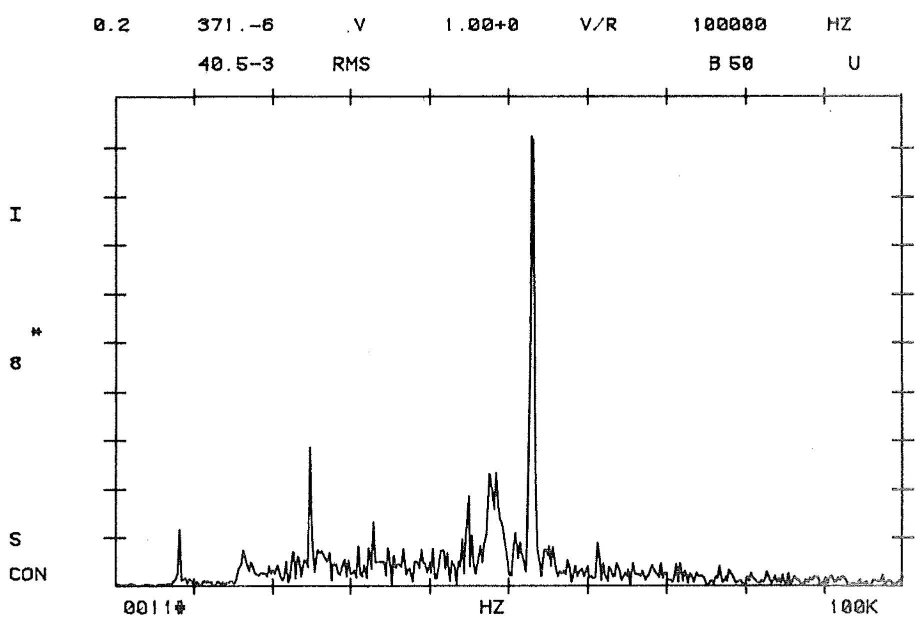


b. Amplitude vs. Frequency Plot

Figure A-13(a). Microseismic Event - Failure Related Continuous Pulse Data

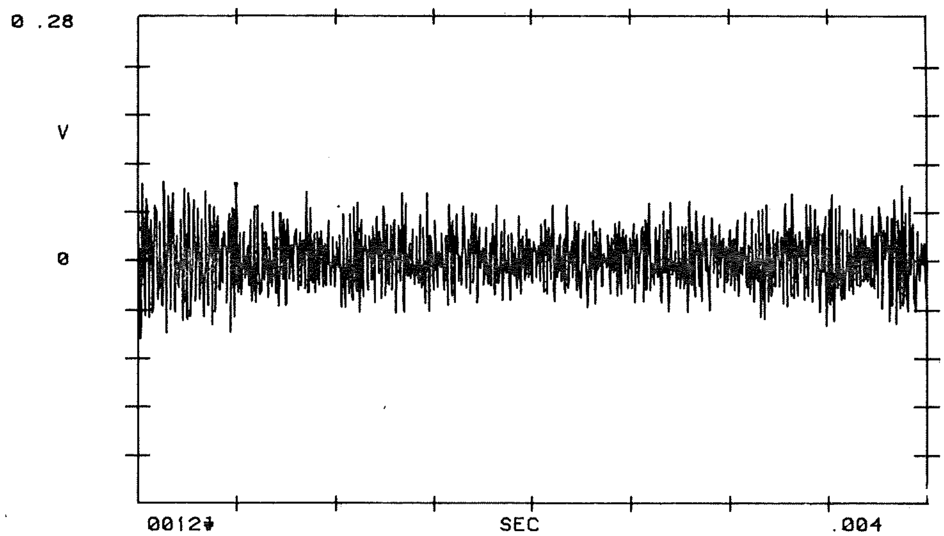


a. Amplitude vs. Time Plot

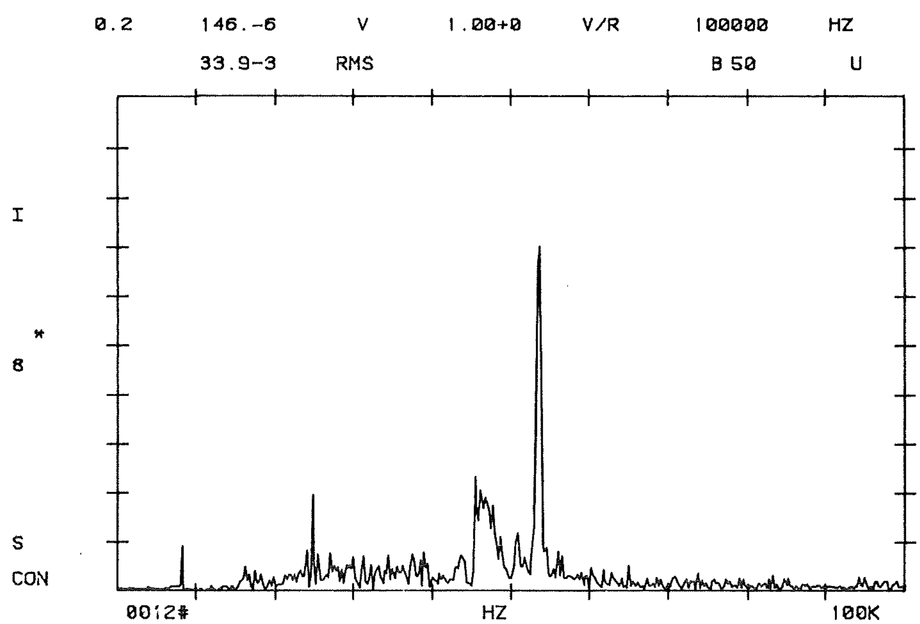


b. Amplitude vs. Frequency Plot

Figure A-13(b). Microseismic Event - Failure Related Continuous Pulse Data

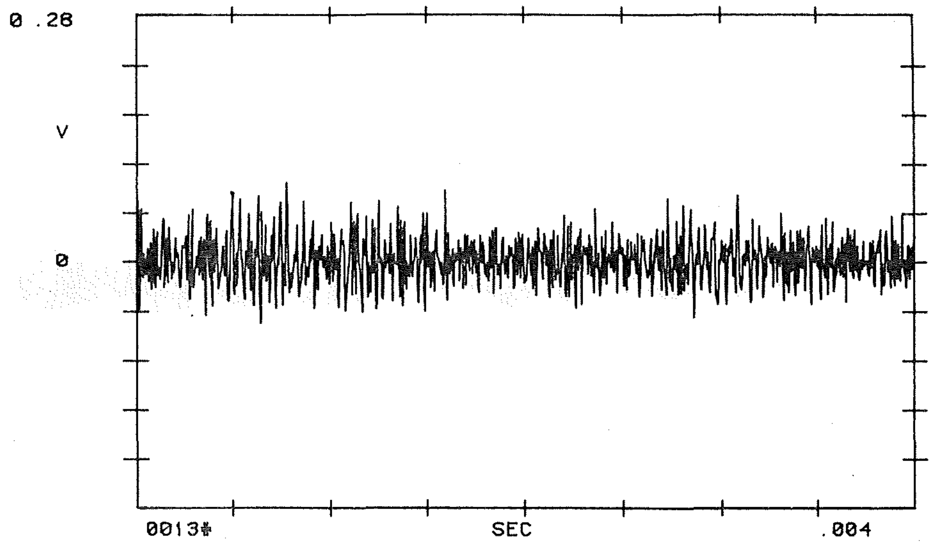


a. Amplitude vs. Time Plot

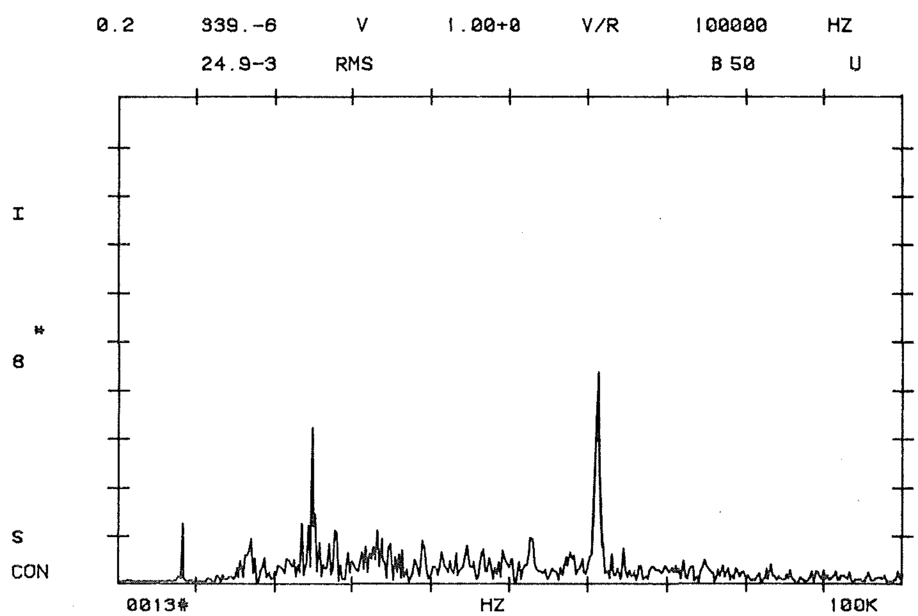


b. Amplitude vs. Frequency Plot

Figure A-13(c). Microseismic Event - Failure Related Continuous Pulse Data

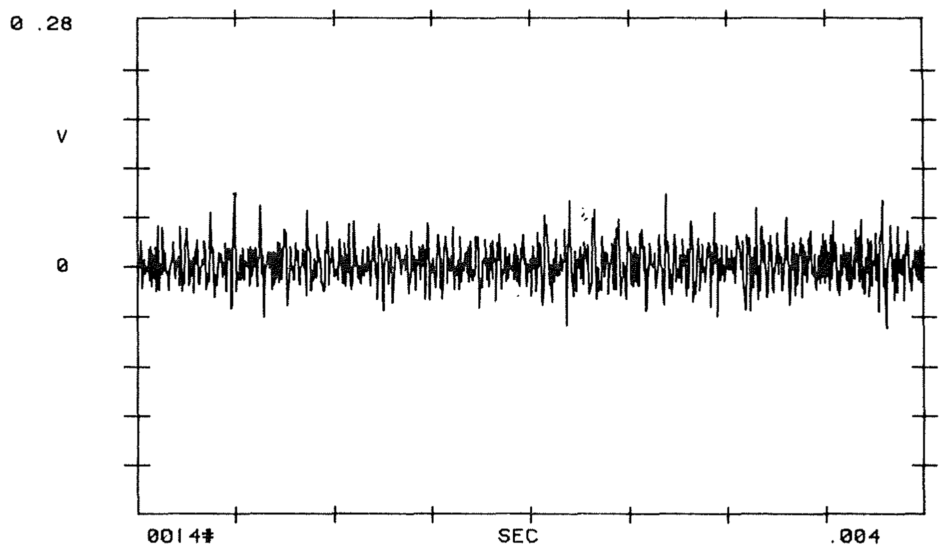


a. Amplitude vs. Time Plot

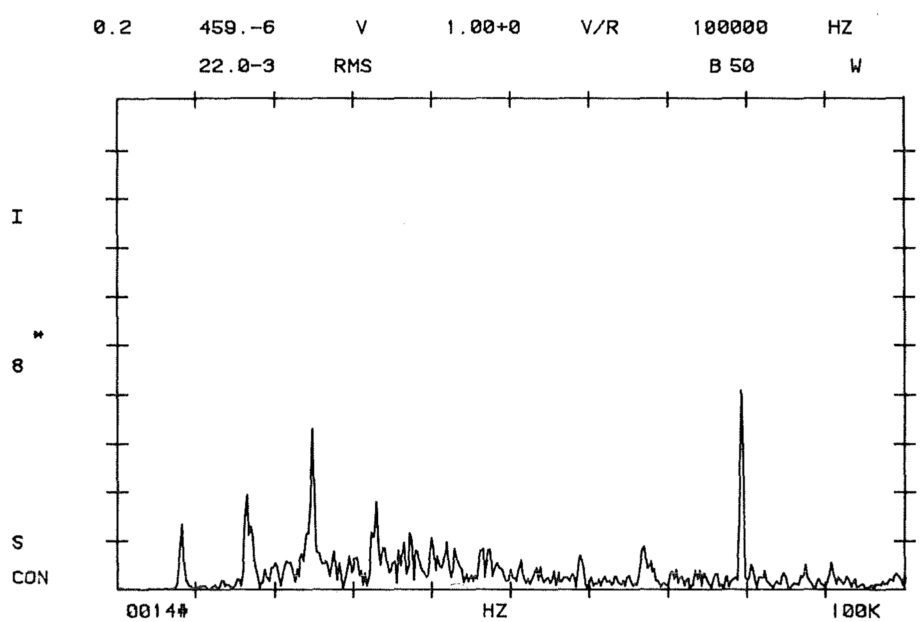


b. Amplitude vs. Frequency Plot

Figure A-13(d). Microseismic Event - Failure Related Continuous Pulse Data

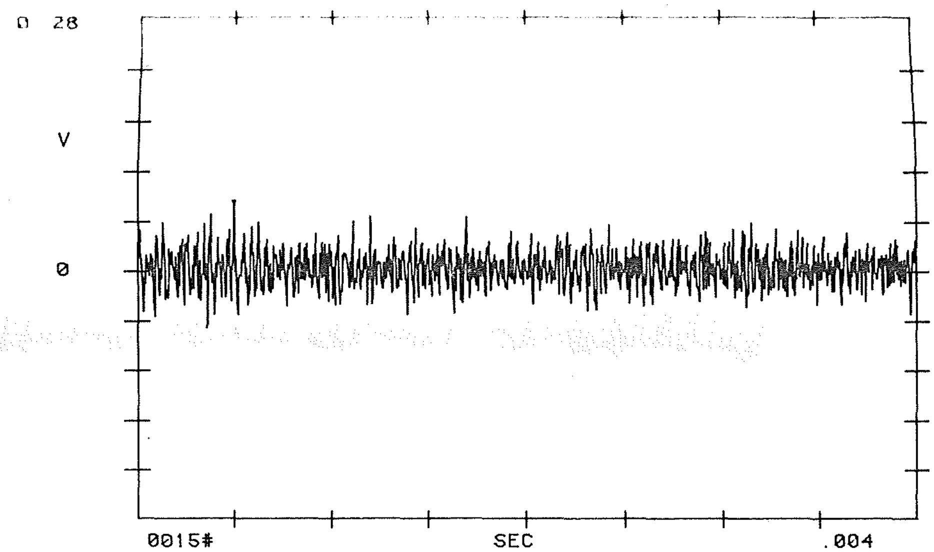


a. Amplitude vs. Time Plot

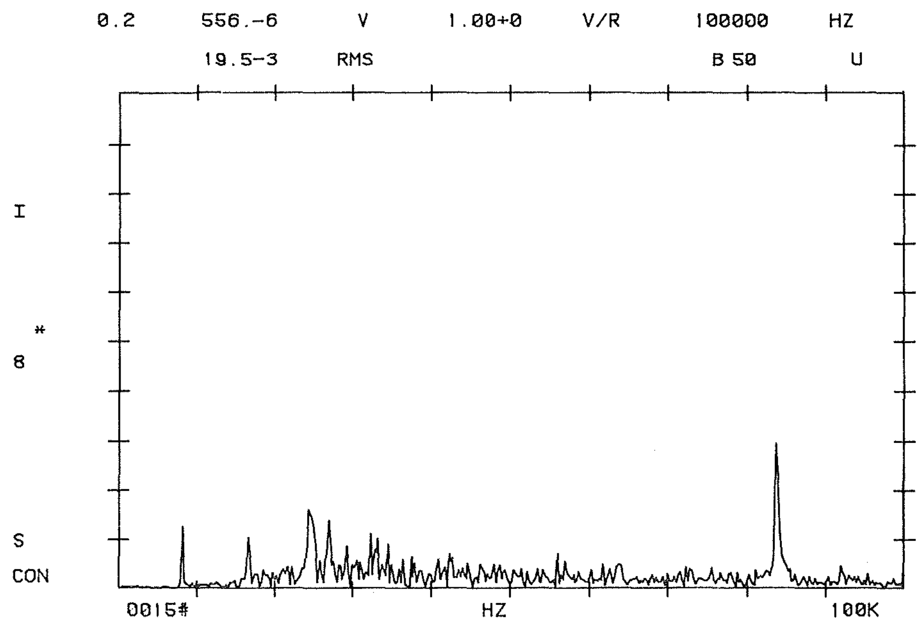


b. Amplitude vs. Frequency Plot

Figure A-13(e). Microseismic Event - Failure Related Continuous Pulse Data

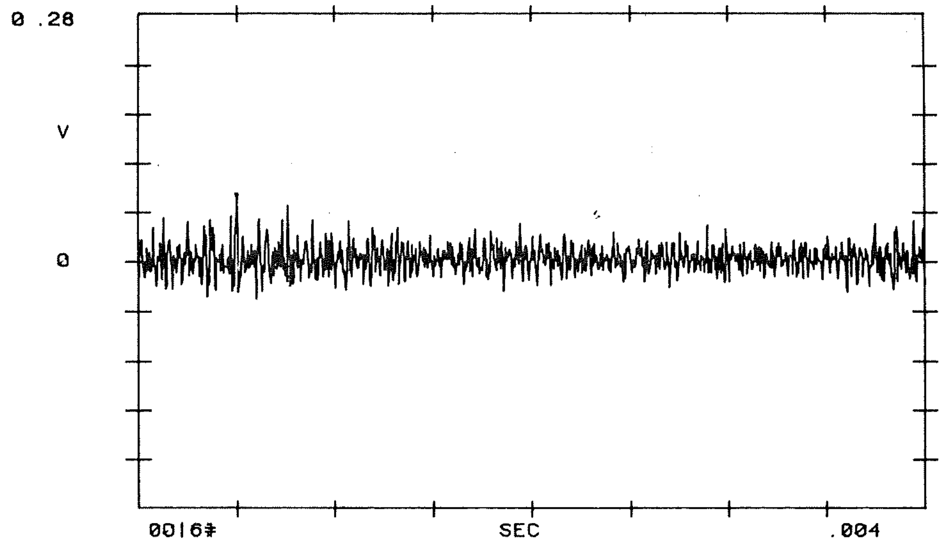


a. Amplitude vs. Time Plot

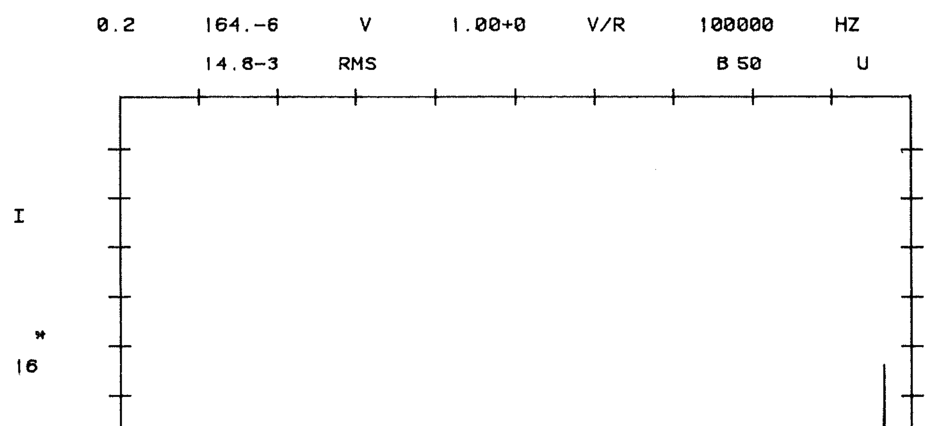


b. Amplitude vs. Frequency Plot

Figure A-13(f). Microseismic Event - Failure Related Continuous Pulse Data

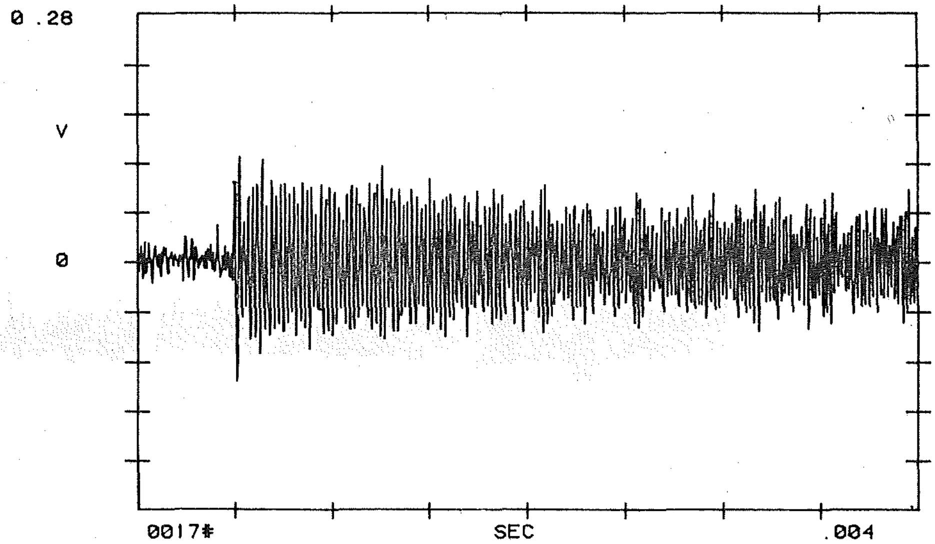


a. Amplitude vs. Time Plot

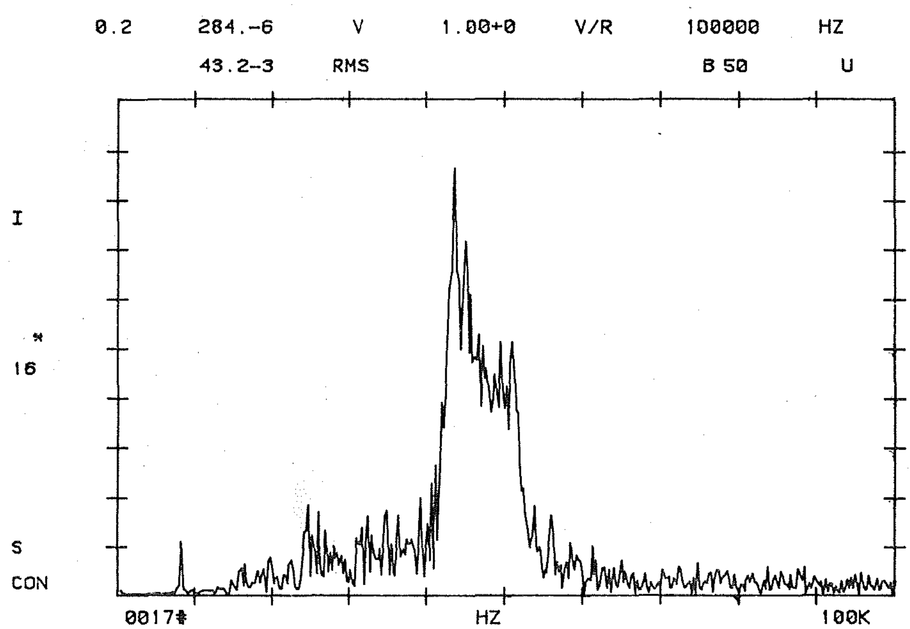


b. Amplitude vs. Frequency Plot

Figure A-13(g). Microseismic Event - Failure Related Continuous Pulse Data

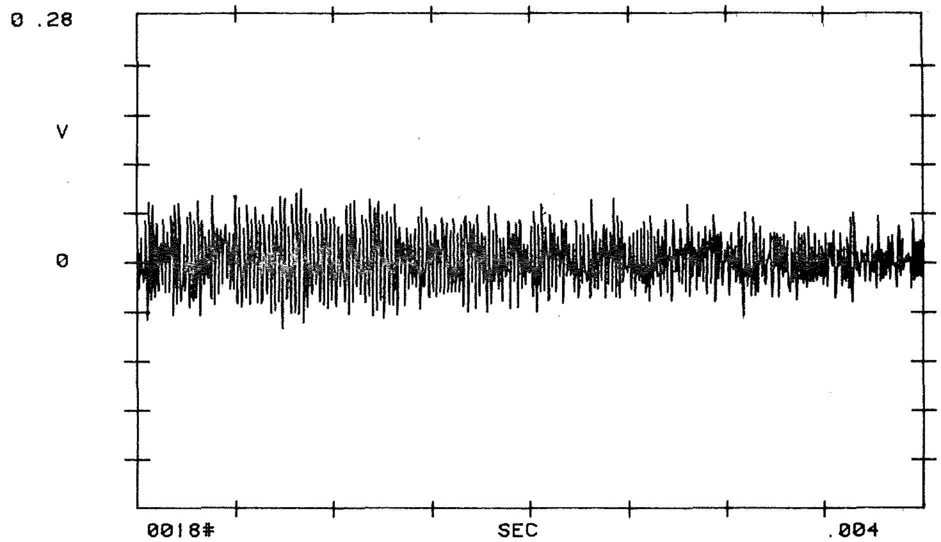


a. Amplitude vs. Time Plot

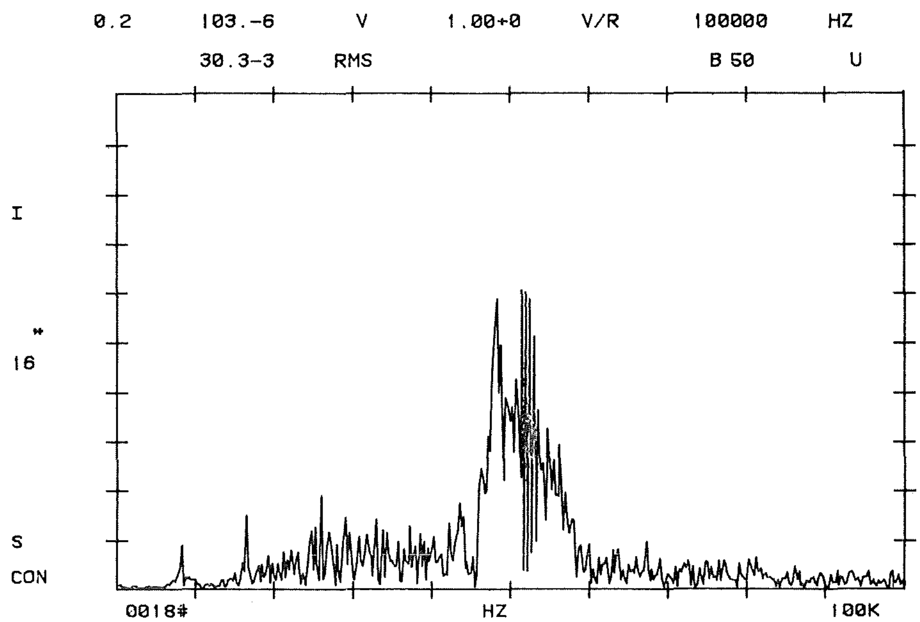


b. Amplitude vs. Frequency Plot

Figure A-14(a). Microseismic Event - Failure Related Continuous Pulse Data

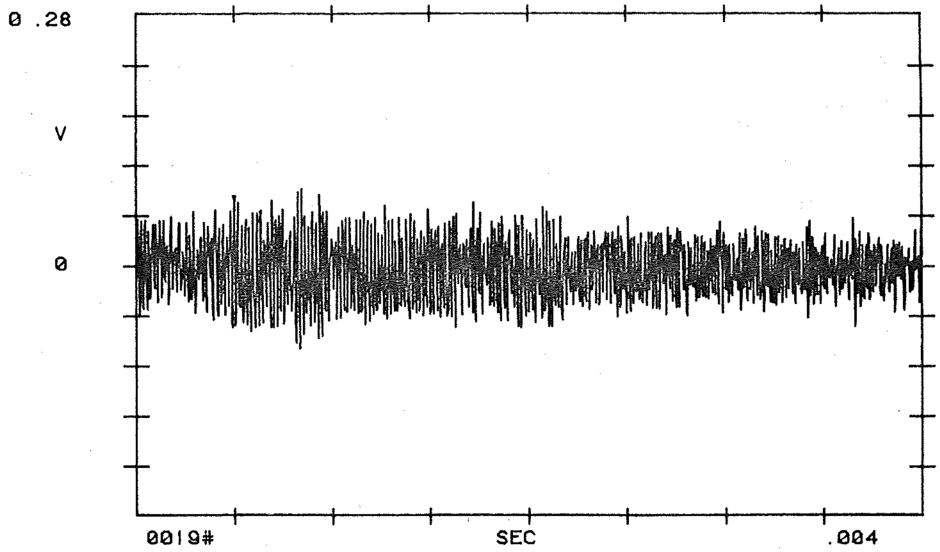


a. Amplitude vs. Time Plot

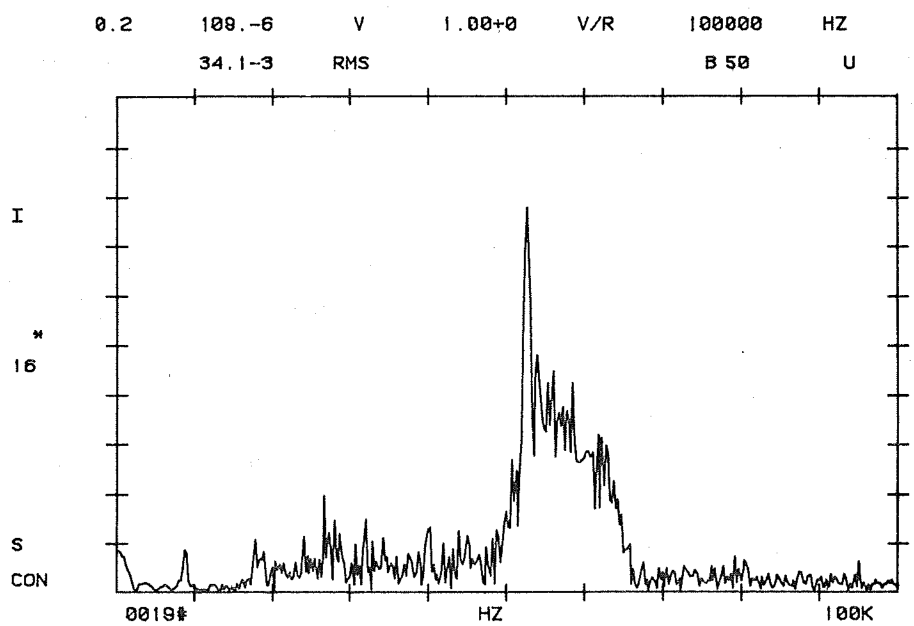


b. Amplitude vs. Frequency Plot

Figure A-14(b). Microseismic Event - Failure Related Continuous Pulse Data



a. Amplitude vs. Time Plot

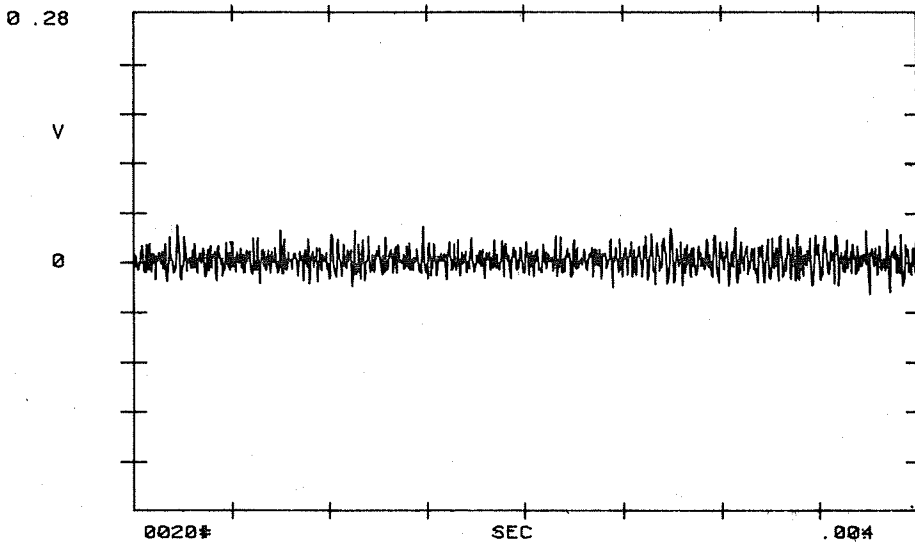


b. Amplitude vs. Frequency Plot

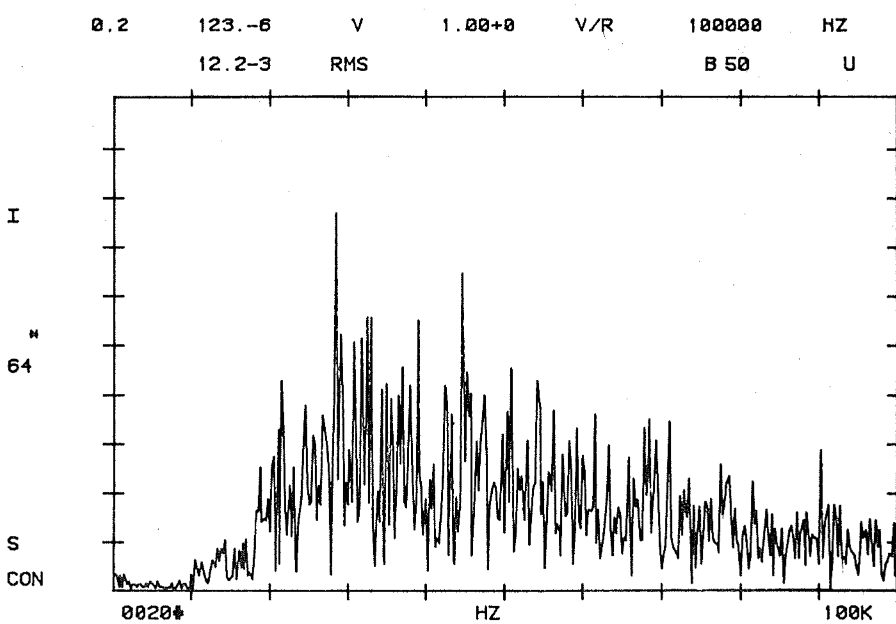
Figure A-14(c). Microseismic Event - Failure Related Continuous Pulse Data of microseismic activity observed. As shown in Figure A-13(a) through A-13(g), the microseismic event can be characterized as a relatively long continuous burst of activity. Figures A-13(a) through A-13(g) are all part of a single event, although all the A-13 figures partially overlap in time. The intent of Figure A-13 is to illustrate the sweep frequency characteristic of this type of event. This, combined with the long duration and lack of frequency components below 45 kHz, uniquely defines this particular event mode. In addition, it also appears to be the physical source of the energy/event count ratio peaks observed in microseismic roof fall data just prior to roof fall.

The third continuous type of microseismic event only lasted for a few minutes and then disappeared completely. If indeed this type of event is unique to roof failure, it can provide a unique indication of imminent roof fall. Since the continuous type event exhibits event durations of from 5 msec to 20 msec and is observed for only a few minutes, it corresponds well to the energy/event ratio peaks seen in microseismic roof fall warning system test data.

Figure A-15 shows the frequency response of the background noise recorded after the microseismic activity ceased and prior to the reported time of fall. The linear decrease in frequency response out to 100 kHz is most likely due to the microseismic transducer preamplifier's frequency response limitations.



a. Amplitude vs. Time Plot



b. Amplitude vs. Frequency Plot

Figure A-15. Background Microseismic Noise

4.0 CONCLUSIONS

Although the magnetic tape recording experiment presented here was hastily performed and is limited by a small dynamic range, it does provide a reasonable verification of the energy/event ratio peak method of roof fall prediction. Data also indicates that the continuous type event may present a uniquely defined frequency and duration associated with imminent roof fall.

Perhaps even more importantly, the well defined differences between types of microseismic events may make possible the determination of dynamic processes of roof deformation and failure in real time. This possibility would, however, require more extensive research.

Further experimentation in in-mine analog microseismic roof fall data recording and analysis in the frequency range above 20 kHz would be well worth the effort in terms of acquiring a better understanding and deeper knowledge of in-situ rock deformation and failure mechanisms.

MICROSEISMIC ROOF FALL WARNING SYSTEM DEVELOPMENT

Field Trials and Commercial Prototype Fabrication

APPENDIX B: EM Transmitter Blasting Cap Susceptibility Testing

Technical

Final Report
F-C4826

Report

BLASTING CAP SAFETY
FOR THE
INTEGRATED SCIENCES
VLF ELECTROMAGNETIC TRANSMITTER

by

Ramie H. Thompson

October 1977

Prepared for

Integrated Sciences Inc.
Longmont, Colorado

Purchase Order Number 2449

THE FRANKLIN INSTITUTE RESEARCH LABORATORIES
THE BENJAMIN FRANKLIN PARKWAY • PHILADELPHIA, PENNSYLVANIA 19103

W. B. Ligett
President and Director

Final Report F-C4826
"Blasting Cap Safety
for the Integrated Sciences
VLF Electromagnetic Transmitter"
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The Franklin Institute Research Laboratories
October 1977
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ABSTRACT

Underground measurements of the coupling between the VLF Electromagnetic Transmitter antenna and wiring configurations easily formed by blasting cap leg wires or blasting wiring indicate that blasting operations in the immediate vicinity of the transmitter antenna are definitely hazardous.

ACKNOWLEDGEMENTS

This project was carried out by personnel of the Applied Physics Laboratory. The author was assisted by Mr. A. W. Cipkins, Technical Associate, in the performance of the measurements.

We would like to thank Messrs. Carl Fisher, Jr. and Tommy L. Finney of Integrated Sciences, Inc., for their cooperation and assistance in the course of the measurements.

Questions and comments should be addressed to the author.

CONTENTS

FIGURES

FIGURES (cont.)

TABLES

1. INTRODUCTION

The overall objective of the project was to determine the possible hazard presented by the *VLF Electromagnetic Transmitter* to blasting operations in coal mines. The *VLF Electromagnetic Transmitter* is the transmitter/transmitting antenna of a digital data link due to play a part in the development of a *Roof Fall Warning System* under development by Integrated Sciences Inc. for the U.S. Bureau of Mines under Contract H0272009 of that agency. The data link is to be used in operating coal mines to collect experimental data for system evaluation; therefore, possible hazardous interactions of the transmitter with blasting caps are of more than theoretical interest.

The overall approach to evaluation of the possible hazard was by direct measurement of the pickup of blasting wiring configurations in close proximity to the operating transmitter at several locations in the Safety Research Coal Mine at the Bureau of Mines facility in Bruceton, Pa.

The measurements were performed on the eleventh through the thirteenth of October 1977 at several sites within the mine. The following sections describe the transmitter, the blasting wiring layouts, the measurement equipment, the measured data and the conclusions.

2. THE ELECTROMAGNETIC TRANSMITTER

The transmitter used in the measurements is essentially a 6 volt, battery powered, semiconductor switching circuit that drives a tuned antenna. The current in the transmitting antenna has a time dependence illustrated in Figure 2-1. The frequency of the 24 ms burst was switch selected to be 2, 3, 4 or 5 KHz. The transmitting antenna itself was a three turn loop of #14 AWG copper wire with a 100 foot perimeter.

The amplitude of the transmitter current was measured periodically during the tests by Integrated Sciences Inc. (ISI) personnel. A 0.1 ohm resistance was inserted in series with the antenna and the voltage drop across the 0.1 ohm resistor displayed on a Tektronix Model 213 oscilloscope. Under normal operating conditions the 0.1 ohm resistance is much less than the magnitude of the loop impedance so that the measured voltage (times ten) is a good measure of antenna current. In free space, i.e. the transmitting antenna deployed on open ground, the peak-to-peak currents were found — by ISI — to be: 4.4 amps, 2 KHz; 4.2 amps, 3 KHz; 4.0 amps, 4 KHz; and 4.0 amps for 5 KHz.

During our first underground measurement we observed that the signal received by our simulated blasting wiring at 4 KHz decayed to approximately one half of its original value in 90 seconds. Later measurements of transmitter-antenna current at 4 KHz showed that the 4 KHz current had dropped to about 1.8 amps (peak-to-peak) from its previous value of 4.0 amps. ISI examination of the 4 KHz tuning capacitor showed that it was faulty. No repairs were possible so measurements were continued. Repeated underground measurements of the other currents showed them to be within +0%, -10% of the values quoted above for free space. For purposes of this report we may assume the transmitter antenna currents to be constant at their lowest measured values without safety error. These are: 2 KHz, 4.0 amps peak-to-peak; 3 KHz, 4.0 amps; 4 KHz, 1.8 amps; 5 KHz, 3.7 amps.

The transmitting antenna is designed to be employed lying on the drift floor and positioned for maximum area.

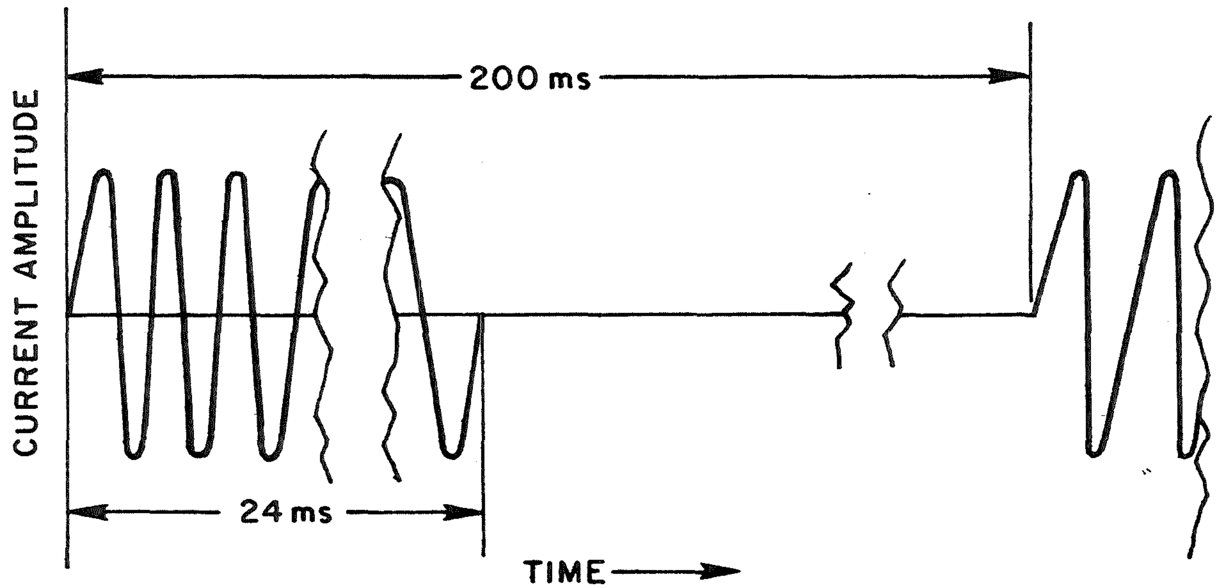

Figure 2-1. Transmitting Antenna Current

3. BLASTING WIRE SIMULATORS

Several wire layouts were used to simulate blasting cap wiring. Measurements were made at all three measurement sites within the mine using a triangular loop antenna that simulates the "patch-in" situation for caps. Figure 3-1 is a sketch of how this configuration can occur in aboveground blasting and a similar condition can occur in underground blasting. Figure 3-2 is a sketch of the triangular type of antenna used in the measurements.

Two other wiring configurations that were used at all measurement sites simulated the fan folded blasting cap leg wires — the transportation configuration — and the unfolded leg wire configuration — a large wire loop formed by the shorted leg wires.

At the one measurement site that was adjacent to a working face additional measurements were made with a wire loop positioned on the periphery of the face. These measurements also used a shot line connected to the simulated wired face running over the transmitter antenna.

Some additional measurements were performed using a square wire loop, 33 cm on a side, terminated in 50 ohms. These measurements were performed to provide a rough estimate of the magnetic field and provide a rough estimate of the measurement equipment and transmitter.

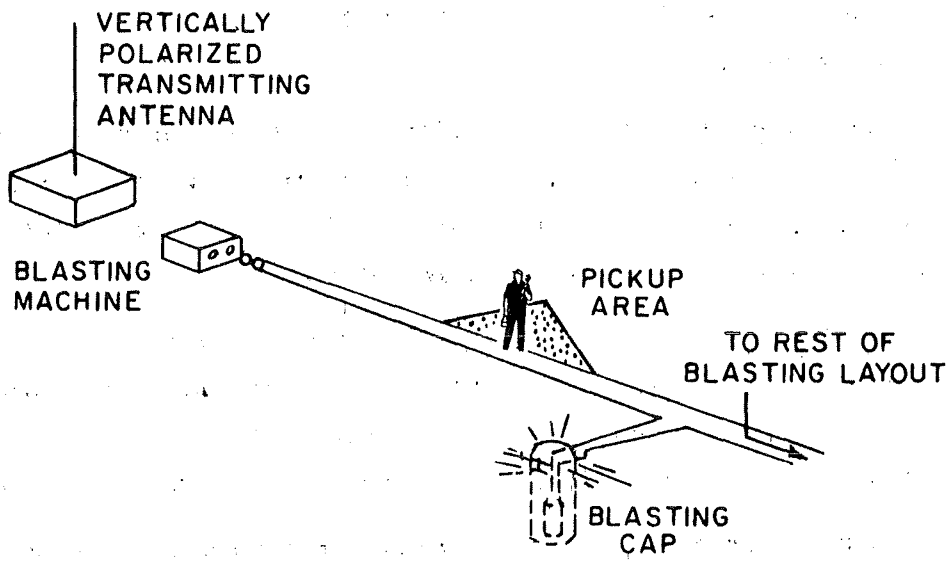

Figure 3-1. Vertical Triangular Loop

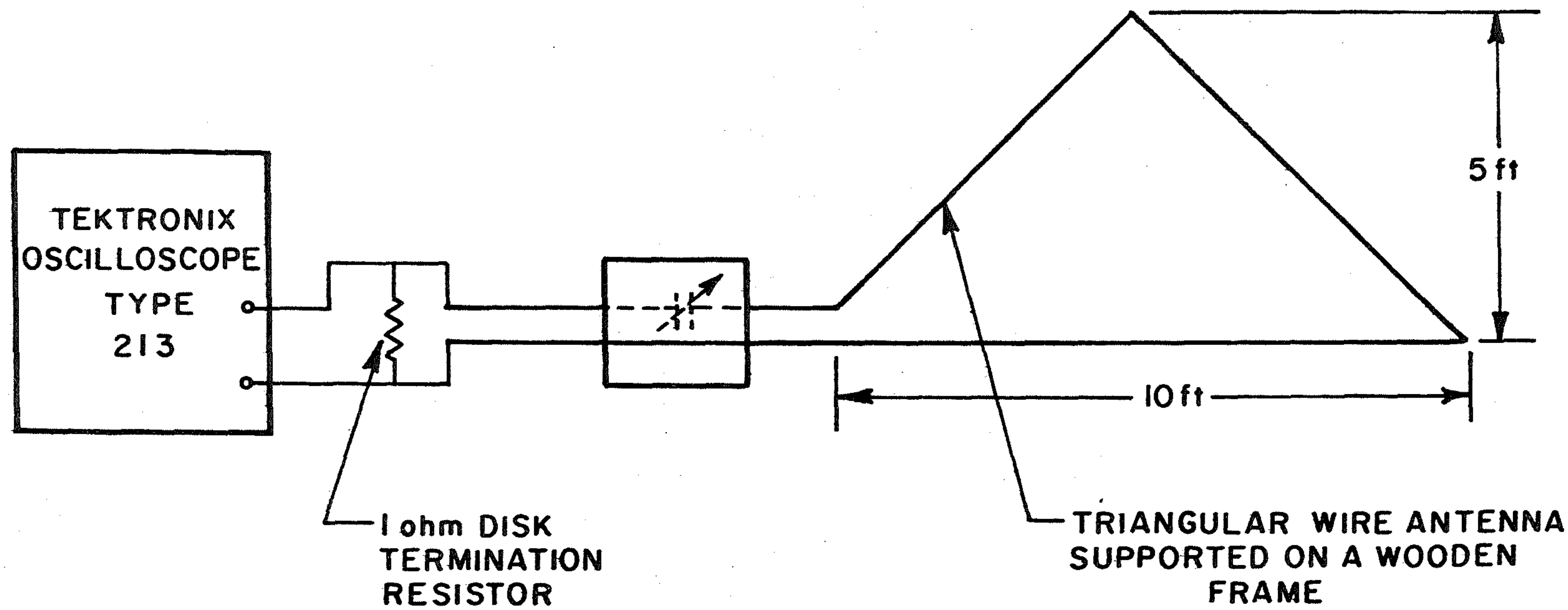

Figure 3-2. The Triangular Antenna

4. THE MEASUREMENT SITES

Figure 4-1 is an incomplete drawing of the workings at the Safety Research Coal Mine at Bruceton. Two of our measurement sites — Site A and Site B — are shown on the figure. The third measurement site, Site C, is not on the figure but is designated in the total mine drawings as "off F BUTT." Figures 4-2, 4-3 and 4-4 show the directions of the individual measurement sites and the location of the transmitter antenna at each site.

Site A was not completely tracked, see Figure 4-2. The roof braces were steel beams about 6 inches wide placed approximately every four feet along the drift. One metal pipe was suspended about 10 inches from the ceiling along one wall. The pipe ran about two thirds of the drift length.

Site B was a tracked haulageway with cables suspended from the roof. The roof supports were steel I beams in a grid arrangement on centers of about 2 feet.

Site C had no conductors other than steel roof support I beams on about 4 foot centers.

All three sites had dry floors. Temperature was estimated at about 50 degrees Fahrenheit at all three sites.

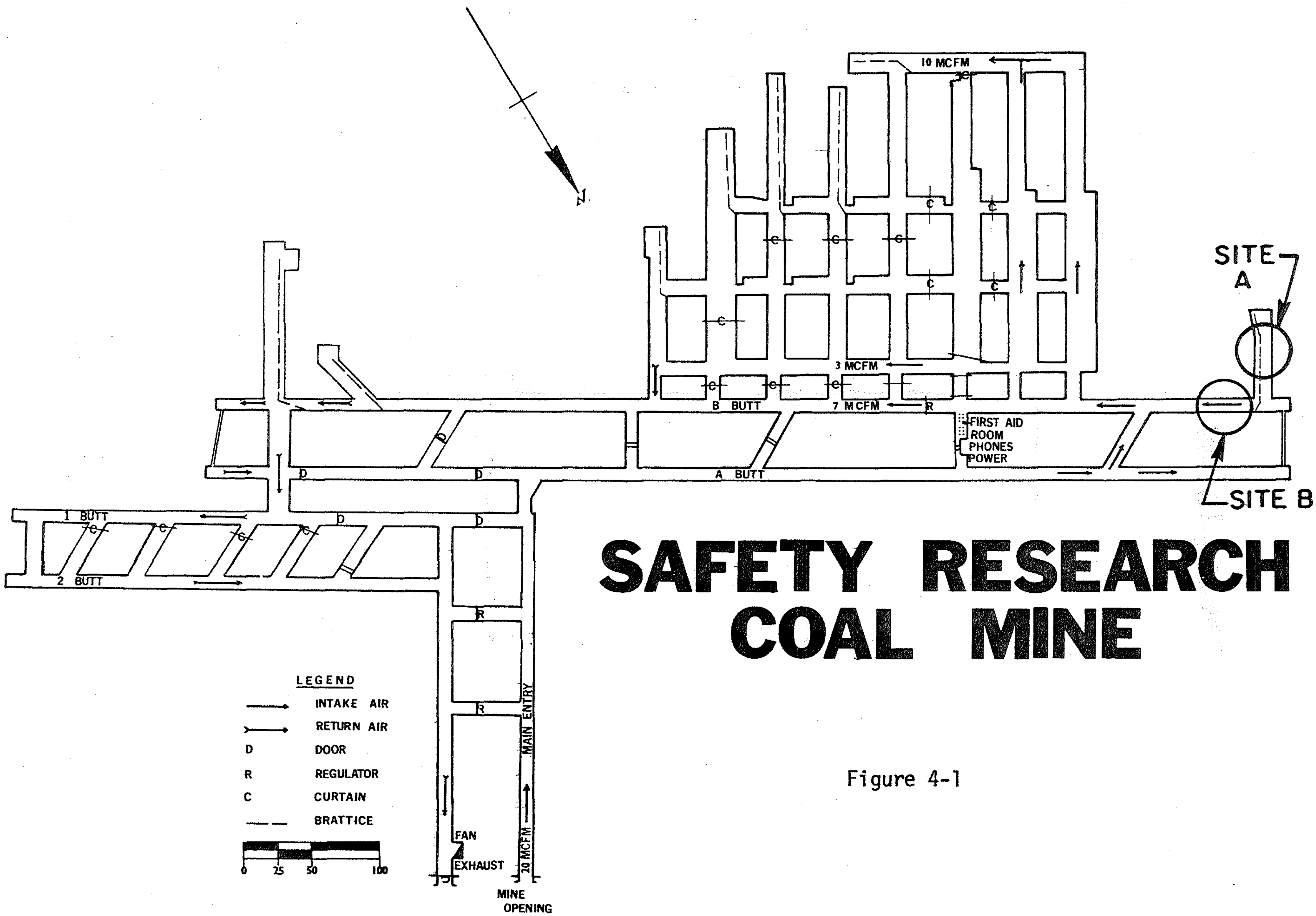
SAFETY RESEARCH
COAL MINE
N
10 MCFM
3 MCFM
7 MCFM
B BUTT
A BUTT
1 BUTT
2 BUTT
SITE A
SITE B
FIRST AID
ROOM
PHONES
POWER
MAIN ENTRY
20 MCFM
FAN
EXHAUST
MINE
OPENING
LEGEND
INTAKE AIR
RETURN AIR
D DOOR
R REGULATOR
C CURTAIN
BRATTICE
0 25 50 100

Figure 4-1

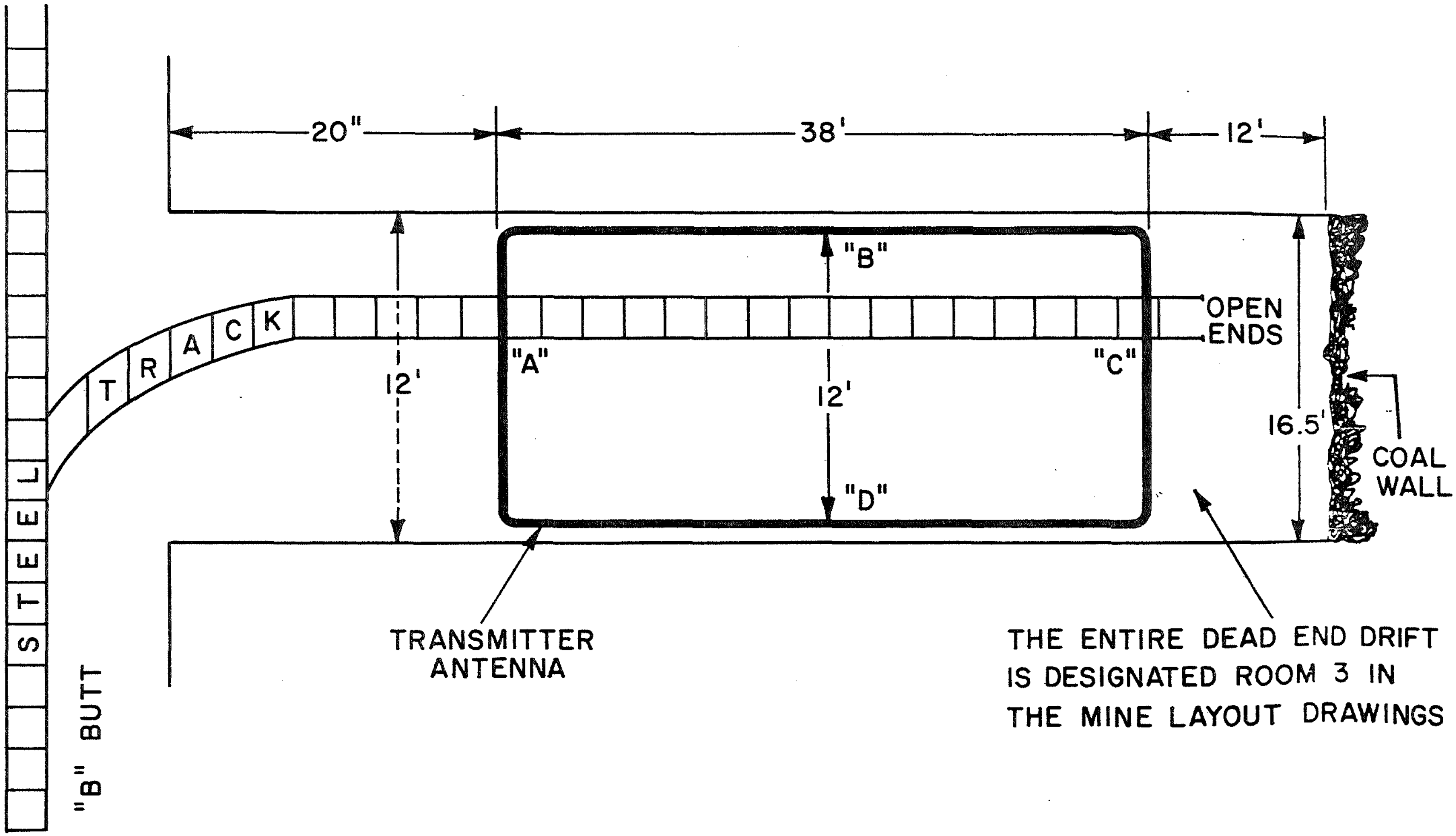

Figure 4-2. Site A

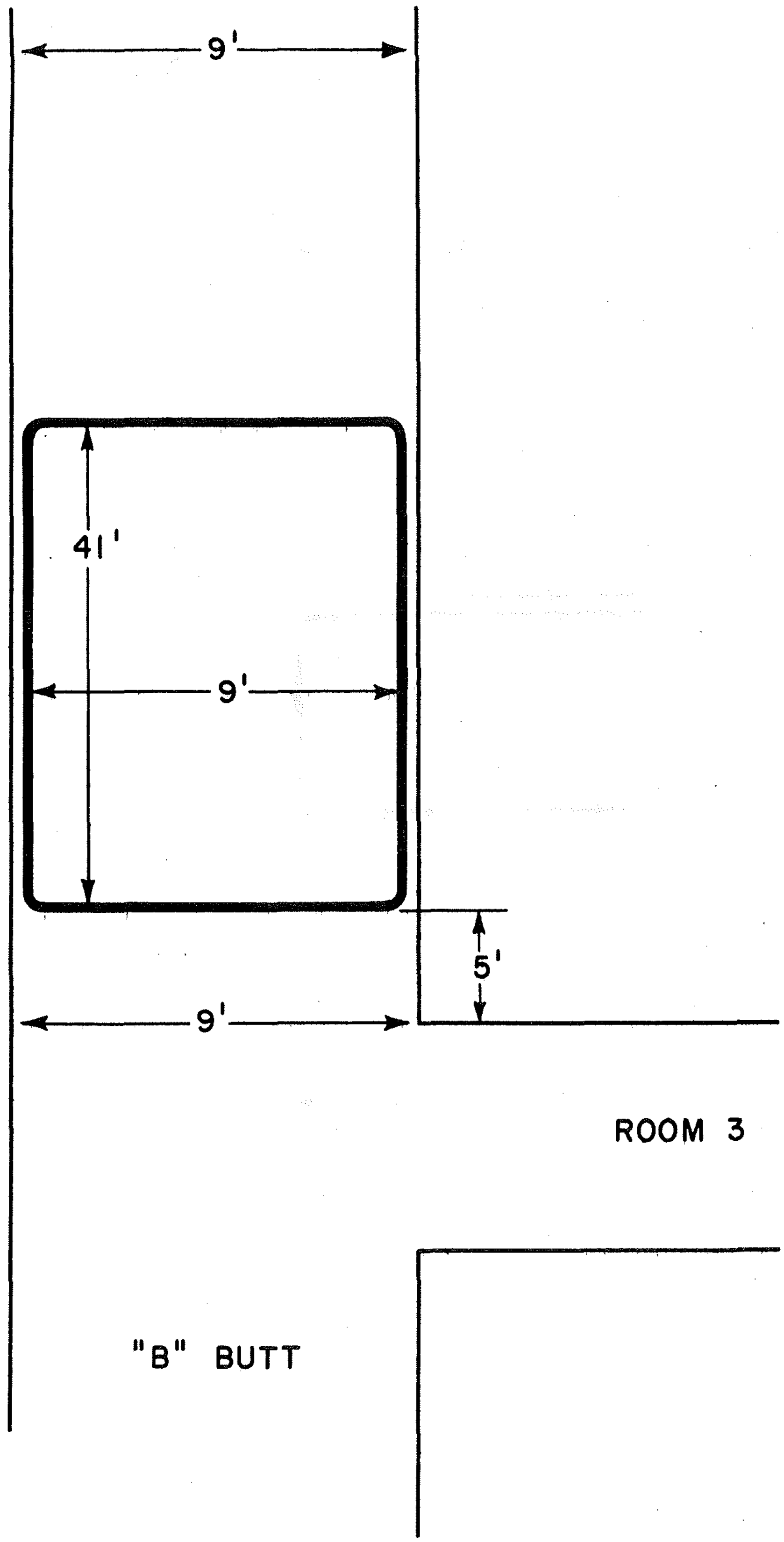

Figure 4-3. Site B

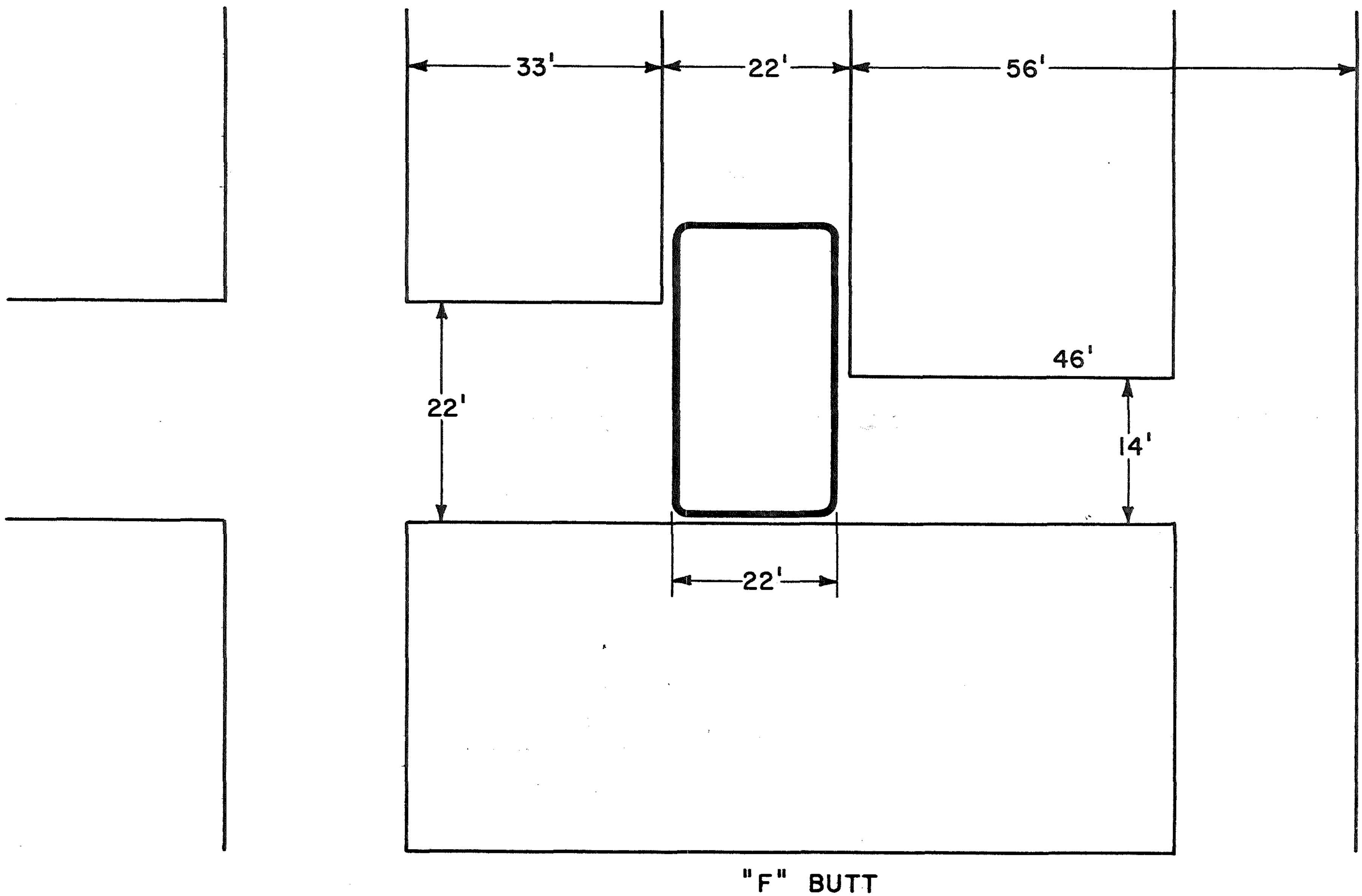

Figure 4-4. Site C

5. MEASUREMENT METHOD

Previous work has shown that, for the frequencies of interest to this project, the hazard mode of concern for blasting caps is the pin-to-pin or normal functioning mode. In addition it can be readily shown that the coupling between the transmitter and the blasting wiring can be considered as strictly magnetic flux coupling without significant error. The simulated blasting wiring layouts that are of concern are thus shorted wire loops that link as much of the magnetic flux as possible. At the frequencies of concern commercial blasting caps have a nominal 1.0 ohm pin-to-pin impedance and the simulated blasting wiring internal impedance is in general very low — say, less than 0.1 ohm. Under these conditions the maximum power that can be delivered to a single cap occurs when the single cap alone loads the wiring. Thus almost all our measurements in this project are directed at determining the power delivered to a 1.0 ohm load on the simulated blasting wiring.

All of our data were obtained with a Tektronix Type 213 oscilloscope connected across the resistance load on the simulated blasting wiring. Voltages were recorded as peak-to-peak volts. The transmitter current time dependance is quite evident on the scope so that we can be assured that what we measured was indeed due to the transmitting antenna.

The Tektronix 213 was calibrated in the mine against the internal voltage generator of a portable Tektronix 321 oscilloscope and the Type 331 voltage generator was checked against another standard on our return to our laboratory. No discrepancies in calibration were evident to the eye. We thus estimate that our peak-to-peak voltage measurements are accurate to better than 5 percent. The 1.0 ohm load used in our measurements is a precision metal film disk resistor with a nominal value of 1.0 ohms.

Average power during the transmitting burst was computed for the resistance load from

$$P_a = \left(\frac{V_{pp}}{2\sqrt{2}}\right)^2 \frac{1}{R} \qquad (5\text{-}1)$$

where

P_a is the average power during the transmitting burst - 24 ms —, watts;

V_{pp} is oscilloscope voltage, volts, peak-to-peak;

and

R is the load resistance, ohms.

Some effort was made to confirm our assumptions of low internal impedance for the simulated blasting wiring and some capacitor matching of the resistance load was attempted. In general, we have found that impedance matching attempts in this frequency range require components that do not represent physical possibilities under actual conditions, so our matching attempts were limited to relatively small capacitances that could conceivably be encountered in actual operation.

6. MEASUREMENT RESULTS

Measurements were first made at site A — see Figure 4-2. All measurements were made using the Tektronix Type 213 oscilloscope. This scope has a probe that incorporates a 6-inch ground lead. Since the ground lead and the probe can be separated to form a small pickup loop we first connected a 1.0 ohm load resistor between the probe and ground lead and positioned the probe as close as possible to the transmitting antenna which was transmitting a 5 KHz signal. The ground lead and probe were formed to obtain the maximum pickup and we observed about 0.030 volts peak-to-peak across the 1.0 ohm resistor. The ground lead was then positioned along the probe and no detectable signal was observed. All subsequent measurements were performed while trying to preserve this minimum probe/lead pickup position.

All recorded voltages were peak-to-peak voltages and reference to voltages are intended to refer to peak-to-peak voltages.

6.1 SITE A RESULTS

The first measurement at site A used the triangular vertical loop positioned at location one of Figure 6-1. Note that Figure 6-1 (and the many similar figures to follow) is not to scale and is presented to provide a concise way of indicating location. In general, locations were selected to be on the symmetry axes of the transmitting loop and this may be assumed to be true unless otherwise noted.

With a 1.0 ohm load on the vertical triangular antenna we recorded 170 mV. This converts to 3.61 mW. Note that we quote all powers as the average power driving the transmitter burst. We will use this convention throughout the reporting of data and derived results. The significance of this parameter, in contrast to true average power, will be commented on later in Section 7. The transmitter frequency for this test was 2 KHz.

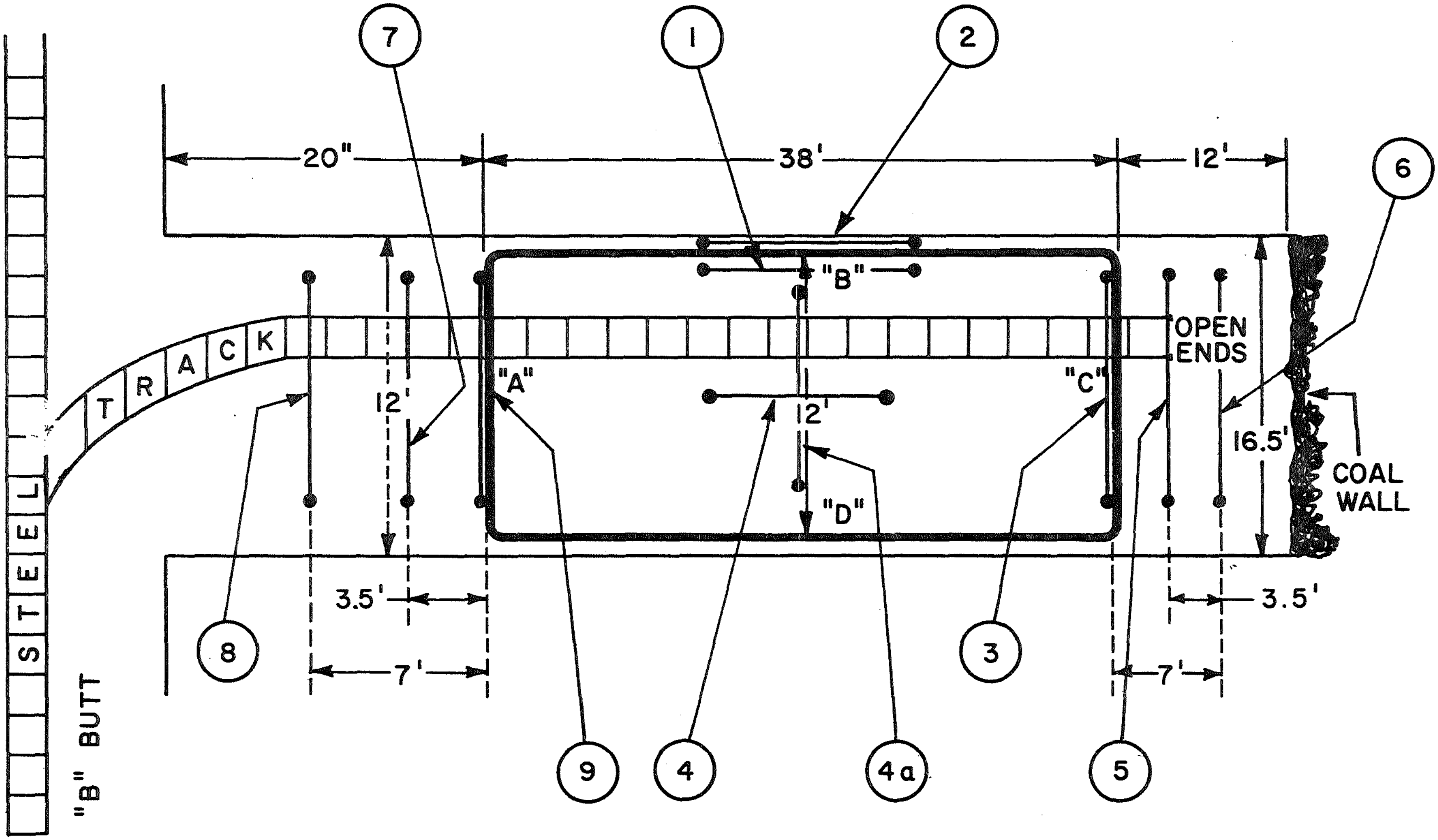

Figure 6-1. Site A - Triangular Loop Locations

Our next measurement was performed at location 2 of Figure 6-1 with the wooden antenna support resting on the transmitting antenna cable. Table 6-1 gives the results of various frequencies and reisistive loads for this configuration. Note that the results support the supposition that the internal impedance is much less than 1.0 ohm — since we receive more power as the load gets smaller. We also tried to reactively match the antenna capacitance at each frequency using the 1.0 ohm load with a series capacitor. The capacitances used varied from 25 picofarads to 0.027 microfarads. Under no condition could we increase the received power from its observed value with a series capacitor.

Also note in Table 6-1 that the 4 KHz values seem to be low in relation to their proper place. It was during the 1000 ohm termination of the loop at 4 KHz that we observed the fall off of the received voltage. This was the first time the transmitter was switched to the 4 KHz position. Our original measurement of the received voltage for a 1000 ohm termination gave 0.7 volts which was observed to decline to 0.36 volts over about 90 seconds. It stabilized at this value. All other readings with the other terminations were taken after this stabilization.

Table 6-2 gives the data and computed power received for various other locations on Figure 6-1 for the vertical triangular antenna with a 1.0 ohm load. Table 6-3 presents the same results for the antenna in the horizontal plane on the ground with the exception that the data for location 9 were obtained with the plane of the antenna about 1.0 foot from the ground.

Measurements were next performed using the "fanfold" antennas to simulate the blasting cap transportation configuration. These antennas are constructed using two pieces of #22 AWG insulated wire — either 30 feet or 15 feet long — the wires are placed side by side and "fan folded" with a 6-inch length until completely folded. One pair of ends is shorted and the other terminated with a 1.0 ohm resistor. The wires can easily be kept in the correct position with a rubber band. The measurements are made with the fan fold in contact with the transmitting antenna or in a position to maximize received signal. Tables 6-4 and 6-5 give the data for the first four locations shown in Figure 6-2. At

Table 6-1

Results

Site A, Triangular Vertical Antenna at Location 2 of Figure 6-1

LOAD RESISTANCE	FREQUENCY KHz													
Ohms	2		3		4		5							
	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
0.5	260	16.9	380	36.1	190	9.03	500	62.5						
1.0	280	9.80	500	31.3	260	8.45	680	57.8						
5.0	400	4.0	660	10.9	340	2.89	880	19.4						
10.0	400	2.0	700	6.13	340	1.45	900	10.1						
100.0	560	0.392	720	0.648	350	0.153	920	1.06						
1000.0	560	0.0392	720	0.0648	360	0.0162	920	0.106						

Table 6-2

Results

Site A, Vertical Triangular Antenna, 1 Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-1													
	3		4		4a		5		6		7		8	
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	380	18.1	7	0.00613	24	0.072	36	0.162	8.5	0.00903	33	0.136	10	0.0125
3	520	33.8	10	0.0125	34	0.145	48	0.288	11	0.0151	44	0.242	12.5	0.0195
4	260	8.45	5	0.00313	18	0.0405	24	0.072	6	0.0045	24	0.072	7	0.00613
5	700	61.3	13	0.0211	48	0.288	64	0.512	14	0.0245	58	0.421	18	0.0405

Table 6-3

Results

Site A, Horizontal Triangular Antenna, 1 Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-1													
	4		6		8		9							
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	160	3.2	23	0.0661	21	0.0551	56	0.392						
3	220	6.05	30	0.113	28	0.098	76	0.722						
4	115	1.65	16	0.032	14	0.0245	40	0.2						
5	290	10.5	40	0.2	37	0.171	110	1.51						

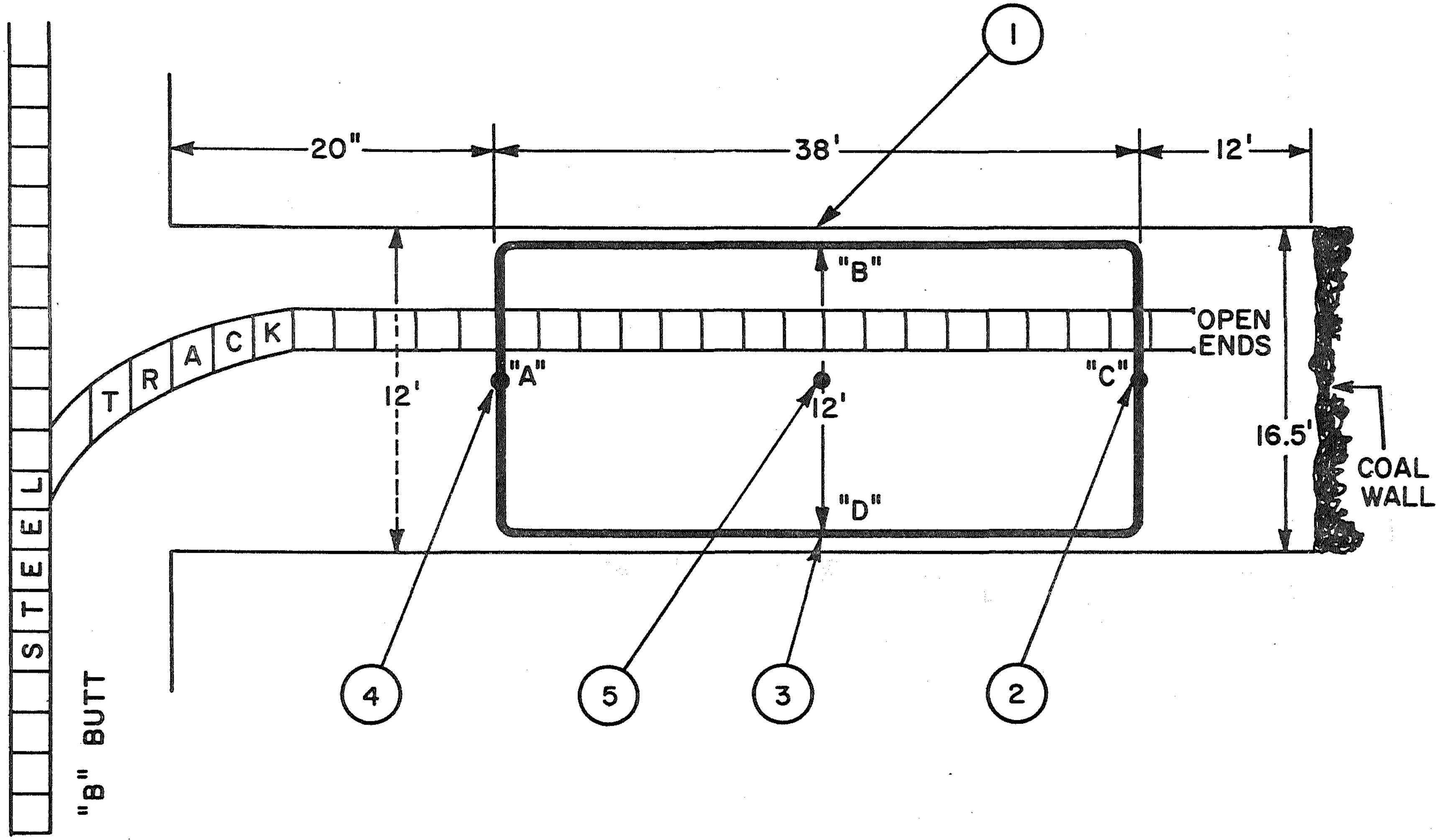

Figure 6-2. Site A - Fanfold Locations

Table 6-4

Results

Site A, Fanfold Antenna, 30 Foot Legwires, 1 Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-2													
	1		2		3		4							
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	5	0.00313	8	0.008	5	0.00313	4	0.002						
3	7.5	0.00703	11	0.0151	6.5	0.00528	4	0.002						
4	4	0.002	5.5	0.00378	3.5	0.00153	2	0.0005						
5	9	0.010	15	.0281	8	.008	8.5	0.00903						

Table 6-5

Results

Site A, Fanfold Antenna, 15 Foot Legwires, 1 Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-2													
	1		2		3		4							
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	4	0.002	4	0.002	4	0.002	5.5	0.00378						
3	6	0.0045	5	0.00313	6	0.0045	8	0.008						
4	3.5	0.00153	3	0.00113	3.5	0.00153	1.5	0.000281						
5	7.5	.00703	6.5	0.00528	8	0.008	10	0.0125						

location 5 no discernible signal could be obtained with either the 15 foot or the 30 foot fanfold antennas.

Measurements at the five locations of Figure 6-2 were next performed using a square loop, 33 centimeters on a side, terminated in a 50 ohm resistance. The purpose was to provide a means to estimate the magnetic field and compare it with a theoretical estimate deduced from the known current in the transmitting antenna. Table 6-6 gives the recorded voltages. The square loop was positioned at locations 1 through 4 directly on the transmitting antenna wire with one side of the loop parallel to the transmitting current.

We assume that the 50 ohm loaded voltage is essentially the open circuit voltage so this voltage should be expressable as

$$V_{oc} = \int_{loop} \frac{\partial \bar{B}}{\partial t} \cdot dA = \mu_o \int_{loop} \frac{\partial \bar{H}}{\partial t} \cdot dA \qquad (6\text{-}1)$$

where

V_{oc} is the open circuit voltage,

$\bar{B}$ is magnetic flux density,

$\bar{H}$ is the magnetic field, and

μ_o is the permeability of free space, equal to $4\pi \cdot 10^{-7}$ H/m , and

dA is the area element of the loops surface.

t is time

If we approximate the antenna field by that of a long straight wire

$$H(r) = \frac{In}{2\pi r} \text{ amperes/meter} \tag{6-2}$$

where

I is the current $= I_p \sin 2\pi ft$

n is the number of current elements,

r is the distance from the wire,

f is the frequency of the current and

I_p is the peak current value, i.e. one half the peak to peak current.

Substituting 6-2 in 6-1 and integrating over the loop we obtain

$$V_{oc} = f\, I_p\, n\, 4\pi\left(0.33 \cdot 10^{-7}\right) \cos(2\pi ft) \int_{0.005}^{0.33} \frac{dr}{r} \tag{6-3}$$

where we assume the loop is within 0.5 cm of the transmitting wires. Simplifying, and multiplying by two to obtain an expression for peak to peak voltage (V_{ocpp}).

$$V_{ocpp} = f\, I_p\, n \cos(2\pi ft) \cdot 1.737 \times 10^{-6}\ . \tag{6-4}$$

Using n equal to 3 and the I_p values given earlier we calculated the values given in column 6 of Table 6-6. Taking into account the fact that we know the 4000 Hz ampere current used in the calculation is high we see that the approximations employed give a reasonable estimate of voltage received close to the transmitting antenna.

Table 6-6

Results

Site A, 33 Cm. Square Loop, 50 Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-2													
	1		2		3		4		5		Calculated			
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	65		80		75		80		12		45.9			
3	90		105		100		100		16.5		65.7			
4	50		55		50		60		8		83.4			
5	125		150		135		160		20		104			

The next measurements used a 60 foot length of #22 AWG wire terminated by one ohm and spread on the drift floor for maximum area. This configuration simulates a 30 foot legwire cap with the short intact and the leg wires unfolded for connection to blasting wiring. The loop was arranged to span the complete width of the drift. The measurements were made with the loop centered on the locations shown in Figure 6-3. Table 6-7 gives the results.

The final set of measurements at site A used a 46 foot length of wire, supported by nails, affixed to the periphery of the working coal face. The loop was loaded with 1.0 ohm. Measurements were taken at the original separation between the transmitter loop and the coal wall as shown on Figure 6-1, i.e. 12 feet; then the transmitting loop was moved so the separation was 5 feet and lastly, the separation was decreased to zero. The results are given in Table 6-8.

With the transmitting antenna bordering on the coal face loop, a 78 foot length of common ac line cord was connected to the coal face loop and passed back over the transmitting loop in the middle of the drift. The ac line cord was shorted at the far end thus simulating a wired face and "shot line" configuration. The "shot line" was next moved so it ran directly alongside one of the transmitting loop's sides on its run down the drift. The data for these configurations are given in Table 6-9.

6.2 SITE B RESULTS

The antennas used were the same as those described for site A. Figure 6-4 gives the locations for the vertical triangular loop measurements and Table 6-10 the results. Table 6-11 gives the results for the triangular loop positioned horizontally in the center of the transmitting loop — location 5 of Figure 6-4.

Figure 6-5 gives the locations of the measurements with the 15 foot leg wire "fanfold" simulator measurements; Table 6-12 gives the results.

Figure 6-6 gives locations for the centers of the 60 foot loop measurements and Table 6-13 gives the results.

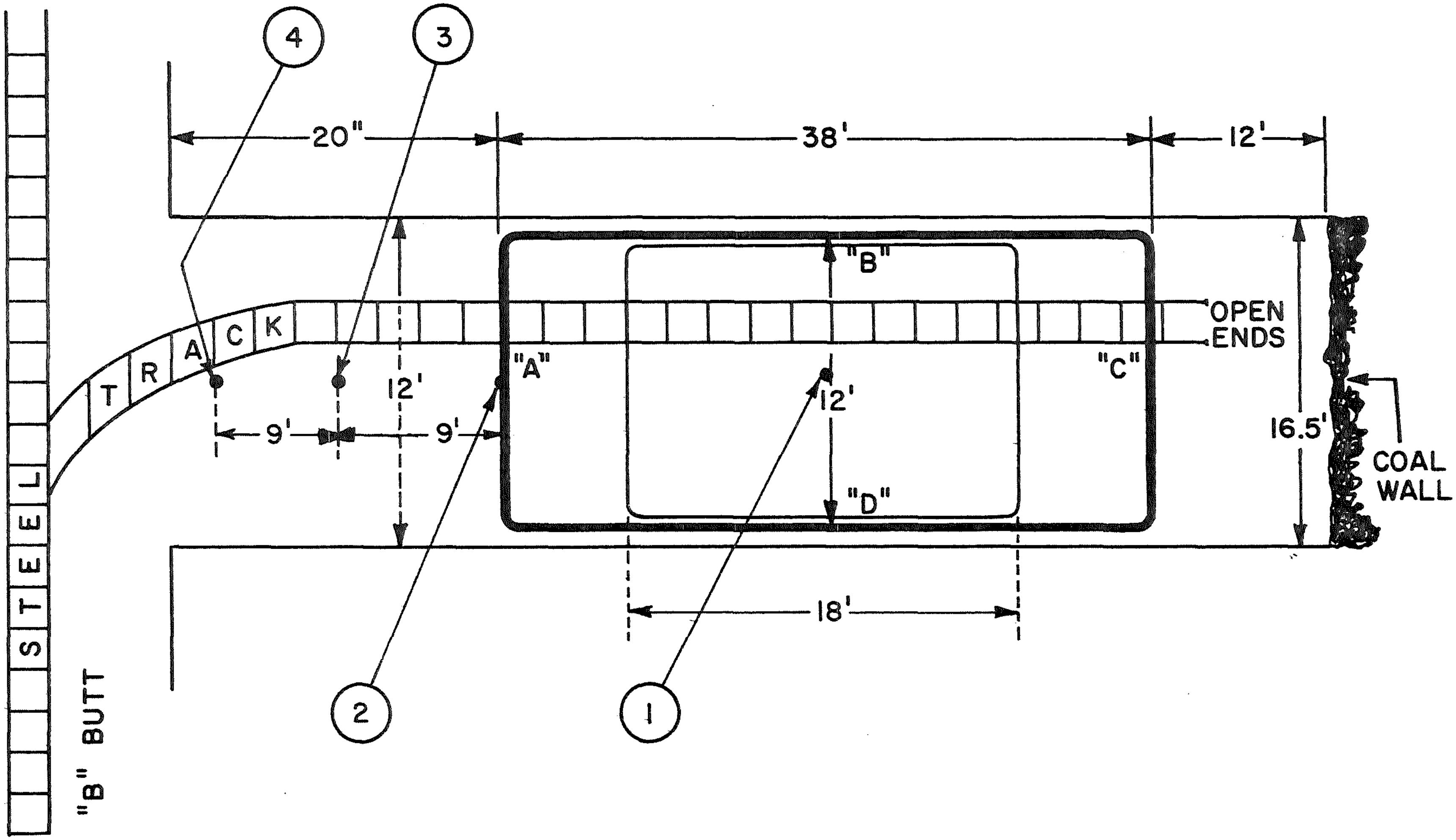

Figure 6-3. Site A - 60 Foot Loop Locations

Table 6-7

Results

Site A, 60 Foot Loop, One Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-3													
	1		2		3		4							
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	2300	661	1250	195	555	37.8	34	0.145						
3	3000	1130	1700	361	750	70.3	44	0.242						
4	1400	245	800	80	400	20	24	0.072						
5	3400	1450	2100	551	1000	125	60	0.45						

Table 6-8

Results

Site A; 46 Foot Loop on Coal Face, One Ohm Load

FREQUENCY	Separation Between Transmitting Antenna and the Coal Face (in Feet)													
	12		5		0									
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	24	0.072	80	0.8	750	70.3								
3	32	0.128	115	1.65	1000	125								
4	16	0.032	55	0.378	500	31.3								
5	44	0.242	160	3.2	1300	211								

Table 6-9

Results

Site A, 46 Foot Loop on Coal Face, 1 Ohm Load, for Two Placemounts of a 78 Foot 2 Conductor "Shot Line"

FREQUENCY														
	Middle of Loop		Alongside Loop											
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	480	28.8	500	31.3										
3	640	51.2	680	57.8										
4	320	12.8	340	14.5										
5	860	92.5	900	101										

Table 6-10

Results

Site B, Vertical Triangular Loop, One Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-4													
	1		2		3		4		5					
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	250	7.81	6.25	.00488	3.5	.00153	320	12.8	5	0.00313				
3	310	12.0	7.5	.00703	4	.002	400	20	6	0.0045				
4	160	3.20	4	.002	No Reading	No Reading	200	5	3.5	0.00153				
5	350	15.3	8	.008	6	0.0045	440	24.2	9	0.0101				

Table 6-11

Site B, Triangular Loop Positioned Horizontally at Location 5 of Figure 6-4, 1 Ohm Load

Frequency	Received Voltage Peak to Peak	Power Received
KHz	mV	mW
2	190	4.51
3	230	6.61
4	130	2.11
5	260	8.45

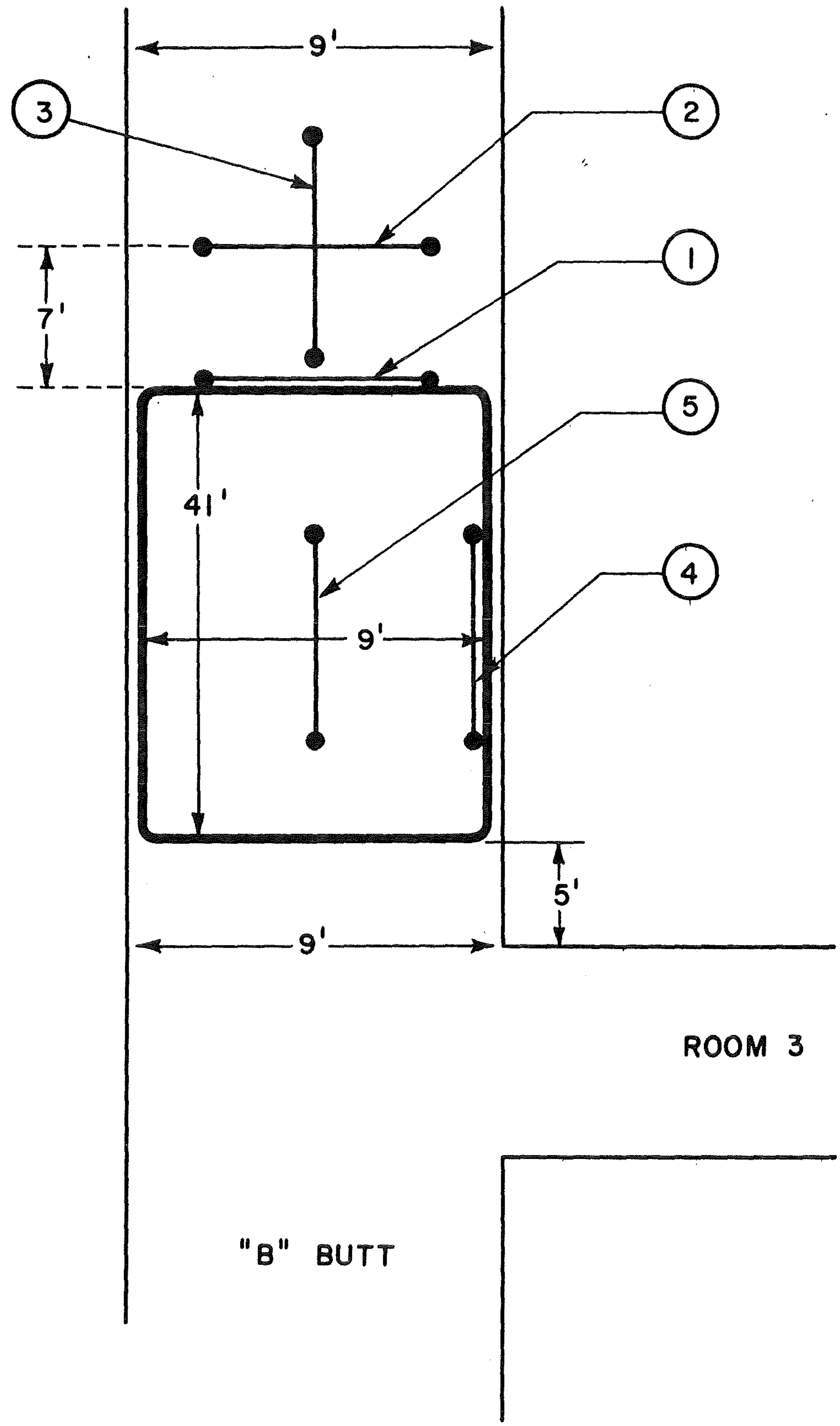

Figure 6-4. Site B Triangular Loop Locations

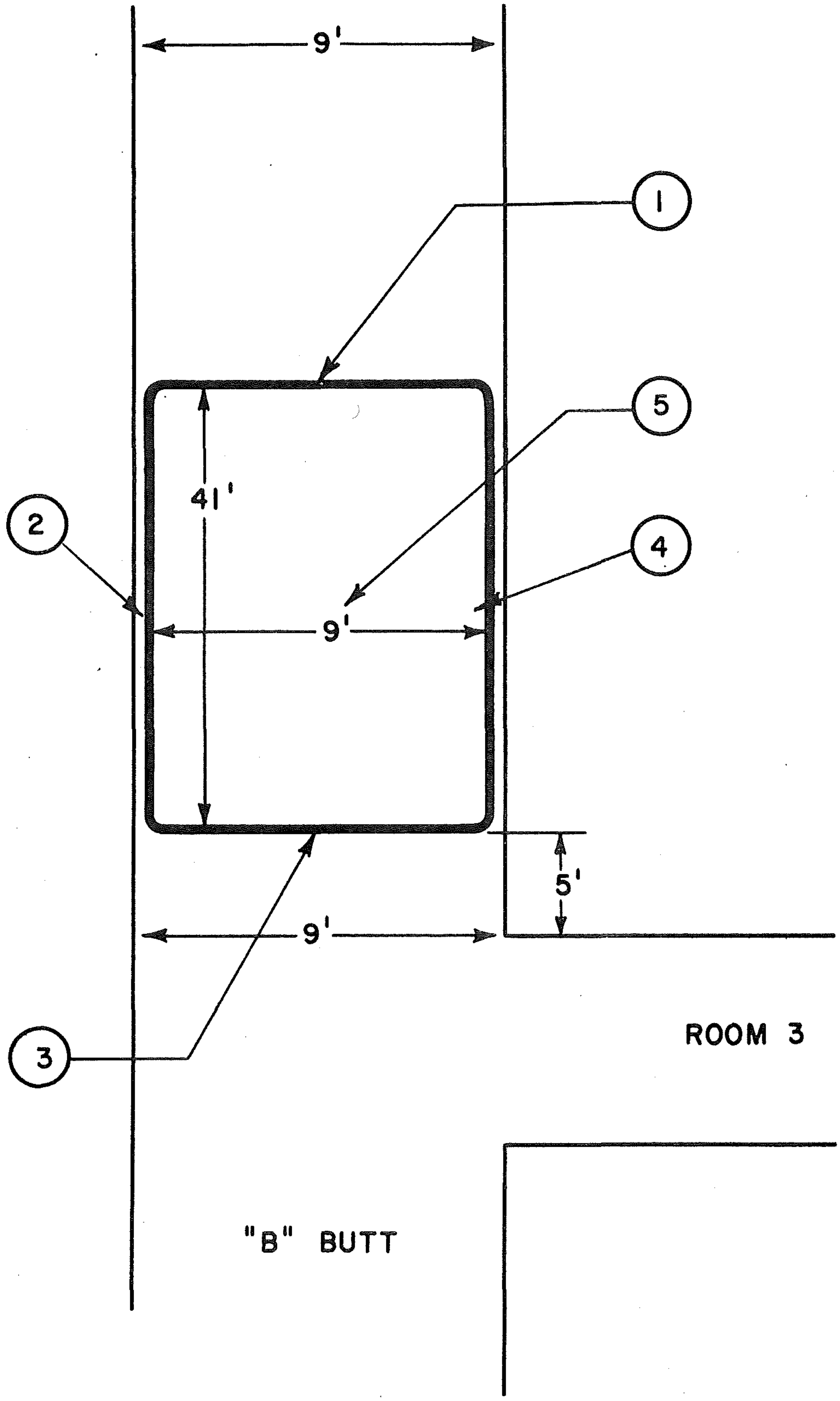

Figure 6-5. Site B - Fanfold Locations

Table 6-12

Results

Site B, 15 Foot Fanfold Simulator, 1 Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-5													
	1		2		3		4							
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	4	.002	5	0.00313	5	0.00313	6	0.0045						
3	5	.00313	6	0.0045	6	0.0045	6.5	0.00528						
4	3	0.00113	4	0.002	3.5	0.00153	4	0.002						
5	6	0.0045	7	0.00613	7	0.00613	8	.008						

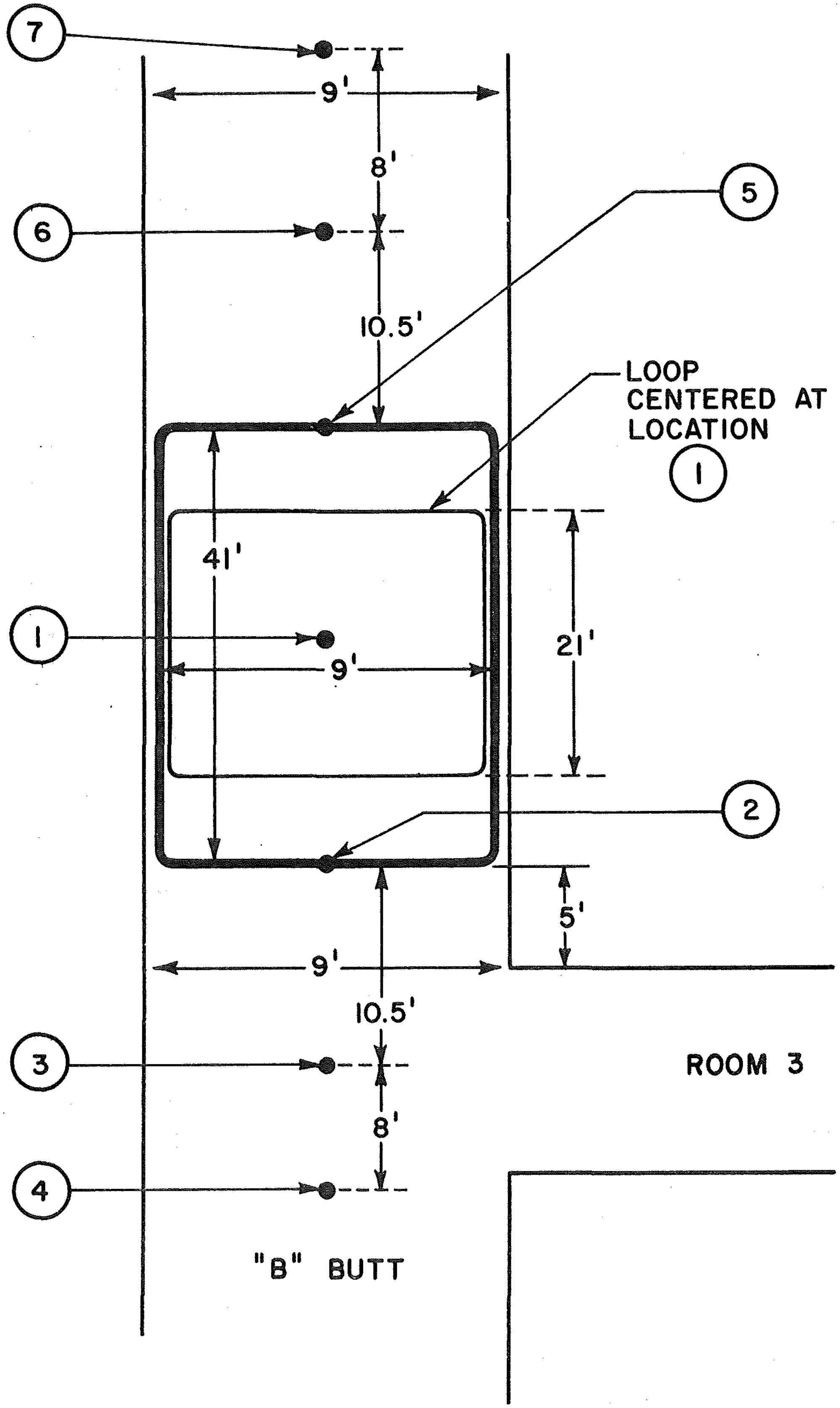

Figure 6-6. Site B - 60 Foot Loop Locations

Table 6-13

Results

Site B, 60 Foot Loop, 1 Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-6													
	1		2		3		4		5		6		7	
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	2200	605	900	101	360	16.2	60	0.45	1000	125	220	6.05	180	4.05
3	2500	781	1100	151	440	24.2	90	1.01	1200	180	270	9.11	200	5.0
4	1400	245	600	45	240	7.2	70	0.613	600	45	160	3.2	130	2.11
5	2700	911	1150	165	600	45	150	2.81	1350	228	300	11.3	240	7.2

6.3 SITE C RESULTS

The measurements performed at Site C were similar to those at Site B.

Figure 6-7 shows the vertical loop locations and Table 6-14 gives the results for these measurements.

Figure 6-8 gives the locations for the 15 foot leg wire "fanfold" simulation measurements. Table 6-15 gives the results. No readings could be obtained at location 4.

Figure 6-9 shows the locations of the 60 foot loop centers for the 60 foot loop measurements. Note that the loop was spread to reach the full width of the drift on both sides of the transmitting loop and, since the widths differ so did the sixty foot loop width. Table 6-16 gives the results.

Table 6-14

Results

Site C, Vertical Triangular Loop, One Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-7													
	1		2		3		4		5		6			
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	400	20.0	8	0.008	360	16.2	13	0.0211	340	14.5	11	0.0151		
3	540	36.5	10	0.0125	460	26.5	18	0.0405	440	24.2	15	0.0281		
4	280	9.8	5	0.00313	240	7.2	9	0.0101	220	6.05	7	0.00613		
5	740	68.5	14	0.0245	640	51.2	24	0.072	600	45	20	0.05		

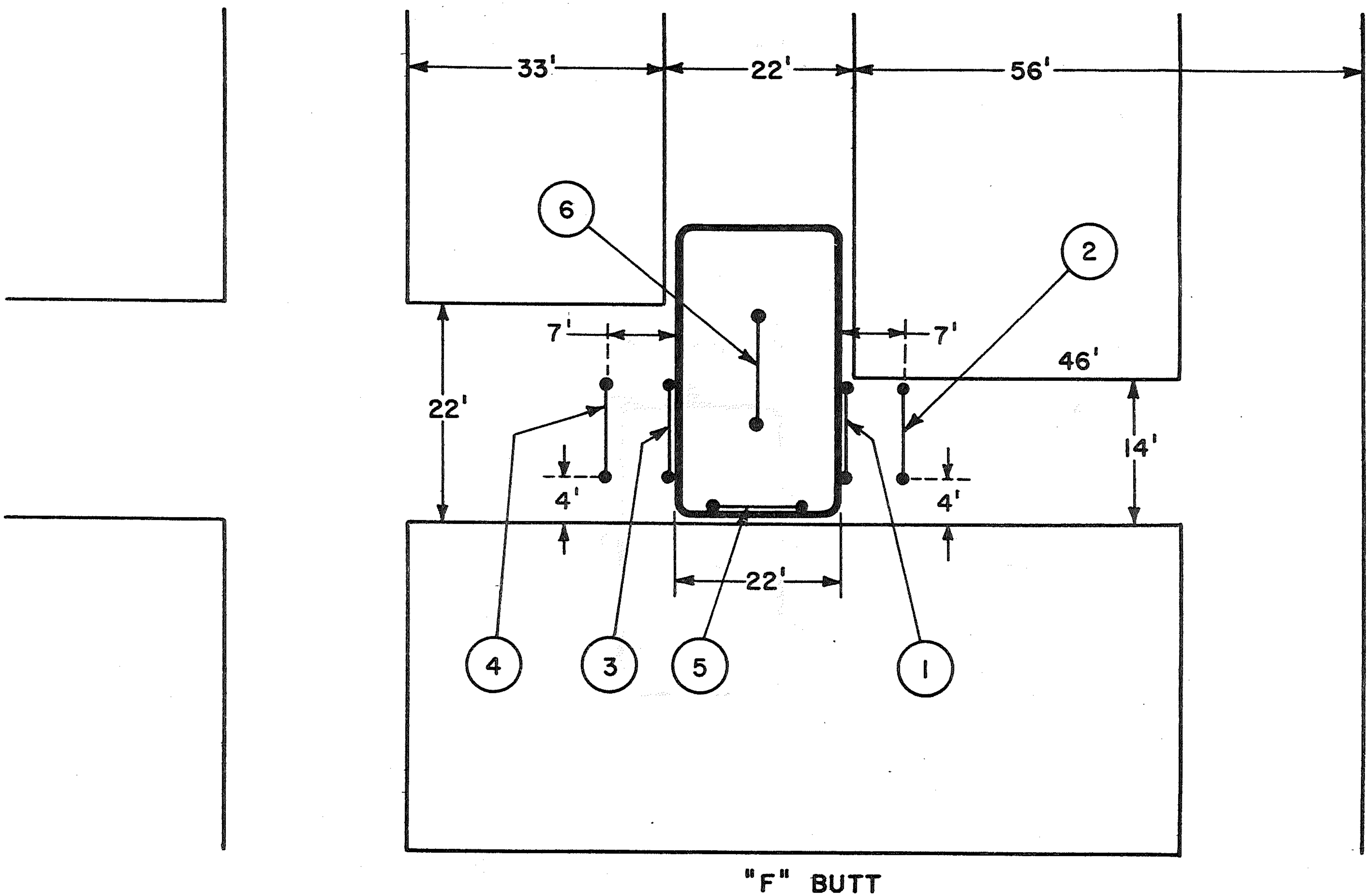

Figure 6-7. Site C - Triangular Loop Locations

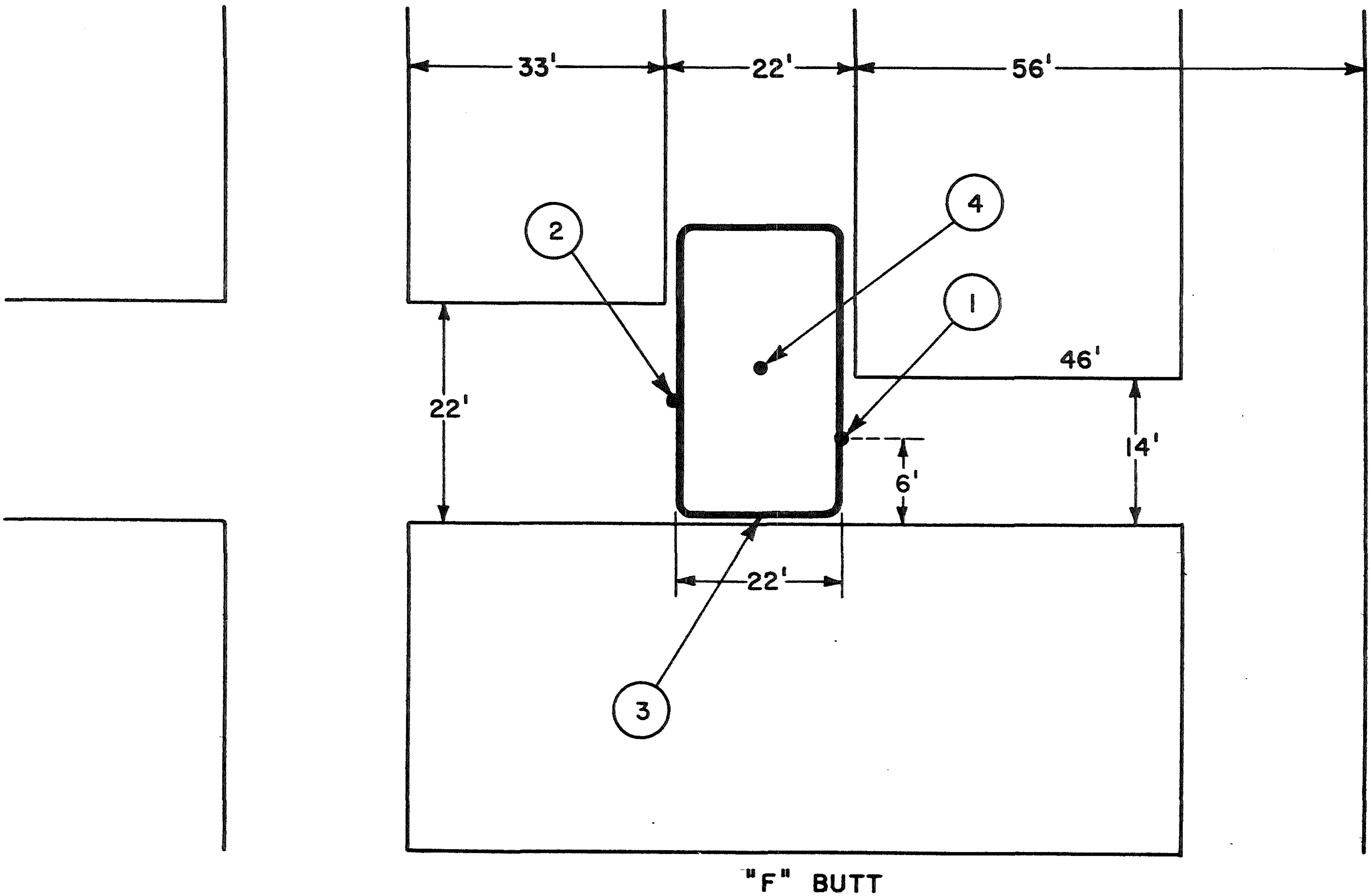

Figure 6-8. Site C - Fanfold Locations

Table 6-15

Results

Site C, 15 Foot Legwire "Fanfold" Simulator, One Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-8													
	1		2		3									
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	5.5	0.00378	5	.00313	8	.008								
3	7.5	0.00703	6	.0045	11	.0151								
4	4	0.002	3	.00113	6	.0045								
5	10	0.0125	8	.008	15	.0281								

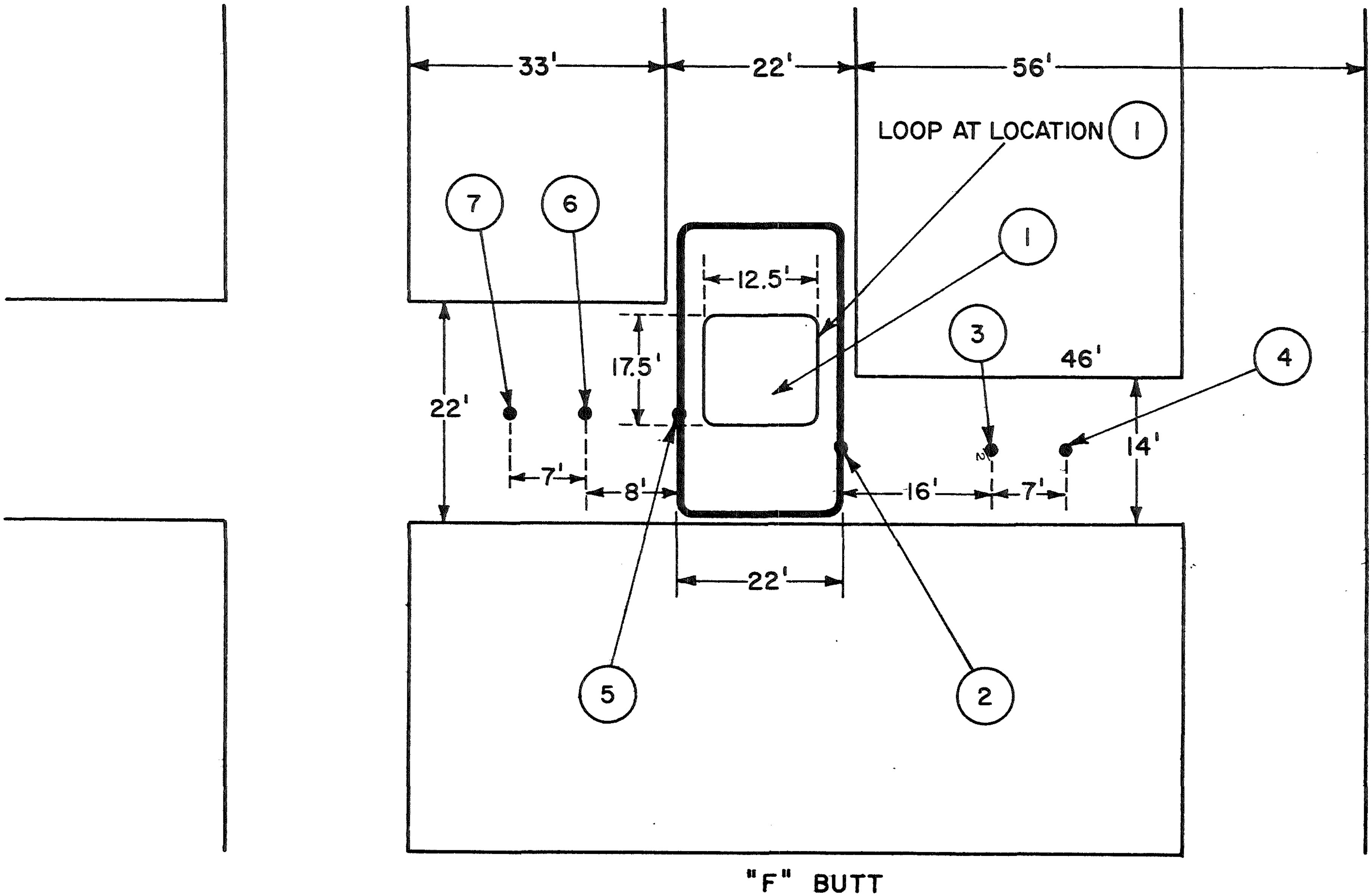

Figure 6-9. Site C - 60 Foot Loop Locations

Table 6-16

Results

Site C, 60 Foot Loop, One Ohm Load

FREQUENCY	LOCATIONS ON FIGURE 6-9													
	1		2		3		4		5		6		7	
KHz	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW	mV	mW
2	1000	125	460	26.5	800	80	72	0.648	700	61.3	600	45	80	0.8
3	1200	180	600	45	1000	125	94	1.1	850	90.3	850	90.3	100	1.25
4	600	45	320	12.8	500	31.3	48	0.288	500	31.3	500	31.3	50	0.313
5	1700	361	840	88.2	1350	228	140	2.45	1200	180	1150	165	150	2.81

7. EVALUATION OF POSSIBLE HAZARD

Franklin Institute Final Report F-C3102, *Evaluation and Determination of Sensitivity and Electromagnetic Interactions of Commerical Blasting Caps*, prepared for the U.S. Bureau of Mines under Contract HO210068, August 1973, shows that the constant current 0.1% (95 % confidence) pin-to-pin firing level of U.S. manufactured blasting caps used in underground operations is greater than 70 mW for 10 second exposure of the cap. The "all fire" 99.9% (95% confidence) level can be as low as 124 mW for these same items. The report also points out that for high power levels, i.e. close to the "all fire" level, the time 'til bridgewire break — an almost sure indication of initiation — is about a millisecond or less. We conclude from these data that, for purposes of evaluating response at 2 to 5 KHz, 24 millisecond stimuli, the average power supplied during the 24 millisecond period can be compared directly with the dc constant current results to estimate possible hazard. This is certainly true for power levels of about 125 mW for some caps and a good conservative estimate for powers of lower value for all caps.

The generally accepted hazard level for blasting caps is 40 mW. Specifically, if average powers greater than 40 mW can be delivered to a blasting cap in a given configuration or situation, that configuration is considered to be potentially hazardous. In light of the considerations above, our criterion for possibly hazardous configurations is that the average power derived during the 24 millisecond "on" time of the transmitter is greater than 40 mW.

Table 7-1 summarizes the maximum received powers for the various blasting wire configurations simulated during the tests. Applying the 40 mW hazard criterion to these data we observe that transportation of *boxed fanfolded* blasting caps over the transmitting antenna will not lead to a potential hazard even if the boxes inadvertently come in contact

Table 7-1. Maximum Received Powers

Simulated Blasting Wiring Configuration	Maximum Received Power (mW)			Notes
	Site A	Site B	Site C	
Vertical Triangular Loop	61.3	24.2	68.5	Vertical loop over transmitter wire.
	3.61	-	-	One foot away
	0.29	0.01	0.25	Middle of loop
Horizontal Triangular Loop	10.5	8.45	-	Middle of transmitter loop
30 Foot Fanfold	0.281	-	-	On Transmitter Wire
15 Foot Fanfold	0.013	0.008	0.0281	On Transmitter Wire
60 Foot Horizontal Loop on Floor	1450	911	361	60 ft. loop centered in transmitting loop
	551	228	180	1/2 in, 1/2 outside transmitting loop
	125	45	165	Touching loop
	0.45	-	-	9' from loop
	-	7.2	-	8' from loop
	-	-	2.81	7' from loop
46 Foot Wired Coal Face	211	-	-	Transmitter antenna touching face wiring

with the transmitting antenna. *However, any blasting operation that involves unfolding the lead wires of caps or involves wiring connected to blasting caps should be strictly prohibited in the immediate area of the transmitting antenna.* *

The data indicate that the potential hazard drops steeply with physical separation from the antenna and that at a 10 foot separation between the transmitting antenna and any blasting wiring there is no potential hazard.

Note that the above observations are based on the worst case results of our measurements. We feel sure -- particularly considering the fairly good agreement between the small loop measurements (Table 6-6) and theory -- that we understand the coupling mechanism for this frequency regime. Hence we note that the coupled power should vary directly as the square of the frequency of the antenna current and also vary directly as the square of the amplitude of the antenna current. Thus

$$P_R = K\ f^2 I^2$$

where

P_R is power received

K is a proportionality constant

f is frequency in kHz, and

I is peak to peak current in amps

describes the functional dependence of our test results on frequency and current. Our worst case results were obtained, without exception, at the 5 KHz/4 amp. peak to peak values for these parameters. If the overall *electromagnetic Tester* were to be operated, at say 2.5 KHz, with a 2 amp. peak to peak antenna current we would expect, from equation 6-5, that the worst case observed powers would drop by a factor of 160. Applying this factor to the results of Table 7-1 we see that only the 60 foot horizontal loop, centered in the transmitting loop, would lead to power levels above the 40 mW hazard level.

Further reductions in frequency and/or current amplitude could thus quite clearly lead to a safe operating system.

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* Signs clearly stating this hazard must be posted in mine areas where the transmitting antenna is used.