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Research and Development Technical Report

ECOM-2919

SEISMIC COMMUNICATIONS TO UNDERGROUND SITES (STERLING HILL MINE EXPERIMENTS)

By

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W. Schneider

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

ECOM-2919

SEISMIC COMMUNICATIONS TO UNDERGROUND SITES
Sterling Hill Mine Experiments

by

Kurt Ikrath
Ronald F. Johnson
Kenneth J. Murphy
Wilhelm Schneider

DECEMBER 1967
DA TASK No. 1PO 14501 B31A 01 43

U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY

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ABSTRACT

Seismic signal transmission experiments made at the Sterling Hill Mine of the New Jersey Zinc Co., Ogdensburg, New Jersey are described. Using less than 100 watts primary power, nominal 80 Hz CW signals and pulsed CW signals were transmitted from experimental seismic transducers placed on rock outcrops atop Sterling Hill. These signals were received with portable 80 Hz resonant experimental seismic transducers at various locations in the mine.

Resultant experimental data such as variations of signal amplitudes versus depth, signal propagation velocities, and wave shape distortions, etc., are analyzed and evaluated.

Implications regarding the design and operation of HARD LINE communications circuits for underground hardened sites are discussed.

FOREWORD

Research was performed and authorized under DA 01743, AMC Code 5011 11 854 01 Project/Task No. 1PO 14501 B31A 01, "Research in Electronics - ECOM".

The assistance of personnel of the New Jersey Zinc Co., Ogdensburg, New Jersey, is hereby gratefully acknowledged. Particular thanks are extended to Mr. S. S. Huyett, Manager of Mines, and Mr. R. W. Metsger, Regional Geologist.

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SEISMIC COMMUNICATIONS TO UNDERGROUND SITES
Sterling Hill Mine Experiments

INTRODUCTION

Experiments performed in the Sterling Hill Mine of the New Jersey Zinc Company, Ogdensburg, N. J. comprise part of a research program for the development of methods and instrumentation for HARD LINE communications through solid earth media and water. The program involves both seismic-acoustic and electromagnetic means of communications in the form of feedback and feed forward systems, whereby either the seismic-acoustic or the electromagnetic transmissions may be used as standards of coherence for detection and deciphering of signals.

This report describes experiments during which nominal 80 Hz seismic signals were transmitted from the top of Sterling Hill, and received at various underground locations in the Sterling Hill Mine.

DISCUSSION

1. Instrumentation

Seismic communications experiments were conducted with our experimental seismic system comprised of six 80 Hz, 10 W max portable seismic transducers (See Fig. 1 and Table 1) and two large 80 Hz, 200 W max seismic transducers (See Fig. 2 and Table 1) plus ancillary equipment, i.e., amplifiers, signal generators, phase shifters, meters, and recorders (Ref. 1).

2. Experimental Setup for Surface to Underground Transmission

The two large seismic transducers were placed on a rock outcrop on the hill. A thin layer of cement was used to couple their steel pistons to the rock surface. These transducers were driven by power amplifiers housed in an M-109 truck. They were operated either separately or as a phased array with the phase between their drive voltages controlled by a resolver-type phase shifter. This setup on the hill formed the seismic transmitter (XTD Site, Fig. 3). Its location relative to the reception sites inside the mine is shown in Fig. 4. The transmitter site is seen to be located above the mine adit roughly halfway between its entrance and the shaft station. (The layout of the adit is shown in Fig. 5). Measurements of signal levels were made with the small portable transducers used as receivers. Signal levels were measured along the concrete walk in the adit (Fig. 6), and on the floor in the vicinity of all stations in the incline shaft (Fig. 4). Simultaneous recordings of pulsed 80 Hz signals were made: (a) next to the transmitter on the hill, (b) inside the adit, and (c) on the 180-ft. level of the mine below the administration building. At this latter location, a drift intersects with an almost vertical emergency escape shaft. An RG-58-A/U cable was laid through the escape shaft to connect the optical recorder in the adit with the receiver transducer at the 180-ft. level (Fig. 4). Another cable was laid from the hill into the adit to connect a monitor transducer at the transmitter

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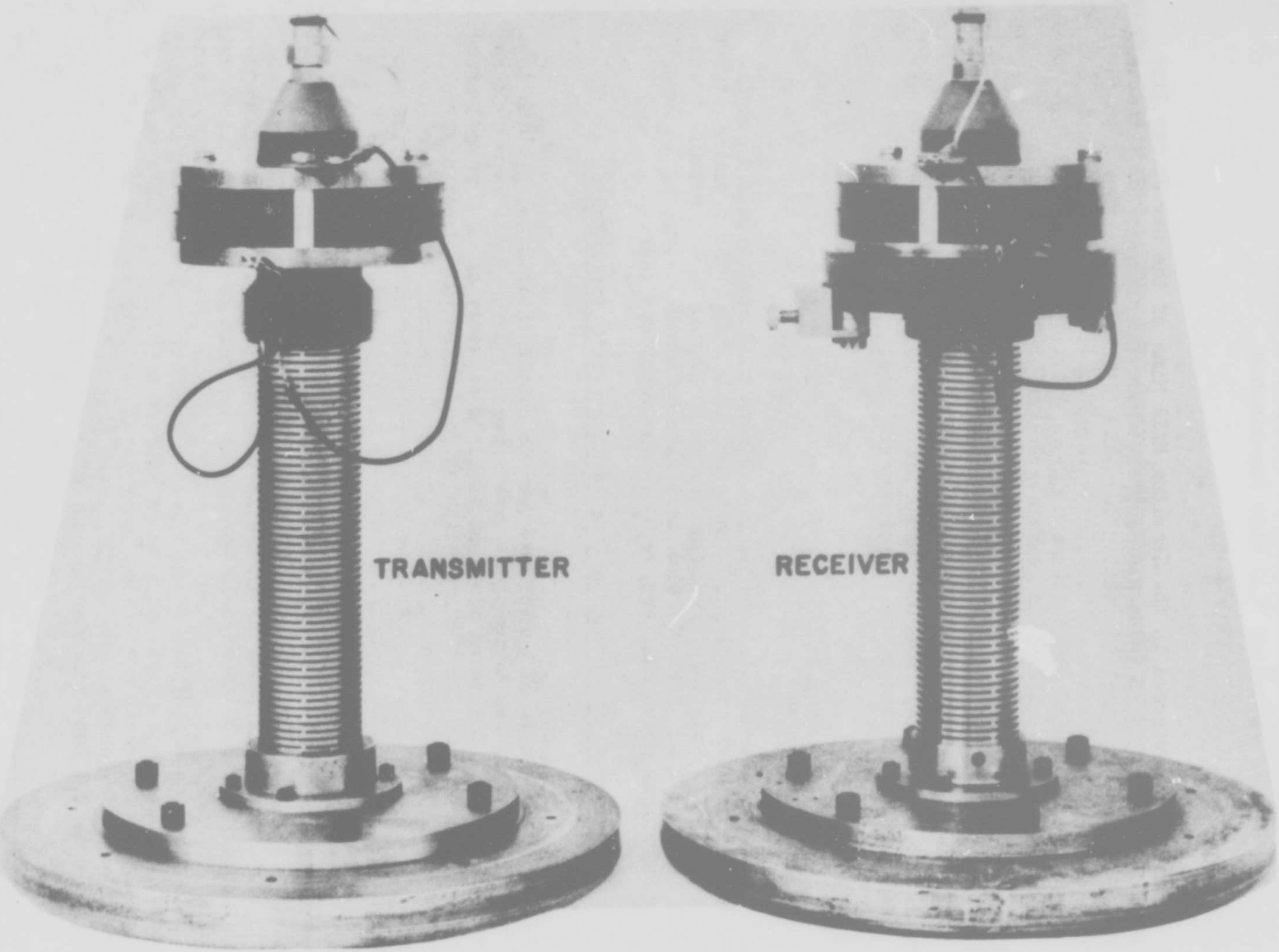
[1] K. Ikrath, W. Schneider, R. Johnson, "Active Seismic Systems for Communications and Surveillance," Technical Report No. ECOM 2695, April 1966.



80 CPS–SEISMIC TRANSDUCER (10 WATT MAX)

FIG. 1

TABLE I

DESIGN DATA FOR 80 Hz SEISMIC TRANSDUCERS

	Small Transducer	Large Transducer
Carbon-Steel Slotted Tube		
Youngs Modulus (kg/cm^2)	2×10^6	2×10^6
Outer Diameter (cm)	5.08	21.83
Mean Diameter (cm)	4.76	20.76
Inner Diameter (cm)	4.45	19.69
Slot Width (cm)	0.08	0.32
Beam Width (cm)	0.28	0.63
Slot Length (cm)	5.00	10.48
Wall Thickness (cm)	0.32	1.07
Slots/Section on Circumf.	3	6
Slot Sections along Length	50	32
Static Stiffness (n/m)	10^5	2×10^6
Mass (kg)		
Slotted Tube (active part)	0.640	14.500
Drive Coil & Coil Mount	0.160	3.090
Ground Piston	18.935	285.100
Drive System		
(Indox V Ceramic Magnet)		
Coil: Turns #20 Copper Wire	168	700
Mean Diameter (cm)	4.55	7.40
Piston Diameter (cm)	30.5	60.33

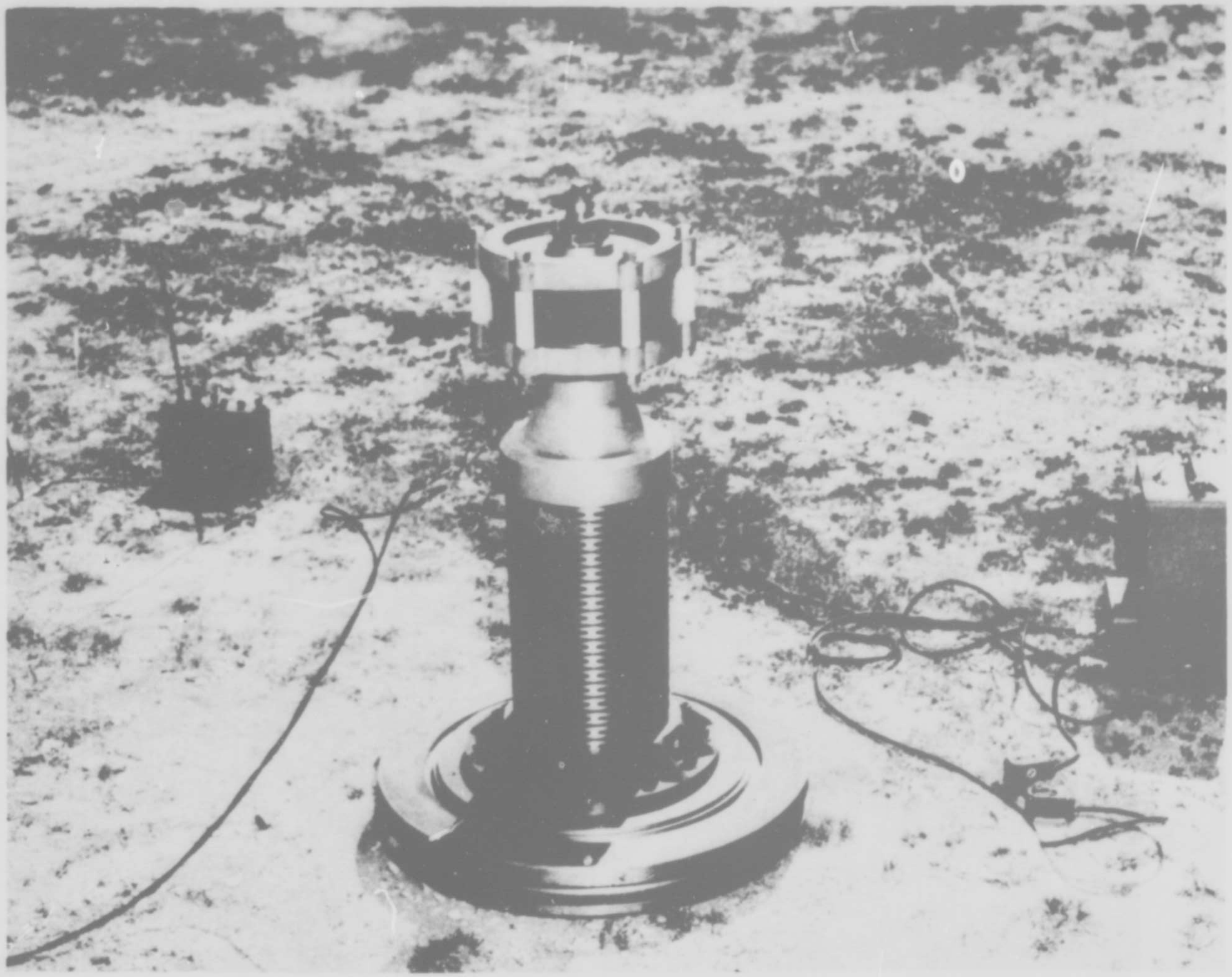
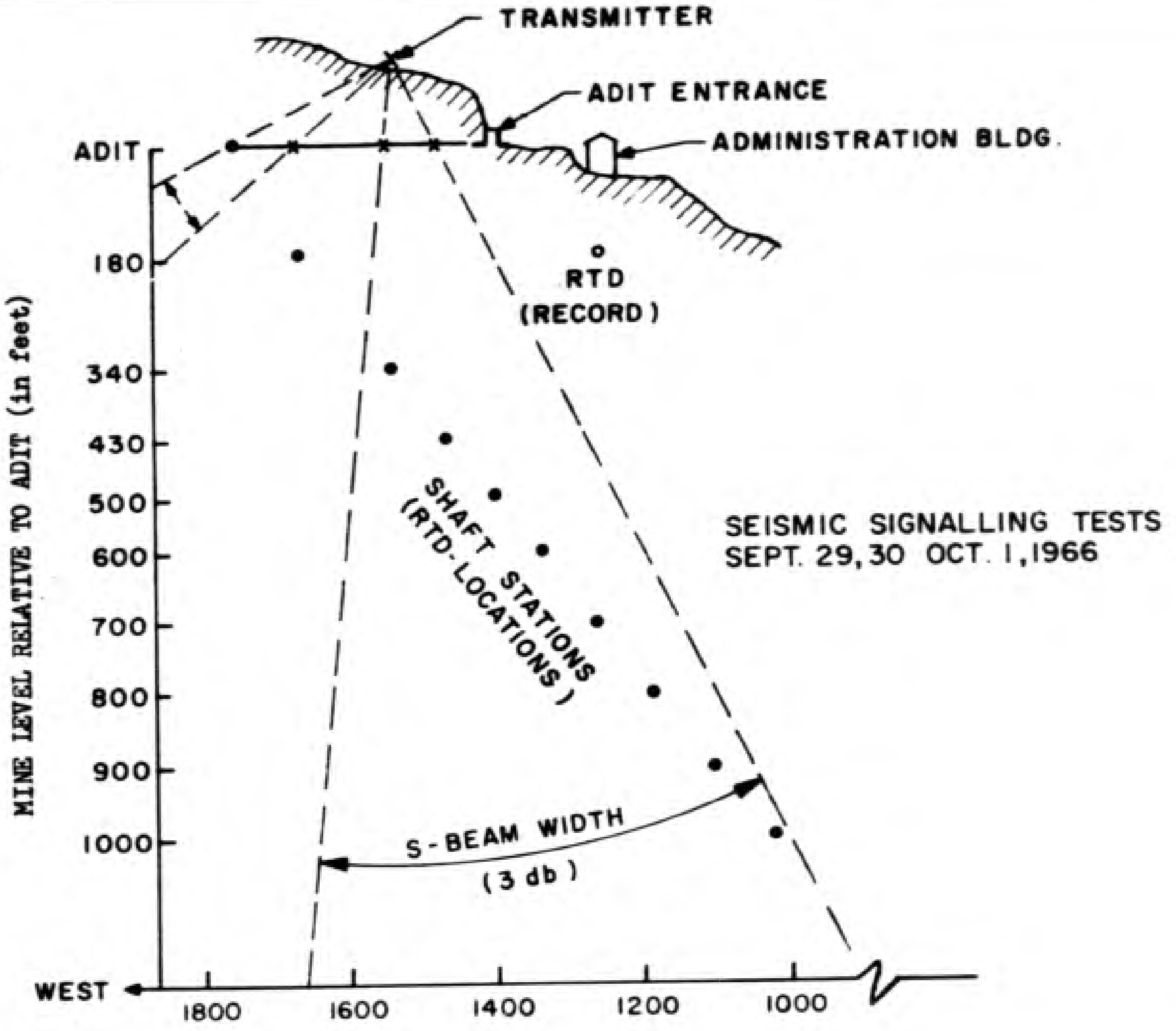


FIG. 2 SEISMIC TRANSDUCER, 200 WATT, 80 Hz

FIG. 3

XTD Site
Sterling Hill,
N. J. Zinc Mine
Ogdensburg, N.J.



VERTICAL - PROJECTION

FIG. 4 [FEET FROM MINE DATA POINT]

FIG. 5

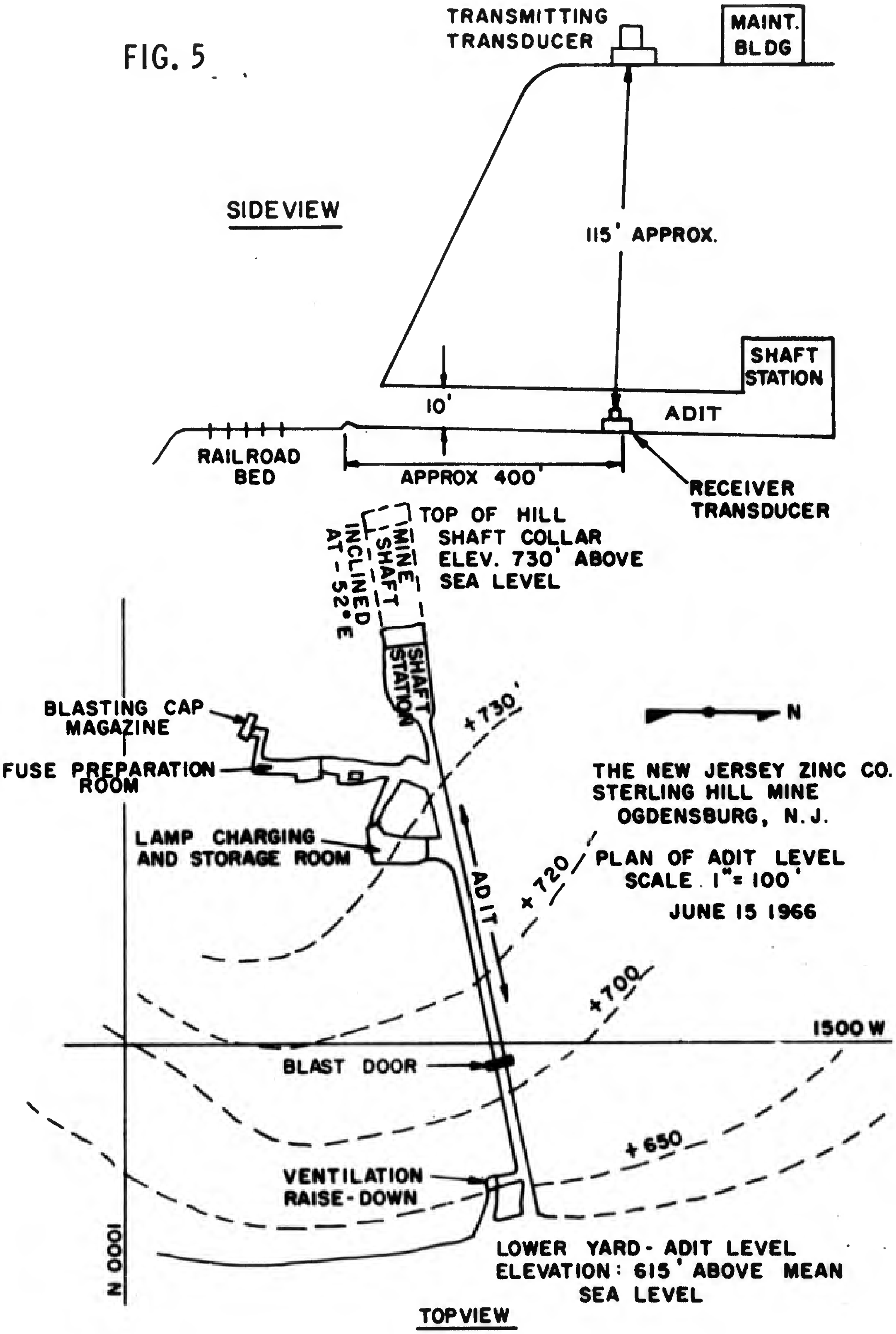

SIDEVIEW
TRANSMITTING TRANSDUCER
MAINT. BLDG
115' APPROX.
SHAFT STATION
10'
ADIT
RAILROAD BED
APPROX 400'
RECEIVER TRANSDUCER
TOP OF HILL
SHAFT COLLAR
ELEV. 730' ABOVE SEA LEVEL
MINE SHAFT
INCLINED AT - 52° E
SHAFT STATION
BLASTING CAP MAGAZINE
FUSE PREPARATION ROOM
LAMP CHARGING AND STORAGE ROOM
+730'
N
THE NEW JERSEY ZINC CO.
STERLING HILL MINE
OGDENSBURG, N. J.
PLAN OF ADIT LEVEL
SCALE 1" = 100'
JUNE 15 1966
ADIT
+720
+700
1500 W
BLAST DOOR
+650
VENTILATION RAISE - DOWN
1000 N
LOWER YARD - ADIT LEVEL
ELEVATION: 615' ABOVE MEAN SEA LEVEL
TOPVIEW

FIG. 6

Adit Level
N. J. Zinc Mine
Ogdensburg, N.J.

site with the optical recorder. Other channels of the optical recorder were connected via cables with receiver transducers inside the adit. It is necessary to point out that humidity in the mine is almost 100%, and for this reason the sensitive optical recorder was not moved to lower levels of the mine. Measurements of signals at different mine levels down to 1500 feet (relative to the adit) were made with one and the same receiver transducer connected via an RG-58-A/U cable to a PAR-JB-5 Lock-In Amplifier. Signal amplitudes (Figs. 7, 8, 9) correspond to the transducer output voltages as displayed on the PAR-JB-5 meter. Power for the PAR-JB-5 was obtained from either a 12-volt lead storage battery via an ac inverter, or from ac outlets at the control panels of the mine elevator.

3. Experiments and Measurements

On July 16, 1966 a preliminary test was made to ascertain whether 80 Hz signals can be received inside self-supported tunnels and shafts embedded in hard rock (Franklin limestone). The seismic transmitter was set up on the hill, and a receiver transducer was placed inside the mine adit on the concrete walk. In spite of the extremely high seismic background noise from mining operations (primarily from a huge three-story-high rock crusher), pulse modulated 80 Hz seismic signals, as well as CW signals, were received with signal plus noise-to-noise ratios of no less than two to one and generally better than three to one.

Encouraged by results of this preliminary test (Table 2), subsequent experiments and measurements were conducted inside the mine during the period from September 28 to October 1, 1966 and in April 1967. Seismic signal propagation measurements were made during the night and in between work shifts to avoid interference from regular mining operations. During the period from September 28 to October 1, 1966 the following measurements were made:

a. The underground radiation patterns of the seismic transducers were probed by measuring CW signal strength along the horizontal adit beneath the transmitter site. The resultant measurement data, obtained with about 100 watts drive power for one of the seismic transducers on the hill, are shown in Fig. 7.

b. The variation of signal strength as a function of depth was measured on the floors of the station chambers along the inclined shaft and on the drifts of several mine levels (Fig. 4).

The first measurements of this type were made in the fall of 1966 when drilling was in progress at the 700-ft. level of the mine. Results of these measurements are plotted in Fig. 8. Three signal levels are given: (1) the initial "pulse on" peak amplitude of the pulse signal (2) the steady-state level of the 80 Hz CW pulse mark period, and (3) the "pulse off" level during the space period. Mark periods and space periods were derived from a GR (General Radio) tone burst generator set at 1.6 seconds on, and about 1.5 seconds off, respectively. One sample measurement of background noise was made at the 800-ft. level when drilling operations at the 700-ft. level were halted for a brief moment (See note in Fig. 8). When the drills were turned off, the noise at the 800-ft. level decreased by 20 dB. However, drilling noise was not received at the 900-ft. level where both signal and noise show a pronounced minimum. In order to verify these results, it was decided to repeat this measurement during a period when drills in the mine were not in operation.

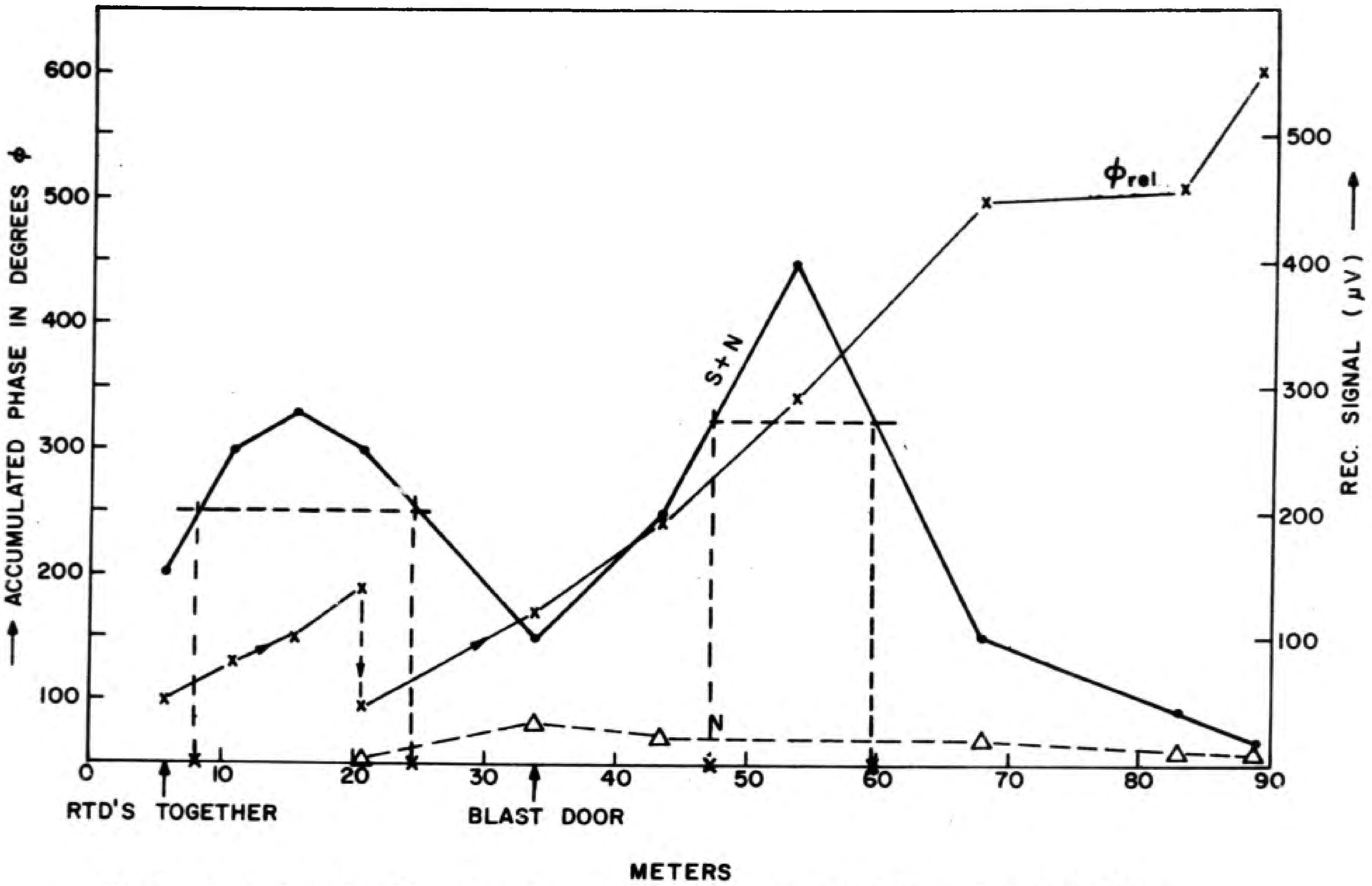
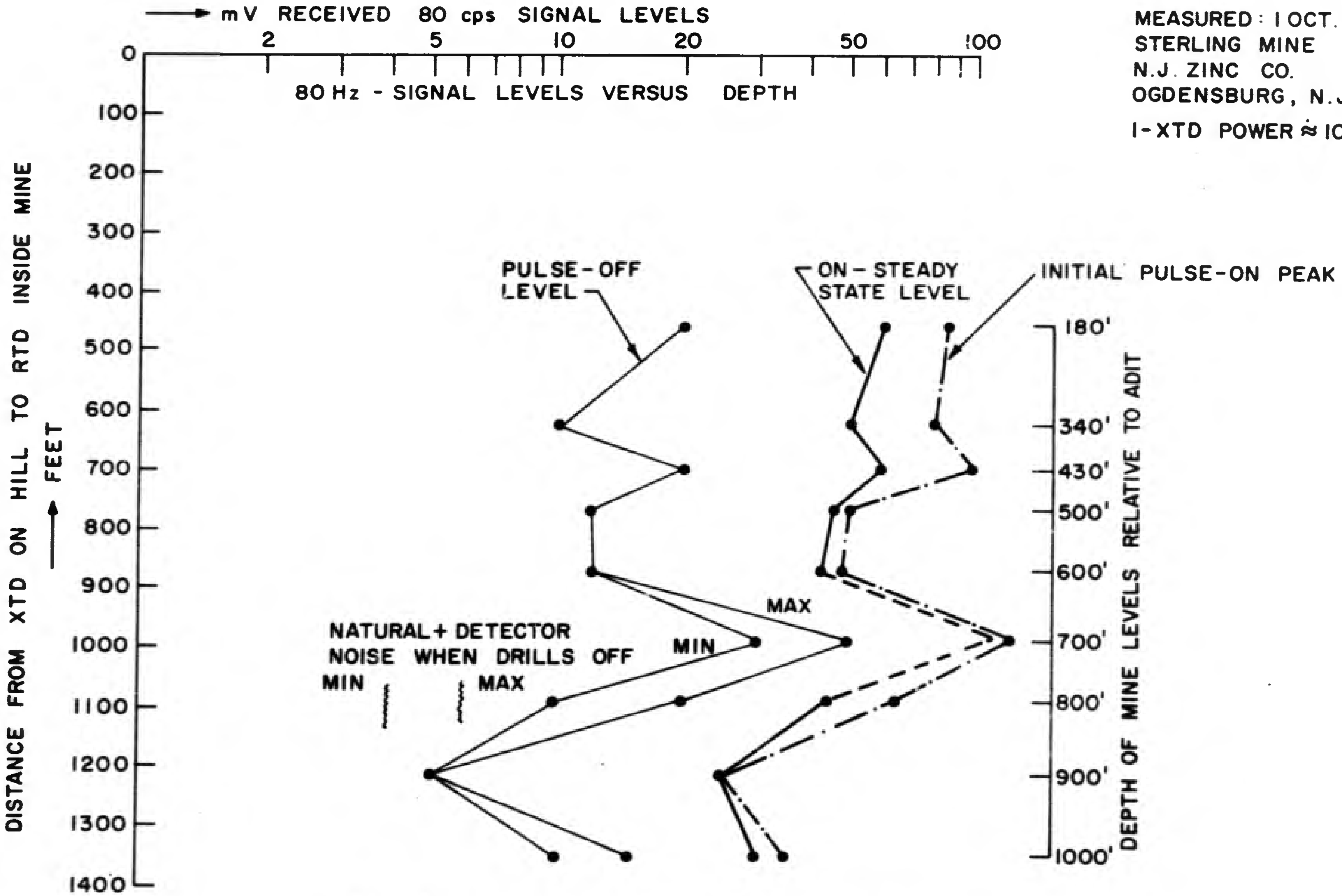
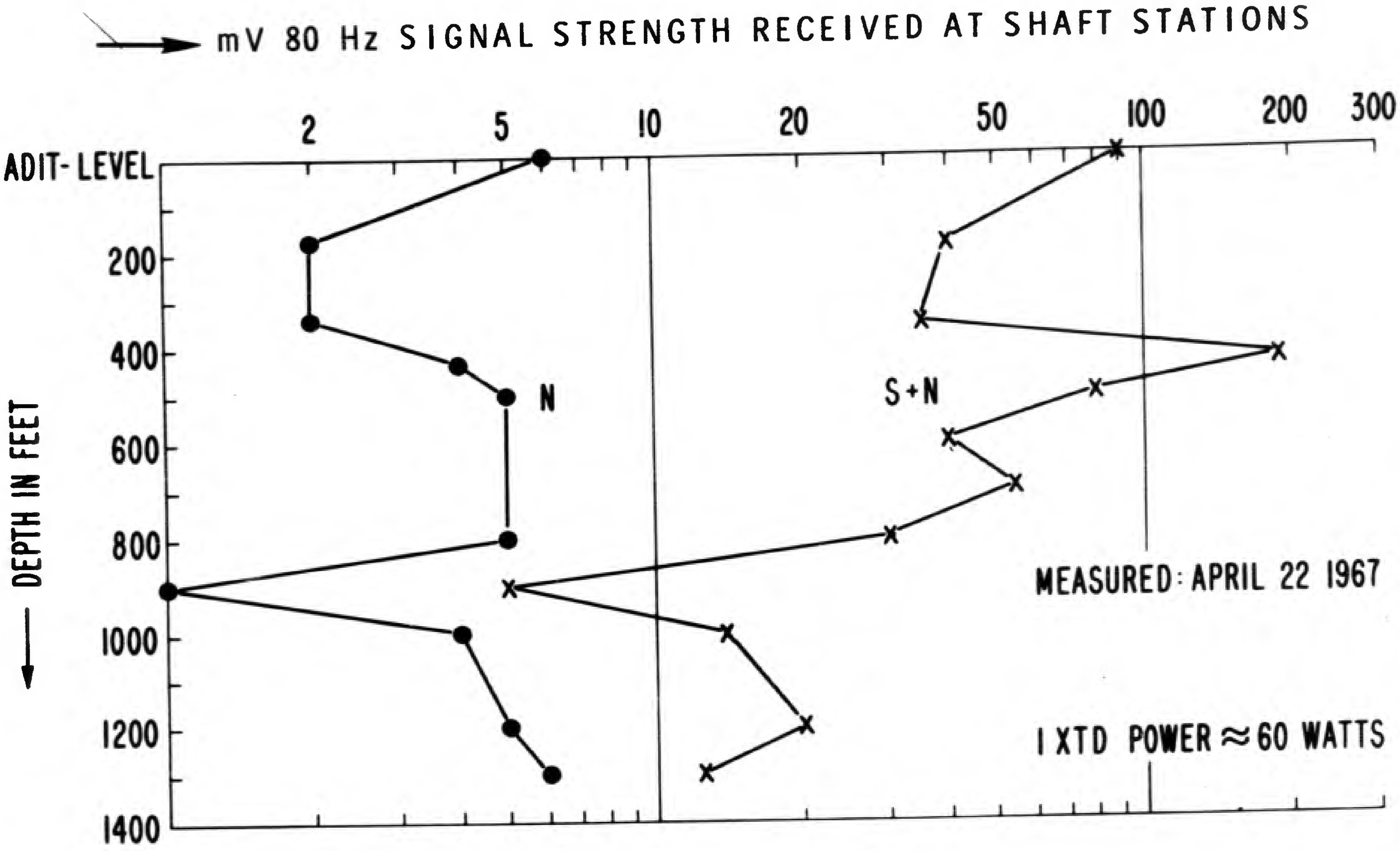


FIG. 7. N. J. Zinc Co. CSW-Amplitude and Phase Along Adit Level (September 29, 1966)



MEASURED: 1 OCT. 66
STERLING MINE
N.J. ZINC CO.
OGDENSBURG, N.J.
1-XTD POWER ≈ 100 WATT

FIG. 8 SIGNAL VS DEPTH ALONG MINE SHAFT
N. J. ZINC MINE, OGDENSBURG, N.J.



MEASURED: APRIL 22 1967

I XTD POWER ≈ 60 WATTS

FIG. 9 SIGNAL VS DEPTH ALONG MINE SHAFT

PRELIMINARY TEST: XTD on Hill; RTD inside Adit
(16 JULY 1966)

TIME APPROX.	XTD POWER IN AMP X VOLT	LOCATION RTD DISTANCE FROM ENTRANCE IN FEET	RTD RECEIVED			REMARKS ON STATUS OF MINING OPERATIONS
			S + N µV	N µV	S + N / N	
1100	1.5 x 55	75	150	50	3:1	Elevators & Rockcrusher ON
1205	2 x 60	75	350	100	3.5:1	Elevators & Rockcrusher ON
1400	2 x 60	140	420	120	3.5:1	Elevators & Rockcrusher ON
1540	2 x 60	140	250	10	25:1	Elevators & Rockcrusher OFF*

NOTE: All measurements made with HR-8 detector connected to RTD output via cable.

HR-8 Settings Q = 25 RC = 3 Sec f = 80 Hz

TABLE 2

The measurement was repeated on a week end in April 1967. This time a transmitter power of only 60 W was used for the single transducer on the hill. The results of this CW measurement, which are plotted in Fig. 9, show a marked improvement in the signal-to-noise ratio when compared to previous measurements made while drills were in operation.

c. The seismic signal propagation velocities in the rock were measured by recording the shapes and delays of transmitted and received pulse-modulated 80 Hz seismic signals. Sample recordings (Fig. 10) show the signals as received on the hill (upper traces); inside the adit (center traces); and on the 180-ft level (bottom traces). Recordings were made with a paper speed of 4 in/s (Fig. 10A) and with 16 in/s (Figs. 10B and 10C). In the latter cases, leading and trailing edges of the received pulse signals are shown separately.

d. The effectiveness of the two transducer arrays on the hill was determined by recording the variation of signal amplitudes received in the adit as a function of continuous variation of phase between the electrical drive voltages of the transducers. The resultant sinusoidal modulation of the 80 Hz carrier is seen in the recording exhibited in Fig. 11. The upper trace is from the monitor transducer on the hill; the lower traces show the signal received simultaneously at various locations inside the adit. These recordings were made in September 1966.

4. Evaluation and Interpretation of the Results

A. Signal Radiation Attenuation

The double-humped curve showing the signal strength along the adit (Fig. 7) indicates that the seismic transducer radiates a split beam of seismic waves into the ground.[2] This is in good agreement with the theory;[2] with measurements made on walls of a cliff;[3] and with radiation patterns obtained in photoelastic gelatin models.[3]

By taking the half-power values (-3 dB points) on both sides of the two humps of the curve, an outline of the two beams can be obtained. The outline of the two beams and their orientation relative to the minimum direction is shown by dashed lines in Fig. 4. Note that when going down from the surface, the inclined shaft intersects first the left beam and then the right beam, with the minimum between.

The variation of signal strength as a function of depth along the inclined shaft in Fig. 9 conforms to the split-beam radiation pattern: beginning at the adit level, first the signal decreases with depth as the receiver locations move out of the left beam; then with increasing depth, the receiver locations begin to move into the right beam until the signal increases to a maximum at 430 ft ; finally at greater depths as the receiver moves out of the right beam, the signal decreases rapidly until it reaches a minimum at the 900-ft level. Interestingly enough, the noise also has a pronounced minimum at the 900-ft level. This minimum of signal and noise at the

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[2] G. F. Miller and H. Pursey, "Field and Radiation Impedance of Mechanical Radiators," Proc. Roy. Soc., Series A223, 1954, pp. 521-541.

[3] R. F. Johnson, "Photoelastic Modelling Techniques for Seismic Wave Propagation," Technical Report ECOM-2769, October 1966, AD No. 644590.

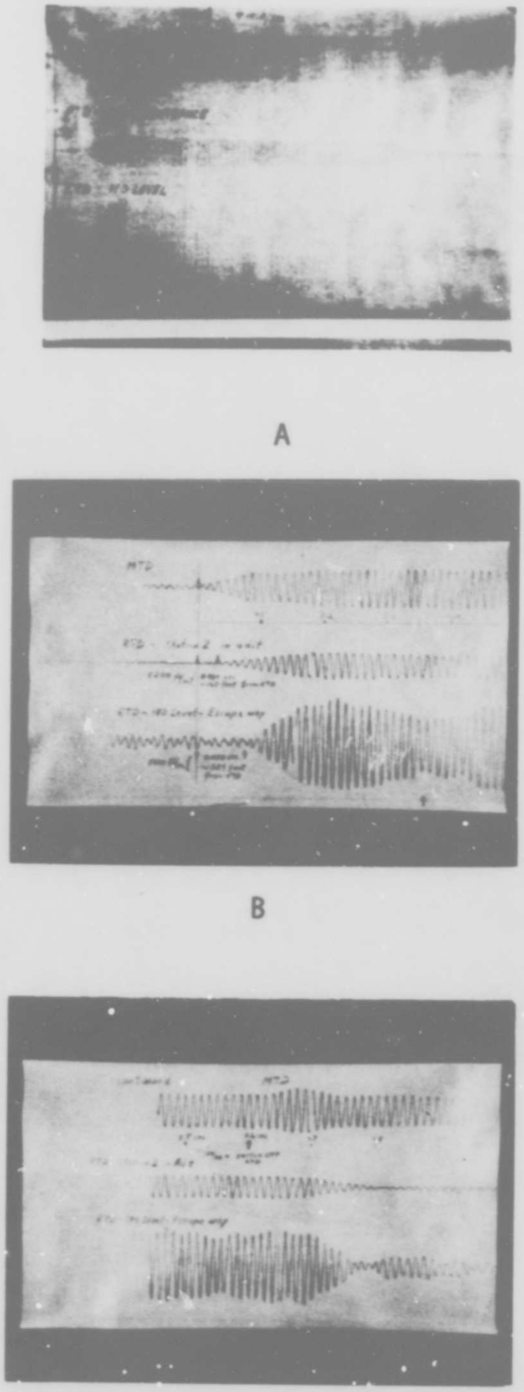

FIG. 10. Recordings of Pulsed 80 Hz Seismic Signals

N. J. ZINC MINE, OGDENSBURG, N.J.

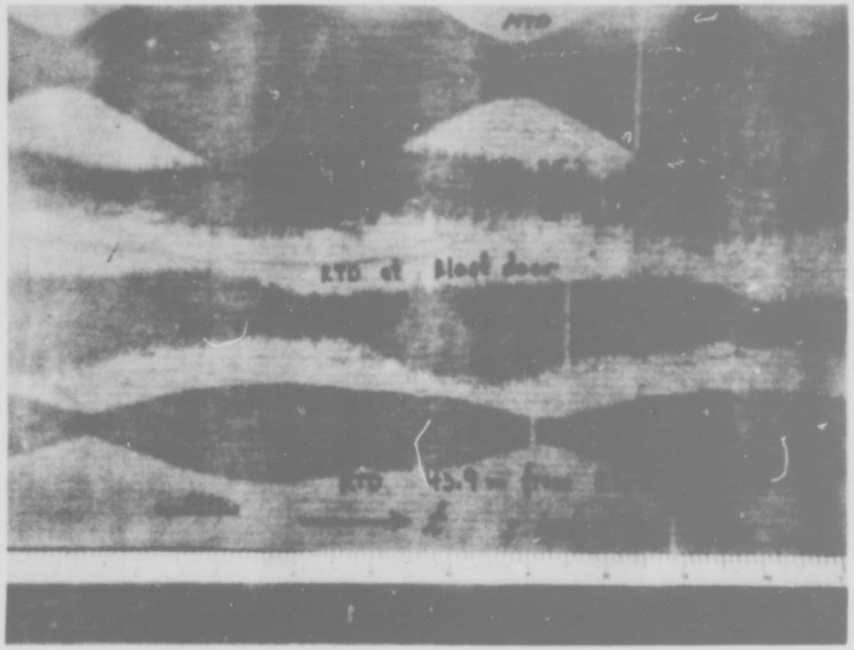

FIG. II SIGNALS RECEIVED FROM XTD ARRAY IN BEAM SWEEPING MODE

900-ft level was obtained in both measurements: (1) during the time drills were in operation in September 1966 (Fig. 8) and (2) during the quieter period on April 22, 1967 (Fig. 9). This minimum of both signal and noise at the 900-ft level was verified by moving the receiver transducer to various locations in the vicinity of the 900-ft station. Thus, these minima at the 900-ft level are geological. Mud pockets similar to those found in other parts of the mine could account for the reduced coupling of signal, as well as noise, to the receiver transducer at the 900-ft level. Further confirmation of this phenomenon is the subsequent increase in signal and noise beyond the 900-ft level. Because of the interrelation of the radiation patterns with the measured signal decay versus depth of stations along the inclined shaft, it is difficult to derive the intrinsic attenuation of the signal with depth. The mean attenuation appears to be roughly 2 to 3 dB per hundred meters depth.

B. Signal Propagation and Distortion

Evaluation of the recordings of pulsed 80 Hz signal transmissions (Fig. 10) yields group velocities of about 1.5 km/sec (5,000 ft/s) and 5 km/sec (16,440 ft/s) between surface and adit level, and between adit and 180-ft levels, respectively. According to Mr. Metsger of the New Jersey Zinc Company,[4] these values compare favorably with the 16,000 to 18,000 ft/s obtained for the Franklin limestone during a refraction survey made by the company in 1955. The much lower group velocity obtained from the recordings made at the adit station is puzzling. Possibly the ray path traversed more weathered ground between the surface and adit level than between adit and 180-ft levels. As explained by Mr. Metsger, such velocity differences are due to deep weathering and not to seismic inhomogeneity of the rock.

As mentioned previously, pockets in which the limestone has been altered to a clay-like mud by penetration of the surface water along joints and faults are common in the vicinity of the test area. While a few thin sheet-like mud zones can be traced to depths over 400 feet, most are probably less than 50 feet deep. This may account for the apparent low group velocity in the shallow zone between the transmitter and the adit level receiver location.

From a communications point of view, the shallow weathered zone is the greatest contributor to the overall delay of signals recorded in Fig. 10. In addition to the propagation delays of the leading edges of the pulse signals, distortion and stretching of the trailing edges of the pulse signals must be considered.

Inspection of the switching-off transients in Fig. 10C reveals the following data:

a. After turning off the drive power of the transmitter (at the 1.6 sec mark, reverberations on the surface of the ground continued with little decay for almost a second (MTD trace). The trailing edge of the signal received underground on the adit level (center traces) shows undulating distortion with a null at 1.8 second (0.2 seconds after XTD drive power

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[4] Letter from New Jersey Zinc Company, dated November 7, 1966, and signed by R. L. Wood, Superintendent, and R. W. Metsger, Regional Geologist.

shut off). The trailing edge of the signal received at the 180-ft level has a similar distortion, but its null is slightly advanced in comparison to that at the adit level.

b. The shape of the pulse received at the 180-ft. level differs from all other pulse shapes received elsewhere by the appearance of a small sinusoidal modulation with a period of about a quarter of a second. This period of time seems to correspond to the period of acoustical reverberations of the escape shaft.

The phenomena involving acoustic low-frequency and seismic high-frequency heterodyning deserve further investigation because of their potential application for detection of infrasonic acoustical signals by active seismic systems.

Returning to measurements along the adit (Fig. 7), one finds that the accumulated phase-distance curve in Fig. 7 is smooth, except for the step-like break at a distance of about 70 meters from the entrance, where horizontal side tunnels lead from the adit to the battery chamber and to the dynamite magazine (Fig. 5). The average slope of the smooth portion of the CSW phase-distance curve (Fig. 7) yields a wavelength of 37 meters, corresponding to a phase velocity of $c = f \times \lambda = 80 \times 37 = 2960$ m/sec (which is about 3 km/sec).

Since the diameter of the adit tunnel is very small (roughly 3 meters) compared to the measured wavelength, the resultant phase velocity (3 km/sec) is practically equal to the shear-wave velocity in the rock.[5] The pressure wave velocity (obtained from the pulse record in Fig. 10) is 5 km/sec. The resulting ratio of 1.66 is typical for rocks composing the earth's crust. This is remarkable since the adit structure is very different before and behind the blast doors. From the entrance to the blast doors, the tunnel walls are solid rock. At about 4 to 5 meters behind the blast doors, the tunnel walls are reinforced with concrete and steel girders. This difference in structure apparently has little or no effect on the CW phase which is normally very sensitive to inhomogeneities. However, the dimensions of the concrete wall reinforcement are so small compared to the wavelengths that they are apparently not resolved by variations (in the form of wiggles) in the CSW phase-distance curve. This is a very important factor in communications for hardened underground sites.

Evidently reception of seismic signals in underground tunnels can be achieved very easily. However, transmission of seismic signals from the underground to the surface is difficult because the stress-stiffened rock walls of tunnels and mine shafts present extremely large mechanical impedances which are difficult to match with transducers made from steel.

C. Seismic-Acoustic Coupling for Upward Transmission

Results of initial seismic transmission experiments inside the mine (April 1967) show that efficient insertion of signals into rock walls is not

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[5] E. White, "Seismic Waves: Radiation, Transmission and Attenuation," McGraw-Hill Book Co., New York, 1965.

the only problem. Excitation of seismic vibrations in the walls of the mine shafts tends to produce acoustical waves which are ducted along the shafts. This acoustic part of the radiated energy is lost for signal transmissions to the surface. Detection of the remaining low seismic signal energy reaching the surface is further confounded by the normally larger seismic noise background at the surface.

Although the design of special seismic transducers for mine shafts is still in an early phase of research and development, certain facts are already clear:

a. Higher frequencies must be used for upward transmission in order to obtain a reasonable match between seismic transducers and the stress-stiffened rock walls of mine shafts

b. These higher frequencies (200 to 500 Hz) cannot penetrate the upper layer of soils, sand, and gravel. However, these frequencies do penetrate sediment layers on the bottoms of lakes and rivers. Therefore, the reception of signals transmitted from mine shafts in hard rock is possible by employing hydrophones submerged in lakes and rivers. The functioning of seismic-acoustic signal transmission from land into water was demonstrated experimentally in joint ECOM-NOL* experiments at Lake Champlain, N. Y. during February 1967.

CONCLUSIONS

An experimental 80 Hz seismic communications system such as employed during these experiments is readily operational for transmission of signals from the surface and their reception at underground installations. In experiments at the Sterling Hill Mine of the New Jersey Zinc Co., Ogdensburg, N.J., 80 Hz seismic signals were received down to the 1500-ft level of the mine (about 1700 feet from the transmitter on the surface) using only 60 to 100 watts transmitter drive power. Measurements made underground yielded the contours of the split-beam radiation pattern of the seismic transmitter transducer atop Sterling Hill.

Measurements of the seismic propagation velocities in the rock, using pulsed 80 Hz and CW signals yielded values in agreement with company data obtained in 1955 by conventional seismic exploration techniques employing explosives. A zone of relative silence (low noise and low signal reception) has been discovered at the 900-ft level of the mine in the vicinity of the elevator station.

Pulsed 80 Hz seismic signals received at the intersection of the 180-ft level and the escape shaft exhibited a low frequency modulation which can be traced to seismically induced acoustic reverberations of the vertical shaft.

While downward-transmission experiments were successful in every respect, initial upward-transmission experiments failed. Only in the battery chamber at the adit level (Fig. 5) was it possible to receive, by coherent detection, an audio frequency signal transmitted from an experimental stack transducer mounted on the wall at the 180-ft level station chamber (See Fig. 12). With the present transmitter setup in the mine shaft, most of the radiated energy is lost by acoustic coupling to the air in the mine shafts.

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*Naval Ordnance Laboratory (USN)

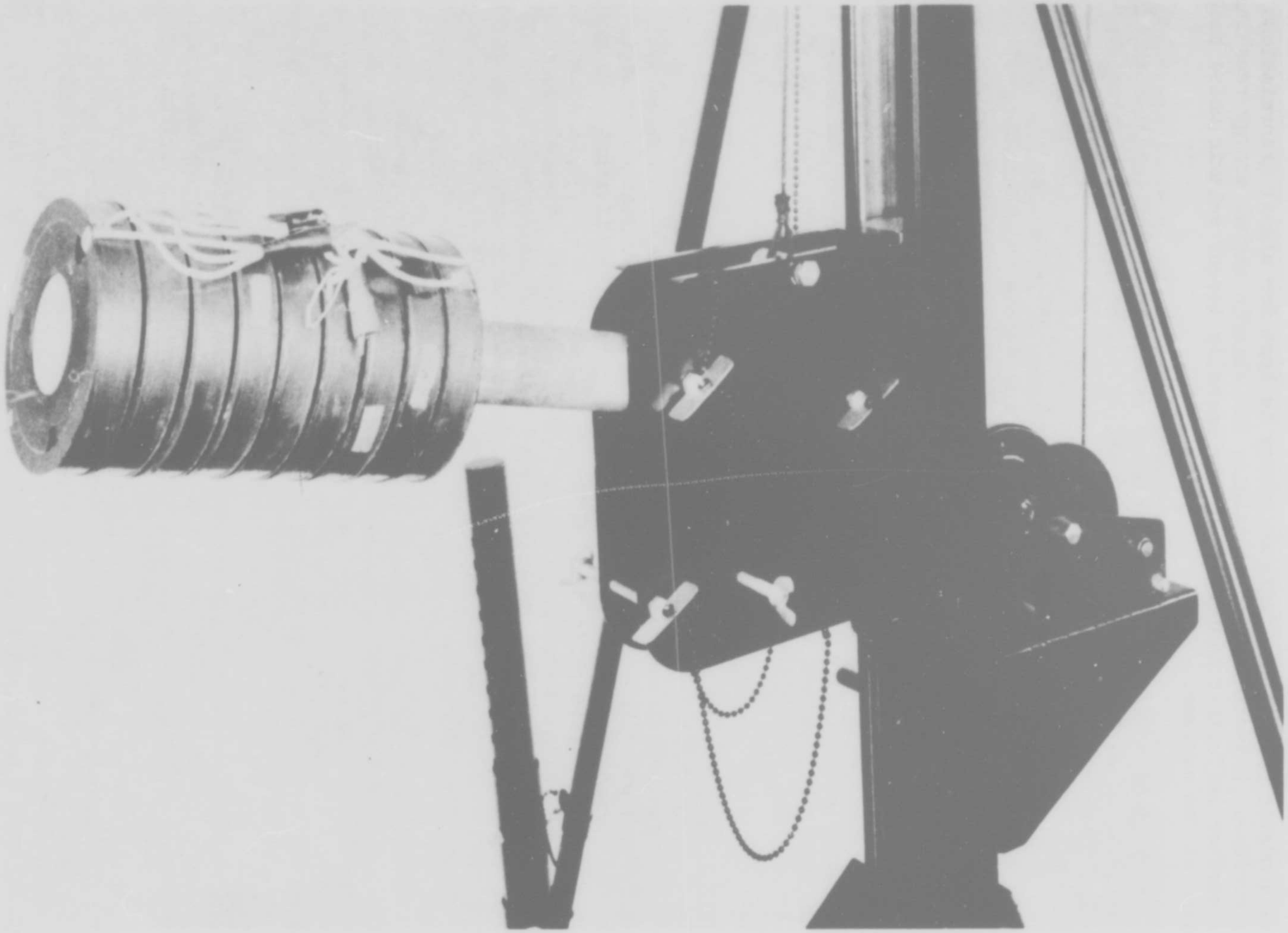

FIG. 12. Experimental Stack Transducer Mounted on the Wall

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Seismic						
80 Hz						
Underground Sites						
Mines						

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