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JULY 16th NUCLEAR EXPLOSION

GEOPHONE MEASUREMENTS OF EARTH MOTION

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ABSTRACT

Records were obtained from 6 geophones out of 12 planted at distances of 800, 1500, and 9000 yards from the implosion gadget set off at Trinity, July 16, 1945. Extrapolation from earth-motion data taken on small charges and on the 100-ton Trinity shot indicate that with an accuracy no better than within a factor of two the gadget exploded with a violence equivalent to 7000 tons of TNT. The earth-motion measurements corroborate the prevailing opinion that a wider damage radius can be obtained by exploding the gadget in the air to increase the effectiveness of the air blast, than by exploding the gadget on the ground to increase earth shock.

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JULY 16th NUCLEAR EXPLOSION

GEOPHONE MEASUREMENTS OF EARTH MOTION

I. INTRODUCTION

The earth motion due to the shock of an explosion does not lend itself to any accurate analysis because of the unknown and nonuniform character of the underground structure. This is particularly true at large distances from the explosion, for the greater distance allows the inhomogeneities to have more effect by reflection, refraction, and interference. However, the 100-ton Trinity shot had indicated that the principal earth motion at distances from 800 to 9000 yards was a Rayleigh wave. The surface wave is least affected by underground structure. Therefore a program of test measurements on Trinity ground was planned for the purpose of correlating the magnitude of the Rayleigh wave with distance, charge size, and height of charge above ground, so that, with the aid of the 100-ton data, one could extrapolate to a larger explosion and thereby estimate the charge equivalent to the gadget.

In addition, the geophone measurements could serve as a basis for estimating building damage caused by the earth shock from a gadget set off near the ground.

II. INSTRUMENTATION

Instrumentation for test measurements and for the gadget shot was identical with that for the 100-ton Trinity test, reported in LA-287, with the following exceptions:

Provision was made for quick adjustment of the mechanical balance of the geophones in the field without removing the case of the instrument.

The linearity of the Model 810 amplifiers was improved and made good to within 5% over the required range. Improvements on the amplifiers were done by T/5 Robert Freyman under the supervision of Matt Sands of Group G-4.

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The flat-frequency-response band of the amplifiers was broadened to cover the range from .5 to 50 cycles per sec, which extends to higher frequencies than the Type B galvanometer of the Heiland recording unit. Fig. 1 gives the overall high-frequency-cutoff character of the amplifier-recorder system. In all test shooting the amplifiers had a flat response up to 500 cycles, though this wide band was not made use of. The present geophones cannot be used at frequencies as high as 100 cycles because this is about the natural frequency of the geophone arm vibrating as a tuning fork.

In order to increase the range of the recording sensitivity, Type B and Type C Heiland galvanometers were used in series to record the same signal in duplicate. The Type B galvanometer has about 8 times the sensitivity of Type C.

Time break signals were impressed into one galvanometer in each of the six-channel Heiland recorders by means of an electronically operated relay which maintained isolation between the galvanometer element and ground. Matt Sands, who designed these circuits, pointed out that isolation was desirable in order to maintain a balanced termination of the twisted-pair signal lines across the terminals of the galvanometers, and thereby to minimize the likelihood of recording extraneous pickup signals.

The geophones were recalibrated with improved technique on the shake table described and illustrated in LA-287. Calibrations were made at two periods, viz., .40 and .80 seconds, and the sensitivities showed no dependence on frequency to within an accuracy of measurement of 5%. It is safe to assume that within 5% the geophones deliver a voltage signal directly proportional to the velocity component perpendicular to the base of the instrument if the period of the motion is less than .8 sec. The sensitivities range in value from 15 to 80 millivolts cm per sec.

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III. TEST SHOTS

It was desired to relate the magnitude of the Rayleigh wave to three variables, viz., charge weight in equivalent lbs of TNT, horizontal distance from charge, and height of charge above or below ground level.

The field layout (see Figs. 2 and 3) for these test shots was measured from a central shot point midway between two 55-foot telephone poles planted about 1½ miles north of shelter "B" at Trinity. Along a straight line running south of the above mentioned shot point, pairs of geophones were planted 2 feet underground at each of 6 distances, viz., 75, 200, 500, 1200, 3000, and 6000 feet. One of each pair measured the vertical earth motion and one the horizontal-radial motion. From each geophone a two-conductor cable was laid along the ground to its amplifier 740 ft farther from the shot point. This distance was sufficient to eliminate amplifier microphonics from air or earth shock at the interesting recording time. Shielded geophone cables were better, though unshielded cable was satisfactory where low amplifier gain was required. Twisted-pair telephone line ran from the amplifiers along a pole line to shelter "B" where the Heiland recorders were located.

All charges were of Composition B, the handling and firing of which was doen by T/3 William Steward of group X-6. Except for the 1000-lb charges the firing was done from a point about 500 yards from the shot point and a twisted pair, connected in parallel with the firing line, carried the signal of firing time to shelter "8". Two 1000-lb shots were fired from shelter "B".

For measurement of earth motion as a function of charge height, only 40-lb charges were used. The charges were elevated to heights of 0, 5, 10, 20, and 30 ft by ropes and pulleys rigged to the telephone poles. Charges were also buried at 2, 4, and 6 ft according to the plan of Fig. 2. Two charges were set off for each height or depth.

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For variation of earth motion with charge weight, two charges of each of the weights 11.6, 40, 200, and 1000 lbs were shot off on the ground. The 200- and 1000-lb charges were located at points 300 ft north of the telephone poles.

IV. TEST SHOT RESULTS AND ANALYSIS

Fig. 4 gives two typical records of the height scaling series of shots. The traces differ mainly in that the trace for the 6-ft buried charge lacks almost entirely the high-frequency large-amplitude deflections which occur in every case for which the charge is not buried more than 2 feet. These high-frequency deflections occur when the air wave arrives over the geophones. The sinusoidal traces are records of the Rayleigh waves with the vertical trace lagging 90° behind the horizontal. The 1200-ft station barely resolves the air and Rayleigh waves sufficiently for measurement. The three closer stations were too close for this resolution to have time to occur and were for this reason useless in the desired analysis.

Data from the records and the calibrations enable one to obtain the maximum earth particle velocity by means of the relation

$$v = h/\alpha g_o$$

where

v = earth particle velocity in cm per sec

h = centimeter deflection on Heiland trace

α = geophone sensitivity in millivolts per unit velocity

g_o = gain of amplifier-galvanometer combination in cm per mv.

On a given trace the deflection measured is the sum of successive opposite deflections which give the largest value, neglecting the air wave and the waves of increasing frequency just before the arrival of the air wave. The value of h is then taken to be equal to half this sum. The amplitude of the earth motion is cal-

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culated from $d = vT/\pi$ where d is twice the amplitude and T the period. This assumes the earth motion is simple harmonic.

Fig. 5 shows the variation of earth particle velocity with height of charge. Amplitudes may be calculated by reference to Table II which gives values for the period of the earth motion. No correlation was observed between period and height of charge. The sharp minimum at about $h = -2$ ft is probably real, though possibly the two charges set off at -2 ft went off at low power for some unknown reason. It does not seem plausible to explain the minimum by assuming that crater formation used up a major portion of the energy which normally goes into the Rayleigh wave, because a charge at -4 ft made a considerably bigger crater. The diameters of the craters in the two cases were 10 and 16 ft respectively.

The principal fact to note from Fig. 5 is that the magnitude of the Rayleigh wave is very insensitive to the height of the charge above ground. For this reason it has been assumed that one can, without consideration of height, extrapolate from small charges set off on the ground and from the 100 tons at 27 ft, to the gadget shot at 100 ft.

Fig. 6 shows the results of variation of ground motion with charge weight, and includes all test shots, the 100-ton shot, and the gadget shot. The weight values indicated apply to equivalent weight of TNT, and assume that Composition B is 20% more effective than TNT. The curves are calculated from the following relations:

$$d_v = W^{.28}\left[\frac{.15}{\lambda} + \frac{100}{\lambda^3}\right]$$

$$d_h = W^{.28}\left[\frac{.10}{\lambda} + \frac{400}{\lambda^3}\right]$$

[redacted]

[redacted]

$$\lambda = r/W^{.28}$$

$$T = .0022\ r^{1/2}\ W^{1/16}$$

$$v_v = (\pi/T)\ d_v$$

$$v_h = (\pi/T)\ d_h$$

The symbol d apologizes for representing twice the earth amplitude rather than the amplitude itself. W is weight of charge in lb, r is distance from charge in feet, and the remaining symbols are defined in the supplement to Table I. The expressions for amplitude have the same form as proposed by Lampson (see AM-670, summary by C. W. Lampson) but the constant factors have been chosen to obtain best agreement with the present experiments. The experimental points shown on Fig. 6 are joined by a line to the curve with which they should agree. The points lie about as much above the lines as below. The discrepancies are sometimes as great as a factor of 3, though this is considered satisfactory agreement, considering the uncertainties of earth motion.

V. JULY 16th SHOT

The field layout for the July 16th shot was similar to that for the 100-ton shot reported in LA-287, the principal difference being that signal wires closer than 3000 yards were laid in shallow trenches, instead of being stretched on poles.

Fig. 7 shows, reduced to half normal size, the record from the south line of geophones as recorded by the Type B galvanometers. At the instant of the explosion all 6 traces go off scale and only 4 of them return. The trace from the 800-yard vertical instrument shows that the large excess velocity of the air wave put the air wave ahead of the major earth wave. The same is true of the 1500-yard horizontal though a large earth amplitude does occur before the air wave arrival.

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At 9000 yards the largest vertical amplitude occurred at about 11.4 seconds, and can be estimated to have a twice amplitude value of .10 cm. The horizontal motion at the same instant was only about .01 cm. The maximum Rayleigh wave at 9000 yds is assumed to occur at a later time, namely 17 sec.

The results of the July 16th shot are tabulated in Table I. Six of the 12 geophones gave readable records. No records were obtained at several of the close stations because the electromagnetic storm due to the exploding gadget induced large signals which either paralyzed the amplifiers or bent the galvanometer suspensions. No galvanometers were burned out. At 9000 yds north the geophones were out of order.

The experimental values for earth particle velocity obtained on the gadget shot are plotted on Fig. 6 and fall in the region between the curves representing 3000 and 8000 tons of TNT.

The tabulated tons of TNT in Table I indicate the magnitude of the gadget blast as estimated by extrapolating according to the equations previously given relating earth motion to charge weight.

VI. COMPARISON OF EARTH- AND AIR-SHOCK DAMAGE

A U.S. Bureau of Mines Publication[1] summarizes a large amount of experimental information on building damage due to earth shock from quarry blasts and supplementary data. From this report one would conclude that the magnitude of the earth shock at 800 yards from the gadget shot was barely large enough to crack plaster in a typical house. Damage scales from earthquake observations[2] would indicate plaster damage at 3000 yards, but these scales are probably unreliable.

1) U.S. Bureau of Mines Bulletin, 442, 1942.

2) L.D. Leet, Practical Seismology and Seismic Prospecting, p. 301.

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Air-blast measurements at Trinity indicate that there would be class A damage out to about 1500 yards which is probably a much larger major damage radius than that due to the earth shock.

TABLE I

July 16th Shot Results

	Yards south and north				Percent Accuracy
	800 S	1500 S	1500 N	9000 S	
c_1	---	6200	----	10,600	3
c_2	1800	1600	1600	1600	20
c_3	2975	1938	1918	1242	3
v_v	11.6	----	5.0	.174	20
v_h	---	6.5	7.6	.157	20
d_v	2.3	----	.72	.041	40
d_h	---	1.5	1.04	.037	40
T_v	.62	----	.45	.74	10
T_h	---	.74	.45	.74	10
tons TNT	5000	7000	8000	6000	

c_1 = propagation velocity of first earth shock; ft per sec

c_2 = " " " Rayleigh wave; ft per sec

c_3 = " " " air wave above ground; ft sec^{-1}

Propagation velocities are computed by dividing distance by arrival time.

v = maximum earth particle velocity in Rayleigh wave; cm per sec

d = twice the maximum earth amplitude in Rayleigh wave; centimeters

T = period of Rayleigh wave; seconds

Subscripts v and h signify vertical and horizontal-radial components of the earth motion.

The accuracy of the values for the 9000 yds S station is better than the indicated value.

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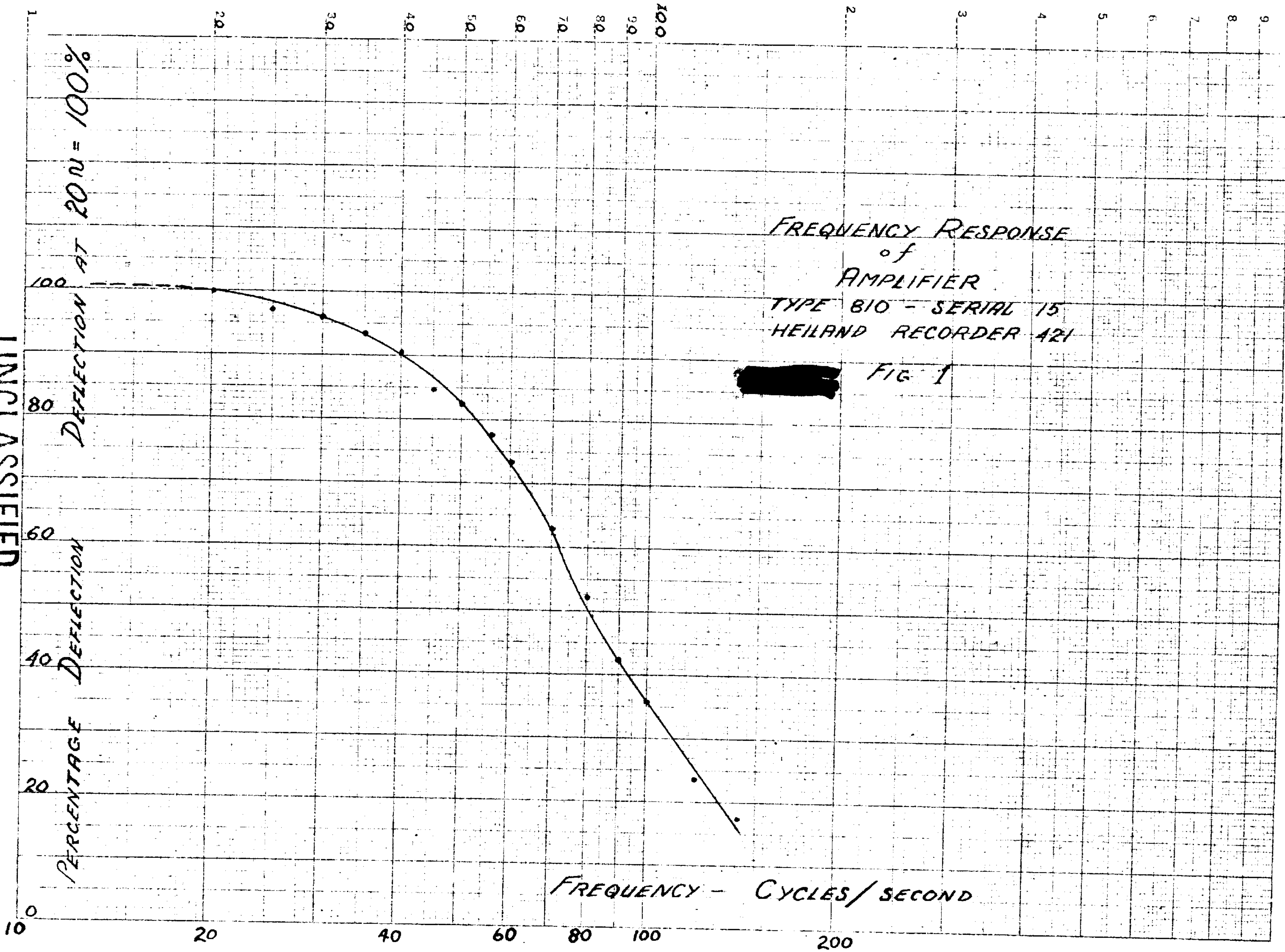
TABLE II

Period of Rayleigh Wave, Observed and Calculated

W TNT equivalent	r feet	T_{obs} sec	$T_{calc} = .0022\ r^{1/2}\ W^{1/16}$ sec
14 lb	1200	.09	.09
	3000	.14	.14
	6000	.20	.20
50 lb	1200	.10	.097
	3000	.15	.15
	6000	.15+	.22
220 lb	1500	.11	.11
	3300	.13	.17
	6300	.13+	.24
1200 lb	1500	.11	.125
	3300	.15	.19
	6300	.23	.26
100 ton	2400	.26	.23
	4500	.24	.32
	27,000	.75	.77
gadget (assume 7000 tons)	2400	.62	.30
	4500	.75, .45	.41
	27,000	.74	1.0

[redacted]



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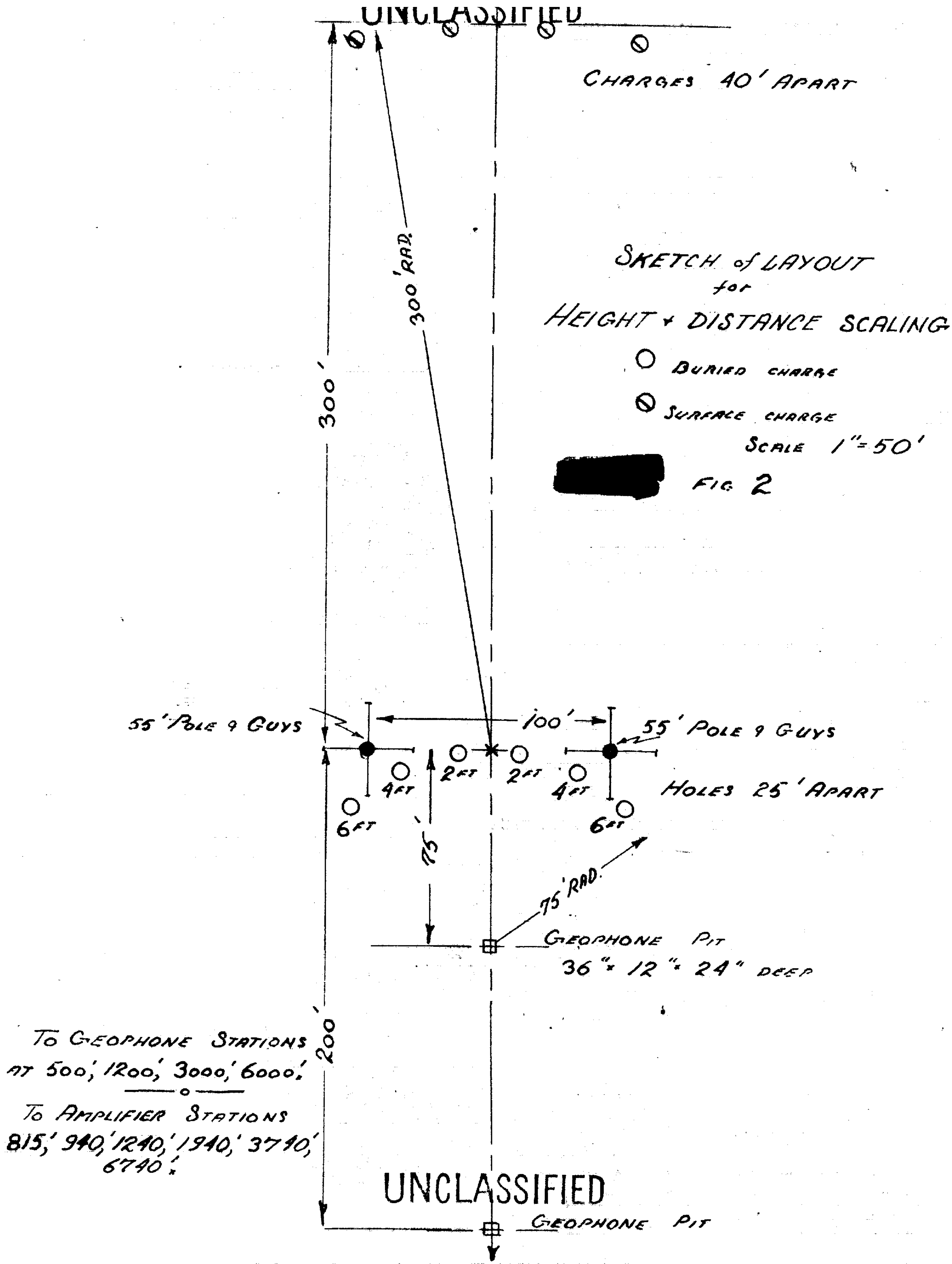

SKETCH of LAYOUT for HEIGHT + DISTANCE SCALING

[redacted] FIG 2

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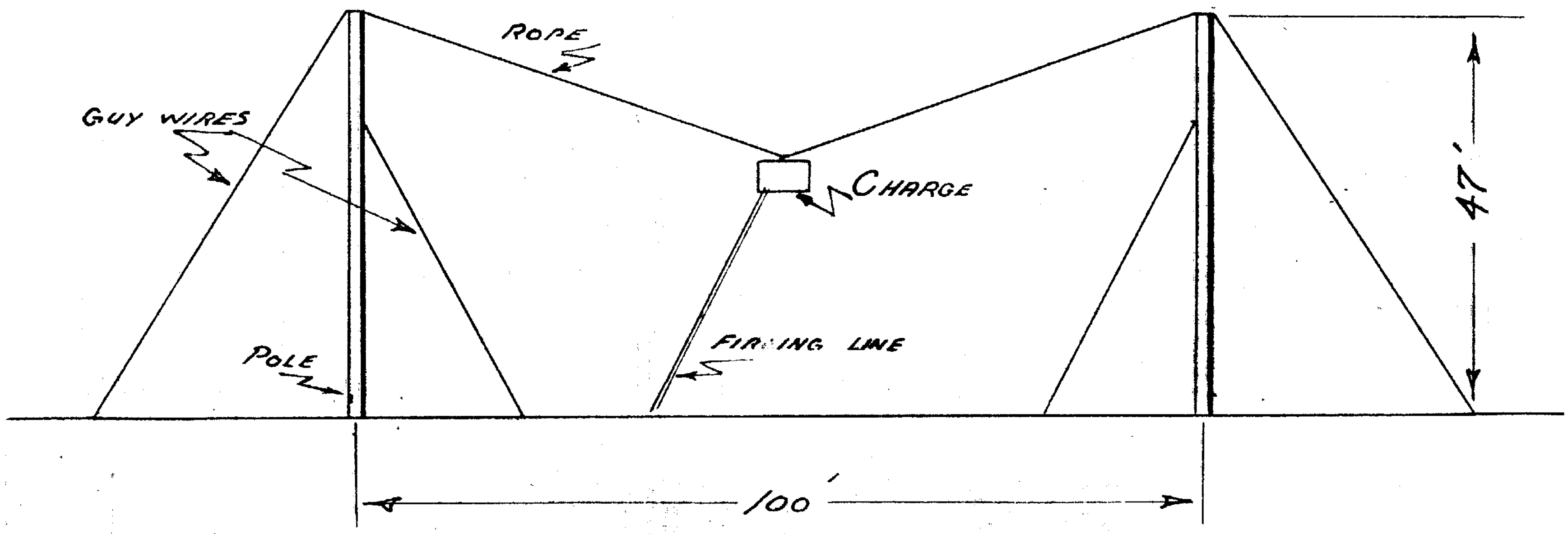
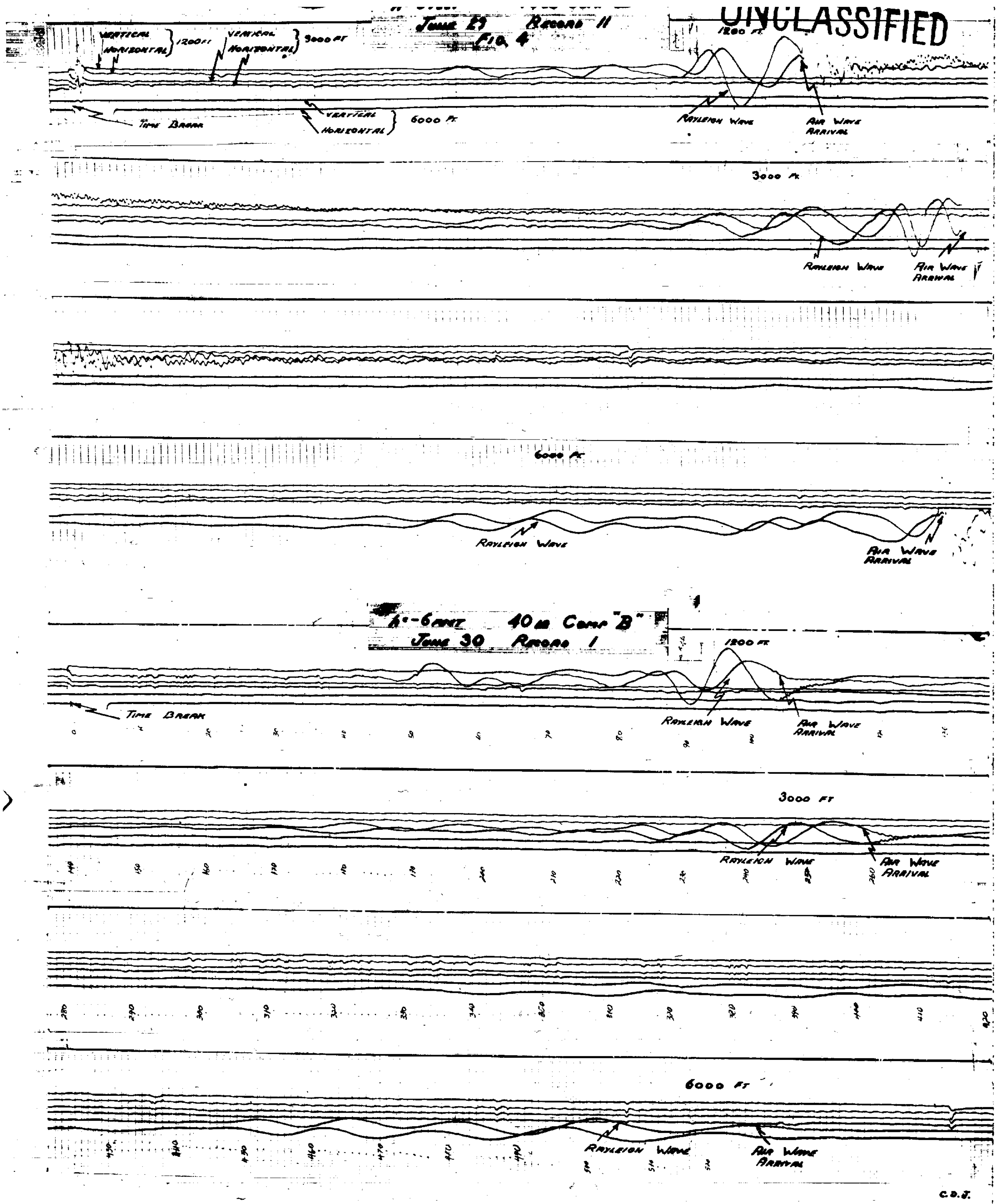
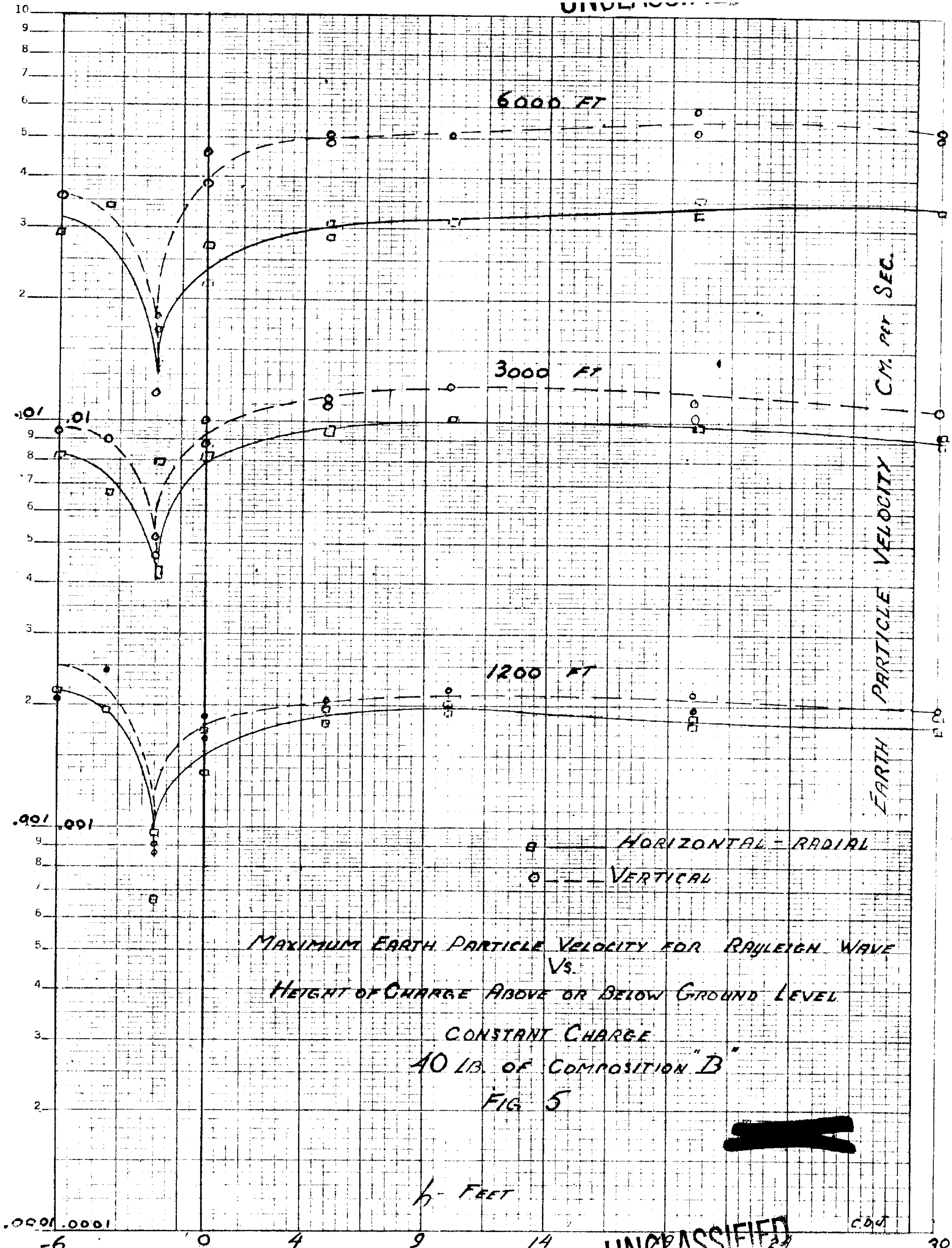


SKETCH of SETUP
for
FIRING ELEVATED CHARGES

SCALE 1" = 20'

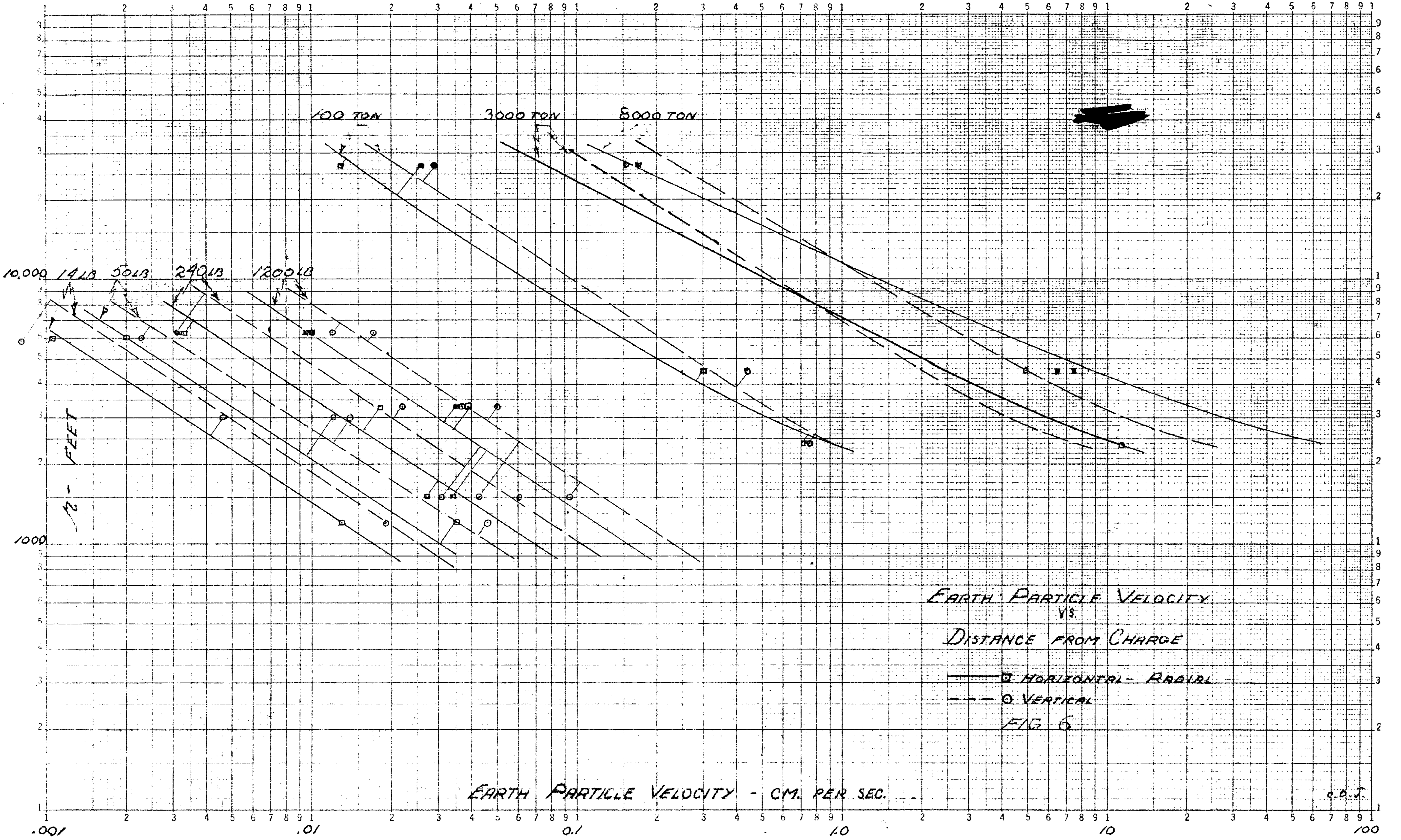
[redacted] FIG. 3


June 29 Record 11
Fig. 4
Vertical
Horizontal
1200 Ft
Vertical
Horizontal
3000 Ft
1200 Ft
Time Break
Vertical
Horizontal
6000 Ft
Rayleigh Wave
Air Wave Arrival
3000 Ft
Rayleigh Wave
Air Wave Arrival
6000 Ft
Rayleigh Wave
Air Wave Arrival
40 lb Comp "B"
June 30 Record 1
1200 Ft
Time Break
Rayleigh Wave
Air Wave Arrival
3000 Ft
Rayleigh Wave
Air Wave Arrival
6000 Ft
Rayleigh Wave
Air Wave Arrival
C.D.J.

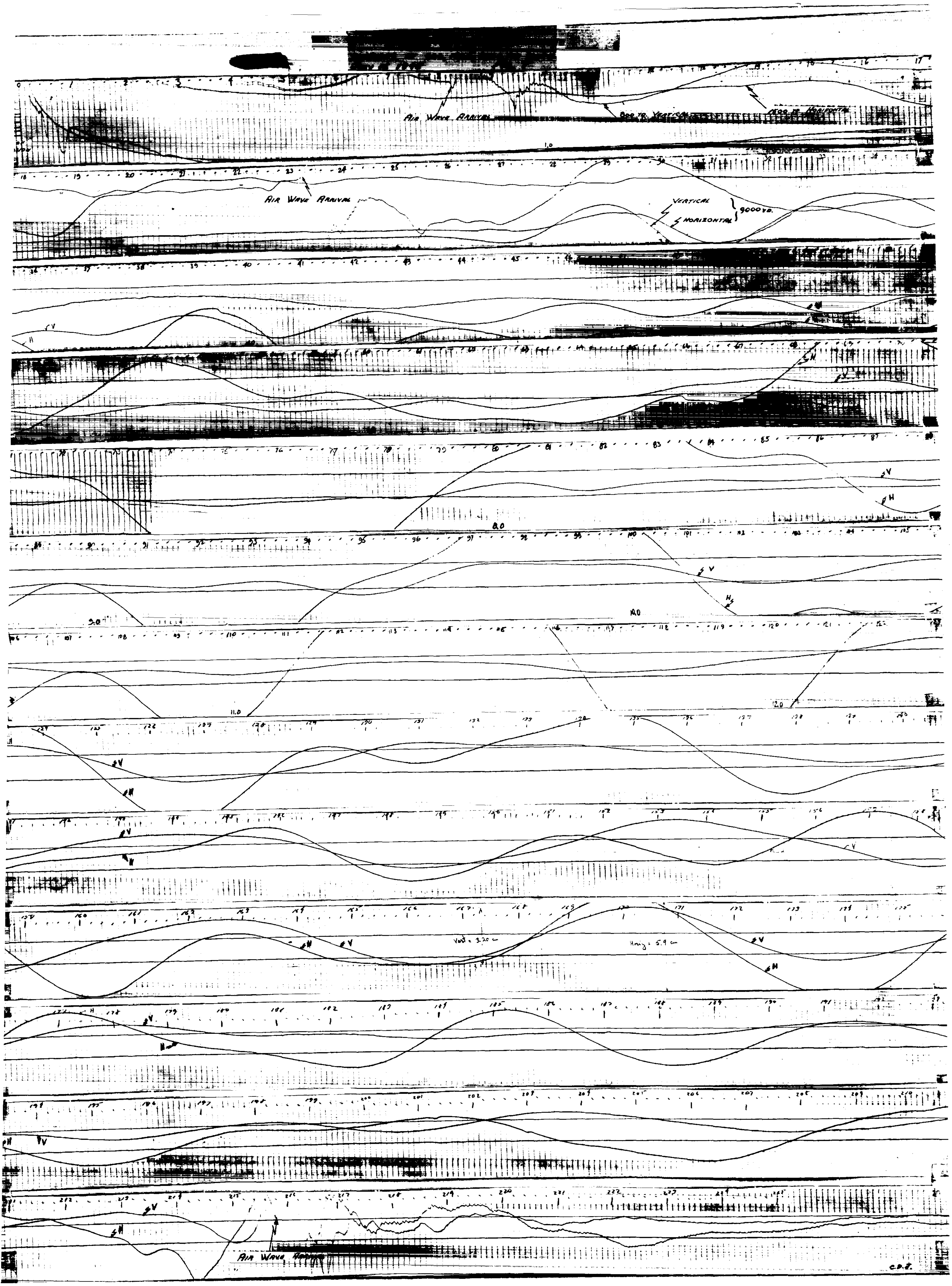


MAXIMUM EARTH PARTICLE VELOCITY FOR RAYLEIGH WAVE
VS.
HEIGHT OF CHARGE ABOVE OR BELOW GROUND LEVEL
CONSTANT CHARGE
40 LB. OF COMPOSITION "B"
FIG. 5

[redacted]



100 TON
3000 TON
8000 TON
[redacted]
10,000
14 LB
50 LB
240 LB
1200 LB
1000
r - FEET
EARTH PARTICLE VELOCITY
VS.
DISTANCE FROM CHARGE
HORIZONTAL - RADIAL
VERTICAL
FIG 6
EARTH PARTICLE VELOCITY - CM. PER SEC.
.001
.01
0.1
1.0
10
100


Air Wave Arrival
Air Wave Arrival
Vertical
Horizontal
9000 yd.
Air Wave Arrival

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