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SEISMIC MEASUREMENTS BY THE
U. S. GEOLOGICAL SURVEY DURING
THE PRE-GNOME HIGH-EXPLOSIVES TESTS
NEAR CARLSBAD, NEW MEXICO: FINAL REPORT

By P. Edward Byerly, S. W. Stewart, and J. C. Roller

Trace Elements Investigations Report 761

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GEOLOGICAL SURVEY

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April 1960

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This report is preliminary
and has not been edited for
conformity with Geological
Survey format and nomenclature.

*Prepared by the U. S. Geological Survey on
behalf of the U. S. Atomic Energy Commission.

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Seismic recordings	1. 760 lb. shot @ 3.9 miles	In envelope
	2. 6260 lb. shot @ 3.9 miles	In envelope
	3. 6260 lb. shot @ 9.7 miles	In envelope
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ABSTRACT

The U. S. Geological Survey monitored three high-explosive test shots at the Gnome site during the Pre-Gnome experiments, and monitored routine blasting in the potash mine of the Duval Sulphur and Potash Company.

Analysis of the data leads to the conclusion that the motion in the potash mines near Carlsbad from a shot of 9 KT of TNT at the Gnome site, 46,000 feet from the nearest potash mine, would not exceed:

displacement:	0.1	-	0.2 cm
velocity:	1.5	-	3 cm/sec @ 2 cps
	2.5	-	5 cm/sec @ 4 cps
acceleration:	0.02	-	0.04g @ 2 cps
	0.06	-	0.12g @ 4 cps

These particle velocities and accelerations are less than those recorded at a distance of 90 feet from a routine 75-pound dynamite blast in a potash mine.

INTRODUCTION

This report summarizes seismic recording, at stations on the ground surface, of high-explosive scaling shots of the Pre-Gnome program and seismic recording of routine blasting in the Duval Sulphur and Potash Company mine.

Measurements of acoustic velocity in pillars of salt and potash ore in the United States Potash Company mine and elastic moduli calculated from these measurements have been presented in a previous report (Roller and others, 1959).

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of officials of the Duval Sulphur and Potash Company and the United States Potash Company. Reynolds Electrical and Engineering Company, and Holmes and Narver, Inc., provided logistical support. Calibrations of seismometers were made with the facilities of the Geotechnical Corporation at Dallas, Texas, the National Bureau of Standards at Boulder, Colorado, and the Colorado School of Mines at Golden, Colorado. Seismic velocity data in the Gnome area were provided by the Shell Oil Company. Information concerning the geology of the Gnome area was provided by Charles L. Jones and James D. Vine of the Geological Survey.

The Geological Survey's investigations were conducted on behalf of the San Francisco Operations Office, U. S. Atomic Energy Commission.

SURFACE SEISMIC MEASUREMENTS

Introductory remarks

The U. S. Geological Survey occupied three-component seismic stations on the ground surface at distances of 0.45, 1.7, 3.9, and 9.7 miles from ground zero during three scaling shots consisting of 190, 760, and 6260 pounds of explosive. The main charges were pelletized TNT with a grain density of 1.6 gm/cm^3 . The shots were fired at a depth of 1200 feet in a shot hole near the center of sec. 34, T.23S., R.30E., in the Nash Draw 15-minute quadrangle, Eddy County, New Mexico (fig. 1).

Figure 1. Location of surface seismic stations occupied by the U.S. Geological Survey during the Pre-Gnome tests in the Nash Draw quadrangle, Eddy County, New Mexico

The 190-pound shot was recorded at 0.45, 1.7, and 3.9 miles with Stanley low-frequency seismograph systems (Stewart, Roller, and Diment, 1959, p. 12-15). The 760-pound shot was recorded at 1.7, 3.9, and 9.7 miles with Stanley systems and at 3.9 miles with a Texas Instruments 7000-B amplifying and recording system and Texas Instruments S-36 moving-coil seismometers with a peak frequency response at 2 cycles per second (cps). The 6260-pound shot was recorded at 1.7, 3.9, and 9.7 miles with Stanley systems. Additional instrumentation for this shot at 3.9 miles included three-component stations using S-36 seismometers and Bruel and Kjaer piezoelectric accelerometers with outputs fed to the 7000-B amplifying and recording system. The accelerometer outputs were fed through cathode-follower coupling circuits to the amplifiers. Additional instrumentation at 9.7 miles included a three-component S-36 seismometer station with outputs fed to a Midwestern Instruments refraction amplifying and recording system.

The Stanley seismometers at all distances and the accelerometers at 3.9 miles for the 6260-pound shot were mounted on concrete piers. The accelerometer mount was fastened to the pier by means of an expansion bolt. The S-36 seismometers have a bomb-shaped housing and could not be mounted on the piers. These instruments were buried just below the surface of the ground near the recording station.

Measurements with the Stanley systems were unsuccessful because of the high frequencies from the shots. Records useful for amplitude measurements were those obtained with the other instrumentation at 3.9 miles for the 760-pound shot and at 3.9 and 9.7 miles for the 6260-pound shot (in envelope).

Calibrations

Calibration curves for systems employed in recording the Pre-Gnome shots are in the Appendix (figs. 5 - 8).

Calibrations in the range 1-12 cps of systems using vertical-component Stanley seismometers were made on the shaking table of the Geotechnical Corporation, Dallas, Texas. Calibrations of the seismometers in the range 10-110 cps were made on the shaking table of the Colorado School of Mines, Golden, Colorado. The response curves of these seismometers showed sharp cusps in the range of about 40-50 cps, apparently as a consequence of resonance in hinge springs. Records obtained with these seismometers generally showed strong wave groups of approximately constant frequency with an envelope suggesting damped resonant vibrations. Amplitudes from these records are suspect, and the data are not discussed further.

Calibrations of the systems including the vertical component S-36 seismometers used at 3.9 miles and the 7000-B amplifying and recording system were made in the range 10-90 cps on the shaking table of the Colorado School of Mines. Similar calibrations for the system employing the Midwestern Instruments amplifying and recording system were made in the range 30-100 cps.

An Electrotechnical Corporation magnetic-tape recorder was used in conjunction with the 7000-B system. A calibration was made for this system in the range 10-110 cps. This calibration includes the vertical-component seismometer used for the 760-pound shot at 3.9 miles. This seismometer was changed for the 6260-pound shot. The reason for this was that somewhat larger amplitudes were recorded by some other seismometers on a 600-meter radial spread set up for the 760-pound shot. It is not known whether the differences in amplitudes are due to seismometer response or seismometer location, but individual seismometer (not system) calibrations suggest the latter.

The calibration of the accelerometer system used for the 6260-pound shot at 3.9 miles is a piece-wise calibration based upon the shaking-table calibration of the accelerometer-cathode follower and the calibration of the 7000-B amplifying and recording system. Piecewise calibration of the system accelerometer-cathode follower and Midwestern Instruments amplifying and recording system is permissible in the range 20-300 cps. The two amplifying and recording systems have generally similar characteristics, and the acceleration calculated for the vertical accelerometer at 3.9 miles is the same as that calculated for the vertical seismometer system within the range of reproducibility of shaking-table measurements.

Calibrations made are steady-state calibrations. The seismometer is connected to the complete system, and driven at a given frequency and amplitude. Calibration seismograms are recorded. Amplifier gains and filter settings are the same as those used in the field. Adjustment for amplifier output is based upon calibration of the amplifiers in the field and at the time of the system calibration. The S-36 seismometers were calibrated separately and in the complete system subsequent to the field measurements.

STRATIGRAPHY AND SEISMIC VELOCITIES

The exposed rocks in the Gnome area locally include the Gatuna (?) formation, Pierce Canyon redbeds, and Rustler formation (Baltz, 1959). The upper part of the Rustler formation includes a section of limestone, dolomite, anhydrite, and gypsum (Moore, 1958). Underlying the Rustler formation is the Salado formation, composed principally of halite and other evaporites. The Salado formation is underlain by the Castile formation which includes three anhydrite members and two salt members (fig. 2). The upper anhydrite member ranges from about 400 to 800 feet in thickness in the Gnome area (Baltz, 1959). The Castile formation, at the Shell Oil Company's 1 James Ranch Unit well, is underlain by at least 14,000 feet of sedimentary rocks including limestone, shale, sandstone, and dolomite.

The stratigraphic units at the shot-hole site to a depth of 1500 feet are shown in figure 2 (Moore, 1958). The interval-velocity log was obtained by the Schlumberger Well Surveying Corporation for Holmes and Narver, Inc. The formations penetrated to a depth of 3715 feet in the Wills and others' 1 Montgomery well in sec. 10, T.23S., R.30E., about 4 miles north of the Gnome site, are also shown in this figure (Charles L. Jones, U. S. Geological Survey, written communication). The Salado formation is about 1700-1800 feet thick in this area.

FIGURE 2. STRATIGRAPHIC UNITS NEAR THE GNOME SITE

The interval of high velocity in the Rustler formation, which overlies the Salado, is approximately 200 feet thick at the shot hole, and is composed principally of anhydrite and gypsum. Refraction (horizontal) velocities in the Rustler in the vicinity of the Shell 1 James Ranch Unit well in sec. 36, T.22S., R.30E. are between 13,000 and 18,000 feet per second (fps). Velocities from a sonic log in the James Ranch well are as follows (fig. 2).

Salado formation		14,250 fps	
Castile formation	{	Upper anhydrite member	19,190 fps
		Second salt member	14,460 fps
		Middle anhydrite member	19,570 fps
		Lower anhydrite member	19,570 fps

These data were provided by L. F. Uhrig of the Shell Oil Company who comments (written communication, 1960), "The Salado salt section is usually washed out to some extent by unsaturated drilling fluid during the drilling process, and these washouts affect the reliability of the sonic log somewhat; therefore, the value of 14,250 feet per second may be slightly low. It is unlikely that the true value is greater than that for the Castile salt which is accurately determined as 14,460 feet per second."

The following comments concerning the stations at 1.7, 3.9, and 9.7 miles are by James D. Vine of the Geological Survey (written communication, 1959).

"The 1.7-mile station is located near the top of the Pierce Canyon redbeds about 575 feet above the top of the salt. The 3.9-mile station is located on the Magenta member of the Rustler formation about 340 feet above the salt. The 9.7-mile station is located near the top of the Rustler formation probably as much as 420 feet above the top of the salt. There are essentially no deep structures between ground zero and the 9.7-mile station, only uniformly horizontal strata. I emphasize the word deep because locally there is considerable near-surface structure resulting from solution and collapse in the zone of ground-water circulation. This is especially true in the vicinity of the 3.9- and 9.7-mile stations. Several open sink holes in the Rustler formation are within a few hundred feet of the 3.9-mile station. The 9.7-mile station is separated from the 3.9-mile station by Nash Draw, a topographic depression that is also a surficial structural depression resulting from solution in the Rustler and also on the top of the salt. Except for this effect of solution all the stratigraphic units described from the core (Moore, 1958) are remarkably uniform and persistent. For example, there is a remarkably uniform bed of anhydrite and gypsum 120 feet thick between the Magenta and Culebra members of the Rustler formation, but it is also one of the units that is subject to local removal by solution. The Pierce Canyon redbeds form a persistent and uniform bed of siltstone 210 feet thick between ground zero and the 1.7-mile station, but do not extend beyond this point."

MEASUREMENTS OF MINE BLASTS

Instrumentation and calibration

The system used to record the mine blasts was composed of Bruel and Kjaer barium titanate accelerometers, cathode-follower coupling circuits, and a standard portable refraction amplifier and oscillographic camera. Six such systems were used to record each blast.

Calibrations of two of the complete systems were made on the shaking table of the National Bureau of Standards at Boulder, Colorado. Two accelerometers were mounted on the shaking table and a recording system identical to that used in the mines was employed. Maximum table motion in units of acceleration of gravity was related directly to the maximum displacement recorded on the oscillogram. Separate calibrations of the cathode follower - refraction amplifier - oscillographic camera system, made by feeding a sinusoidal voltage of known amplitude and frequency into the system and measuring the maximum amplitude recorded on the oscillogram, indicate that it is permissible to calibrate the accelerometers separately without introducing substantial error into the final calibration (Appendix, fig. 9). By calibrating the cathode follower-refraction amplifier - oscillographic camera system in the Duval mine before or after each blast it is then a simple matter to arrive at a system calibration by inserting the appropriate accelerometer calibration.

All accelerations as determined from the Duval mine records were calculated from this "piece-wise" method of system calibration. Although the system calibrations for simple harmonic oscillations can probably be repeated within ± 10 percent on the existing calibration facilities, various difficulties associated with calibrations made in the Duval mine would set limits of about ± 25 percent on the actual system calibrations for this work. Because the frequencies recorded from the mine blasts are in the range 100 - 500 cycles per second, and the slope of the system-calibration curve in this region is steep, additional error in computing maximum acceleration is introduced when an attempt is made to associate one predominant frequency and amplitude with a complex waveform. For these reasons the maximum accelerations presented here are approximations.

Discussion of results

A sample of the recordings obtained in the Duval mine is included (Record 4). The frequencies of direct seismic energy recorded are in the range 100 - 500 cycles per second. After the direct seismic energy has passed the recording point, low-amplitude reverberations continue for more than one second. These reverberations are in the frequency range 80 - 200 cycles per second, and may represent either falling rock after the blast or returns of seismic energy from distant reflecting interfaces.

It is usually possible to distinguish the first two or three delay-charge firings in the blast as a series of separate large-amplitude arrivals on the record. The maximum acceleration is usually associated with the first or second of the series of delay charges. Evidently the time delay is great enough to prevent or minimize any major interference of the separate pulses with each other.

The maximum accelerations recorded from blasts at distances ranging from 100 to 800 feet are summarized in table 1, along with other pertinent data, and are plotted in figure 3. For most of the recordings the waveforms may be considered as approximately simple harmonic sinusoidal waves over a few cycles at a time. Record 4, however, which was taken at the nearest recording point (90 feet) to the largest blast (75 pounds) has the appearance of a succession of one-sided impulses, each impulse corresponding in time to a delay charge going off. It appears that the output of the accelerometers was great enough to overdrive the amplifying system and distort the recorded waveform into something that is not related directly to the accelerometer motion. For the lower amplitude, less distorted waveforms on this record estimates of maximum acceleration are given in table 1 and plotted in figure 3. For the greatly distorted waveforms rough estimates of the maximum acceleration are shown in figure 3, identified as "estimated."

The relatively small amounts of data in figure 3 do not show any obvious relation of charge size to maximum acceleration, chiefly because the parameters charge size and distance could not be varied sufficiently during the blasting operations. The best scaling relation to be derived is therefore based on the points in figure 3.

The solid line in this figure represents an average value of maximum acceleration as a function of distance. Its slope is fixed as an attenuation proportional to the inverse square of the distance.

Table 1 : Maximum accelerations recorded in the Duval mine February 20 - 21, 1959

Trace No.	Orientation of Accelerometer	Accelerometer Position	Azimuth from station to shot	Distance (feet)	Maximum Acceleration (g)	Frequency of maximum acceleration
RECORD NO. 2		75 POUNDS AT ZERO DELAY				
1	EW	Face	N31E	800	.20	290
2	NS	Floor	"	"	Amplitudes too large	
3	EW	Floor	"	"	Amplitudes too large	
4	V	Floor	"	"	.26	170
5	V	Face	N34E	"	Calibration questionable	
6	NS	Face	"	"	Calibration questionable	
RECORD NO. 3		50 POUNDS AT ZERO DELAY				
1	EW	Face	N104W	190	1.8	200
2	V	"	N109W	"	1.3	300
3	NS	"	N109W	"	2.5	120
4	EW	"	N109W	"	1.4	240
5	EW	"	N112W	"	Calibration questionable	
6	NS	"	N112W	"	1.5	150
RECORD NO. 4		75 POUNDS AT ZERO DELAY				
1	EW	Face	N90W	90	2.6+	200
2	V	"	N90W	"	Amplifier overdriven	
3	NS	"	N90W	"	Amplifier overdriven	
4	EW	"	N90W	"	2.4+	220
5	EW	"	N90W	"	Amplifier overdriven	
6	NS	"	N90W	"	Amplifier overdriven	
RECORD NO. 5		25 POUNDS AT ZERO DELAY				
1	V	Floor	S10W	240	1.4	400
2	EW	Floor	S10W	240	1.2	450
3	NS	Floor	S10W	240	No calibration	
4	EW	Face	S10W	260	5.9	400
5	V	Face	S10W	260	8.3	450
6	NS	Face	S10W	260	3.7	300
RECORD NO. 6		25 POUNDS AT ZERO DELAY				
1	V	Floor	N25E	215	0.8	300
2	EW	Floor	N25E	215	1.0	500
3	NS	Floor	N25E	215	No calibration	
4	EW	Face	N25E	200	4.7	400
5	V	Face	N25E	200	5.0	450
6	NS	Face	N25E	200	Amplitudes too small	
RECORD NO. 7		75 POUNDS AT ZERO DELAY				
1	V	Floor	N30E	280	0.9	320
2	EW	Floor	N30E	280	1.2	480
3	NS	Floor	N30E	280	No calibration	
4	EW	Face	N30E	280	2.7	320
5	V	Face	N30E	280	4.3	370
6	NS	Face	N30E	280	1.9	250

FIGURE 3 : MAXIMUM ACCELERATIONS AS A FUNCTION OF DISTANCE
RECORDED IN DUVAL MINE, FEBRUARY 20-21, 1959

The dashed lines in this figure represent accelerations computed from the scaling formula of Thoenen and Windes (1942) for blasts in mines where the observations are on the same rock stratum. Their formula relates charge size and distance to maximum displacement. To compute accelerations, frequencies of 100, 200 and 400 cycles per second are assumed. Although they make no mention of frequencies above 50 cycles per second, the extrapolation of their data to higher frequency ranges gives good agreement with the observations in the Duval mine.

Similarly, the X-s in the figure are extrapolations of displacement data obtained by Habberjam and Whetton (1952) from quarry blasts at a distance of 400 feet.

Both calculations are for charges of 25 pounds.

Maximum accelerations as tabulated for records 5, 6 and 7 (table 1) seem to indicate that accelerations recorded on the wall (face) of the mine are significantly larger than those recorded on the floor. This observation could be real, but it could also reflect differences in the coupling of the accelerometers to the wall and to the floor. Shaking-table tests indicate that the output of the accelerometer depends to some extent upon how well it is bolted to the table.

In summary, six routine blasts recorded in the Duval mine produced accelerations estimated as high as 20 units of gravity at a distance of 90 feet from a three-face blast. The accelerations as recorded are in good agreement with extrapolations from the work of Thoenen and Windes (1942) and Habberjam and Whetton (1952).

EXTRAPOLATION TO LARGER EXPLOSIONS

Discussion

The raw data obtained from the moving-coil seismometers are essentially particle-velocity data. Fourier analyses of the records have not been made. Motion has been calculated considering the records to be composed of parts of sine-waves. A graphical integration of the beginning of strong motion on the vertical component seismometer at 3.9 miles for the 3.1-ton shot is shown in figure 4. Intervals (B) and (C) in which the motion was calculated from the calibration curves are also shown. Calculations of motion from the tape playback with 120 MM high-cut filter (40 percent of maximum response is developed at 120 cps; attenuation 80 db/octave above 120 cps) were used for the 760-pound shot at the 3.9-mile station. The numbers calculated are listed below:

3.9-mile station; 6260-pound shot

(A)	4.1×10^{-3} cm/sec. @	80 cps
(B)	14.5×10^{-3} cm/sec. @	55-60 cps
(C)	36×10^{-3} cm/sec. @	50-55 cps

3.9-mile station; 760-pound shot

(A)	0.5×10^{-3} cm/sec. @	95 cps
(B)	1.9×10^{-3} cm/sec. @	70 cps
(C)	2.2×10^{-3} cm/sec. @	85 cps

9.7-mile station; 6260-pound shot

(D)	3.3×10^{-3} cm/sec @	55 - 60 cps
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-
(A)	Pulse about 0.16 sec. after beginning of low-amplitude arrivals
(B)	first strong pulse
(C)	motion about 0.065 sec. after onset of strong motion (760 lb.);
maximum in train beginning about 0.085 sec. after onset of
strong motion (6260 lb.)
(D)	first strong group

FIGURE 4. INTEGRATED TRACE - 3.1 TON SHOT AT 3.9 MILES

If displacements are estimated from these data on the sine-wave approximation, they are as listed below:

3.9-mile station; 6260-pound shot

- (A) 8.2×10^{-6} cm.
- (B) 38×10^{-6} cm.
- (C) 110×10^{-6} cm.

3.9-mile station; 760-pound shot

- (A) 0.85×10^{-6} cm.
- (B) 4.3×10^{-6} cm.
- (C) 4.1×10^{-6} cm.

9.7-mile station; 6260-pound shot

- (D) 9.5×10^{-6} cm.

Displacement exponents for yield (W) calculated from these data are (A) 1.1⁻; (B) 1.0⁺; (C) 1.5-1.6. The last value is unreasonable, and the (C) data are not suitable for determining exponents. The (A) and (B) events are likely to be the same on the records, while the (C) events are not. Particle velocity exponents for events (A) and (B) are about 1.0. Consequently the data are not suitable for scaling anything but displacement. The data produce scaling similar to that obtained from sampling a spectrum at a fixed frequency. In order to obtain the largest estimates of motion from the numbers previously calculated, an exponent 1.1 will be used for displacement, and events (C) and (D) will be scaled from 3 tons to 9 kilotons. The results are: 3.9 miles (0.7 cm); 9.7 miles (0.06 cm).

If the apparent frequency in the displacement pulse for the 3-ton shot is taken as about 30 cps (Carder and others, 1960), and this frequency is scaled as $W^{-1/3}$, the apparent frequency for 9 kilotons is about 2 cps. The apparent frequency in the velocity pulse may then be about 3-4 cps. A frequency of 4 cps is obtained by scaling to 9 kilotons the 55 cps frequency in events (C) and (D) for the 6260-pound shot. Scaling the previous displacements at 2 and 4 cps, the following numbers are obtained:

distance	3.9 miles	9.7 miles
displacement	0.7 cm	0.06 cm
<hr/>		
velocity	9 cm/sec. @ 2 cps	0.8 cm/sec. @ 2 cps
	18 cm/sec. @ 4 cps	1.5 cm/sec. @ 4 cps
<hr/>		
acceleration	0.1 g @ 2 cps	0.01 g @ 2 cps
	0.45 g @ 4 cps	0.04 g @ 4 cps
<hr/>		

To the level of the previous analysis, the value at 3.9 miles may be considered to be approximately the maximum motion, whereas the radial motion at 9.7 miles may be approximately 2-3 times that listed.

The apparent propagation velocities, neglecting shot depth, of event (B), the beginning of the group containing event (C), and event (D) are, respectively, 14,000 fps, 13,400 fps, and 13,800 fps. These velocities suggest direct or reflected and refracted compressional waves, an interpretation not incompatible with the particle motion or attenuation of amplitude with distance.

For long waves the surface layers overlying salt in the Salado formation will not provide any constructive effects upon amplitude, nor will the underlying Castile formation for sufficiently long waves.

To obtain some independent comparative information, the strain data of Duvall and Atchison (1957) in granite gneiss were examined. The pulse from an explosion in this medium was considered to produce a radial displacement in the form of a sine-wave describable near the explosion as

$$u_R = A \left[-e^{-ik_\alpha R} R^{-2} - ik_\alpha e^{-ik_\alpha R} R^{-1} \right] e^{i\omega t}$$

$$= -\frac{A}{R} \sqrt{\frac{1}{R^2} + \frac{\omega^2}{\alpha^2}} e^{i(\omega t - k_\alpha R + \tan^{-1} \frac{\omega R}{\alpha})}$$

where $k_\alpha = \frac{\omega}{\alpha}$; R = radial distance

α = compressional velocity.

The requirement that $u_R (\text{max.}) = U$ when $R = a$
gives

$$u_R = \frac{\alpha a^2 U}{\sqrt{\omega^2 a^2 + \alpha^2}} \left[-e^{-ik_\alpha R} R^{-2} - ik_\alpha e^{-ik_\alpha R} R^{-1} \right] e^{i\omega t} \quad (1)$$

At distance such that $\omega R \gg \omega d$, where d is shot depth and R horizontal distance, the part of the term in R in (1) corresponding to vertical displacement at the surface in the direct compressional wave is, according to Sakai (1934, p. 32),

$$\frac{-2n^2}{(n^2-2)} \left\{ ik_\alpha d + \frac{4\sqrt{n^2-1}}{(n^2-2)^2} \right\} \frac{e^{-ik_\alpha R}}{R^2} \quad (2)$$

where $n = \alpha/\beta$, the ratio of compressional to shear velocity.

The similar expression for the horizontal radial component of displacement is (Sakai, 1934),

$$\frac{-4n^2\sqrt{n^2-1}}{(n^2-2)^2} \left\{ ik_\alpha d + \frac{4\sqrt{n^2-1}}{(n^2-2)^2} \right\} \frac{e^{-ik_\alpha R}}{R^2} \quad (3)$$

Taking $n = \sqrt{3}$ (a Poisson's ratio of 0.25) the vertical component of particle displacement becomes

$$u_z = -6U \left(\frac{a}{R} \right)^2 \frac{\sqrt{\omega^2 d^2 + 32\alpha^2}}{\sqrt{\omega^2 a^2 + \alpha^2}} e^{i(\omega t - k_\alpha R + \tan^{-1} \frac{\omega d}{4\sqrt{2}\alpha})} \quad (4)$$

and the ratio of horizontal to vertical displacement is

$$\frac{2\sqrt{n^2-1}}{(n^2-2)} = 2\sqrt{2} \doteq 3$$

The data of Duvall and Atchison (1957) are for peak radial strains, apparently involving charges up to 32 pounds of different types of explosives. The data will be considered scalable in terms of TNT.

Let $e_R(R, \tau)$ be the radial strain and $u_R(R, \tau)$ the radial displacement. An approximate value of the maximum displacement can be found for distance a as

$$u_R(a, t)_{\max.} \doteq \int_a^{a+\alpha T} e_R(R, \tau) dR$$

$$\tau = t - (R-a)/\alpha \quad ; \quad T = t_n + t_f \quad @ \quad R = a$$

t_n = rise-time of the scaled strain pulse

t_f = fall-time of this pulse (Duvall and Atchison, 1957)

(see Lampson, 1950, p. 418).

Approximating the strain pulse as a triangular pulse,

$$u_R(a)_{\max.} \doteq \frac{\alpha}{2} e_{R \max.} (t_n + t_f)$$

Take $a = 800$ feet ($\sim 3W^{1/3}$; ft., lb.^{1/3}).

Then scaling of the data in figure 13 of Duvall and Atchison (1957)

to 9 kilotons gives $e_{R \max.} \doteq 500-600 \times 10^{-6}$;

$t_n + t_f \doteq 30 \times 10^{-3}$ sec. With $\alpha = 5.6 \times 10^5$ cm/sec.

(18,500 ft./sec.), this gives

$$u_{R \max} \doteq 4 - 5 \text{ cm at } 800 \text{ feet}$$

To determine a value of "frequency" in (4), it will be necessary to use the previous strain data, although the indications are that the equivalent displacement pulses are decidedly asymmetrical and probably involve permanent displacement. Taking $(t_r + \frac{1}{2}t_f) \sim (4f)^{-1}$, where f will be considered a frequency associated with the displacement pulse, f varies from about 8 to 4 cps as R goes from $20W^{1/3}$ to $40W^{1/3}$. Calculations made in (4) with $U = 4$ cm., and $f = 4, 8$ cps yield:

distance (feet)		20,000	30,000	46,000
4 cps	u_z	0.15 cm.	0.07 cm.	0.03 cm.
	$\dot{u}_z$	3.8 cm./sec.	1.8 cm./sec.	0.8 cm/sec.
	$\ddot{u}_z$	0.1 g	0.05 g	0.02 g
8 cps	u_z	0.1 cm	0.05 cm	0.02 cm
	$\dot{u}_z$	5 cm/sec.	2.5 cm./sec.	1 cm./sec.
	$\ddot{u}_z$	0.25 g	0.13 g	0.05 g

u_z = vertical component of displacement
 radial component = 3 times vertical component

These calculations can also be applied to the non-dispersive Rayleigh wave in granite gneiss (Sakai, 1934, p. 29), and the vertical displacement becomes

$$u_z = \frac{\alpha a^2 U}{\sqrt{\omega^2 a^2 + \alpha^2}} \left\{ -7.3 \sqrt{2\pi} \left(\frac{\omega}{\alpha} \right)^{3/2} \frac{e^{-1.6 \frac{\omega d}{\alpha}}}{\sqrt{r}} \right\} e^{i \left[-\frac{\pi}{4} + \omega \left(t - \frac{r}{C_R} \right) \right]}$$

d = shot depth; C_R = Rayleigh wave velocity; $\omega r/\alpha$ is large.

Taking $f = 4$ cps, the vertical displacement at the surface at a distance of 46,000 feet is about 0.5 cm.

All of these calculations imply a homogeneous terrain of granitic gneiss, and involve application of elastic theory in the inelastic range near the shot, with resultant over-estimation of amplitudes. In the absence of inhomogeneities it seems likely that at a distance of several miles the integrated strain in salt would exceed that in granite gneiss, but that the peak strain might be greater in gneiss. Presumably, then, displacements in salt would exceed those in gneiss, but peak particle velocities and accelerations in salt would be about the same as or less than in gneiss.

There is, of course, no absence of inhomogeneities, and the number calculated for the Rayleigh wave is too large to be applicable. The calculations are considered to provide support for the scaled observations.

The following comments concern the effect of layering on amplitudes.

The upper anhydrite member of the Castile formation, which underlies salt in the Salado formation, is about 700-800 feet thick in the vicinity of the Gnome site and to the south, but thins to about 400 feet to the north (see Baltz, 1959). The velocity of compressional waves in the anhydrite is about 19,000 fps. At frequencies below a certain value, the high-velocity section of the Rustler formation can be ignored, and the section considered to consist of the Salado formation and underlying anhydrite in the Castile formation. The attenuation with depth in the anhydrite of plane elastic channel waves through the salt, if the anhydrite is considered to extend indefinitely with depth, involves factors

$$\exp\left[-\frac{\omega}{C}\sqrt{1-\left(\frac{C}{\alpha_c}\right)^2}z\right] ; \exp\left[-\frac{\omega}{C}\sqrt{1-\left(\frac{C}{\beta_c}\right)^2}z\right]$$

α_c, β_c = compressional and shear velocities in the anhydrite.

z = depth in anhydrite

C = horizontal phase velocity corresponding to angular frequency ω
for a particular mode.

For $Z = 400$ feet, $C \doteq 8100$ fps (approximate velocity of shear waves in the salt), and $f = 5$ cps, amplitudes at this depth are about $1/4$ to $1/3$ of those at the top of the anhydrite. For $f = 10$ cps, the amplitudes are about $1/16$ and $1/9$ of those at the top of the anhydrite for the terms in α_c and β_c respectively. It is therefore likely that effective development and propagation of channel waves through the salt over a distance of about 10 miles in a northerly direction requires that frequencies exceed about 10 cps. Amplitudes of such waves cannot be calculated without a knowledge of the blast spectrum, for this introduces the dispersion. Efforts have been made to determine a spectrum by fitting observed near-shot particle-velocity pulses with expressions of form $K(\Omega R)^{-1} f(\Omega \tau)$ and applying the equivalent cavity theory (Sharpe, 1942; Blake, 1952), but, at this stage, the results are not considered adequate for calculating numbers for shots in salt.

The following factors may be noted:

(a) The velocity contrast between the salt and anhydrite is insufficient to permit unattenuated normal mode propagation through the salt channel of the compressional phase of higher-mode Rayleigh-type or Sezawa-type waves, and the source is essentially a compressional source (see Oliver & Ewing, 1957).

(b) Suppose the upper anhydrite extends indefinitely with depth, and the Rustler formation is ignored. Then the minimum group-velocities, and presumably strongest amplitudes, in the first and second modes of Love waves are found at frequencies of about 2 cps and 6 cps respectively (Ewing, Jardetzky, and Press, 1957, p. 213; in this reference the contrast in physical properties of layers is about the same as at Gnome). It is likely that the minimum group-velocity of the M_2 mode of Sezawa is also found at a frequency approaching 6 cps (see Oliver and Ewing, 1958). At these frequencies the anhydrite is essentially transparent to wave motion and normal mode waves restricted to the salt channel do not develop.

It should be pointed out that the event scaled at 3.9 miles may represent waves reflected from the anhydrite, and the largest events on the calibrated records have been scaled. Although the surface layering at Gnome is conducive to the propagation of channel waves, these will presumably be in a frequency range containing a small percentage of the energy of the blast.

The velocity distribution with depth in the Gnome area is evidently less simple than a two-layer problem. Probably the next most important section is that at depths of 15,600 - 17,500 feet in the Shell 1 James Ranch Unit Well. The dolomites in this interval have the following velocities (data courtesy of G. S. Corey, Shell Oil Company):

15,600 - 16,600 ft.; 23,000 fps

16,600 - 17,500 ft.; 19,000 fps

The elastic scaling of frequencies from explosions in elastic rocks may not be applicable except at distances of perhaps a mile from 9 KT of TNT, although the major part of the material or dissipative dispersion may arise at comparatively short distances. The point here is that reflections from a depth of 3 miles are not considered to be exceptionally energetic, both because of intermediate reflections and distance. Similarly, if there are initial high-amplitude reflections from the anhydrite near the shot, these will imply higher frequencies than 2-4 cps, but also amplitudes outside the elastic range, and continuous inelastic dissipation of energy. These considerations are the basis for believing the Salado to Castile interval the most important for this application, and this has already been discussed.

CONCLUSIONS

In summary, it is believed that the motion at 9.7 miles (and also at 46,000 feet) from 9 KT of TNT would not exceed:

displacement: 0.1 - 0.2 cm
velocity: 1.5 - 3 cm/sec. @ 2 cps
 2.5 - 5 cm/sec. @ 4 cps
acceleration: 0.02 - 0.04 g @ 2 cps
 0.06 - 0.12 g @ 4 cps

It is presumably generally agreed that the blast-equivalence of a nuclear device in the Gnome application will be less than that of the energy-equivalent in TNT. This fact is a consequence of the reason for testing the efficiency of an underground nuclear explosion as a source of power.

In comparison with the above figures, data from blasting in the mines indicate that within a distance of 90 feet of a 75 lb. three-face blast accelerations transverse and normal to faces are of the order of 3 g @ 200 cps up to at least 10 g @ around 100 cps or so. The equivalent particle velocity in the first case is about 2.5 cm/sec., and is well above 5 cm/sec. in the second case. Although there may be some question as to what was being measured with some of the accelerometers at a distance of 90 feet, motion equivalent to particle velocities of about 2 to 4 cm/sec. was recorded at distances of about 200 feet. It is concluded that particle velocities and accelerations at a distance of 46,000 feet from 9 KT of TNT would not exceed those generated by a routine 75 lb. blast at a distance of about 90 feet.

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FIGURE 5 : COMPLETE SYSTEM CALIBRATION FOR HTL SYSTEM EMPLOYED
AT 3.9 MILE STATION FOR 6260 POUND SHOT

FIGURE 6 : SYSTEM CALIBRATION FOR ACCELEROMETER-HTL SYSTEM
EMPLOYED AT 3.9 MILE STATION FOR 6260 POUND SHOT

FIGURE 7: COMPLETE SYSTEM CALIBRATION FOR HTL-MIDWESTERN SYSTEM EMPLOYED AT 9.7 MILE STATION FOR 6260 POUND SHOT.

FIGURE 8 : COMPLETE SYSTEM CALIBRATION OF SEISMOMETER, AMPLIFIER
AND MAGNETIC TAPE RECORDER EMPLOYED AT 3.9
MILE STATION FOR 760 POUND SHOT.

FIGURE 9: COMPARISON OF COMPLETE SYSTEM CALIBRATION AND PIECE-WISE SYSTEM CALIBRATION FOR TRACE NUMBER 4, RECORDS 3 AND 4, DUVAL MINE SHOTS OF FEBRUARY 20, 1959.

RECORD 1

1 TRANSVERSE (#379)
2 INLINE (#421)
3 VERTICAL (#246)

TRACE

TAPE PLAYBACK

760 LB. SHOT @ 3.9 MILES

GAIN 5 FILTERS: LOW CUT - OFF

HIGH CUT - 215 cps MM

1 INCH

0.1 SECONDS

1 TRANSVERSE (#379)
2 INLINE (#421)
3 VERTICAL (#246)

TRACE

TAPE PLAYBACK

760 LB. SHOT @ 3.9 MILES

GAIN 5 FILTERS: LOW CUT - OFF

HIGH CUT - 120 cps MM

1 INCH

0.1 SECONDS

1.44 SEC.

RECORD 2

This report is preliminary and has not been edited for conformity with Geological Survey format and nomenclature

RECORD 3

9.7 MILE STATION
3.1 TON SHOT

INLINE (# 430)

VERTICAL (# 346)

TRANSVERSE (# 325)

1 INCH

← 0.1 SECOND →

3.5

3.6

↑
WV TIME

4.0

This report is preliminary and has not
been edited for conformity with Geological
Survey format and nomenclature

RECORD 4

This report is preliminary and has not
been edited for conformity with Geological
Survey format and nomenclature

175

8-121

90-1A

175

8-121

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