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Particle Motions near Explosions in Halite

BYRON F. MURPHEY

Sandia Laboratory, Albuquerque, New Mexico

Abstract. Peak particle velocities and displacements were measured for tamped (coupled) and cavity (decoupled) explosions in halite. Recordings are illustrated of particle velocity versus time in the salt medium and of pressure versus time on the cavity wall. Peak particle velocities from tamped shots decrease as $d^{-1.65}$ over distances equivalent to 40 to 800 feet for 1000 pounds of high explosive.

Decoupling factors that were directly observed apply only to close-in stations. One method of extrapolating close-in data yields distant decoupling factors ranging from 40 to 100 for these particular experiments. Actual measurements (verbal communication from Herbst, 1960) of distant decoupling factors give larger numbers by a factor of 2. Extrapolation to nuclear explosions is not attempted here.

Introduction. Project Cowboy was an experiment designed to determine to what extent underground explosions could be effectively concealed simply by firing the explosion in a large cavity. Comparative measurements of earth motion were obtained from tamped charges of high explosives and high-explosive (HE) charges of similar yield fired in large cavities in halite. The tamped explosions are referred to as coupled shots and the explosions in cavities as decoupled shots. The function of the cavity is to decouple the explosion from the surrounding medium and thus conceal the explosion by reducing the amount of energy transmitted to the medium at low frequencies.

Instrumentation was included to measure ground motion, both in the salt near the explosions and on the earth's surface out to ranges of several miles.

Measurements close to the explosions were required for two main reasons: to indicate the actual pressure-time histories on the walls of the cavities and to show comparative motions of the salt from coupled and decoupled explosions of identical yield.

Measurement of the cavity pressure-time history and particle displacement in the salt medium provided data for comparison with and verification of theoretical calculations. Actually, precise measurement of *permanent* displacement is difficult to achieve. Values of peak transient velocities and *peak* displacements are readily obtainable.

For tamped explosions, the most useful quantity to measure is permanent displacement, although, again, values of transient peak velocities and displacements are also useful.

Background. The idea that underground explosions can be concealed has been published in a RAND Corporation report and is republished in this Journal [*Latter, LeLevier, Martinelli, and McMillan,* 1961]. Since the ideas involved a combination of elasticity theory in the behavior of cavities in hard rock and experimental observation of particle motion near a 1.7-kt nuclear explosion (Rainier), it seemed highly desirable to obtain more experimental confirmation of the theory. Lawrence Radiation Laboratory was requested to conduct the experiment, designated Project Cowboy. Sandia Laboratory was requested by LRL to provide strong-motion instrumentation within the surrounding rock at various distances from the explosions.

At the time the experiment was planned (early summer, 1959) we decided to use available commercial instruments because of the anticipated short time scale. Since displacement gages were not available, we suggested that the primary instrumentation be velocity gages. Use of accelerometers was also planned in the event velocity gages were not adequate; velocity gages were, however, satisfactory.

The experiment was conducted at depths near 800 feet in the Carey Company salt mine near Winnfield, Louisiana. All instrumentation provided by Sandia was located in the mine. Since both coupled and decoupled shots were fired in the salt medium, factors describing concealment refer to comparable shots in salt.

Theory. The ratio of the distant signals in the limit of low frequencies between a coupled and a decoupled explosion is given by equation 11 of *Latter, LeLevier, Martinelli, and McMillan* [1961]:

$$\text{decoupling factor} = \frac{16}{3(\gamma - 1)} \frac{c_h}{c} \mu_h \frac{r_0^2 d_0}{W} \quad (1)$$

where

γ = ratio of specific heats applicable to explosion in cavity.
c_h = velocity of sound in medium around cavity.
c = velocity of sound in medium around tamped shot.
μ_h = shear modulus in medium around cavity.
r_0 = distance from tamped explosion at which permanent displacement d_0 is measured in elastic zone.
W = explosion energy release.

This expression involves the assumption that energy W is distributed uniformly over the cavity volume, giving a step-function pressure p on the wall [*Latter, LeLevier, Martinelli, and McMillan*, 1961, eq. 1]:

$$p = \frac{(\gamma - 1)W}{(4/3)\pi a^3} \quad (2)$$

where a is the radius of the cavity. Of course the actual pressure observed on the wall was not simply that given by (2) because expected short-duration pressure pulses did occur.

This fact emphasizes the necessity for using the observed (or, more accurately, calculated) pressure-time history at the cavity wall to determine close-in particle motion. Actually, in the direct application of (1) values of p are not needed; only W is used. A difficulty in the use of (1) is the inability to determine the permanent displacement d_0 accurately. Observed transient displacements can be used to verify the assumption of elastic behavior of the cavity walls.

In the Cowboy experiments spherical charges of Pelletol (TNT at 1 g/cm³) were placed at the center of the cavity, which was then evacuated to about 1/20 of an atmosphere. Nothing is stated in (1) about the maximum value of W which can be released in the cavity. One purpose of these experiments was to determine how great W could be, and the close-in measurements indicated whether displacements were proportional to W for large W.

Some insight into the experiment can be obtained from an approximate elementary theory of the behavior of peak velocities and displacements. We assume that the effective pressure on the cavity wall is p_0, and that p_0 is small enough in magnitude for the pressure at radius r from the center of a cavity of radius a to vary as

$$p = p_0(a/r) \quad (3)$$

The $1/r$ dependence at large r is a valid approximation [*Sharpe*, 1942]. We assume also that

$$p = \rho c u \quad (4)$$

where

u = peak particle velocity.
c = velocity of sound.
ρ = density.

Equation 4 is a close approximation at large r. We may then write

$$u = (p_0/\rho c)(a/r) \quad (5)$$

If it is assumed that u varies sinusoidally with time, it is permissible to obtain peak displacement from $d = u/\omega$. If, in addition, it is true that $\omega = c/a$ because of the elastic behavior of the cavity walls, then

$$d \propto (p_0/\rho c^2)(a^2/r) \qquad r > a \quad (6)$$

(Equations 5 and 6 will not hold at distances so close to the cavity that inductive mass motion occurs involving dependence on $1/r$ and $1/r^2$.)

For the tamped explosion some effective pressure p_{0t} exists at some effective radius a_t, such that peak velocities and displacements are given by

$$u_t = (p_{0t}/\rho_t c_t)(a_t/r) \quad (7)$$

and

$$d_t \propto (p_{0t}/\rho_t c_t^2)(a_t^2/r) \quad (8)$$

To obtain close-in decoupling factors for peak values, we need only look at the observed ratios u_t/u and d_t/d. When $\rho = \rho_t$ and $c = c_t$, as in the Cowboy experiments, we find

$$\frac{u_t}{u} = \frac{p_{0t}a_t}{p_0 a} \qquad r \gg a,\ a_t \quad (9)$$

$$\frac{d_t}{d} = \frac{p_{0t}a_t^2}{p_0 a^2} \qquad r \gg a,\ a_t \quad (10)$$

The distant decoupling factor is further increased in proportion to ω_0/ω_{0t}, where $\omega_{0t} = c/a_t$ and $\omega_0 = c/a$ [*Latter, LeLevier, Martinelli, and McMillan*, 1961]. Such an increase in decoupling would be observed at large distances or close in with low-pass measuring instruments for which $\omega_t << \omega_0$. The low-frequency limit of the Fourier transform of displacement related to ω_{0t} is higher than the corresponding limit for ω_0 as the ratio ω_0/ω_{0t}. As a result the amplitudes and waveforms of initial driving pressures at the elastic radii are similar,

$$\frac{d_t(\omega < \omega_0)}{d(\omega < \omega_0)} = \frac{p_{0t}a_t^3}{pa^3}$$

$$= \text{distant decoupling factor,} \qquad (11)$$

see also *Latter, Martinelli, and Teller* [1959].

The ratios

$$p_{0t}/p_0 \quad \text{and} \quad a_t/a$$

are calculable from ratios of observed peak velocities and displacements. Therefore, the distant decoupling factor is calculable from (11). However, (10) will apply in case the measuring station has instruments that respond near ω_0 and the station is not far enough away for waves of this frequency to be attenuated by solid friction.

If the transient peak pressure on the cavity wall has large amplitude compared with the pressure calculated from (2) and if its duration is shorter than a time comparable to $1/\omega_0$, then the propagated pressure pulse may not be characterized by ω_0, and (6) may not be strictly applicable. Nevertheless, equations 9 through 11 seem to be useful for an understanding of strong-motion data obtained, but the equations do not reveal why a may be, and usually is, significantly smaller than a_t.

The exact manner in which pressure falls off with distance in salt was not known at the start of Project Cowboy. We did know that in air or soil, in the range of measurement planned for salt, dependence would be r^{-3}, and that in water [*Cole*, 1948], dependence had been observed to be $r^{-1.12}$. Presumably, the exponent for salt would be between these, since a dependence near $r^{-2.3}$ had been calculated for nuclear shots in tuff (unpublished notes by John Nuckolls, 1959). In calculating velocities to be anticipated, a further difficulty arose, since, at close distances, mass motion of material near the explosion introduced an r^{-2} term.

In practice, for the tamped explosion, our method of predicting velocity was to make a guess and hope that we would be correct within a factor of 5. After one shot had been fired and measurements obtained at two distances, empirical formulas were then established for prediction for later explosions. For high explosives, the similarity principle can be invoked for explosions of different size, namely, equal velocities are anticipated at corresponding distances scaled in proportion to $W^{1/3}$. Incidentally, this cannot be done for nuclear explosions generally, since the starting pressure at the edge of the nuclear explosive on the cavity wall depends on the yield of the explosion. For similar high-explosive charges (closely tamped Pelletol was always used in the coupled Cowboy shots), the starting pressure at the edge of the tamped explosion is independent of the yield.

Results of the tamped explosions soon indicated that we could write the empirical expression for peak velocities as $u \propto r^{-1.65}$ over the range of $r/W^{1/3} = 4$ to 80, where r is in feet and W is yield in pounds. It is quite probable that this relation is nearly correct for high explosives in any hard rock.

We now consider the term $r_0^2d_0$ which occurs in (1). This term represents the permanent mass motion which would occur after an explosion in a perfectly elastic incompressible medium. That is, the increase in volume of the cavity is observable at any distance r_0 as a permanent displacement d_0 such that the permanent volume change in the cavity is equal to $4\pi r_0^2d_0$. *Latter, LeLevier, Martinelli, and McMillan* [1961] were naturally hopeful that we might obtain a good measurement of d_0. The intent was to integrate the velocity-time records. It turned out that this could not be done accurately because the peak displacements were quite large compared with the permanent displacements, even for the tamped explosions. This problem is mentioned here to point out the fact that the assumption that a coupled explosion injects a step function of pressure at some elastic radius is valid only for frequency components much lower than the dominant information frequency as observed close to the explosion. This is a basic assumption of the decoupling theory.

The above discussion should serve to show that

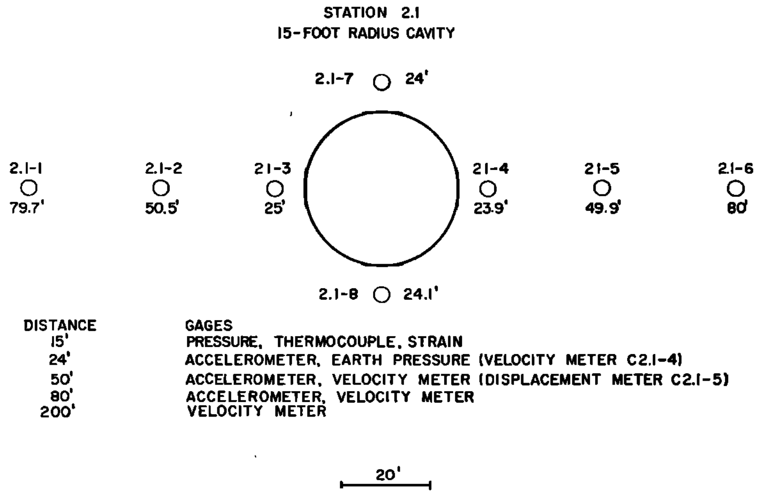

Fig. 1. Schematic gage layout near 15-foot cavity.

primary close-in measurements should be (*a*) pressure versus time at the cavity wall and (*b*) velocities and displacements in the medium near coupled and decoupled explosions. Of course, distant seismic signals provide direct measurement of decoupling factors, modified by the response and location of the seismometers.

Description of experiment. The Cowboy experimental area is located in an unused portion of the Carey Salt Company mine near Winnfield, Louisiana. Tamped explosions were placed in drill holes at depths of 45 and 110 feet below the tunnel floor. Cavities 6 and 15 feet in radius were constructed at the ends of new tunnels driven about 75 feet from existing tunnel walls. Cavity explosives consisted of spherical charges placed at the centers of the cavities.

A schematic drawing of instrument locations

TABLE 1. Summary of Shot Data, Project Cowboy

Shot No.	Date	Time* (CST) h m s	Yield,† lbs	Station	Type
1	Dec. 17	00 15	20	1.2	Coupled, 45-ft hole
2	Dec. 17	00 45	20	1.1	Decoupled, 12-ft-dia. sphere
3	Dec. 19	00 00	100	1.1	Decoupled, 12-ft-dia. sphere
4	Dec. 19	00 15	100	1.3	Coupled, 45-ft hole
5	Jan. 23	00 00 00.113	198.35	2.1	Decoupled, 30-ft-dia. sphere
6	Jan. 30	00 01 00.112	200.0	2.1	Decoupled, 30-ft-dia. sphere
7	Jan. 30	01 01 00.112	199.65	2.2	Coupled, 110-ft hole
8	Feb. 6	00 01 00.115	477.4	2.1	Decoupled, 30-ft-dia. sphere
9	Feb. 6	01 01 00.113	499.7	2.3	Coupled, 110-ft hole
10	Feb. 13	19 01 00.113	954.0	2.1	Decoupled, 30-ft-dia. sphere
11	Feb. 13	20 01 00.114	1003.0	2.4	Coupled, 110-ft hole
12	Feb. 20	00 01 00.112	929.0	1.1	Decoupled, 12-ft-dia. sphere
13	Feb. 20	01 00 59.614	987.6	2.5	Coupled, 110-ft hole
14	Feb. 27	00 01 00.127	1902.4	1.1	Decoupled, 12-ft-dia. sphere
15	Feb. 28	04 01 00.131	936.2	2.6	Coupled, 110-ft hole
16	Mar. 3	23 01 00.128	199.5	1.4	Coupled, 45-ft hole
17	Mar. 4	00 01 00.130	199.8	1.3–1	Coupled, 45-ft hole

* All times for shots 5 through 17 are derived from comparisons with WWV. Accuracies are ± 0.001 sec, except for shot 15, which is ± 0.003 sec.

† All yields include 'Nitramon' booster and detonator weights of either 2 or 3 pounds.

near the 15-foot-radius cavity is shown in Figure 1. Gages were placed to measure radial particle motion. Similar gage positions were used for the tamped explosions. Although a variety of gages was used, it is sufficient in this paper to consider measurements made by velocity and pressure gages only.

In the cavity of 15-foot radius, four pressure gages were used to indicate pressure as a function of time. Two of these gages were located in a plate near the entrance to the cavity. The other two were placed 45° and 90° away on the horizontal great circle. A pressure gage with a long fill time was used to read pressure in the cavity at long times compared with the duration of the transient pressure pulse.

A summary of the shots fired during Project Cowboy is given in Table 1. The explosive used in all cases was Pelletol, which was contained in plastic spherical shells for all decoupled shots.

Results. Values of observed peak velocities and peak displacements for all explosions are listed in Tables 2, 3, and 4. Except for displacements from the gages listed as –DR, all peak displacements were obtained by integrating velocity-time recordings. The –DR gages are experimental displacement gages which were installed late in the program.

Peak velocities and displacements observed for the three 200-pound tamped explosions are plotted in Figure 2 to illustrate the degree to which the data are consistent. An example of a velocity-time recording and the corresponding integration is shown in Figure 3.

All peak-velocity data for tamped explosions (20 pounds through 1000 pounds) have been plotted in Figure 4 as a function of distance divided by the cube root of the charge weight.

TABLE 2. Peak Velocities and Displacements, Tamped Explosions

Gage	Distance, ft	Shot No.	W, lbs	Peak Vel., in/sec	$W^{1/3}$	Peak Displ., mils	Mils/$W^{1/3}$	$D/W^{1/3}$
1.2–3–V	19.4	1	20	12	2.71	...		7.15
1.2–4–V	36			9.4			low	13.3
1.3–7–V	19.3	4	100	90	4.64	...		4.16
1.3–8–V	35.9			28.4		...		7.73
2.2–3–V	49	7	200	40	5.84	24	4.11	8.4
2.2–2–V	50.3			42		26	4.46	8.6
2.2–1–V	79.4			15.5		10.4	1.79	13.6
2.2–4–V	80.6			10		8	1.37	13.8
2.1–17–VB	452.5			1.0		1.0	0.172	77.5
1.2–4–V	157	16	200	3.9	5.84	3.0	0.515	26.9
1.2–3–V	173			3.0		2.3 low	0.395	29.7
1.3–7–V	223			3.4		2.5	0.429	38.2
1.3–8–V	207			3.7		2.5	0.429	35.5
2.1–17–VB	431			1.1		0.8	0.137	73.8
2.1–17–VC	431			1.0		0.8	0.137	73.8
1.3–7–V	99	17	200	11.2	5.84	8.2	1.4	17
1.3–8–V	116			9.1		8.1	1.39	19.9
1.2–3–V	150			4.4		3.4	0.583	25.7
1.2–4–V	167			4.1		3.2	0.55	28.6
2.1–17–VC	274			1.8		1.5	0.257	47
2.3–2–V	50.5	9	500	48	7.92	48	6.07	6.38
2.3–1–V	79.6			20		22.5	2.85	10
2.3–4–V	79.7			23		20	2.53	10
2.1–17–VB	368.8			2.0		2.9	0.37	46.6
2.4–1–V	77.5	11	1000	46	10	42	4.2	7.75
2.4–15–V	208.2			6.5		9.3	0.93	20.8
2.4–15–DR				...		11.6	1.16	20.8
2.1–17–VB	477.7			2.1		3.2	0.32	47.8
2.5–4–V	80.9	13	1000	40		39	3.9	8.1
2.4–15–V	351.7			4.3		5.6	0.56	35.2
2.4–15–DR				...		6.1	0.61	35.2
2.1–17–VB	585.5			1.3		1.7	0.17	58.6

TABLE 3. Peak Velocities and Displacements, 15-Foot Cavity

Gage	Distance, ft	Shot No.	W, lbs	Peak Vel., in/sec	Peak Displ., mils
2.1-2-V	50.5	5	200	1.4	0.53
2.1-1-V	79.7			0.45	0.25
2.1-4-V	23.9	6	200	2.2	1.44
2.1-2-V	50.5			1.0	0.5
2.1-1-V	79.7			0.4	0.25
2.1-6-V	80			0.4	0.26
2.1-11-V	200.1			0.17	0.09
2.1-4-V	23.9	8	500	7.8	2.5
2.1-2-V	50.5			3 8	1.2
2.1-5-V	49.9			3.4	1.2
2.1-5-DR	49.9			...	1.2
2.1-1-V	79.7			2.0	0.55
2.1-6-V	80			1.6	0.5
2.1-11-V	200.1			0.6	0.2
2.1-17-VA	366.6			0.28	0.1
2.1-4-V	23.9	10	1000	13	5
2.1-5-V	49.9			5.1	1.8
2.5-5-DR				...	2.2
2.1-2-V	50.5			6	2.1
2.1-1-V	79.7			2.6	0.9
2.1-6-V	80			2.4	0.6
2.1-11-V	200.1			0.83	0.28
2.1-17-VA	366.6			0.4	0.14

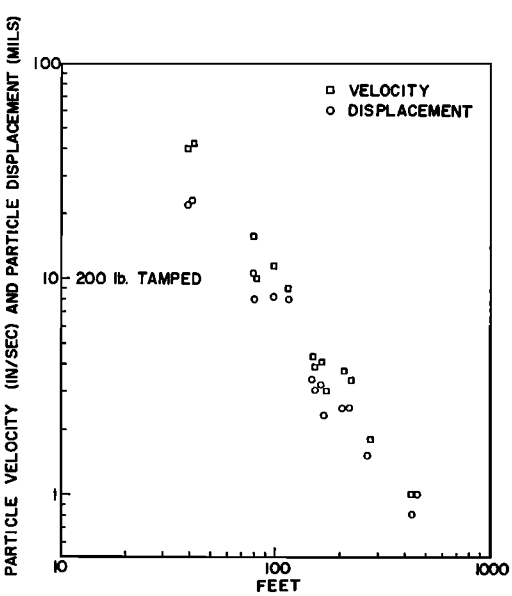

Fig. 2. Peak velocity and displacement versus distance for 200-pound tamped explosions.

This plot shows that, over the range of scaled distances from 4 to 80, peak velocities fall off with distance as $r^{-1.65}$.

Similarly, Figure 5 is a plot of observed peak displacements for all tamped explosions. However, peak displacement divided by $W^{1/3}$ must be used in the scaled plot. $d/W^{1/3}$ is found to depend on distance as $r^{-1.65}$.

Apparent differences in the frequencies of signals from tamped and cavity explosions may be inferred qualitatively from inspection of the corresponding velocity-time recordings. Copies of actual velocity measurements made by an oscillograph recording on film are reproduced in Figures 6 and 7.

Notable for the coupled shots is the fact that rise time for the change in particle velocity is slow enough for the gage to follow the motion with some accuracy. Such is not the case for the decoupled shots. The high frequency to be seen on the recordings of velocities from decoupled explosions is caused by ringing of the canister containing the gages. The degree of ringing varies from gage to gage because of variation in precautions taken to avoid the ringing. This ringing

TABLE 4. Peak Velocities and Displacements, 6-Foot Cavity

Gage	Distance, ft	Shot No.	W, lbs	Peak Vel., in/sec	Peak Displ., mils
1.1-2-V	20.7	3	20	0.7	...
1.1-1-V	35.1			0.5	...
1.1-6-V	36.2			0.45	...
1.1-5-V	19.6	4	100	3.4	...
1.1-2-V	20.7			2.1	...
1.1-1-V	35.1			1.3	...
1.1-6-V	36.2			1.9	...
1.1-5-V	19.6	12	929	32	21.3
1.1-2-V	20.7			24.5	16
1.1-1-V	35.1			12.5	6.7
1.1-6-V	36.2			10.5	7.8
1.1-9-V2	100.7			4	2.4
2.1-17-VB	461.2			0.3	0.3
1.1-5-V	19.6	14	1903.4	71	52
1.1-2-V	20.7			54	43
1.1-1-V	35.1			26.5	18.5
1.1-6-V	36.2			27	19
1.1-9-V2	100.7			6.7	5.5
2.1-17-VB	461.2			0.6	0.6

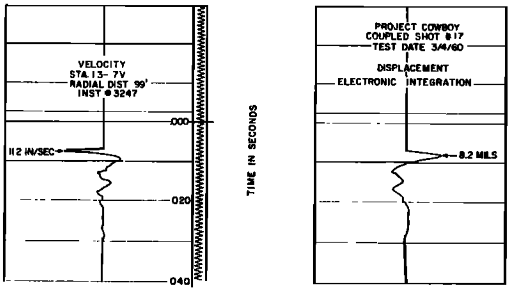

Fig. 3. Velocity-time recording and corresponding integration.

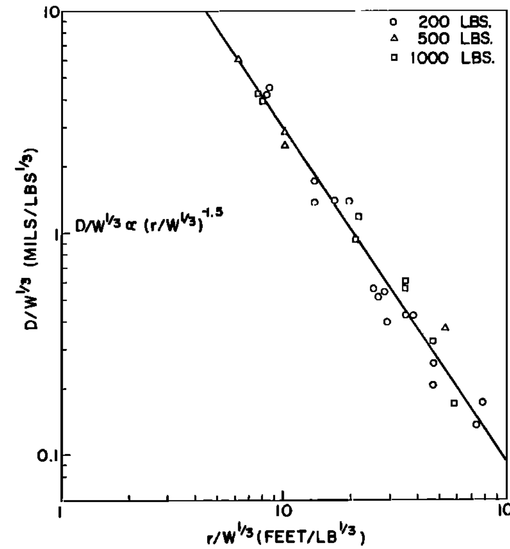

Fig. 5. Scaled peak displacements versus scaled distance for all tamped explosions.

can be filtered out in playing back data from magnetic-tape recordings; indeed this is done automatically during integration to give displacement. It is questionable whether actual peak particle velocity is always recorded accurately for decoupled explosions. The inaccuracy involved can be guessed at by extrapolating back to arrival time of the shock front, if it is assumed that a step shock front existed.

Since the pressure on the cavity wall from an explosion is not truly a step function, actual pressure-time histories in the cavity were desired over both short and long time intervals. Pressure gages were placed near the door and at horizontal angles of 45° and 90° from the door. A slow-response pressure gage was also placed near the door to measure cavity pressure at long times after the explosion.

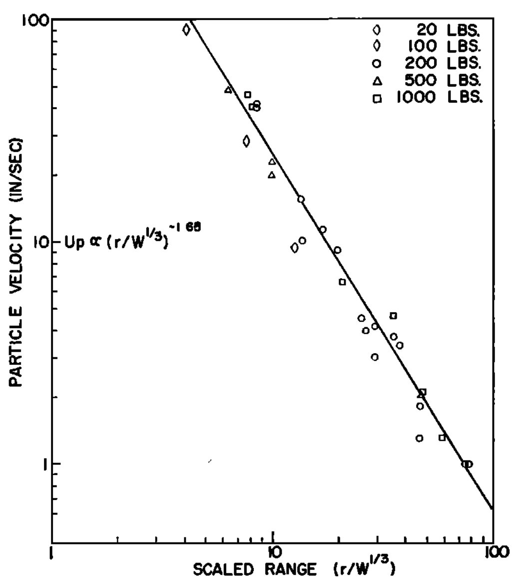

Fig. 4. Peak velocity versus distance/$W^{1/3}$ for all tamped explosions.

The best illustration of pressure versus time in the cavity is provided by results from shot 10. Data recorded from one of the gages is illustrated in Figure 8 for 1000 pounds of Pelletol in the cavity of 15-foot radius. The first pressure pulse had an amplitude near 900 psi, the second about 300 psi, and the third about 100 psi. The gas pressure continued to oscillate for some time. Figure 9 illustrates the cavity pressure at long times for the same explosion. This gage was purposely arranged to have a long fill time so that it would not record peak transient pressures. The cavity pressure at 100 milliseconds is 90 psi, or about one-tenth of the initial peak pressure.

Comparative peak pressures and pressures at 100 msec after zero time for explosions in the 15-foot cavity are listed in Table 5.

TABLE 5. Pressures in 15-Foot Cavity

W, lbs	Shot No.	Peak Pressure, psi	Pressure at 100 msec, psi	$p = \frac{(\gamma - 1)W}{4/3\pi\ 15^3}$, psi
198	5	~300	22	28
477	8	500	44	67
954	10	900	92	135

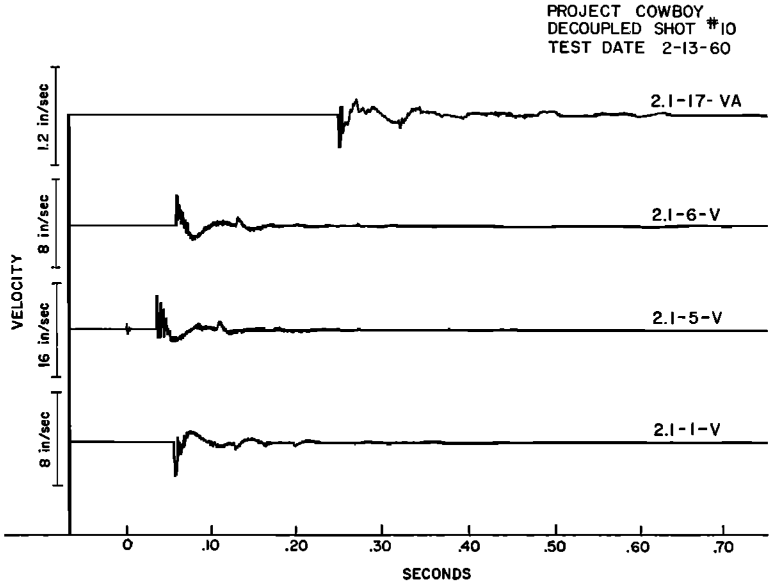

Fig. 6. Particle velocity versus time (1000 pounds, decoupled, 15-foot cavity, shot 10, Feb. 13, 1960).

In the table, $\gamma = 1.2$ has been used because the cavity was evacuated and the energy release of Pelletol was assumed to be 1000 cal/g. If the pressure at 100 msec is extrapolated back to zero time and if peak pressure is ignored, values closer to calculated pressures are obtained.

Analysis of results. Given observed data for tamped chemical explosions in halite and theoretical behavior of a cavity, a decoupling factor can be calculated. This calculation will be compared with data obtained from the cavity explosions.

From the peak velocity and displacement for tamped explosions, plotted in Figures 4 and 5, an effective elastic radius as a function of distance can be computed from the expression

$$a_t \cong c\ d/u$$

(For a precise expression the exact form of the stress curve would have to be taken into account; the above expression gives a low estimate of a_t.) The velocity of sound c is observed from transit time between gage positions to be about 14,500 ft/sec. The equation then gives, for a charge of 1000 pounds, an effective elastic radius of 22.8 ft as observed from 1000 ft away, or a radius of 16 ft as observed from 50 ft.

This variation in radius reflects a variation in d/u with distance. Presumably the ratio will not continue to change much more at greater distance, although complete change-over to $1/r$ behavior is not yet evident at 1000 feet. At scaled distances $r/W^{1/3} = 100$, the value of a_t will be $2.3W^{1/3}$ for explosions of Pelletol in halite. If the approximation that $c/a_t = 2\pi f$ is valid, the observed positive phase duration T of the velocity pulse should be approximately equal to $1/2f$ or $\pi a_t/c$. Since $\pi a_t/c = 5$ msec and $T = 3$ to 4 msec, it is unlikely that a_t is much larger than 23 feet for explosions of 1000 pounds of Pelletol in halite. However, assumptions of elastic behavior beyond the 'elastic radius' a_t are not entirely correct because a_t depends on the distance of observation.

The effective value of p_0 at a can be calculated from

$$u = (p_0/\rho c)(a_t/r)$$

If we take

$r =$ 1000 feet
$u =$ 0.59 in/sec $=$ 1.5 cm/sec
$a_t =$ 23 feet
$\rho =$ 2.13 g/cm^3
$c =$ 14,500 ft/sec $= 4.4 \times 10^5$ cm/sec, then
$p_0 =$ 61 bars $=$ 900 psi $\cong$1000 psi.

Provided that the cavity can withstand 1000 psi and that an explosion yield is chosen to give

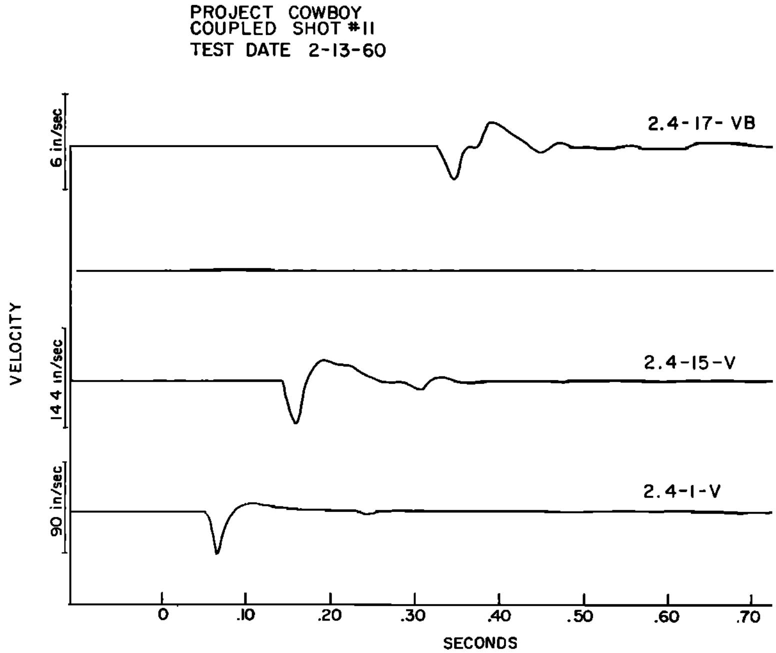

Fig. 7. Particle velocity versus time (1000 pounds, coupled, shot 11, Feb. 13, 1960).

1000 psi in the cavity, the theoretical distant decoupling factor is simply a_t^3/a^3, where a_t is the tamped elastic radius and a is the cavity radius. From (2), the value of W required to give 1000 psi in a 15-foot cavity is 6900 pounds. The corresponding a_t is 44 feet. This 'theoretical' distant decoupling factor a_t^3/a^3 is 25 for halite. Comparison with close-in observation follows.

Observed decoupling factors for peak velocities and displacements permit calculation of distance decoupling factors for each halite experiment. From (9), (10), and (11), the distant decoupling factor is given by $d_t^2u_c/d_c^2u_t$.

Results in Table 6 yield numbers as much as 4 to 5 times larger than the number calculated above.

The third column gives distant decoupling factors which would be observed by distant velocity or displacement meters that were responsive at low frequencies. *The numbers apply only to the specific experiment to which they refer*, i.e., tamped and cavity HE explosions in halite. Smaller numbers could easily be observed in the Cowboy experiments by nearby surface instruments of proper frequency response.

The numbers listed in column 3, Table 6, are not precise, since the condition that the comparison be made in the region where velocities fall off inversely as distance is not fulfilled. Table 7 shows how the numbers vary with distance of comparison.

The reason the decoupling factor is higher for the higher-yield explosions in the 15-foot cavity is simply that the recorded pulse from the cavity is relatively sharper for the higher-yield ex-

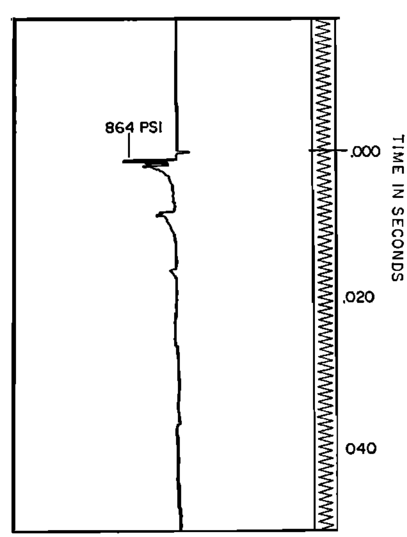

Fig. 8. Pressure versus time (1000 pounds, decoupled, 15-foot cavity, Feb. 13, 1960).

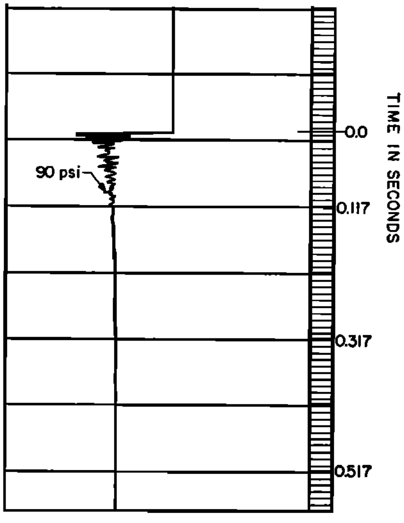

Fig. 9. Cavity pressure at long times (1000 pounds, decoupled, 15-foot cavity, Feb. 13, 1960).

plosions. The duration of the velocity pulse from the tamped explosion increases with yield as $W^{1/3}$. Velocity pulses for the cavity retained a higher-frequency content than would be characteristic for the oscillating cavity and are really more characteristic of the driving pressure pulses.

The reason that the observed distant decoupling factors are nearer 100 than 25 appears to be that more of the energy is concentrated in high frequencies than is allowed for in the calculation. The after pressure at 100 msec is also smaller than was calculated from (2). Experimentally, the after pressure at 100 msec from 1000 pounds in the 15-foot cavity was 92 psi. According to this observation, 11,000 pounds of Pelletol would be required to give 1000 psi at

TABLE 6. Decoupling Factors for HE in Halite (from peak values)

u_t/u_c	d_t/d_c	$\frac{(d_t/d_c)^2}{u_t/u_c}$	W, lbs	r, ft	Shot No. (cavity)	Cavity Radius, ft
20	30.5	47	200	200	6	15
7.3	23	72	500	370	8	15
7.5	30	120	1000	365	10	15
35	...	...	20	35	2	6
25	...	...	100	35	3	6
6.7	10	15	1000	460	12	6
5	8.6	15	2000	460	14	6

TABLE 7. Decoupling versus Distance of Close-in Observation

u_t/u_c	d_t/d_c	$\frac{(d_t/d_c)^2}{u_t/u_c}$	r, ft	Shot No.
15	39.2	100	50	8
13.9	43.8	138	80	8
9.3	29	91	200	8
7.3	23	72	370	8

100 msec after the explosion. On this basis, a_t for 11,000 pounds is 51 feet and a_t^3/a^3 would be 40. Since the effective value of a_t calculated from distant observations would be larger than that used here, distant decoupling factors between 40 and 100 can be estimated from the close-in observed peak velocities and displacements for these particular Cowboy experiments in the 15-foot cavity.

The same calculation made for the 15-foot cavity can be made for the 6-foot cavity and should give the same result. The filling weight to give 1000 psi is 710 pounds, for which $a_t = 20.6$ feet and $a_t^3/a^3 = 40$.

Extrapolation of peak velocities and displacements from Tables 2 and 4 to the 6-foot cavity wall gives peak velocity = 130 in/sec and peak displacement = 0.1 in. The corresponding peak radial-compressive strain and peak tangential-tensile strain are, therefore, for 929 pounds of Pelletol:

$$E_r = u/c = 750\ \mu\text{in/in} \qquad \text{compression}$$

$$E_t = d/r = 1400\ \mu\text{in/in} \qquad \text{tension}$$

Similarly, for 1900 pounds in the 6-foot-radius cavity:

$$E_r = 1800\ \mu\text{in/in} \qquad \text{compression}$$

$$E_t = 4200\ \mu\text{in/in} \qquad \text{tension}$$

Unconfined halite specimens in laboratory tests exhibit a Young's modulus near 800,000 psi and tensile failure at less than 100 psi. Tensile strength of the cavity wall is almost entirely due to overburden compressive stress that must be overcome before the wall goes into tension. Since large tensile strains occurred, the wall developed tensile cracks. Compressive strains were too small to result in failure in compression, a value of several thousand μin/in would be required.

At the time of maximum tangential-tensile strain, the radial strain is zero. Shortly afterwards small tensile radial strain develops, so that some spalling would occur if a large enough shot were fired in the cavity. As yield increases from small values, radial cracking extends farther and farther from the wall, causing the cavity to be inelastic. Apparently serious cracking does not occur until the confining overburden pressure is considerably exceeded.

Propagation velocities in the halite were observed from transit time between velocity gages to be 14,500 to 15,000 ft/sec. In this report we have used $c = 14{,}500$ ft/sec for halite and $\rho = 2.13$ g/cm^3. With these numbers, $\lambda + 2\mu =$ 415 kilobars. If $\lambda = \mu$, then $\sigma = 0.25$ and $\mu = 137$ kilobars, or if $\lambda = 2\mu$, then $\sigma = 0.3$ and $\mu = 103$ kilobars.

Shear-wave velocity was not determined from our records, since gages were always radial except for the distant accelerometers where reflections obscure the data.

Conclusions. Radial motion close to tamped explosions in halite was adequately determined over scaled distances from 6 to 80 ft/lb$^{1/3}$. Permanent displacements at the closest ranges were considerably less than would be expected for incompressible motion. Evidently, measurements as close as a scaled distance of 2 ft/lb$^{1/3}$ are needed to obtain an accurate measure of permanent displacement from tamped explosions. It is suggested that, for 1000-pound explosions, measurements be obtained at distances of 20, 30, and 50 feet, but it should be noted that accelerometers or long-base displacement gages would have to be used. Larger explosions would make measurements easier to obtain. Radial stress measurements should also be made in the halite at the same distances, as a check on the degree of elasticity.

Adequate measure of motion near the cavities is difficult to obtain because the centrally located charge gives a fast-rising, short-duration pulse that is difficult to measure unless the HE charges are large. Measurements for charges of 500 pounds and larger appear to be good enough. Low-frequency motions near the cavities were too small to measure. Use of gas in the cavities would presumably make the fast pressure pulse less signfiicant and make measurement easier.

Enough transient measurements were obtained to make possible a calculation of the motion near the 15-foot cavity. For such calculations we need use only the observed pressure-time history on the wall as an input to equation described by *Sharpe* [1942] or *Blake* [1952]. Computed transient velocities may then be compared with observations of velocity versus time. Such calculations will be published separately. Clearly, motion of the medium near the cavity depends on details of the pressure-time history in the cavity. Empirically, motion at large distances from the cavity falls off faster than r^{-1}. If this is due to attenuation of high frequencies caused by frictional effects, it will not occur to the same extent for larger cavities and larger explosions. Scaling of these data to very large chemical explosions is not necessarily accurate.

Data obtained from Cowboy definitely prove that decoupling in halite of from 40 to 100 can be obtained for high explosives. Actual measurements (verbal communication from Herbst, 1960) of distant decoupling factors give larger numbers by a factor of 2. Experimental proof of the degree of decoupling that could be obtained from nuclear explosions can be obtained only from nuclear explosions, for two reasons: (1) A tamped nuclear explosion causes a very high initial pressure in the medium. In fact, the starting pressure increases with nuclear yield, so that nuclear explosions of different yield do not even exhibit similar behavior. Thus, the similarity principle invoked for various-yield chemical explosions cannot be used in the same way for nuclear explosions. (2) A nuclear explosion in a cavity will behave in a manner different from a chemical explosion simply because of the very different pressure-time history of the nuclear explosion. However, a nuclear shot in a cavity has been calculated [*Latter, LeLevier, Martinelli and McMillan*, 1961] to give the same signal at large distances as a chemical explosion of the same yield.

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